第一届“粤港澳”核物理论坛

Ab initio no-core Gamow shell model calculations of Multineutron systems

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In collaboration with

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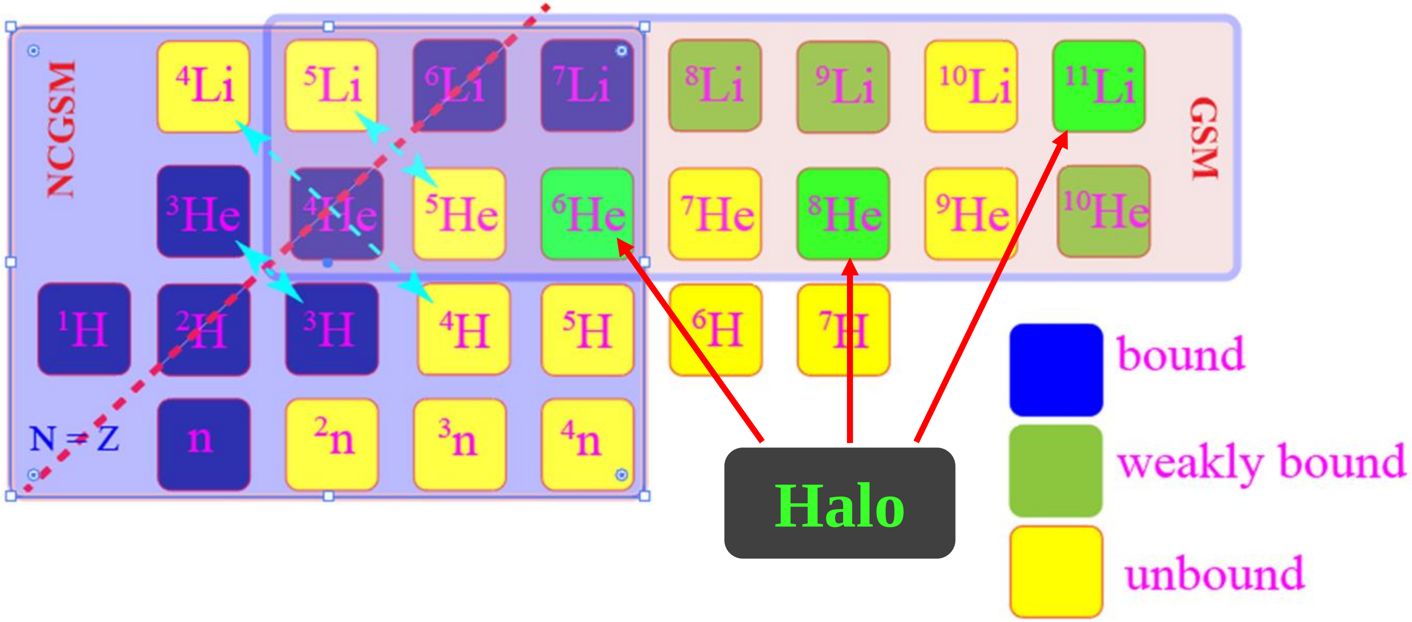
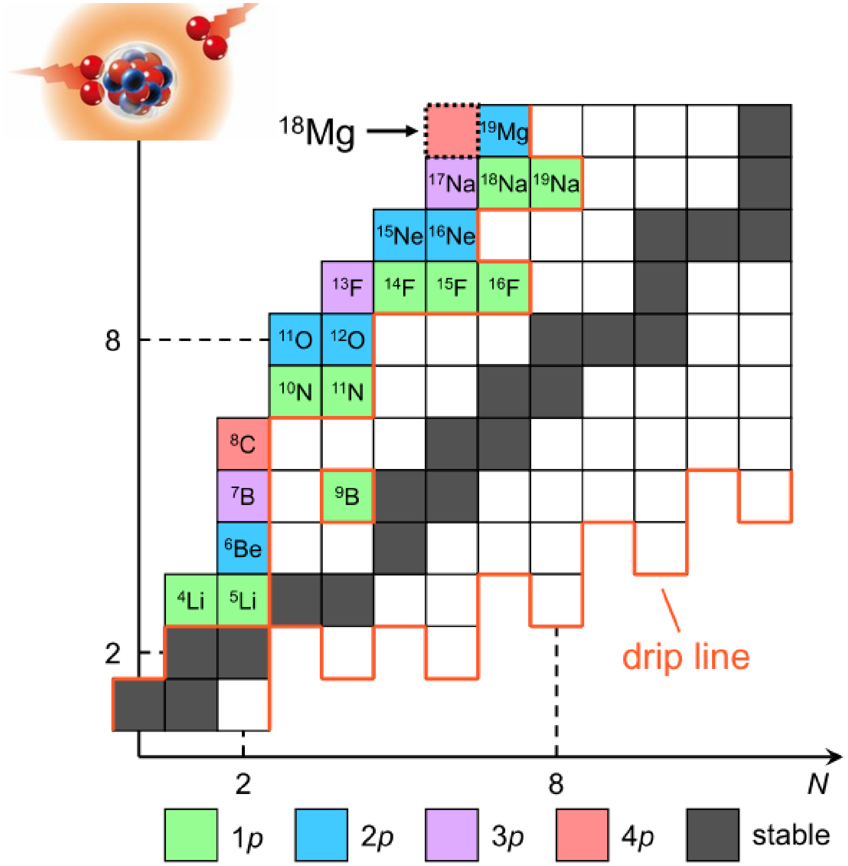
Dripline nuclei





Y. Jin et al., Phys. Rev. Lett. 127, 262502 (2021).

Exotic properties in dripline nuclei

- ✓ Halo structure ^{6,8}He, ^{11}Li, ^{11}Be, ^{8}B, ^{17}Ne, ^{29}F
- ✓ Particle emission *p,n,2p,2n,4n,2n+2n,...*
- ✓ Thomas Erhman-shift
- ✓ …

Resonance and continuum couplings are important and need to be exactly treated!

