Four-body structure of Tetraneutron system

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Selected for a Viewpoint in *Physics*

PRL **116,** 052501 (2016) PHYSICAL REVIEW LETTERS week ending 5 FEBRUARY 2016

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

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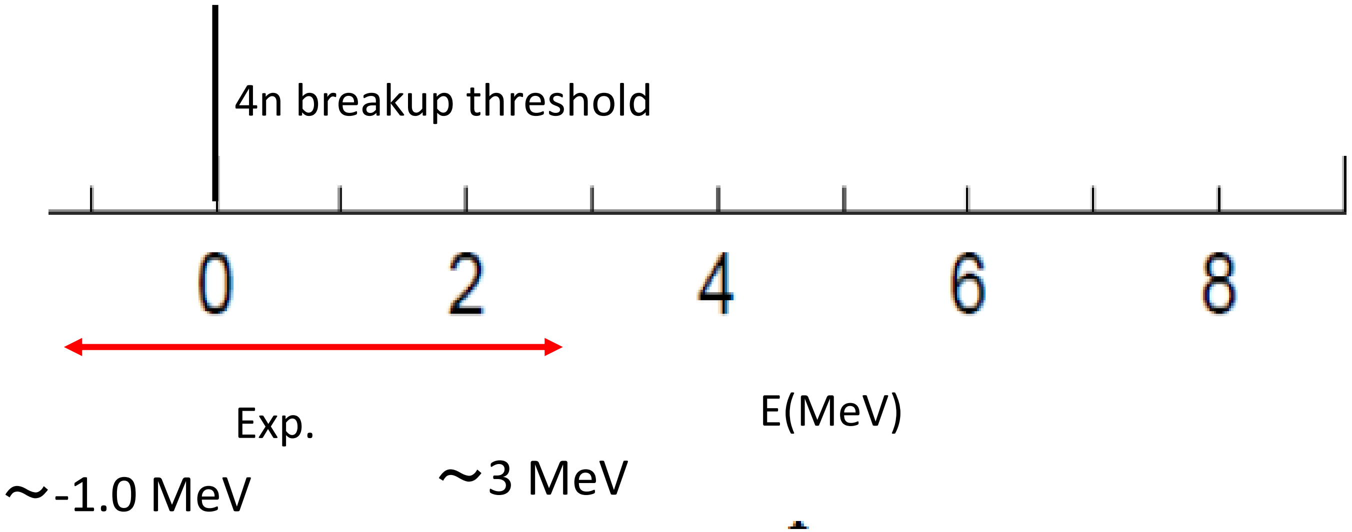
(Received 30 July 2015; revised manuscript received 11 October 2015; published 3 February 2016)

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.

PHYSICAL REVIEW C **93**, 044004 (2016)

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

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(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}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).

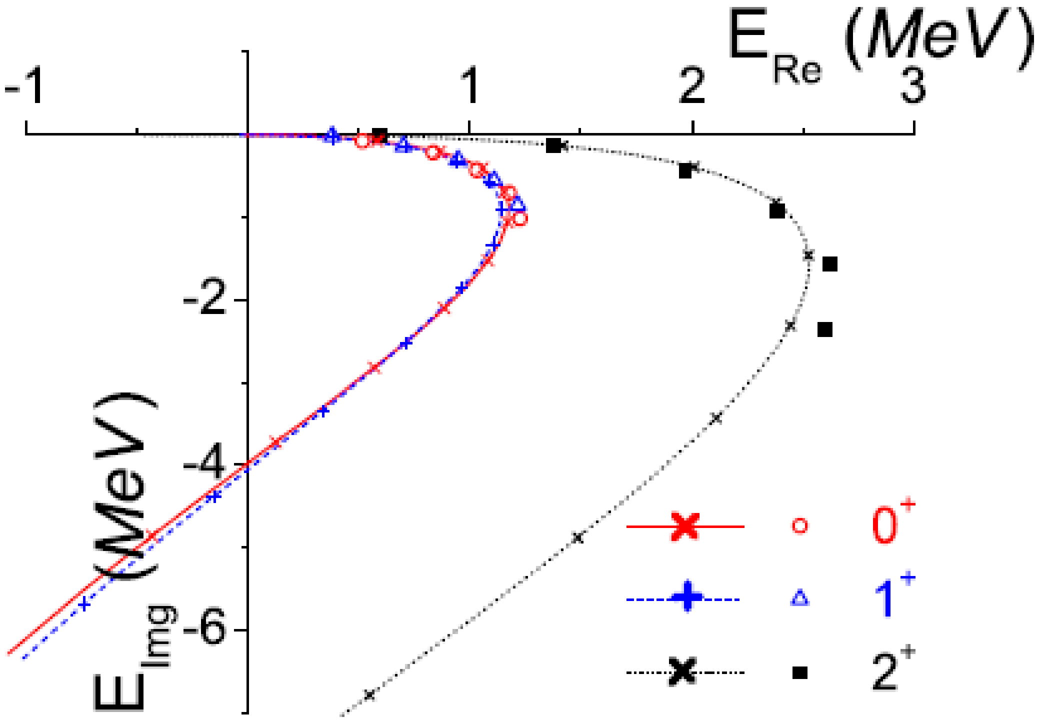
Unlikely evidence of tetraneutron system

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

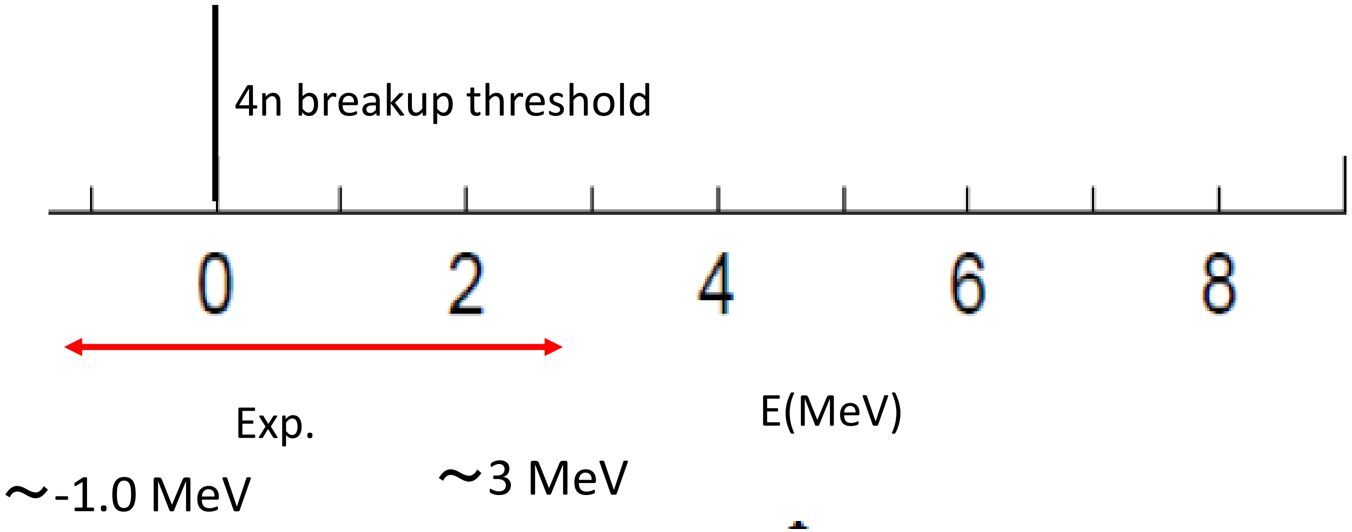
$$V_{4n} = -W\rho e^{-\frac{\rho}{\rho_0}}, \qquad \text{hyperradius } \rho = \sqrt{x^2 + y^2 + z^2}$$



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.



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

Γ=2.6 MeV (Upper limit)

Now, we have new data for tetraneutron system.

Theoretical important issue:

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$E_R = 0.83 \pm 0.65 \pm 1.25$ 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).
I shall show my work on few-nucleon systems using AV8 potential and the above three nucleon force, briefly.

To show that our method can provide with accurate energies and wavefunction,

・We performed a benchmark test calculation for the ground state of 4He using AV8 NN potential among 7 different few-body research group.

Kamada et al., Phys. Rev. C64 (2001), 044001

・We calculated the energy of the second 0+ state of 4He and inelastic electron scattering.

E. Hiyama, B.F. Gibson and M. Kamimura,

Phys. Rev. C **70** (2004) 031001(R)

Benchmark-test 4-body calculation ： Phys. Rev. C64 (2001), 044001

Benchmark test calculation of a four-nucleon bound state

by 7 groups

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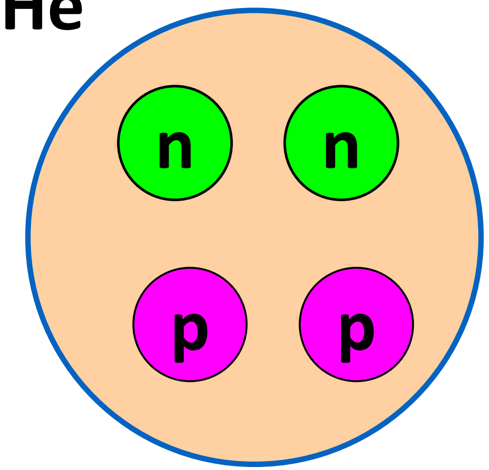
^{4}He



4 nucleon bound state

Realistic NN force: 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)
CRCGV	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

