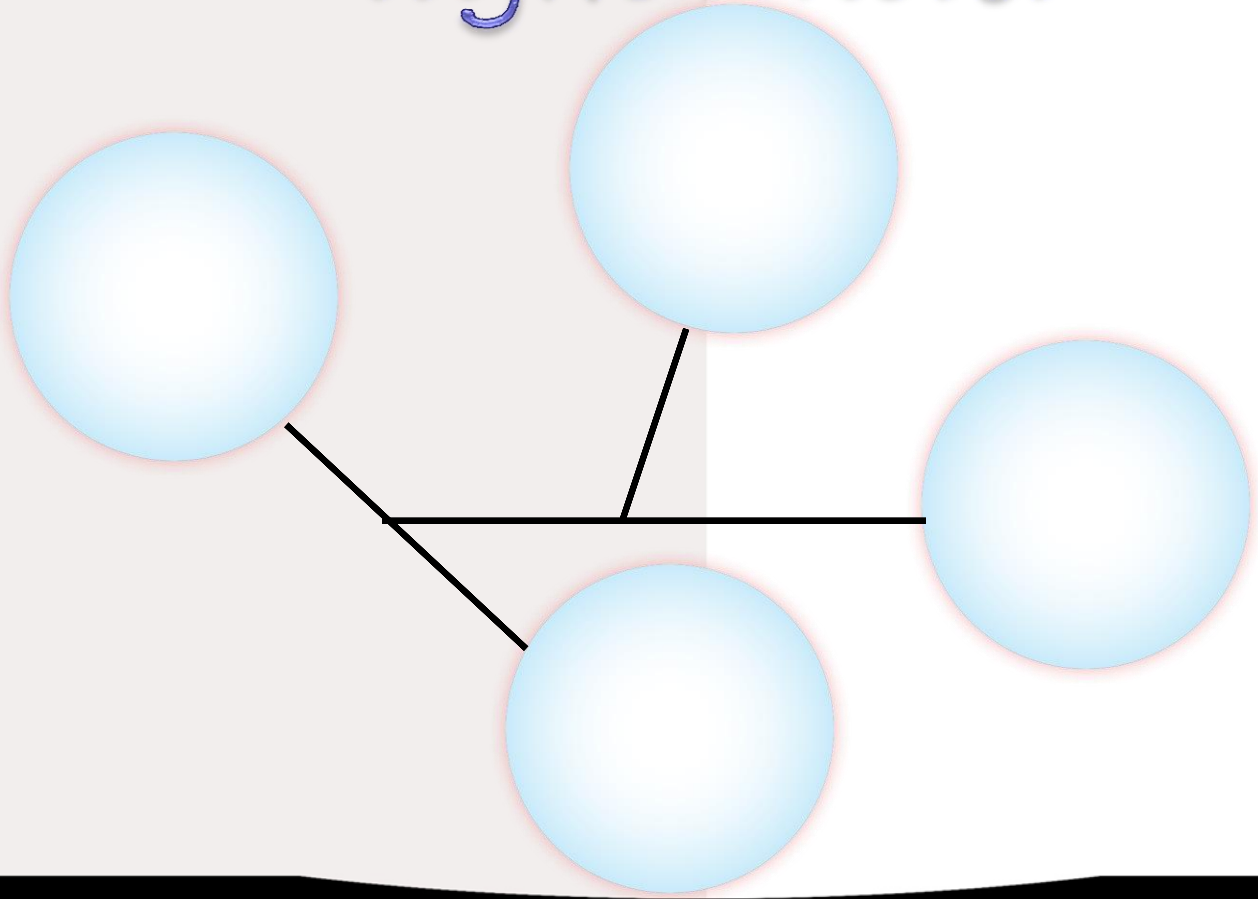
Description of neutron-rich light nuclei



J. Carbonell (IPNO), E. Hiyama & M. Kamimura (Riken), R. L.

^{4}n experiment

As searching for Bigfoot (Hibagon): even though nobody have proved its existence, it does not prove contrary.

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)

- $^4He(\gamma, 2\pi^+)^4n$
- $^4He(\pi^-, \pi^+)^4n$

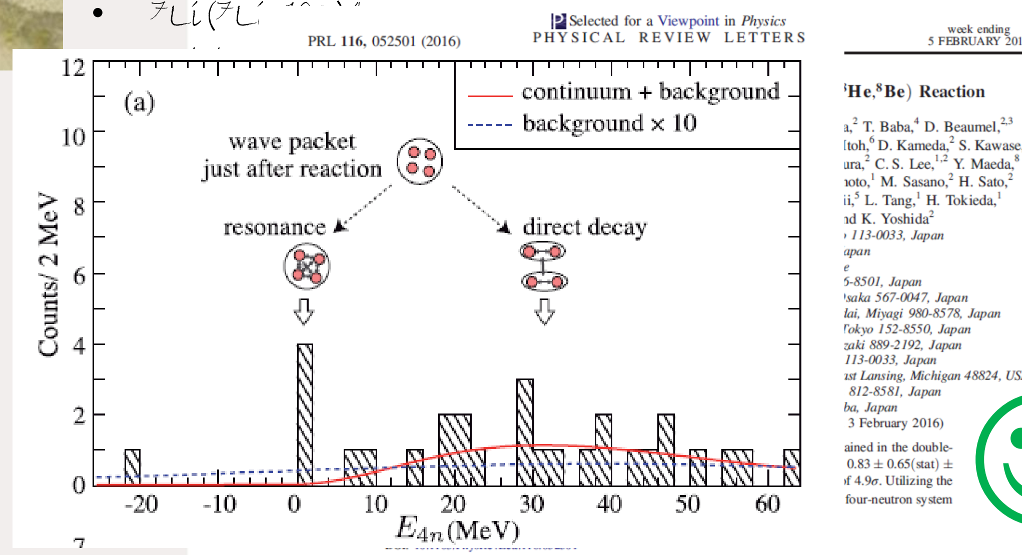
T. P. Gorringe et al., Phys. Rev. C 40, 2390

- $^7Li(\pi^-, {}^3He)^4n$

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

- $^7Li(^7L$

$^{14}Be \rightarrow {}^{10}Be + {}^4n$: 6 events consistent with bound or resonant
F.M. Marqués et al: Phys. Rev. C 65 (2002) 044006 et arxiv:nucl-ex/0504009



$^4He(^8He, {}^8Be)^4n$:
K. Kisamori et al., Phys. Rev. Lett. 116 (2016) 052501

J. Carbonell (IPNO), E. Hiyama & M. Kamimura (Riken), R. L.

^{4}n to be or not to be?

- ^{2}n is allready resonant in $^1S_0$ state

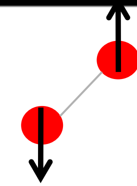
n-n	AV18	INOY	Reid93	Exp
a_{nn} (fm)	-18.49	-18.60	-17.54	-18.5(4)
r_0 (fm)	2.84	2.82	2.84	2.80(11)
$r(V_{min})$	0.874		0.930	-
γ_s	1.080	1.102	1.087	-

- Enhancement factor $\gamma_s \sim 1.09$ ($V_\gamma = \gamma V_{nn}$) is enough to bind ^{2}n in $^1S_0$ state
- **Pauli principle pre... from binding! At t...**

$a_{ff} \rightarrow +\infty$: a...

a...

