Structure of light neutron-rich nuclei

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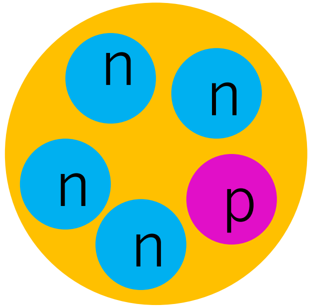
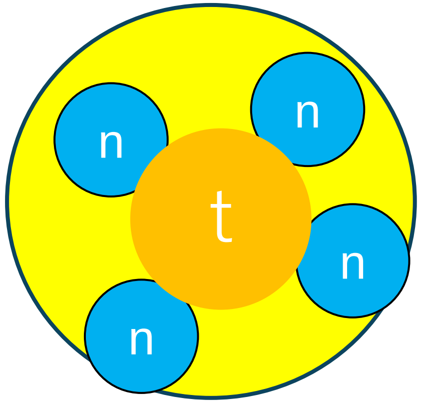
Outline of my talk:

(1)



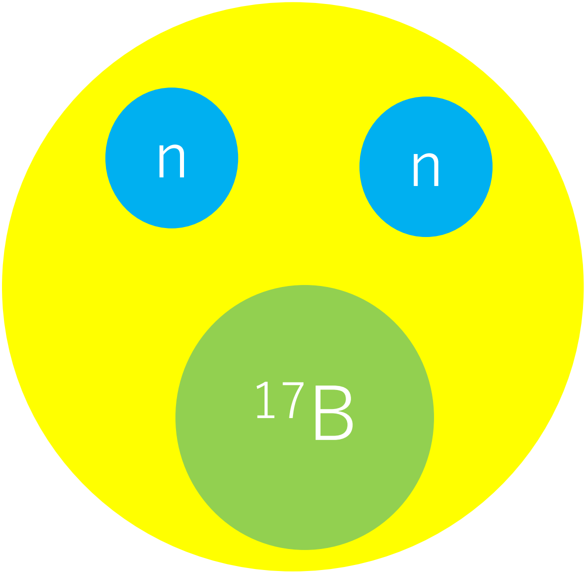
^{5}H



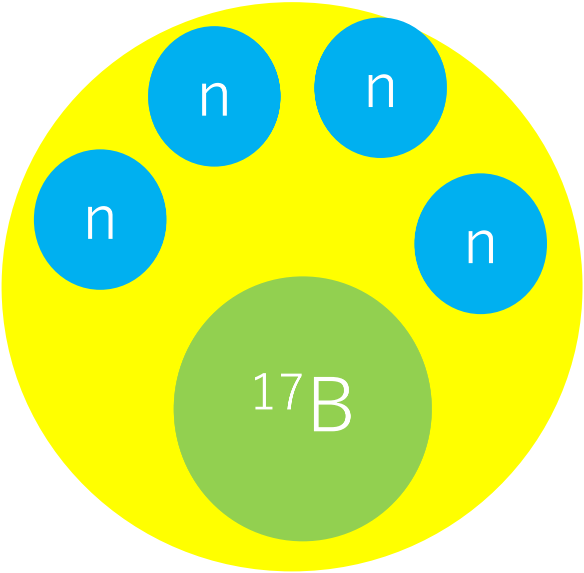
^{7}H

(2)

^{19}B



^{21}B



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

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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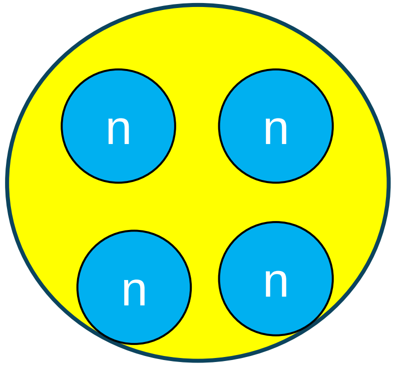
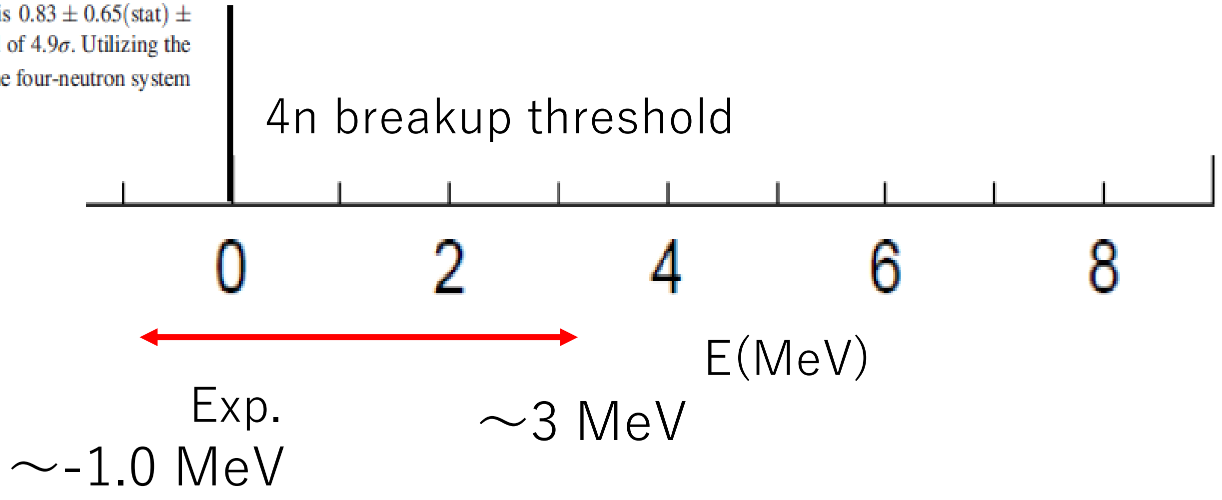
A candidate resonant tetraneutron state is found in the missing-mass spectrum obtained in the double-charge-exchange reaction ^{4}He(^{8}He, ^{8}Be) at 186 MeV/u. The energy of the state is 0.83 ± 0.65(stat) $\pm$ 1.25(syst) MeV above the threshold of four-neutron decay with a significance level of 4.9σ. 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)

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

Motivation:

Article

Observation of a correlated free four-neutron system

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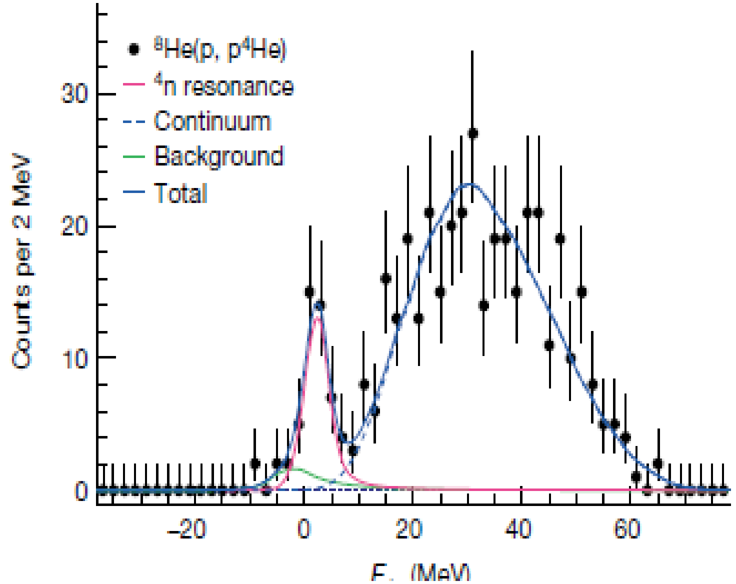
Check for updates

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)