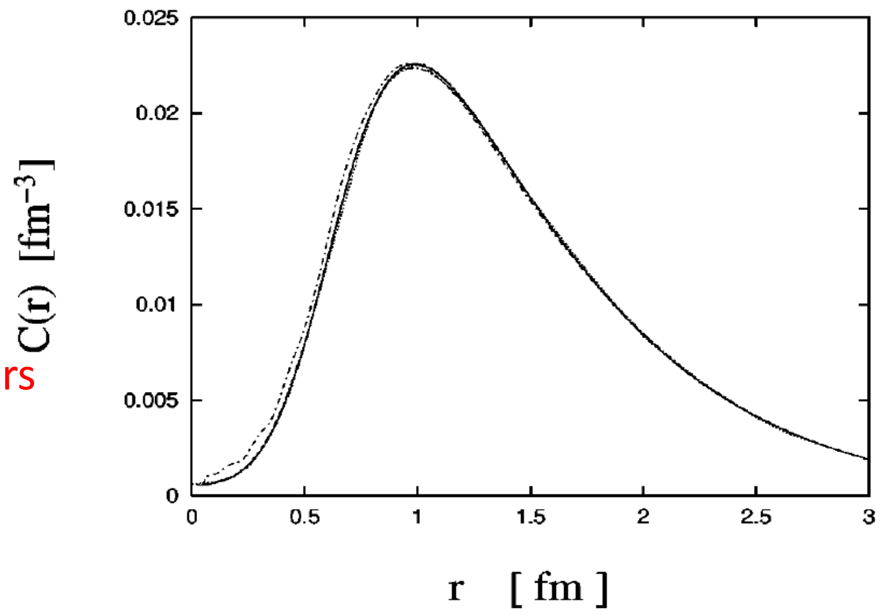
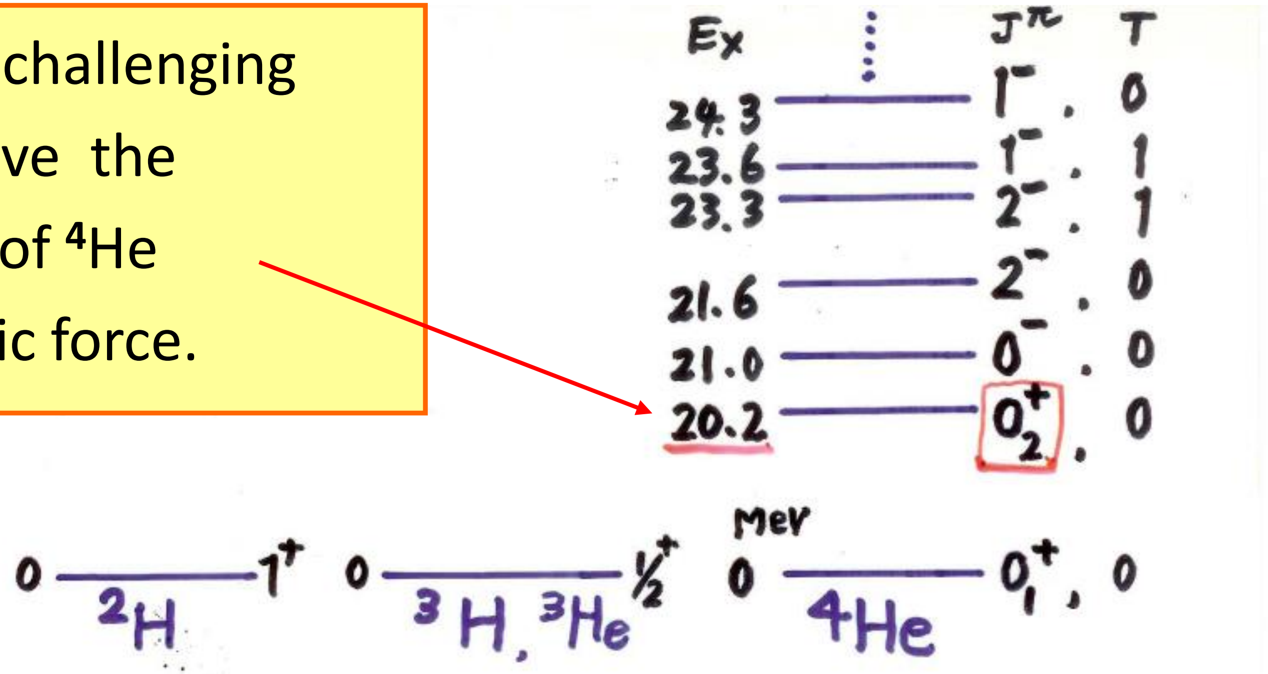


FIG. 1. Correlation functions in the different calculational schemes: EIHH (dashed-dotted curves), FY, CRCGV, SVM, HH, and NCSM (overlapping curves).

One of the next challenging problems: to solve the **second 0^+** state of ^{4}He using the realistic force.



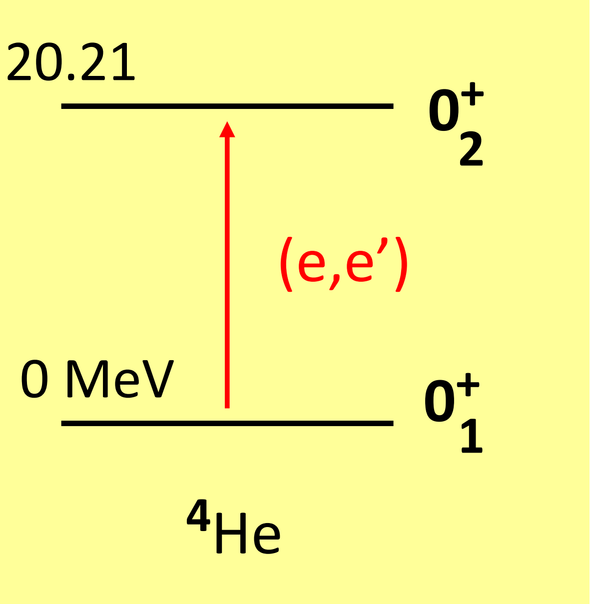
^{4}He is the lightest nucleus that exhibits discrete excited states.

The **second 0+ state** at E_x=20.2 MeV has the same spin, isospin and parity as the ground state.

Therefore, this excited state should have quite a different spatial structure in order to be orthogonal to the ground state.

Important questions to be answered are:

1) Is it possible to reproduce the energies of the 1st and 2nd $\mathbf{0^+}$ states simultaneously?



2) Is it possible to explain the inelastic electron scattering data $^4\mathrm{He}(e,e')^4\mathrm{He}(0_2^+)$?

3) The second 0^+ state exhausts only **11 %** of the energy-weighted E0 sum rule value (EXP).

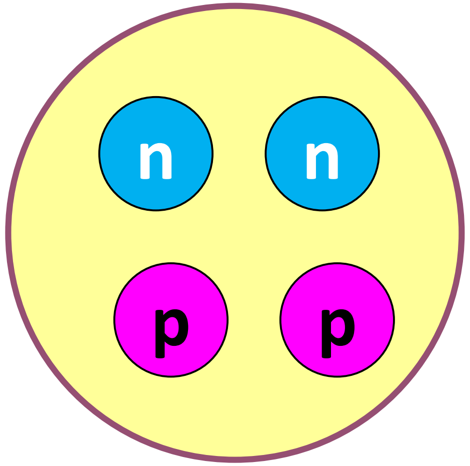
This means that the second 0^+ state is not a collective state.

Where is the major component of the sum rule value situated?

All the questions were clearly answered in our paper:

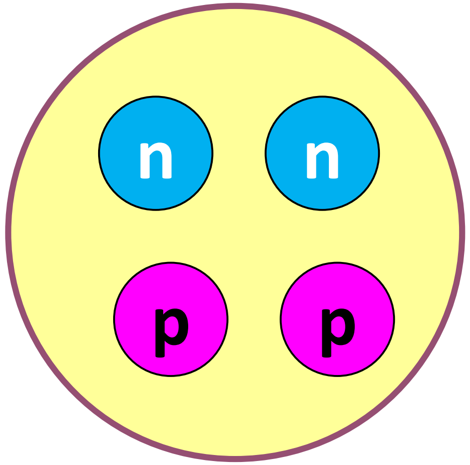
E. Hiyama, B.F. Gibson and M. Kamimura,
Phys. Rev. C **70** (2004) 031001(R)

based on 4-body calculation with our method.

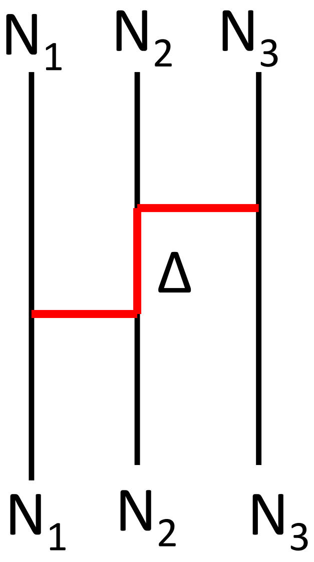


In this work, we took

AV8' NN force + Coulomb force



Use of the two-body force alone does **not** reproduce the observed binding energies of ^{3}H, ^{3}He and ^{4}He.



We additionally employ a phenomenological three-body force (2-range Gaussians) so as to reproduce those binding energies. Precise spin-isospin property is not needed for the present subject.