Resonance state

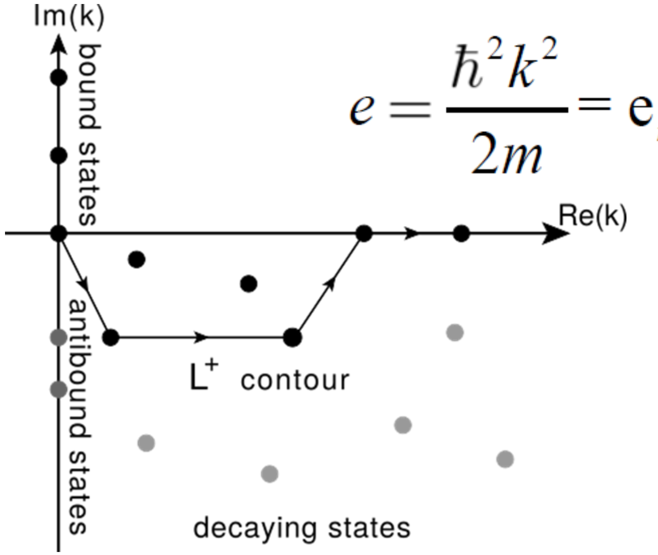
A resonance state, which represents a decaying process, is time dependent.

Berggren complex-*k* space transfers a time-dependent problem to a time-independent problem !

The radial wave function

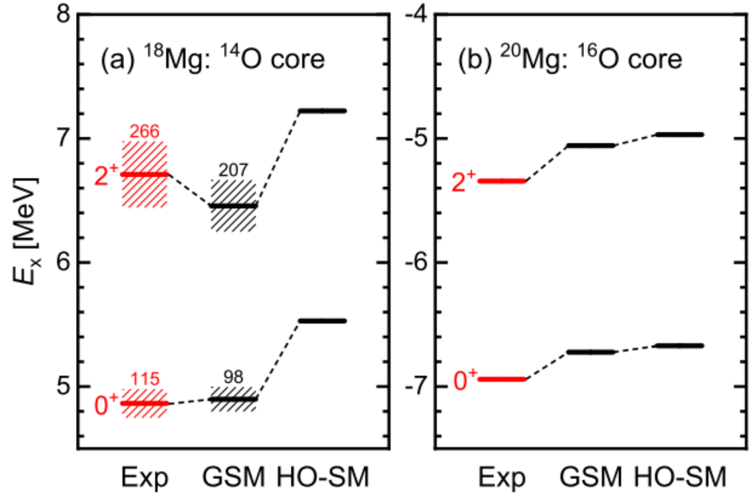
$$\frac{d^2u(k,r)}{dr^2} = \left(\frac{\ell(\ell+1)}{r^2} + \frac{2m}{\hbar^2}V(r) - k^2\right)u(k,r)$$

$$e = \frac{\hbar^2 k^2}{2m} = e_n - i\frac{\gamma_n}{2}$$

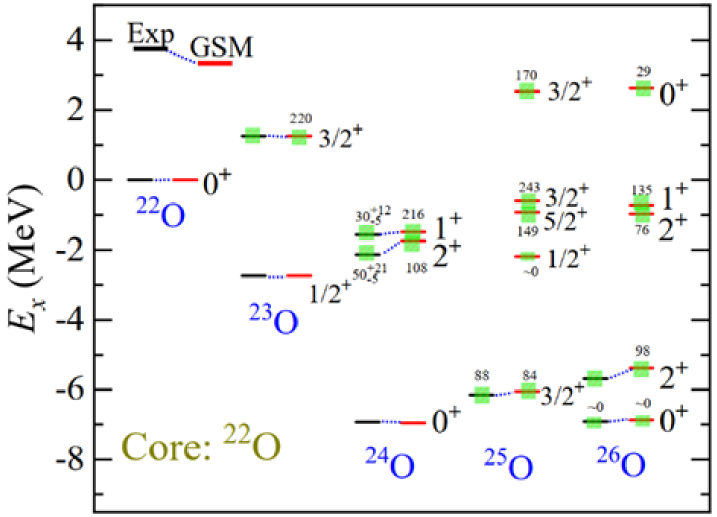


$$\sum_{n\in(b,d)} |u_n\rangle\langle u_n| + \int_{L^+} |u(k)\rangle\langle u(k)|dk = 1$$

