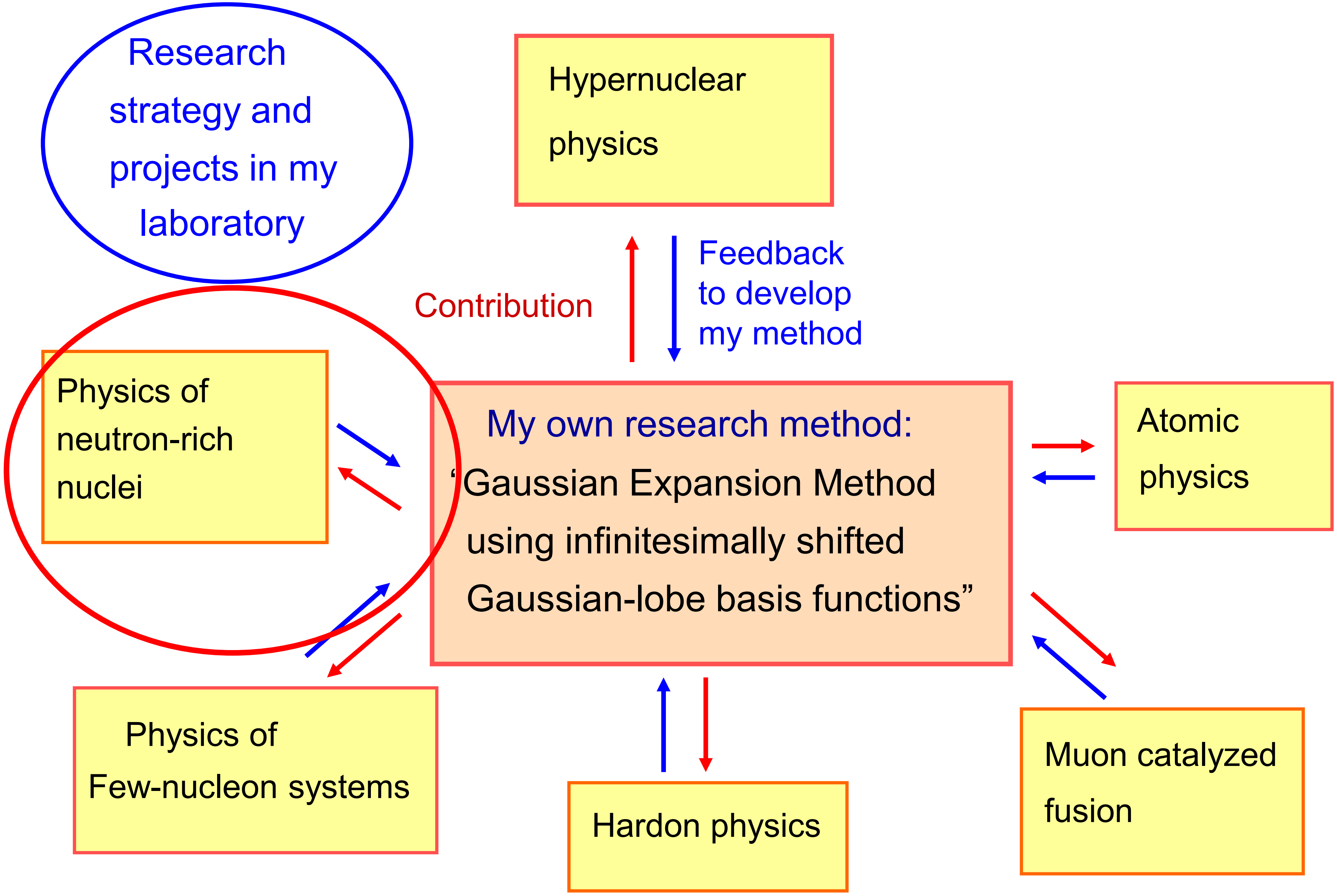
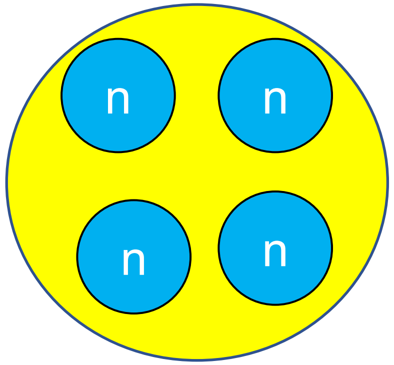


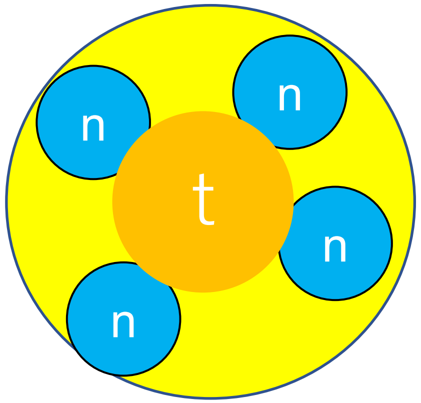
4n system and ^{7}H

Outline of my talk

- Introduction
- 4n system
- ^{7}H system
- conclusion



4n

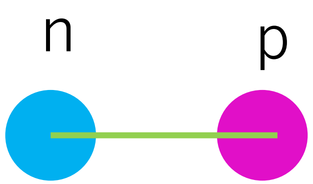


^{7}H

Introduction:

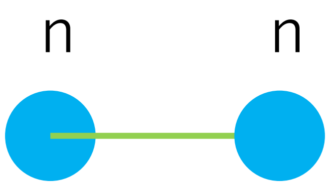
The lightest isotope is Hydrogen (H).

Exp.



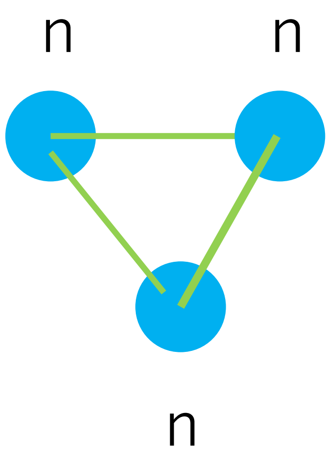
^{2}H $J=1^{+}$ -2.22 MeV

What about n-n?

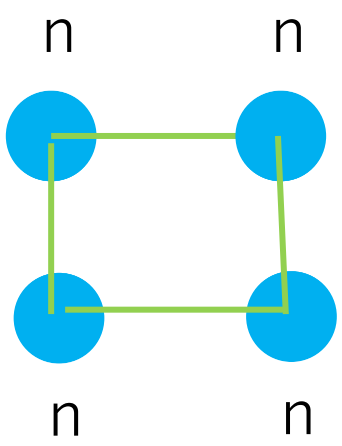


L=0 S=0

No bound state



Might not bound



?

. . . .

Neutron matter

bound

How many neutrons make bound?

Theoretical calculation

S.C. Peiper et al., Phys. Rev. Lett. 90, 252501 (2003).

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.

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

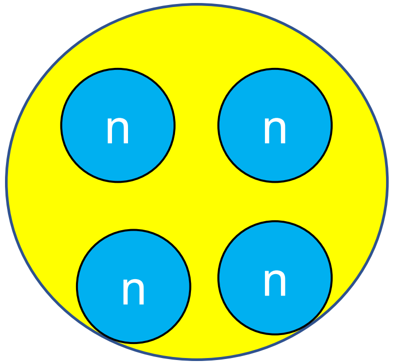
K. Kisamori,[1,2] S. Shimoura,[1] H. Miya,[1,2] S. Michimasa,[1] S. Ota,[1] M. Assie,[3] H. Baba,[2] T. Baba,[4] D. Beaumel,[2,3] M. Dozono,[2] T. Fujii,[1,2] N. Fukuda,[2] S. Go,[1,2] F. Hammache,[3] E. Ideguchi,[5] N. Inabe,[2] M. Itoh,[6] D. Kameda,[2] S. Kawase,[1] T. Kawabata,[4] M. Kobayashi,[1] 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]