Use of

AV8' + Coulomb force + phenomenological 3-body force

well reproduces simultaneously

B.E.(^{3}H) **:** -8.42 MeV (CAL)

-8.48 (EXP)

B.E.(^{3}He) **:** -7.74 MeV (CAL)

-7.77 (EXP)

B.E.(^{4}He) **: -28.44** MeV (CAL)

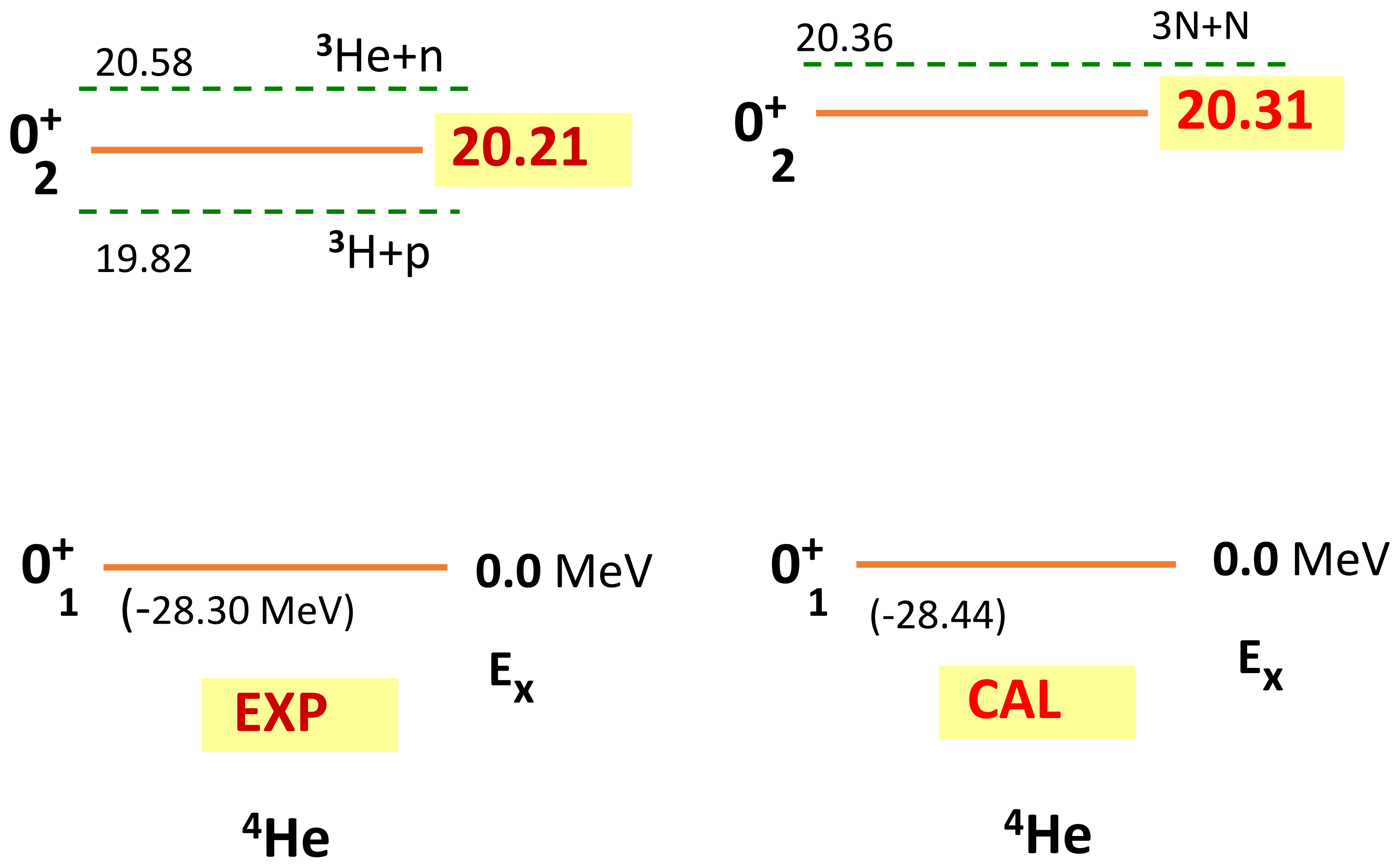
-28.30 (EXP)

r.m.s. charge radius of ^{4}He (0^+_1) **:** **1.658** fm (CAL)

1.671$\pm$0.014 fm (EXP)

How about the second 0^+ state?

Answer to question 1) : Energy of 0_2^+ of ^{4}He



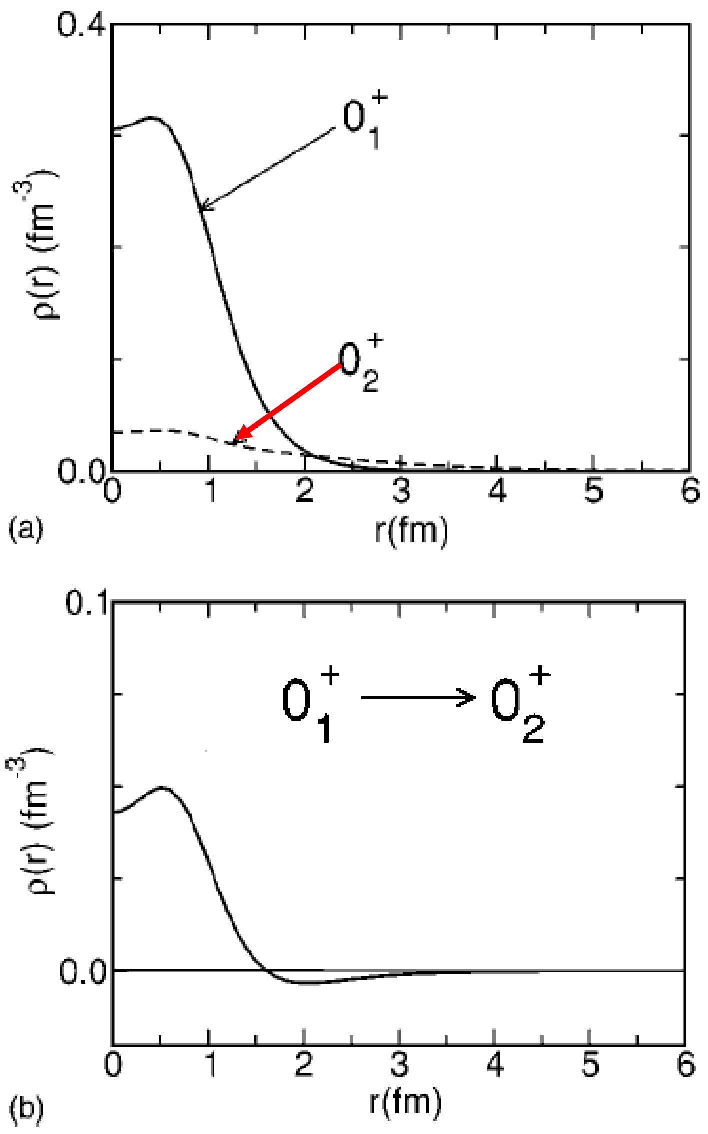


FIG. 2. Mass densities of the 0_1^+ and 0_2^+ states of ^{4}He (upper) and the transition density between them (lower).

mass density

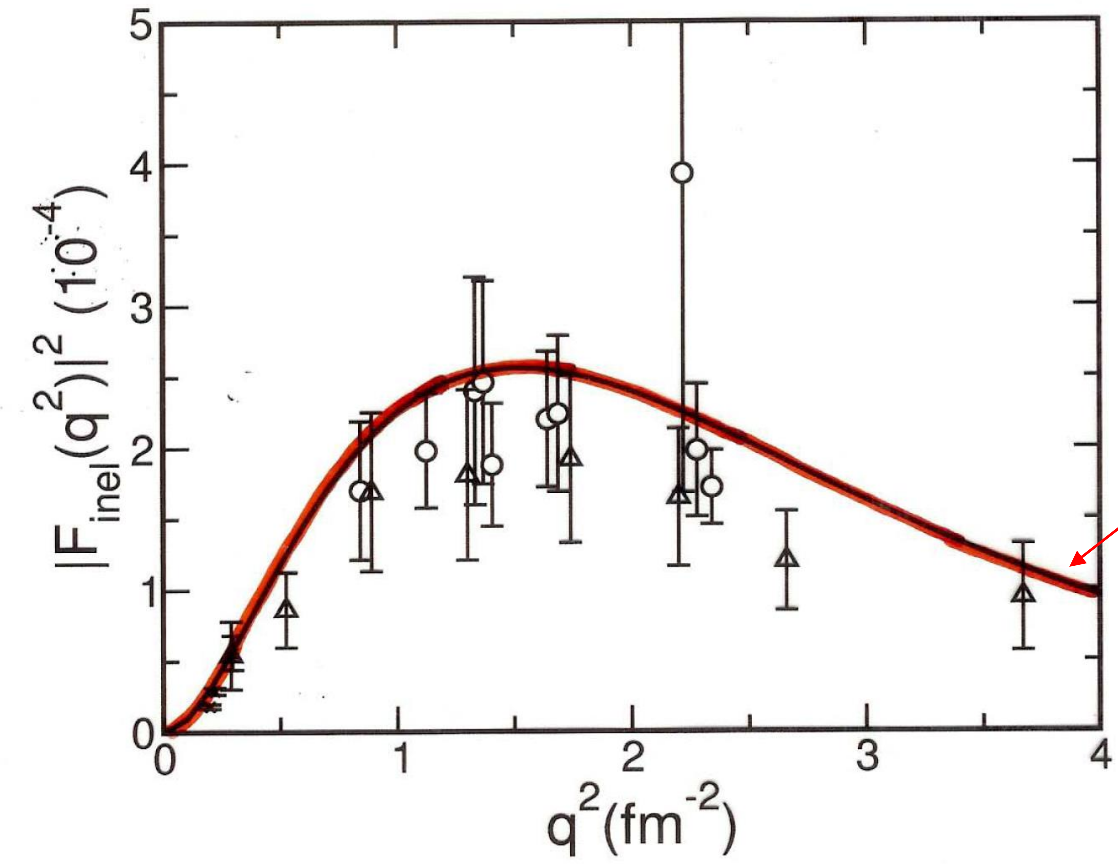
The density of the second 0^+ state
in the internal region is
so much lower than that of the
ground state.

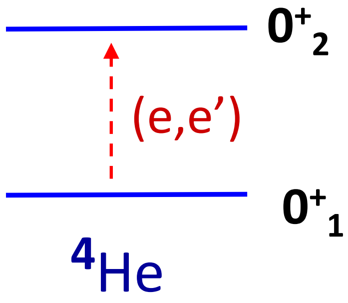
transition density

$$|F_{\rm inel}(q^2)|^2 = \frac{1}{4\pi}\left|\int e^{i\mathbf{q}\cdot\mathbf{r}}\rho_{0_1^+0_2^+}(r)Y_{00}(\hat{\mathbf{r}})d\mathbf{r}\right|^2 f_{\rm p}(q^2),$$

The Fourier transformation of the
transition density gives the
form factor of the inelastic electron
scattering.

Answer to question 2) : $^4\mathrm{He}(e,e')^4\mathrm{He}(0_2^+)$





Hiyama, Gibson, Kamimura
Phys. Rev. C70 (2004)
031001(R).

(No other successful
4-body calculation)

We understand that our method is suitable for describing both compactly bound states and loosely coupled states as well as transitions between them.