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

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

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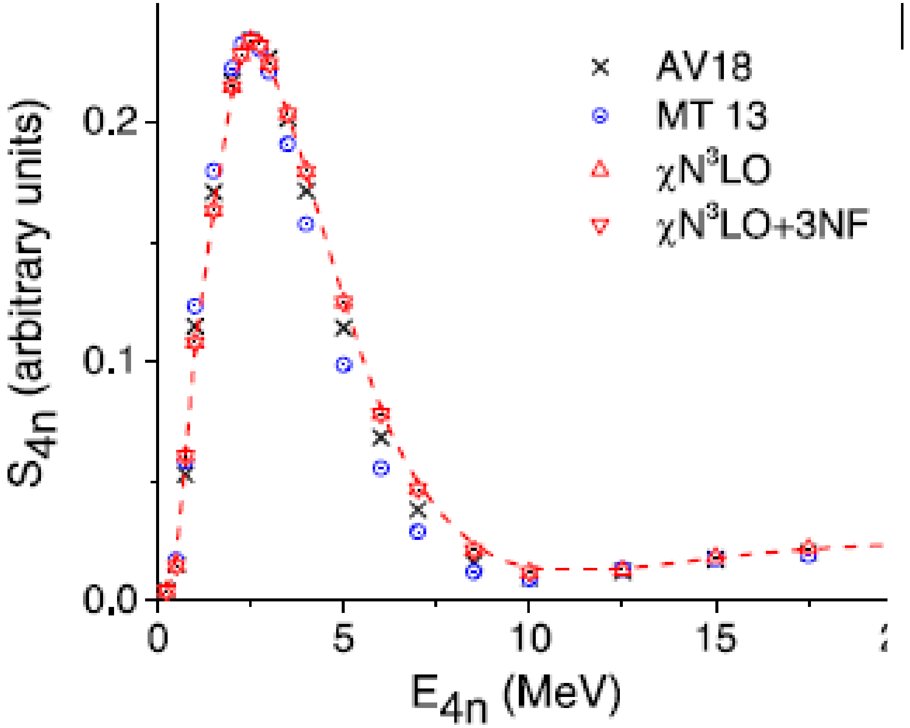
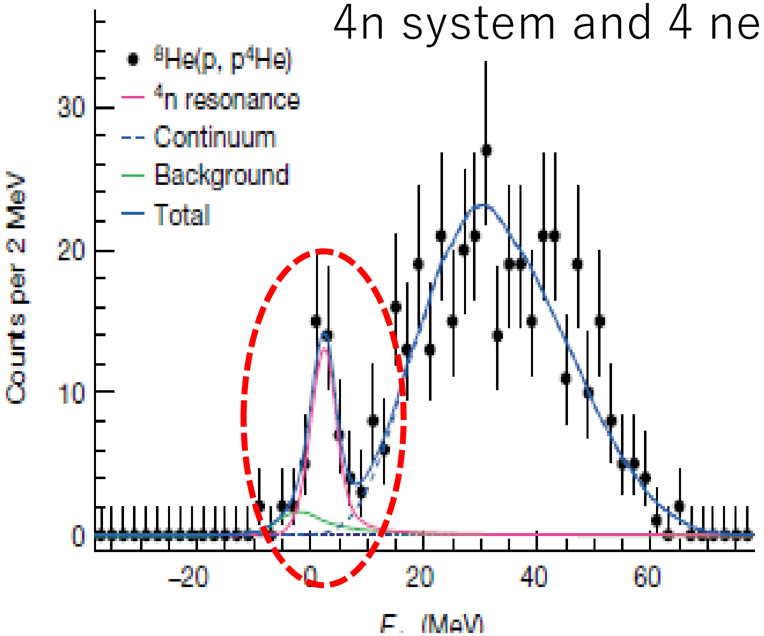
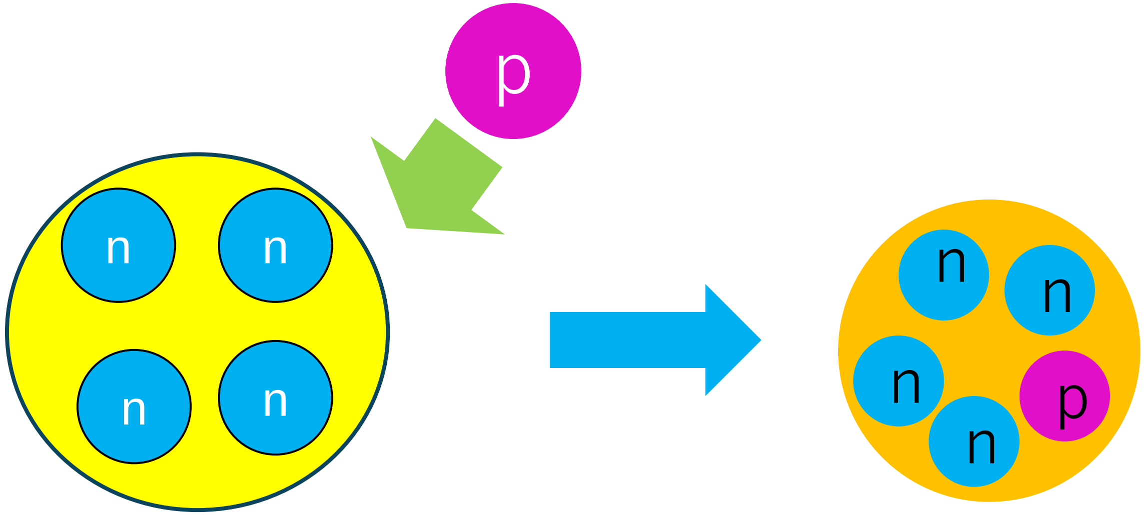
We calculated the reaction using several kinds of NN interaction.
We see to have a peak near 4n threshold without 3NF force.
We include 3NF force. But effect of 3NF is small.
We interpret that a peak is emerged as a consequence of the final interaction among 4n system and 4 neutrons in ^{8}He projectile.





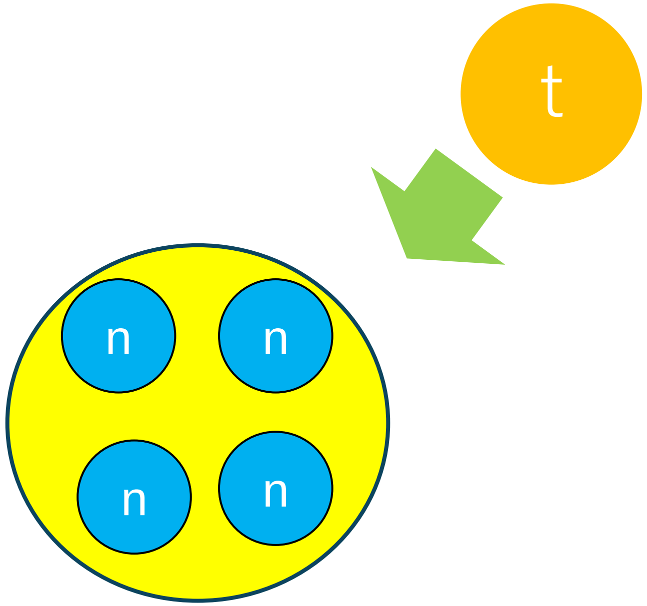
To understand 4n system in more detail….

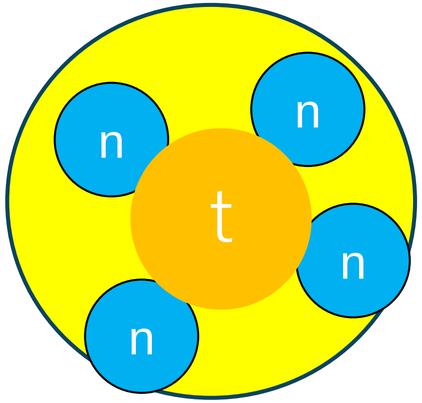


^{5}H

Let's add one triton to 4n.

^{7}H



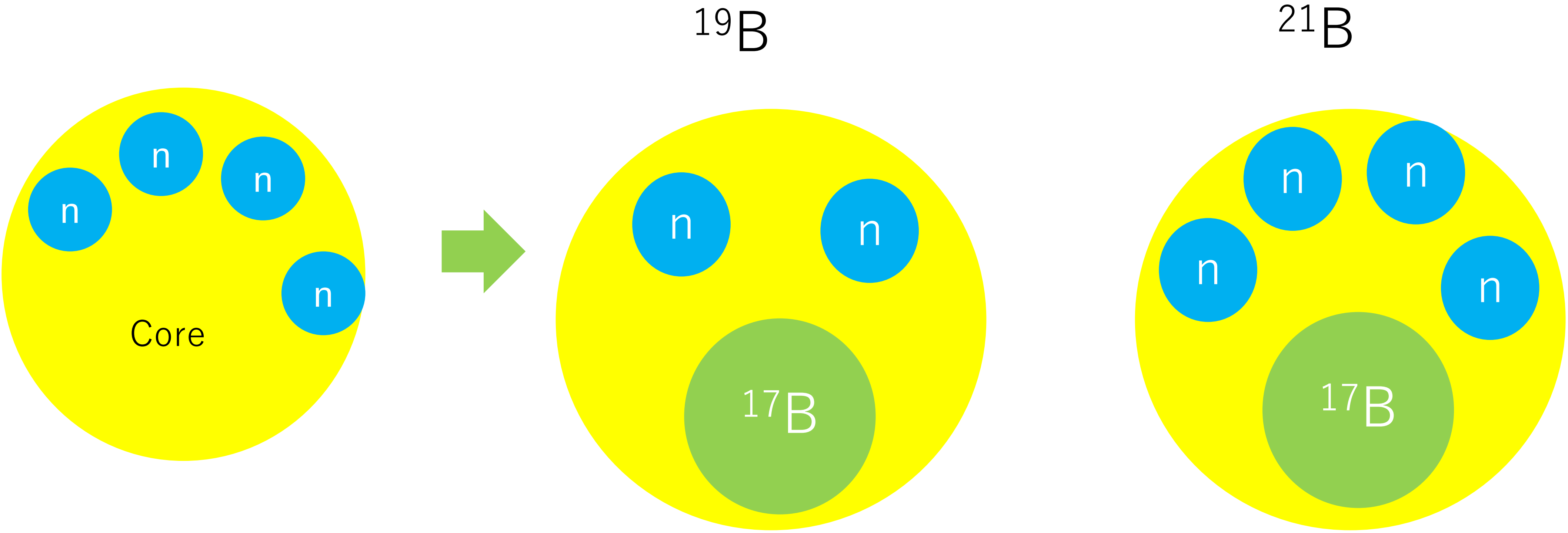


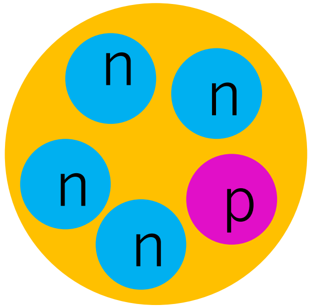
Neutron:6
Proton: 1

Super heavy hydrogen

Can we understand ^{5}H and ^{7}H with NN interaction so far proposed?