[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*

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

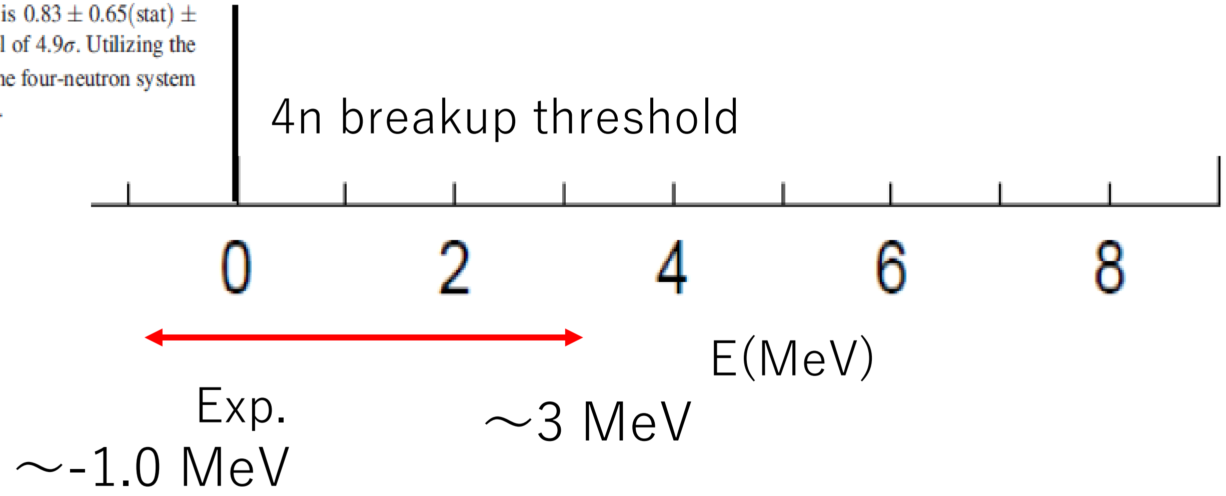
A candidate resonant tetraneutron state is found in the missing-mass spectrum obtained in the double-charge-exchange reaction ^{4}He(^{8}He, ^{8}Be) at 186 MeV/u. The energy of the state is $0.83 \pm 0.65(\mathrm{stat}) \pm 1.25(\mathrm{syst})$ MeV above the threshold of four-neutron decay with a significance 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



Theoretical important issue:

・Can we describe observed 4n system using realistic NN interaction?



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

Γ =2.6 MeV (Upper limit)

After the observed data, there have been positive and negative theoretical results.

Positive result:

A.M. Shirokov et al., PRL117, 182502 (2016).

Non-core shell model calculation+JISP16 NN interaction

Er=0.8 MeV with Γ =1.4 MeV

S. Gandolfi et al., PRL118, 232501 (2017)

Quantum Monte Calro Method +Chrial (NNLO)

interaction+Woods

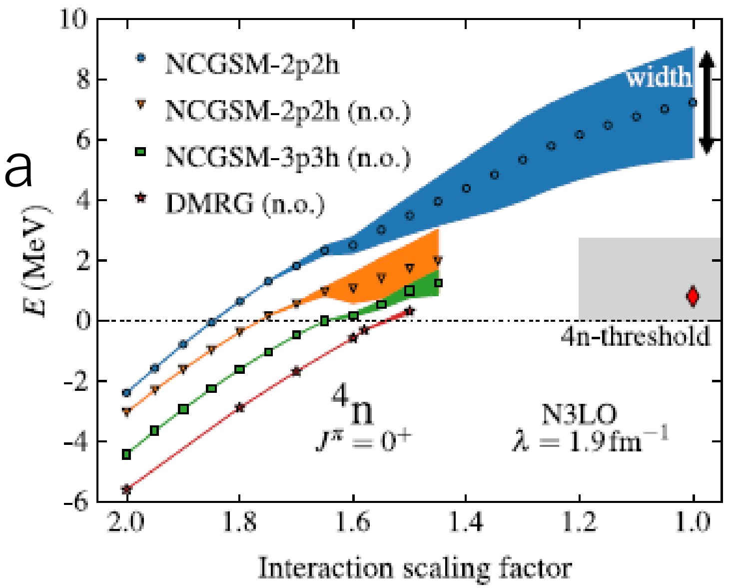
Saxon-well : extrapolation

Er=1.84 MeV with Γ =0.282 MeV

Not positive , not negative result

K. Fossez et al., PRL119, 032501 (2017)
no-core Gamow shell model+ N3LO, JISP16
Er～ 7 MeV, Γ　～3.5 MeV to 3.7 MeV

Much higher energy and
broader width than observed data



$f \times V_{NN}$

Scaling factor

Negative results

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

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

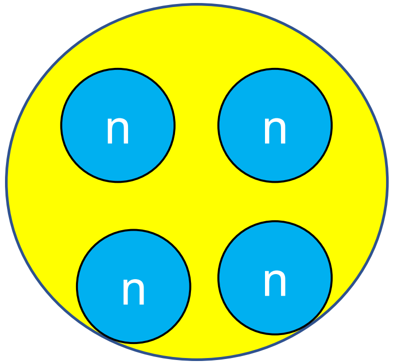
E. Hiyama
Nishina Center for Accelerator-Based Science, RIKEN, Wako, 351-0198, Japan

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.



Introduce our paper

First, let me explain my method for this calculation.

Our few-body caluclational method

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,

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

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

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

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

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

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

Where the energy and overlap matrix elements are given by

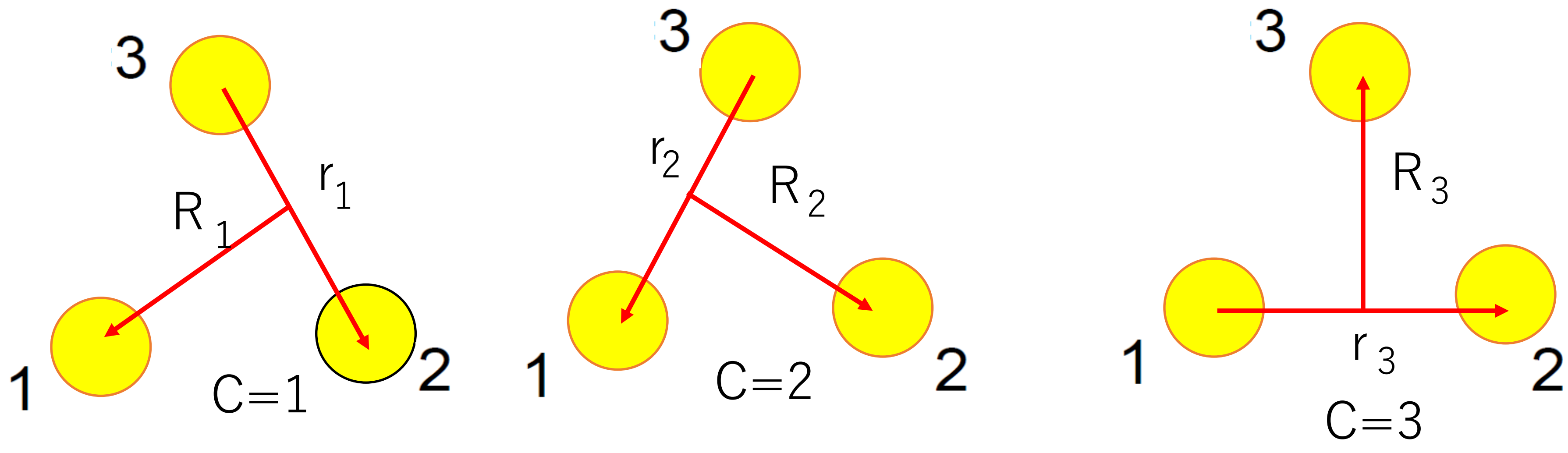
$$H_{in} = \langle \Phi_i \mid H \mid \Phi_n \rangle$$