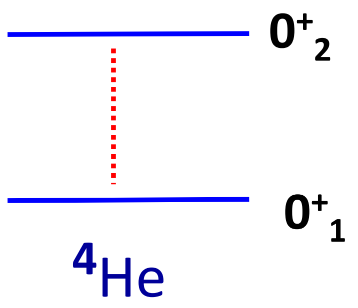
Energy-weighted **E0** sum rule in ^{4}He

$$\sum_{n\geqslant 2}^{\infty}(E_n - E_1)\left|\langle 0_n^+|\sum_p r_p^2|0_1^+\rangle\right|^2 = \frac{\hbar^2 Z}{m_N}\langle r_p^2\rangle_{0_1^+},$$

E0 strength of the second 0^+ state,

$\langle 0_2^+|\Sigma_p r_p^2|0_1^+\rangle$ =1.10 ± 0.16 fm^2 (EXP),

was derived from the $^4\mathrm{He}(e,e')^4\mathrm{He}(0_2^+)$:



But, this contribution from the second 0^+ state exhausts only **11** % of the sum rule limit. → The second 0^+ state is not a collective mode.

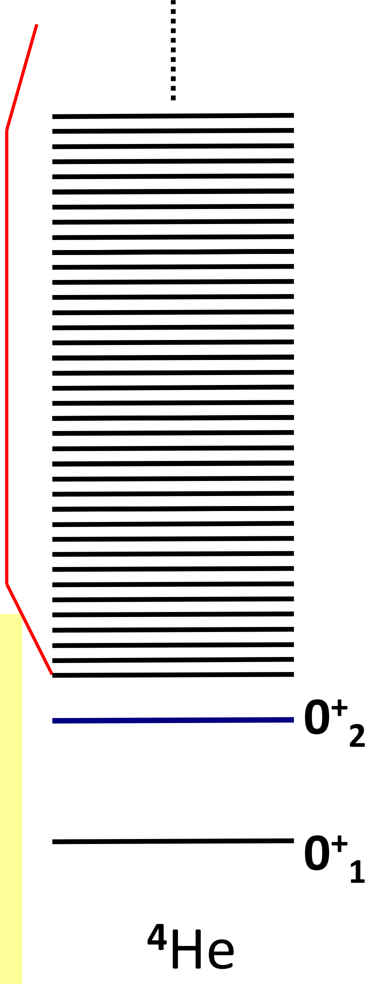
Where is the major component of the E0 sum rule limit situated?

(This has been a long-standing puzzle of ^{4}He nucleus since 1970's.)

Energy-weighted E0 sum rule:

$$\sum_{n \geqslant 2}^{\infty} (E_n - E_1) \left| \langle 0_n^+ | \sum_p r_p^2 | 0_1^+ \rangle \right|^2 = \frac{\hbar^2 Z}{m_N} \langle r_p^2 \rangle_{0_1^+},$$

precisely-discretized non-resonant continuum states (～ **20,000**)

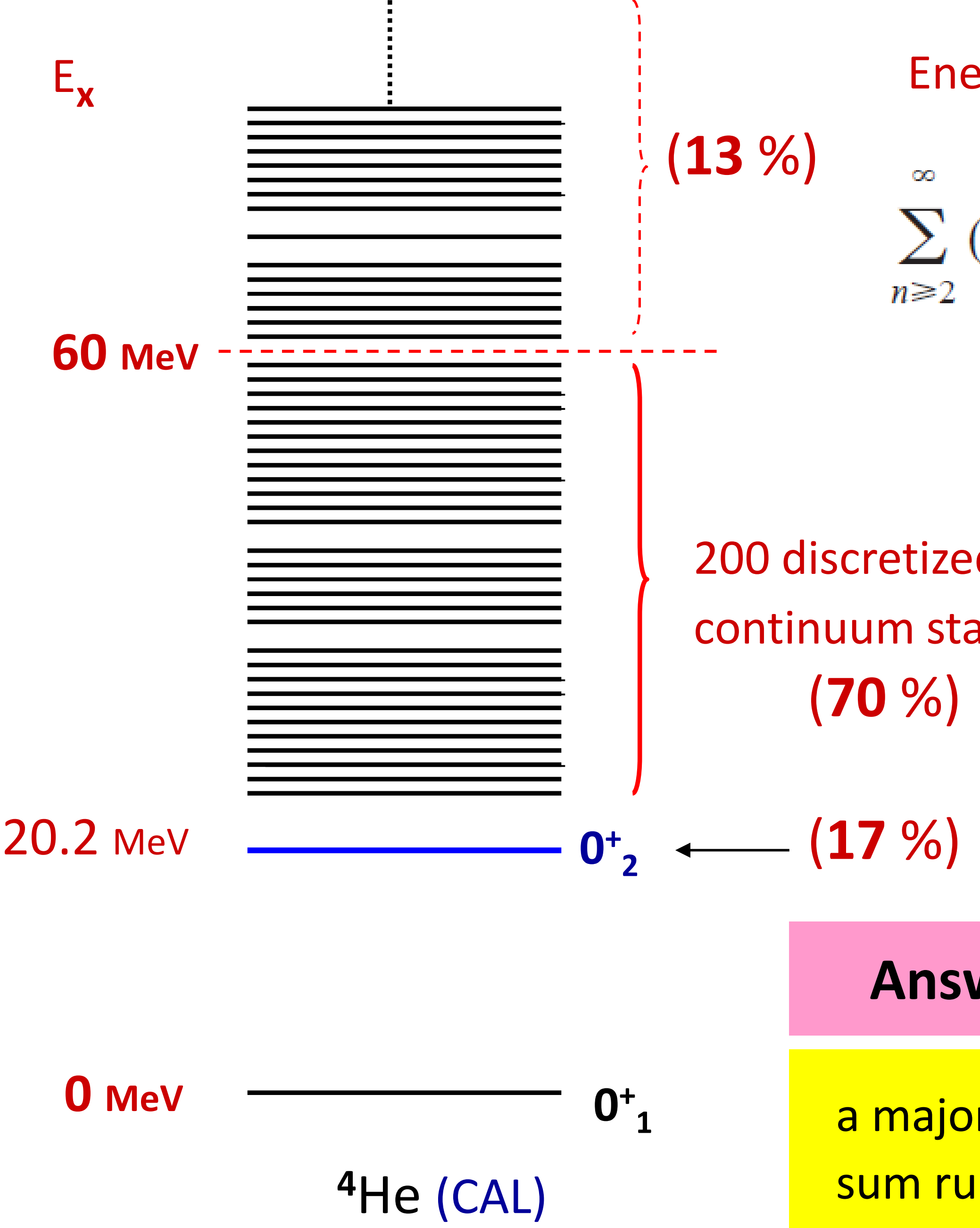


We solved this puzzle as following**:**

1) Using the 4-body Gaussian basis functions, we diagonalized the total Hamiltonian.

2) Since we employed **～20,000** basis functions, we obtained the same number of 4-body eigenstates. Above the second 0^+ state, we have presicely-discretized non-resonant continuum states.

3) We calculated the energy-weighted E0 strength to all the discretized eigenstates, and found the following fact:



Energy-weighted E0 sum rule:

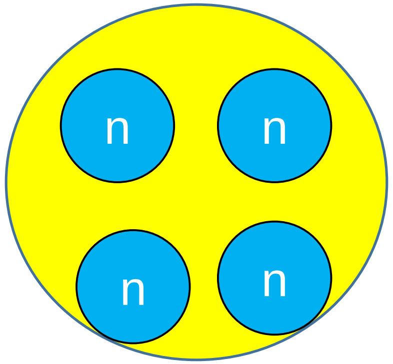
$$\sum_{n\geqslant 2}^{\infty}(E_n-E_1)\left|\langle 0_n^+|\sum_p r_p^2|0_1^+\rangle\right|^2=\frac{\hbar^2 Z}{m_N}\langle r_p^2\rangle_{0_1^+},$$

Contribution from these continuum states amounts to **70** %
of the sum rule limit.

Answer to question 3) :

a major part of the energy-weighted E0 sum rule is exhausted by non-resonant, low-energy continuum states.

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 $\quad$ b_1=4.0fm => W_1 should be adjusted so as to reproduce the observed 4n system

W_2(T=3/2) = +35 MeV $\quad$ 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.

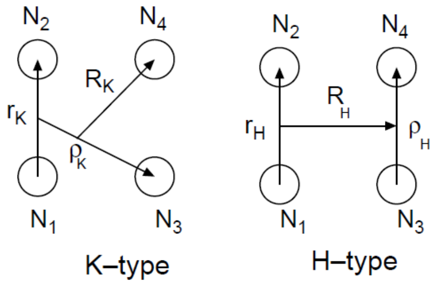
Then if Shimoura san might observe the ground state, the state should be $J=0^+$ state.

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.

