Significance of studies on Light Hypernuclei

E. Hiyama (RIKEN)

2016/3/15 JLab Hyp. WS

The 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

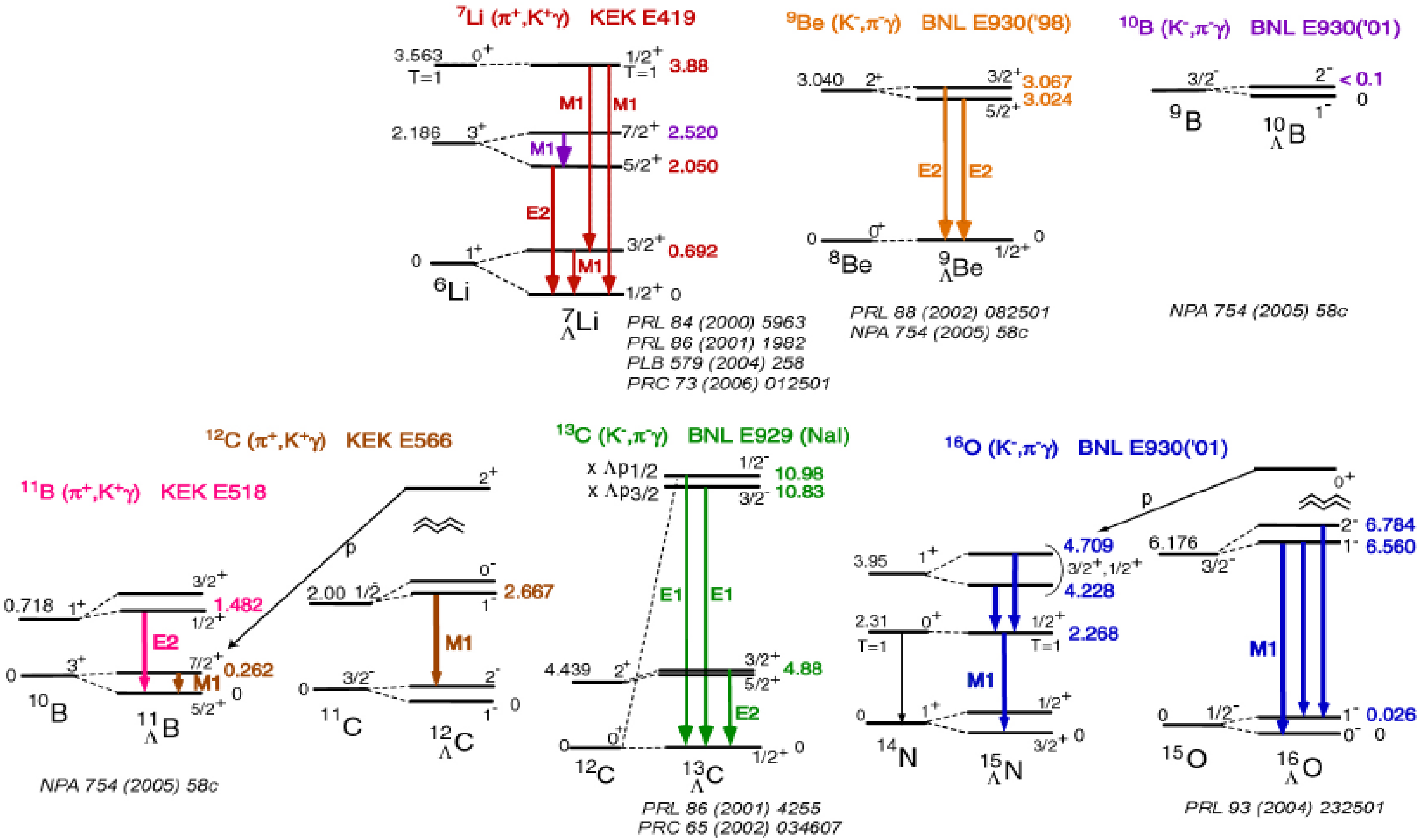
- Total number of differential cross section Hyperon (Y) -Nucleon (N) data: **40**
- **NO** YY scattering data

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)



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

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

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

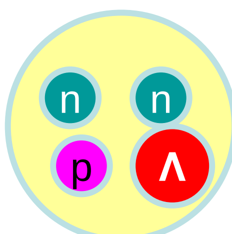
(1) Charge symmetry breaking

(2) ΛN－ΣN coupling

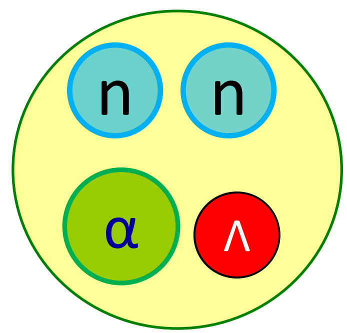
J-PARC : Day-1 experiment E13

Jlab E05-115,

Mainz



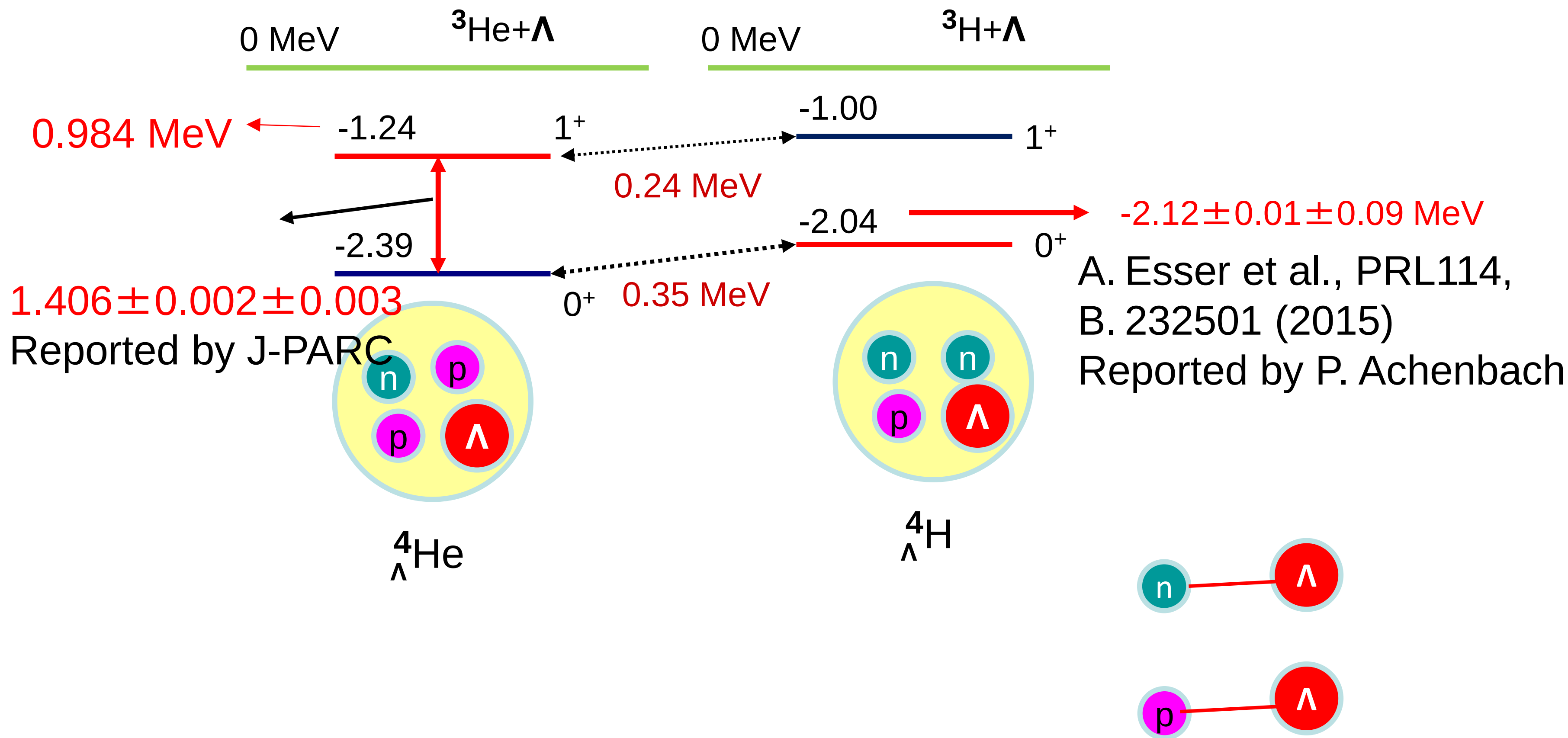
$^{4}_{\Lambda}$H



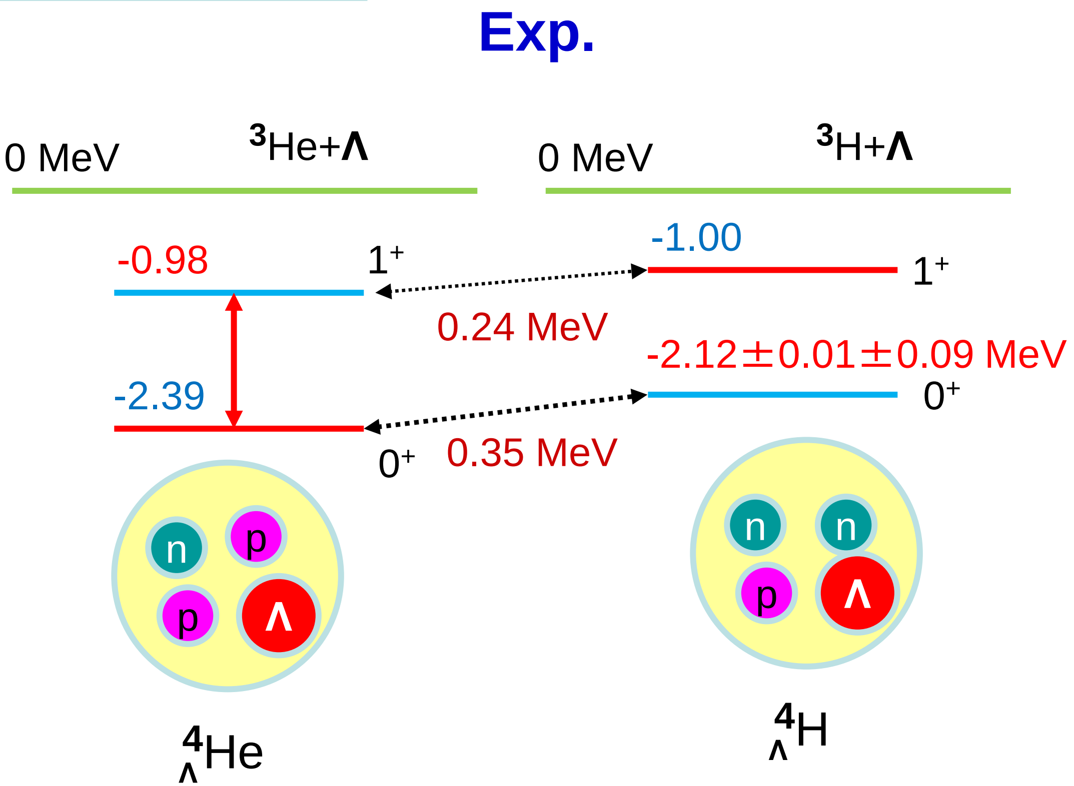
$^{7}_{\Lambda}$He

In S= -1 sector

Exp.



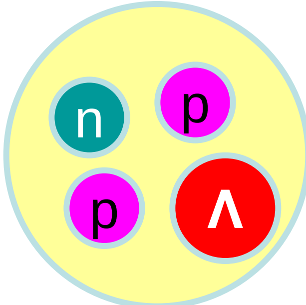
In S= -1 sector



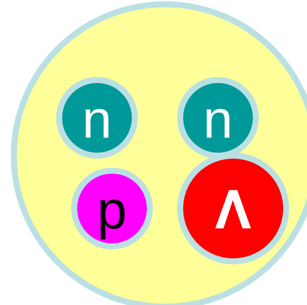
Homework:
Please confirm below two states.
(1) The ground state of ${}^{4}_{\Lambda}He$
(2) The excited state of ${}^{4}_{\Lambda}H$
=> JLab

In this way, it is important to confirm all of four states in A=4 Λ hypernuclei.