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

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

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

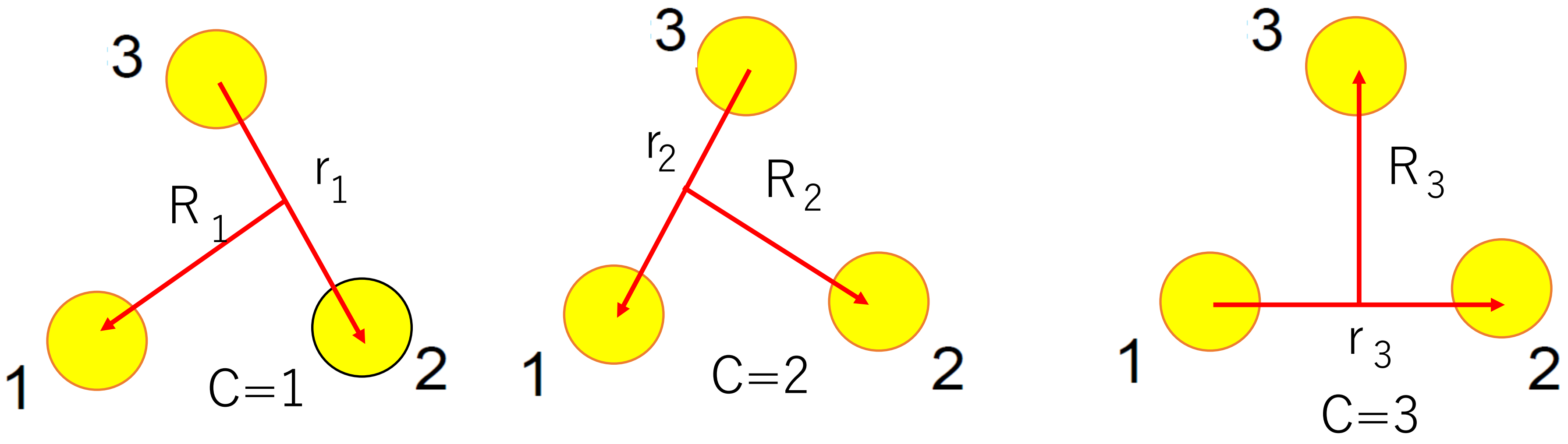
Gaussian Expansion Method (GEM)



$$H = -\frac{\hbar^2}{2\mu_{r_c}} \nabla^2_{\mathbf{r}_c} - \frac{\hbar^2}{2\mu_R} \nabla^2_{\mathbf{R}_C} + V^{(1)}(r_1) + V^{(2)}(r_2) + V^{(3)}(r_3)$$

$$[\, H - E \,]\, \Psi_{JM} = 0$$

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



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

Basis functions of each Jacobi coordinate

$(c = 1 - 3)$

$$\phi^{(c)}_{\underline{nl}}(r_c)\, Y_{\underline{lm}}(\hat{\mathbf{r}}_c), \quad \psi^{(c)}_{NL}(R_c)\, Y_{LM}(\widehat{\mathbf{R}}_c)$$

$$\Phi^{(c)}_{JM}(\mathbf{r}_c, \mathbf{R}_c) = \sum_{nl,NL} \underline{C_{NL,lm}}\, \phi^{(c)}_{nl}(r_c)\, \psi^{(c)}_{NL}(R_c)\, [Y_l(\hat{\mathbf{r}}_c) \otimes Y_L(\hat{\mathbf{r}}_c)]_{JM}$$

$(c = 1 - 3)$

Determined by diagonalizing H

Radial part : Gaussian function

$$\phi_{nl}(r) = r^l \, e^{-(r/r_n)^2}$$

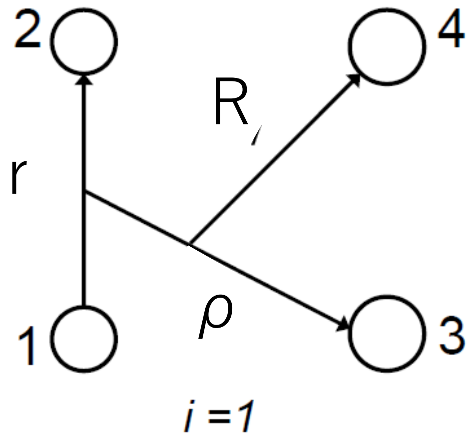
$$\psi_{NL}(R) = R^L \, e^{-(R/R_N)^2}$$

Gaussian ranges in geometric progression

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

$$R_N = R_1 \, A^{N-1} \qquad (N = 1 - N_{\max})$$

Both the short-range correlations and the exponentially-damped tail are simultaneously reproduced accurately.



K-type (*i* =1-12)

In the case of four-body problem,
We have one more Jabobi coordinate.

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

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

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

Benchmark test calculation of a four-nucleon bound state

by 7 groups

① H. Kamada,* A. Nogga, and W. Glöckle
Institut für Theoretische Physik II, Ruhr-Universität Bochum, D-44780 Bochum, Germany

② E. Hiyama
High Energy Accelerator Research Organization, Institute of Particle and Nuclear Studies, Tsukuba 305-0801, Japan

M. Kamimura
Department of Physics, Kyushu University, Fukuoka 812-8581, Japan

③ K. Varga
Solid State Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37380
and Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), Debrecen 4000, PO Box 51, Hungary

Y. Suzuki
Department of Physics, Niigata University, Niigata 950-2181, Japan

④ M. Viviani and A. Kievsky
INFN, Sezione di Pisa, I-56100 Pisa, Italy

S. Rosati
INFN, Sezione di Pisa, I-56100 Pisa, Italy
and Department of Physics, University of Pisa, I-56100 Pisa, Italy

⑤ J. Carlson
Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

⑥ Steven C. Pieper and R. B. Wiringa
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

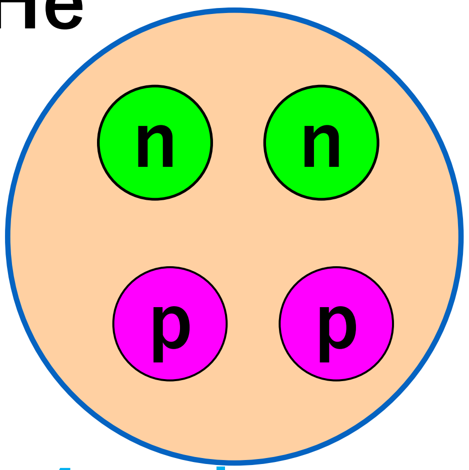
P. Navrátil
Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, California 94551
and Nuclear Physics Institute, Academy of Sciences of the Czech Republic, 250 68 Řež near Prague, Czech Republic

B. R. Barrett
Department of Physics, P.O. Box 210081, University of Arizona, Tucson, Arizona 85721

⑦ N. Barnea
The Racah Institute of Physics, The Hebrew University, 91904 Jerusalem, Israel

W. Leidemann and G. Orlandini
Dipartimento di Fisica and INFN (Gruppo Collegato di Trento), Università di Trento, I-38050 Povo, Italy

^{4}He



4 nucleon bound state

Realistic NN force: AV8'

Only two-body NN interaction

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

Exp. -28.33 MeV

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

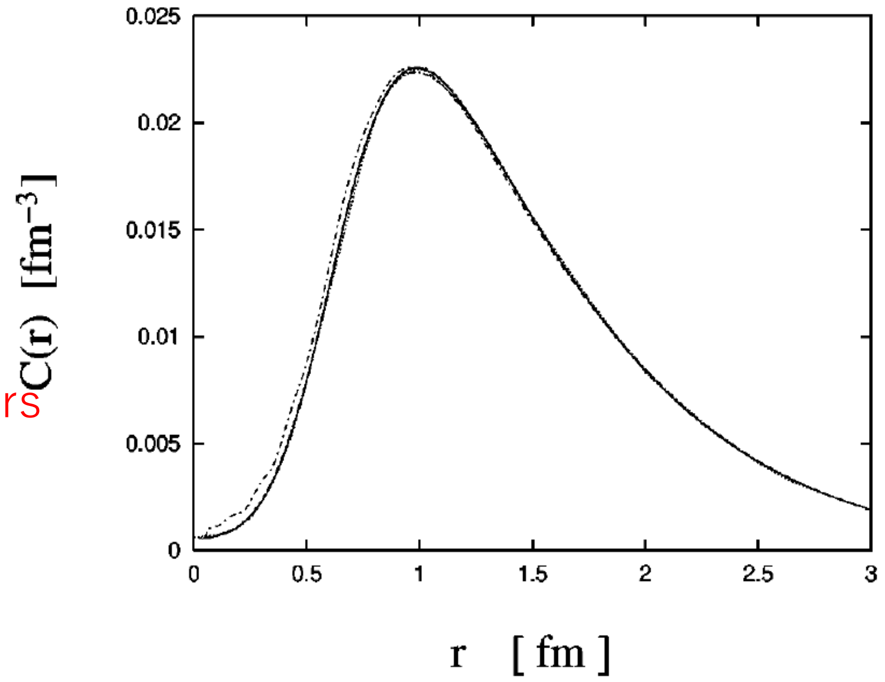


FIG. 1. Correlation functions in the different calculational schemes: EIHH (dashed-dotted curves), FY, CRCGV, SVM, HH, and NCSM (overlapping curves).