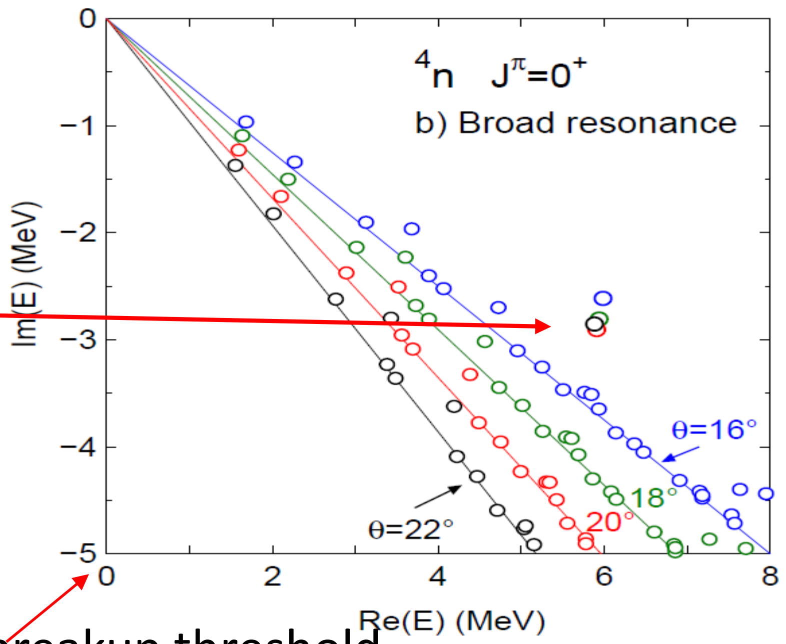
$$[H(\theta) - E(\theta)]\Psi_{JM,TT_z}(\theta) = 0$$

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



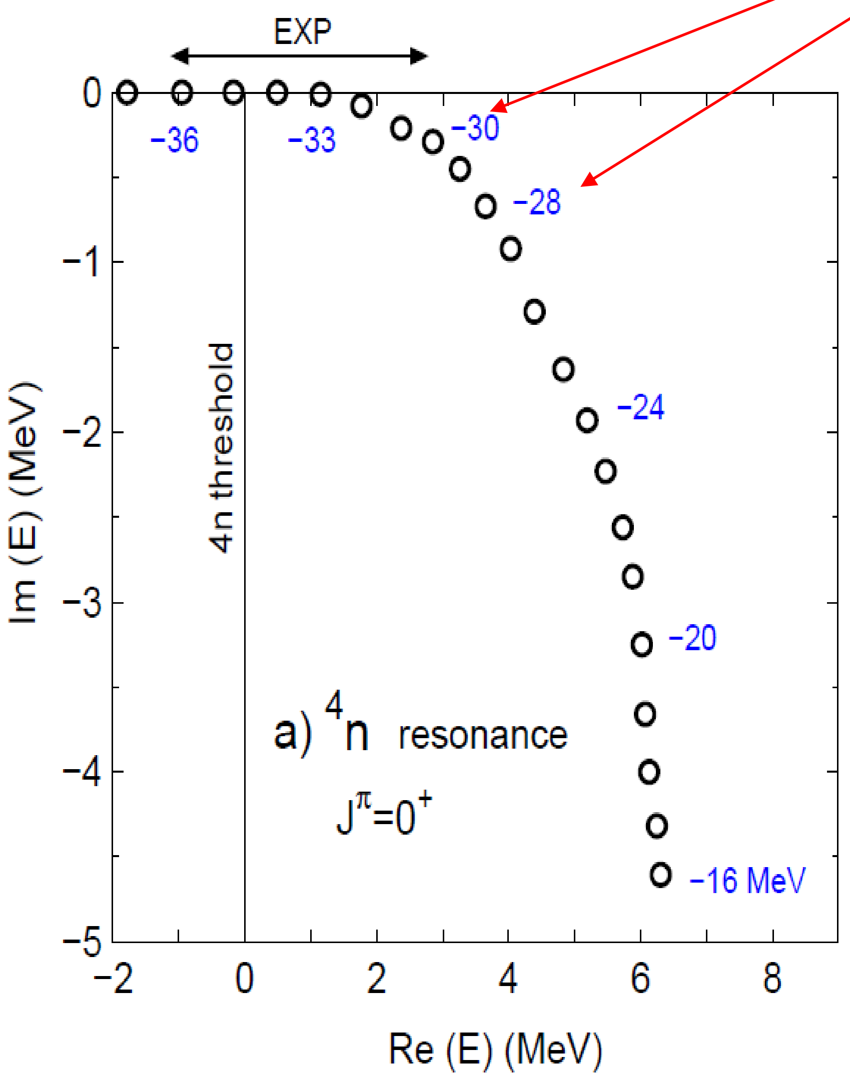
$$r_c \to r_c e^{i\theta}, \ R_c \to R_c e^{i\theta}, \ \rho_c \to \rho_c e^{i\theta} \quad (c = \mathrm{K}, \mathrm{H})$$

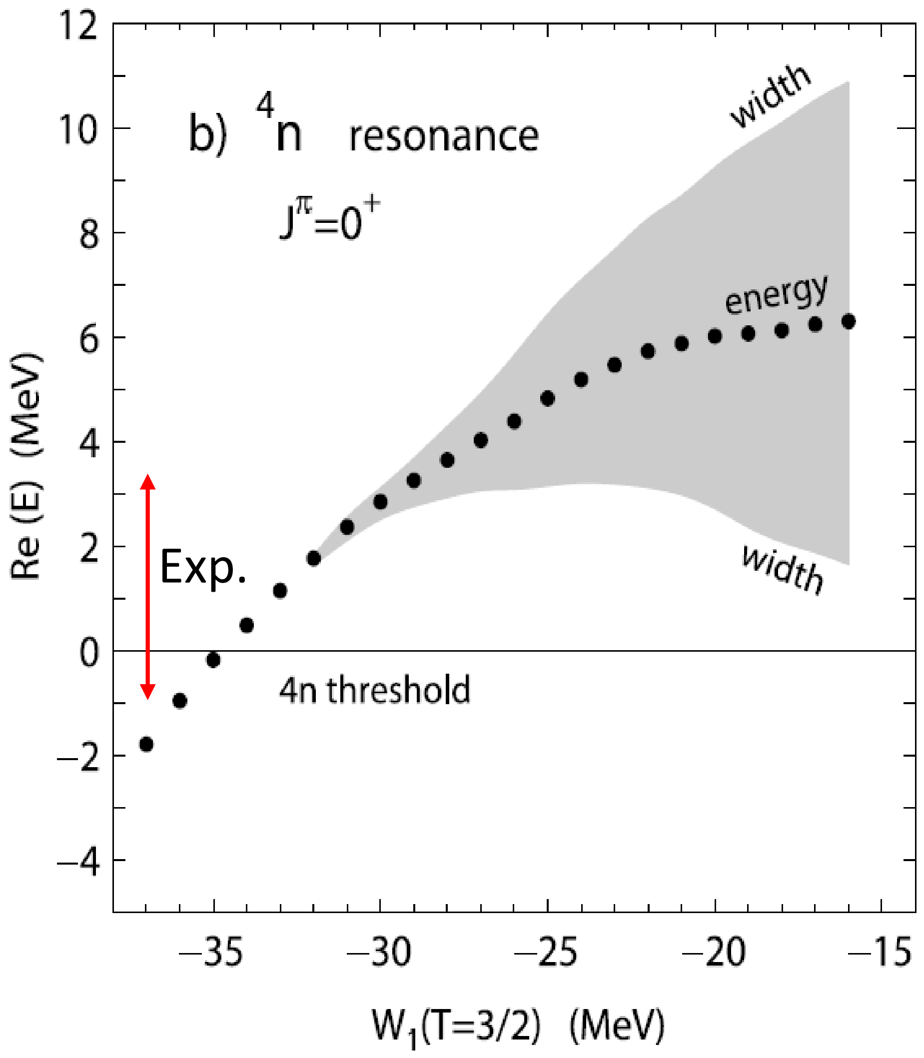
The energy pole is stable with respect to θ.
Re(E) corresponds to energy With respect to 4n breakup threshold.
Im(E) corresponds to Γ/2.



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.

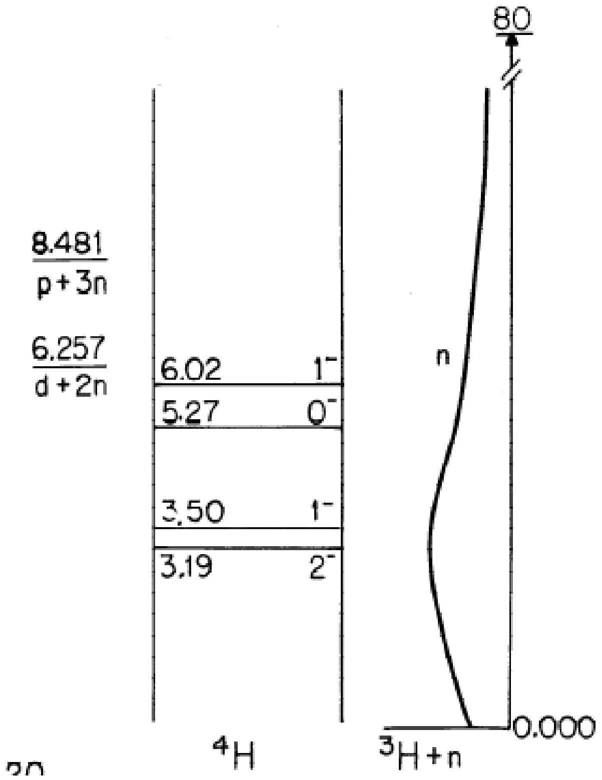
It should be noted that W_1(T=1/2)=-2.04 MeV
to reproduce the observed binding energy
of ^{4}He, ^{3}He and ^{3}H.

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

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 ^{4}H,^{4}He(T=1),^{4}Li.



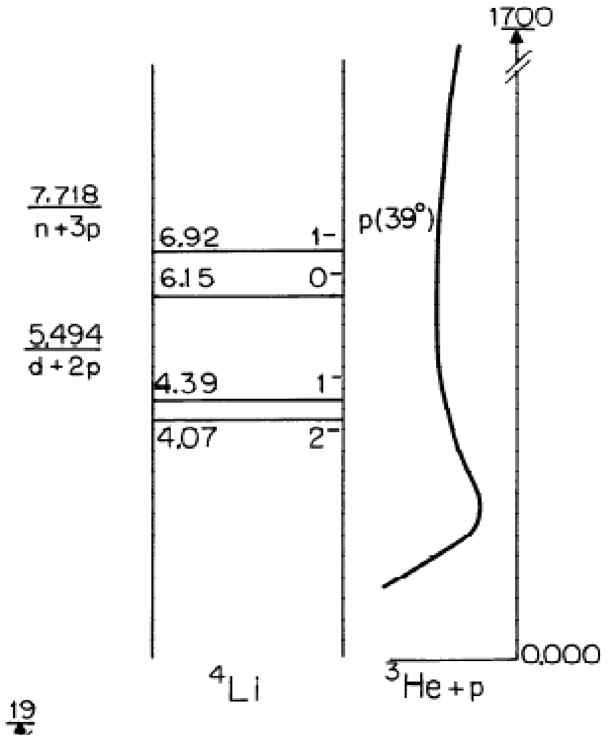


Table 4.1: Energy levels of ^{4}H defined for channel radius $a_n = 4.9$ fm. All energies and widths are in the cm system.

