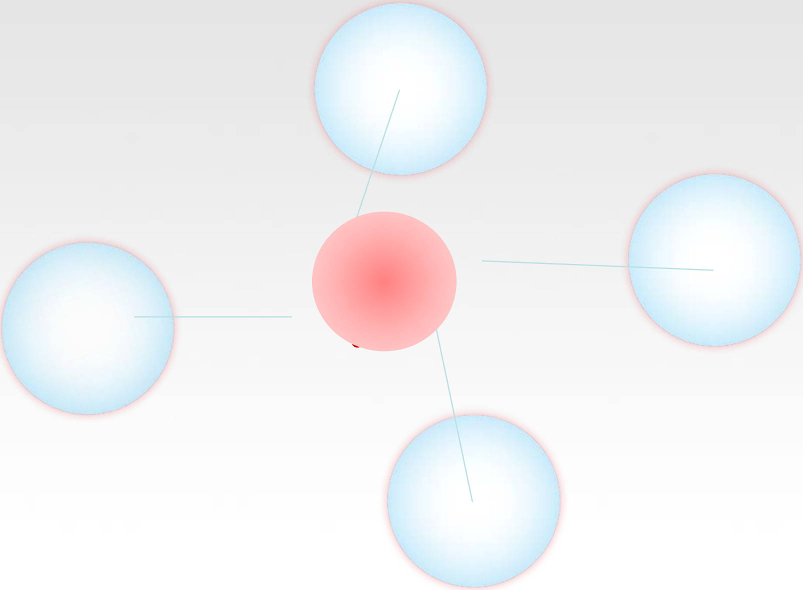


Selected cases of exotic neutron rich systems

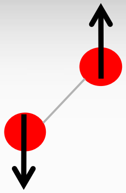
R. Lazauskas (IPHC), E. Hiyama (Sendai U., RIKEN), J. Carbonell (IJCLab)

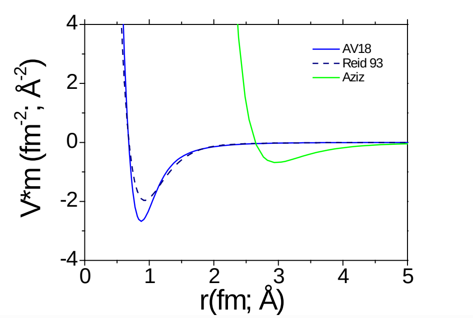
Bound multineutron: no way?

^2n is allready resonant in $^1S_0$ state

n-n	AV18	INOY	Reid93	Exp
a_{nn} (fm)	-18.49	-18.60	-17.54	-18.5(4)
r_0 (fm)	2.84	2.82	2.84	2.80(11)
$r(V_{min})$	0.874		0.930	-
γ_s	1.080	1.102	1.087	-

*Enhancement factor γ_s~1.09 ($V_\gamma=\gamma V_{nn}$) is enough to bind ^2n in $^1S_0$ state





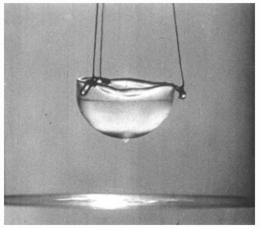
^{3}He-^{3}He	Aziz
a (Å)	-7.61
r_0 (Å)	13.5
$r(V_{min})$	2.97
γ_s	1.299

…

Needs gravity to be bound in n-stars..

$(^3He)_A$ is bound for A>34

R. Guardiola, J. Navarro, Phys. Rev. Lett. 84 (2001) 1144



at 1mK

Bound light multineutron: no way!

.. apart from some unsound speculations

Th. Faestermann *et al.*, Phys. Lett. **B 824**, 136799 (2022)

- No any significant experimental evidence
- Theory (in unison): no way for ^3n-^8n!

S. Pieper, PRL 90, 252501 (2003)

C. Bertulani & V. Zelevinsky, J. Phys. G 29 2431 (2003)

N.K. Timofeyuk, arXiv:nucl-th/0203003

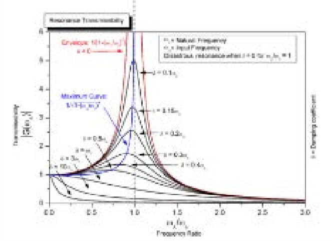
R.L., PhD thesis Université Joseph Fourrier (2003)

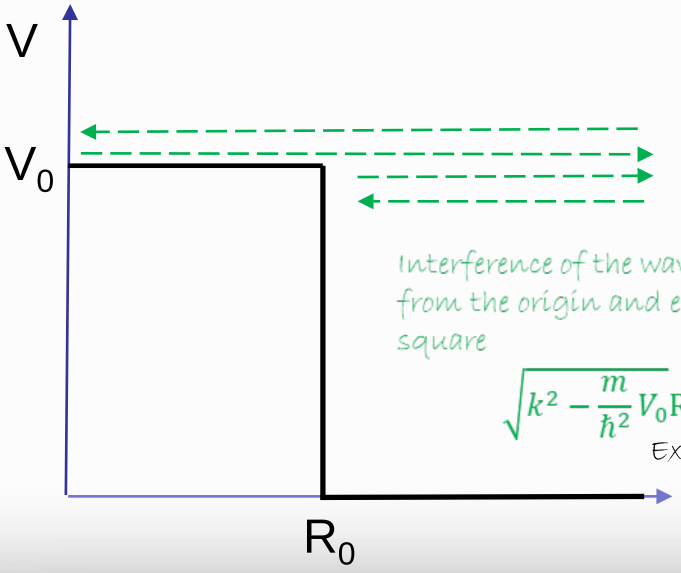
…

- Simplistic NN interactions
- Realistic NN interactions

Resonant multineutron: how we define it?

- Experiment : some rapid variation (preferentially rise) of cross section in a process related with ${}^{A}n$ production… **OK, BUT not every hill is a mountain**
  - ⇨ Signal from X+${}^{A}n$ - resonance **from X, ${}^{A}n$ or +**?
  - ⇨ Rapid cross section variations are also produced in repulsive systems!



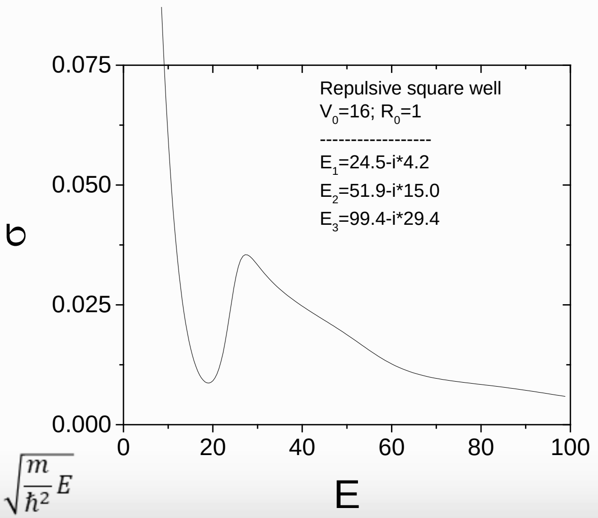


Interference of the waves reflected from the origin and edge of the square

$$\sqrt{k^2-\frac{m}{\hbar^2}V_0}R_0 \approx n\pi$$

Exact relation for resonance positions:

$$\boxed{\tanh\left[i\sqrt{k^2-\frac{m}{\hbar^2}V_0}R_0\right]+k=0;}\qquad k=\sqrt{\frac{m}{\hbar^2}E}$$

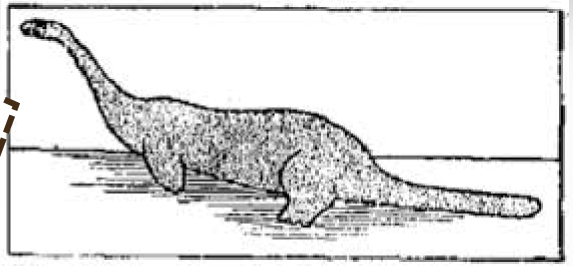


Resonant multineutron: experimental results

As searching for Lochness monster

As in most experiments of this sort, however, a negative result cannot be regarded as conclusive and further experiments are needed to give additional weight to our result.

P. Schiffer and R. Vandenbosch, ``Search for a Particle-Stable TetraNeutron," Phys. Lett.5 292 (1963)



The Loch Ness Monster, As Sketched by Mr. A. Grant From Lieut.-Commander Gould's Interesting Monograph Upon the Subject.