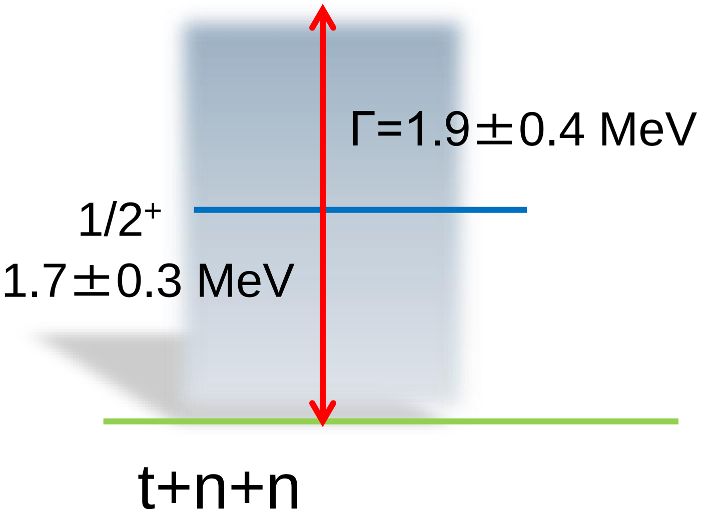
In more generally, ・ ・ ・





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

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



Superheavy hydrogen

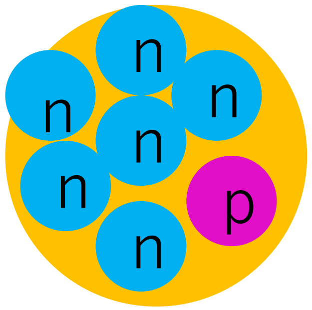
(E_R, Γ_R) (MeV)	
J^π	$1/2^+$
^{5}H (full)	(1.57, 1.53)
^{5}H ($d = 0$)	(1.55, 1.35)
Theor. [16]	(2.26, 2.93)
Theor. [12]	(2.5–3.0, 3–4)
Theor. [13]	(3.0–3.2, 1–4)
Theor. [15]	(1.59, 2.48)
Exp. [3]	$(1.7 \pm 0.3, 1.9 \pm 0.4)$
Exp. [8]	$(1.8 \pm 0.1, < 0.5)$
Exp. [4]	(1.8, 1.3)
Exp. [5]	(2, 2.5)
Exp.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

[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.

Energy of 5H is similar. But decay width is dependent on experiment.

In 2017, we have a new data on ^{5}H.
A. H. Wuosmaa, Phys. Rev. C95, 014310 (2017)
$^{6}He(d,{}^{3}He)\,{}^{5}H$

$$E_r = 2.4 \pm 0.3 \text{ MeV} \quad \Gamma = 5.3 \pm 0.4 \text{ MeV}$$



^{7}H

A. A. Korsheninnikov et al., PRL 90, 082501 (2003)
M. Caamano et al., PRL99, 062502(2007)
PRC 78, 044001 (2008)

$$E_r = 0.57^{+0.42}_{-0.21} \text{ MeV}$$ from t+4n threshold

$$\Gamma = 0.09^{+0.94}_{-0.06} \text{ MeV}$$

$^{12}C(^{8}He,{}^{7}H)^{13}N$ reaction

If we have narrow decay at lower energy, we could have heavier H-hydrogen isotope such as ^{9}H.

What is limit for H-isotope? Probably ^{7}H?

Theoretical calculation for ^5H and ^7H

N. K. Timofeyuk, PRC65, 064306(2002), PRC69 , 034336(2004)
Volkov NN potential, Hyperspherical harmonics method: 5-body and 7-body calculations
^5H: about 1 MeV above t+n+n threshold.
^7H: about 3MeV above t+4n threshold
She calculated the energies with bound state approximation.
Then, she did not give decay width for these nuclei.

S. Aoyama and N. Itagaki, PRC80,021304 (R)
Volkov NN potential, AMD calculation
^7H: 4.2 MeV above t+4n threshold, no calculation for decay width
No report for the energy of ^5H

H. H. Li et al., PRC 104, L061306 (2021)
Gamow shell model calculation using Minnesota NN potential.

Energy and decay width of ^5H is 1.4 MeV and 0.5 MeV, respectively.
Energy and decay width of ^7H is about 2-3MeV and about 0.1 MeV, respectively. They predicted to have very narrow decay width for ^5H and ^7H.

Experiment situation:

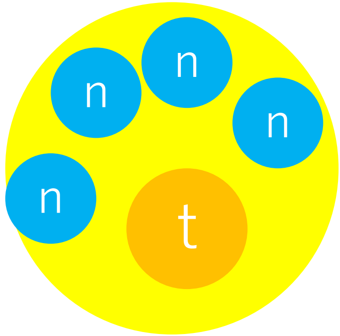
Recently, ^{8}He (p,2p) ^{7}H reaction has been done at RIBF.
RIBF Experimental Proposal NP1512-SAMURAI34.
The analysis is on going.

Then, it is timely to calculate ^{7}H to obtain the energy and width theoretically.

Motivated by this situation, we study ^{7}H structure within the framework of t+4n 5-body problem. We also discuss on the energy and decay width of ^{5}H within t+n+n three-body problem.

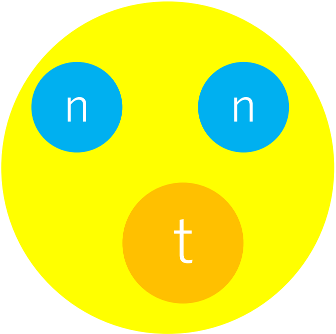
Framework

NN: Minnesota potential (central potential)

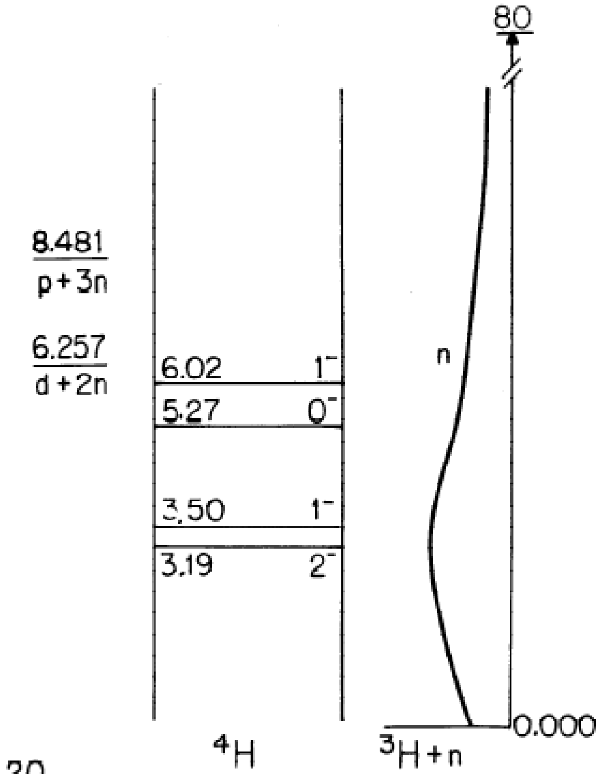


$^7H = t + 4n$ model

t-n potential => there is a large degree of ambiguity.
Only several data for phase shift of t-n



^5H



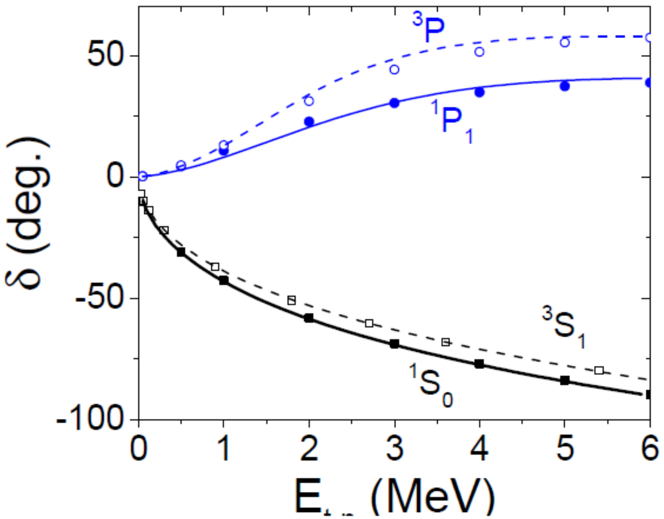
$$V(r,l,s)_{nt} = \delta_{l,0}|\varphi_0\rangle\lambda_\infty\langle\varphi_0| + \sum_{i=1}^{2}\left(v_i^{(c)} + (-)^l v_i^{(P)} + \frac{\hat{s}^2}{2}v_i^{(s)} + (-)^l\frac{\hat{s}^2}{2}v_i^{(SP)}\right)\exp(-\alpha_i r^2)$$

$$|\varphi_0\rangle = \exp(-a_0 r^2)$$

$$\lambda_\infty = \infty$$

i	1	2
$\alpha_i(fm^{-2})$	0.471241	0.0549825
$v_i^{(c)}(MeV)$	−41.3619	1.22768
$v_i^{(P)}(MeV)$	−0.309720	6.89574
$v_i^{(s)}(MeV)$	−28.2483	−0.972465
$v_i^{(SP)}(MeV)$	10.3308	−1.25695

$$a_0 = 0.1979068 \quad fm^{-2}$$



Based on four-body calculation with MT I-III

α_i	V_{nt} (1)	4N [12]
$L = 1^-, S = 0$	1.28-2.61 i	0.88(5)-2.20(5) i
$L = 1^-, S = 1$	1.33-1.84 i	1.08(3)-2.03(3) i

Two-body calculation of t-n is almost consistent with that of 4-body calculation.