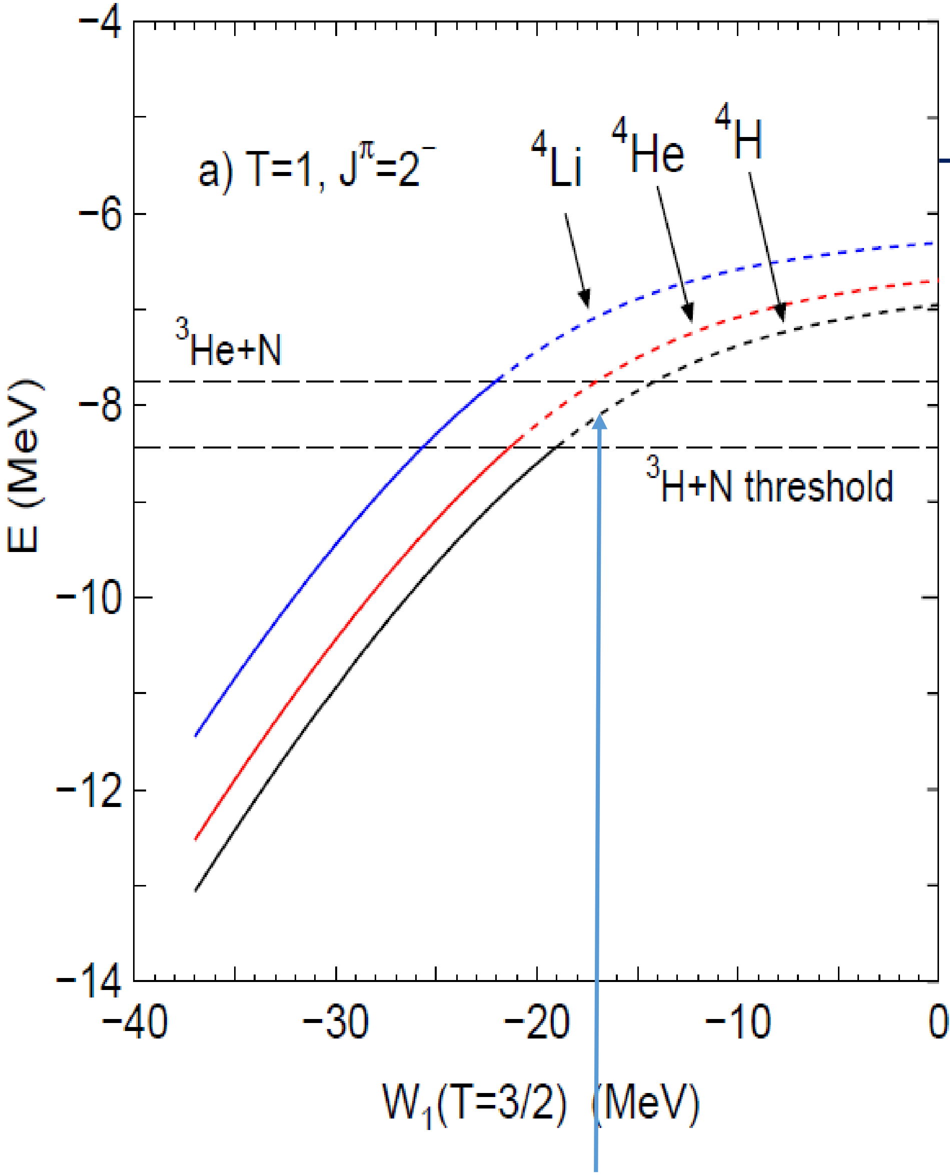
E_x (MeV)	J^π	T	Γ (MeV)	Decay	Reactions
g.s. [a]	2^-	1	5.42	n, ^{3}H	1, 11
0.31	1^-	1	6.73 [b]	n, ^{3}H	11, 12
2.08	0^-	1	8.92	n, ^{3}H	
2.83	1^-	1	12.99 [c]	n, ^{3}H	11, 12

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

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

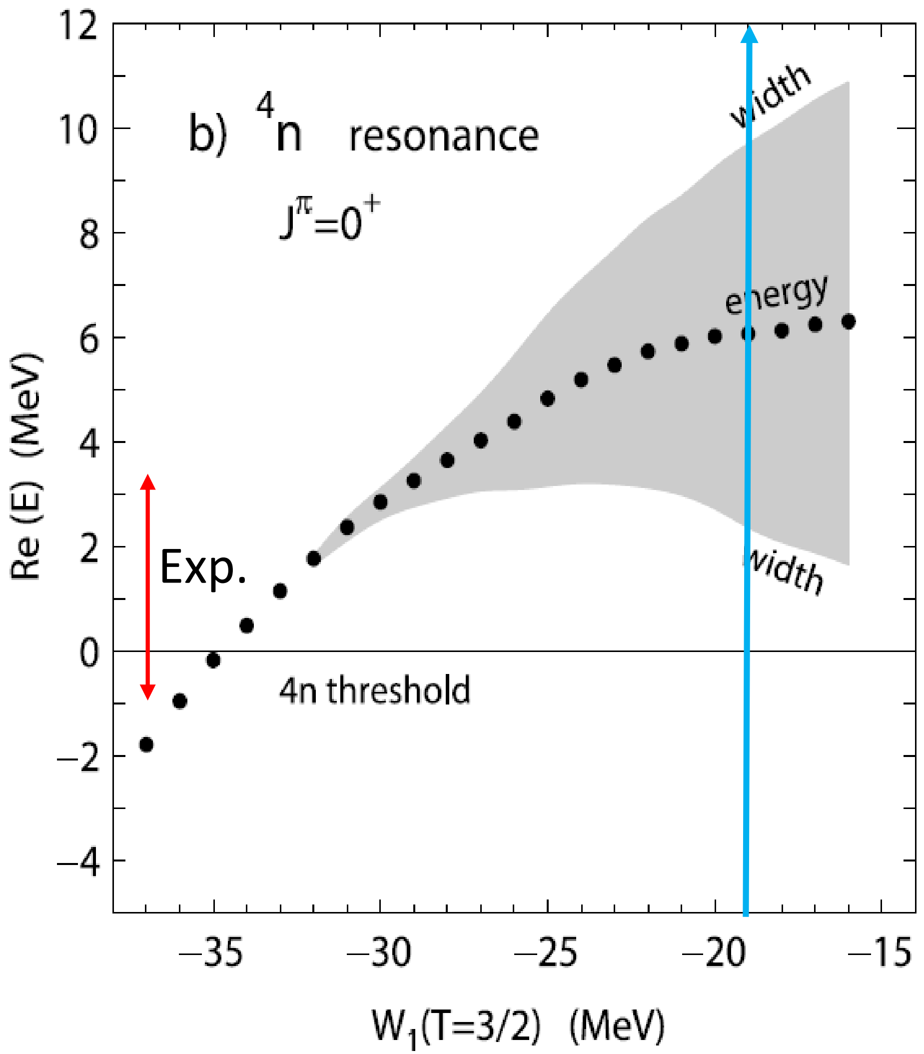
[a] 4.07 MeV above the p + ^{3}He mass.
[b] Primarily $^{3}P_1$.
[c] Primarily $^{1}P_1$.



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)～-18 MeV, the energy of tetraneutron is ～-6M
and Γ=8MeV, which is inconsistent with recent data of tetraneutron.