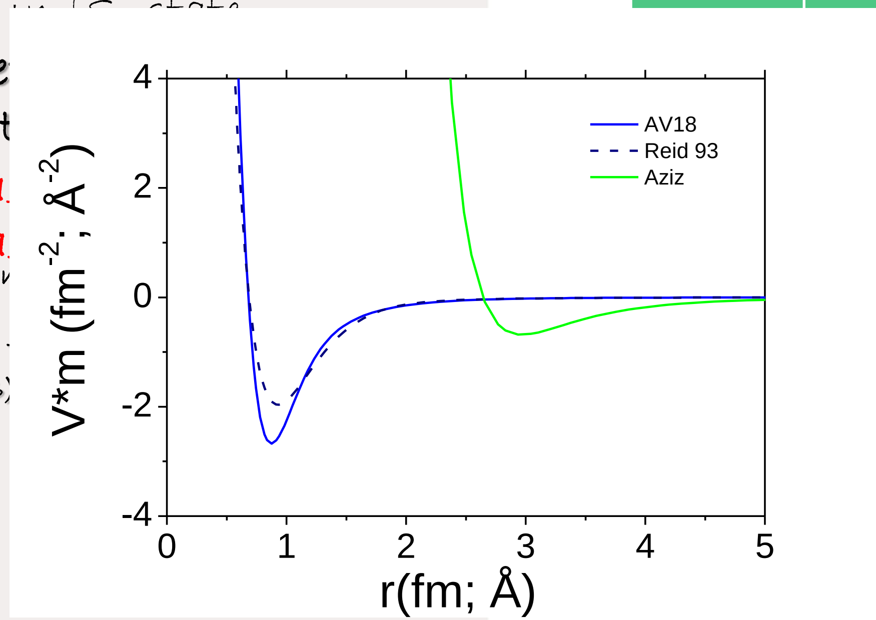
D. S. Petrov, C. Salomon, a... Lett. 93, 090404
G.V. Skorniakov and K.A. ... Teor. Phys. 31, 775 (1956)



- $(^3He)_N$ is bound for N>34

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

^{3}He-^{3}He	Aziz
a (Å)	-7.61
	...5
	...z
	...9



J. Carbonell (IPNO), E. Hiyama & M. Kamimura (Riken), R. L.

✓ Not-bound (almost in unison)

S. Pieper, PRL 90(2003):252501

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

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

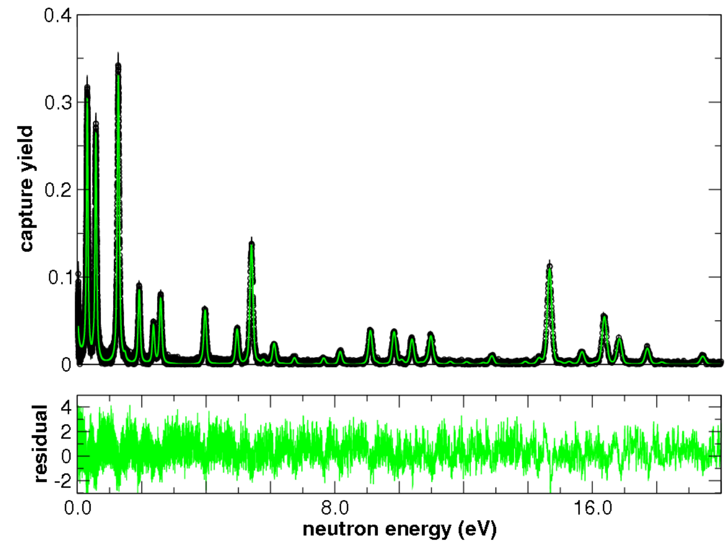
R.L., PhD thesis Université Joseph Fourrier (2003)

✓ Is Resonant ???

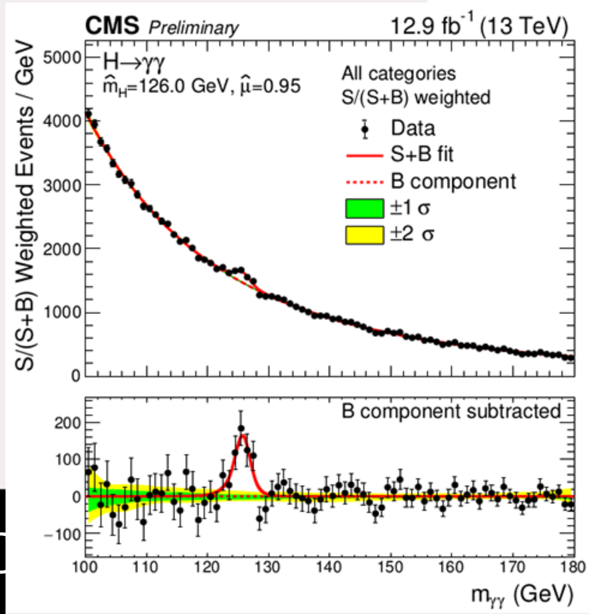
What is resonance?

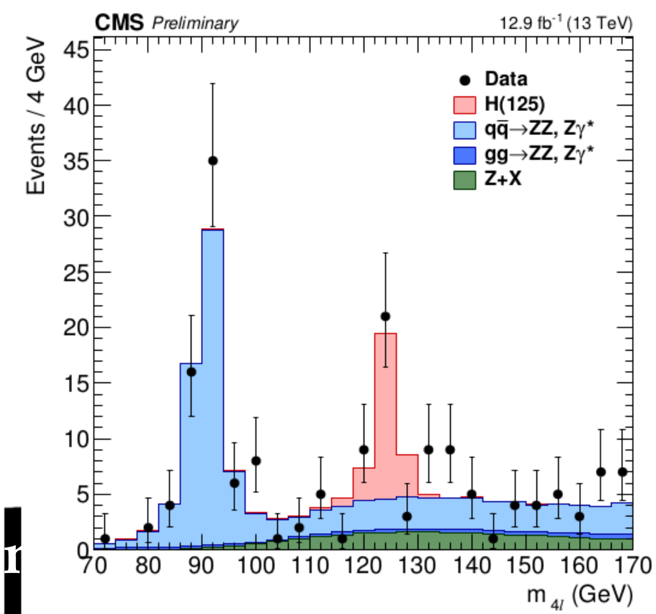
In physics, **resonance** is a phenomenon in which a vibrating system or external force drives another system to oscillate with greater amplitude at a specific preferential frequency.

Some are spectacular… $n+{}^{241}Am$ at nTOF (CERN)



Others get Nobel prize… CMS





- Simplistic NN interactions
- Realistic NN interactions

✓ Not-bound (almost in unison)

S. Pieper, PRL 90(200 3):252501

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

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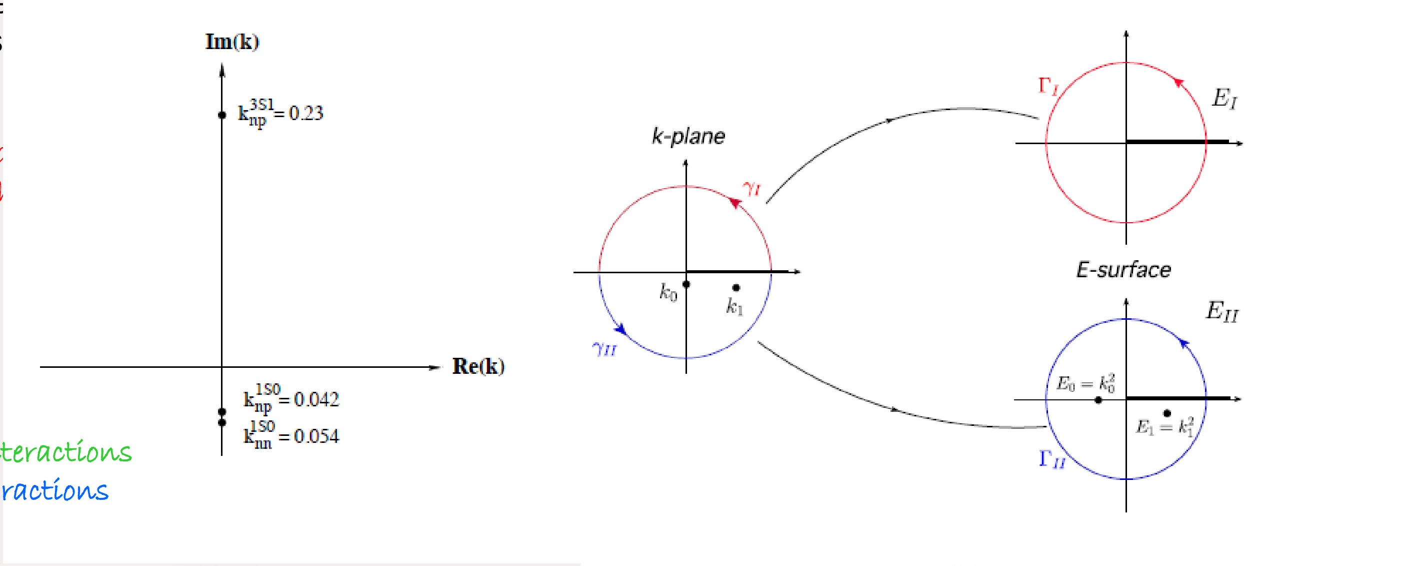
a. S-matrix pole.. One ca
Physical poles, non-ph



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S. Pieper, PRL 90(200 3):252501

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)

✓ Is Resonant ???

