Structure of light neutron-rich nucleus, ^{5}H

E. Hiyama (RIKEN)
R. Lazauskas (IPHC)
J. Carbonell (CNRS)
M. Kamimura (Kyushu Univ./RIKEN)

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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]

[1]*Center for Nuclear Study, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan*
[2]*RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[3]*IPN Orsay, 15 Rue, Georges, Clemenceau 91400 Orsay, France*
[4]*Department of Physics, Kyoto University, Yoshida-Honcho, Sakyo, Kyoto 606-8501, Japan*
[5]*Research Center for Nuclear Physics, Osaka University, 10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan*
[6]*Cyclotron and Radioisotope Center, Tohoku University, 6-3 Aoba, Aramaki, Aoba-ku, Sendai, Miyagi 980-8578, Japan*
[7]*Department of Physics, Tokyo Institute of Technology, 2-12-1 O-Okayama, Meguro, Tokyo 152-8550, Japan*
[8]*Faculty of Engineering, University of Miyazaki, 1-1 Gakuen, Kibanadai-nishi, Miyazaki 889-2192, Japan*
[9]*Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan*
[10]*National Superconducting Cyclotron Laboratory, Michigan State University, 640 S Shaw Lane, East Lansing, Michigan 48824, USA*
[11]*Department of Physics, Kyushu University, 6-10-1 Hakozaki, Higashi, Fukuoka 812-8581, Japan*
[12]*National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage, Chiba, Japan*

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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 $0.83 \pm 0.65(\text{stat}) \pm 1.25(\text{syst})$ 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.

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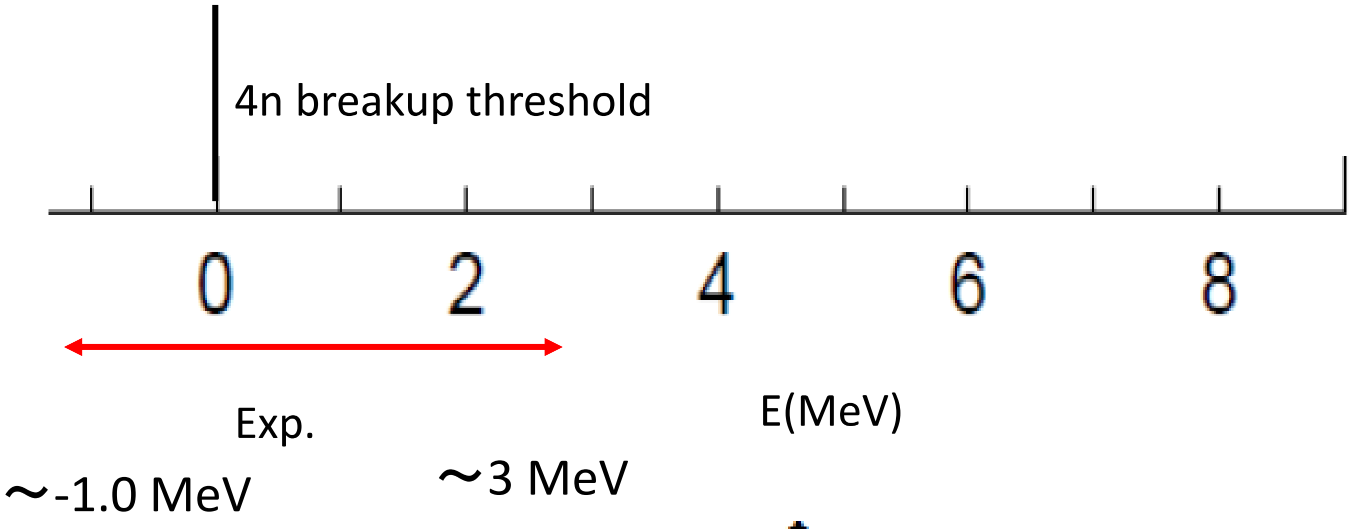

$$E_R = 0.83 \pm 0.65 \pm 1.25$$

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.

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Possibility of generating a 4-neutron resonance with a $T = 3/2$ isospin 3-neutron force

E. Hiyama
Nishina Center for Accelerator-Based Science, RIKEN, Wako, 351-0198, Japan

R. Lazauskas
IPHC, IN2P3-CNRS/Universite Louis Pasteur BP 28, F-67037 Strasbourg Cedex 2, France

J. Carbonell
Institut de Physique Nucléaire, Université Paris-Sud, IN2P3-CNRS, F-91406 Orsay Cedex, France

M. Kamimura
Department of Physics, Kyushu University, Fukuoka 812-8581, Japan
and Nishina Center for Accelerator-Based Science, RIKEN, Wako 351-0198, Japan
(Received 27 December 2015; revised manuscript received 26 February 2016; published 29 April 2016)

We consider the theoretical possibility of generating a narrow resonance in the 4-neutron system as suggested by a recent experimental result. To that end, a phenomenological $T = 3/2$ 3-neutron force is introduced, in addition to a realistic NN interaction. We inquire what the strength should be of the $3n$ force to generate such a resonance. The reliability of the 3-neutron force in the $T = 3/2$ channel is examined, by analyzing its consistency with the low-lying $T = 1$ states of ^{4}H, ^{4}He, and ^{4}Li and the $^3\mathrm{H} + n$ scattering. The *ab initio* solution of the $4n$ Schrödinger equation is obtained using the complex scaling method with boundary conditions appropriate to the four-body resonances. We find that to generate narrow $4n$ resonant states a remarkably attractive $3N$ force in the $T = 3/2$ channel is required.

Published in PRC in April in 2016.

Introduction : historical overview for tetraneutron system

Search for tetraneutron system as a bound or resonant state has been performed for about 50 years… talked by Shimoura san.
It was so difficult to confirm existence of tetraneutron system.
And then, recently Shimoura san observed 4n system.

Regarding to theoretical calculations,
For example,
S. A. Sofianos et al., J. Phys. G23, 1619 (1997).
N. K. Timofeyuk, J. Phys. G29, L9 (2003).

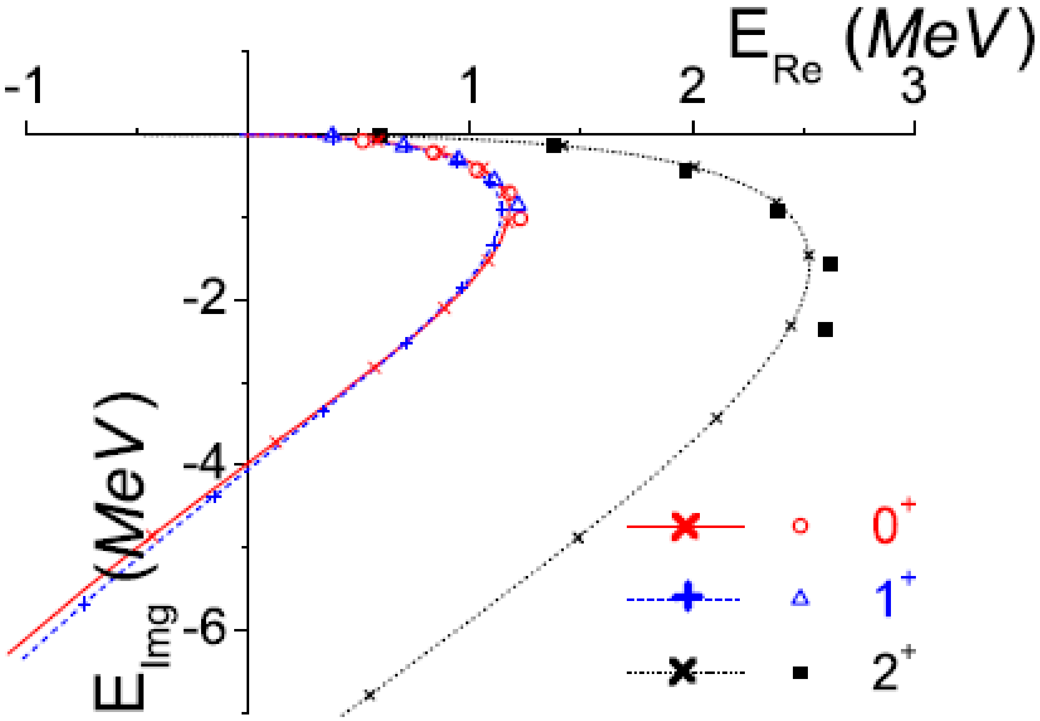
Unlikely evidence of tetraneutron system

S.C. Peiper et al., Phys. Rev. Lett. 90, 252501 (2003).
Especially, Peiper et al. suggested that there would be possibility to exist a tetraneutron system as a resonant state at Er=2 MeV using AV18＋IL2 3N force with GFMC.

R. Lazauskas, and J. Carbonell, Phys. Rev. C72, 034003 (2005).

Charge-symmetry-breaking Reid93 nn potential +a phenomenological 4N force

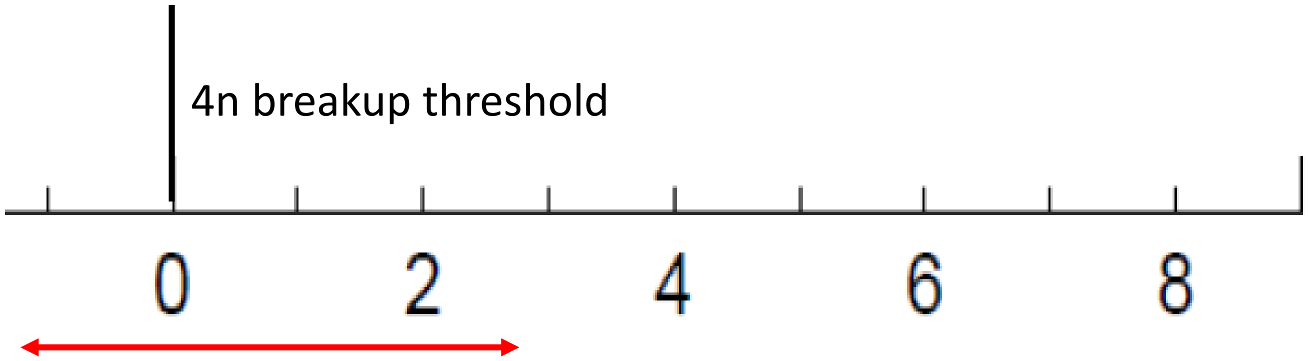
$$V_{4n} = -W\rho e^{-\frac{\rho}{\rho_0}}, \qquad \text{hyperradius } \rho = \sqrt{x^2 + y^2 + z^2}$$



Since we did not have any observed data at that time, then in this paper it was difficult to tune the strength of W.

If W=0,

energy pole goes to the third quadrant.



E(MeV)

Exp.

∼-1.0 MeV ∼3 MeV

$$E_R = 0.83 \pm 0.65 \pm 1.25$$

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?

$E_R = 0.83 \pm 0.65 \pm 1.25$ 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?
In 2005, Rimas and Jaume already pointed out that only two-boy NN interaction could not find any existence of tetraneutron system.
We need T=3/2 three-nucleon force.

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.

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

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

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).