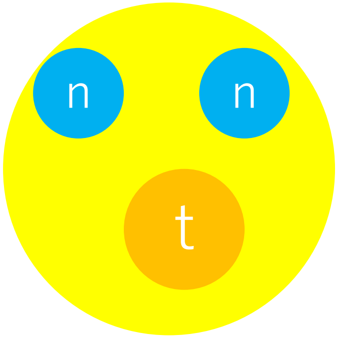
This is origin of breaking effect of ^{3}H core.

＋ I introduce a phenomenological three-body t-n-n force to obtain energy trajectory.

$$V_{tnn}(\rho) = -V_0\, e^{-\frac{\rho^2}{b_3^2}} \qquad \rho^2 = \frac{m_n}{M} r_{nn}^2 + \frac{m_t}{M^2} r_{nt}^2 + \frac{m_t}{M^2} r_{nt}^2 \qquad M = 2m_n + m_t$$

V_0,b_3 : parameters. → Fit so as to reproduce the data of ^{5}H

↓ apply

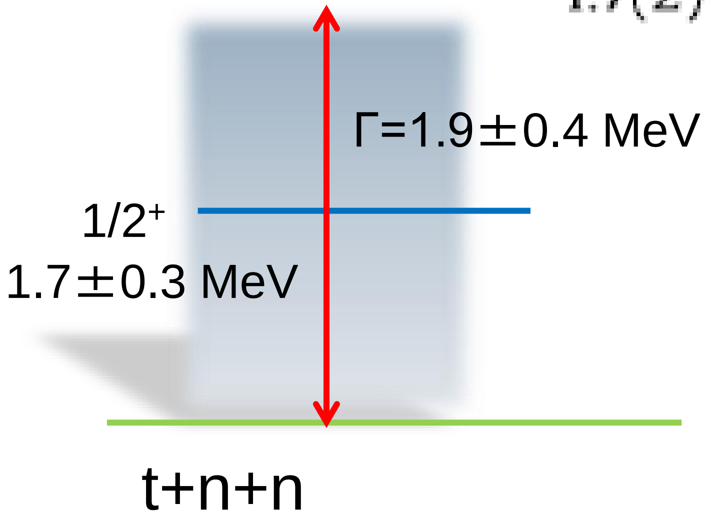


^{5}H

Question: Which experimental data of ^{5}H should we fit?

R. Lazauskas, E. Hiyama, J. Carbonell, PRB 791 335 (2019)
Fadeev-Yakubovsky method calculation of ^5H

	J=1/2$^+$	
	E_R	Γ
N3LO $^{(ACCC)}$	1.8(1)	2.4(2)
$^{(SECS)}$	1.9(2)	2.4(2)
INOY $^{(ACCC)}$	1.7(1)	2.4(2)
$^{(SECS)}$	1.8(1)	2.4(2)
MT13 $^{(ACCC)}$	1.4(1)	2.4(2)
$^{(SECS)}$	1.7(2)	2.4(2)



We take this result as 'exp.' data.

Close to the below exp.data

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

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.

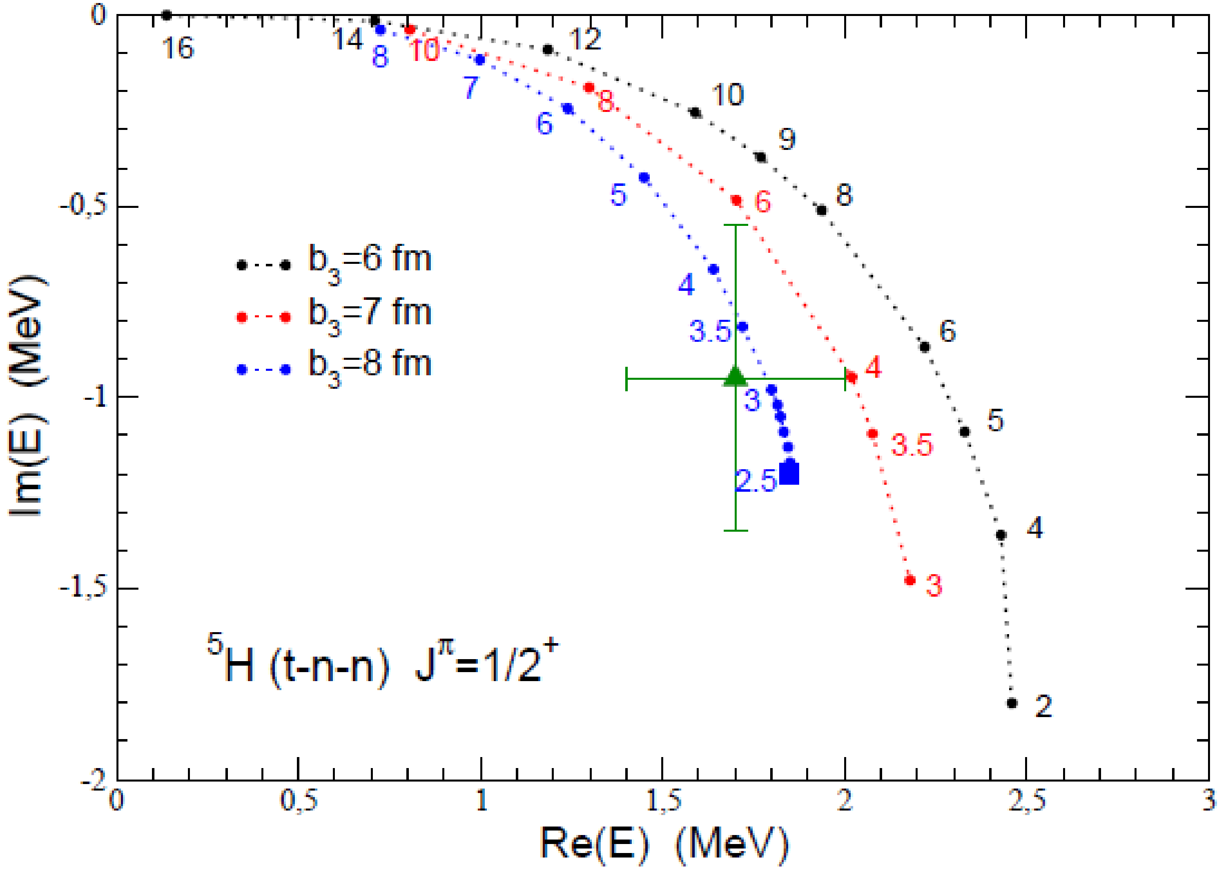
High-precision calculations of various 3- and 4-body systems:

Exotic atoms / molecules ,
3- and 4-nucleon systems,
multi-cluster structure of light nuclei,