T. Berggren, Nucl. Phys. A109 (1968) 265



Y. Jin et al., Phys. Rev. Lett. 127, 262502 (2021).

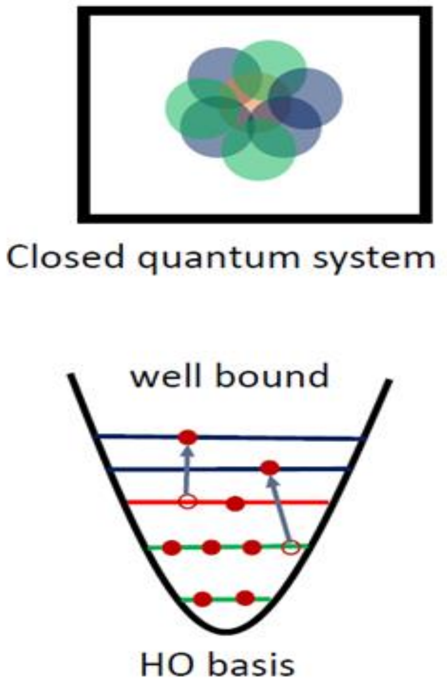


J. G. Li, et al. Phys. Rev. C 103, 034305 (2021)

Many-Body calculations in HO or Berggren basis

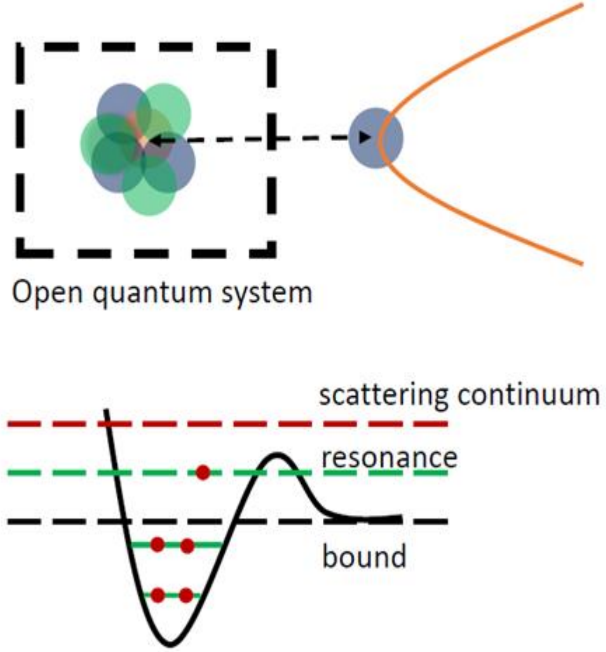
$$H = -\sum_i \frac{\hbar^2}{2m} \nabla_i^2 + \sum_{ij} V_{ij} + \sum_{ijk} V_{ijk}$$

NCSM/SM



Including resonance and continuum coupling via using Berggren basis

NCGSM/GSM



Berggren basis

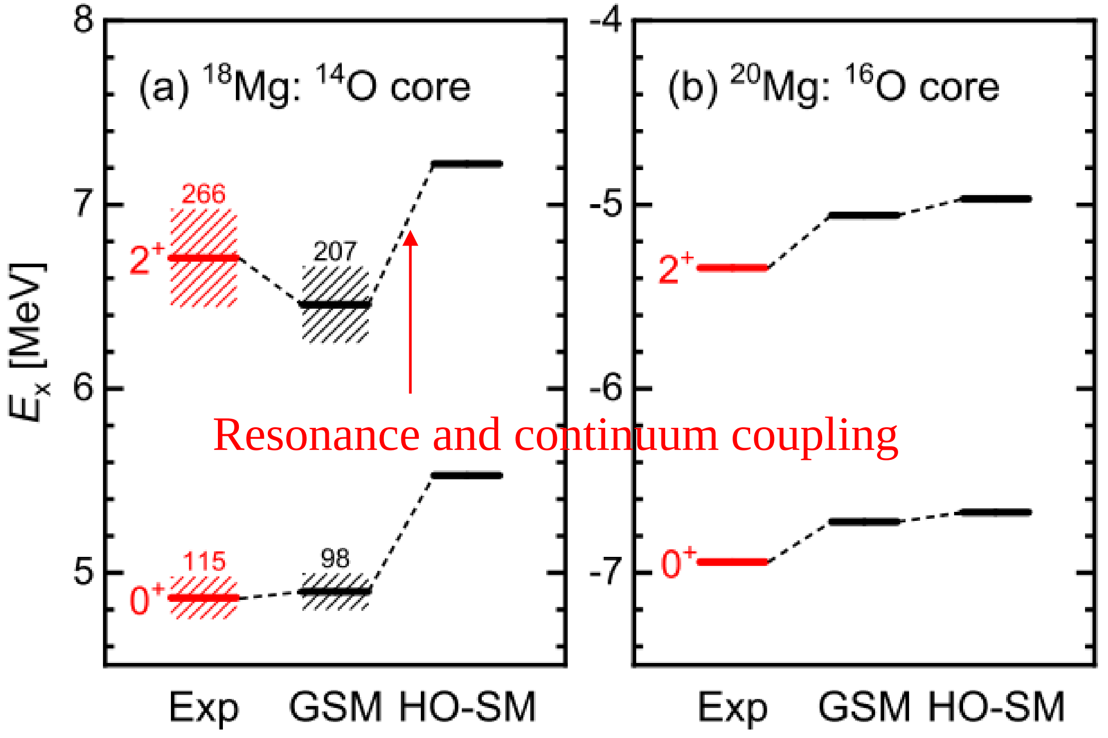
E. Caurier, et al. RMP 77,427 (2005)
T. Otsuka, et al, RMP. 92,015002 (2020)
B. R. Barrett, P. Navratil, and J. P. Vary PPNP 69,131(2013)

N. Michel, M. Płoszajczak, The Gamow Shell Model, Springer ;
N. Michel, et al., JPG 36,013101 (2009)
J. G. Li, et al., Physics 3, 977 (2021)
J. G. Li, et al., Phys. Rev. C 100, 054313 (2019)
J. G. Li, et al., Phys. Rev. C 104, 024319 (2021)