After confirmation,
I am planning to calculate following…



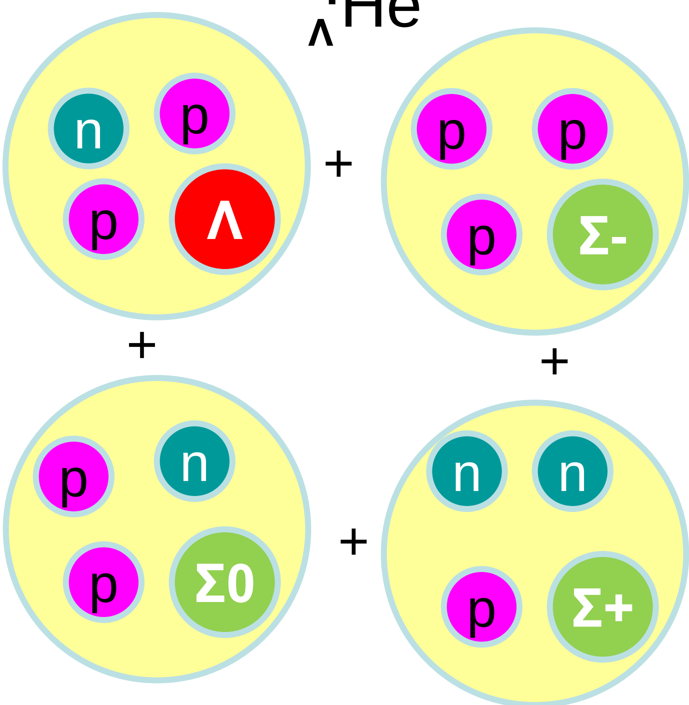
$^{4}_{\Lambda}$He



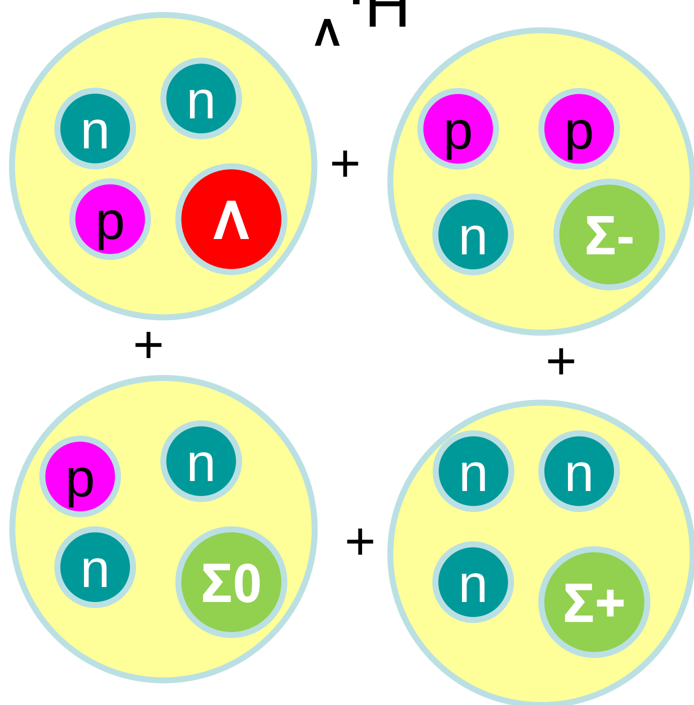
$^{4}_{\Lambda}$H

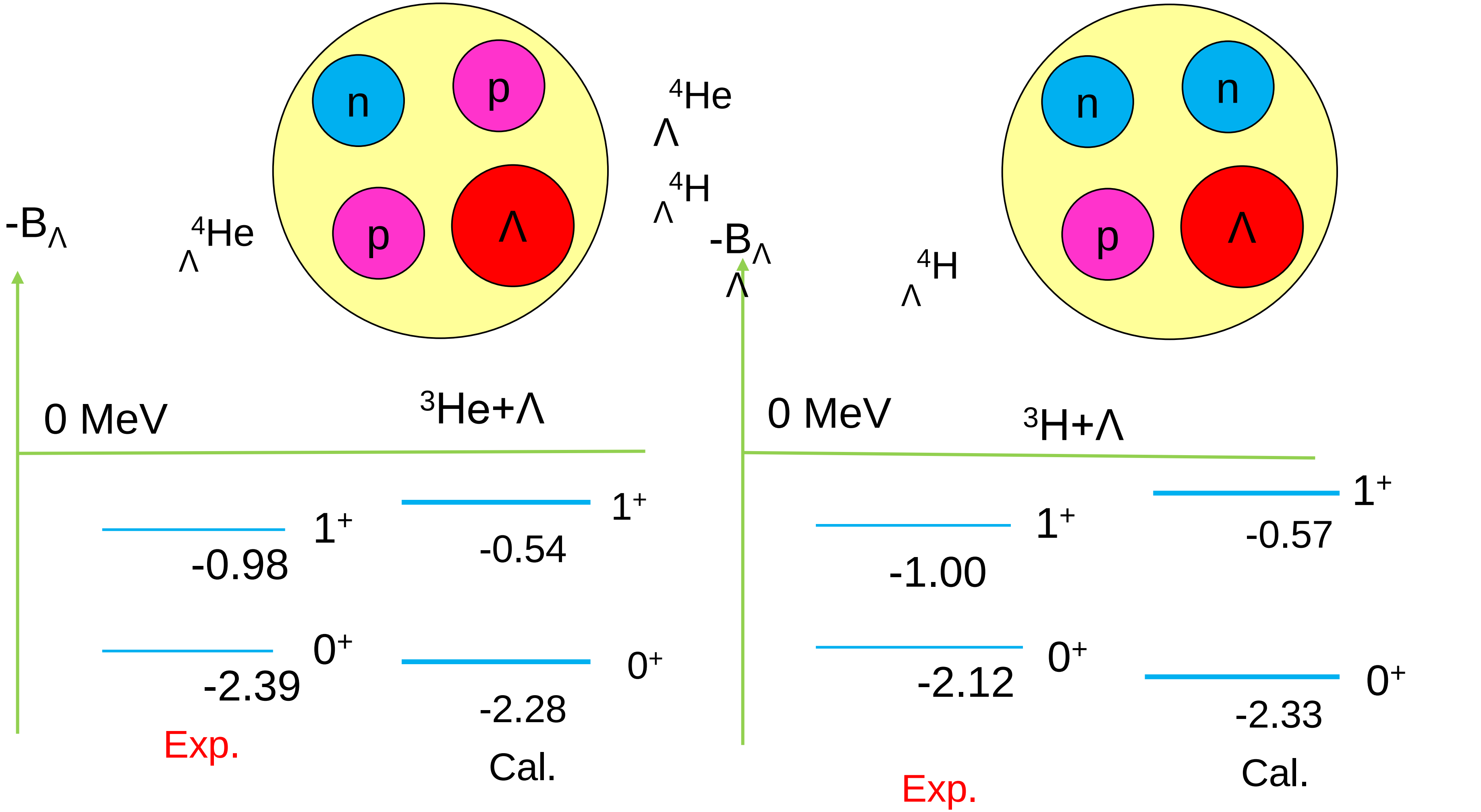
However, Λ particle has no charge.

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



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





Our four-body calculation using NSC97f potential.
You see that the results do not reproduce the data.
This means that we need more reliable YN interaction.
After confirmation experiment, by combining new data and our calculation, we can finally solve CSB important issue.

In S= -1 sector,
what are the open questions in YN interaction?

(1) Charge symmetry breaking

(2) ΛN－ΣN coupling

J-PARC : Day-1 experiment JLAB

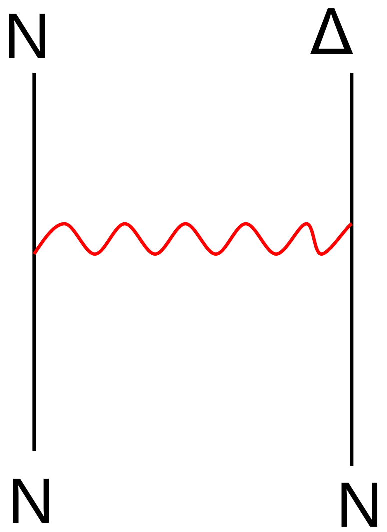
・E13 "γ-ray spectroscopy of light hypernuclei"
by Tamura and his collaborators

$^{11}_{\Lambda}B$ $^{4}_{\Lambda}He$

・E10 "Study on Λ-hypernuclei with the doubleCharge-Exchange reaction"
by Sakaguchi , Fukuda and his collaboratiors

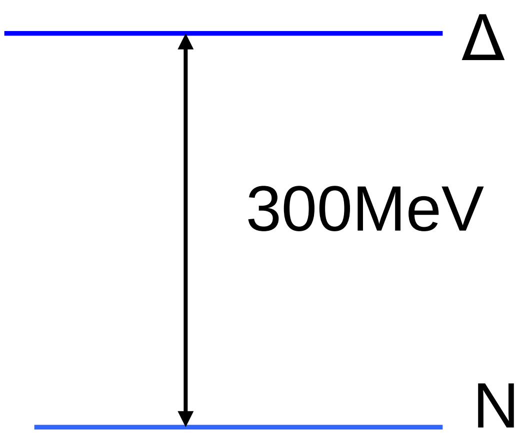
$^{9}_{\Lambda}He$ $^{6}_{\Lambda}H$

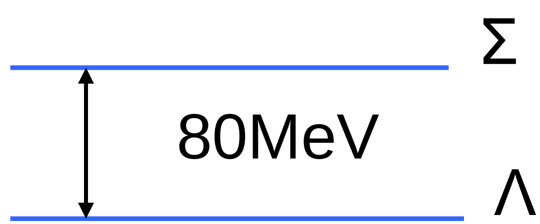
Non-strangeness nuclei

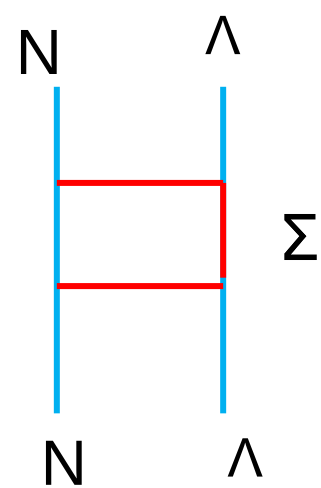


Nucleon can be converted into Δ. However, since mass difference between nucleon and Δ is large, then probability of Δ in nucleus is not large.