What is resonance?

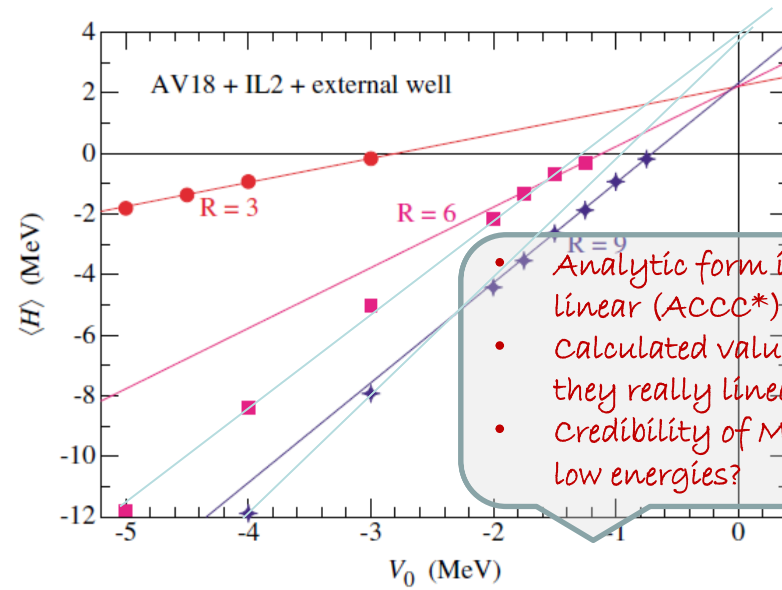
a. S-matrix pole.. One can always find some S-matrix poles. Physical poles, non-physical little shaky, but we are used to it..

S. Pieper, Phys. Rev. Lett. 90(2003):252501

S. Gandolfi et al., arXiv:1612.01502 –realistic interaction

M. Shirokov et al., Phys. Rev. Lett. 117, 182502 (2016) – questionable models and stability of the rsults!!!

- Simplistic NN interactions
- Realistic NN interactions



- Analytic form is not linear (ACCC*)!
- Calculated values, are they really linear?
- Credibility of MC at low energies?

“This suggests that there might be a ^4n resonance near 2 MeV, but since the GFMC calculation with no external well shows no indication of stabilizing at that energy, the resonance, if it exists at all, must be very broad.”

*ACCC: Analytic Continuation in the coupling constant
V. I. Kukulin, V. M. Krasnopol’sky, J. Horáček : “Theory of Resonances_ Principles and Applications”

✓ Not-bound (almost in unison)

S. Pieper, PRL 90(25 Pt 1):252501

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)

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No observable ^3n resonances:

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)

No observable ^4n resonances:

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

Arai. K, Phys. Rev. C 68 (2003): 034303

R.L et al., Phys. Rev. C 93, 044004 (2016) , Phys. Rev. C 72, 034003 (2005)

- Simplistic NN interactions
- Realistic NN interactions

J. Carbonell (IPNO), E. Hiyama & M. Kamimura (Riken), R. L.

Theoretical tools

R. L. & Jaume Carbonell

- ✓ Faddeev-Yakubovsky equations in configuration space

Emiko Hiyama & Masayasu Kamimura

- ✓ Gaussian expansion method

Solution technique

- ✓ FY equations in configuration space
- ✓ Schrodinger equation
- ✓ Partial-wave expansion in angular momentum, spin, isospin
- ✓ Expansion in Lagrange-mesh basis

D. Baye, Physics Reports 565 (2015) 1

- ✓ Expansion in Gaussians with ranges in geometric progression

M. Kamimura, Phys. Rev. A 38, 621 (1988); E. Hiyama et al., Progress in Particle and Nuclear Physics 51 (2003) 223

- ✓ CS method for resonances

J. Nuttal and H. L. Cohen, Phys. Rev. ***188*** *(1969) 1542*
T. Myo, Y. Kikuchi et al.: Prog. Part. Nucl. Phys. 79 (2014) 1

☺ Well-adapted for the scattering process

☹ Non-variational, slow convergence

- ✓ Iterative linear algebra methods

Matrix size ~10^7

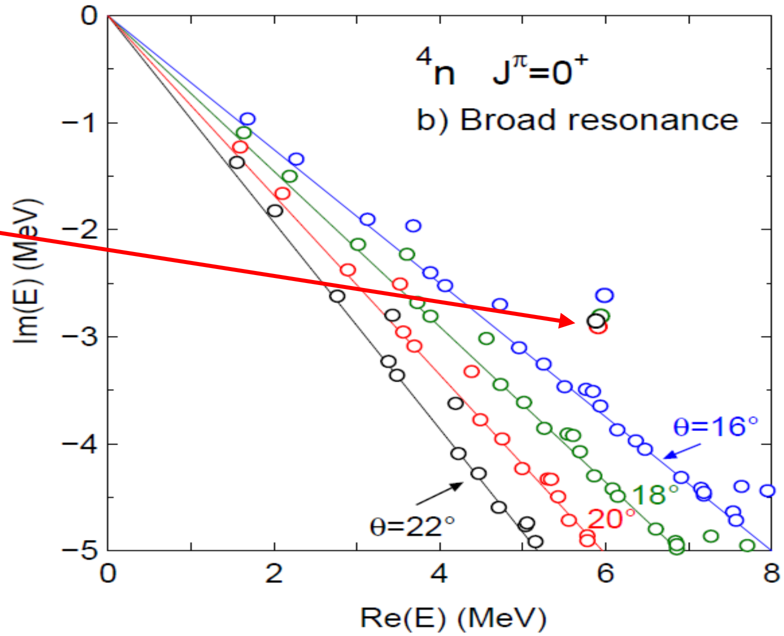
- ✓ Full matrix diagonalisation,

Matrix size ~10 000

E. H. and M.K. technique due to diagonalisation of full matrix allows to identify also resonances in a vicinity of real-E axis, which does not necessarily evolve from b.s.
But we have not observed such!

Within CS method and according Balslev and Combes thorem. 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.

E. Balslev and J. M. Combes, Commun. Math. Phys 22, 1971, 280



How to favorize ^{A}n, maybe something missing?

NN interactions are not perfect, in particular nn part!

- nn S-wave ... (results at un ... ne nuclear data.
- nn P-waves ...