- ^{4}He(γ, 2π^+)^{4}n
- ^{4}He(π^-, π^+)^{4}n

T. P. Gorringe et al., Phys. Rev. C 40, 2390 (1989)

- ^{7}Li(π^-, ^{3}He)^{4}n

Y.A.Batusov et al., Sov.J.Nucl.Phys. 26, 129 (1977)

- ^{7}Li(^{7}Li, ^{10}C)^{4}n

D.V.Aleksandrov, Yad.Fiz. 47, 3 (1988)

- ^{7}Li(^{9}Be, ^{12}N)^{4}n
- ^{7}Li(^{11}B, ^{14}O)^{4}n
- ^{9}Be(^{9}Be, ^{14}O)^{4}n

Belozyorov et al., Nucl .Phys. A 477 (1988) 131

- ^{14}Be→^{10}Be+^{4}n: 6 events

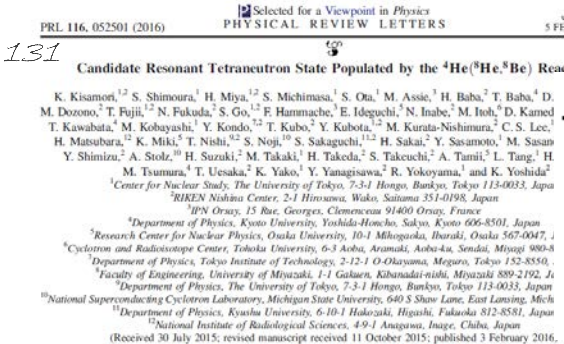
F.M. Marqués et al: Phys. Rev. C 65 (2002) 044006 et arxiv:nucl-ex/0504009

- ^{4}He(^{8}He, ^{8}Be)^4 n: 4 events

K. Kisamori, S. Shimoura et al., Phys. Rev. Lett. **116** (2016) 052501

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

M.Duer,.., S. Shimoura et al. Nature **606** (2022) 678



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.
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. Kamed
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]
H. Matsubara,[12] K. Miki,[5] T. Nishi,[9,2] S. Noji,[10] S. Sakaguchi,[11,2] H. Sakai,[2] Y. Sasamoto,[1] M. Sasan
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.
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, Japa*
[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,*
[6]*Cyclotron and Radioisotope Center, Tohoku University, 6-3 Aoba, Aramaki, Aoba-ku, Sendai, Miyagi 980-*
[7]*Department of Physics, Tokyo Institute of Technology, 2-12-1 O-Okayama, Meguro, Tokyo 152-8550,*
[8]*Faculty of Engineering, University of Miyazaki, 1-1 Gakuen, Kibanadai-nishi, Miyazaki 889-2192, J*
[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, Mich*
[11]*Department of Physics, Kyushu University, 6-10-1 Hakozaki, Higashi, Fukuoka 812-8581, Japan*
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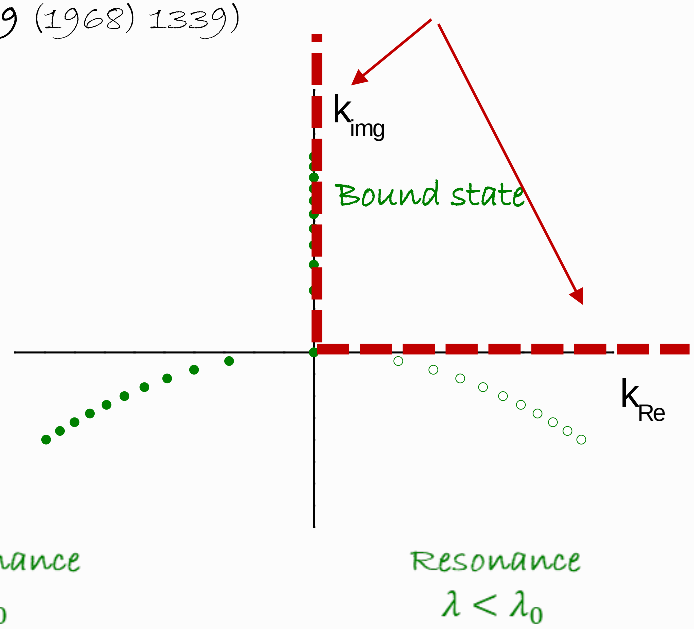
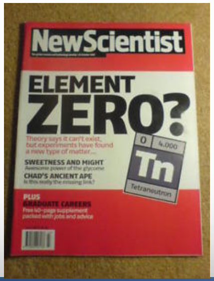
Observation of a correlated free four-neutron system

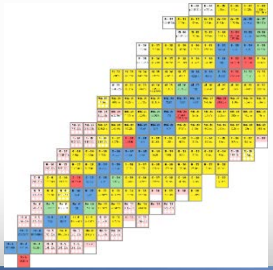
M. Duer, T. Aumann, R. Gernhäuser, V. Panin, S. Paschalis, D. M. Rossi, N. L. Achouri, D. Ahn, H.

Resonant multineutron: how we define it?

- Theory: pole of the scattering amplitude in the vicinity of the ^{A}n physical region… not much better, if not even worse…
- Mathematical object in 2D-manifold, verified by physical observable in 1D
  - ⇨ Possibility to manipulate poles - create false ones
  - ⇨ Rapid variations of cross section without poles in the scattering amplitude (Calucci G., Ghirardii C, Phys. Rev. **169** (1968) 1339)
  - ⇨ Poles, which has no link (evolve) to bound states (see repulsive square well example)







in nuclear physics resonances are associated with 'almost' bound structures?!

Resonant Multineutron: theoretical results

Rigorous treatment of the continuum:

No observable ^3n resonant states:

A. Csótó et al., Phys. Rev. **C 53**, 1589 (1996)
H. Witala et al., Phys. Rev. **C 60**, 024002 (1999)
A. Hemmdan et al., Phys. Rev. **C 66**, 054001 (2002)

R.L et al., Phys. Rev. **C 71**, 044004 (2005)
A. Deltuva, Phys. Rev. **C 97**, 034001 (2018)
S. Ishikawa, Phys. Rev. **C 102**, 034002 (2020)

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S. A. Sofianos et al., J. Phys. **G 23**, 1619 (1997)

K. Arai, *Phys. Rev.* **C 68**, *034303 (2003)*
R.L et al., Phys. Rev. **C 72**, 034003 (2005);

E. Hiyama et al., Phys. Rev. **C93**, 044004 (2016);
PTEP 2017, 073D03 (2017)

A. Deltuva et al., *Phys. Lett.* **B 782**, 238-241 (2018); *Phys. Rev.* **C 100**, 044002 (2019)
K. Fossez et al.,Phys. Rev. Lett. **119**, 032501
M.D. Higgins et al., *Phys. Rev. Lett.* **125.5**, 052501 (2020).

Non-rigorous continuum:

Observable ^3n & ^4n resonant states:

S. Gandolfi et al., Phys. Rev. Lett. **118**, 232501 (2017)
J. G. Li, Phys. Rev. **C 100**, 054313 (2019)

Observable ^4n resonant states:

S. Pieper, Phys. Rev. Lett. **90** (2003), 252501
M. Shirokov et al., Phys. Rev. Lett. **117**, 182502 (2016)

interactions
nteractions

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S. Ishikawa, Phys. Rev. **C 102**, 034002 (2020)

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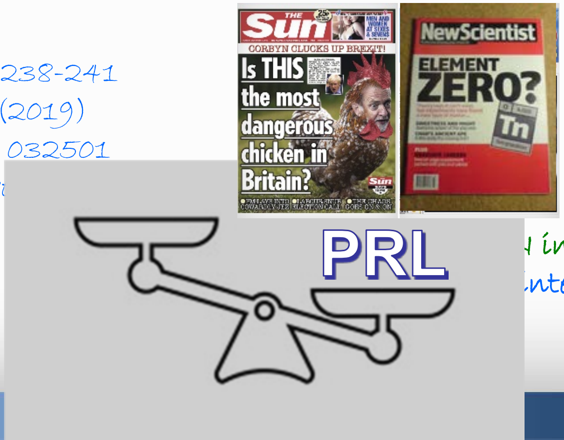

interactions
interactions

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A. Deltuva, Phys. Rev. **C 97**, 034001 (2018)
S. Ishikawa, Phys. Rev. **C 102**, 034002 (2020)

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S. Gandolfi et al., Phys. Rev. Lett. **118**, 232501 (2017)
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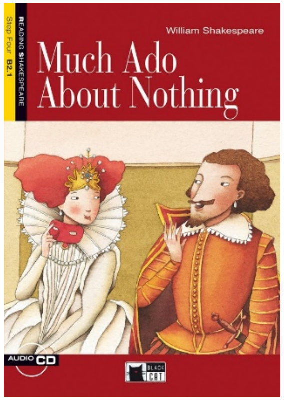

- The most favorable state to form tetraneutron is 0^+
- For trineutrons $3/2^-$ state is found to be the most favorable.