NN: AV potential (Central +spin-orbit +tensor)

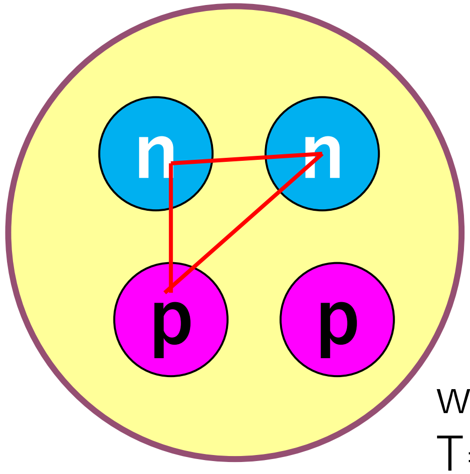
+

A phenomenological three-body force

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

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

This potential has been applied to ^{4}He.
E. Hiyama, B.F. Gibson and M. Kamimura, Phys. Rev. C **70** (2004) 031001(R)



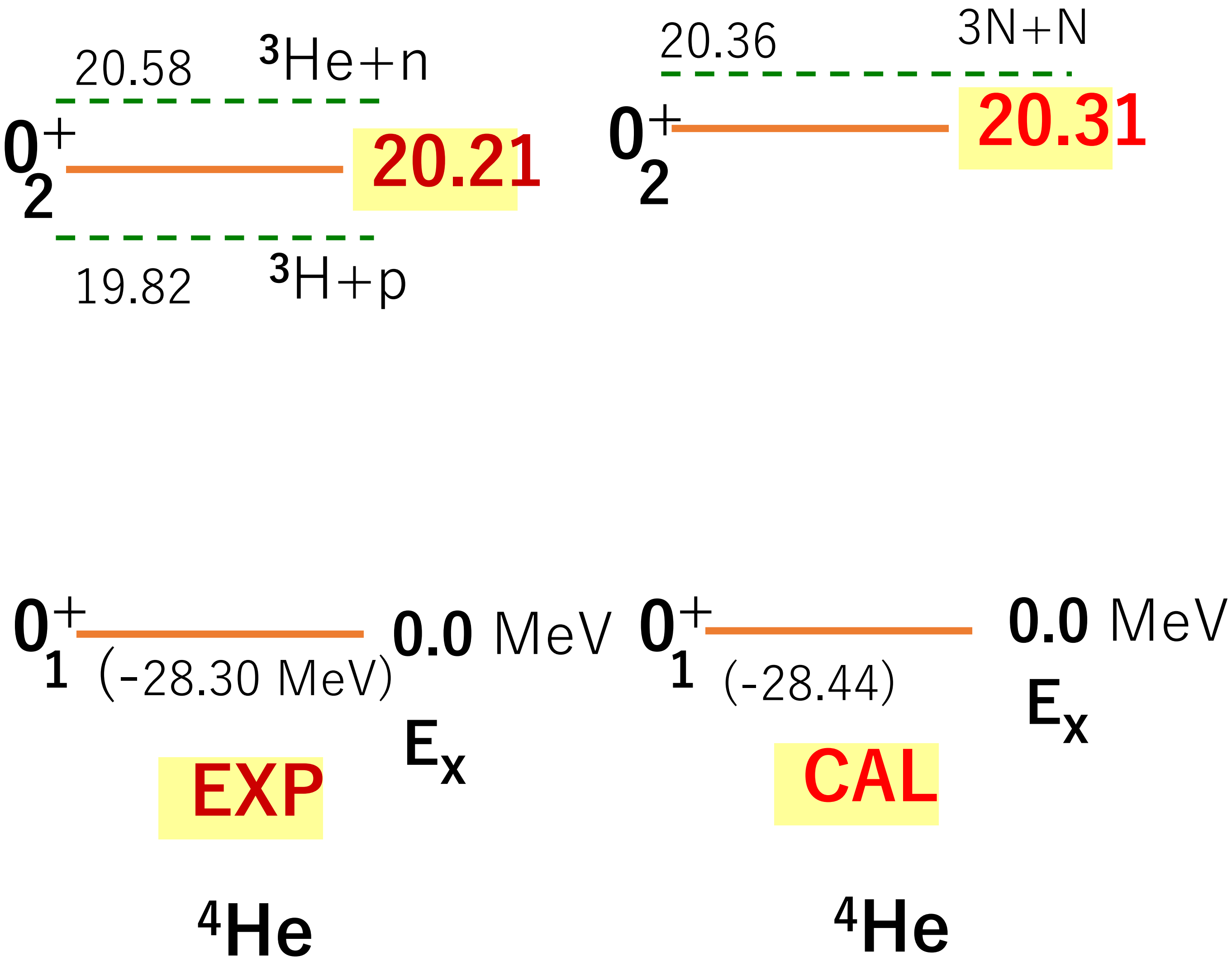
$T_{NNN} = 1/2$

we use
T=1/2 three-body force

^{4}He

To distinguish proton or neutron, we use isospin.
Proton=> $t=1/2$, $t_z=+1/2$
Neutron=> $t=1/2$, $t_z=-1/2$

$T_z = 1 \times 1/2 + 2 \times (-1/2) = 1/2$



AV8 NN +Coulomb potential + three-body force reproduce the data.

NN: AV potential (Central +spin-orbit +tensor)

+

A phenomenological three-body force

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

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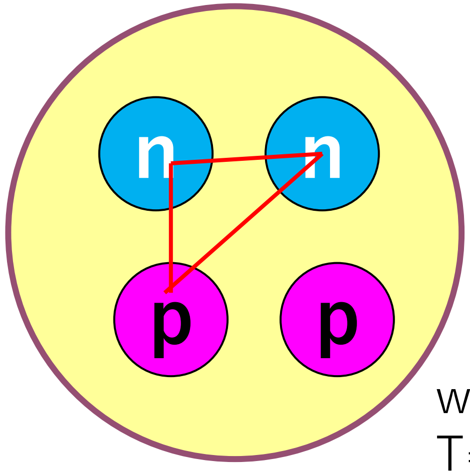
This potential has been applied to ^{4}He.
E. Hiyama, B.F. Gibson and M. Kamimura, Phys. Rev. C **70** (2004) 031001(R)

Apply to nnnn system



T_{NNN}= 1/2

we use
T=1/2 three-body force

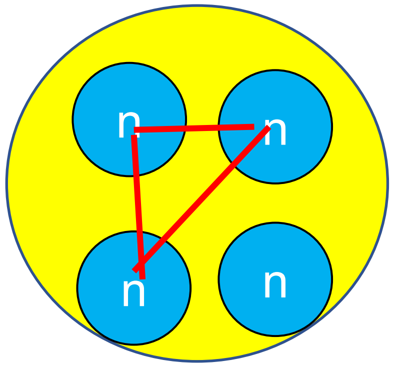
^{4}He

To distinguish proton or neutron, we use isospin.
Proton=> t=1/2, t_z=+1/2
Neutron=>t=1/2,t_z=-1/2

T_z= 1x1/2+2x(-1/2)=1/2

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

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



^{4}n

T_{nnn}=3/2

We need T=3/2 three-body force. But, we have no idea how much attraction we need.

$T_z(nnn)=3x(-1/2)=-3/2$

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

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.