NCSM : also see Xingbo Zhao and Peng Ying’s Presentations

Resonance and continuum coupling in dripline nuclei :examples

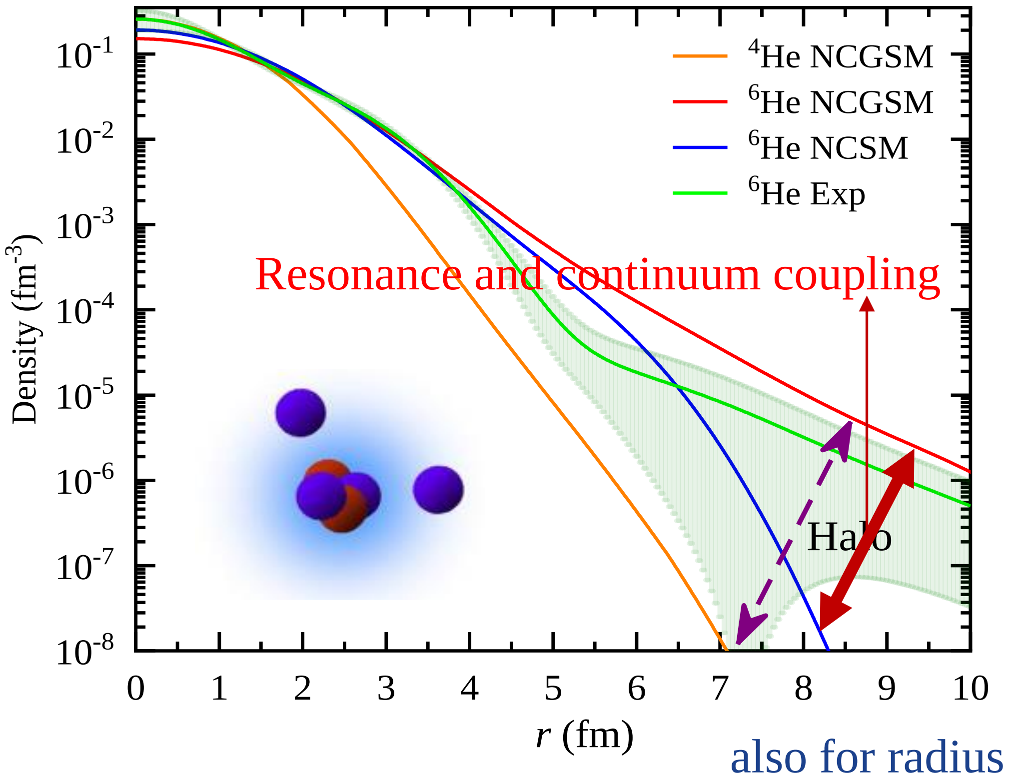
^{18}Mg : 4p-decay to ^{14}O



Theoretical calculations are provided by **J. G. Li** and N. Michel

Y. Jin et al., Phys. Rev. Lett. 127, 262502 (2021).

^{6}He: Two-neutron Halo



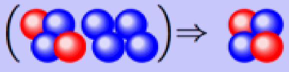
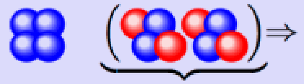
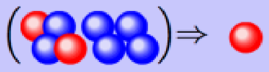
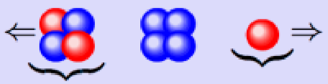
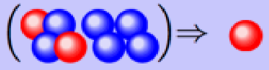
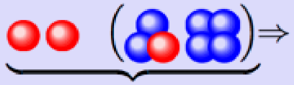
also for radius

***J. G. Li**, et al., in preparation*

History of Multineutron system

- More than 50 years of multi-neutron searches, especially the tetraneutron.
  See arXiv:1608.00169[nucl-th] (2016) Eur. Phys. J. A 57,105(2021),
- Earlier experiments gave negative results, no information about the multi-neutron systems.
- In 2002, Marqués *et al* reported the possible existence of a **bound** tetraneutron observed in a breakup reaction of the ^{14}Be→^{10}Be+4n channel. Marqués *et al.*, PRC 65, 044006 (2002)
- In 2016, Kisamori *et al* observed of few events of tetraneutron in the doubly charge-exchange reaction ^{4}He(^{8}He,^{8}Be) . Interpreted the tetraneutron as a candidate **resonance** with **Er = 0.83 ± 0.65(stat) ± 1.25(syst) MeV** and width **Γ ≤ 2.6 MeV**. Kisamori *et al.*, PRL 116, 044006 (2016)

Future tetraneutron experiments

reaction	initial state	final state	σ	results
^{4}He (^{8}He, $\alpha\alpha$) ^{4}**n** Shimoura, NP1512-SHARAQ10			nb	$N_{evt} \sim 10$s ^{4}n : E, Γ
^{8}He (p,pα) ^{4}**n** Paschalis, NP1406-SAMURAI19			μb	$N_{evt} \sim 1000$s ^{4}n : E, Γ
^{8}He (p,2p) {^{3}**H**+^{4}**n**} FMM/Yang, NP1512-SAMURAI34			**mb**	$N_{evt} \sim$ **10,000**s ^{4}n & ^{7}H : E, Γ, Ω

Nature 2022

History of theoretical researches for the multi-neutron systems

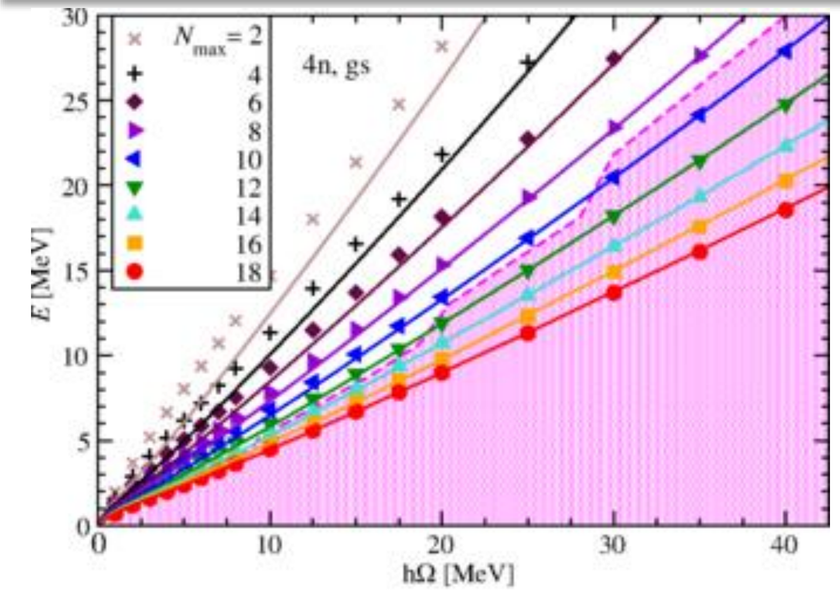
Year	Author	Journal	Conclusion
2003	Bertulani et al	J. Phys. G 29, 2431	gave no bound 4n combined dineutron-dineutron molecule and a toy NN potential
2003	Steven C. Pieper	PRL. 90, 252501	employed the GFMC calculated the tetraneutron, showed the modern nuclear force can not tolerate a bound tetraneutron and suggested the a tetraneutron resonance near 2MeV
2005	Lazauskas and Carbonell	PRC 72, 034003	used Complex scaling based on Reid 93 NN potential: no low-lying 4n resonances : no low-lying tetraneutron resonance.
2016	E.Hiyama *et al*	PRC **93**, 044004	employed Complex scaling using AV8'+(toy)NNN, low 4*n* resonance possible only by strongly strongly modify the nuclear force
2016	A.M.Shirokov *et al*	PRL **117**,182502	performed the NCSM with JISP16 interaction conformed a resonant state in tetraneutron around 0.8 MeV, width 1.4 MeV
2017	S. Gandofi *et al*	PRL **118**, 232501(2017)	presented the QMC calculations of multi-neutron systems, suggested the trineutron and tetraneutron were both resonance