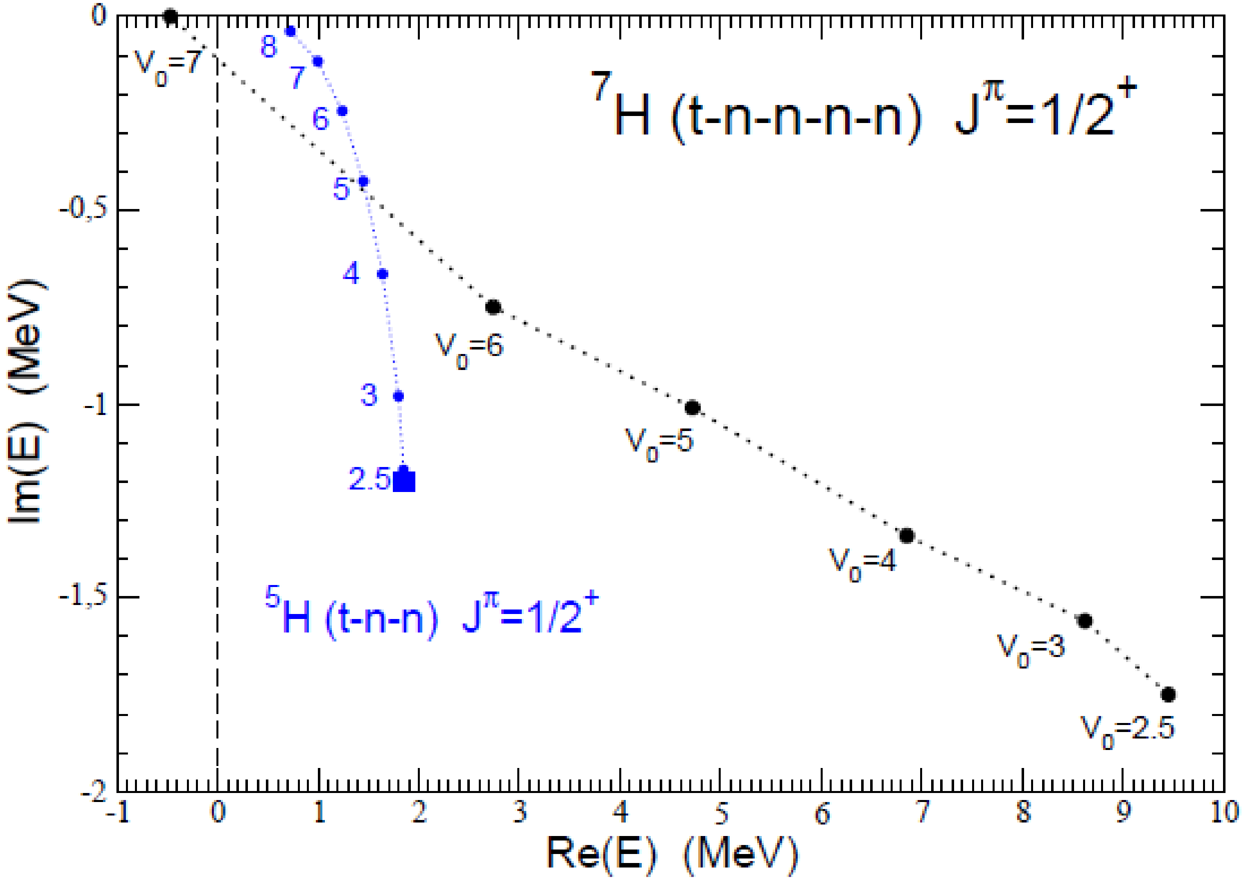
Light hypernuclei,
3-quark systems,

$$V_{tnn}(\rho) = -V_0 \; e^{-\frac{\rho^2}{b_3^2}} \qquad \rho^2 = \frac{m_n}{M} r_{nn}^2 + \frac{m_t}{M^2} r_{nt}^2 + \frac{m_t}{M^2} r_{nt}^2 \qquad M = 2m_n + m_t$$

When b_3=8 fm and V_0=3 to 2.5 MeV, the energy pole of ^{5}H is close to exp. data. If we have this potential parameter, what is energy pole of ^{7}H?

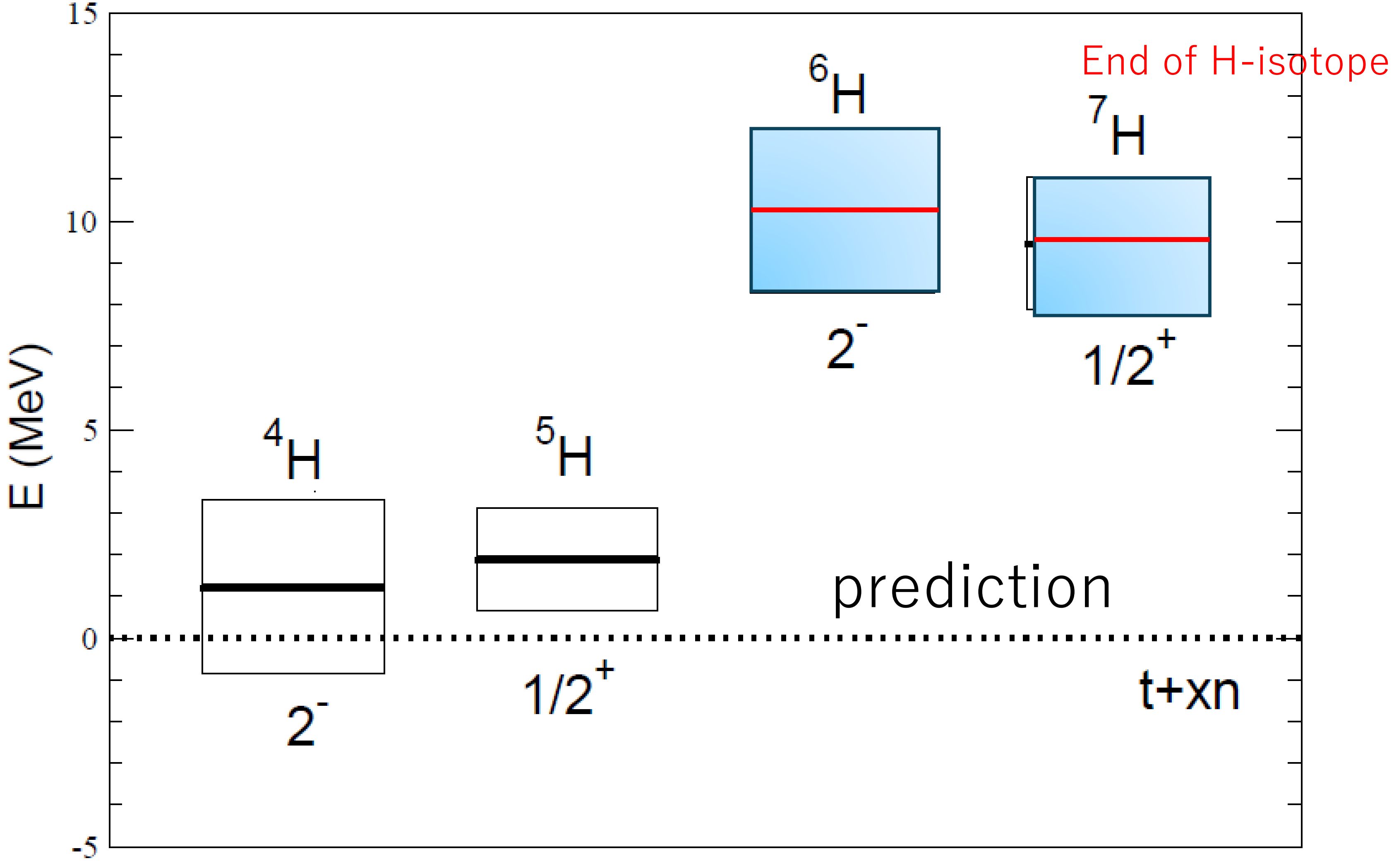


Im (E)=Γ /2



For V_0=2.5, we reproduce the data of ^{5}H accurately.
In this case, the energy pole of ^{7}H, E=9.5 MeV, Γ ～3.5 MeV.
Our energy of ^{7}H is much higher and broad decay width.

Summary of H-isotope (according to our calculation)



We are waiting for experimental data for ^{7}H. Once the energy and decay width of ^{7}H is determined, we can also determine the energy and decay width of ^{5}H.

Outline of my talk:

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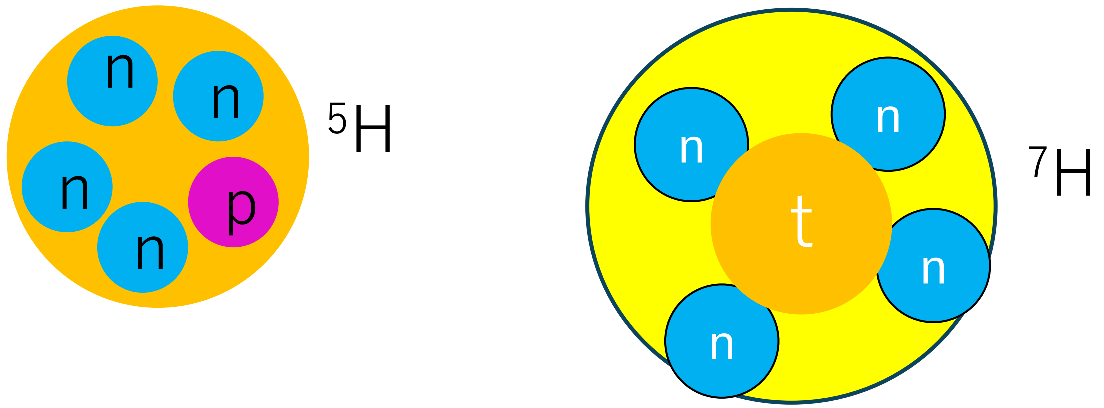

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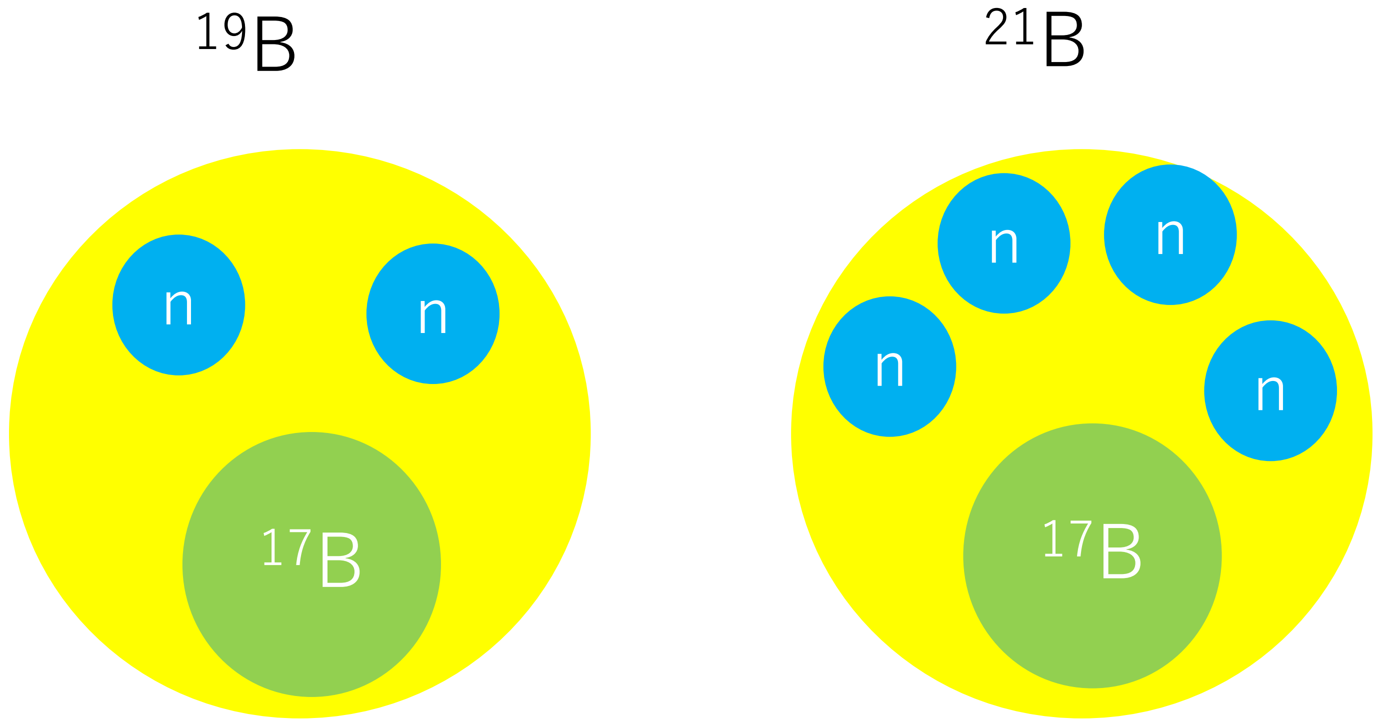