1. If one boos ... nt (bound)
2. If one boos ... . However boost factor to ... $\gamma_P \sim$ ... tering.

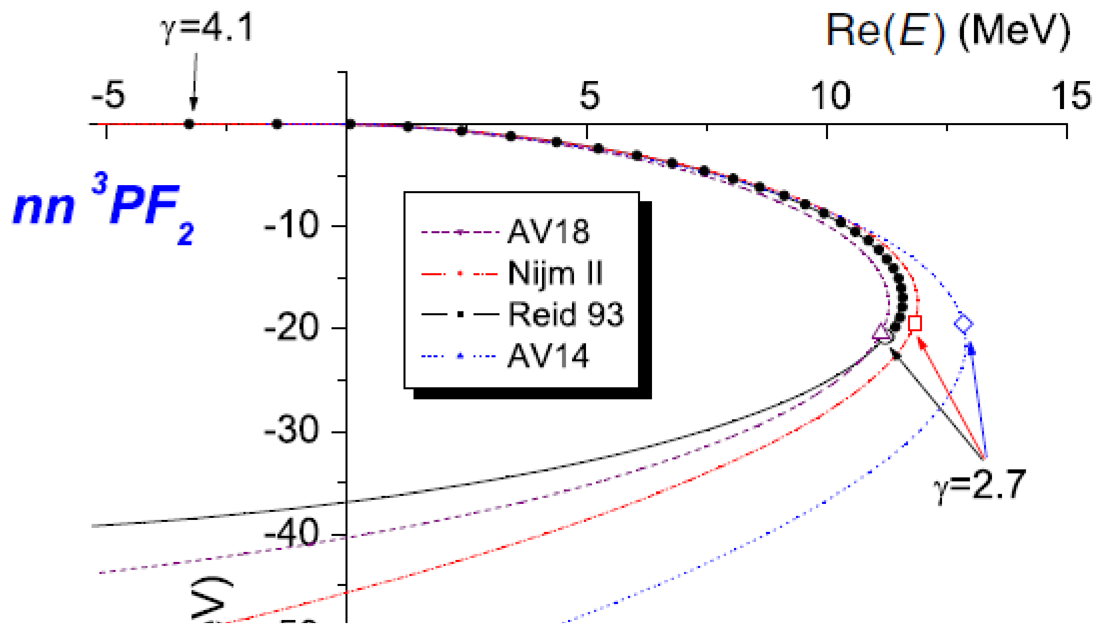


TABLE III. Enhancement factor values (γ_c') at which dineutron resonances become subthreshold ($\varepsilon_{res} = 0$), and imaginary energy values Im $(E)(\gamma_c')$ at this point (MeV). Resonance energy E_{res} for physical *nn* interaction (i.e., at $\gamma = 1$) obtained using ACCC method.

	$^3P_0$				$^3PF_2$			
	Nijm II	Reid 93	AV14	AV18	Nijm II	Reid 93	AV14	AV18
γ_c'	2.27	2.26	2.08	2.24	1.64	1.71	1.46	1.73
Im $(E)(\gamma_c')$	−10.2	−10.3	−10.6	−10.2	−45.6	−36.9	−56.2	−40.3
$E_{res}(\gamma = 1)$	$-14.1-17.2i$	$-14.2-18.5i$	$-10.3-18.1i$	$-12.1-18.0i$	$-20.5-64.8i$	$-15.9-39.9i$	$-17.9-80.1i$	$-34.1-45.4i$

J. Carbonell (IPNO), E. Hiyama & M. Kamimura (Riken), R. L.

How to favorize ^3n, maybe something missing?

NN interacti

- nn S-waves
(results at unit

the nuclear data.

- nn P-waves:
1. If one boost
2. If one boost

boost factor to h

$\gamma_P \sim 1.$

ant (bound)

^4n. However

attering.

TABLE IV.
nn channel to
$J^\pi = 2^-$ dineu

$\gamma_c(^3n)$
$E(^2n)$ MeV

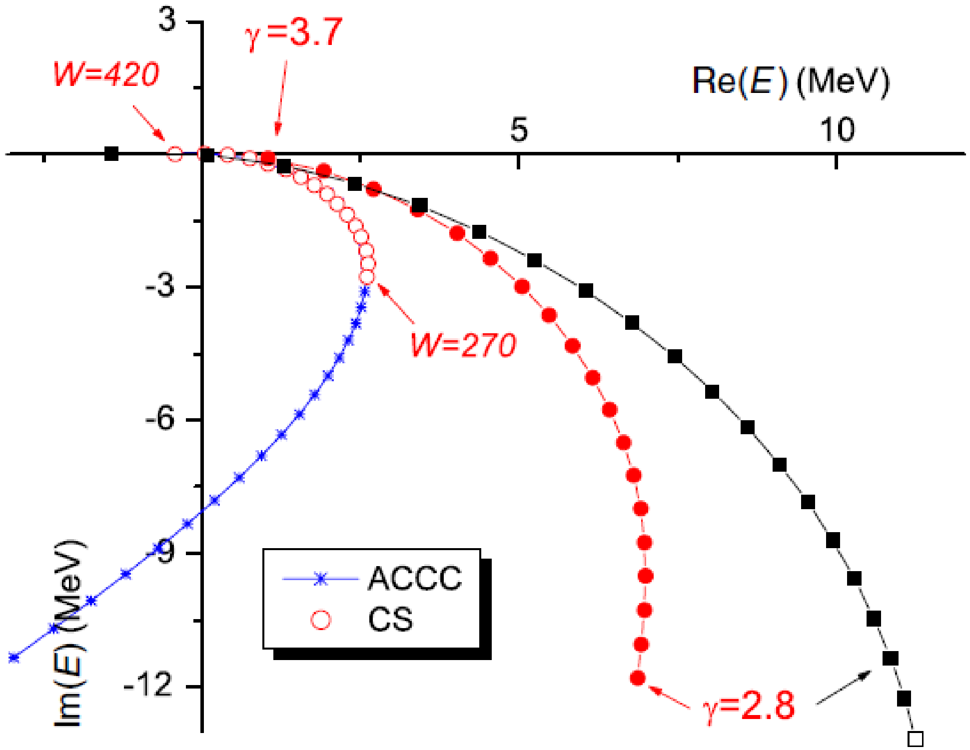


FIG. 6. (Color online) $J^\pi = 3/2^-$ three-neutron state resonance trajectory obtained when reducing the strength W of phenomenological Yukawa-type force (open circles for CS and solid line+star points for ACCC methods). The trajectory depicted by full circles represents one obtained using CS, when reducing enhancement factor γ for $^3P_2$–$^3F_2$ *nn* interaction. The trajectory depicted by full squares is the dineutron resonance path in the $^3P_2$–$^3F_2$ channel, obtained by enhancing *nn* interaction in these waves. Presented results are based on the Reid 93 model.

How to favorize ^4n, maybe something missing?

NN interactions are not perfect, in particular nn part!

- nn **S-waves** can not render dineutron pairs attractive

(results at unitarity limit!!). Moreover they are the most constrained by the nuclear data.

- nn **P-waves**: ($^3PF_2$ attractive, $^3P_0$ is moderate, $^3P_1$ is very repulsive)

1. If one boost all the P-waves 'democratically'. Dineutron becomes resonant (bound)
2. If one boost only attractive P-waves, one may get bound or resonant ^4n. However

boost factor to have reasonably resonant ^4n should be γ ~3!!!

γ_P~1.1 is ... nuclear scattering.

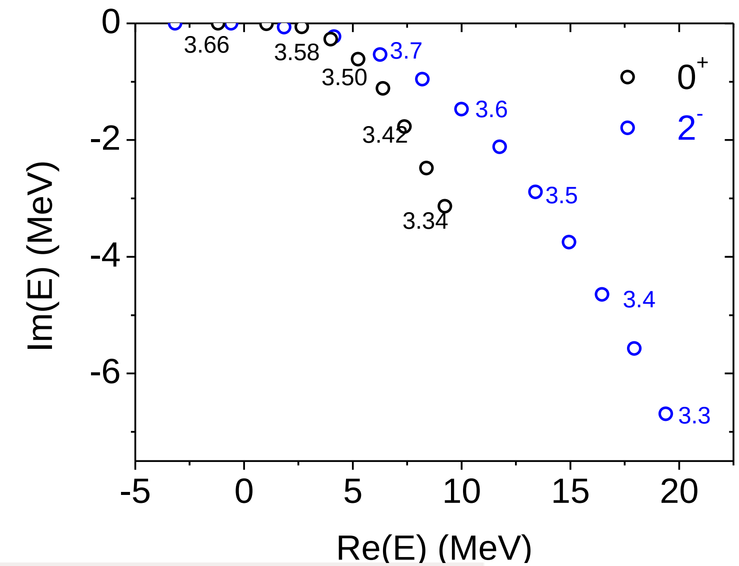


Table 3.5: Critical en ... tineutrons.