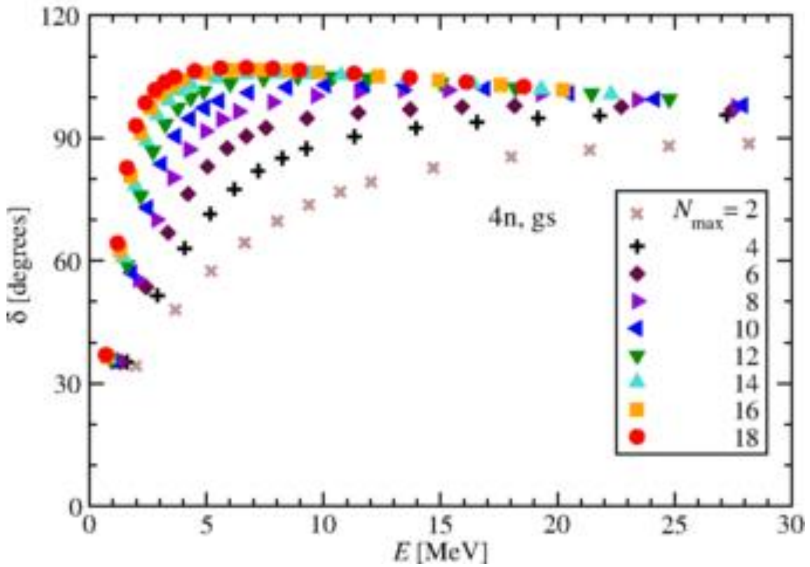
→ 2016 experiment

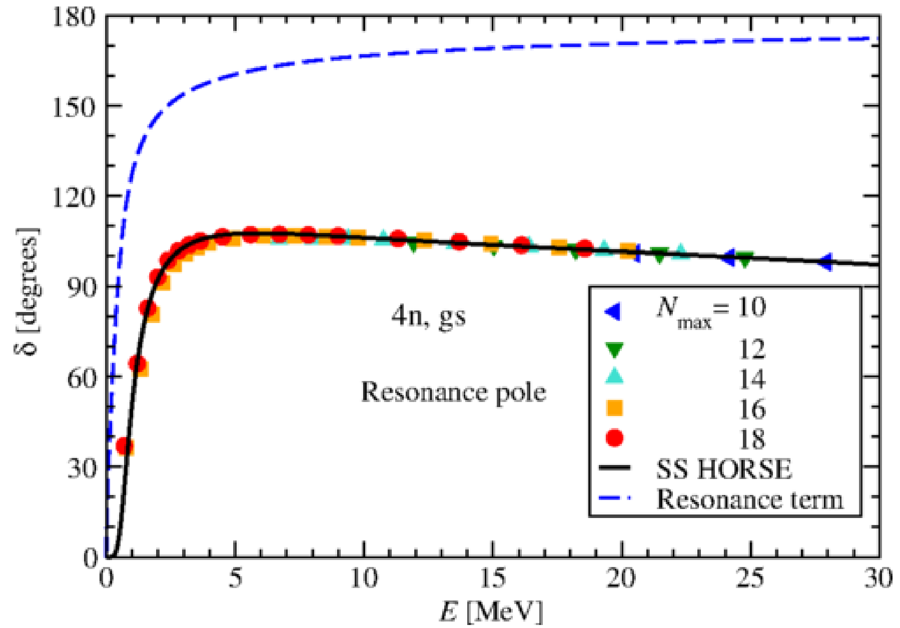
History of theoretical researches for the multi-neutron systems

Year	Author	Journal	Conclusion
2017	K. Fossez *et al.*	PRL **119**, 032501	performed NCGSM gave energy of tetraneutron may be compatible with experimental value, but the width must be too large
2018	A.Deltuva	PRC **97**, 034001 (2018), PLB **782**, 238 (2018)	employed Faddeev method gave the absence of an observable trineutron and tetraneutron resonance based on modern two-body force
2018	A.M.Shirokov *et al.*	AIP Conf. proc 020038	Performed NCSM for tetraneutron with different two-body force, similar results are obtained
2019	A.M.Shirokov *et al.*	Presentation in Nanjing@China 2019	updated their calculations and gave two resonance states in tetraneutron
2019	J. G. Li *et al.*	PRC 100 054313	Performed NCGSM for trineutron and tetraneutron, predicting that $E(^3n) = 1.29$ MeV $\Gamma(^3n) = 0.91$ MeV $E(^4n) = 2.64$ MeV $\Gamma(^4n) = 2.38$ MeV
2020 2021	Michael D. Higgins *et al.*	PRL 125,052501 PRC 103 024004	Using adiabatic hyperspherical framework, Predicting that that no resonance and no bound state exists for the tetraneutron system