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 ,

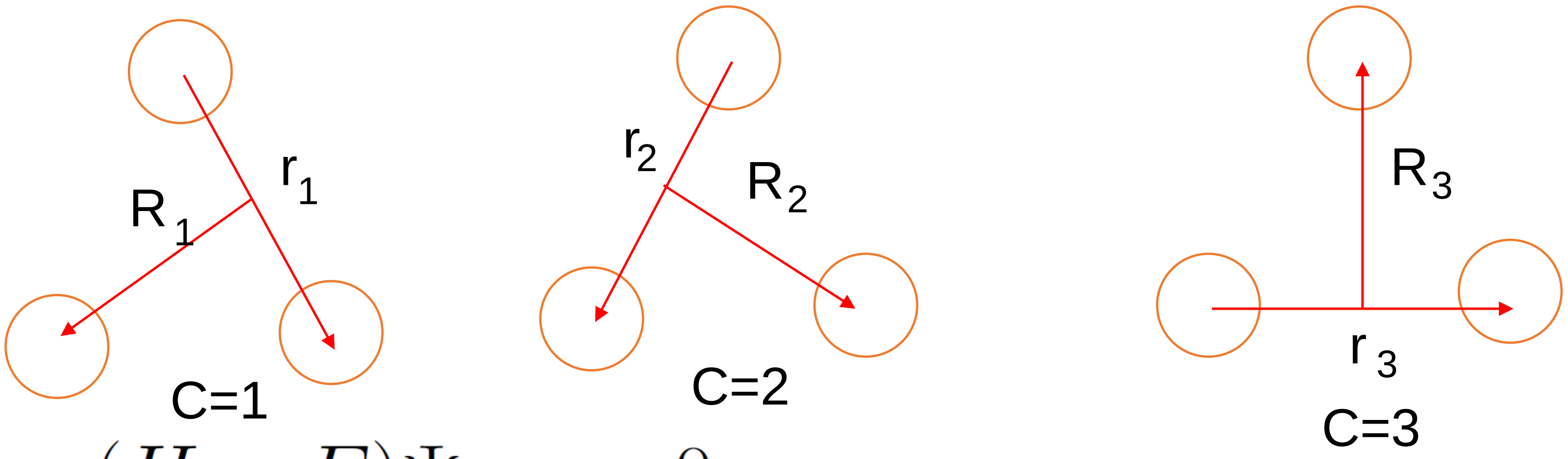
3- and 4-nucleon systems,

multi-cluster structure of light nuclei,

Light hypernuclei,

3-quark systems,

^{4}He-atom tetramer



$$(H - E)\Psi_{JM} = 0$$

$$H = T + V_1(\mathbf{r}_1) + V_2(\mathbf{r}_2) + V_3(\mathbf{r}_3)$$

$$T = \frac{\hbar^2}{2m}\nabla^{\mathbf{2}}_{\mathbf{r}} + \frac{\hbar^2}{2M}\nabla^{\mathbf{2}}_{\mathbf{R}}$$

$$\Psi_{JM} = \Phi^{(1)}_{JM}(\mathbf{r}_1, \mathbf{R}_1) + \Phi^{(2)}_{JM}(\mathbf{r}_2, \mathbf{R}_2) + \Phi^{(3)}_{JM}(\mathbf{r}_3, \mathbf{R}_3)$$

This **Schrödinger equation is solved with Rayleigh-Ritz variational method and we obtain eigen value E and eigen function Ψ.**

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

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

$$\mathbf{\Psi} = \sum_{n=1}^{N} \mathbf{C}_n \mathbf{\Phi}_n$$

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

$$\langle \mathbf{\Phi}_i \,|\, \mathbf{H} - \mathbf{E} \,|\, \sum_{n=1}^{N} \mathbf{C}_n \mathbf{\Phi}_n \rangle = 0\,, \qquad (\mathbf{i} = 1, \ldots, \mathbf{N})$$

$$\underbrace{\sum_{n=1}^{N} \mathbf{C}_n \mathbf{\Phi}_n}_{=\,\mathbf{\Psi}}$$

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.

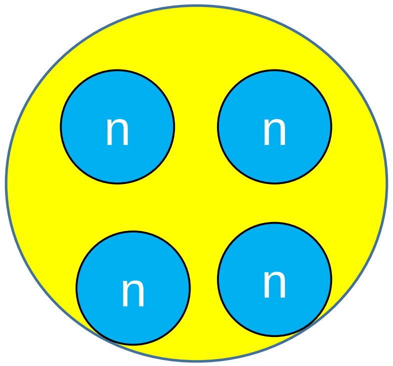
$$\Phi_{lmn}(r) = r^{\ell} e^{-\nu_n r^2} Y_{\ell m}(\hat{\mathbf{r}})$$

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

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

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.

Using our method and AV8 NN potential, we start to study the structure of tetraneutron system.



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 adjusted so as to reproduce the observed 4n system

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

Now, we have a question: What is spin and parity for the reported ^{4}n system?

Candidate states: J=0^+, 1^+, 2^+, 0^-, 1^-, 2^-

$$E_R = 0.83 \pm 0.65 \pm 1.25$$

The lowest value is -1.07 MeV with respect to 4n threshold.

To get this value, how much is W_1 for each J^π？

TABLE I: Critical strength $W_1^{(0)}(T = 3/2)$ (MeV) of the phenomenological $T = 3/2$ $3N$ force required to bind the $4n$ system at $E = -1.07$ MeV, the lower bound of the experimental value [8], for different states as well as the probability (%) of their four-body partial waves.

J^π	0^+	1^+	2^+	0^-	1^-	2^-
$W_1^{(0)}(T=\frac{3}{2})$	-36.14	-45.33	-38.05	-64.37	-61.74	-58.37
S-wave	93.8	0.42	0.04	0.07	0.08	0.08
P-wave	5.84	98.4	17.7	99.6	97.8	89.9
D-wave	0.30	1.08	82.1	0.33	2.07	9.23
F-wave	0.0	0.05	0.07	0.0	0.10	0.74

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

$W_1(T=3/2)$= free b_1=4.0fm

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

Since W_1^0のof J=0^+ is the smallest, then J=0^+ might be the ground state.

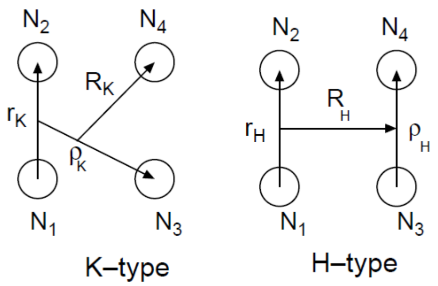
Then if Shimoura san might observe the ground state, the state should be J=0^+ state.

So, we assume that the observed state is J=0^+ state.

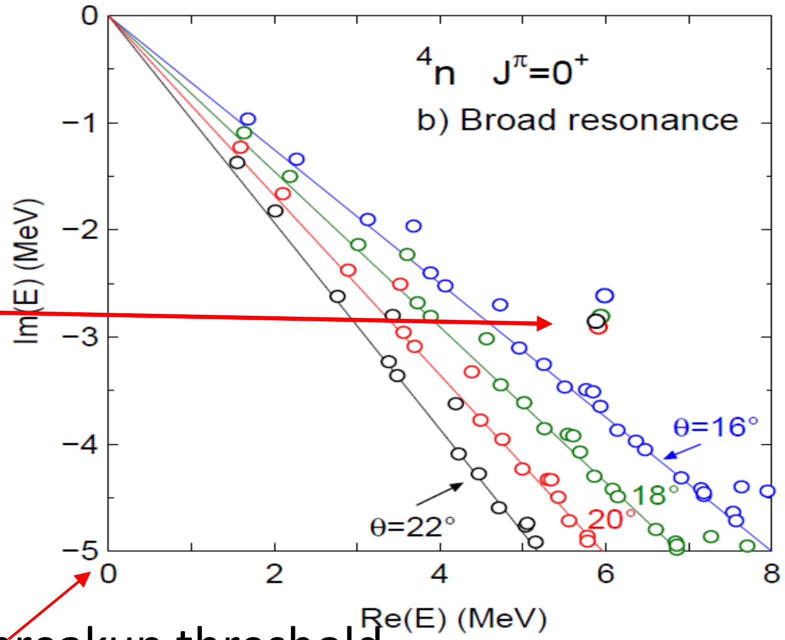
The observed 4n system was reported from the bound region to resonant region. In order to obtain energy position (E_r) and decay width (Γ), we use complex scaling method.

$$[H(\theta) - E(\theta)]\Psi_{JM,TT_z}(\theta) = 0$$

$$\Psi_{JM,TT_z}(\theta) = \sum_{\alpha} C_{\alpha}^{(\mathrm{K})}(\theta)\Phi_{\alpha}^{(\mathrm{K})} + \sum_{\alpha} C_{\alpha}^{(\mathrm{H})}(\theta)\Phi_{\alpha}^{(\mathrm{H})}$$



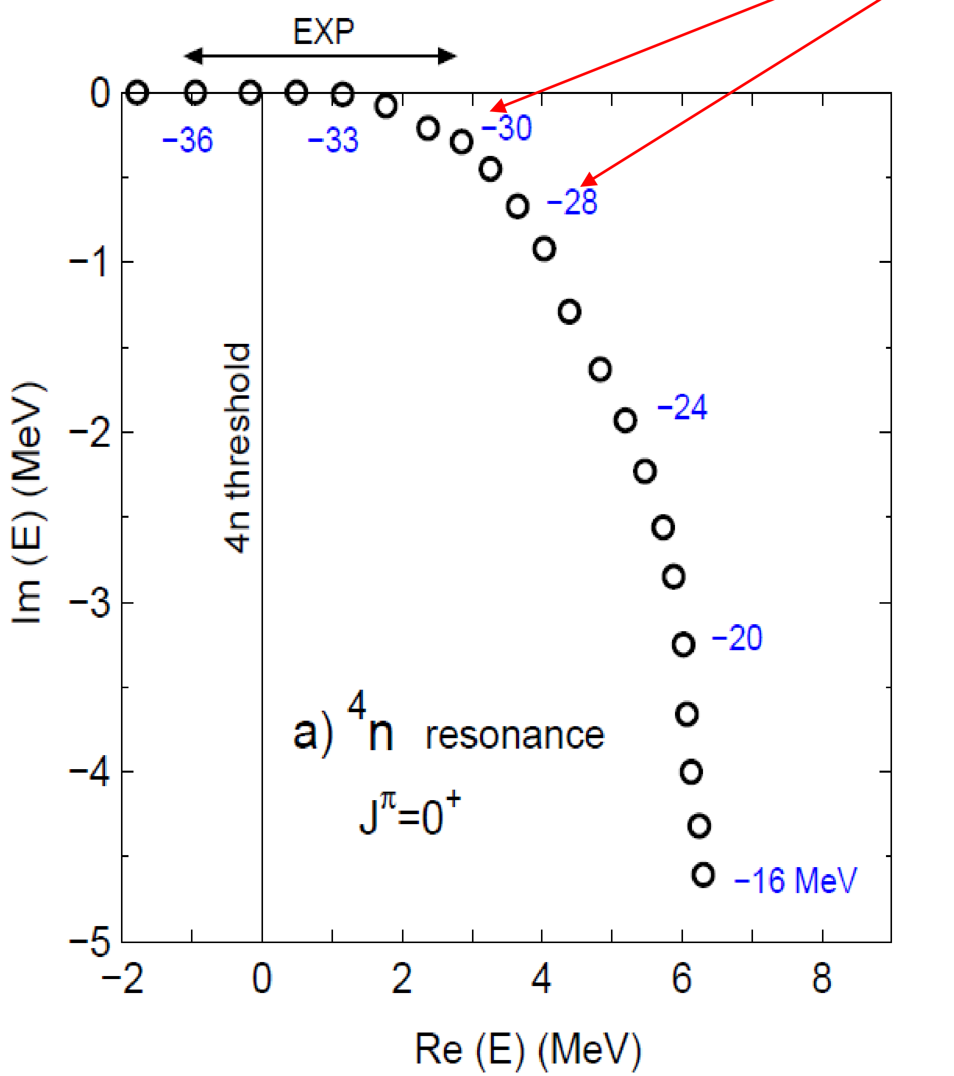
$$r_c \to r_c\, e^{i\theta},\ R_c \to R_c\, e^{i\theta},\ \rho_c \to \rho_c\, e^{i\theta}\ \ (\mathrm{c} = \mathrm{K}, \mathrm{H})$$

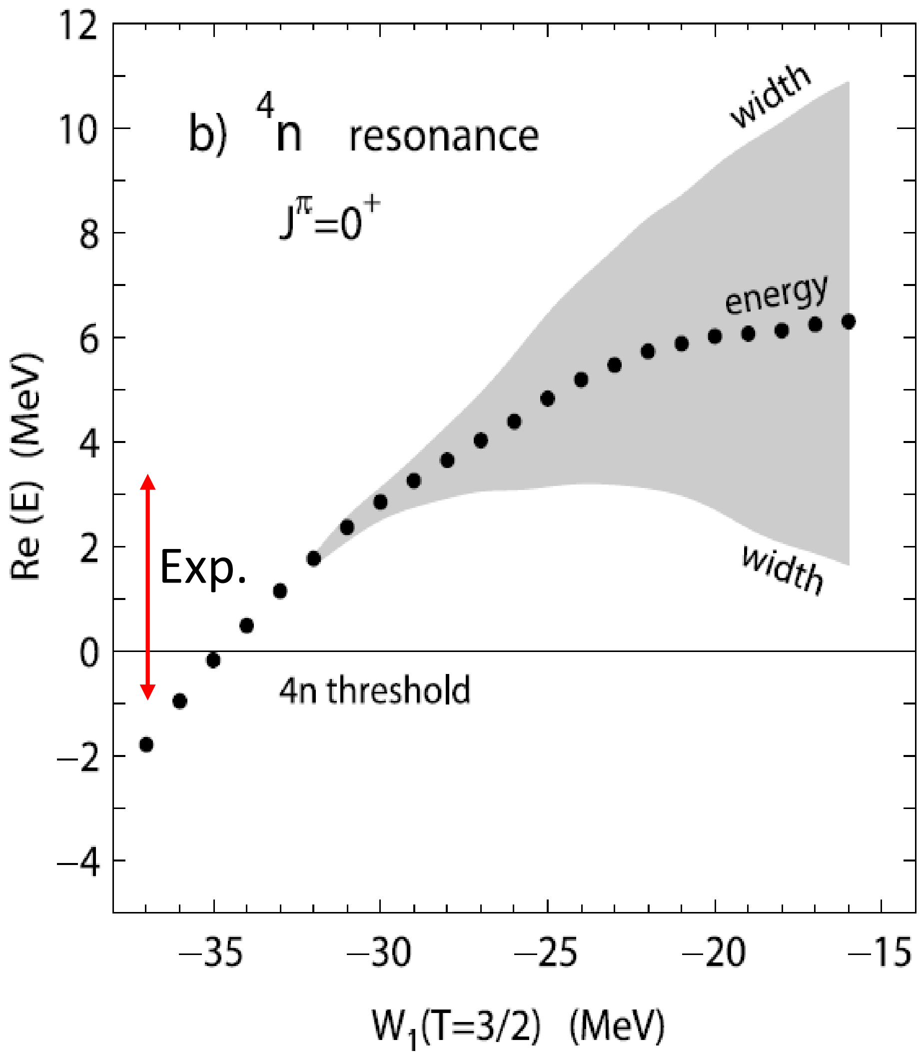


The energy pole is stable with respect to θ.
Re(E) corresponds to energy
With respect to 4n breakup threshold.
Im(E) corresponds to Γ/2.