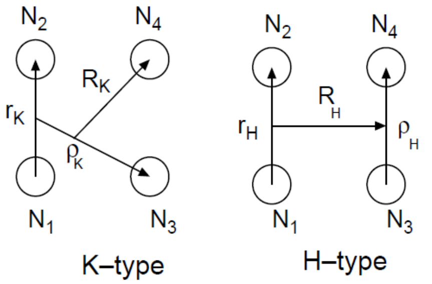
$$[H(\theta) - E(\theta)]\Psi_{JM,TT_z}(\theta) = 0$$

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

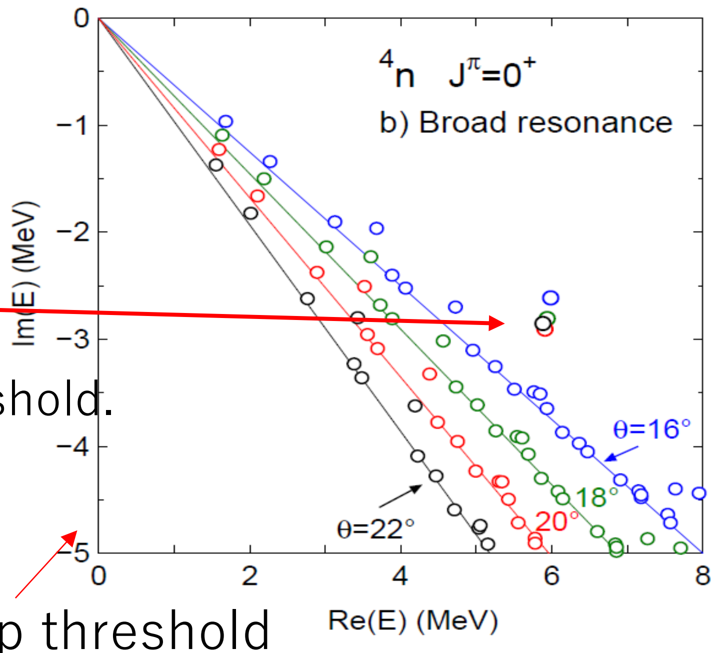
$$\phi_{nl}(r) = r^l\, e^{-(r/r_n)^2}$$

$$\psi_{NL}(R) = R^L\, e^{-(R/R_N)^2}$$

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

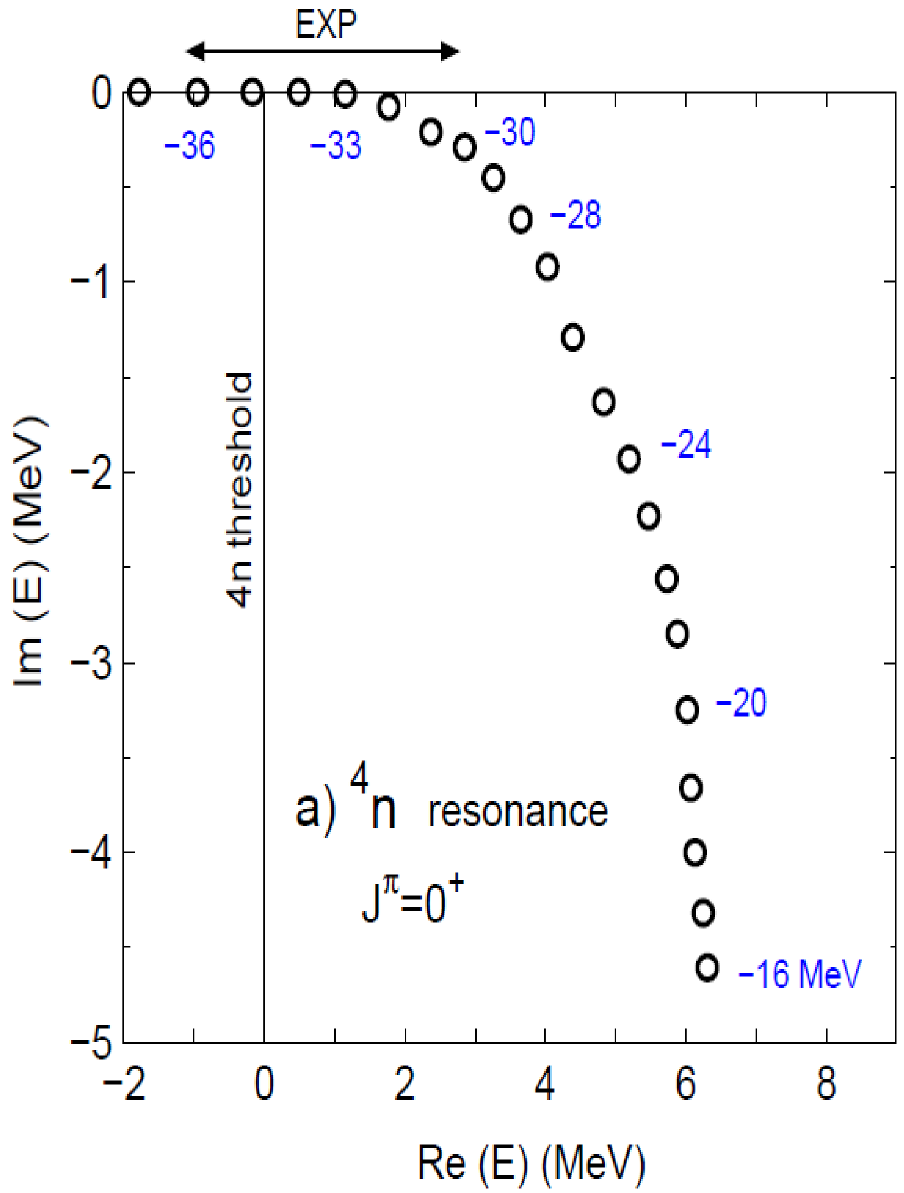


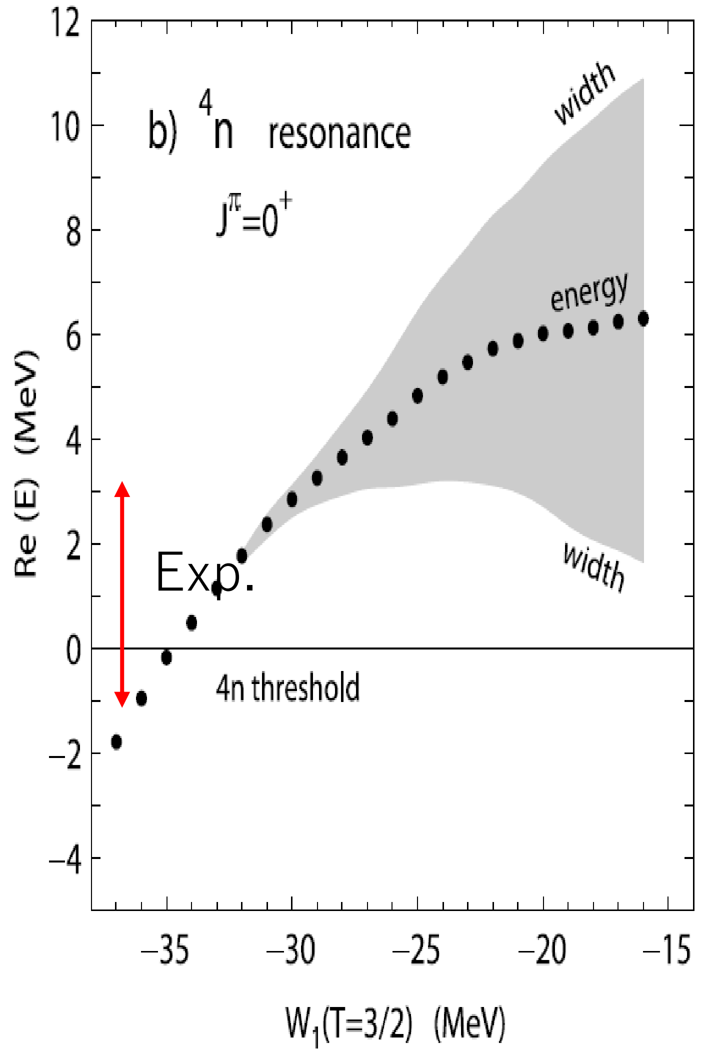
The energy pole is stable with respect to θ.
Re(E) corresponds to energy
With respect to 4n breakup threshold.
Im(E) corresponds to $\Gamma/2$.



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.