NCSM for tetraneutron







E(tetraneutron) = 0.8 MeV   Γ (tetraneutron) = 1.4 MeV

*A. M. Shirokov,et al, PRL **117**,182502 (2016)*

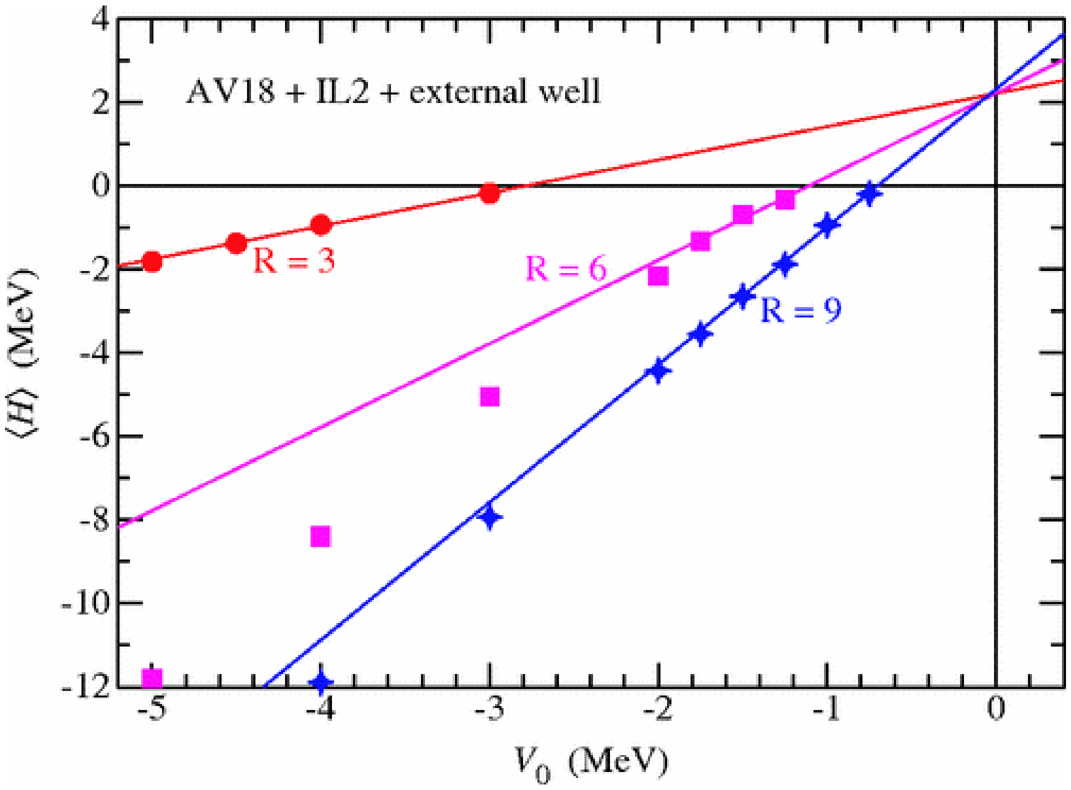
2019' workshop, they predict two resonance states of tetraneutron:

1st: E(4n) ~ 0.3 MeV   Γ (4n) ~ 815 keV
2st: E(4n) ~ 0.8 MeV   Γ (4n) ~ 1.3 MeV

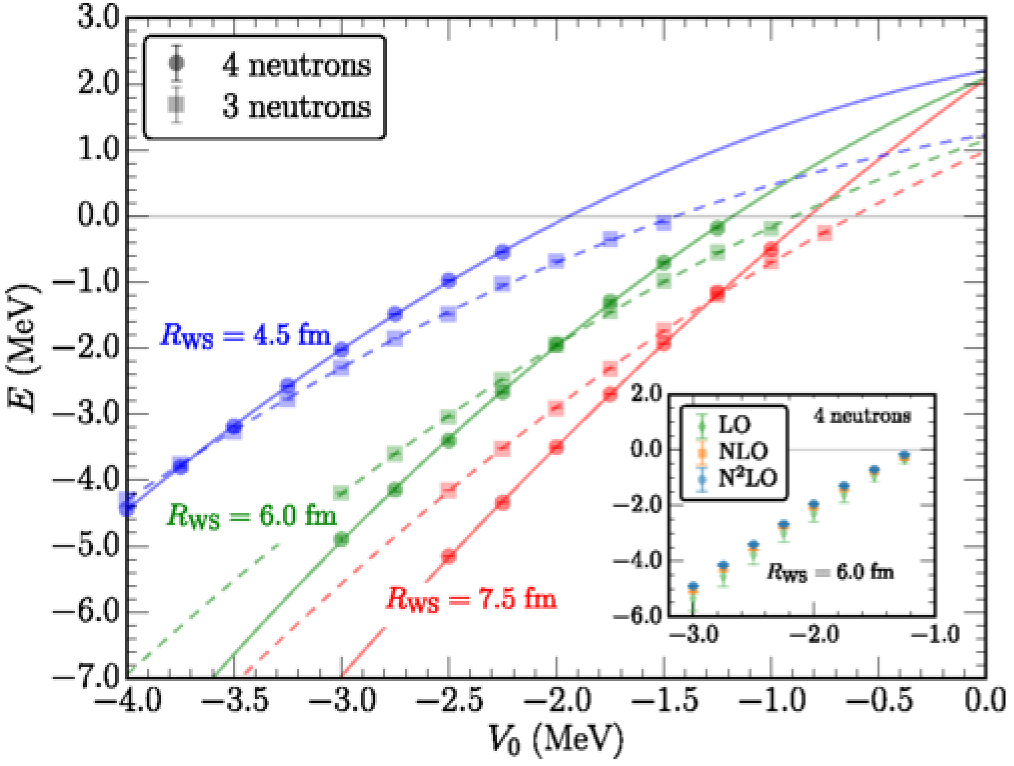
A. M. Shirokov Presentation in Nanjing@China 2019