4n breakup threshold

energy trajectory of J=0+ state changing W_1





In order to reproduce the data of 4n system,
We need $W_1(T=3/2)$= -36 MeV～-30MeV.

Attraction is 15 times
Stronger.

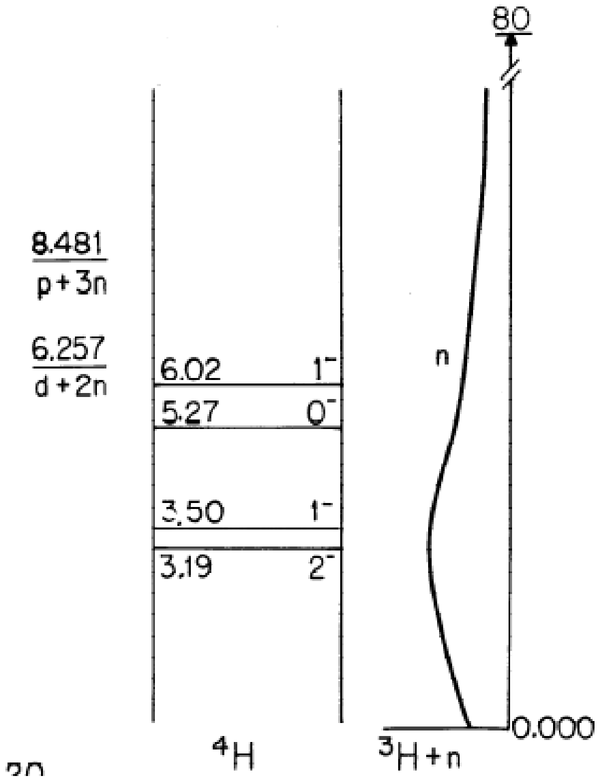
It should be noted that $W_1(T=1/2)$=-2.04 MeV
to reproduce the observed binding energy
of ^4He, ^3He and ^3H.

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

$W_1(T=3/2)$= free b_1=4.0fm
$W_2(T=3/2)$ = +35 MeV b_2=0.75 fm

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

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



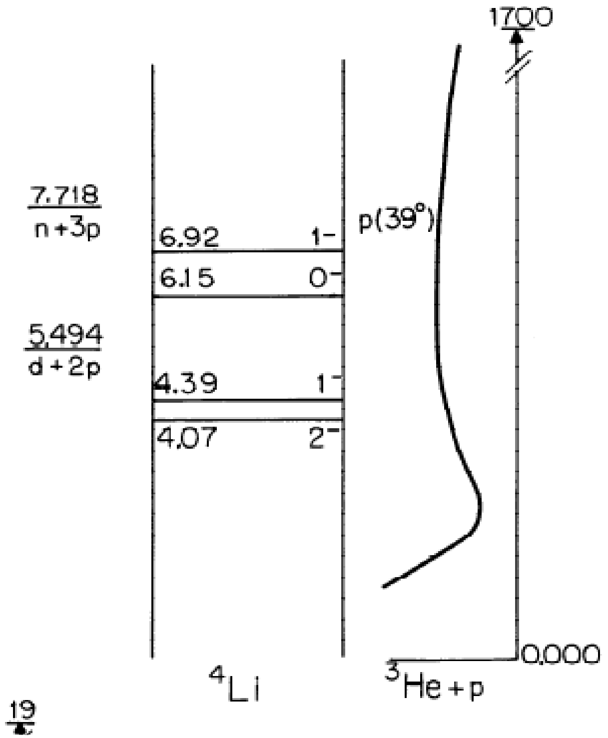


Table 4.1: Energy levels of ^{4}H defined for channel radius $a_n = 4.9$ fm. All energies and widths are in the cm system.

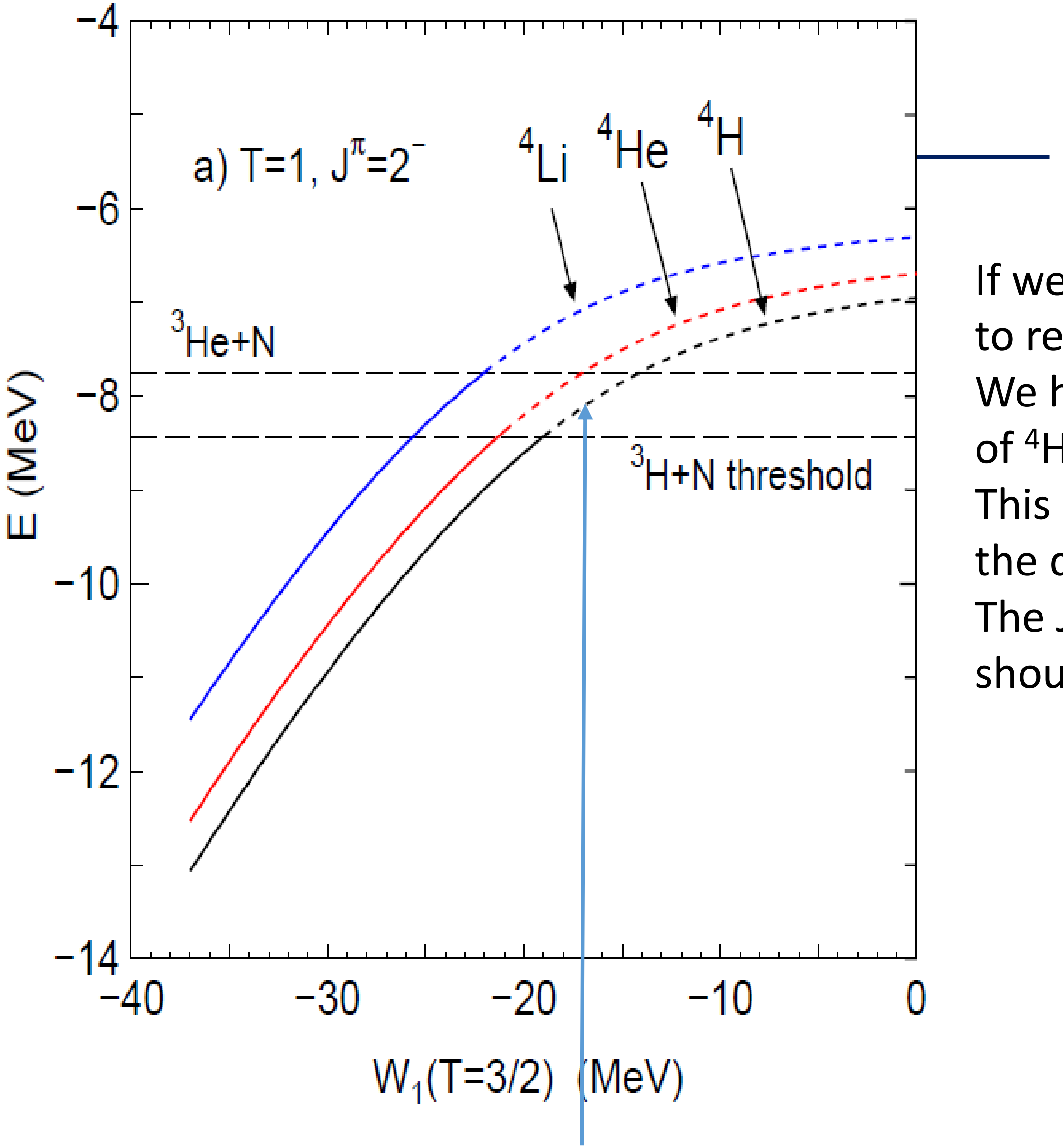
E_x (MeV)	J^π	T	Γ (MeV)	Decay	Reactions
g.s. [a]	2^-	1	5.42	n, ^{3}H	1, 11
0.31	1^-	1	6.73 [b]	n, ^{3}H	11, 12
2.08	0^-	1	8.92	n, ^{3}H	
2.83	1^-	1	12.99 [c]	n, ^{3}H	11, 12

[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

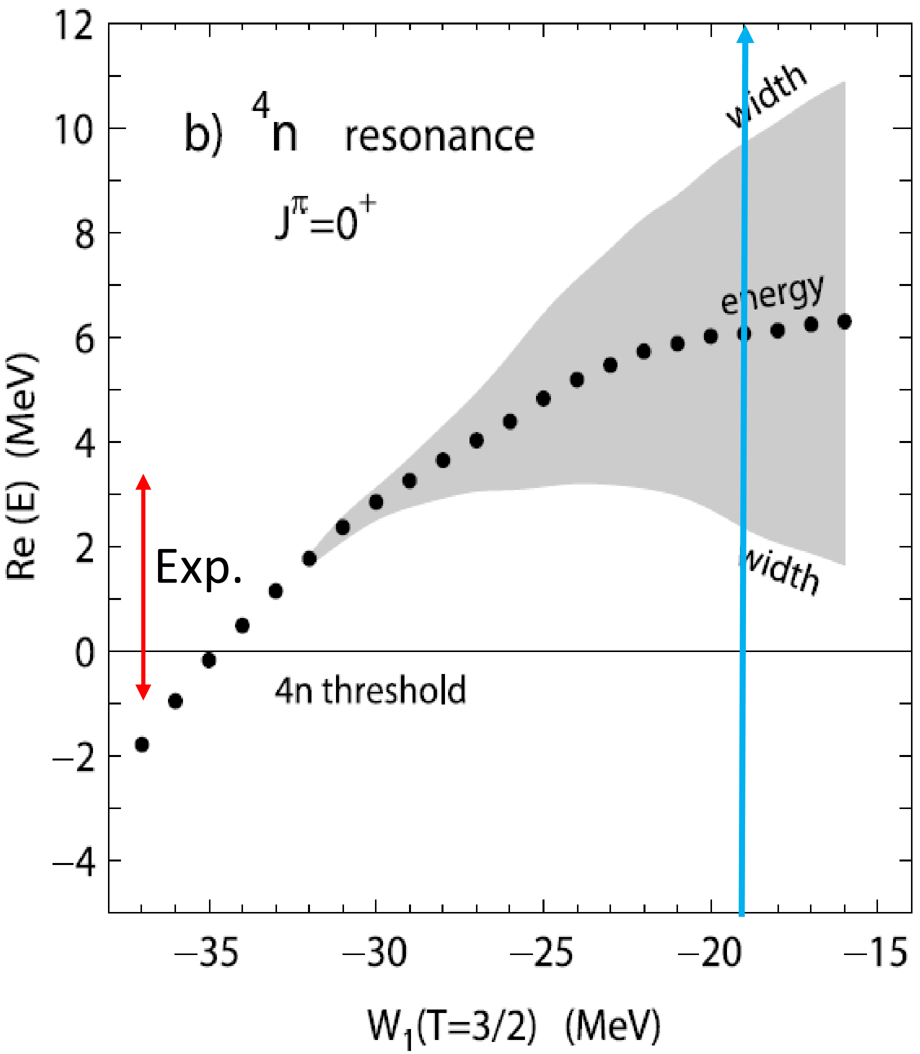
[a] 4.07 MeV above the p + ^{3}He mass.
[b] Primarily $^3P_1$.
[c] Primarily $^1P_1$.



Exp. ^{4}H (-5.29 MeV)

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.

On the contrary, when W_1～-18 MeV, we have unbound states for A=4 nuclei. How about tetraneutron system?



If $W_1(T=3/2) \sim -18$ MeV, the energy of tetraneutron is $\sim$-6M
and Γ=8MeV, which is inconsistent with recent data of tetraneutron.