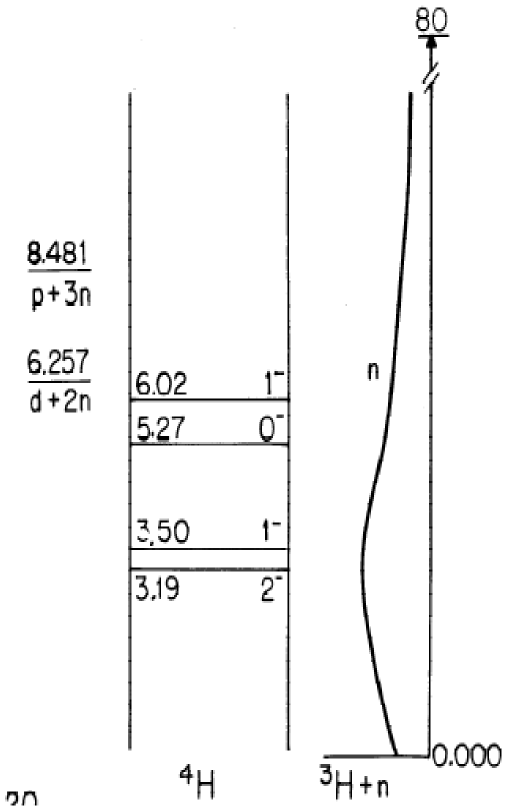
$$V^{3N}_{ijk} = \sum_{T=1/2}^{3/2} \sum_{n=1}^{2} W_n(T) e^{-(r^2_{ij}+r^2_{jk}+r^2_{ki})/b^2_n} \mathcal{P}_{ijk}(T)$$

$W_1(T=3/2)=$ 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.

It is noted that I took benchmark test of
4n with Faddeev-Yakubovsky method by Lazauskas. My result is the same as that by FY.



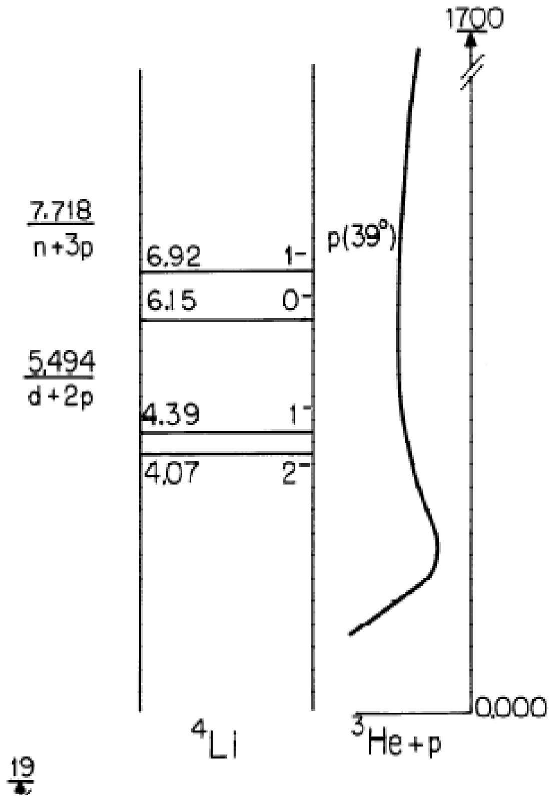


Table 4.1: Energy levels of ^{4}H defined for channel radius $a_n = 4.9$ fm. All energies and widths are in the cm system.

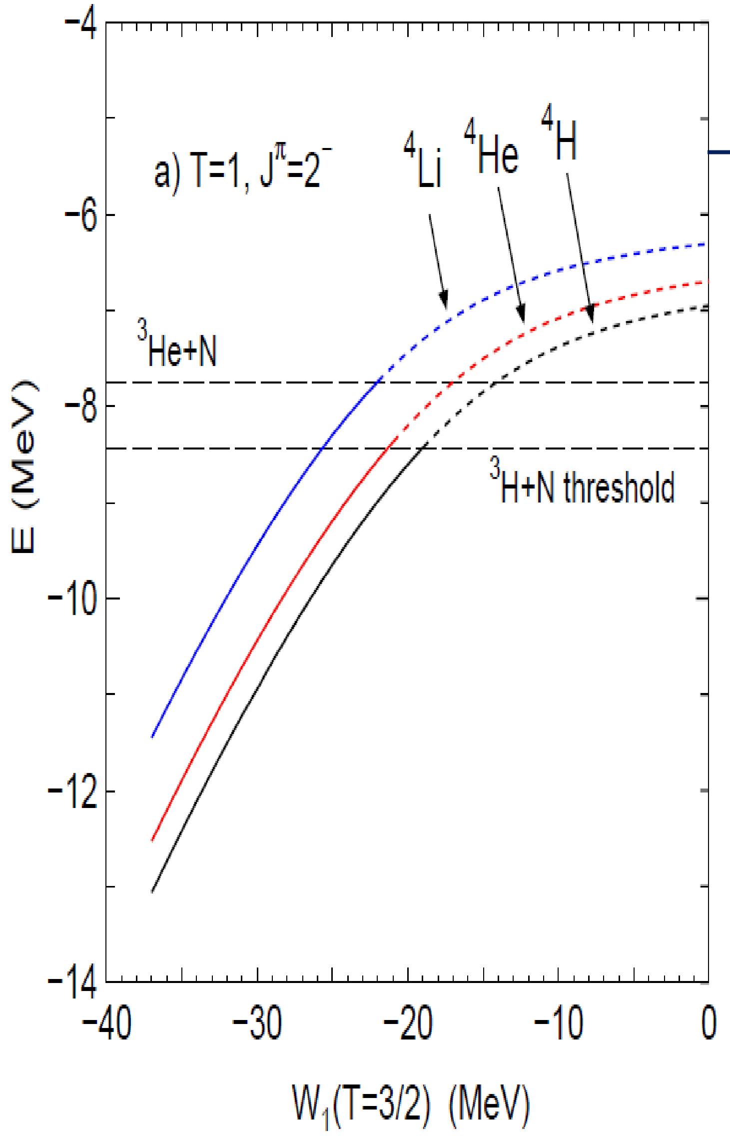
E_x (MeV)	J^π	T	Γ (MeV)	Decay	Reactions
g.s. [a]	2^-	1	5.42	n, ^{3}H	1, 11
0.31	1^-	1	6.73 [b]	n, ^{3}H	11, 12
2.08	0^-	1	8.92	n, ^{3}H	
2.83	1^-	1	12.99 [c]	n, ^{3}H	11, 12

[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 $^1P_1$.



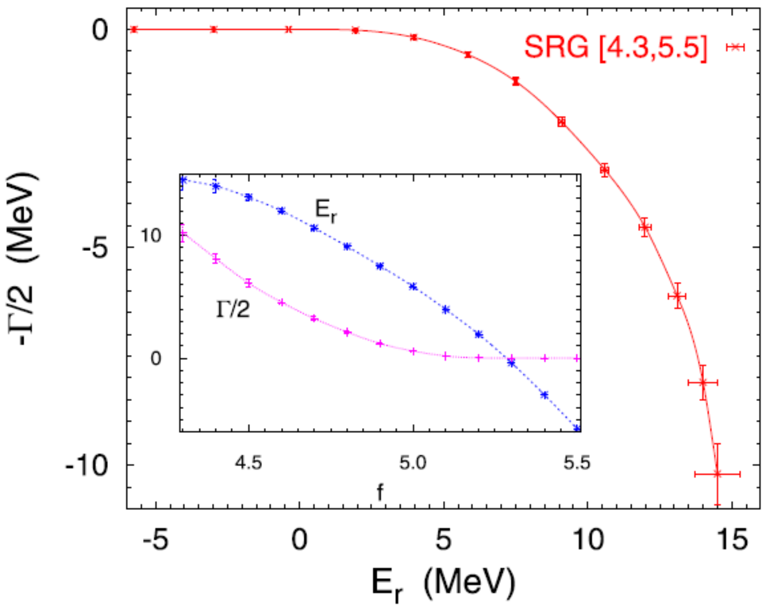
Exp. ^{4}H (-5.29 MeV)

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.

Conclusion: to reproduce the data of 4n, unlikely attractive three-body force is required.