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



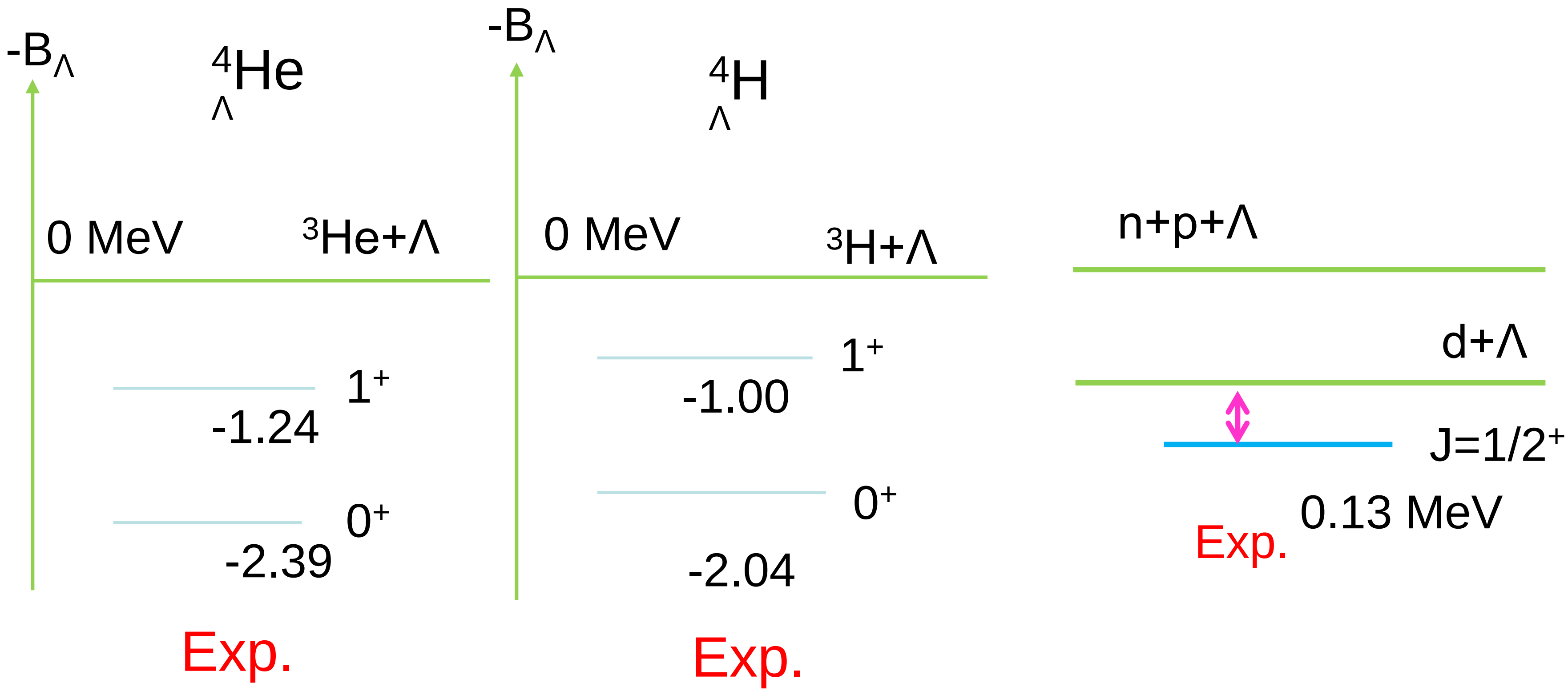


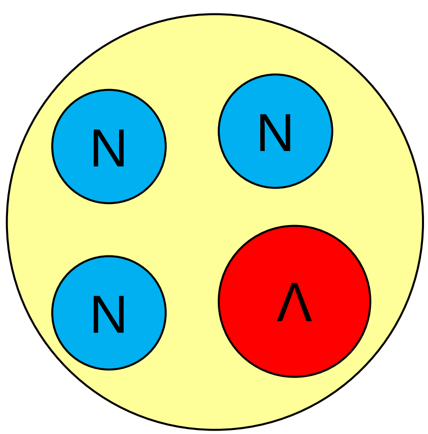


Interesting Issues for the ΛN-ΣN particle conversion in hypernuclei

(1)How large is the mixing probability of the Σ particle in the hypernuclei?

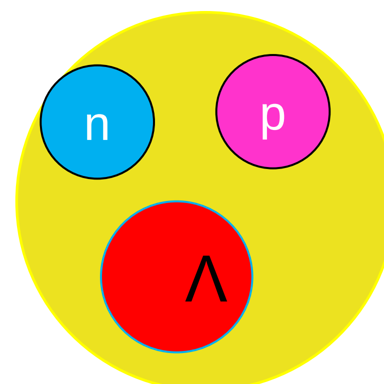
(2) How important is the ΛN—ΣN coupling in the binding energy of the Λ hypernuclei?





$^4_\Lambda$He

$^4_\Lambda$H



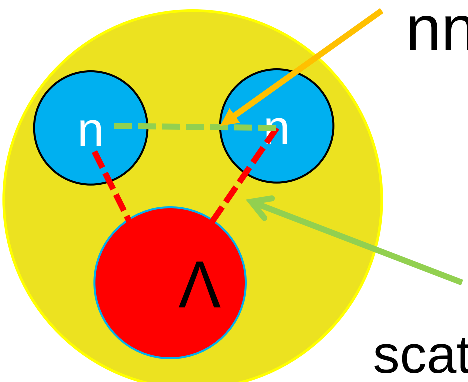
These hypernuclei are suited for studying ΛN-ΣN coupling.

$^3_\Lambda$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 ${}^{6}\mathrm{Li} + {}^{12}\mathrm{C}$ 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

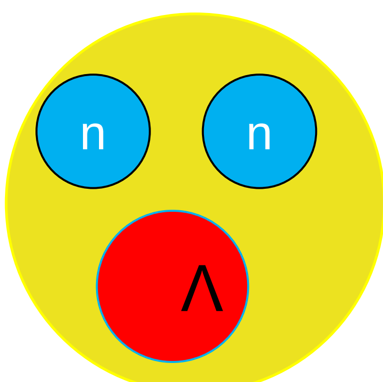
nnΛ breakup threshold

?
They did not report the binding energy.

scattering length:-2.68fm

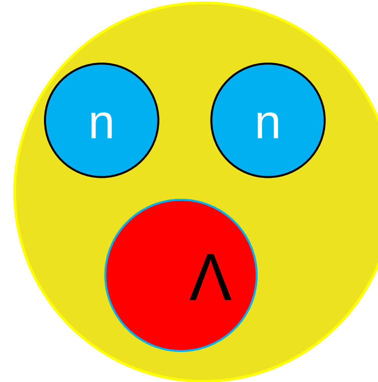
Observation of nnΛ system (2013)
This is also important to get information on ΛN-ΣN coupling.

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



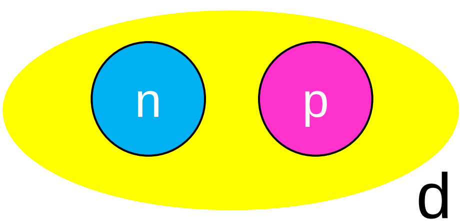
E. Hiyama, S. Ohnishi,
B.F. Gibson, and T. A. Rijken,
PRC89, 061302(R) (2014).

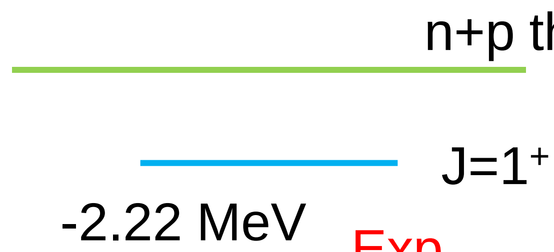
What is interesting to study nnΛ system?



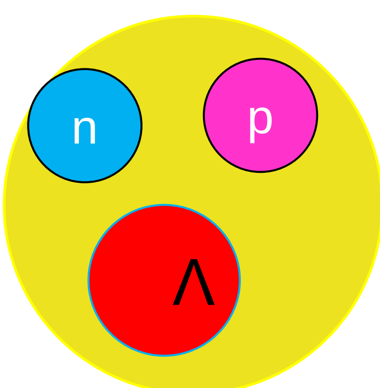
S=0

The lightest nucleus to have a bound state is deuteron.



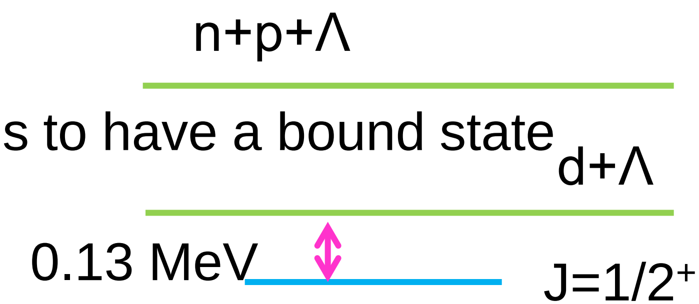


S=-1 (Λ hypernucear sector)



Lightest hypernucleus to have a bound state

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



Exp.

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

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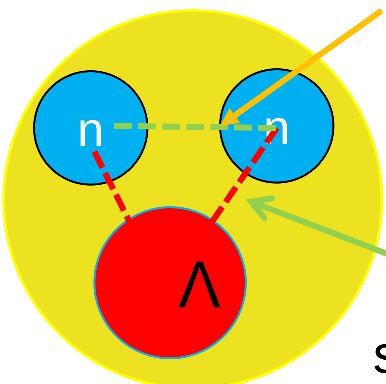


nn unbound

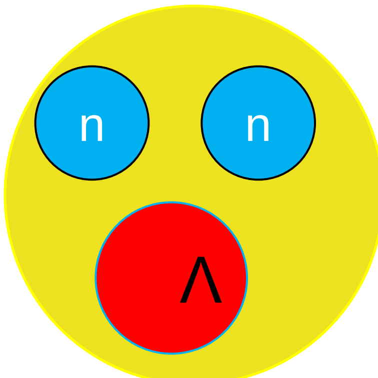
nnΛ breakup threshold

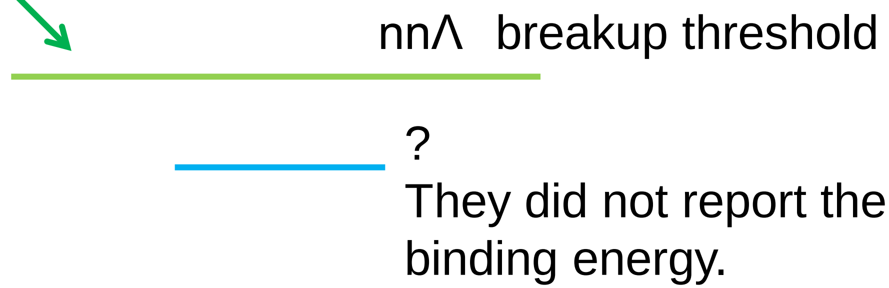
?
They did not report the binding energy.

scattering length:-2.68fm

Observation of nnΛ system (2013)
One of the lightest bound hypernuclei

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?



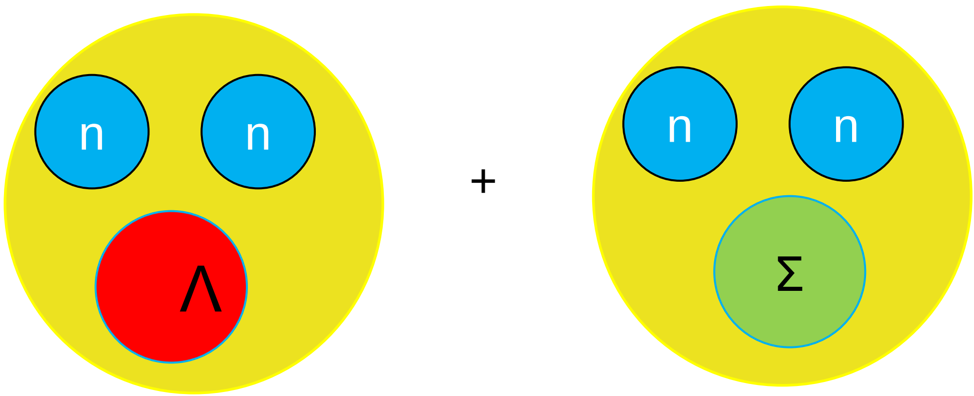


NN interaction : to reproduce the observed binding energies of ^{3}H and ^{3}He

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

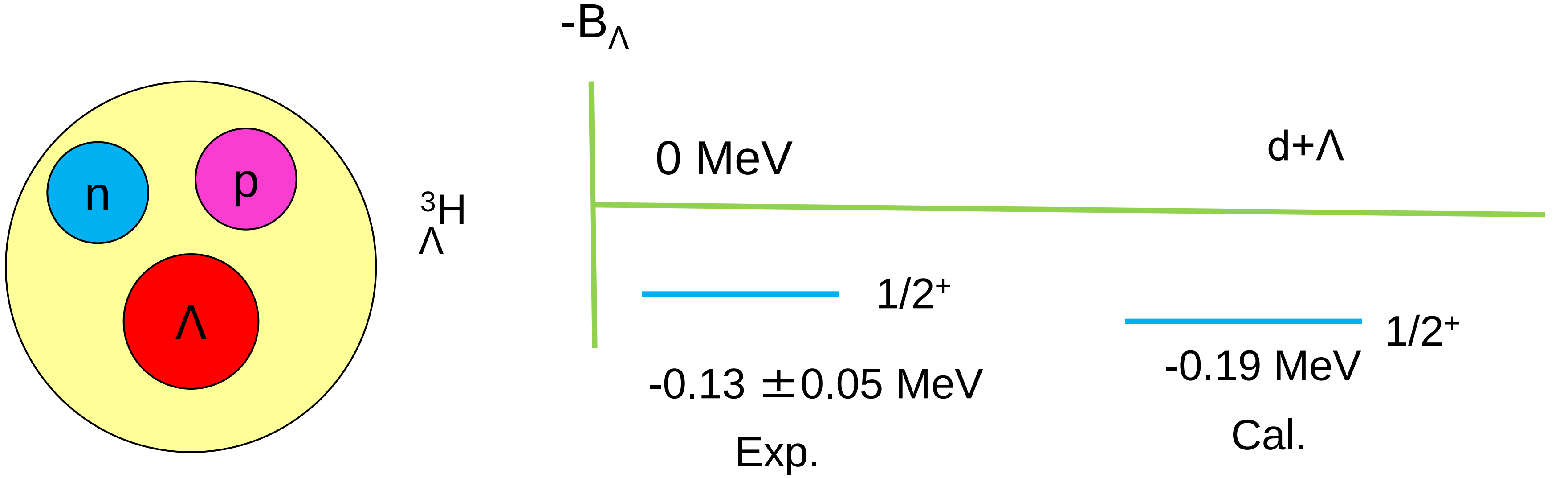
How about YN interaction?