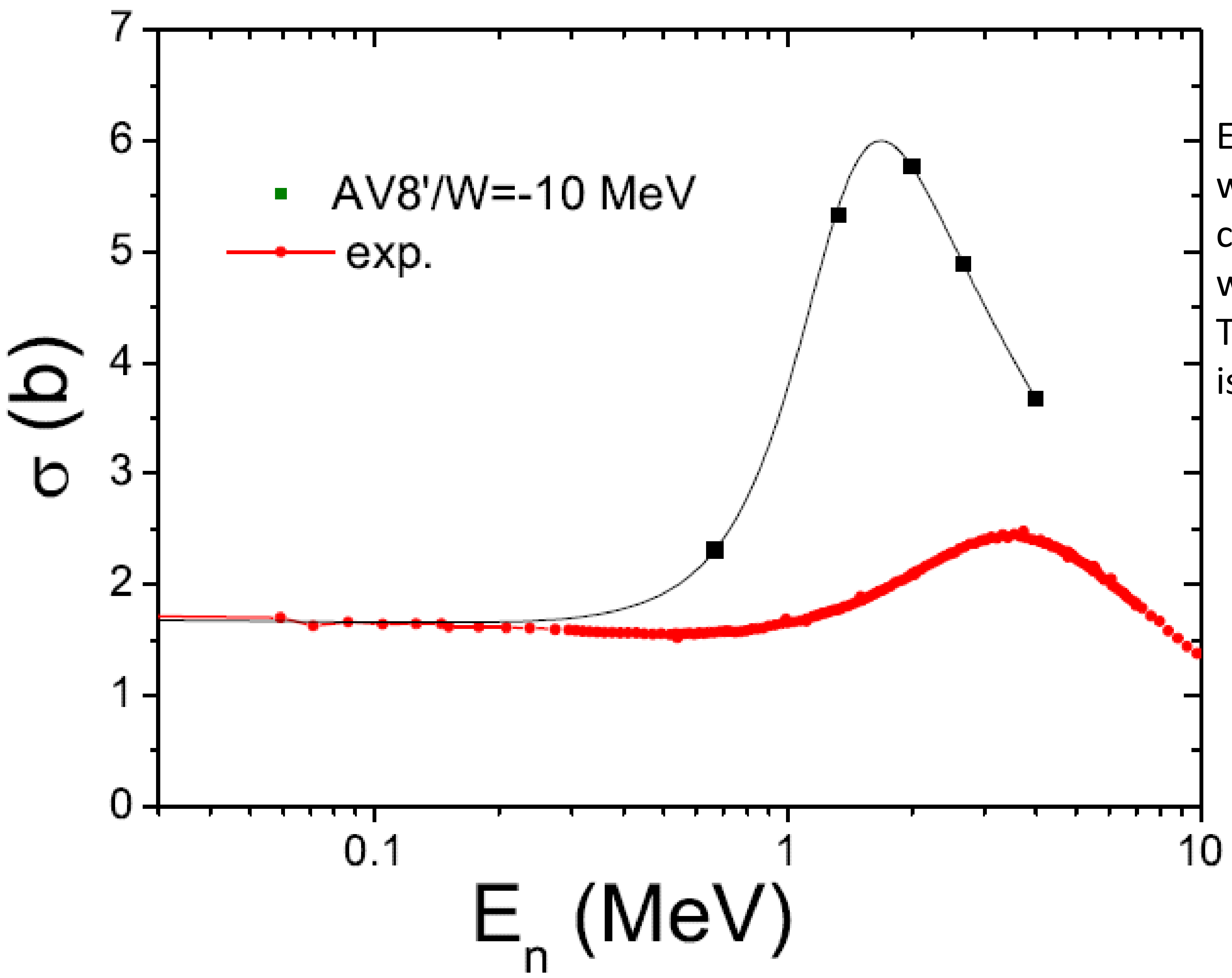
still 9 times strong attraction

It should be noted that $W_1(T=1/2)=-2.04$ MeV to reproduce the observed binding energy of ^4He, ^3He and ^3H.

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

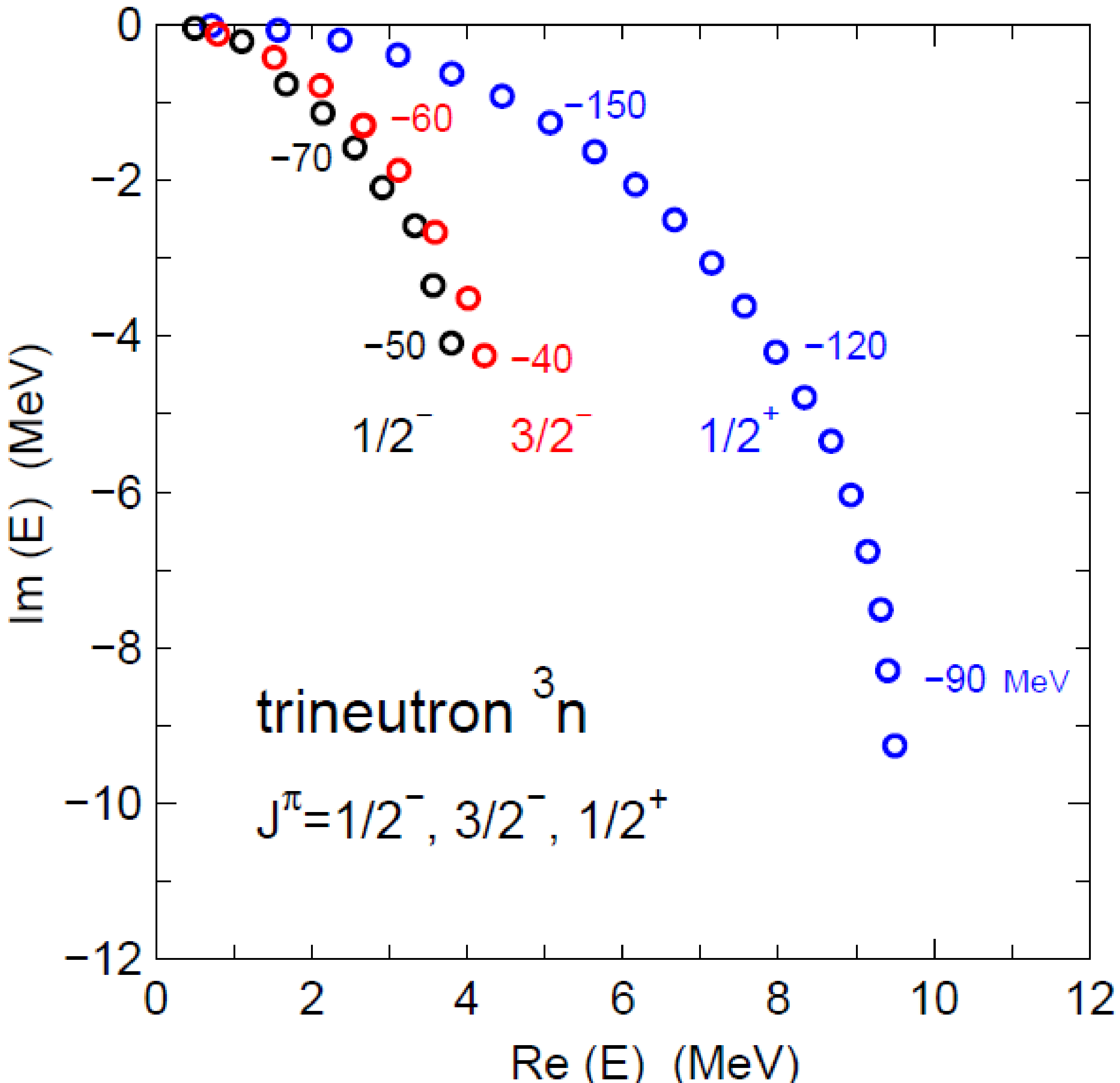
$W_1(T=3/2)$= free b_1=4.0fm
$W_2(T=3/2)$ = +35 MeV b_2=0.75 fm

Further to check the validity of T=3/2 three nucleon force, we calculated the ^3H+n total cross section using $W_1 \sim -10$ MeV.



Even if W_1=-10 MeV, we have a large total cross section comparing with the experimental data. This means that W_1=-10 MeV is still to strong attraction.

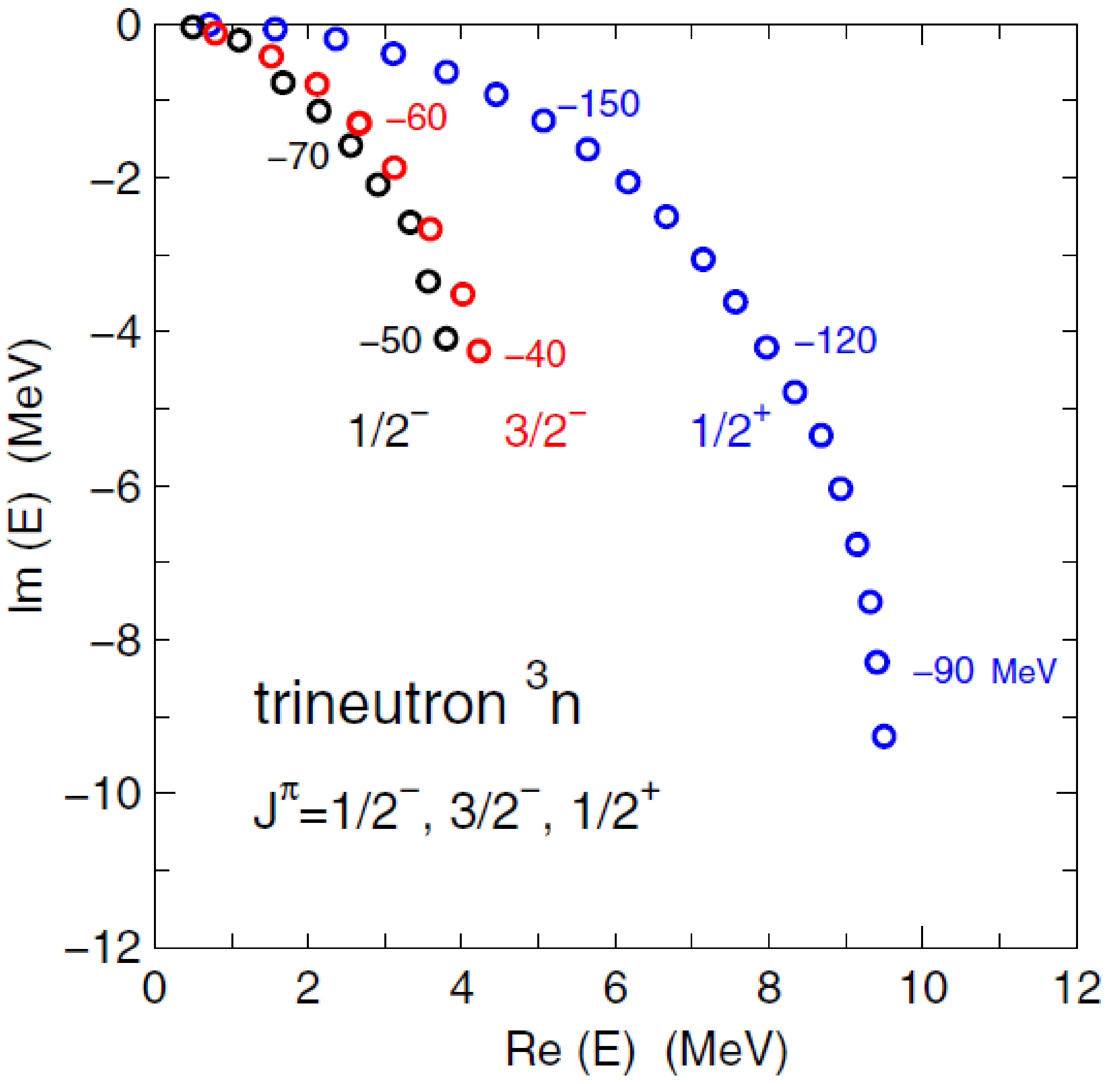
We calculated 3n system.

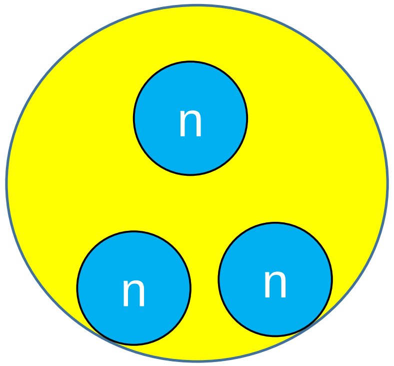


The lowest state should be J=3/2-.
We need W_1=-40 MeV to have resonant state for 3n system.
W_1=-40 MeV is much more attractive than the case of 4n system.
Then, there might not exist 3n system as a resonant state.