A. Deltuva, Physics Letters B 782, 238 (2019).

Faddeev Yakubovsky method+SRG potential (based on AV18 potential)



$f x V(^1s_0)$

Scaling factor: f< 4.3=> no resonant state

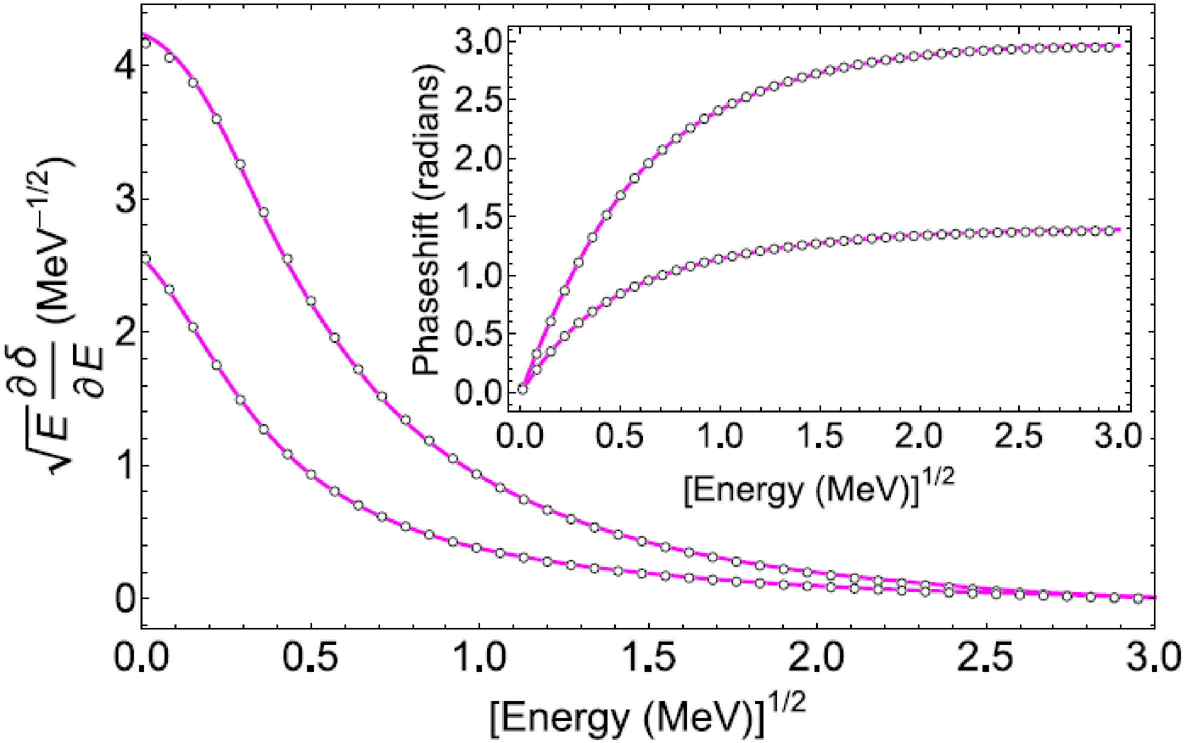
M. D. Higgins, C.H. Greene, A. Kievsky, M. Vivianni,

Phys. Rev. Lett. 125, 052501(2020)

Phys. Rev. C 103, 024004 (2021)

Hypersherical harmonics Method

AV8 potential which is the same one used by me.



No resonant state

They used AV18 potential and they had no resonant state.

Summary of the 4n calculation

Author	Method	How to obtain resonant state	V_{NN}	resonance
A.M. Shirokov et al.	Non-core shell model + phase shift analysis		JISP16	Er=0.8 MeV Γ =1.4 MeV
S. Gandolfi et al.	Quantum Monte Calro	extrapolation	chiral(NNLO)	Er=1.84 MeV Γ =0.282 MeV
K. Fossez et al.,	no-core Gamow shell model		N3LO, JISP16,	Er～7MeV Γ ～3.5MeV
E. Hiyama, R. Lazauskas et al.,	Gaussian Expansion + CSM Faddeev Yakubovsky		AV8	No resonance
Deltuva,	Faddeev Yakbobsky	+ AGS	SRG(AV18),NLO,	No resonance
M. D. Higgins et al.,	Hypersherical harmonics	phase shift analysis	AV8, AV18,	no resonance

L. Wu, S. Elhatissari, U. Meissner, S. Shen, L-S. Geng, and Y. Kim, EFT lattice, PRL 136, 142502(2026)
Chiral N3LO no plauteu

Article

Observation of a correlated free four-neutron system

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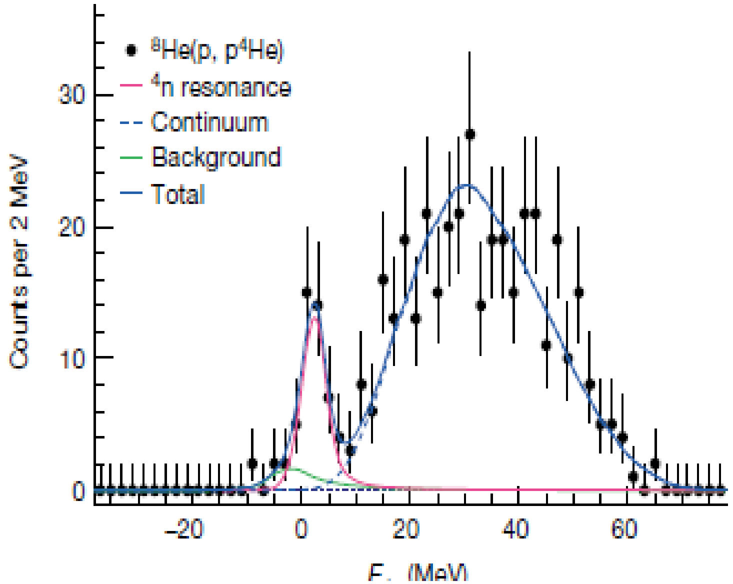
M. Duer[1,✉], T. Aumann[1,2,3], R. Gernhäuser[4], V. Panin[2,5], S. Paschalis[1,6], D. M. Rossi[1], N. L. Achouri[7], D. Ahn[5,16], H. Baba[5], C. A. Bertulani[8], M. Böhmer[4], K. Boretzky[2], C. Caesar[1,2,5], N. Chiga[5], A. Corsi[9], D. Cortina-Gil[10], C. A. Douma[11], F. Dufter[4], Z. Elekes[12], J. Feng[13], B. Fernández-Domínguez[10], U. Forsberg[6], N. Fukuda[5], I. Gasparic[1,5,14], Z. Ge[5], J. M. Gheller[9], J. Gibelin[7], A. Gillibert[9], K. I. Hahn[15,16], Z. Halász[12], M. N. Harakeh[11], A. Hirayama[17], M. Holl[1], N. Inabe[5], T. Isobe[5], J. Kahlbow[1], N. Kalantar-Nayestanaki[11], D. Kim[16], S. Kim[1,16], T. Kobayashi[18], Y. Kondo[17], D. Körper[2], P. Koseoglou[1], Y. Kubota[5], I. Kuti[12], P. J. Li[19], C. Lehr[1], S. Lindberg[20], Y. Liu[13], F. M. Marqués[7], S. Masuoka[21], M. Matsumoto[17], J. Mayer[22], K. Miki[1,18], B. Monteagudo[7], T. Nakamura[17], T. Nilsson[20], A. Obertelli[1,9], N. A. Orr[7], H. Otsu[5], S. Y. Park[15,16], M. Parlog[7], P. M. Potlog[23], S. Reichert[4], A. Revel[7,9,24], A. T. Saito[17], M. Sasano[5], H. Scheit[1], F. Schindler[1], S. Shimoura[21], H. Simon[2], L. Stuhl[16,21], H. Suzuki[5], D. Symochko[1], H. Takeda[5], J. Tanaka[1,5], Y. Togano[17], T. Tomai[17], H. T. Törnqvist[1,2], J. Tscheuschner[1], T. Uesaka[5], V. Wagner[1], H. Yamada[17], B. Yang[13], L. Yang[21], Z. H. Yang[5], M. Yasuda[17], K. Yoneda[5], L. Zanetti[1], J. Zenihiro[5,25] & M. V. Zhukov[20]



Just recently, experimentally, one peak near 4n breakup threshold in the cross section has been reported.

$$^{8}\mathrm{He}(p, p\,^{4}\mathrm{He})4n$$

Question: How do we interpret this experimental data theoretically?