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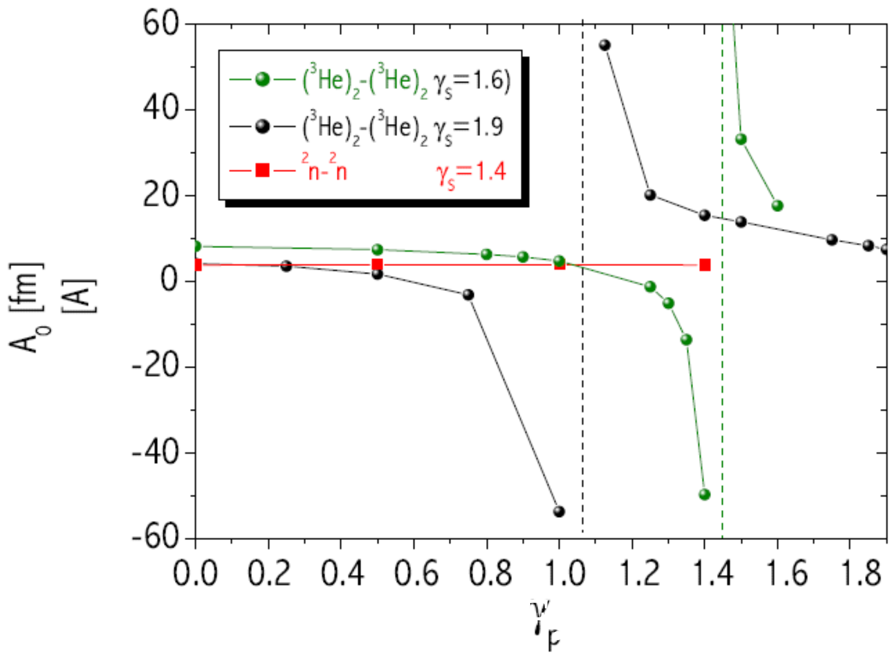
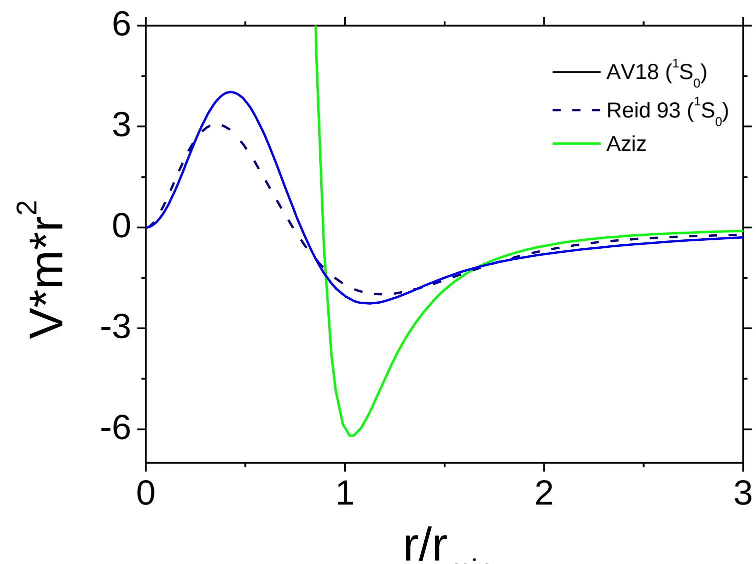
Dencies in nuclear scattering.





mimura (Riken), R. L.

Theory

R.L, Jaume Carbonell; Physical Review C 72 (2005) 034003

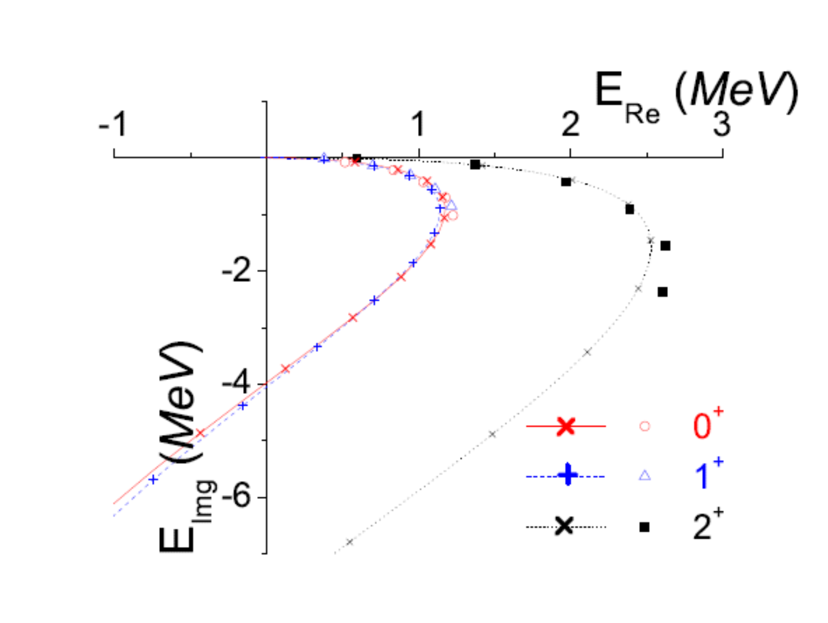
- V_{nn} interaction Reid 93
- No V_{nnn}
- Collective interaction is added and then gradualy removed:

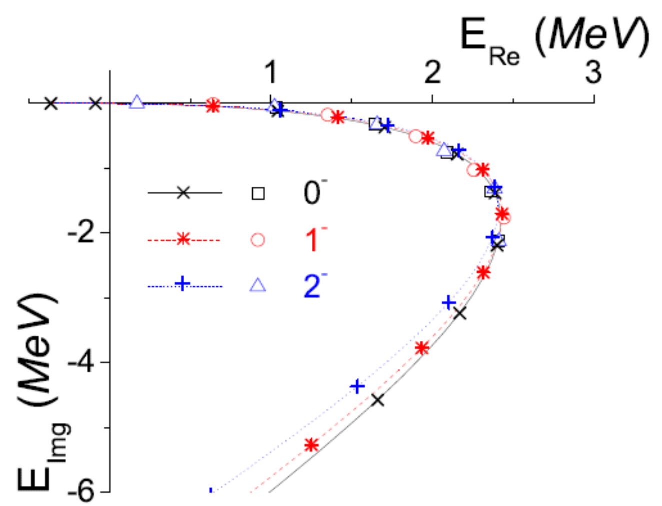
$$V_{4n} = We^{-\rho/\rho_0};\ \rho = \sqrt{2(r_1^2 + r_2^2 + r_3^2 + r_4^2)}$$

$$\rho_0 = 2.5\ fm$$

Not answered:
1) If there is a S-matrix pole, which does not evolve from b.s.
2) Effect of uncertainty in nn interaction, presence of 3NF
3) If resonance is not related to S-matrix pole

J^π	0^-	1^-	2^-	0^+	1^+	2^+
W_0	38.70	38.67	38.68	22.90	22.92	40.38
W'	3.0	3.2	3.9	3.5	3.6	4.1
$E_{res}(W=0)$	-1.0-9.9i	-1.1-9.8i	-1.4-9.7i	-1.1-6.3i	-1.1 -6.5i	-1.4-10.9i





J. Carbonell (IPNO), E. Hiyama & M. Kamimura (Riken), R. L.

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1. If one boost all the P-waves 'democratically'. Dineutron becomes resonant (bound)
2. If one boost only attractive P-waves, one may get bound or resonant ^4n. However boost factor to have reasonably resonant ^4n should be $\gamma_P \sim 3$!!!

$\gamma_P \sim 1.1$ is enough to account for the dis… …lear scattering.