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.

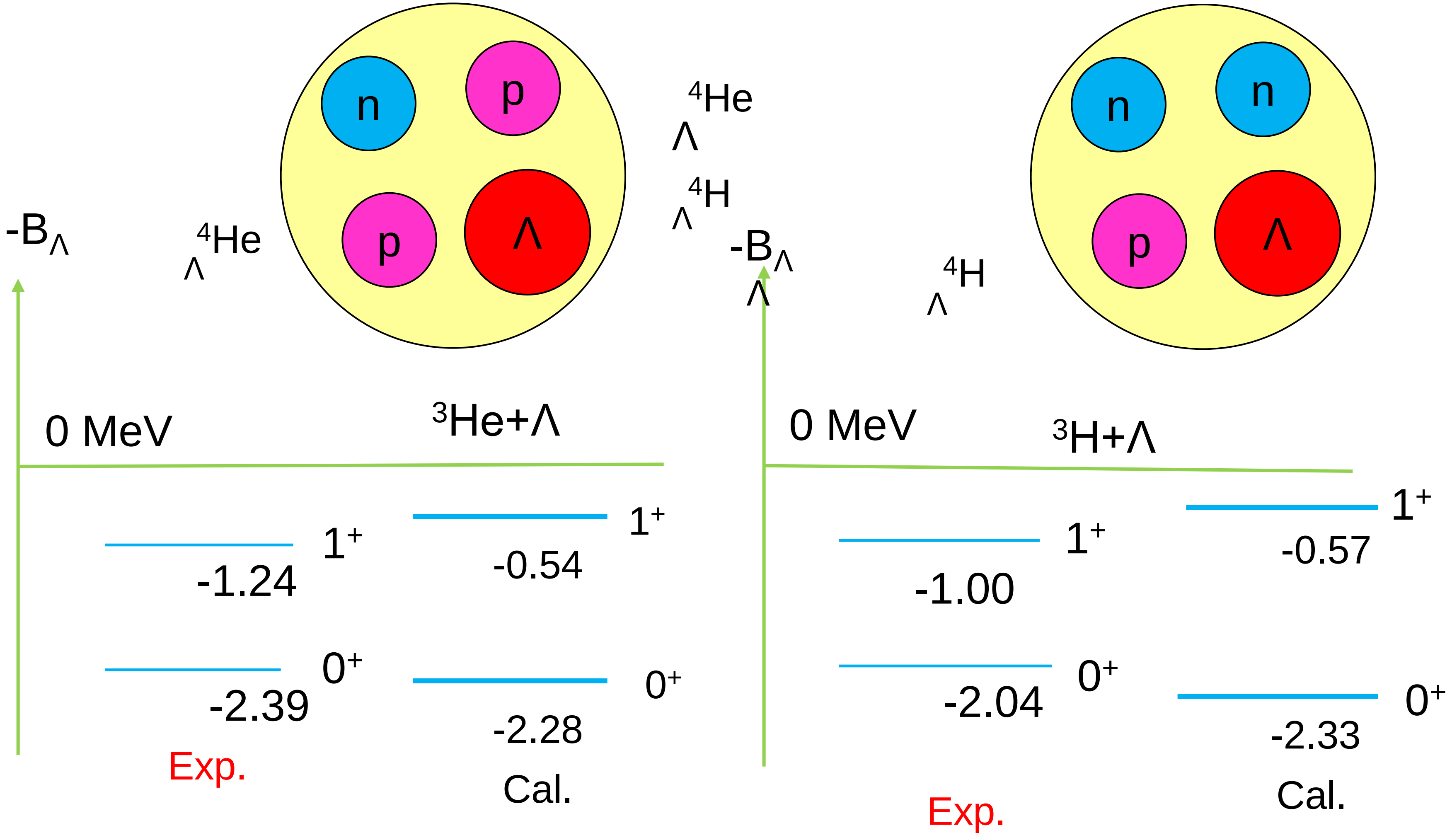


YN interaction: Nijmegen soft core '97f potential (NSC97f) proposed by Nijmegen group

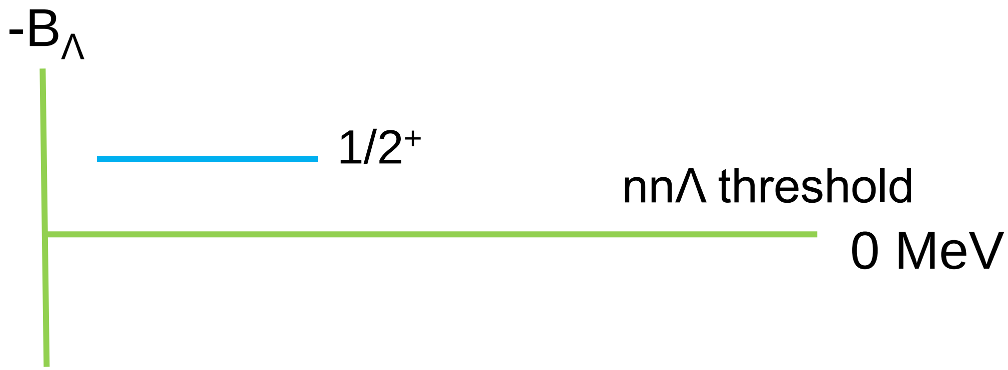
reproduce the observed binding energies of $^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$ and $^{4}_{\Lambda}He$

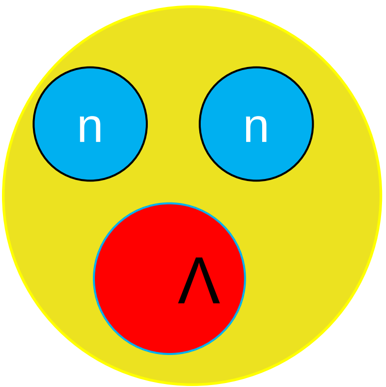


n
p
Λ
${}^{3}_{\Lambda}H$
$-B_{\Lambda}$
0 MeV
d+Λ
1/2+
1/2+
-0.13 ±0.05 MeV
-0.19 MeV
Exp.
Cal.



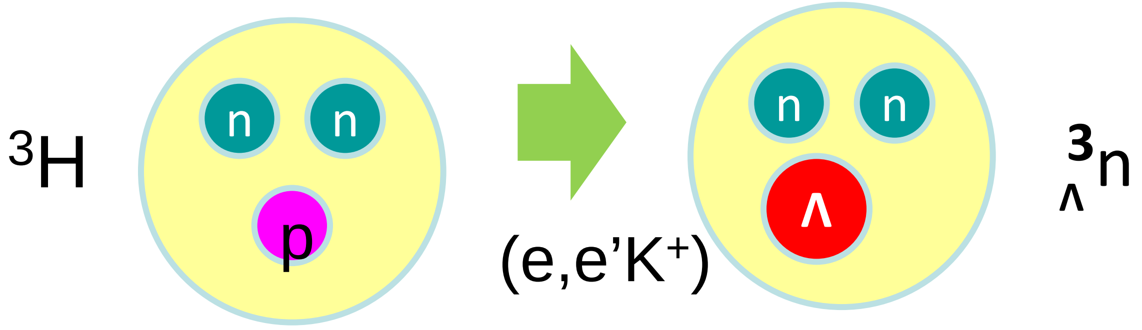
What is binding energy of nnΛ?





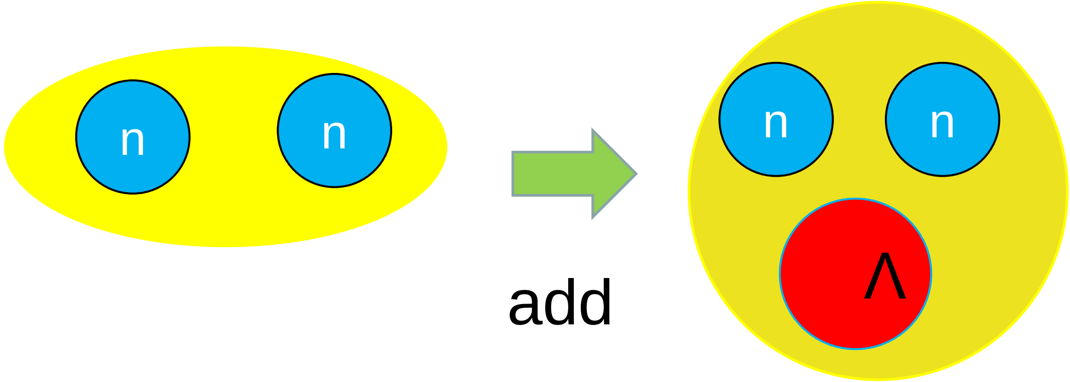
We have no bound state in nnΛ system.
This is inconsistent with the data.

In this way, we have no possibility to have a bound state for nnΛ system.
Then, I hope that confirm experiment of this system will be performed again at GSI or JLab using ^{3}H target.

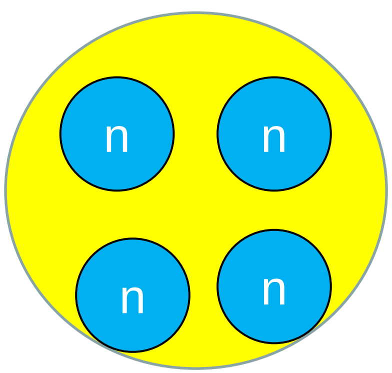


Also, it is pointed out that nnΛ system might be resonant state by Dr. Gibson. He will give a talk about it in this workshop.

Now, we have a question. If we add more two neutrons
In this system, what happen?



four-body calculation of ^{4}n



PRL 116, 052501 (2016)

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

week ending 5 FEBRUARY 2016

Candidate Resonant Tetraneutron State Populated by the ^{4}He(^{8}He,^{8}Be) Reaction

K. Kisamori,[1,2] S. Shimoura,[1] H. Miya,[1,2] S. Michimasa,[1] S. Ota,[1] M. Assie,[3] H. Baba,[2] T. Baba,[4] D. Beaumel,[2,3] M. Dozono,[2] T. Fujii,[1,2] N. Fukuda,[2] S. Go,[1,2] F. Hammache,[3] E. Ideguchi,[5] N. Inabe,[2] M. Itoh,[6] D. Kameda,[2] S. Kawase,[1] T. Kawabata,[4] M. Kobayashi,[1] Y. Kondo,[7,2] T. Kubo,[2] Y. Kubota,[1,2] M. Kurata-Nishimura,[2] C. S. Lee,[1,2] Y. Maeda,[8] H. Matsubara,[12] K. Miki,[5] T. Nishi,[9,2] S. Noji,[10] S. Sakaguchi,[11,2] H. Sakai,[2] Y. Sasamoto,[1] M. Sasano,[2] H. Sato,[2] Y. Shimizu,[2] A. Stolz,[10] H. Suzuki,[2] M. Takaki,[1] H. Takeda,[2] S. Takeuchi,[2] A. Tamii,[5] L. Tang,[1] H. Tokieda,[1] M. Tsumura,[4] T. Uesaka,[2] K. Yako,[1] Y. Yanagisawa,[2] R. Yokoyama,[1] and K. Yoshida[2]