- All the studies agree on:
  - ✓ the dominance of $V_{nn}(^1S_0)$ in multineutron systems.
  - ✓ Minor role of V_{nn} P-waves : moreover $^3PF_2$ is attractive, $^3P_1$ is repulsive, $^3P_0$ is moderate
  - ✓ Negligible contribution of 3nF (3n never gets close to each other)

Theory is ruthless for ^3n & ^4n

^2n is allready resonant in $^1S_0$ state

n-n	AV18	INOY	Reid93	Exp
a_{nn} (fm)	-18.49	-18.60	-17.54	-18.5(4)
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$r(V_{min})$	0.874		0.930	-
γ_s	1.080	1.102	1.087	-

*Enhancement factor $\gamma_s \sim 1.09$ ($V_\gamma = \gamma V_{nn}$) is enough to bind ^2n in $^1S_0$ state

- Special case of physics treated by Effective field theory (EFT) : since $a_{nn} >> r_0$, at low energies this system is insensitive to the details of the interaction and depends solely on a_{nn}
- Now let promote multineutron by making its interaction in $^1S_0$ wave slightly moe attractive, just to bind dineutron with $B=-E=+\varepsilon$ ($a_{nn} = +\infty$), for this case we get universal prediction of EFT:

$a_{ff} \to +\infty$: $a_{ff,ff} = 0.5986(5)\ a_{ff}\ (J=0^+)$

$a_{f,ff} = 1.18\ a_{ff}\ (J=1/2^+)$

$a^3_{f,ff} = -0.952\ a^3_{ff}\ (J=1/2^-, 3/2-)$, ...

D. S. Petrov, C. Salomon, and G. V. Shlyapnikov Phys. Rev. Lett. **93**, 090404
A. Deltuva, Phys. Rev. A **96** (2017) 022701
S. Endo et al., Few-body Syst. **51** (2011) 207
G.V. Skorniakov and K.A. Ter-Martirosian, Zh. Eksp. Teor. Phys. **31** , 775 (1956) [Sov. Phys. JETP **4**, 648 (1957)]

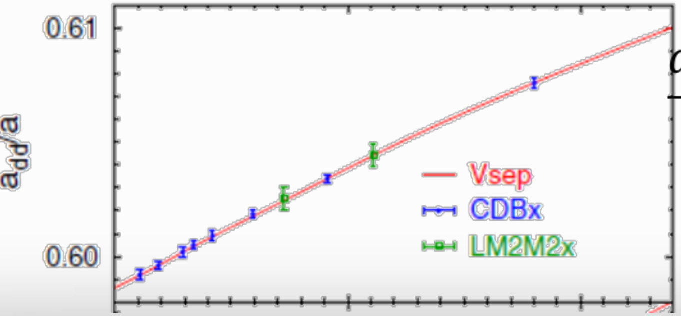
Theory is ruthless for ^3n & ^4n

- Now let promote multineutron by making its interaction in $^1S_0$ wave slightly more attractive, just to bind dineutron with B=-E=+ε ($a_{nn}= +\infty$), for this case we get universal prediction of EFT:

Case	J^π,I	$(a_{n\text{-}nn}/a_{nn})^{2I+1}$		EFT (r_0=0)
n-(nn)	$^1/_2{}^+$,0	$1.19(1)^{\mathrm{INOY}}$	$1.18(1)^{\mathrm{AV18}}$	1.18
	$^1/_2{}^-$,1	$-0.96(1)^{\mathrm{INOY}}$	$-0.95(1)^{\mathrm{AV18}}$	-0.952
	$^3/_2{}^-$,1	$-0.96(1)^{\mathrm{INOY}}$	$-0.95(1)^{\mathrm{AV18}}$	-0.952
(nn)-(nn)	0^+,0	0.599^{CDBonn}		0.5986(5)

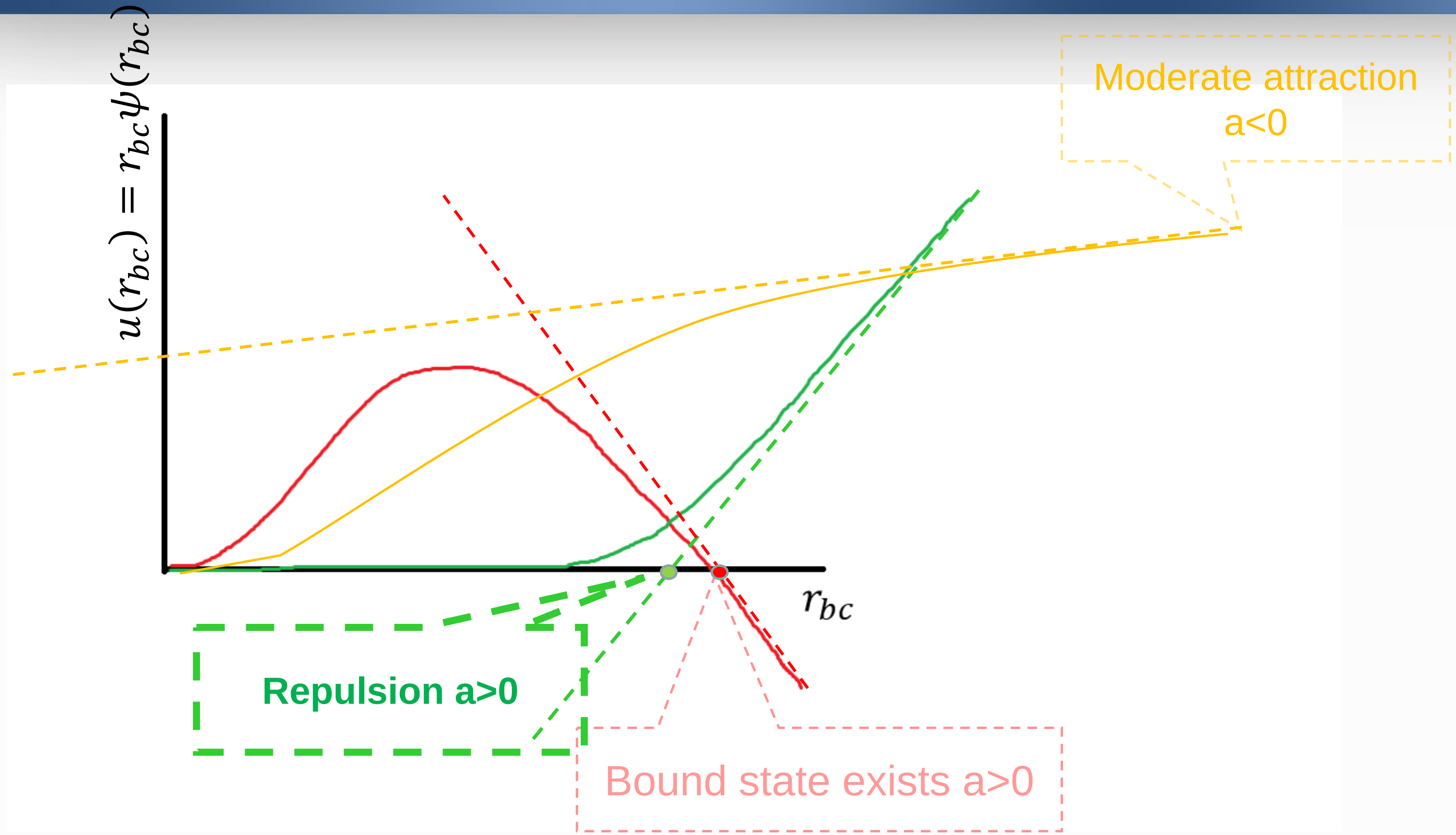
D. S. Petrov et al, Phys. Rev. Lett. **93**, 090404, A. Deltuva, Phys. Rev. A **96** (2017) 022701,
S. Endo et al., Few-body Syst. **51** (2011) 207