PHYSICAL REVIEW LETTERS **130,** 102501 (2023)

Low Energy Structures in Nuclear Reactions with 4*n* in the Final State

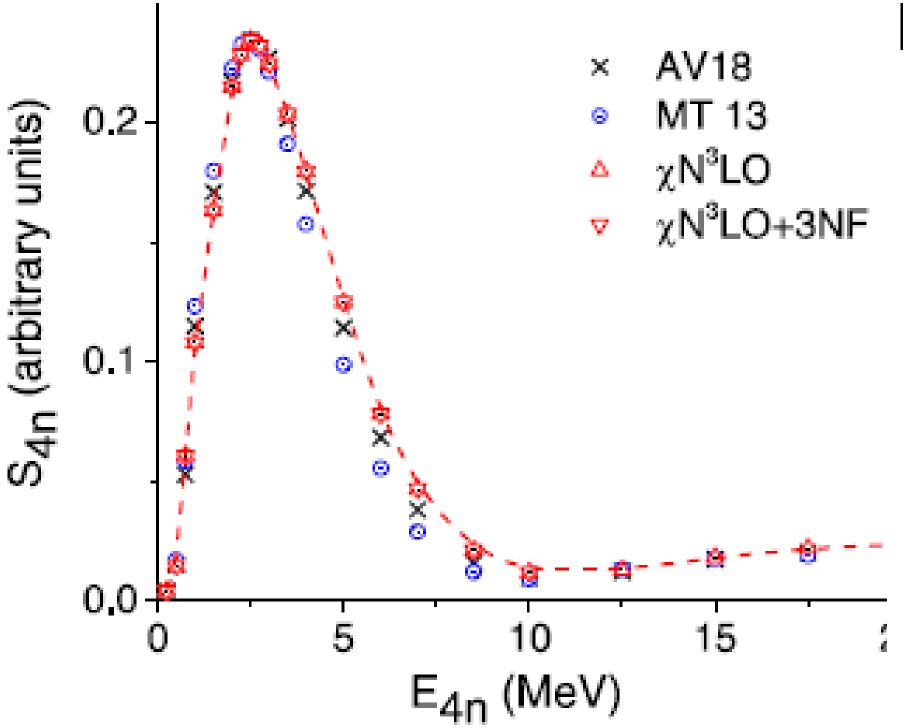
Rimantas Lazauskas
Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France

Emiko Hiyama
Department of Physics, Tohoku University, Sendai 980-8578, Japan and RIKEN Nishina Center, Wako 351-0198, Japan

Jaume Carbonell
Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

$^{8}He(p, p^{4}He)4n$

We calculated the reaction using several kinds of NN interaction.
We see to have a peak near 4n threshold without 3NF force.
We include 3NF force. But effect of 3NF is small.
We interpret that a peak is emerged as a consequence of the final interaction among 4n system and 4 neutrons in ^{8}He projectile.



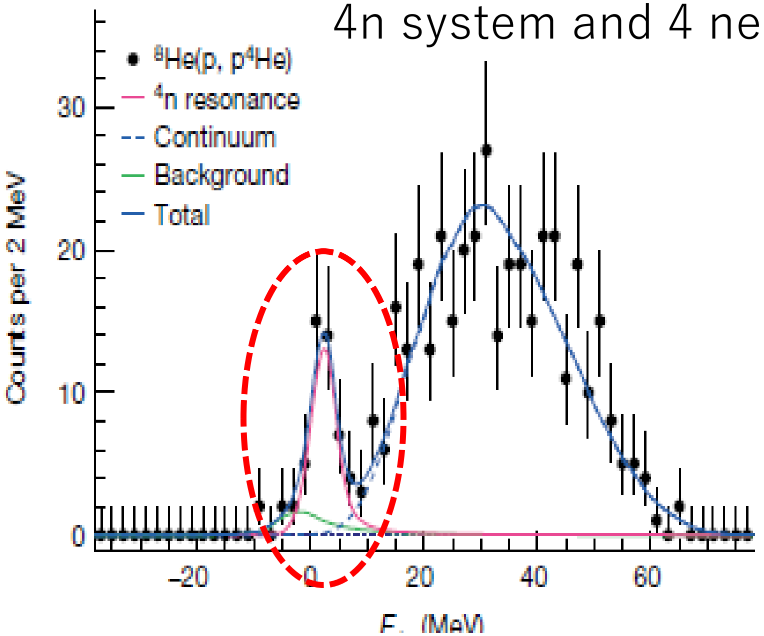
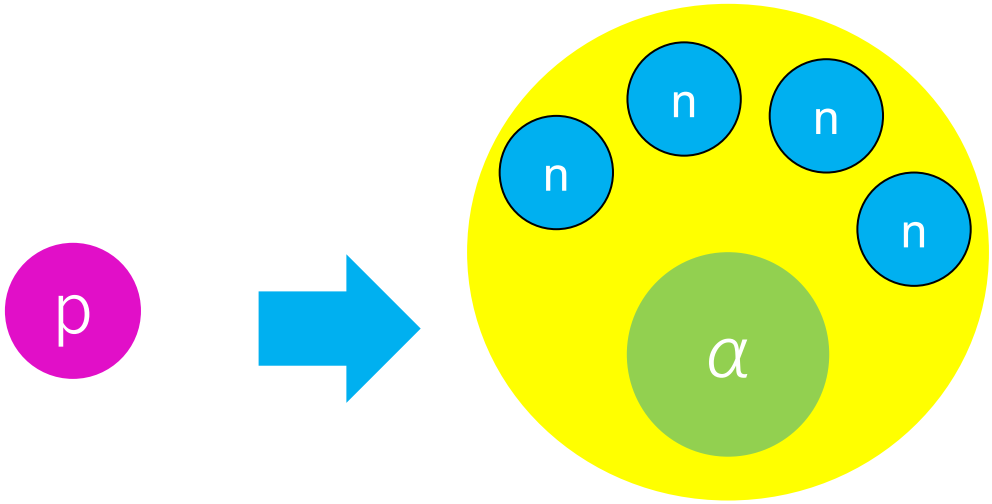
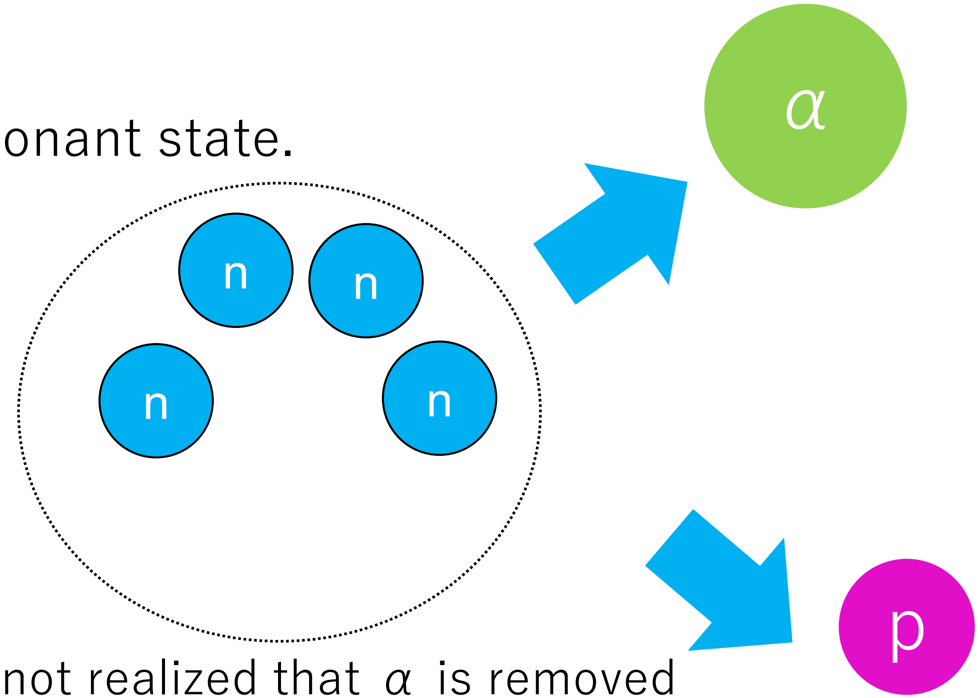


Table cloth puller

- https://youtu.be/W0mzk-wBIQI

What is definition of ‘resonant state’?
Mathematically, when we have a pole, this is a resonant state.





4n are not realized that α is removed
by proton. Can we say this is resonant state?

Thank you!