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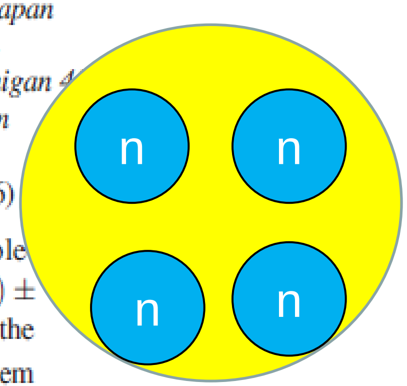
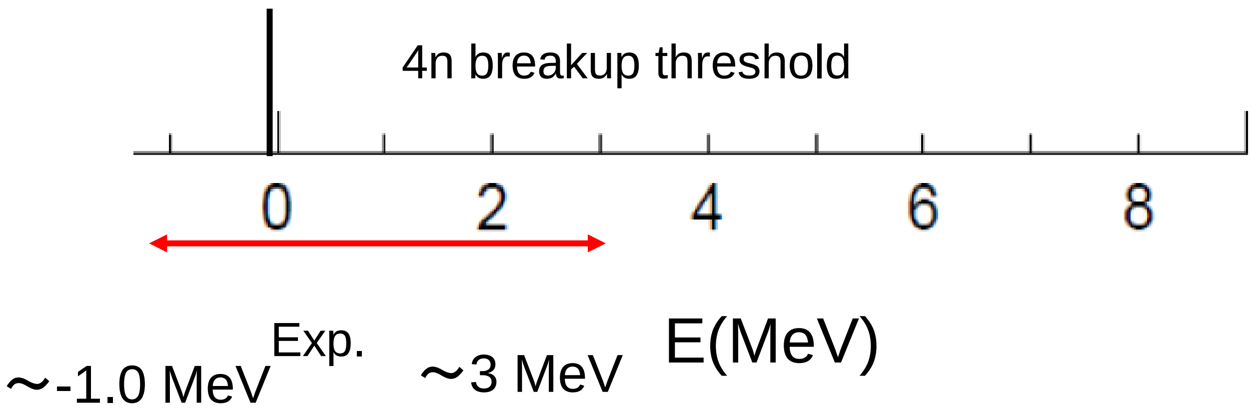
[12]*National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage, Chiba, Japan*

(Received 30 July 2015; revised manuscript received 11 October 2015; published 3 February 2016)



A candidate resonant tetraneutron state is found in the missing-mass spectrum obtained in the double charge-exchange reaction ^{4}He(^{8}He, ^{8}Be) at 186 MeV/u. The energy of the state is $0.83 \pm 0.65(\mathrm{stat}) \pm 1.25(\mathrm{syst})$ MeV above the threshold of four-neutron decay with a significance level of 4.9σ. Utilizing the large positive Q value of the (^{8}He, ^{8}Be) reaction, an almost recoilless condition of the four-neutron system was achieved so as to obtain a weakly interacting four-neutron system efficiently.

DOI: 10.1103/PhysRevLett.116.052501



$$E_R = 0.83 \pm 0.65 \pm 1.25$$ Γ=2.6 MeV (Upper limit)

Now, we have new data for tetraneutron system.

Theoretical important issue:

・Can we describe observed 4n system using realistic NN interaction and T=3/2 three-body force?

Motivated by experimental data, we started to study tetra neutron system.

On the possibility of generating a 4-neutron resonance with $T = 3/2$ isospin 3-neutron forces

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Department of Physics, Kyushu University, Fukuoka 812-8581, Japan and
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(Dated: March 14, 2016)

Submitted in PRC.
We are waiting for referee comments.

$$E_R = 0.83 \pm 0.65 \pm 1.25$$ Γ=2.6 MeV (Upper limit)

For the study of tetraneutron system

We should consider interaction and method:

NN interaction: realistic NN interaction
Method: They reported the energy of tetraneutron was bound energy region to resonant energy region.
Especially, for the resonant energy region, we should use Complex scaling method.

For this purpose, we use AV8 NN interaction (central, LS, Tensor).
The NN potential is applicable for complex scaling method.

Any other missing part in our Hamiltonian?
We need T=3/2 three-nucleon force.
R. Lazauskas, and J. Carbonell, Phys. Rev. C72, 034003 (2005).
S.C. Peiper et al., Phys. Rev. Lett. 90, 252501 (2003).

As for 3 nucleon forces, we have Illinois potentials, for example.
However, this potential is too complicated to use in order to get resonant state with CSM.
At present, we use a simple potential. For this purpose, we use the following shape.

$$V_{ijk}^{3N} = \sum_{T=1/2}^{3/2} \sum_{n=1}^{2} W_n(T) e^{-(r_{ij}^2 + r_{jk}^2 + r_{ki}^2)/b_n^2} \mathcal{P}_{ijk}(T)$$

$$W_1(T = 1/2) = -2.04 \text{ MeV} \quad b_1 = 4.0 \text{ fm}$$
$$W_2(T = 1/2) = +35.0 \text{ MeV} \quad b_2 = 0.75 \text{ fm}$$

Two range Gaussian potentials
Four parameters are fixed so as to reproduce the low-energy properties of ^{3}H, ^{3}He and ^{4}He(T=0).

To answer these issues,
We employ AV8 NN potential + a phenomenological three-body force.

$$V_{ijk}^{3N} = \sum_{T=1/2}^{3/2} \sum_{n=1}^{2} W_n(T) e^{-(r_{ij}^2 + r_{jk}^2 + r_{ki}^2)/b_n^2} \mathcal{P}_{ijk}(T)$$

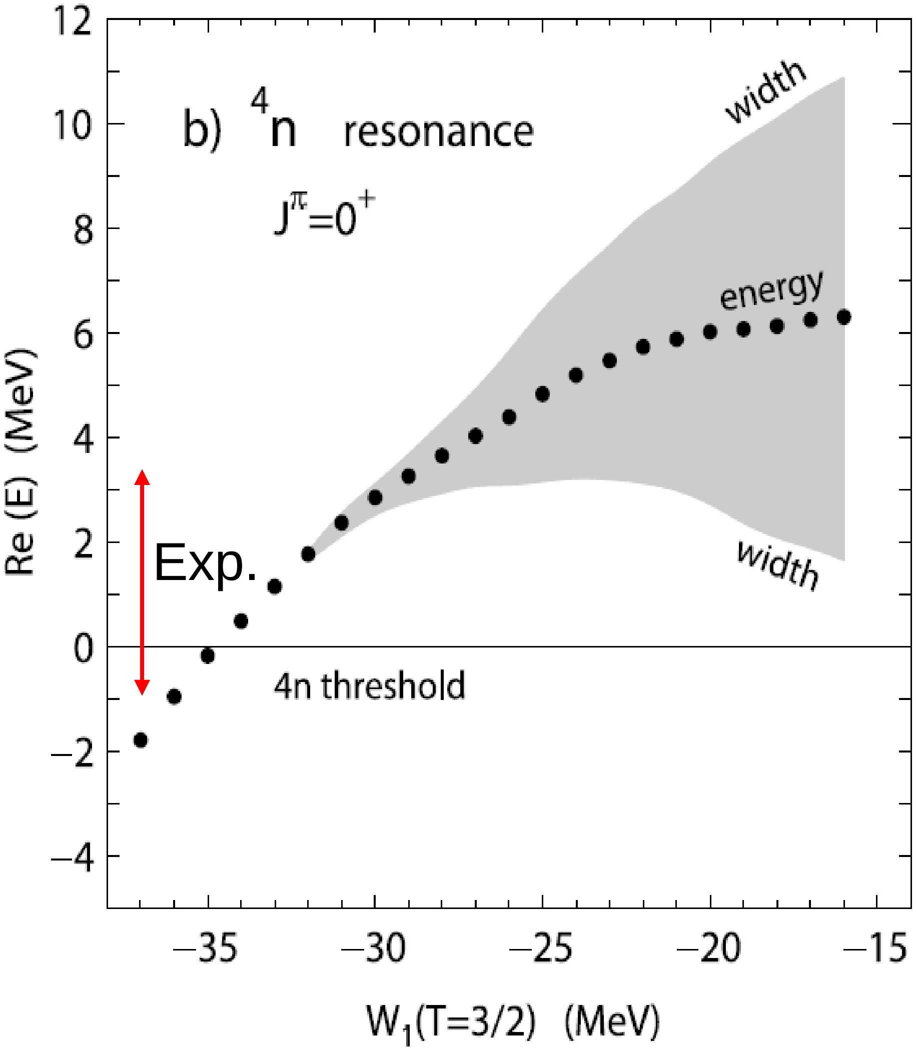
$$\begin{aligned} W_1(T=1/2) &= -2.04 \text{ MeV} \quad b_1 = 4.0 \text{ fm} \\ W_2(T=1/2) &= +35.0 \text{ MeV} \quad b_2 = 0.75 \text{ fm} \end{aligned}$$

These parameters (W_1,W_2,b_1,b_2) are determined so as to reproduce the binding energies of the ground states of ^{3}H, ^{3}He and ^{4}He.

For 4n system, we need T=3/2 three-body force. We use the same potential with T=1/2, but, different parameter of W_1.

W_1(T=3/2)= free b_1=4.0fm => W_1 should be tuned so as to reproduce the observed 4n system

W_2(T=3/2) = +35 MeV b_2=0.75



In order to reproduce the data of 4n system, We need W_1= -36 MeV～-30MeV.

Attraction is 15 times Stronger.

It should be noted that W1=-2.04 MeV to reproduce the observed binding energy of ^{4}He, ^{3}He and ^{3}H.

Question: W_1 value for T=3/2 is reasonable?

To check the validity of three-body force, we calculate the energies of ^{4}H,^{4}He(T=1),^{4}Li.

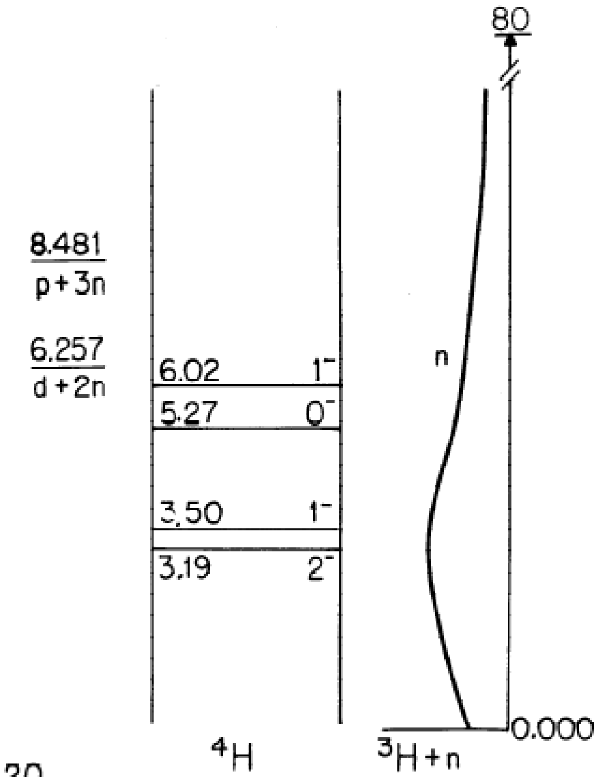


Table 4.1: Energy levels of ^{4}H defined for channel radius $a_n = 4.9$ fm. All energies and widths are in the cm system.

E_x (MeV)	J^π	T	Γ (MeV)	Decay	Reactions
g.s. [a]	2^-	1	5.42	n, ^{3}H	1, 11
0.31	1^-	1	6.73 [b]	n, ^{3}H	11, 12
2.08	0^-	1	8.92	n, ^{3}H	
2.83	1^-	1	12.99 [c]	n, ^{3}H	11, 12

[a] 3.19 MeV above the n + ^{3}H mass.
[b] Primarily $^3P_1$.
[c] Primarily $^1P_1$.