- But ^4n system still has the last Trump card:

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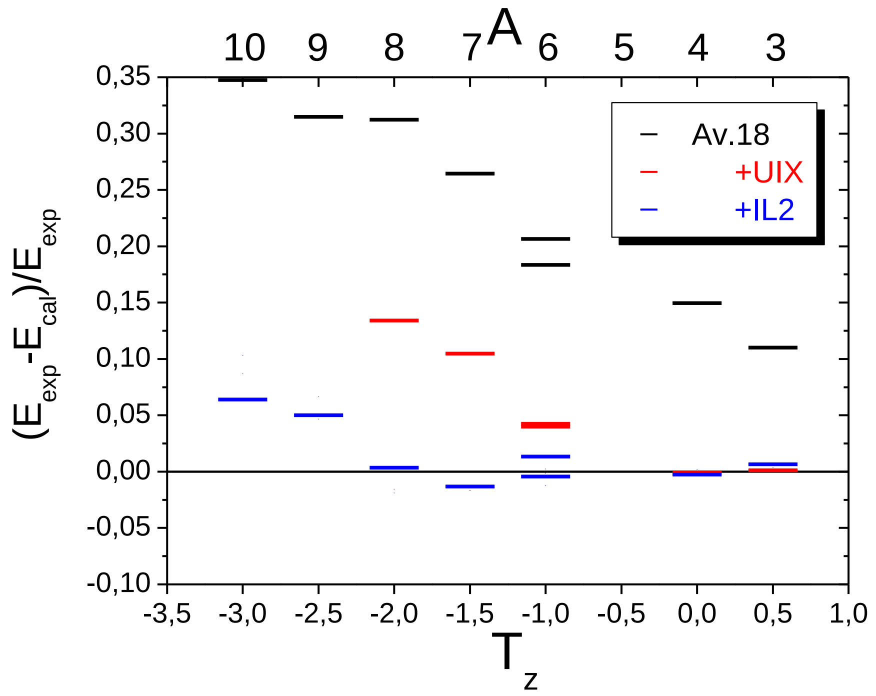
Sisyphe effect of the traditional 3NF's
in neutron rich systems:



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Explore an effect of 3nF

AV8' + Coulomb force

B.E.(^{3}H) : -7.76 MeV
B.E.(^{3}He) : -7.02 MeV
B.E(^{4}He) = -25.1 MeV

AV8' + Coulomb force +

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

$W_1(T=1/2) = -2.04$ MeV $b_1 = 4.0$ fm
$W_2 = +35$ MeV $b_2 = 0.75$ fm

B.E.(^{3}H) : -8.42 MeV
B.E.(^{3}He) : -7.74 MeV
B.E(^{4}He) = -28.44 MeV
rms(^{4}He) = 1.658 fm

Experiment:

B.E.(^{3}H) : -8.48 MeV
B.E.(^{3}He) : -7.77 MeV
B.E(^{4}He) = -28.30 MeV
rms(^{4}He) = **1.671** ± 0.014 fm (EXP)

11

J. Carbonell (IPNO), E. Hiyama & M. Kamimura (Riken), R. L.

AV8' + Coulomb 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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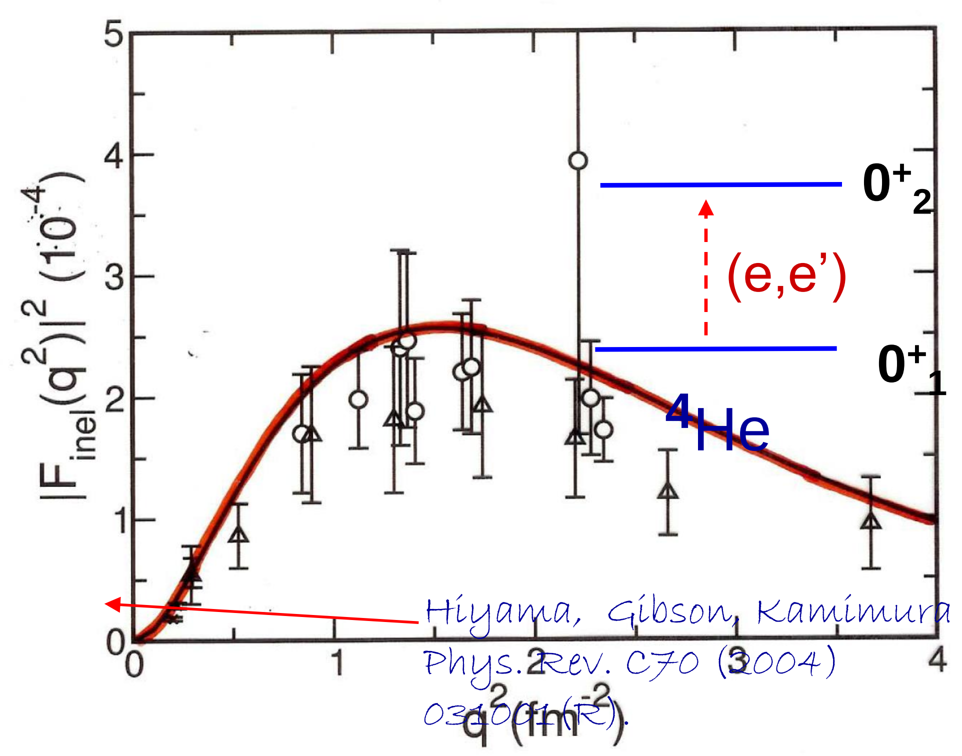
$W_2= +35$ MeV $b_2=0.75$ fm

2) : FF of inelastic e scatt.