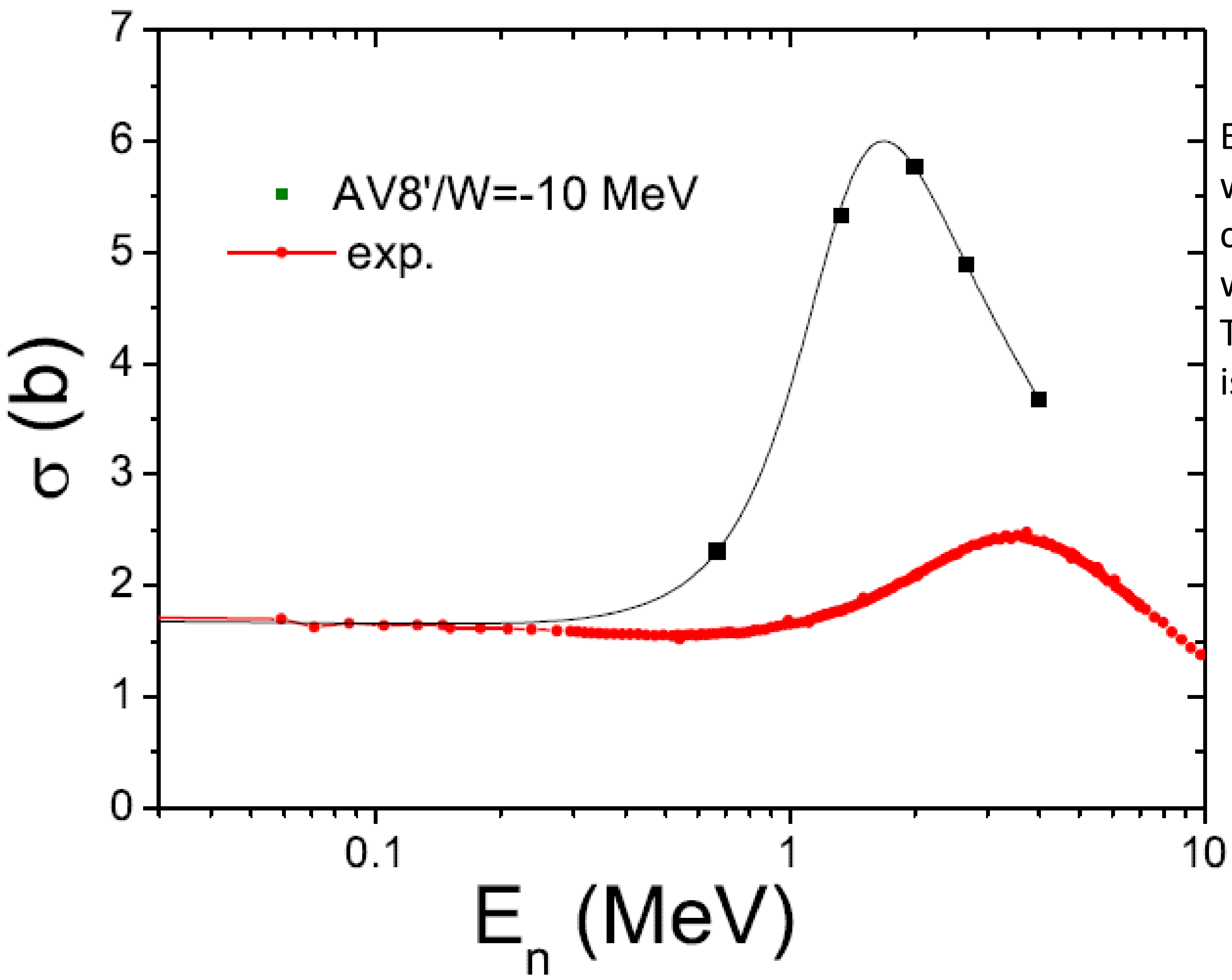
still 9 times strong attraction

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

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

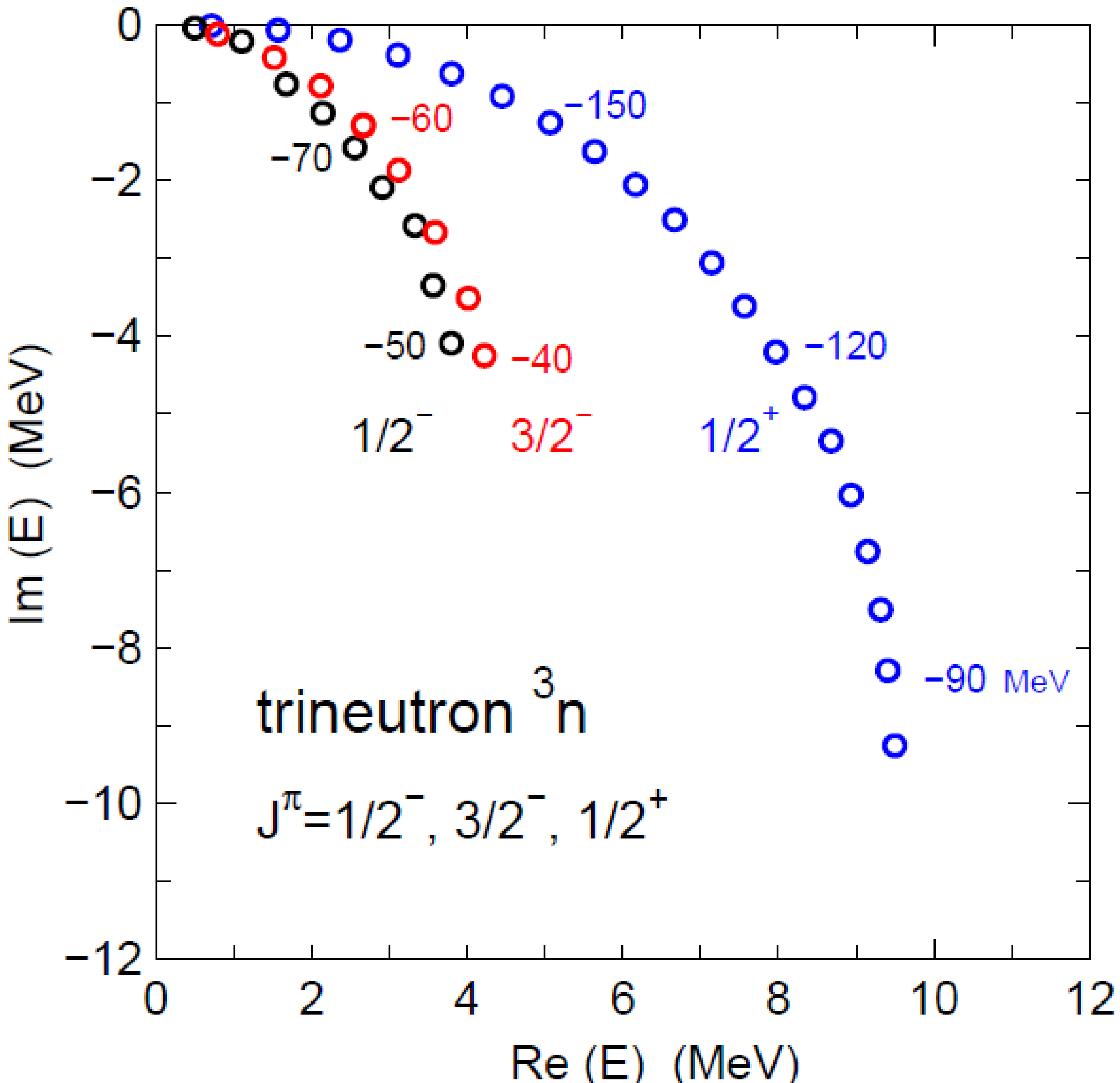
W_1(T=3/2)= free b_1=4.0fm
W_2(T=3/2) = +35 MeV b_2=0.75 fm

Further to check the validity of T=3/2 three nucleon force, we calculated the ^{3}H+n total cross section using W_1～-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.

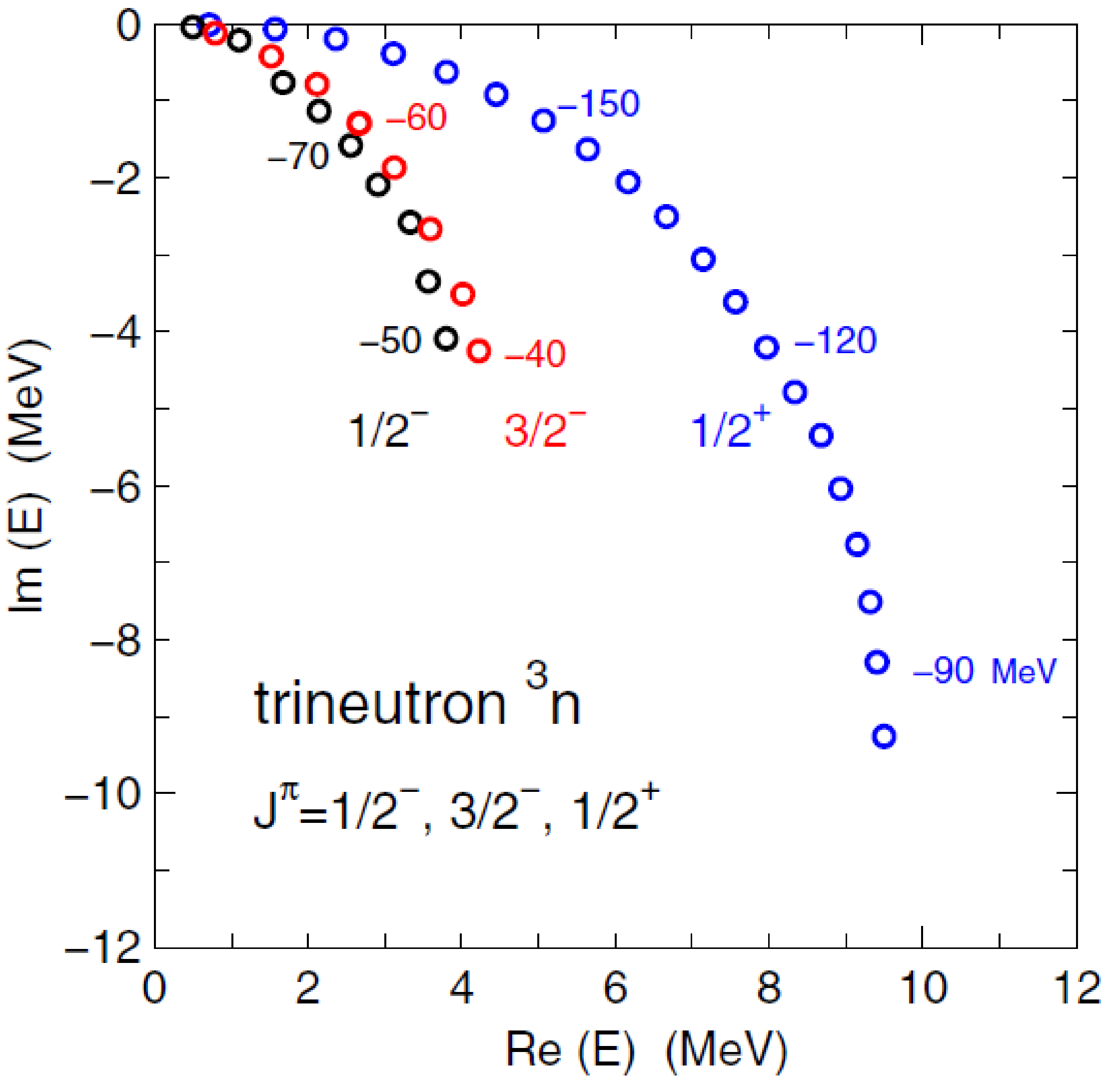
We calculated 3n system.



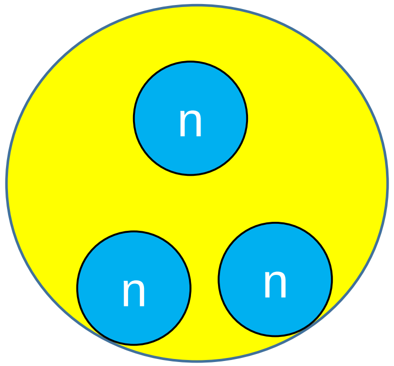
The lowest state should be J=3/2-.
We need W_1=-40 MeV to have resonant state for 3n system.
W_1=-40 MeV is much more attractive than the case of 4n system.
Then, there might not exist 3n system as a resonant state.

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

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



0
−2
−4
−6
−8
−10
−12
0
2
4
6
8
10
12
Im (E) (MeV)
Re (E) (MeV)
−150
−60
−70
−120
−50
−40
1/2−
3/2−
1/2+
−90 MeV
trineutron ³n
Jπ=1/2−, 3/2−, 1/2+



n
n
n

How do we consider this inconsistency?