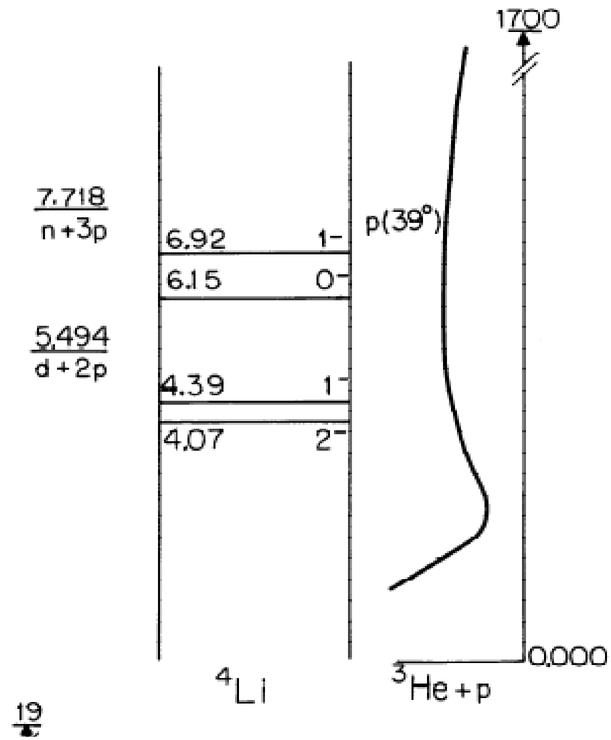
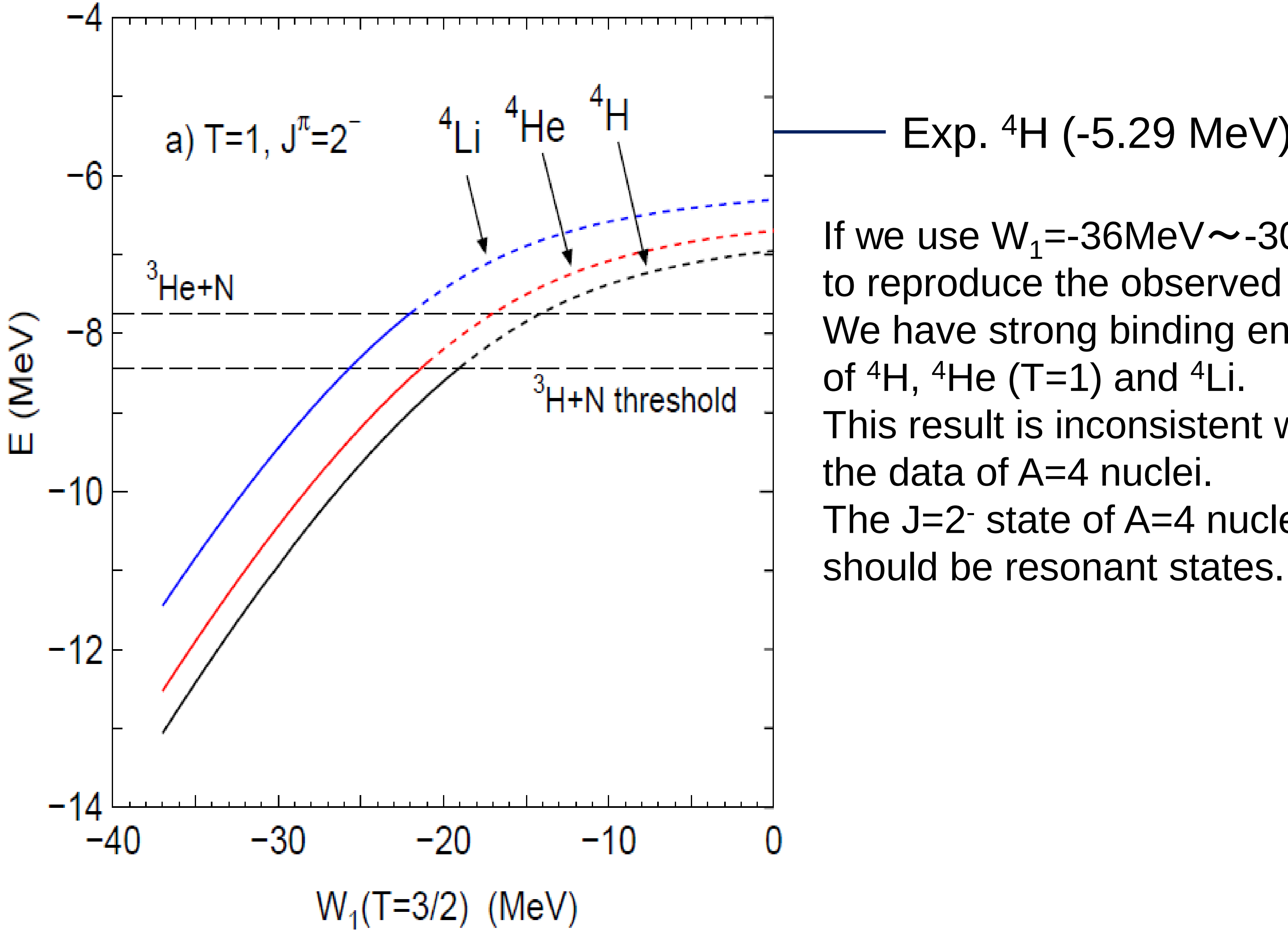


Table 4.24: Energy levels of ^{4}Li defined for channel radius $a_p = 4.9$ fm. All energies and widths are in the c.m. system.

E_x (MeV)	J^π	T	Γ (MeV)	Decay	Reactions
g.s. [a]	2^-	1	6.03	p, ^{3}He	3
0.32	1^-	1	7.35 [b]	p, ^{3}He	3
2.08	0^-	1	9.35	p, ^{3}He	3
2.85	1^-	1	13.51 [c]	p, ^{3}He	3

[a] 4.07 MeV above the p + ^{3}He mass.
[b] Primarily $^3P_1$.
[c] Primarily $^1P_1$.



If we use W_1=-36MeV～-30 MeV
to reproduce the observed data of 4n,
We have strong binding energies
of ^{4}H, ^{4}He (T=1) and ^{4}Li.
This result is inconsistent with
the data of A=4 nuclei.
The J=2^- state of A=4 nuclei
should be resonant states.

How do we consider this inconsistency?

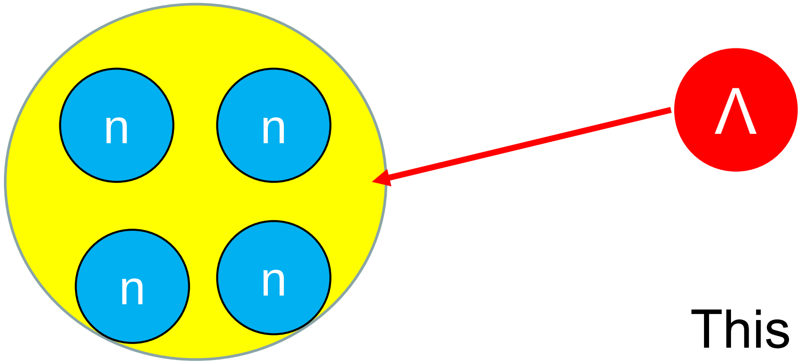
・The T=3/2 force is just a phenomenological.

$$V_{ijk}^{3N} = \sum_{T=1/2}^{3/2} \sum_{n=1}^{2} W_n(T) e^{-(r_{ij}^2 + r_{jk}^2 + r_{ki}^2)/b_n^2} \mathcal{P}_{ijk}(T)$$

Should we consider spin-dependent term in three-body force?
Tensor force, spin-orbit force???

The confirmation experiment for 4n will be performed this year at RIBF.
I am waiting for this confirmation.

If the experiment for 4n is confirmed to have a bound state or resonant state,
…

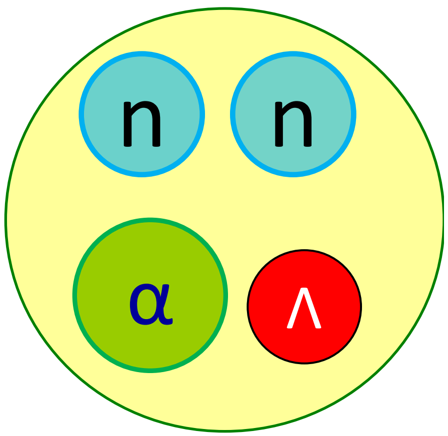


${}^{5}_{\Lambda}n$ should be bound!

This is important to study ΛN-ΣN coupling .
Then, I hope that production of ${}^{5}_{\Lambda}n$ will be performed at JLab using decay pion spectroscopy in the future.

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

PRC91, 054316 (2015)



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

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

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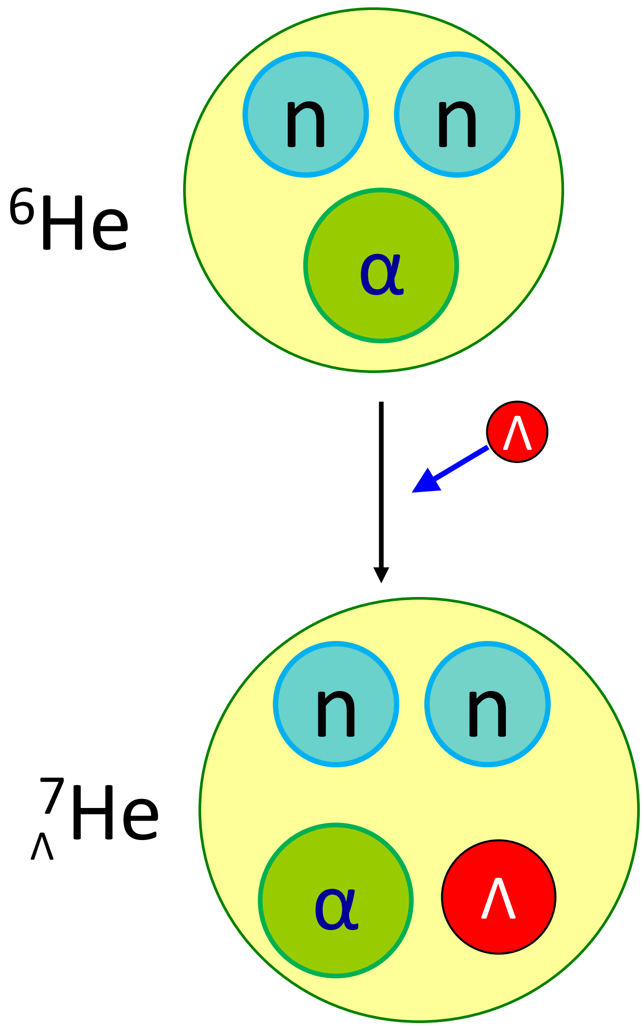
The structure of neutron-rich Λ hypernucleus, $^{7}_{\Lambda}$He is studied within the framework of $\alpha+\Lambda+n+n$ four-body cluster model. We predict second $3/2^+$ and $5/2^+$ states as narrow resonant states to be 0.03 MeV and 0.07 MeV with width $\Gamma \sim 1$ MeV with respect to $\alpha+\Lambda+n+n$ threshold which correspond to the second 2^+ state of ^{6}He coupled to $0s$ Λ. By estimation of differential cross section of ^{7}Li$(\gamma, K^+)^{7}_{\Lambda}$He, there is a possibility to observe these state at JLab in the future. We also calculate second 2^+ state of ^{6}He as resonant state within the framework of $\alpha+n+n$ three-body cluster model. Our result is 2.81 MeV with $\Gamma = 4.63 MeV$ with respect to $\alpha+n+n$ threshold, which is inconsistent with the recent SPIRAL data. It is suggested that search experiment at JLab of the second $3/2^+$ and $5/2^+$ states of $^{7}_{\Lambda}$He would provide an opportunity to confirm the second 2^+ state of the core nucleus ^{6}He.