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

$W_1(T=3/2)$= free b_1=4.0fm
$W_2(T=3/2)$ = +35 MeV b_2=0.75 fm


trineutron ^{3}n
J^π=1/2$^-$, 3/2$^-$, 1/2$^+$
1/2$^-$
3/2$^-$
1/2$^+$
−150
−60
−70
−50
−40
−120
−90 MeV
Im (E) (MeV)
Re (E) (MeV)
0
−2
−4
−6
−8
−10
−12
0
2
4
6
8
10
12


n
n
n

How do we consider this inconsistency?

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

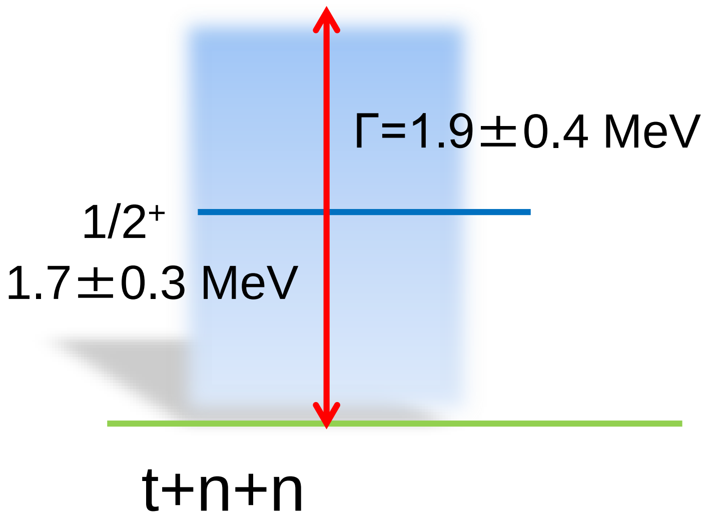
$$V_{ijk}^{3N} = \sum_{T=1/2}^{3/2} \sum_{n=1}^{2} W_n(T) e^{-(r_{ij}^2 + r_{jk}^2 + r_{ki}^2)/b_n^2} \mathcal{P}_{ijk}(T)$$

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

In this way, at present, in our calculation, it would be difficult to describe resonant state for a tetraneutron system.

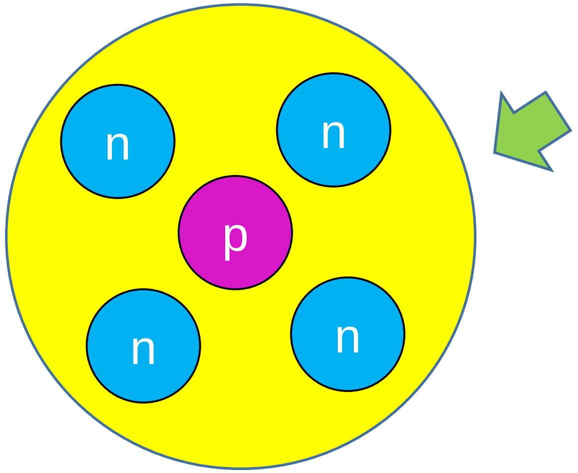
Further investigation of T=3/2 force and existence of tetra neutron system:

structure of ^{5}H is one of good candidate.



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

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



T=3/2 and T=1/2 three-body forces contribute to the energies of 5H.

However, I found that

(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]	$(1.7 \pm 0.3, 1.9 \pm 0.4)$ ←
Exp. [8]	$(1.8 \pm 0.1, < 0.5)$
Exp. [4]	(1.8, 1.3)
Exp. [5]	(2, 2.5)
Exp. [6]	(3, 6)
Exp. [9]	$(5.5 \pm 0.2, 5.4 \pm 0.6)$

We cited this experiment.
However, you have many different decay widths.

To confirm the energy and width of 5H is important for the study of hypernuclear physics.

I shall explain why.

[3] A.A. Koroshenninnikov 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.

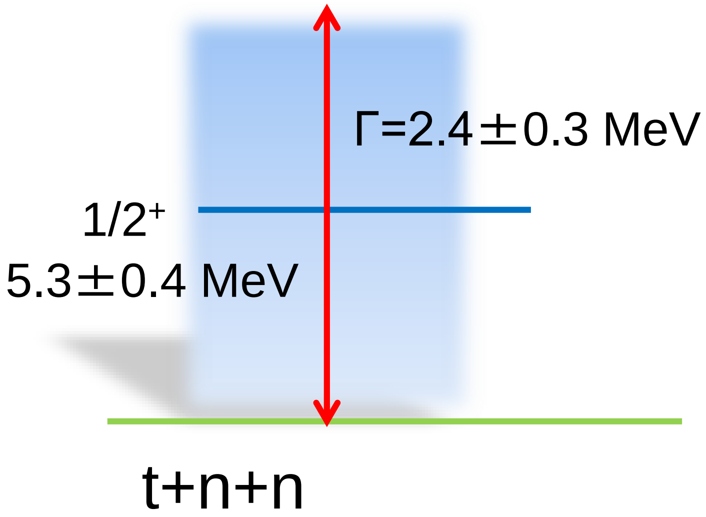
PHYSICAL REVIEW C **95**, 014310 (2017)

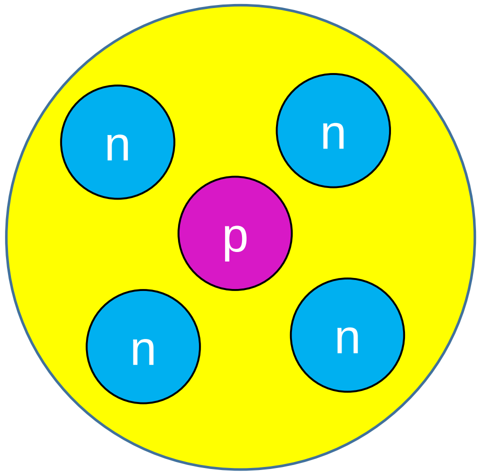
Ground-state properties of ^{5}H from the ^{6}He(d,^{3}He)^{5}H reaction

A. H. Wuosmaa,[1,2,*] S. Bedoor,[1,2,†] K. W. Brown,[3,‡] W. W. Buhro,[4] Z. Chajecki,[4] R. J. Charity,[3] W. G. Lynch,[4] J. Manfredi,[4] S. T. Marley,[5,§] D. G. McNeel,[1,2] A. S. Newton,[2] D. V. Shetty,[6] R. H. Showalter,[4] L. G. Sobotka,[3] M. B. Tsang,[4] J. R. Winkelbauer,[4,‖] and R. B. Wiringa[7]

[1]*Department of Physics, University of Connecticut, Storrs, Connecticut 06268-3046, USA*
[2]*Department of Physics, Western Michigan University, Kalamazoo, Michigan 49008-5252, USA*
[3]*Departments of Chemistry and Physics, Washington University at St. Louis, St. Louis, Missouri 63130, USA*
[4]*National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[5]*Department of Physics and Astronomy, University of Notre Dame, South Bend, Indiana 46558, USA*
[6]*Department of Physics, Grand Valley State University, Allendale, Michigan 49401, USA*
[7]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

(Received 3 October 2016; published 11 January 2017)





5H is important from side of hypernuclear physics.

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

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

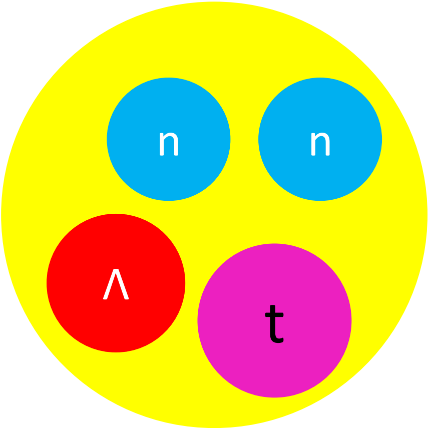
M. Agnello,[1,2] L. Benussi,[3] M. Bertani,[3] H. C. Bhang,[4] G. Bonomi,[5,6] E. Botta,[7,2,*] M. Bregant,[8] T. Bressani,[7,2] S. Bufalino,[2] L. Busso,[9,2] D. Calvo,[2] P. Camerini,[10,11] B. Dalena,[12] F. De Mori,[7,2] G. D'Erasmo,[13,14] F. L. Fabbri,[3] A. Feliciello,[2] A. Filippi,[2] E. M. 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

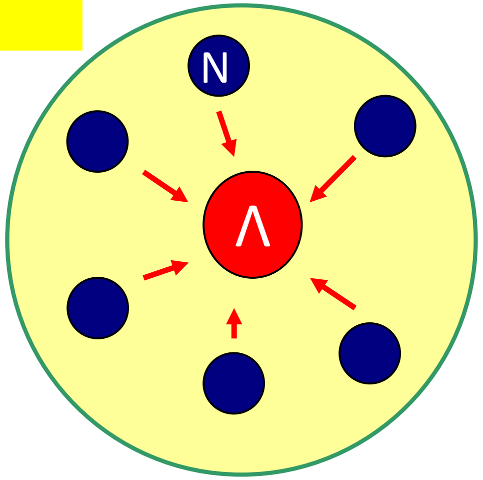
(Received 2 November 2011; published 24 January 2012)