J. Carbonell (IPNO), E. Hiyama & M. Kamimura (Riken), R. L.

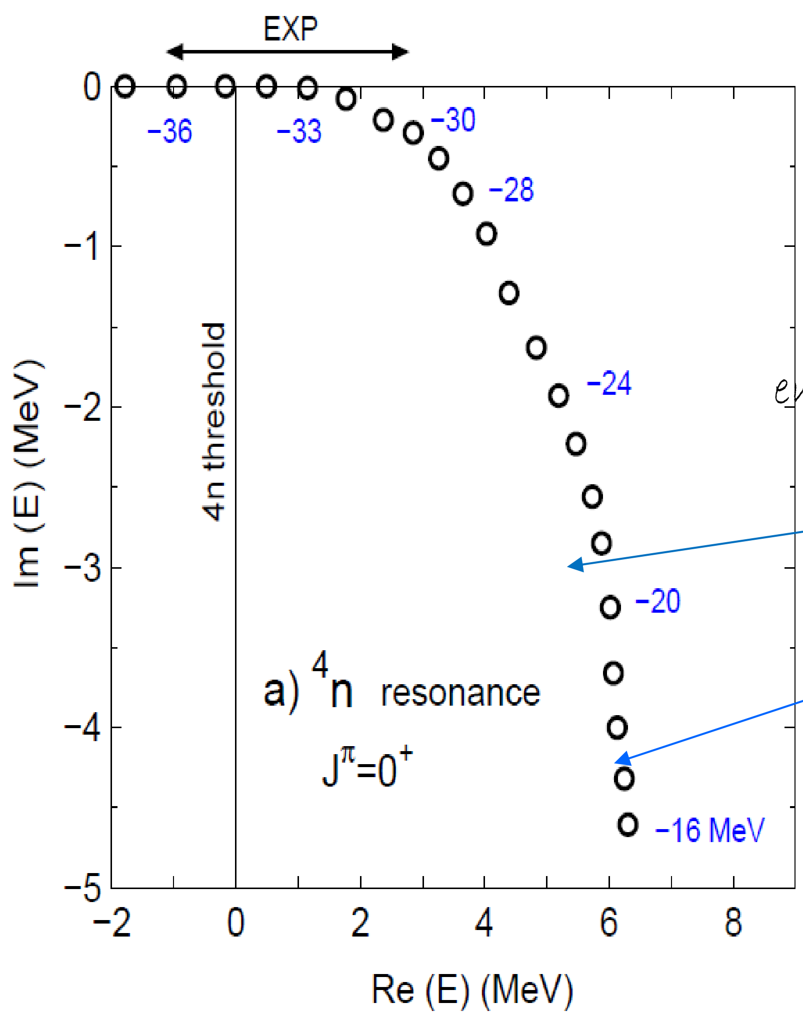
Explore effect of 3nF

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

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

$W_2= +35$ MeV $b_2=0.75$ fm

energy trajectory of $J=0^+$ state changing W_1



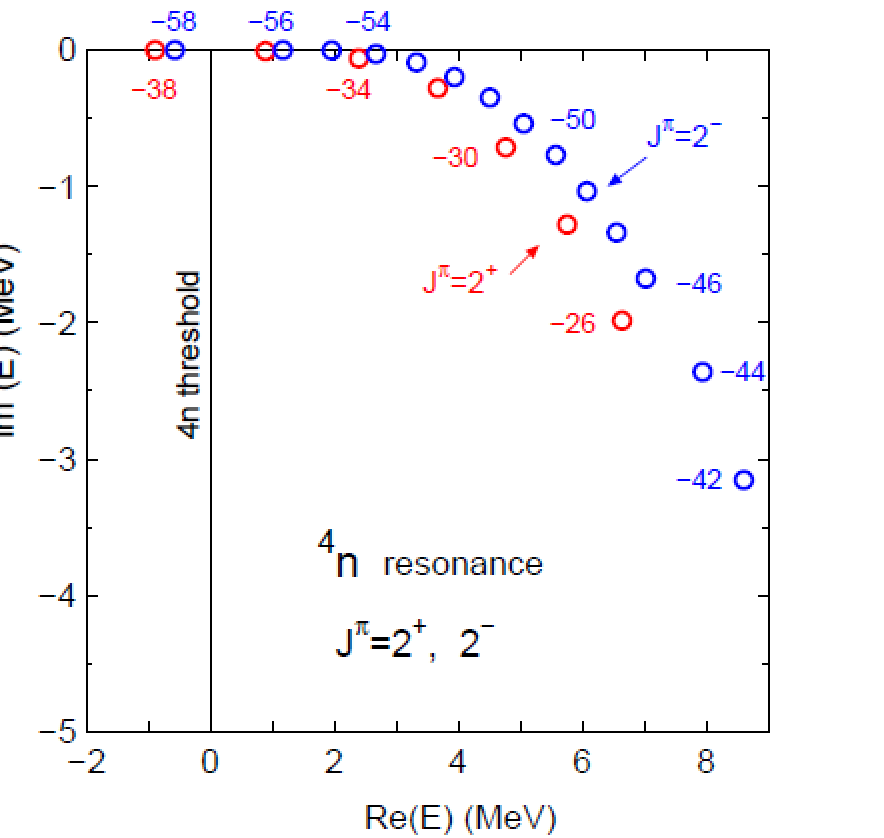
J. Carbonell (IPNO), E. Hiyama & M. Kamimura (Riken), R. L.

Explore effect of 3nF

AV8' + Coulomb force +

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

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



energy trajectories for $J=2^-$ & $J=2^+$ states, qualitatively the same, but even larger W_1 are involved

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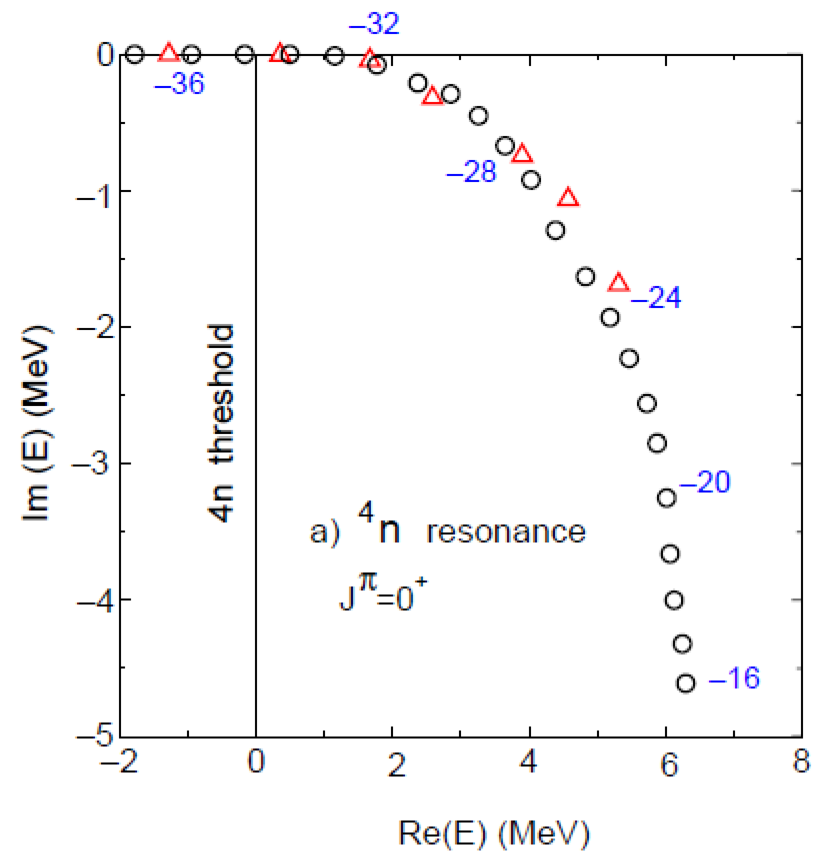
Little dependence on NN interaction

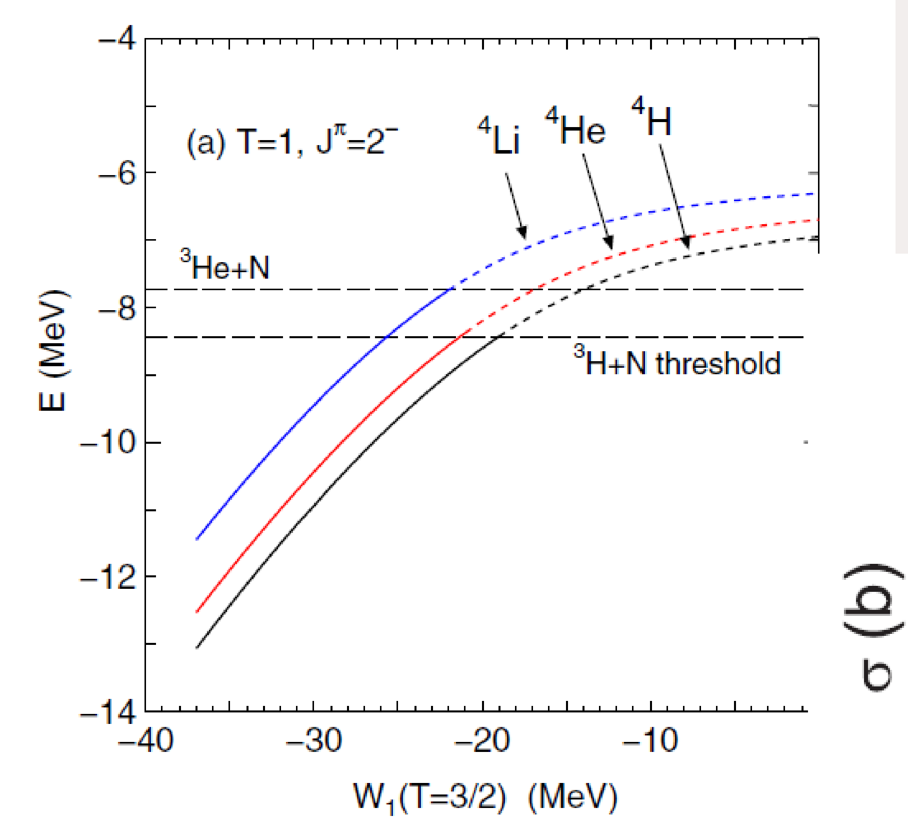


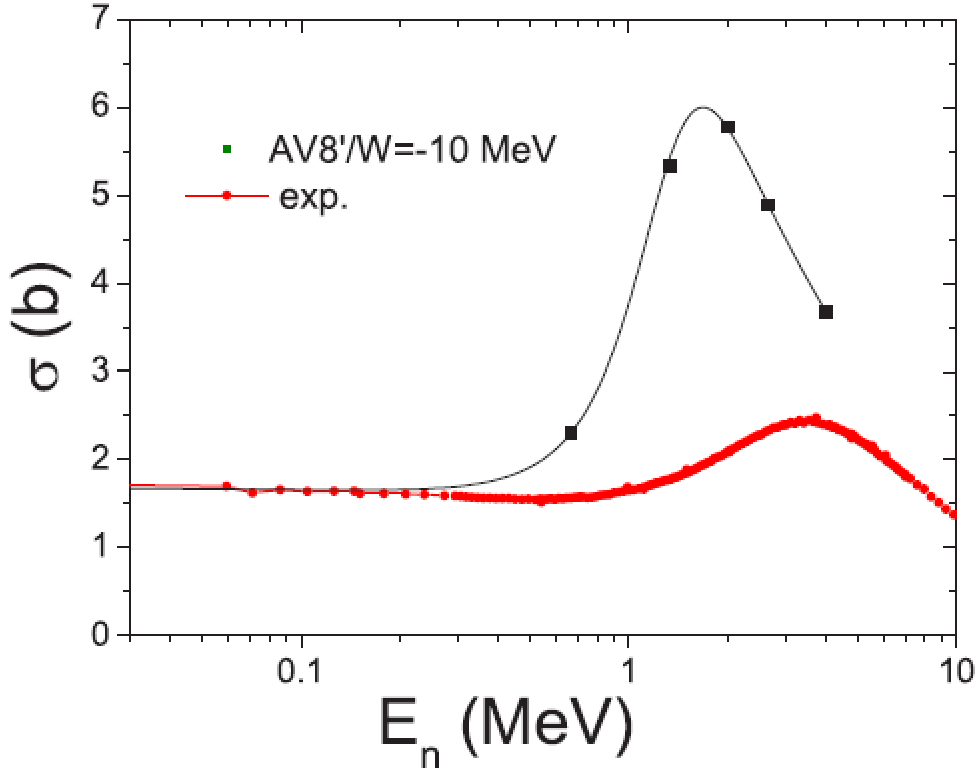
INOY

AV8'