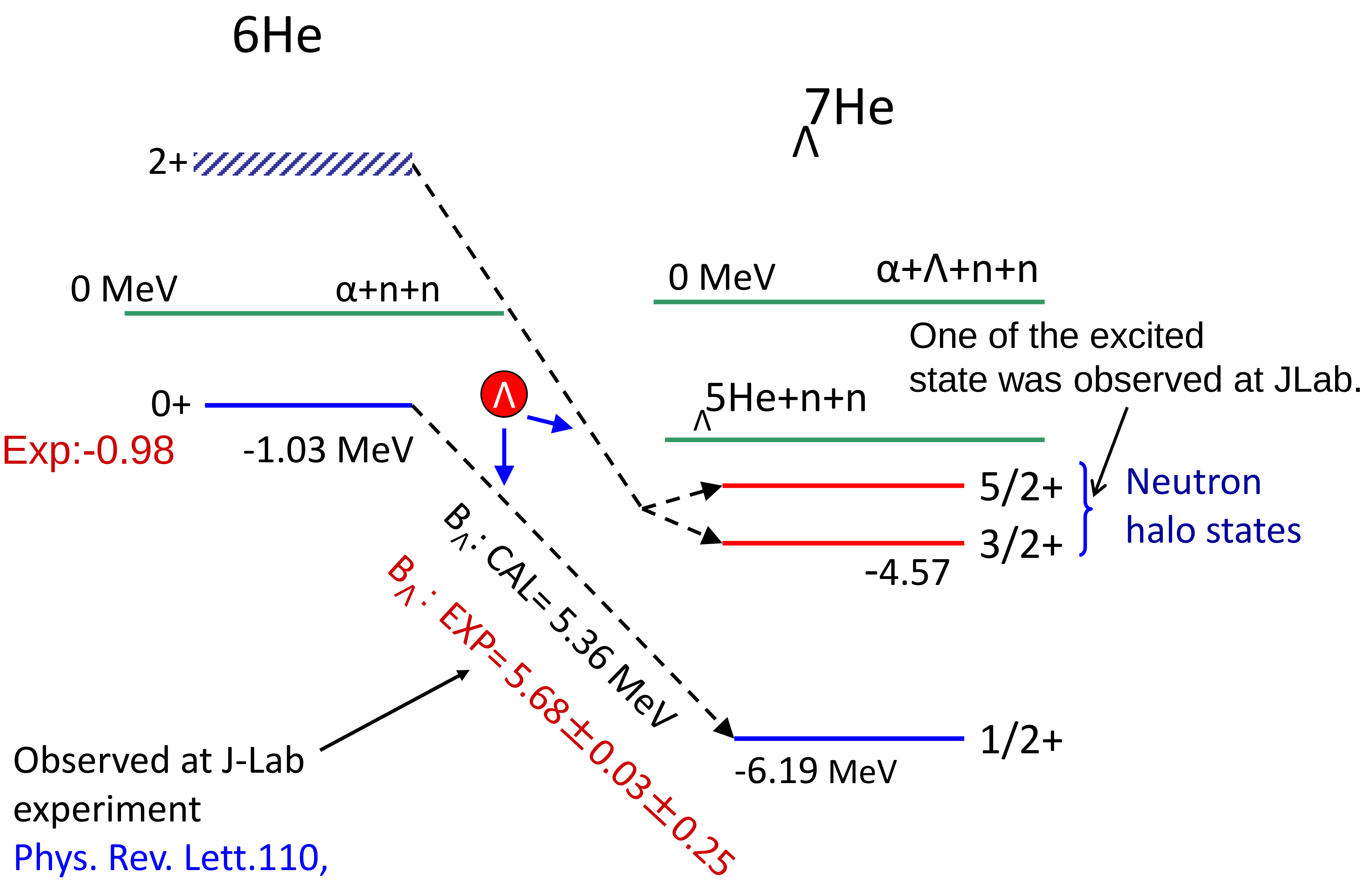


^{6}He : One of the lightest n-rich nuclei

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

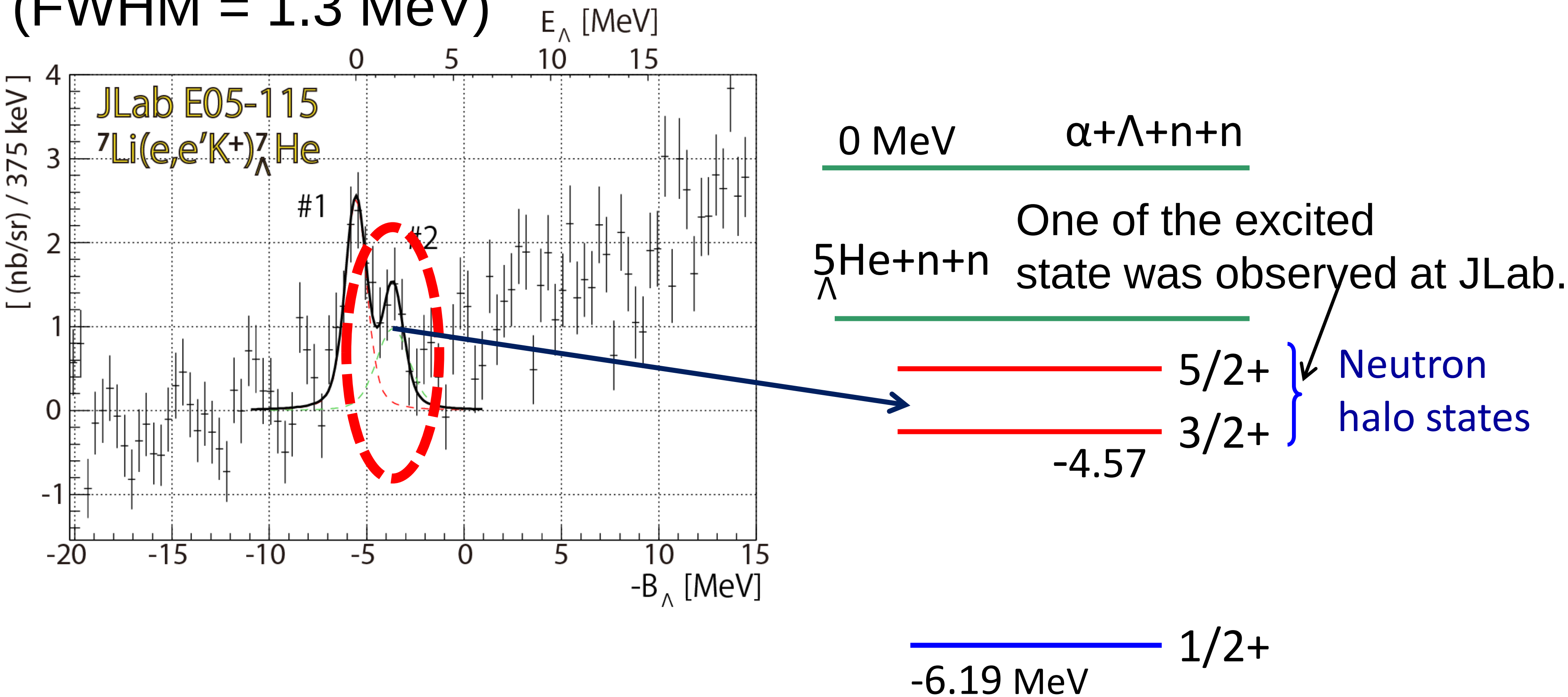


Observed at J-Lab experiment

Phys. Rev. Lett.110, 012502 (2013).

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

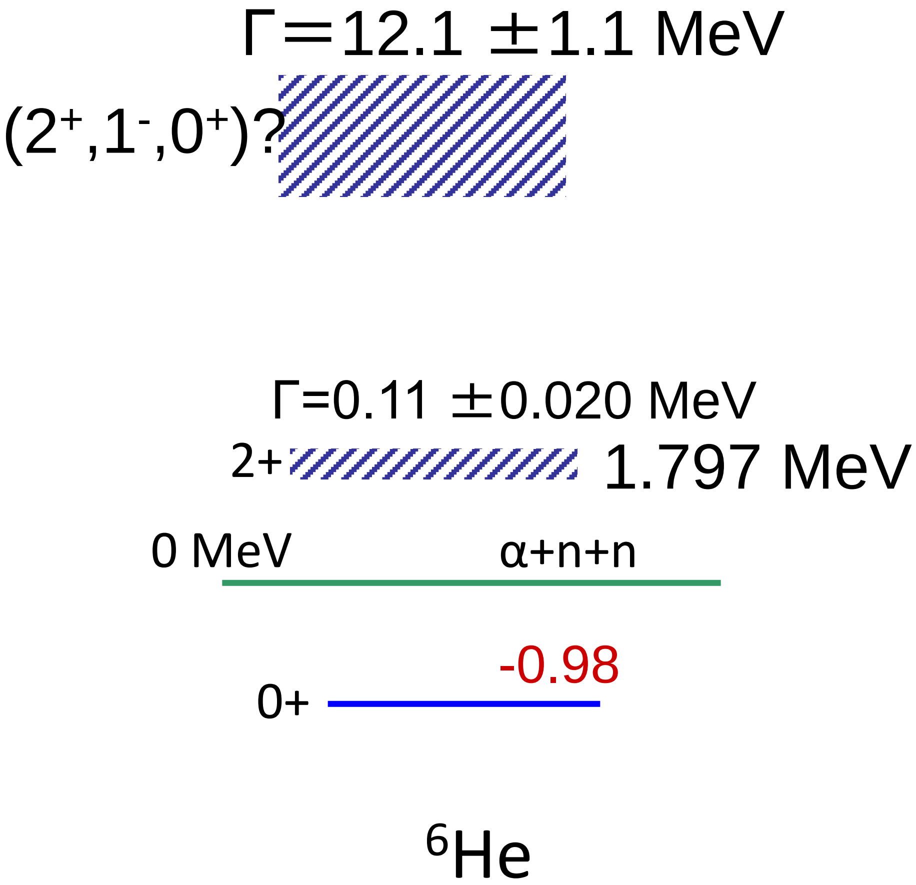
(FWHM = 1.3 MeV)



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

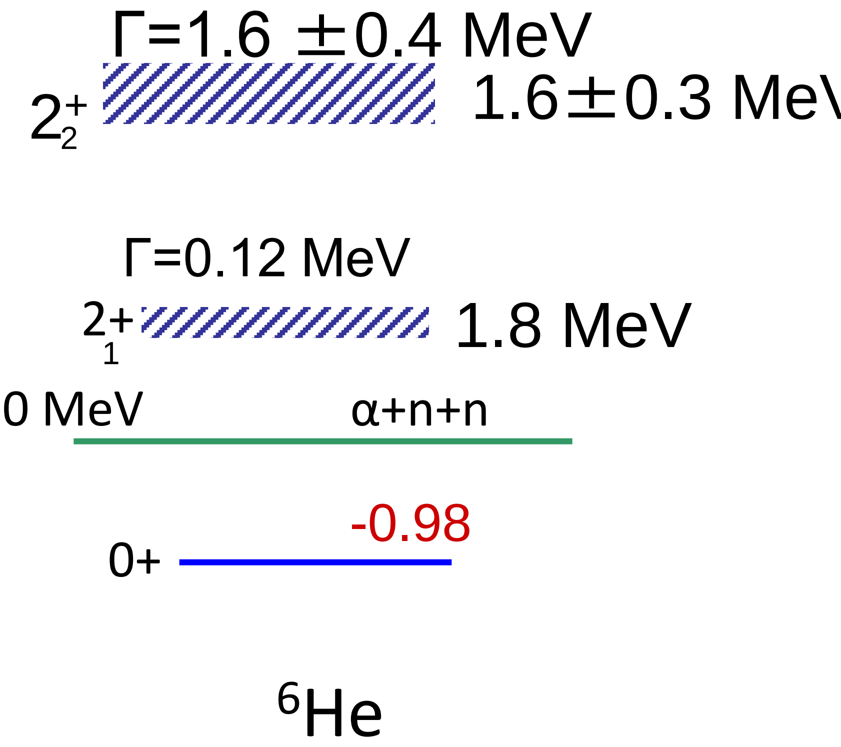
Question: In ${}_{\Lambda}^{7}He$, do we have any other new states?
If so, what is spin and parity?

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



Exp.

Data in 2002

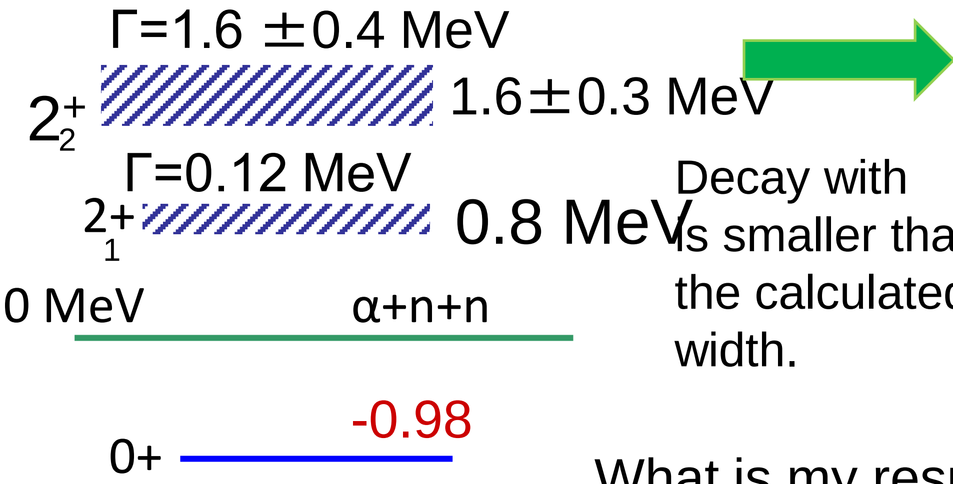


Exp.