A. Deltuva, Phys. Rev. A **96** (2017) 022701



$$\frac{a_{ff,ff}}{a_{ff}} = 0.5986 + 0.105\frac{r_e}{a} \pm 0.0005$$

Theory is ruthless for ^{3}n & ^{4}n



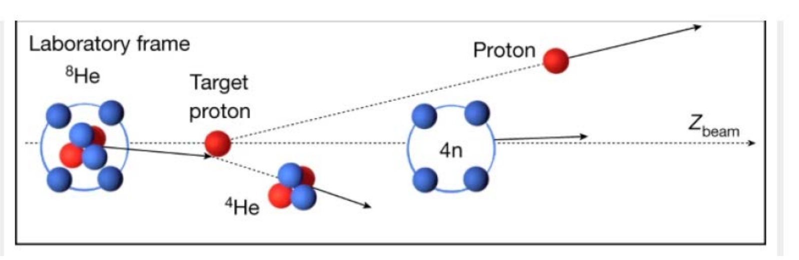
Moderate attraction
a<0

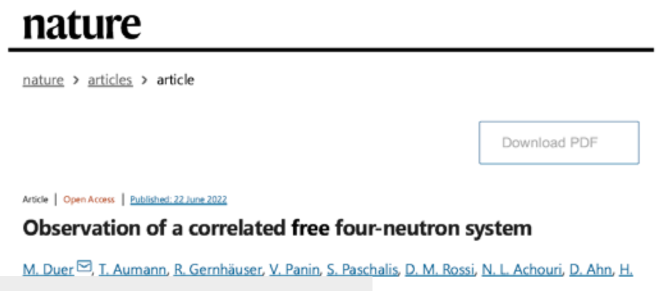
Repulsion a>0

Bound state exists a>0

Presence of ^{3}n & ^{4}n resonant states is not compatible with QM!

Results of Duer et. al.

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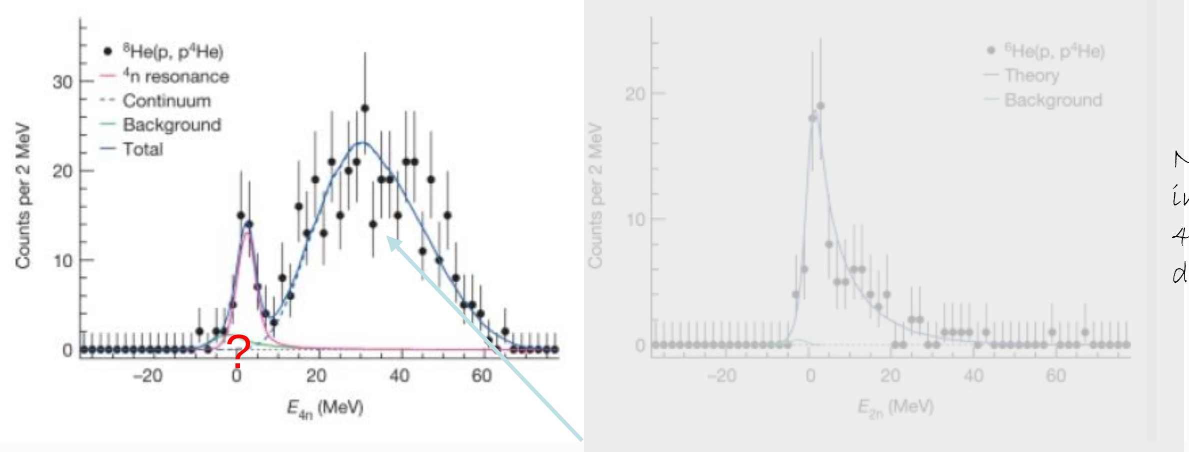
Observation of a correlated free four-neutron system

M. Duer, T. Aumann, R. Gernhäuser, V. Panin, S. Paschalis, D. M. Rossi, N. L. Achouri, D. Ahn, H.

Fig. 3: Missing-mass spectra.



Non-interacting 4n distribution

HO corresponding ^{8}He radius

Right peak is succesfully described using COSMA model of:

V. Grigorenko et al., Eur. Phys. J. **A 19** (2004) 187

$$S(E) = \left|\langle \Psi_f^{4n}(E) \middle| \Psi_i^{4n} \rangle\right|^2$$

How to explain the left peak?

Drawbacks of COSMA

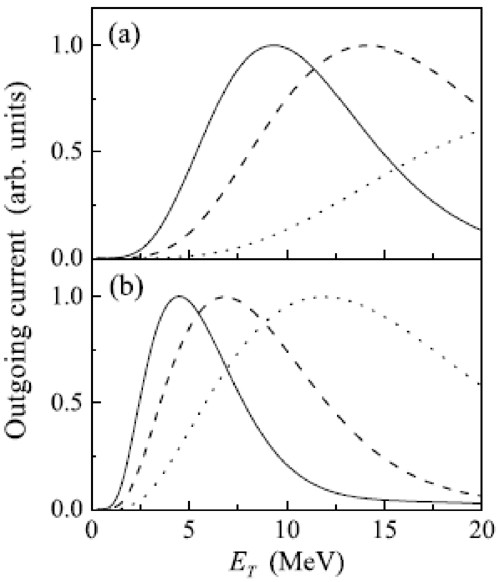
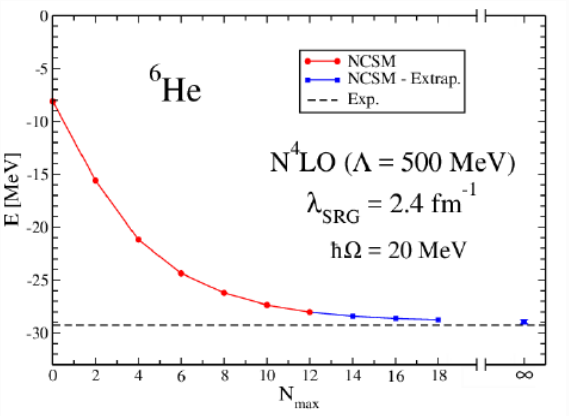
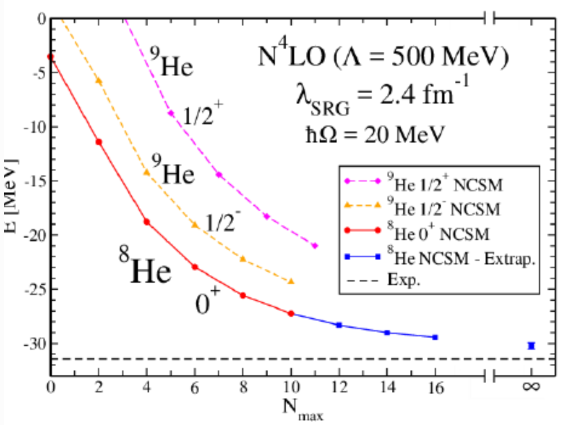


Fig. 11. Continuum response of the ^{4}n system in the MWS with a "Gaussian" source (13). Solid, dashed and dotted curves correspond to rms hyperradius $\langle\rho_{\mathrm{sour}}\rangle$ of the source equal to 8.9, 7.3, and 5.6 fm, respectively. Panels are calculated with (a) no final-state interaction, (b) RT potential (the correct n-n scattering length). All calculations are normalized to unity at the peak.

V. Grigorenko et al., Eur. Phys. J. **A 19** (2004) 187

- Why consider free 4n distribution in the final state? n's are strongly correlated.
- There is no consistency between the final and the initial states of 4n
- ^{8}He wave function is very complex, since valence neutrons are strongly correlated. Lowest HO shell largely fails to account for the complexity of ^{8}He.