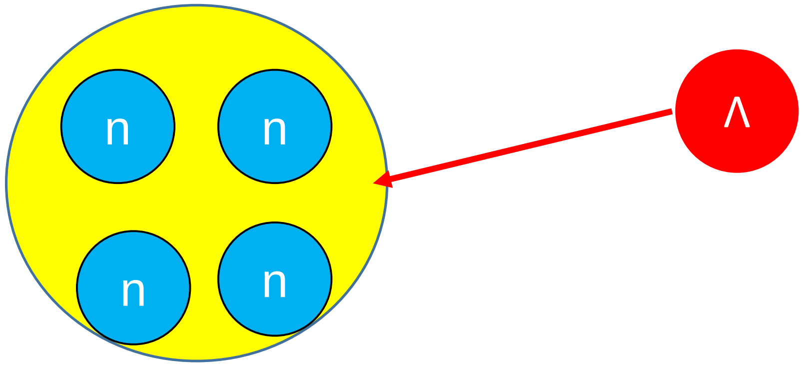
・The T=3/2 force is just a phenomenological.

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

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

One possibility: even-part and odd-state three-body force should are changed?

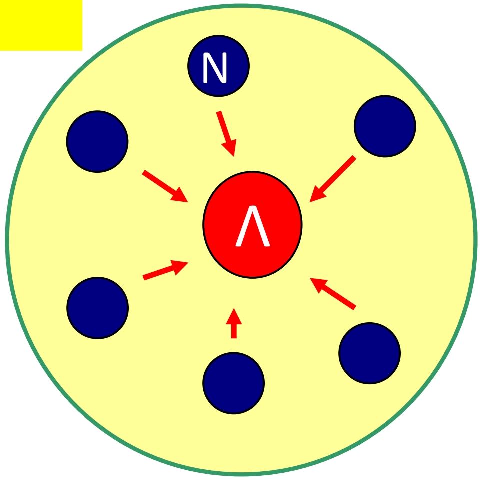
$J=0^+$ 4n system	S-wave: 93.8 % P-wave:5.84 % D-wave: 0.30%	J=2 - ^4H	S-wave: 0.08 % P-wave: 89.9% D-wave:9.23 %



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

Why do we think to have a bound state of $^{5}_{\Lambda}$n?

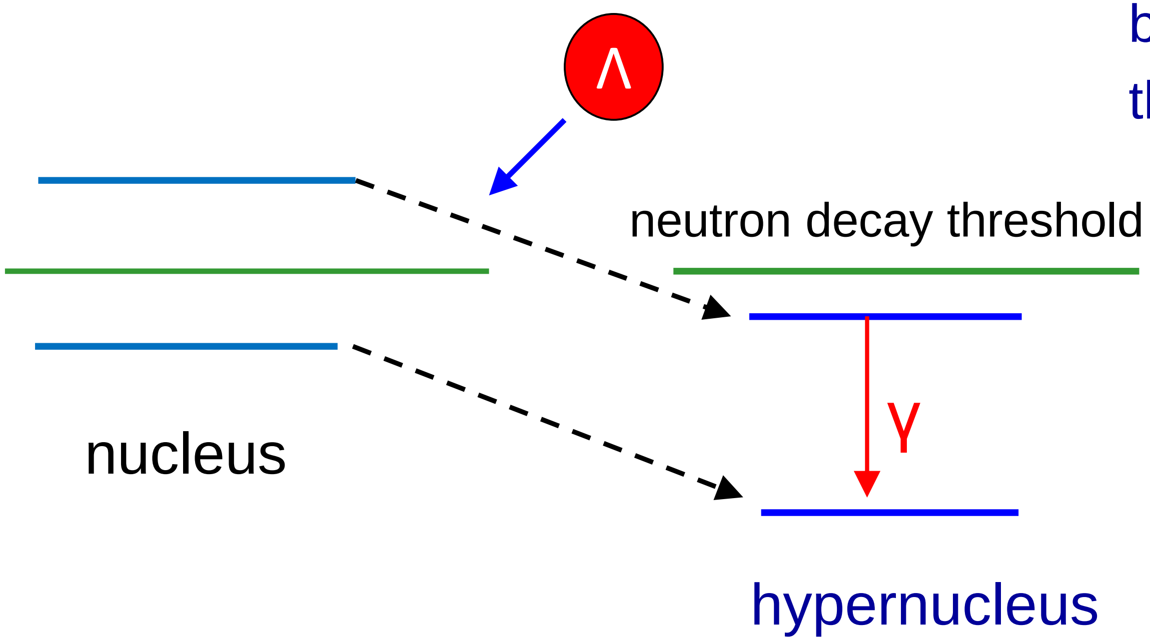
No Pauli principle
Between N and Λ



Hypernucleus

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

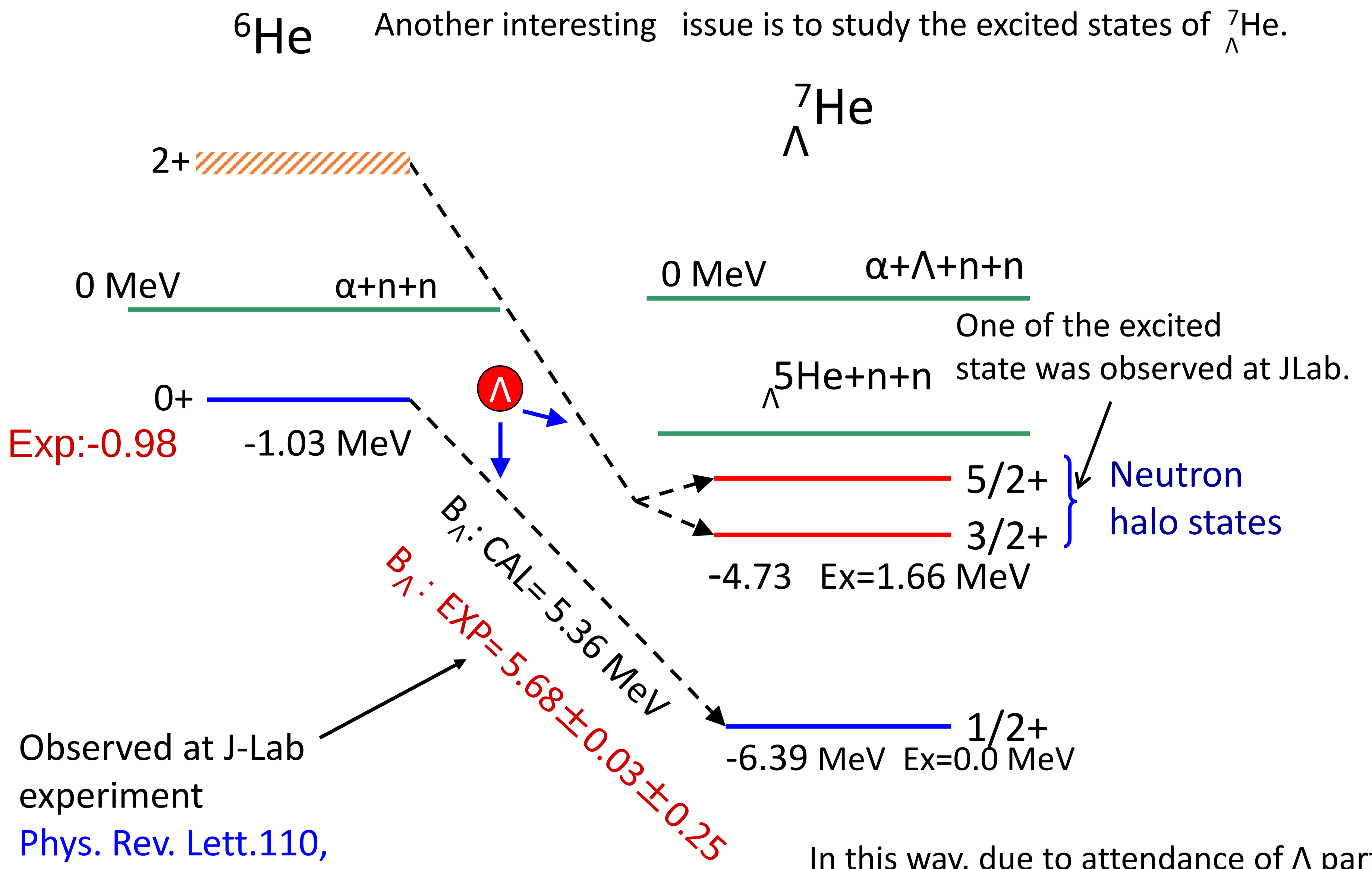
Due to the attraction of Λ N interaction, the resultant hypernucleus will become more stable against the neutron decay.



We call this phenomena ‘gluelike’ role of Λ particle.

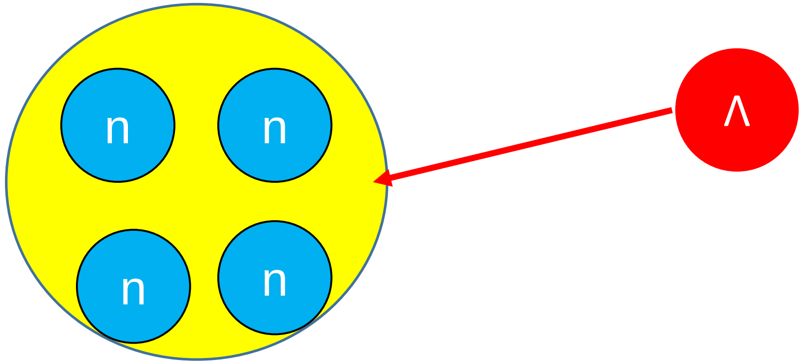
CAL: E. Hiyama et al., PRC 53, 2075 (1996), PRC 80, 054321 (2009)

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



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.



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

Using the phenomena such as gluelike role of Λ particle,
If 4n system is bound or narrow resonant state,
we should have a bound state of $^{5}_{\Lambda}n$.

If we have bound state or narrow resonant state of $^{5}_{\Lambda}n$,
We can also confirm the existence of tetraneutron system!

Then, I hope that production of $^{5}_{\Lambda}n$
will be performed at GSI or J-PARC using
heavy ion collision in the future.

Thank you!