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?

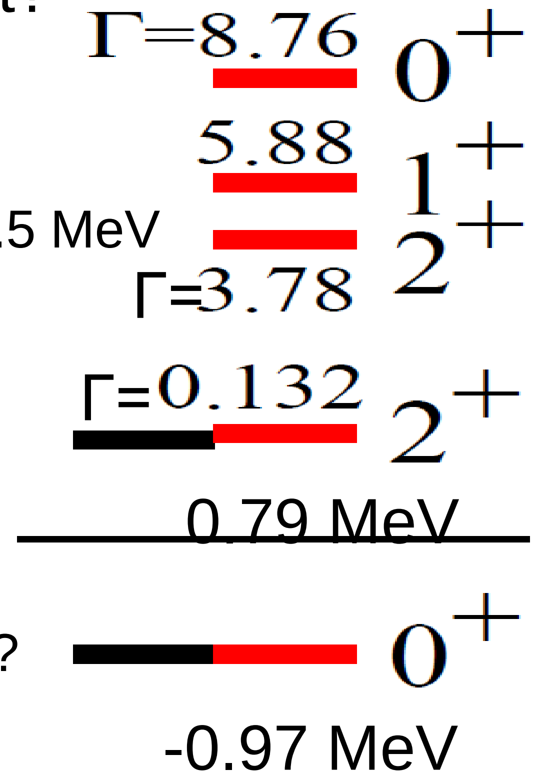


^{6}He

Exp.

Decay with is smaller than the calculated width.

What is my result?



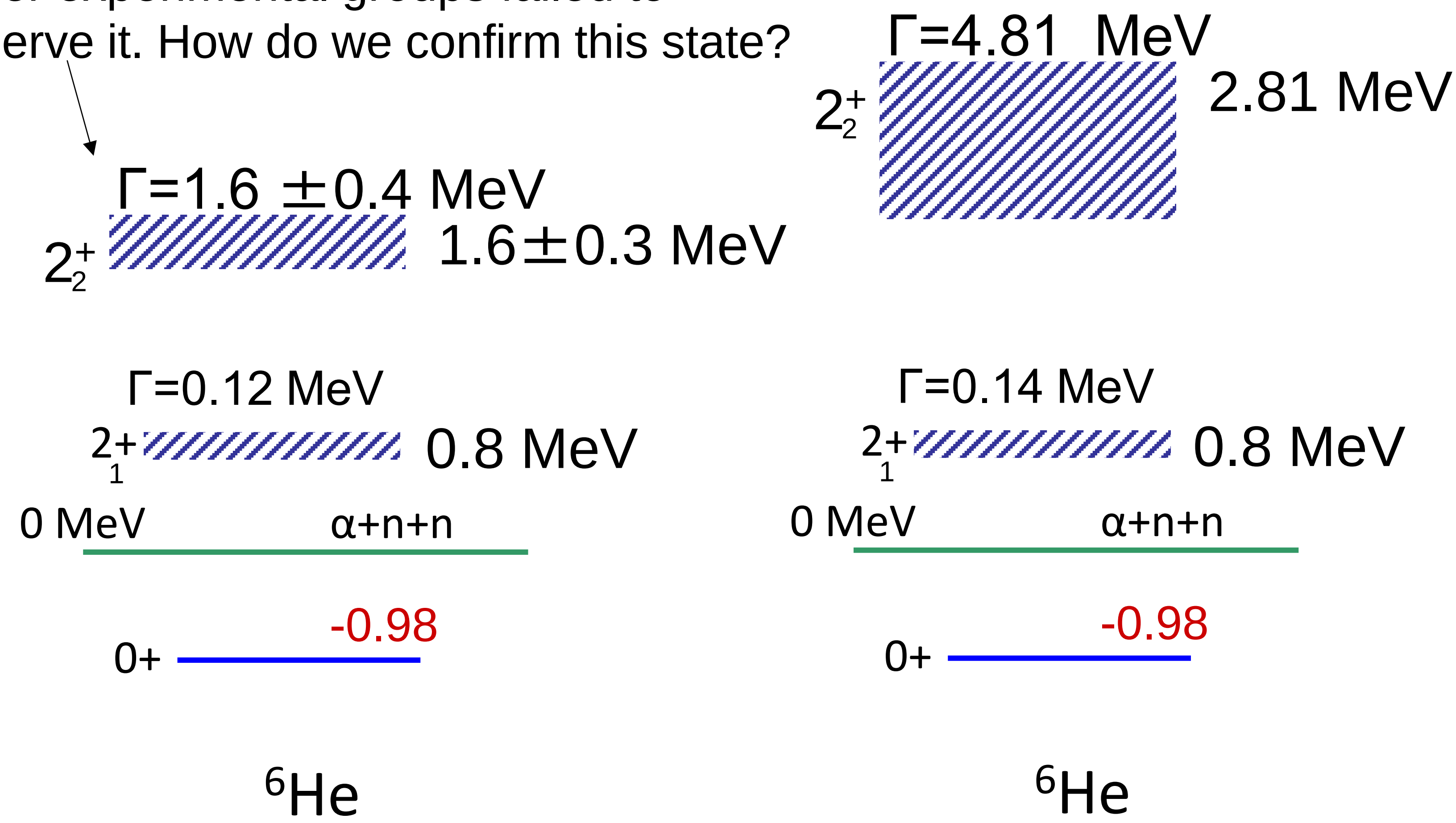
theory

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

^{6}He

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

Only GANIL group observed this state.
Other experimental groups failed to observe it. How do we confirm this state?

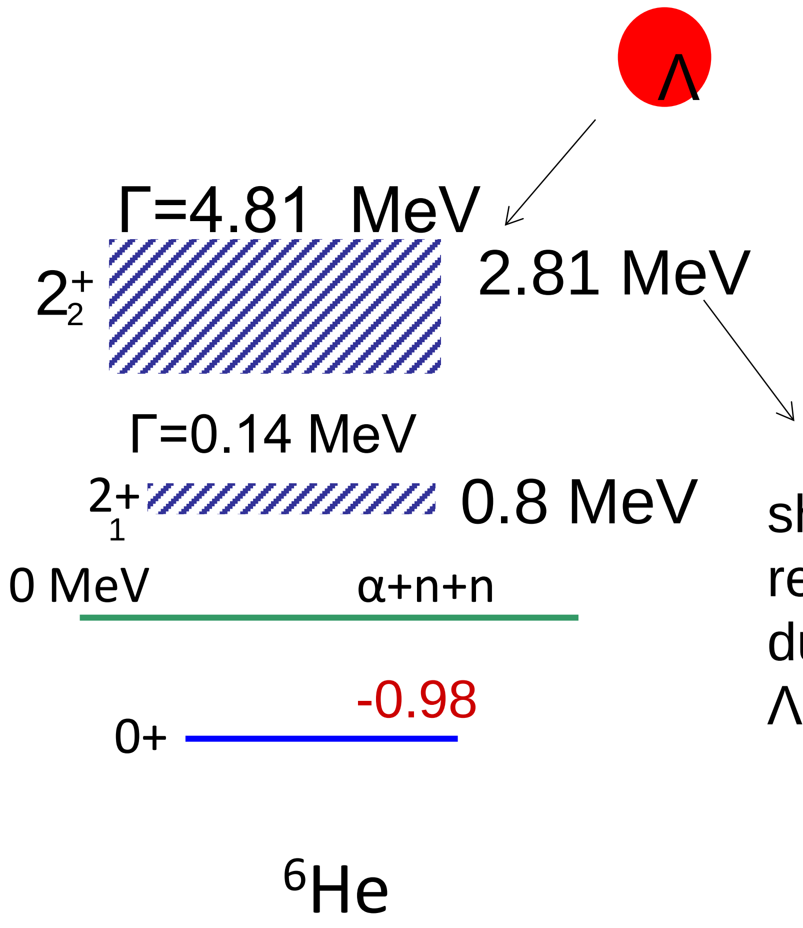


Exp.

Cal.

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

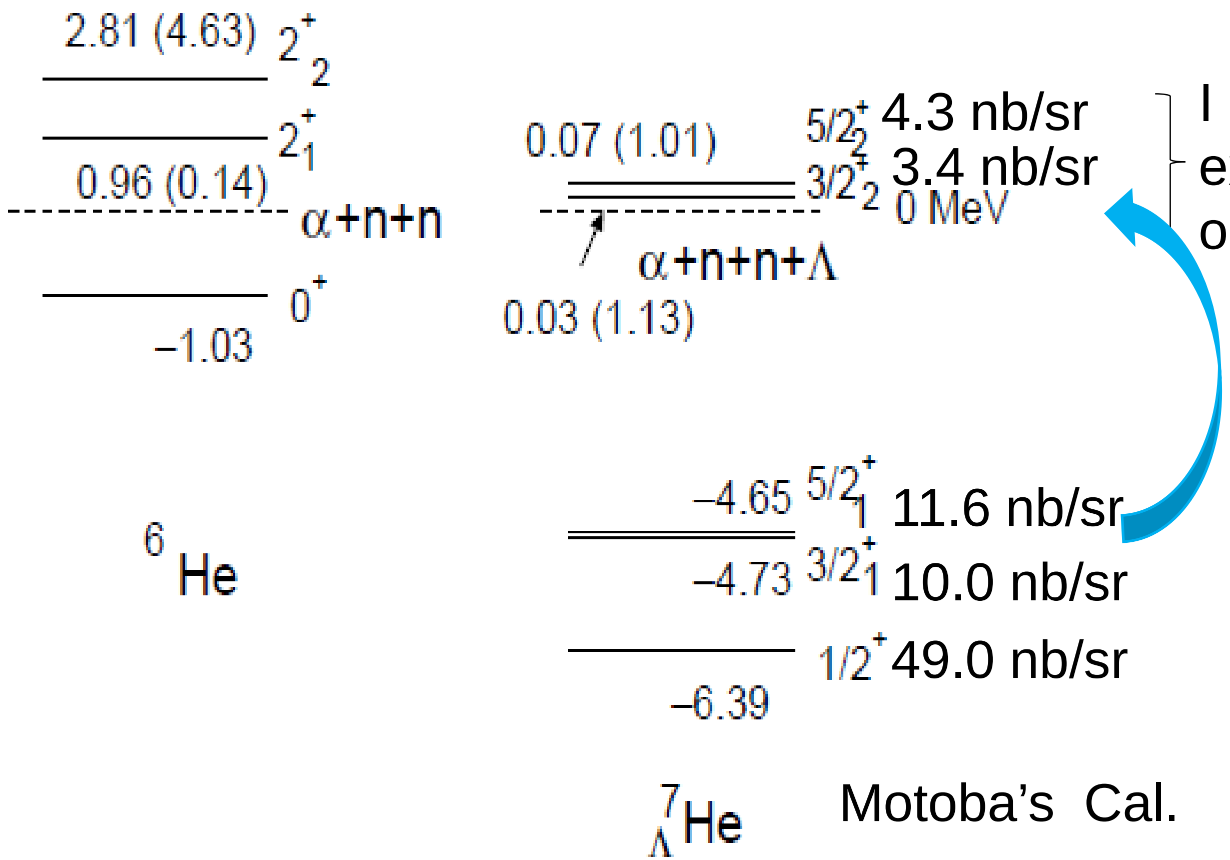
I propose to measure $3/2^+, 5/2^+$ states in $^7_\Lambda He$ at JLab.



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

should be narrower resonant states due to the attraction of ΛN interaction.

Cal.



I propose to experimentalists to observe these states.

40% reduction

Motoba's Cal.

If we observe second $5/2^+$,$3/2^+$ states in $^7_\Lambda$He at JLab, we can confirm the second 2^+ state in ^{6}He.
In this way, hypernuclear physics can contribute to unstable nuclear physics.

Summary

I suggest to measure the following three hypernuclei.

(1) 1^+ state of $^4_\Lambda H$

Important to obtain information on CSB effect.

(2) $^5_\Lambda n$

Important to obtain information on ΛN-ΣN coupling
, T=3/2 three-body force and to confirm the existence of ^4n

(3) The second $3/2^+$,$5/2^+$ states in $^7_\Lambda He$

Important to confirm the second 2+ state of 6He
This is a great contribution to unstable nuclear physics.
‘bridge physics of hypernuclei and unstable nuclei’

I hope to have these new data at JLab in the future.

Thank you!