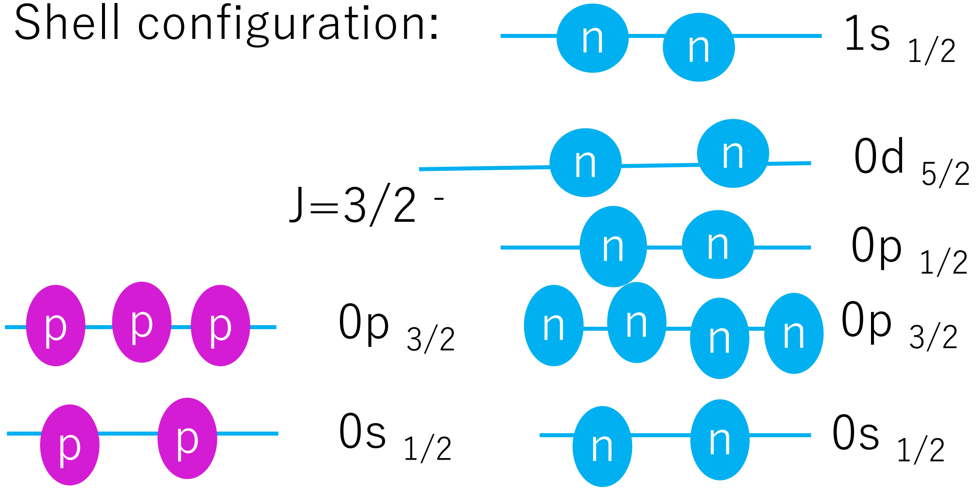
Boron isotope is interesting for studying halo state and universality.

^{17}B: $^{15}B+2n$ $S_{2n}=1.39\pm0.14$ MeV => The binding energy is not weak.

A matter radius: 4.10 ± 0.46fm E.Liatard et al., Europhys. Lett. 13, 401 (1990).
3.0 ± 0.6 fm A. Ozawa et al., Phys. Lett. B 334, 18 (1994).

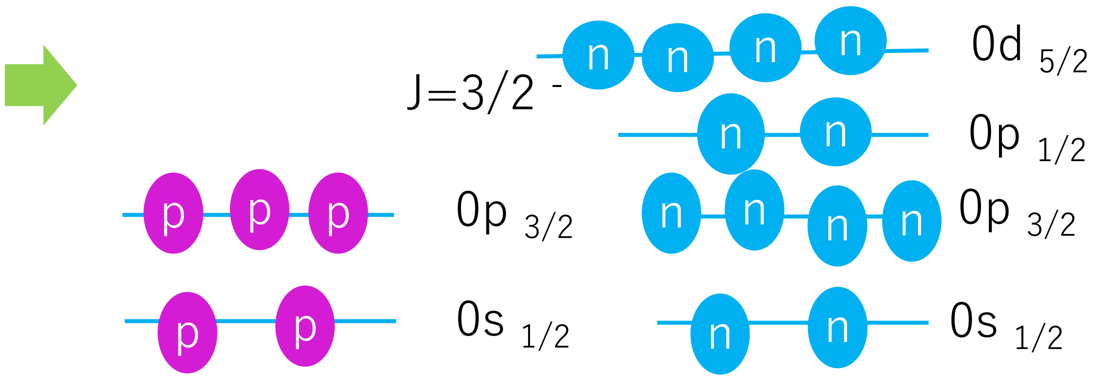
Large radius=> neutron halo ?

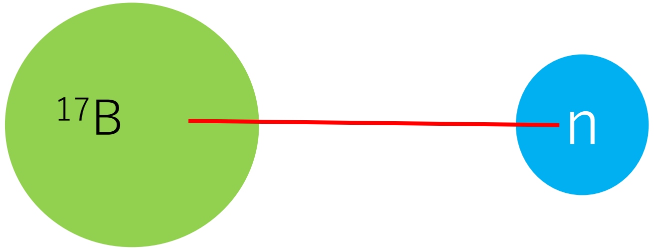
Shell configuration:



If we consider this configuration, we understand to have a halo structure in ^{17}B.

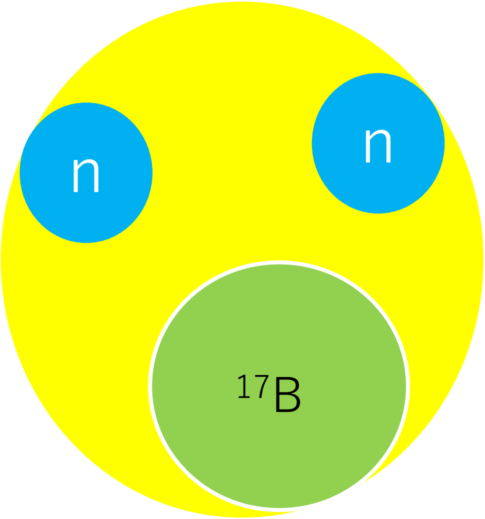
Z.H. Yang et al., PRL 126, 082501 (2021)
Valence two neutrons should be occupied in $0d_{5/2}$.
It is difficult to have halo state in ^{17}B.





S-wave large scattering length

$a_s \sim 100$fm   A. Spyrou et al., Phys. Lett. B683, 129 (2010).

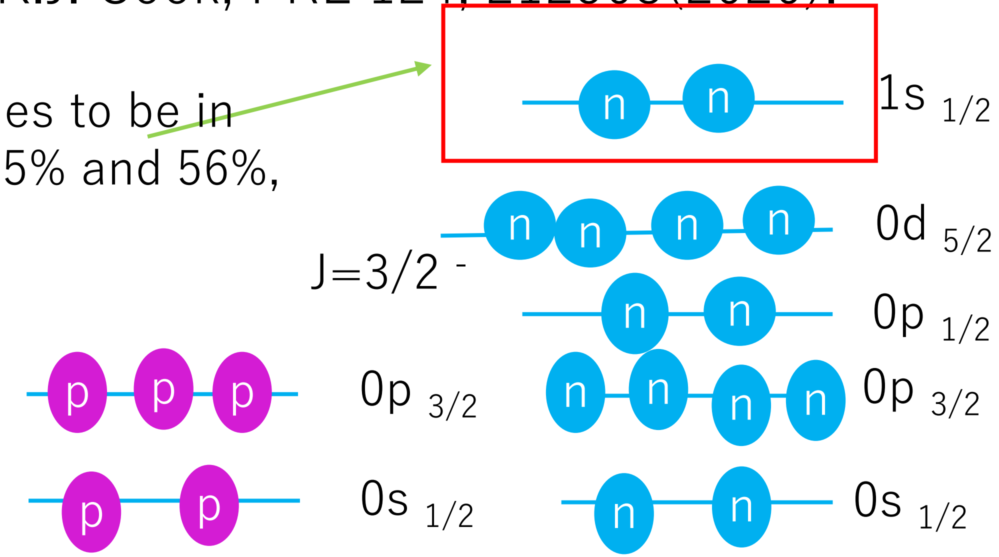


^{19}B S_{2n}= 0.14 ±0.39 MeV L.Gaudefroy et al., PRL109, 202503 (2012).

= 0.09 ±0.56 MeV M. Wang et al., Chin. Phys. C41, 030003(2017).

=0.5 MeV, a_s=-50 fm, K.J. Cook, PRL 124, 212503(2020).

Since the probabilities to be in $1s_{1/2}$ and $0d_{5/2}$ are 35% and 56%, Respectively, ^{19}B is bound.