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

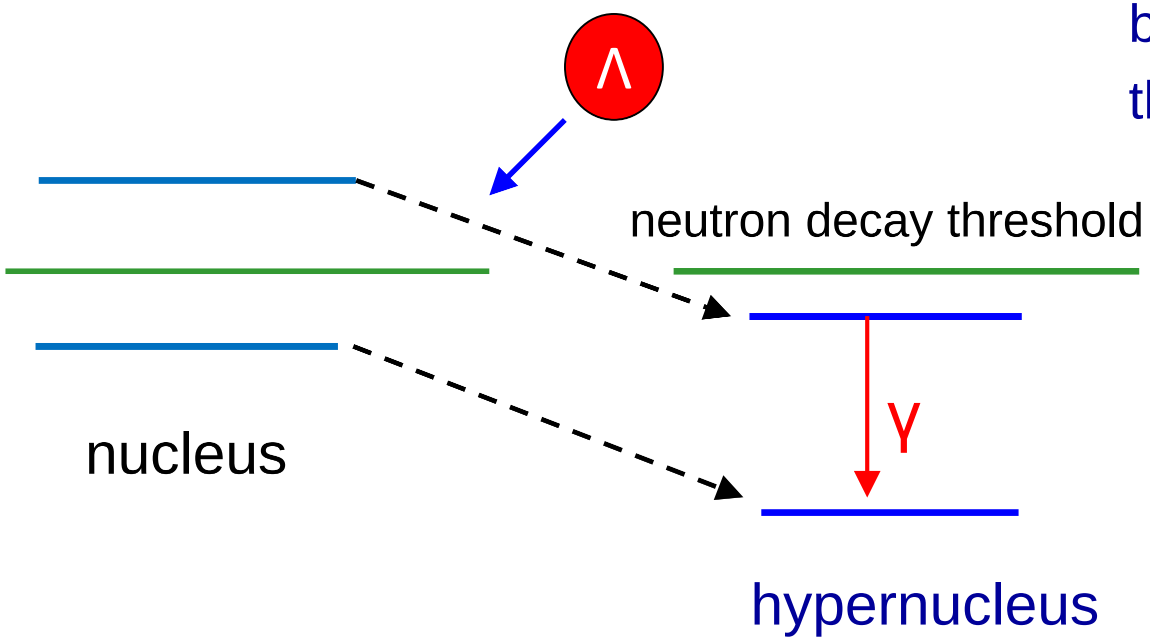
No Pauli principle
Between N and Λ

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



Hypernucleus

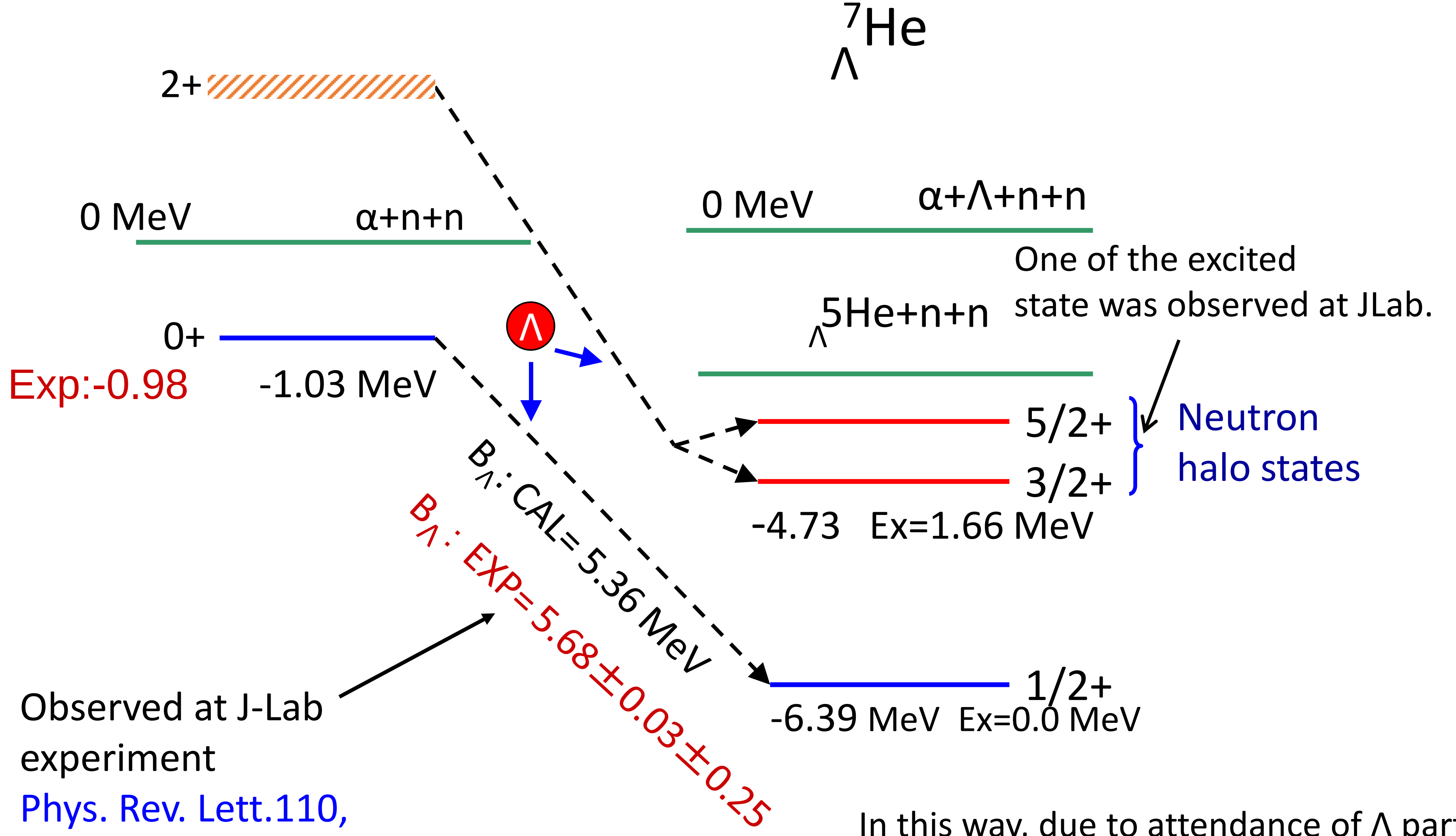
Due to the attraction of Λ N interaction, the resultant hypernucleus will become more stable against the neutron decay.



We call this phenomena 'gluelike' role of Λ particle.

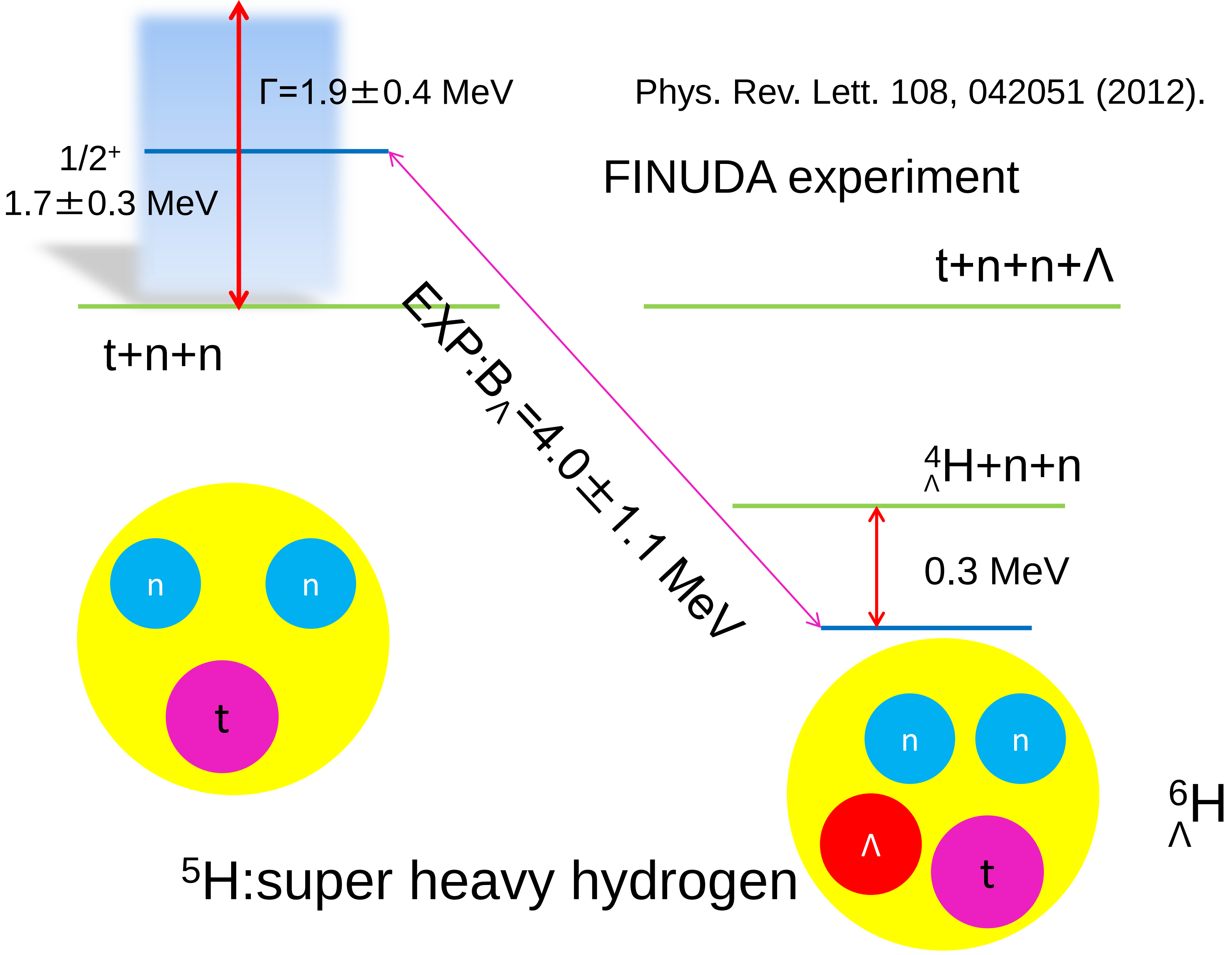
CAL: E. Hiyama et al., PRC 53, 2075 (1996), PRC 80, 054321 (2009)

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



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

In this way, due to attendance of Λ particle, we have more stable hypernuclear states.


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:B$_\Lambda$ =4.0±1.1 MeV
$^4_\Lambda$H+n+n
0.3 MeV
n
n
t
n
n
Λ
t
$^6_\Lambda$H
^{5}H:super heavy hydrogen

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

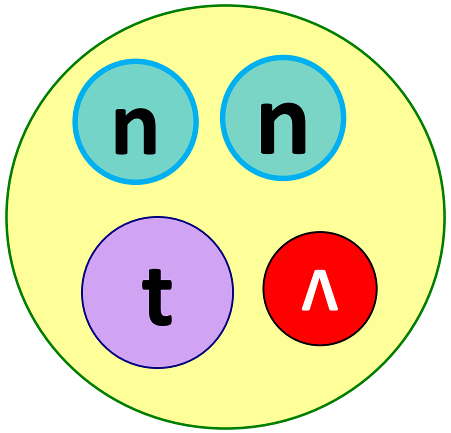
(1) R. H. Dalitz and R. Kevi-Setti, Nuovo Cimento 30, 489 (1963).

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

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

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

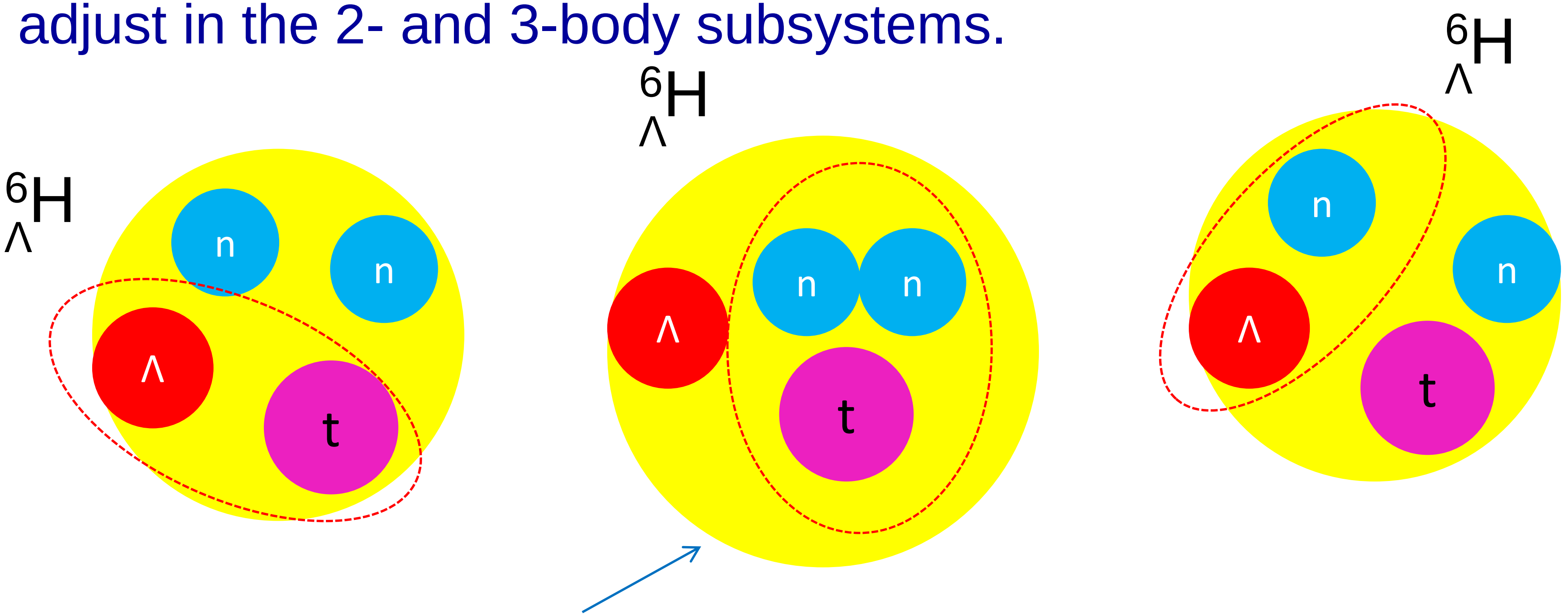
Four-body calculation of $^{6}_{\Lambda}H$



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

Before doing full 4-body calculation,
it is important and necessary to reproduce the observed binding energies of all the sets of subsystems in ${}^{6}_{\Lambda}H$.

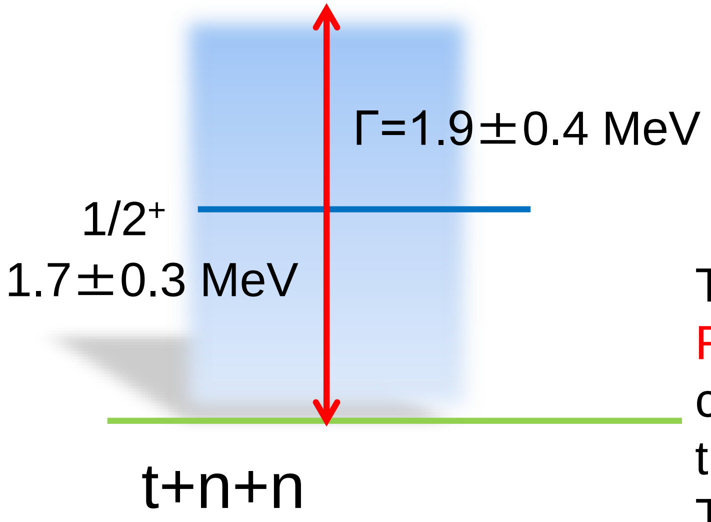
Namely, All the potential parameters are needed to
adjust in the 2- and 3-body subsystems.