J. Carbonell (IPNO), E. Hiyama & M. Kamimura (Riken), R. L.

Reality of strongly attractive 3nF: n-^{3}H scattering



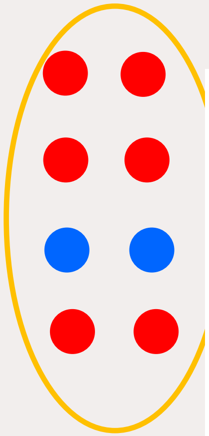


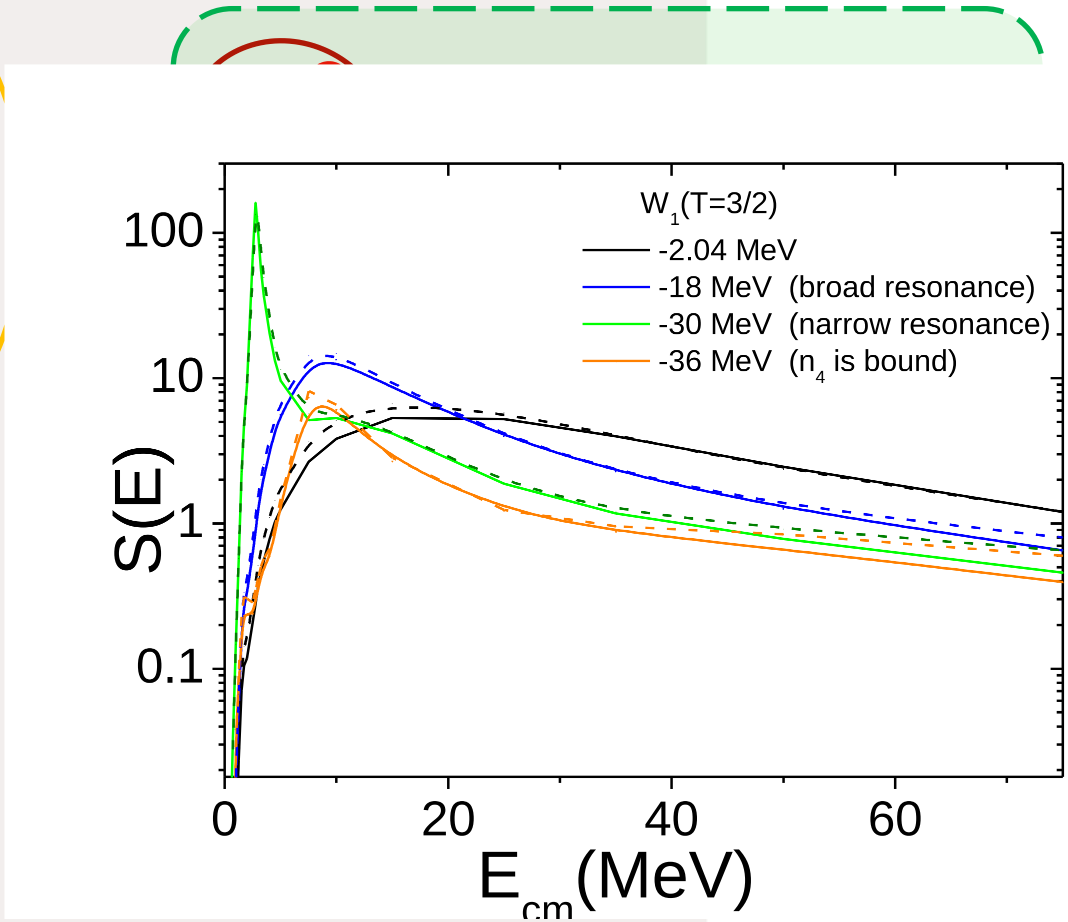
J. Carbonell (IPNO), E. Hiyama & M. Kamimura (Riken), R. L.

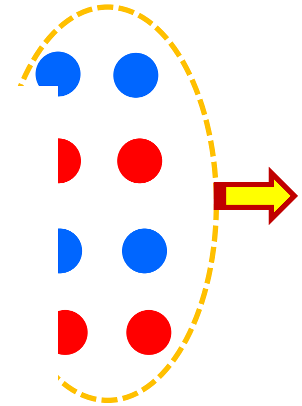
Approximation of the experimental observable

b. And if rapid variation of observables without presence of S-matrix poles in the vicinity?

Calucci G., Ghirardil C, Phys. Rev. 169 (1968) 1339







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5H system

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	$\approx$3	$\approx$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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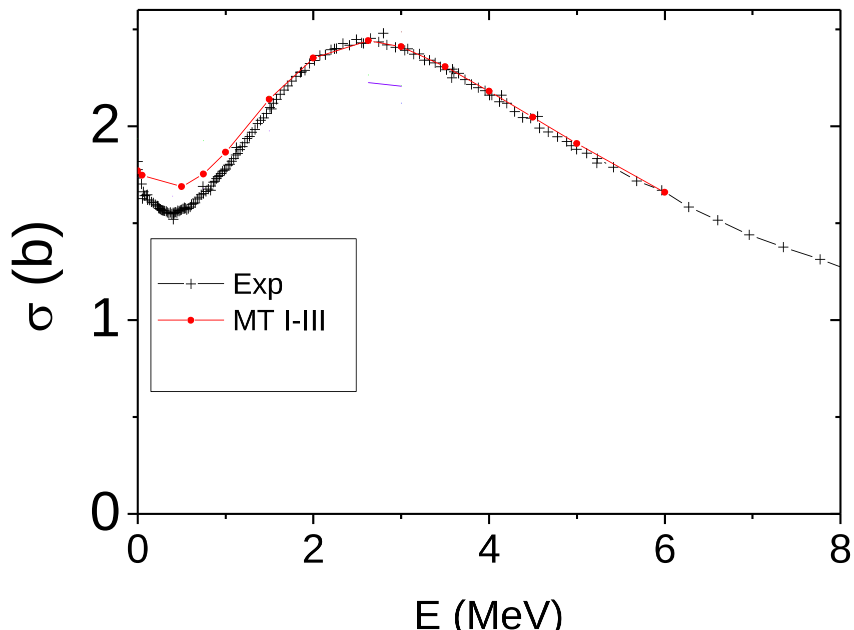
5H system

$^3PF_2$ wave enhancement factor needed to bind

^{2}n	^{3}n	^{4}n	^{4}H	^{5}H	Pot.
4.39	3.99	3.55	2.50	~2.40	AV18
4.42	3.98	3.53	2.35		INOY
5.38	4.80	4.20	2.76	2.68	N3LO



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Conclusion

• Existence of the bound ^4n system is not consistent with the modern nuclear interaction models

• Presence of the observable resonant ^4n states also seems to be inconsistent with our current understanding of nuclear interaction

• If this resonance reconfirmed experimentaly there remain three posibilities with increasing theoretical challenge to unveil the underlaying phenomena:

- ✓ The observed resonant behavior is not artifact of resonant ^4n, but some complex reaction mechanism involving 12-nucleons
- ✓ We have non-standard resonance in ^4n, which appears without presence of S-matrix pole in vicinity of real energy axis
- ✓ We fail to understand nuclear dynamics based on nucleon degrees of freedom

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