^{20}B

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First Observation of ^{20}B and ^{21}B

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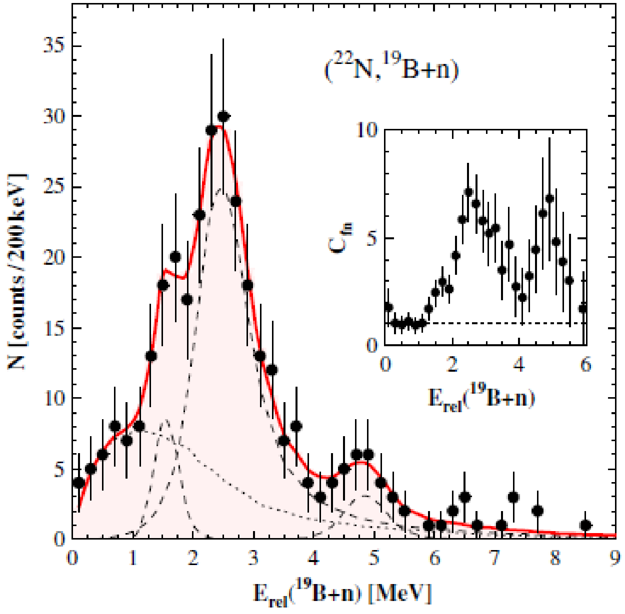
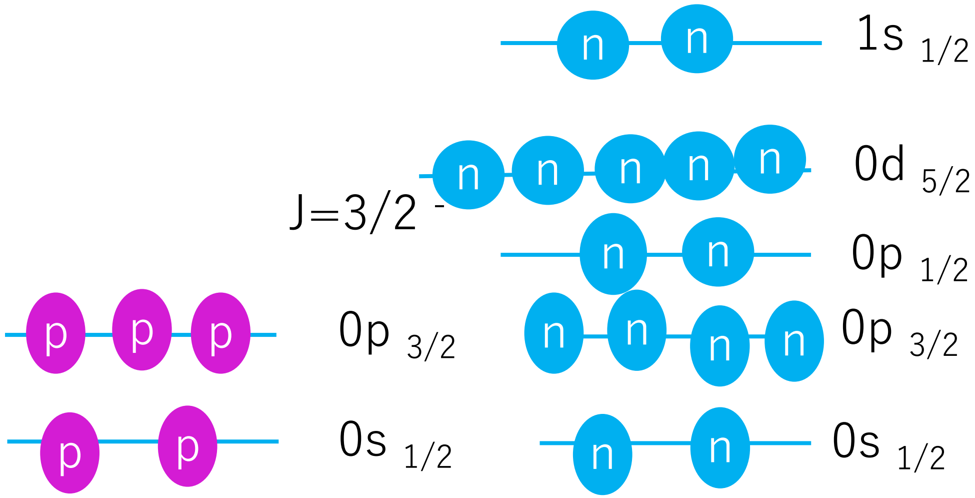
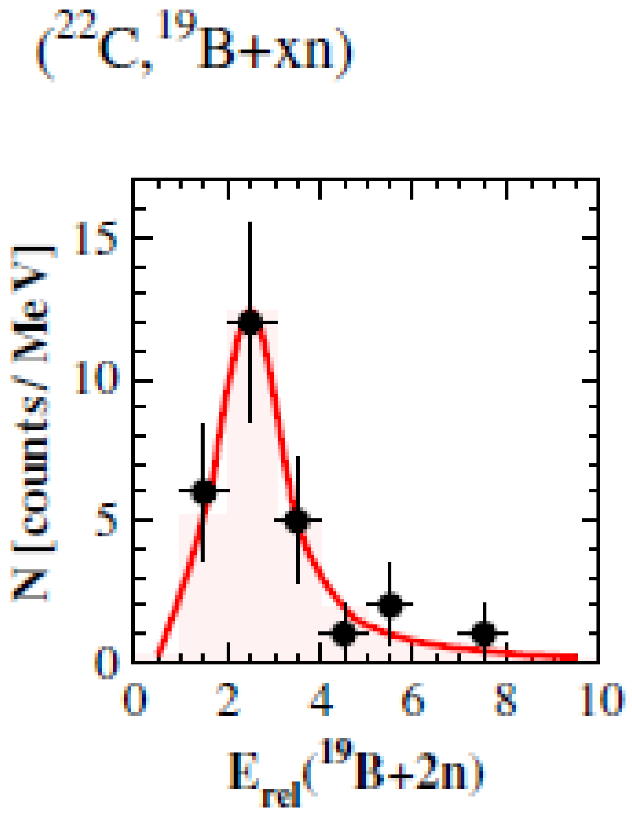


FIG. 2. Relative-energy spectrum of $^{19}B + n$ events following two-proton removal from ^{22}N. The red line corresponds to the best fit ($\chi^2/\mathrm{ndf} = 0.33$), including the nonresonant continuum (dotted) and ^{20}B resonances at 1.56, 2.50, and 4.86 MeV (dashed lines). The inset shows the fragment-n correlation function C_{fn} (see text).

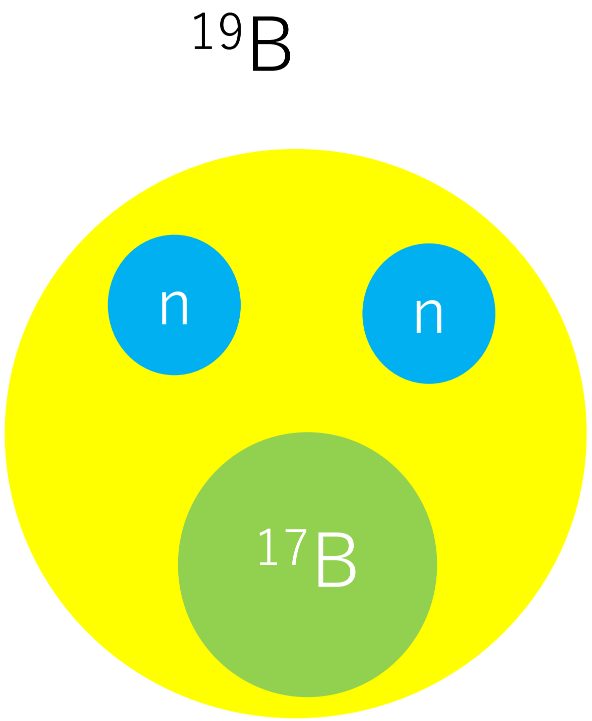
Observation of D-wave resonant states

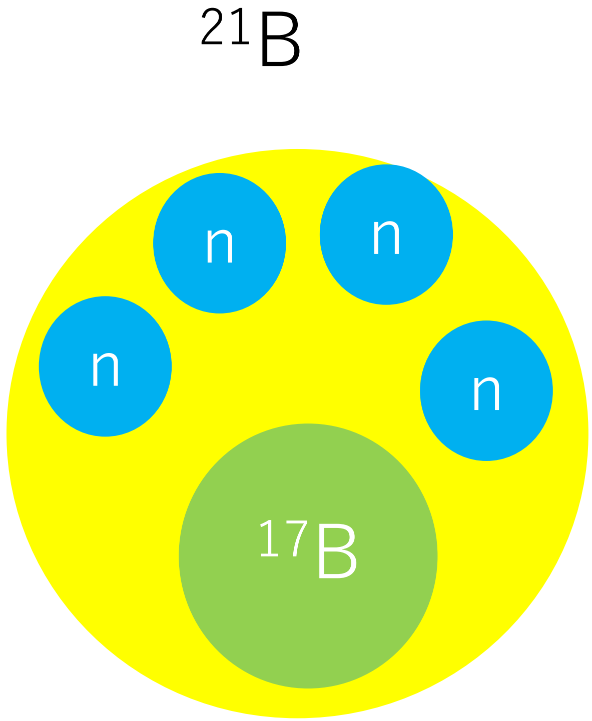


^{21}B



By proton removal from ^{22}C, they observed ^{21}B to be resonant state by 2.47 ± 0.19 MeV with respect to ^{19}B+2n threshold.