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



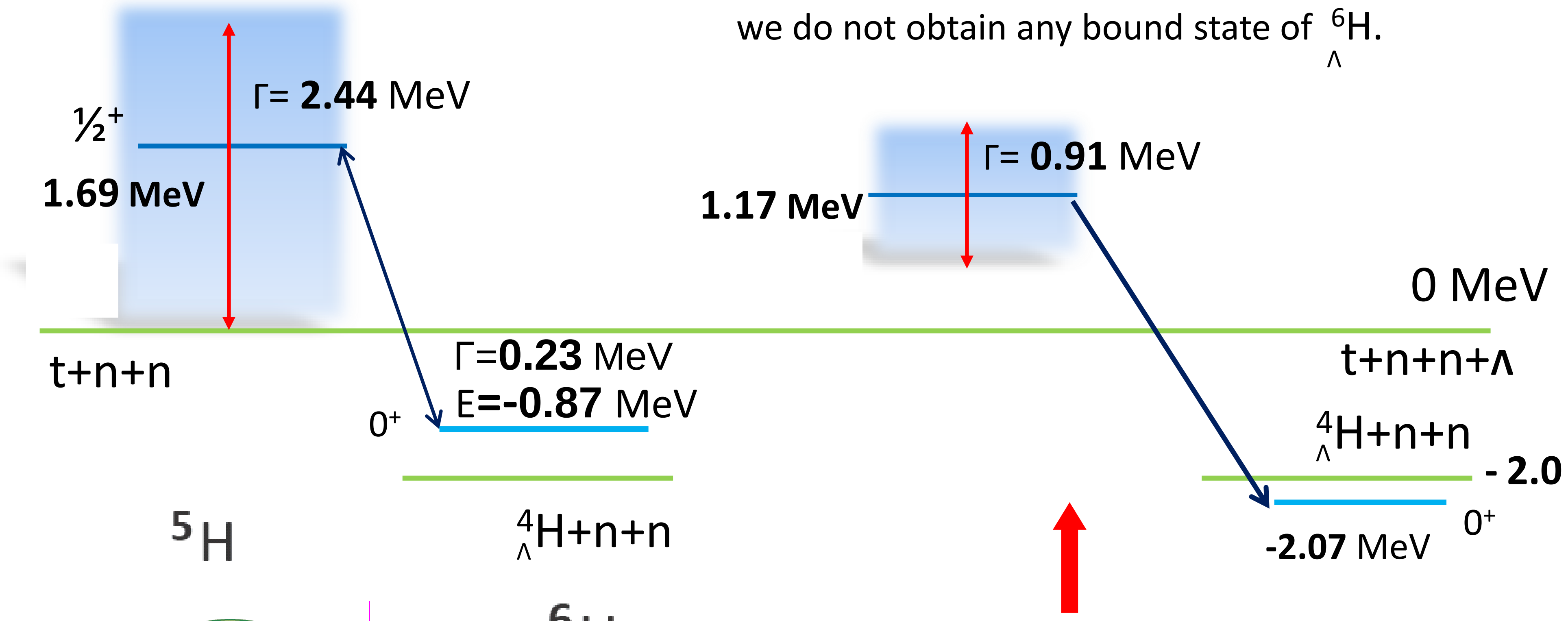
transfer reaction p(^{6}He, ^{2}He)^{5}H

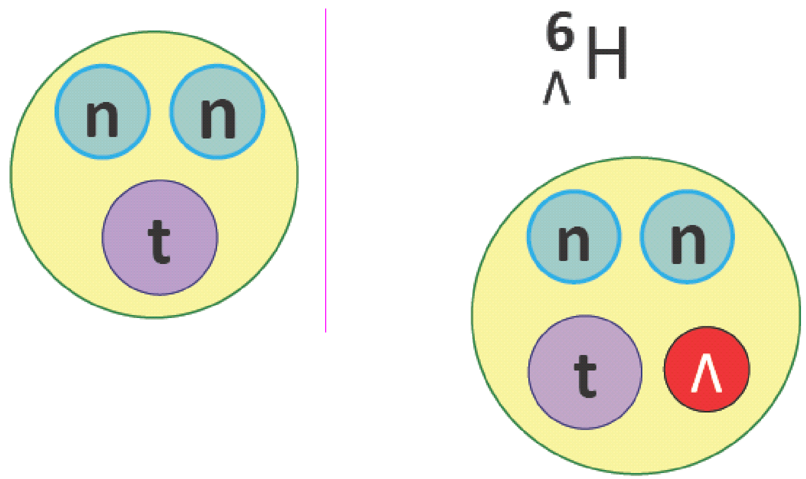
A. A. Korcheninnikov, et al. Phys. Rev. Lett. 87 (2001) 092501.

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

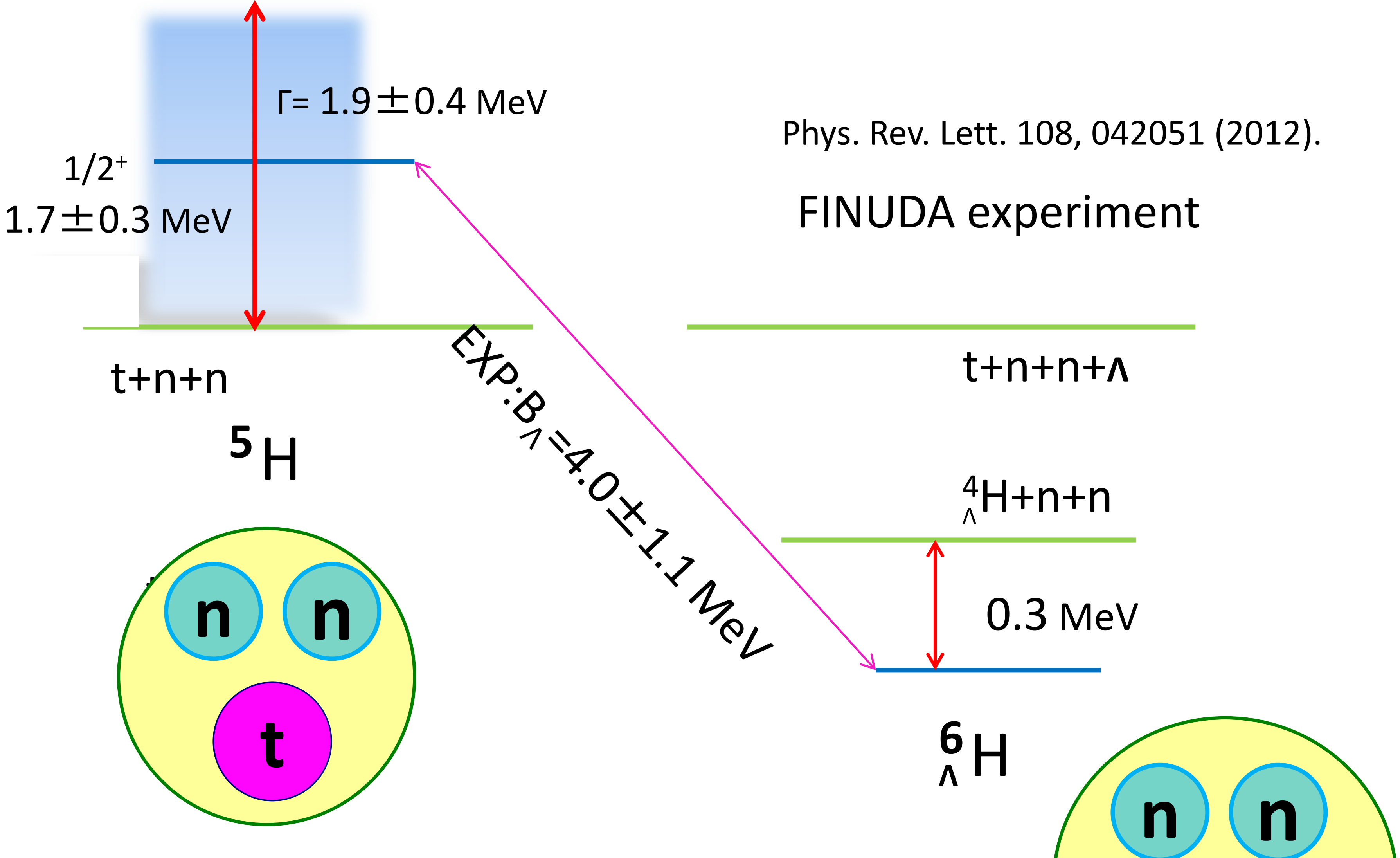




On the contrary, if we tune the potentials to have a bound state in $^{6}_{\Lambda}H$, then what is the energy and width of ^{5}H?

Phys. Rev. Lett. 108, 042051 (2012).

FINUDA experiment

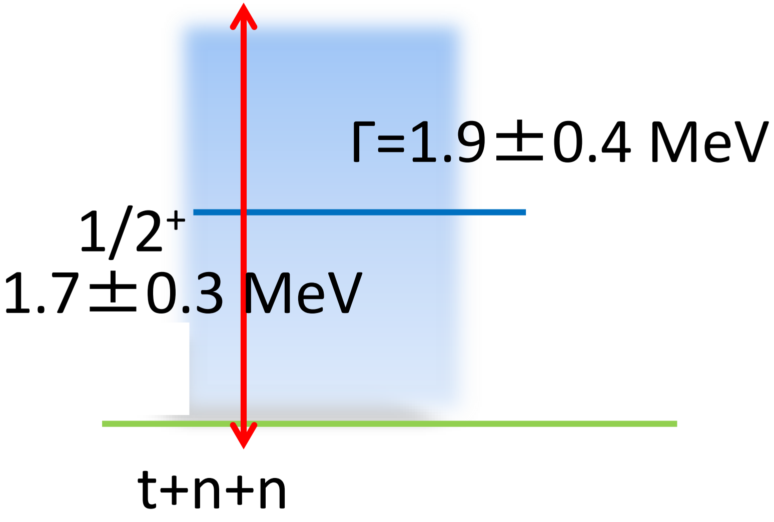


^{5}H:super heavy hydrogen

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 ${}^{6}_{\Lambda}H$, the energy should be lower than the present data.

(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)
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Exp. [5]	(2, 2.5)
Exp. [6]	(3, 6)
Exp. [9]	(5.5 ± 0.2, 5.4 ± 0.6)

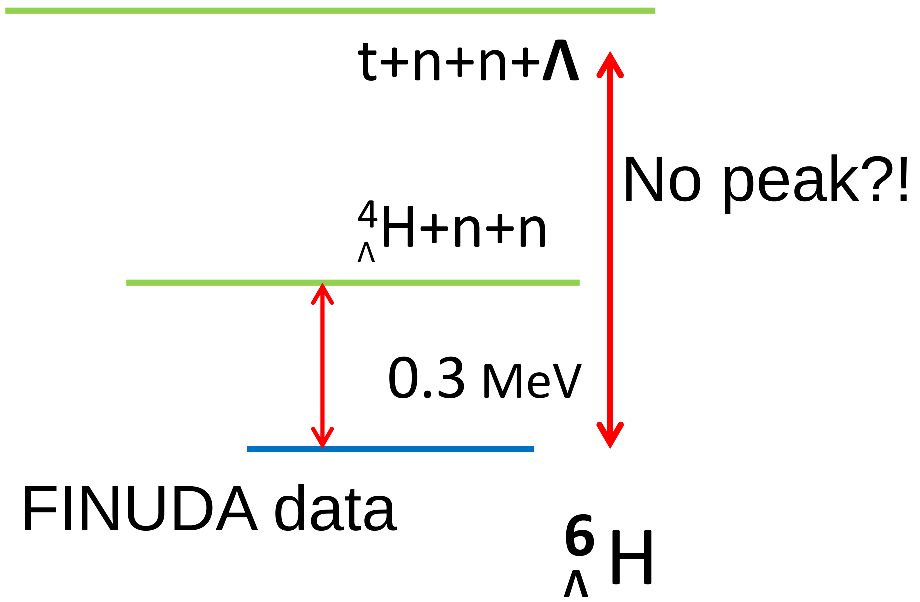
We cited this experiment.
However, you have many
different decay widths.
width is strongly related to
the size of wavefunction.