QMC calculations of multineutron systems

$$H = -\sum_i \frac{\hbar^2}{2m}\nabla_i^2 + \sum_i V_{WS}(r_i) + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk}$$



*Steven C. Pieper PRL **90**, 252501(2002)*

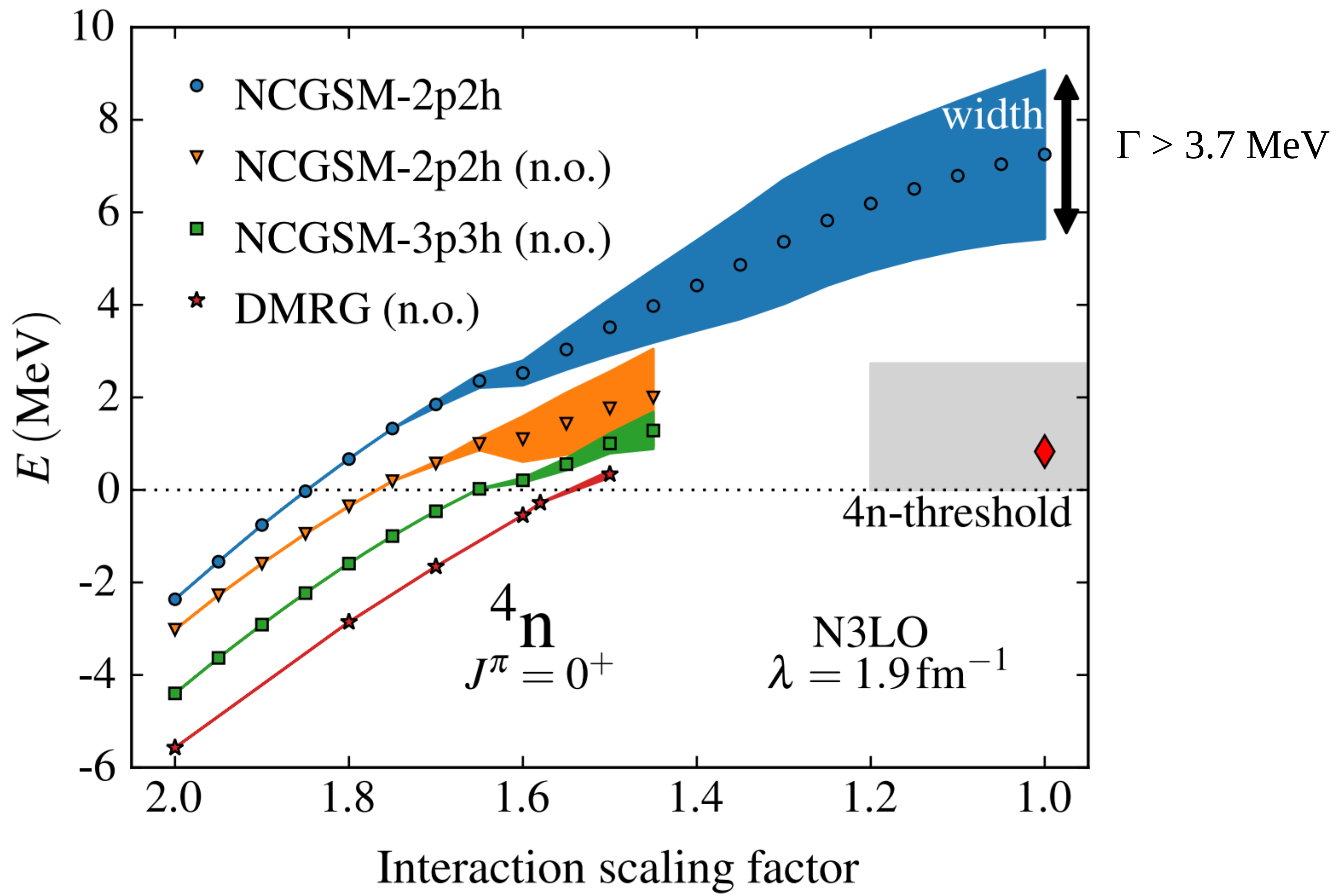


*S. Gandofi, et al., PRL **118**, 232501(2017)*

Only energy, no width!

NCGSM calculations of multineutron systems

	$\lambda = 1.7\ \mathrm{fm}^{-1}$	$\lambda = 1.9\ \mathrm{fm}^{-1}$	$\lambda = 2.1\ \mathrm{fm}^{-1}$
N3LO	7.27 (3.69)	7.28 (3.67)	7.28 (3.69)
$\mathrm{N2LO_{opt}}$	7.32 (3.74)	7.33 (3.78)	7.34 (3.95)
$\mathrm{N2LO_{sat}}^{*}$	7.24 (3.48)	7.22 (3.58)	7.27 (3.55)
JISP16		7.00 (3.72)	



*K. Fossez, J. Rotureau, N. Michel, and M. Ploszajczak, PRL **119**, 032501 (2017)*