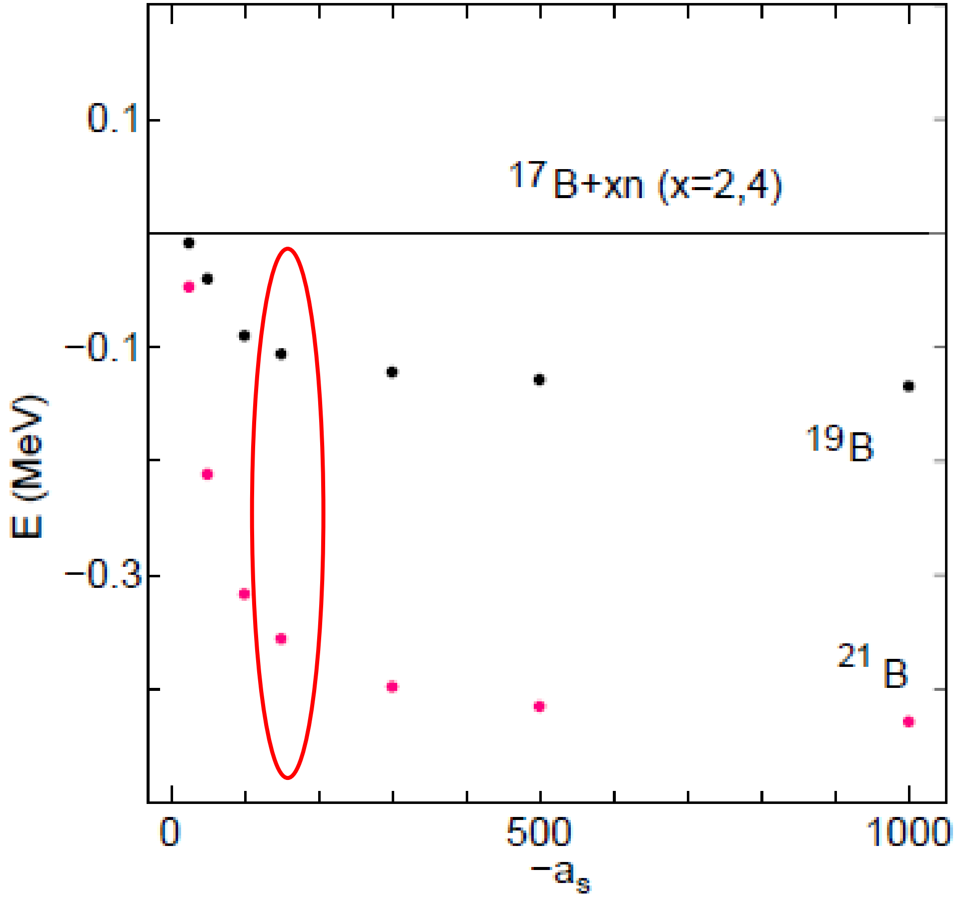


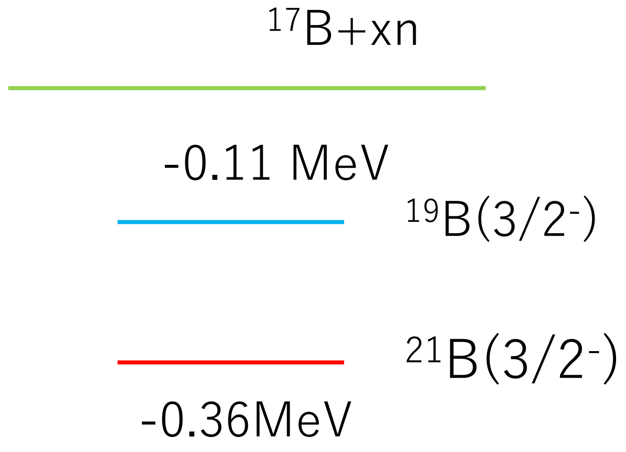


NN potential: Minnesota potential which is used in ^{7}H calculation.

$$V_{n^{17}\mathrm{B}}(r) = V_r\left(e^{-\mu r} - e^{-\mu R}\right)\frac{e^{-\mu r}}{r},$$

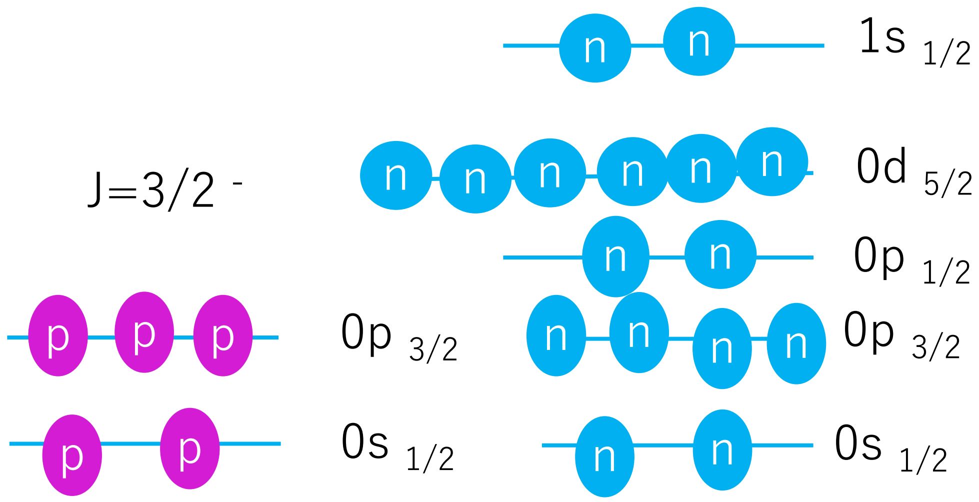
n-^{17}B potential has some ambiguity. So, we use several potential parameters for scattering length a_s=-25fm to -1000fm.

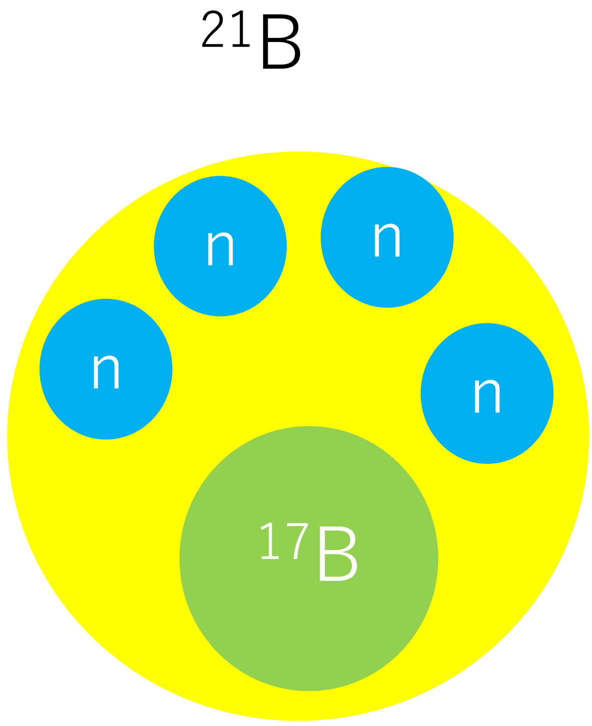




The ground state of ^{21}B is bound !

How should we understand inconsistency with our result and experimental data?

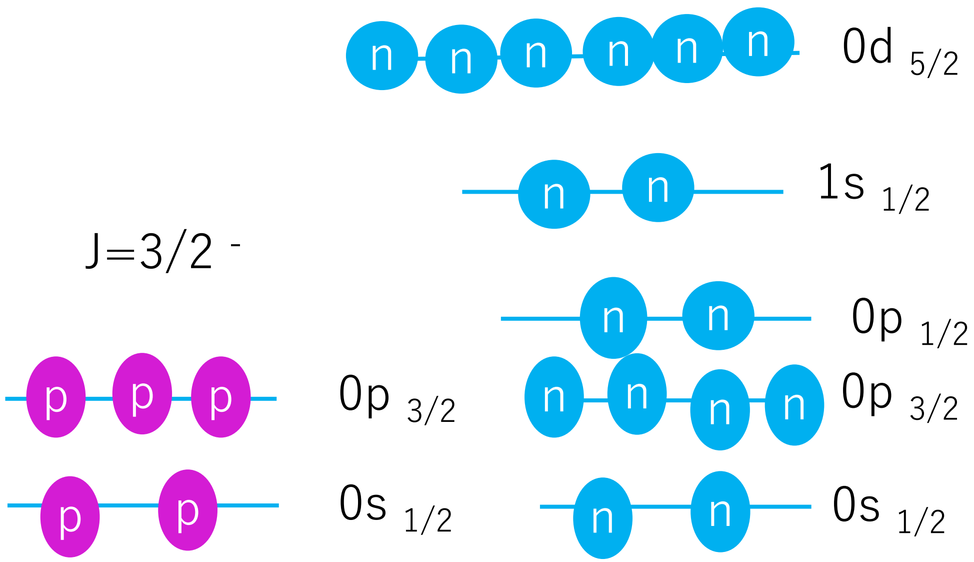


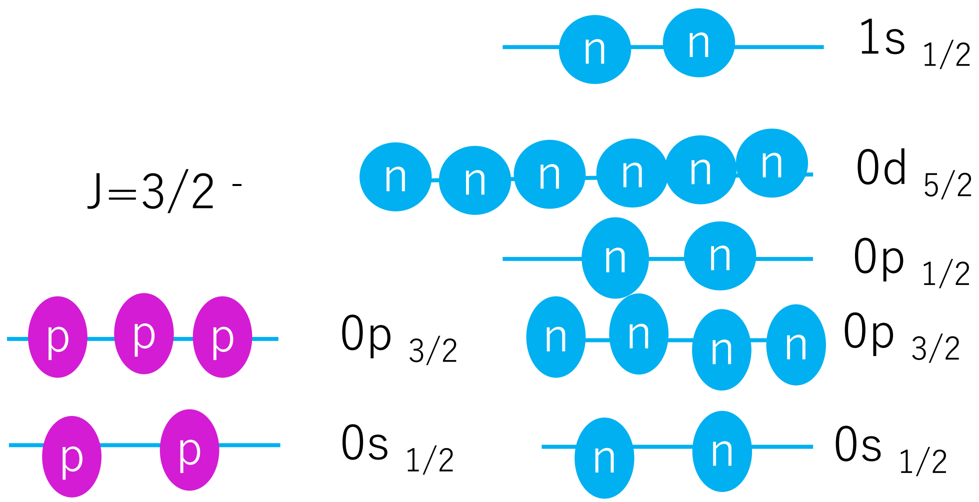


It seems that ^{21}B should be bound like ^{17}B and ^{19}B.
But, ^{21}B is not bound experimentally. Why?

If configuration in ^{21}B is like ^{19}B,
It might have bound state.

^{21}B is this configuration?
If so, I understand that ^{21}B is unbound.





Which configuration is correct?

Summary

When I use ^{17}B-n potential with scattering length -150fm, we have a very weakly bound state (100-200 keV) with the lowest threshold) in ^{21}B.
How should we understand it?
One possibility is that my potential of ^{17}B-n is too simple?

$$V_{n^{17}\mathrm{B}}(r) = V_r \left(e^{-\mu r} - e^{-\mu R}\right) \frac{e^{-\mu r}}{r},$$

Do I need to use more sophisticate potential?

Question: Does experiment create the ground state of ^{21}B or excited state?
Core $_{17}B$ is not good? But ^{19B} can be described with ^{17}B+n+n.