M. Vorrabi et al., Phys. Rev. **C 97**, 034314 (2018), //indico.ectstar.eu/event/1/contributions/48/attachments/36/42/Vorabbi.pdf

Model

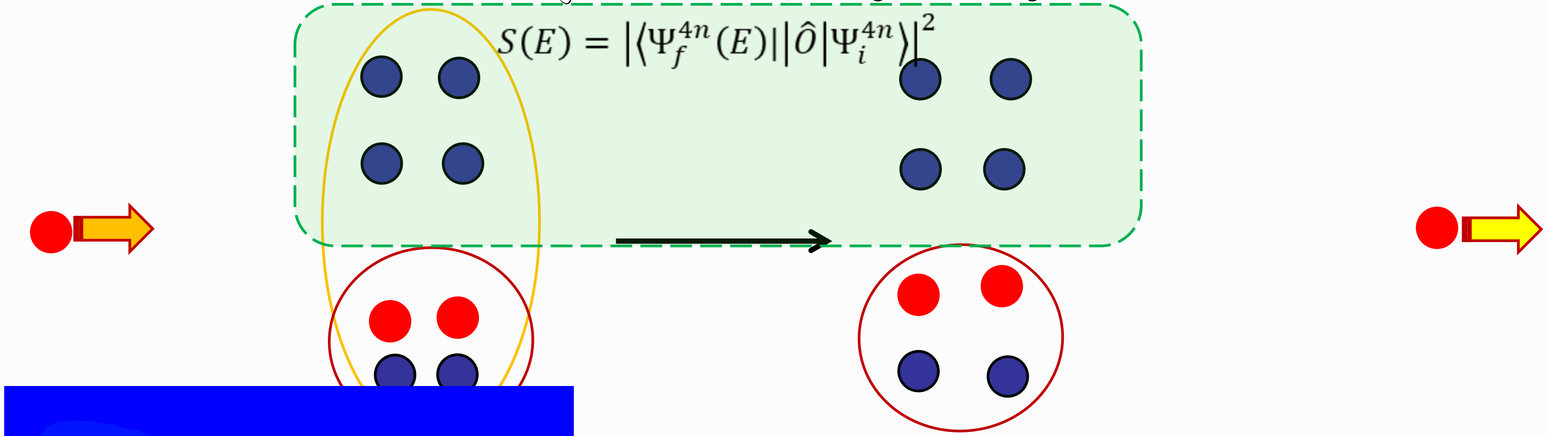
$$H_i = H_0 + \lambda \sum_{i=1}^{N} |\psi_\alpha(r_i)\rangle\langle\psi_\alpha(r_i)| + \sum_{i<j=1}^{N} V_{nn}(r_{ij}) + \sum_{i=1}^{N} V(r_i) + \sum_{i<j=1}^{N} W_{ij}(\rho, r_{ijG}), \quad (1)$$

$$H_i \mid \Psi_i\rangle = E_i \mid \Psi_i\rangle.$$

$$H_f = H_0 + \sum_{i<j=1}^{4} V_{nn}(r_{ij}).$$

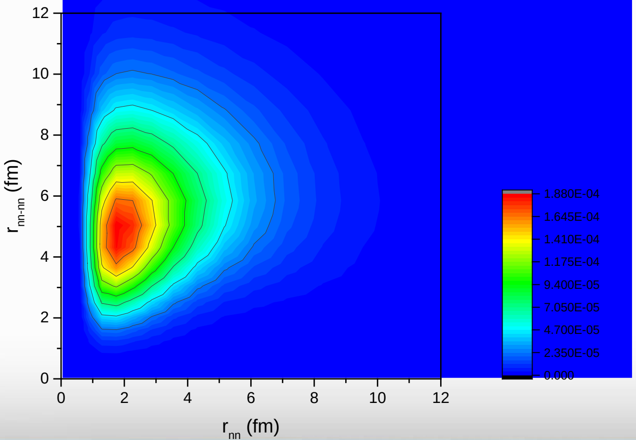
$$H_f|\Psi_f\rangle = E_{4n}|\Psi_f\rangle.$$

Action of ⁴He mean field on valence n's, adjusted to ⁶He & ⁸He gs binding



$$S(E) = |\langle\Psi_f^{4n}(E)||\hat{O}|\Psi_i^{4n}\rangle|^2$$

⁴He



Technology

- FY equations & CS method

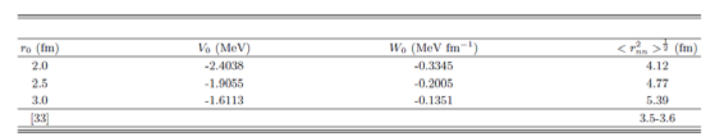
Numerical solution:

- PW expansion & Lagrange –mesh method

RL, J. Carbonell, E. Hiyama

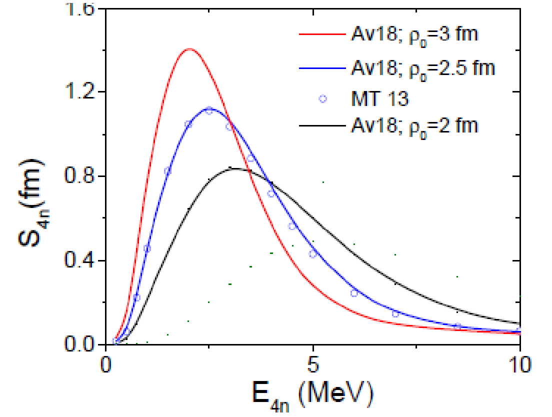
Low energy peak is well reproduced without any ^{4}n resonance

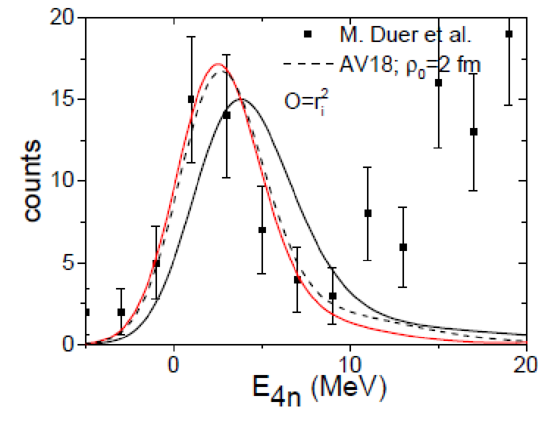
No forbidden states:



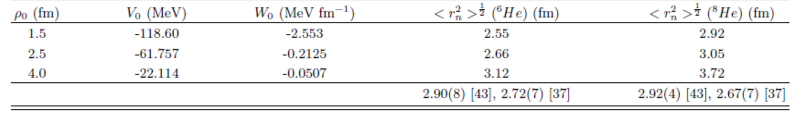
r_0 (fm)	V_0 (MeV)	W_0 (MeV fm^{-1})	$< r_{nn}^2 >^{\frac{1}{2}}$ (fm)
2.0	-2.4038	-0.3345	4.12
2.5	-1.9055	-0.2005	4.77
3.0	-1.6113	-0.1351	5.39
[33]			3.5-3.6

TABLE I: Strength parameters of the phenomenological α-core neutron interactions (described in section II) as a function of interaction range r_0, adjusted to reproduce binding of neutron halos in ^{6}He and ^{8}He nuclei. In the last column calculated halo neutron radii in ^{8}He are presented and compared with an estimation from *ab-initio* calculation of ref. [33] using expression of eq. (9).





With Pauli blocking of HO states:



ρ_0 (fm)	V_0 (MeV)	W_0 (MeV fm^{-1})	$< r_n^2 >^{\frac{1}{2}}$ (^6He) (fm)	$< r_n^2 >^{\frac{1}{2}}$ (^8He) (fm)
1.5	-118.60	-2.553	2.55	2.92
2.5	-61.757	-0.2125	2.66	3.05
4.0	-22.114	-0.0507	3.12	3.72
			2.90(8) [43], 2.72(7) [37]	2.92(4) [43], 2.67(7) [37]