[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



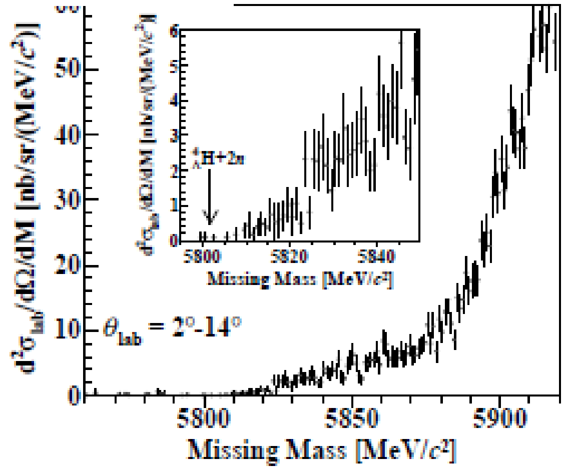
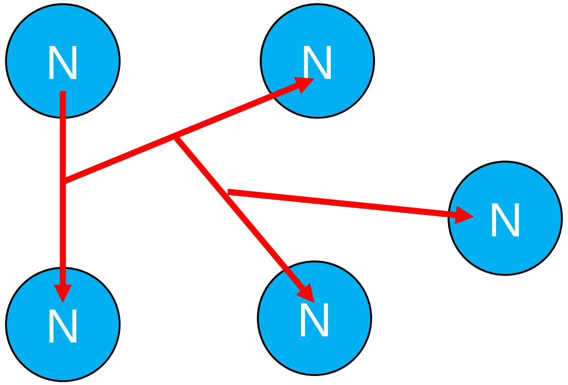


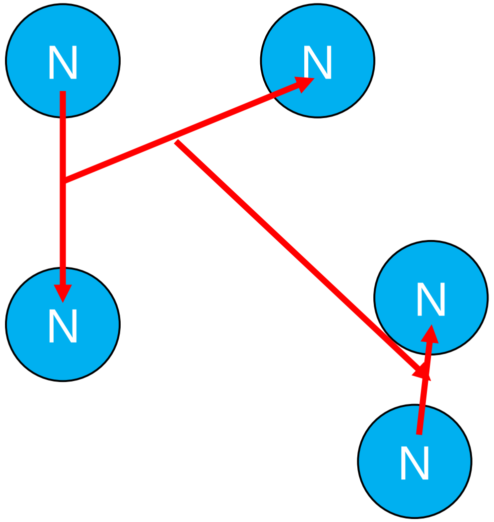
Figure 5: Missing-mass spectrum of the ^{6}Li(π^-, K^+) reaction at 1.2 GeV/c. A magnified view around the Λ bound region is shown in the inset. The arrow labeled as $^{4}_{\Lambda}$H+2n shows the particle decay threshold (5801.7 MeV/c^2).

I hope that the confirmation experiment for 6ΛH is important. Also, the confirmation experiment, especially to determine decay width of 5H
is important to conclude whether or not to have a bound state in 6ΛH.

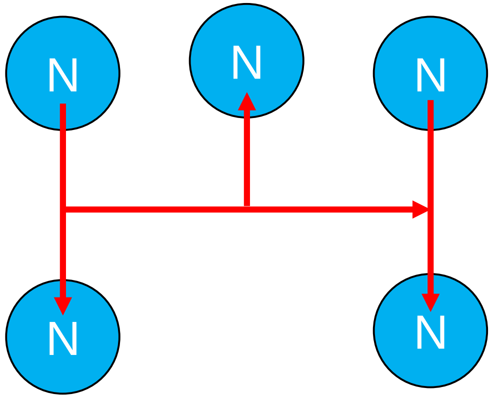
Therefore, we started to calculate ^5H as five-body problem.



K-channel (I used 60 kinds of channel.)



3+2 channel (30 kinds)



H-channel (30 kinds)

Totally, 120 Jacobian coordinates

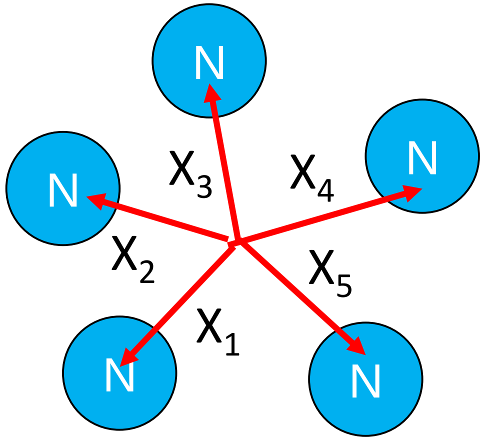
Hamiltonian:

To discuss the validity of T=3/2 3-body force and NN two-body force,
I should use AV8' and T=3/2 force used our 4n paper.

But, first, as the first step, to calculate ^5H, it is much easier to use just central force +5-body force to check my code of 5-body problem with Rimas.
For this purpose, I use MT13 potential (central force) and 5-body force.
deuteron: -2.2 MeV, the energy of ^3H:-8.5 MeV

$V=5V_0\exp(-(x_1^2+ x_2^2+ x_3^2+x_4^2+x_5^2)/(5r_0^2))$

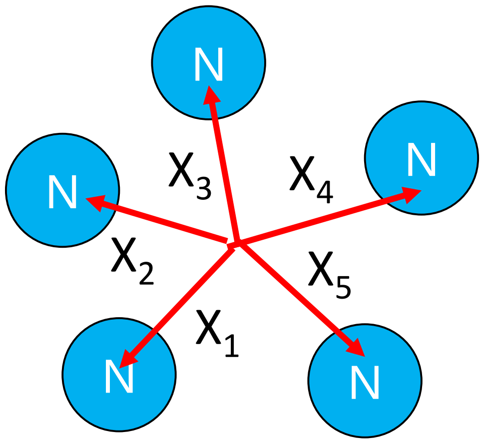
V_0 and R_0 are parameters.
Just to check our (I and Rimas) calculation,
Two parameters are tuned so as to have bound.



$V=5V_0\exp(-(x_1^2+x_2^2+x_3^2+x_4^2+x_5^2)/(5r_0^2))$

R_0=3.0fm Energy of ^5H

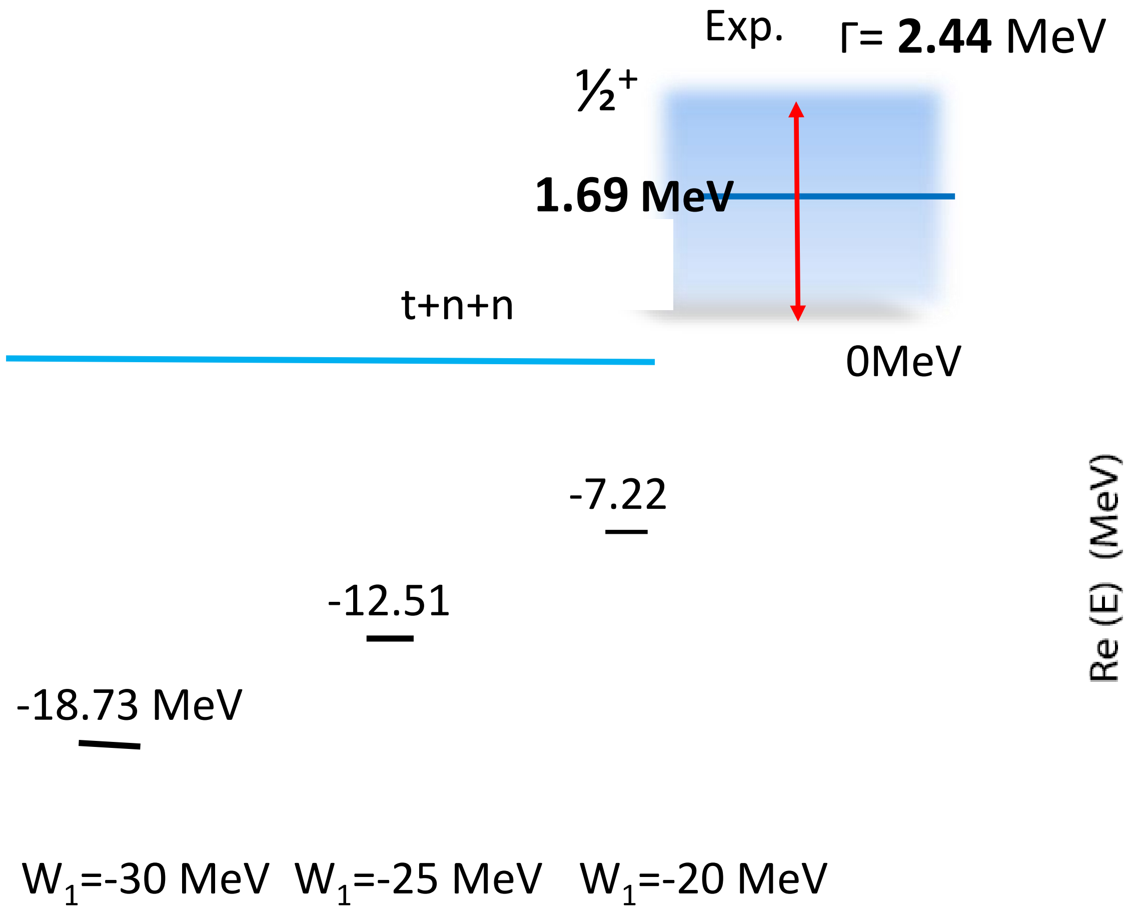
V_0	Rimas	Emiko
-3.0	-11.16 MeV	-11.57 MeV
-2.5	-10.27	-10.57
-2.0	-9.39	-9.65
-1.55	-8.65	-8.93

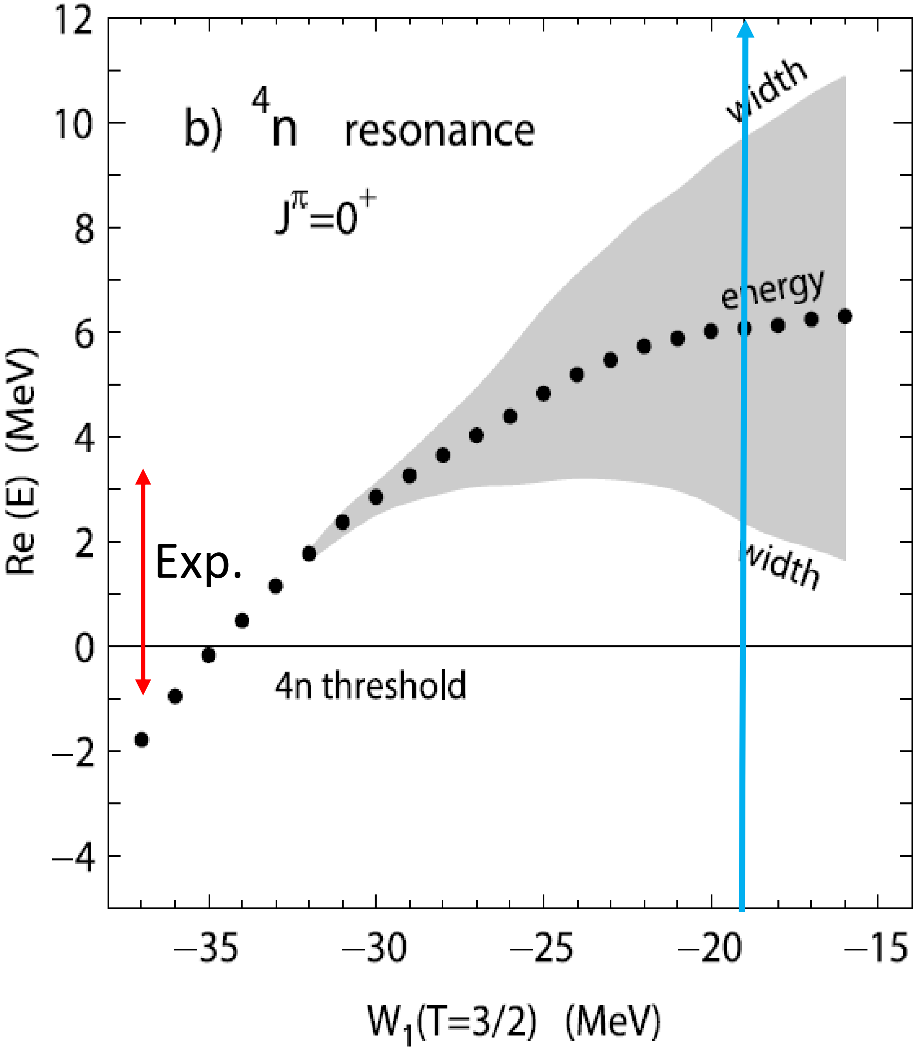


We are happy to see our results are consistent with each other.

Just yesterday, I succeeded in making code of 5H with MT13+ three-body force.

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





New results!

We see deeply bound state for 5H,

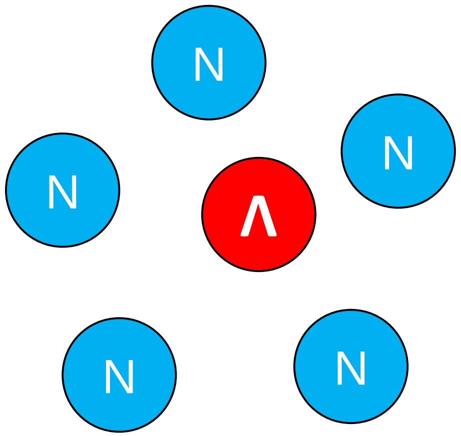
Future plan

AV8’ potential +three-body force

CSM method?

What is value for $W_1(T=3/2)$ to reproduce the data of 5H?
What is decay width?

I will answer the experimental result of $^{6}_{\Lambda}H$ as six-body problem.



Thank you!