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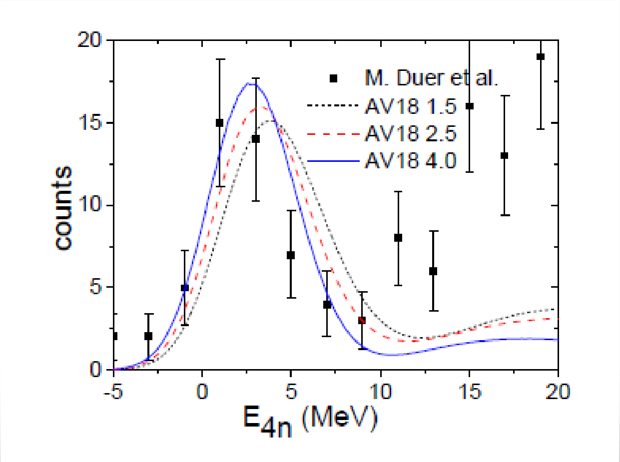
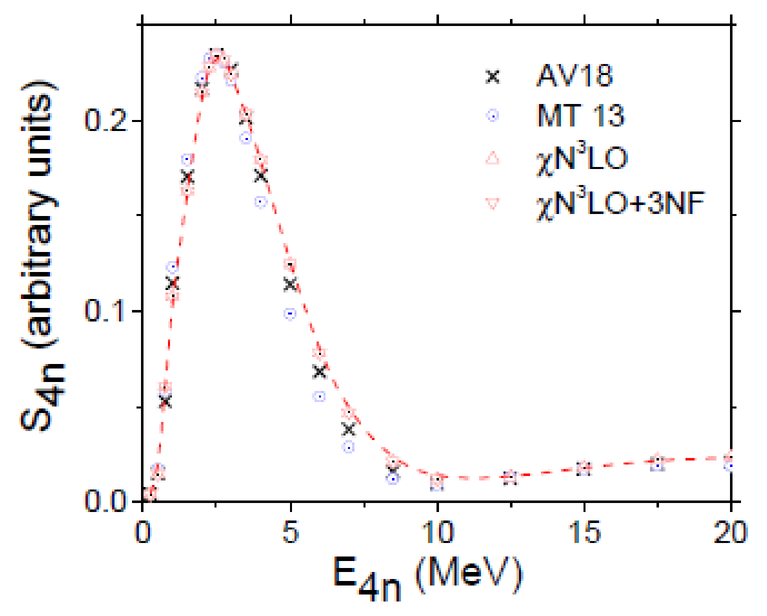


Independence of nn interaction

- Low energy response does not depend on the details of nn(n) interaction, only a_{nn}!
- Consistent with EFT arguments



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Importance of 2n+2n correlations

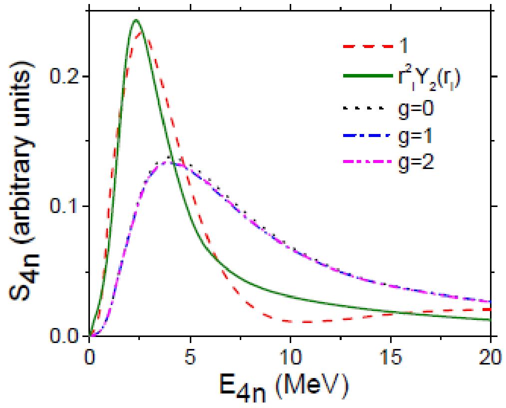

FIG. 2: Low energy four-neutron response functions calculated with the AV18 nn interaction and ρ_0=2.5 fm. Different transition operators $\hat{O}$ were considered in order to visualize the effect of the core-recoil corrections. The olive-dashed curve corresponds $\hat{O} = \sum_i^4 r_i^2 Y_2(\hat{r}_i)$; red-dotted together with the dashed-dotted curves are for $\hat{O} = \sum_i \{\vec{r}_i \otimes \vec{\sigma}_i\}_g$ operators, solid-black curve represents the reference result with $\hat{O}$=1.

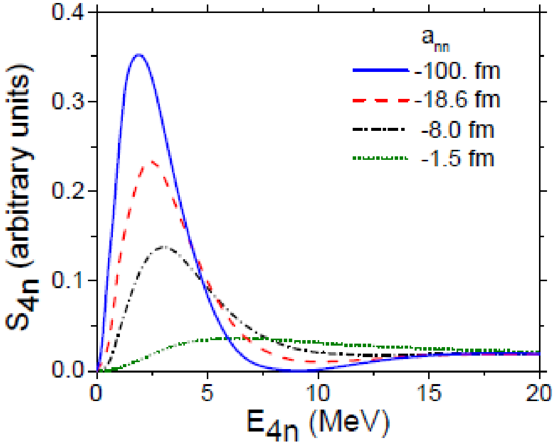

FIG. 3: Low energy four-neutron response functions for the scaled nn MT13 potential adjusted to reproduce different scattering lengths values.

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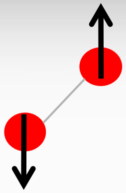
Bound multineutron: no way?

^2n is allready resonant in $^1S_0$ state

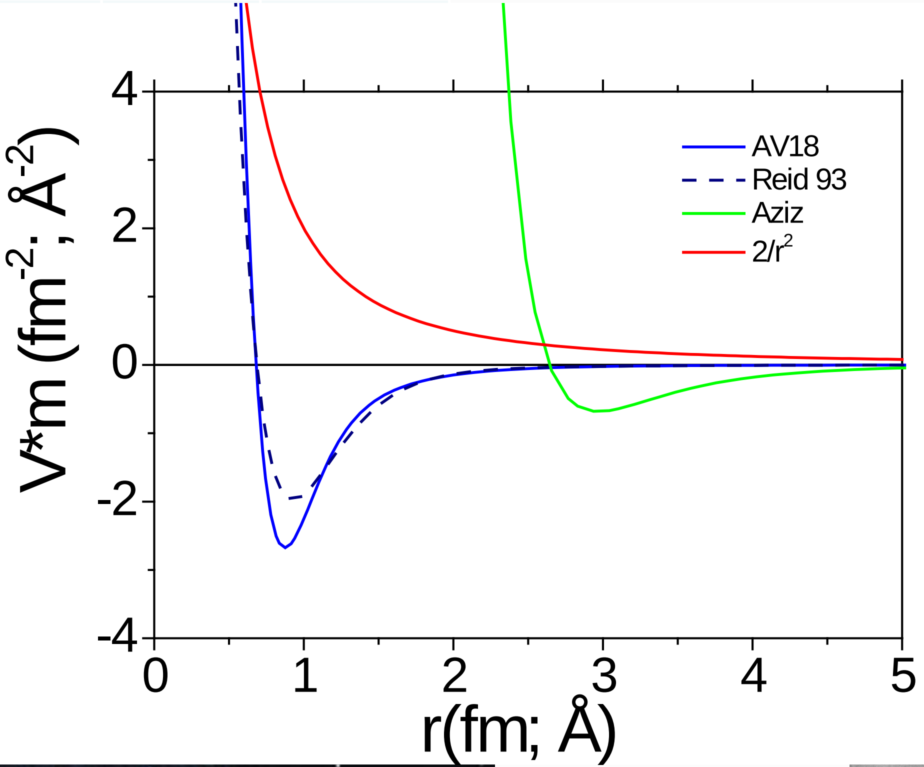
n-n	AV18	INOY	Reid93	Exp
a_{nn} (fm)	-18.49	-18.60	-17.54	-18.5(4)
r_0 (fm)	2.84			
$r(V_{min})$	0.874			
γ_s	1.080			

*Enhancement facto

state



^{3}He-^{3}He	Aziz
a (Å)	-7.61
r_0 (Å)	13.5
$r(V_{min})$	2.97
γ_s	1.299



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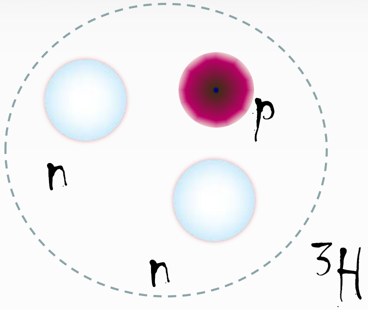
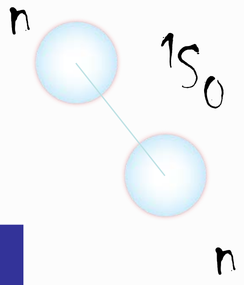
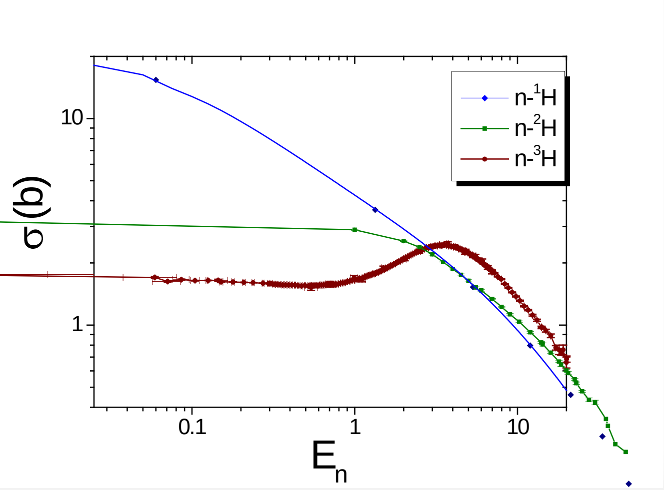
at 1mK

H isotopes

n	H	E (MeV)
1	^{2}H	-2.22
2	^{3}H	-8.48
3	^{3}H+n	Broad resonant states
4-..	$^{5-}$H	?







$J^\pi(^4H)$	$E(^4H)-E(^3H)$ (MeV)
2^-	1.2-2.0i
1^-	1.0-2..0i
0^-	0.8-4.1i
1^-	0.2-2.5i

^{5}H case

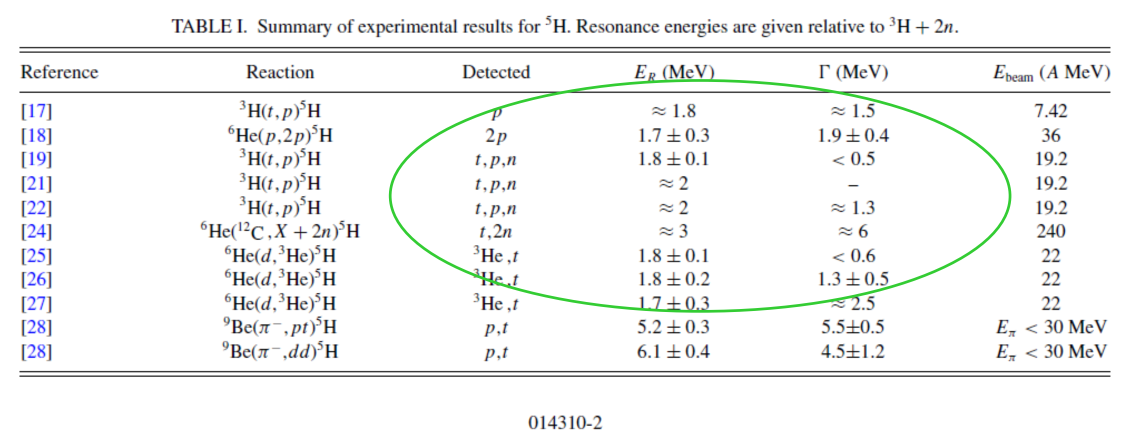


TABLE I. Summary of experimental results for ^{5}H. Resonance energies are given relative to ^{3}H + 2n.

Reference	Reaction	Detected	E_R (MeV)	Γ (MeV)	E_{beam} (A MeV)
[17]	^{3}H$(t,p)^5$H	p	≈ 1.8	≈ 1.5	7.42
[18]	^{6}He$(p,2p)^5$H	$2p$	1.7 ± 0.3	1.9 ± 0.4	36
[19]	^{3}H$(t,p)^5$H	t,p,n	1.8 ± 0.1	< 0.5	19.2
[21]	^{3}H$(t,p)^5$H	t,p,n	≈ 2	–	19.2
[22]	^{3}H$(t,p)^5$H	t,p,n	≈ 2	≈ 1.3	19.2
[24]	^{6}He$(^{12}$C$,X+2n)^5$H	$t,2n$	≈ 3	≈ 6	240
[25]	^{6}He$(d,^3$He$)^5$H	^{3}He$,t$	1.8 ± 0.1	< 0.6	22
[26]	^{6}He$(d,^3$He$)^5$H	^{3}He$,t$	1.8 ± 0.2	1.3 ± 0.5	22
[27]	^{6}He$(d,^3$He$)^5$H	^{3}He$,t$	1.7 ± 0.3	≈ 2.5	22
[28]	^{9}Be$(\pi^-,pt)^5$H	p,t	5.2 ± 0.3	5.5 ± 0.5	$E_\pi < 30$ MeV
[28]	^{9}Be$(\pi^-,dd)^5$H	p,t	6.1 ± 0.4	4.5 ± 1.2	$E_\pi < 30$ MeV

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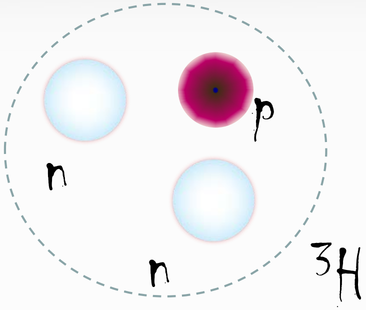

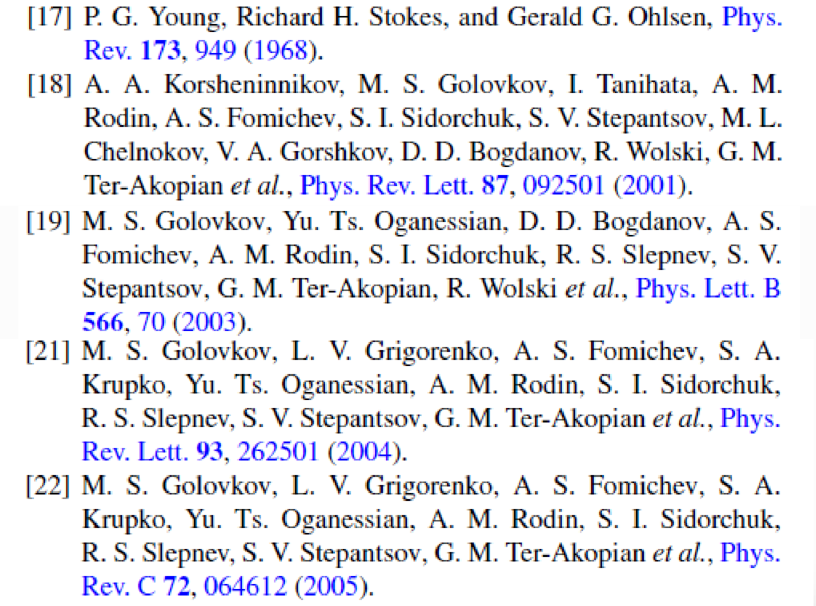

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^{5}H case

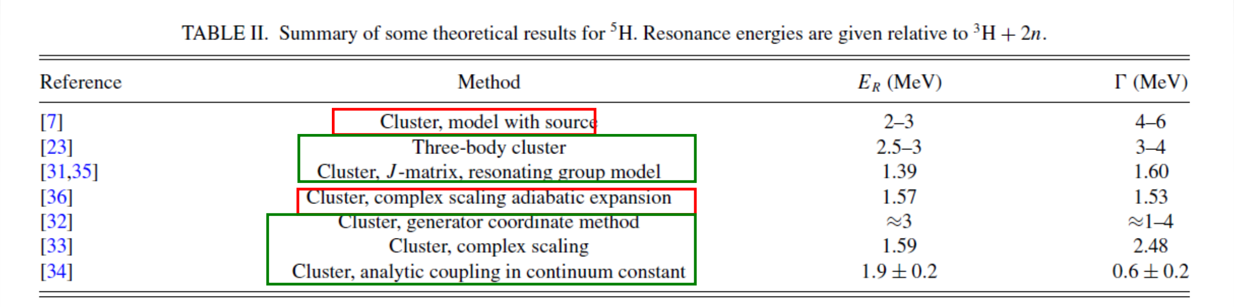
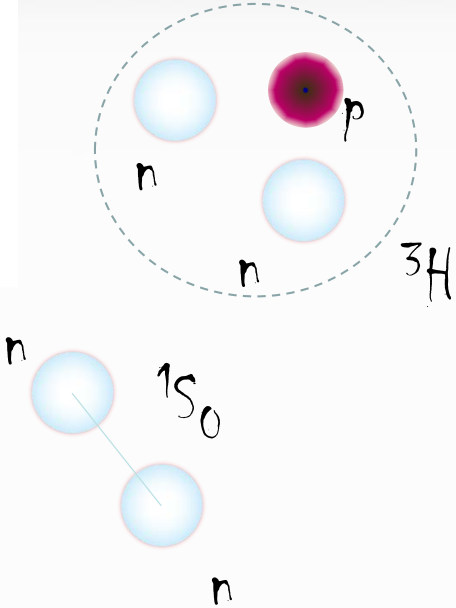


TABLE II. Summary of some theoretical results for ^{5}H. Resonance energies are given relative to ^{3}H + 2n.

Reference	Method	E_R (MeV)	Γ (MeV)
[7]	Cluster, model with source	2–3	4–6
[23]	Three-body cluster	2.5–3	3–4
[31,35]	Cluster, J-matrix, resonating group model	1.39	1.60
[36]	Cluster, complex scaling adiabatic expansion	1.57	1.53
[32]	Cluster, generator coordinate method	≈3	≈1–4
[33]	Cluster, complex scaling	1.59	2.48
[34]	Cluster, analytic coupling in continuum constant	1.9 ± 0.2	0.6 ± 0.2



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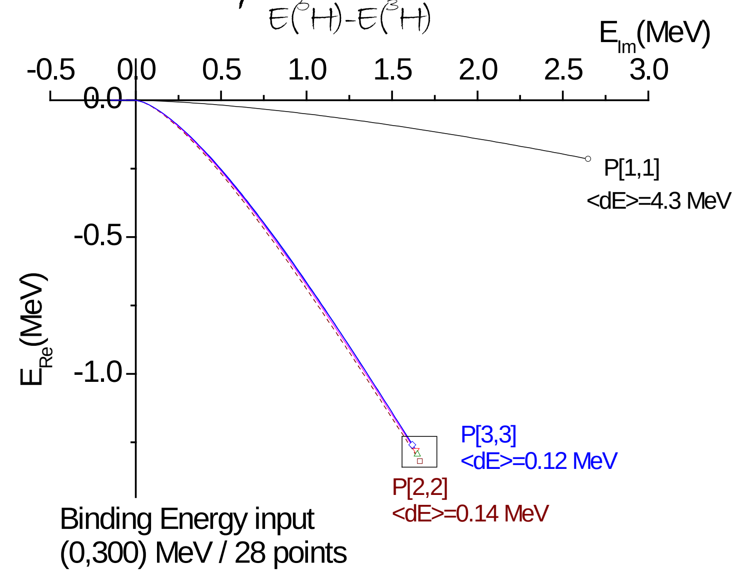
Cluster models, involvig approximations for 5-body dynamics

- ^{3}H+n+n models: without n-antisymetrization between the core &valence
- ^{3}H+n+n models: including n-antisymmetrization, however by freezing ^{3}H core

^{5}H case

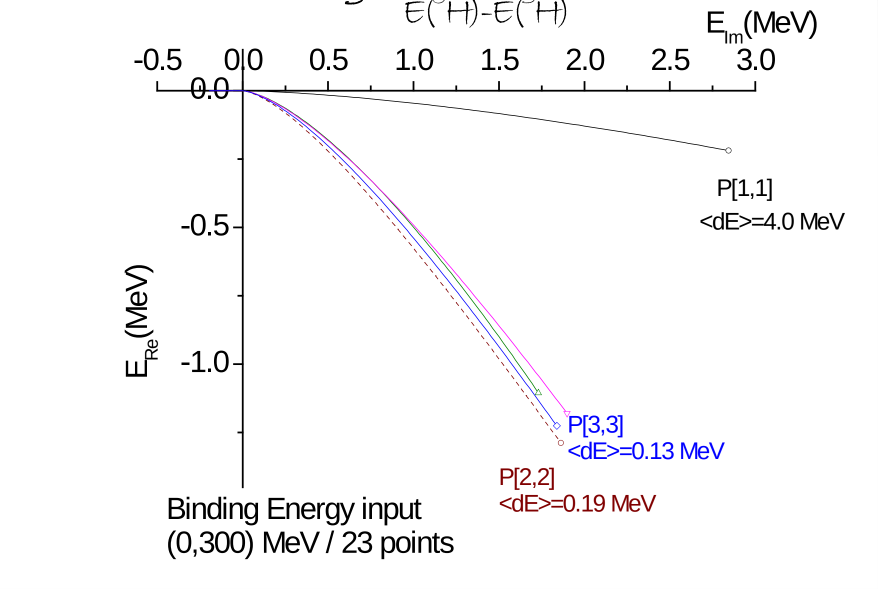
INOY Potential



$E(^5H)-E(^3H)=1.65(5)-i1.26(6)$

SECSM: $1.8(1)-i1.2(1)$

N_3LO Potential



$E(^5H)-E(^3H)=1.8(1)-i1.15(15)$

SECSM: $1.85(10)-i1.20(5)$

To compare with ^{4}H resonances $J=2^-$:

$E(^4H)-E(^3H)=1.31(3)-2.08(2)$

$E(^4H)-E(^3H)=1.17(3)-1.99(3)$

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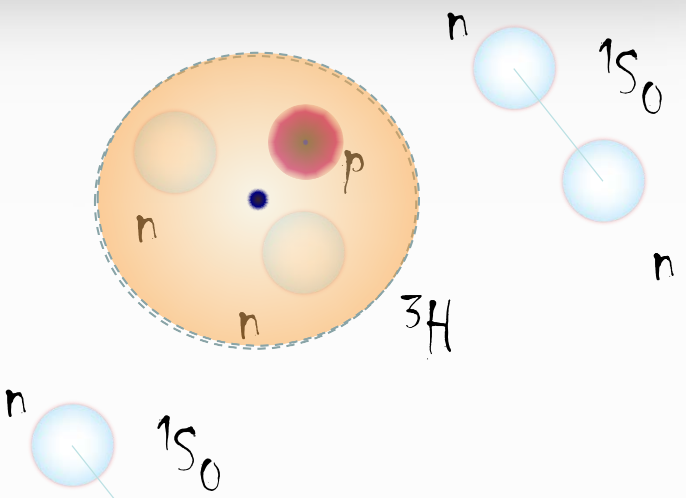
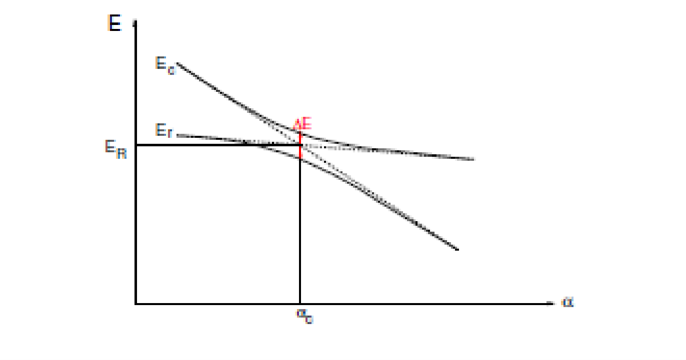
^{7}H case

5-body cluster model $4n+^3$H:

- Pauli blocking between valence neutrons & ones within 3H core mimicked by projecting out forbidden HO states
- n-^{3}H potential adjusted to n-^{3}H scattering
- Gaussian expansion method to solve bound state problem & stabilization technique to estimate resonance position





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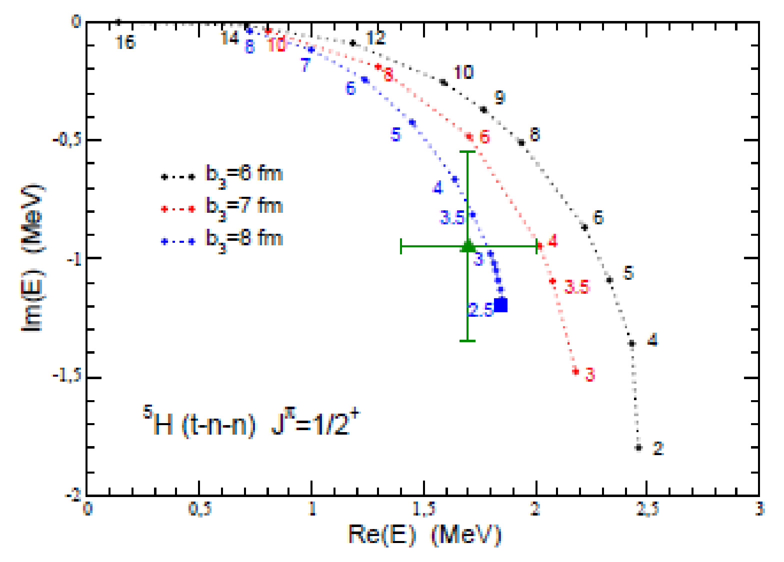

In conflict with:
H.H. Li et al., Phys.Rev.C 104 (2021) 6, L061306

Conclusions

- Presence of 3n and 4n resonant states is not compatible with QM
- Very striking dynamical phenomena was observed by Duer et al., where sharp low-energy peak appears naturally without any underlying ^{4}n resonant state
- Presence of the peak is independent of nn/3n interaction and is consequence of weakly bound 4n being in the initial state (halo nucleus), enhancing 2n+2n structures
- Effect should manifest in similar atomic or nuclear systems: 4n Halo nuclei are priviledged place to look for.
- We confirm existence of a pronounced resonant state in ^{5}H. However we do not expect to find narrow resonances in heavier hydrogen isotopes.