NCGSM for multi-neutron systems

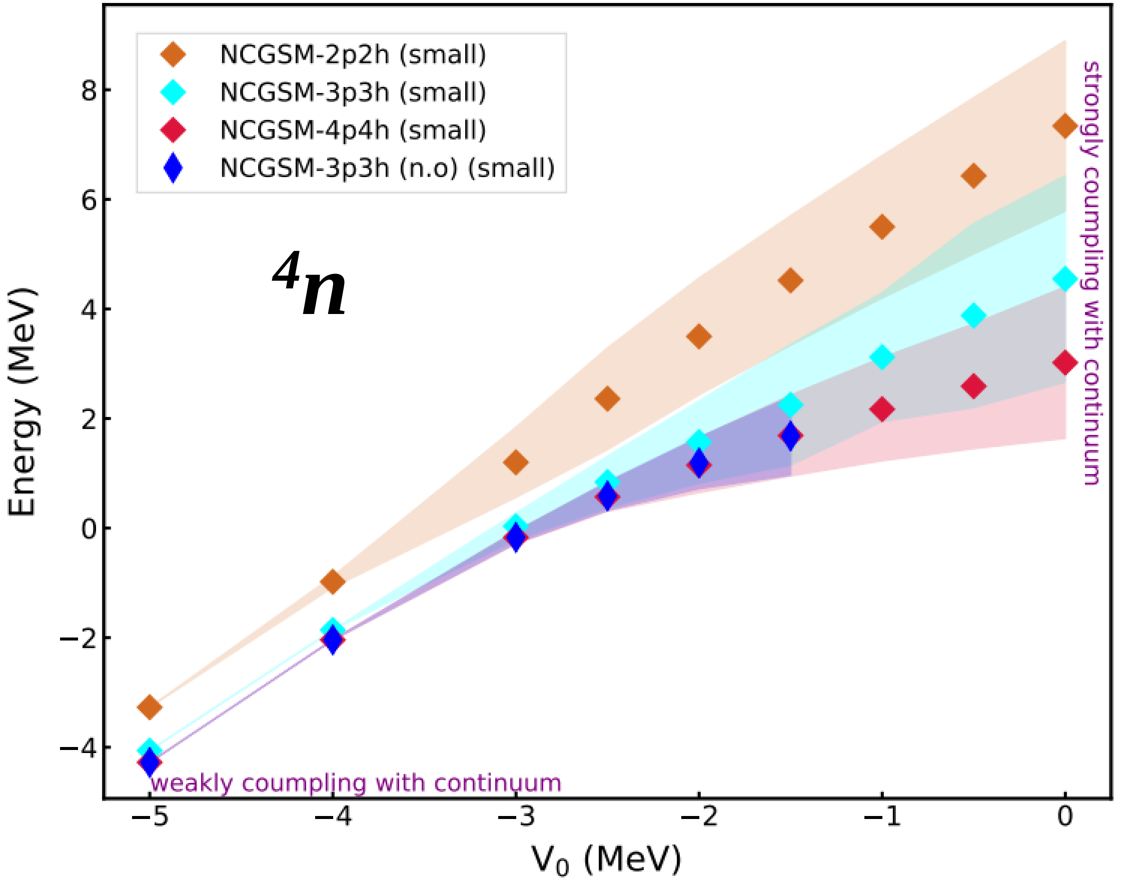
Interaction : N3LO $V_{low\text{-}k}$ 2.1fm^{-1}
Model space : $s_{1/2}$, $p_{3/2}$ in Bergrren basis (45 points)
$p_{1/2}$, $d_{5/2,3/2}$, $f_{5/2,7/2}$, $g_{9/2}$ in HO basis. ($N_{max}\leq 20$)
Method : Davison + overlap method
N. Michel, W. Nazarewicz, M. Ploszajczak, and T. Vertse, JPG 36, 013101 (2009)

Multineutron systems

↓ Unbound

Strongly coupling with continuum →

$$H = \frac{1}{A}\sum_{i}^{A}\frac{(p_i - p_j)^2}{2m} + \sum_{i<j}^{A} V_{NN}^{i<j} + \sum_{i}^{A} V_{WS}$$

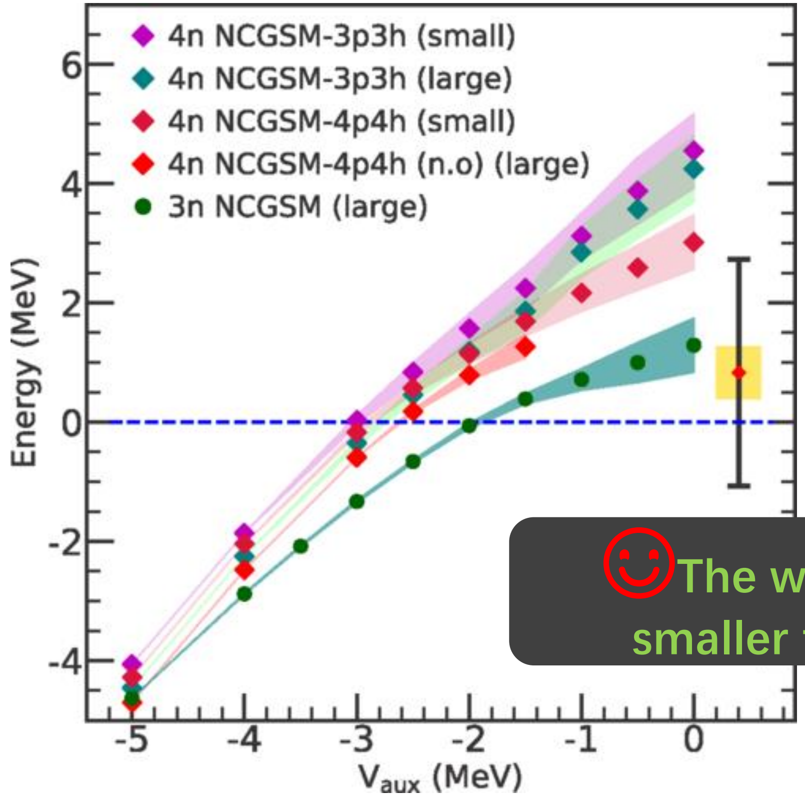


small model space : $s_{1/2}$, $p_{3/2}$ in Bergrren basis (45 points)
$p_{1/2}$, $d_{5/2,3/2}$, $f_{5/2,7/2}$, $g_{9/2}$ in HO basis. ($N_{max}\leq 4$)

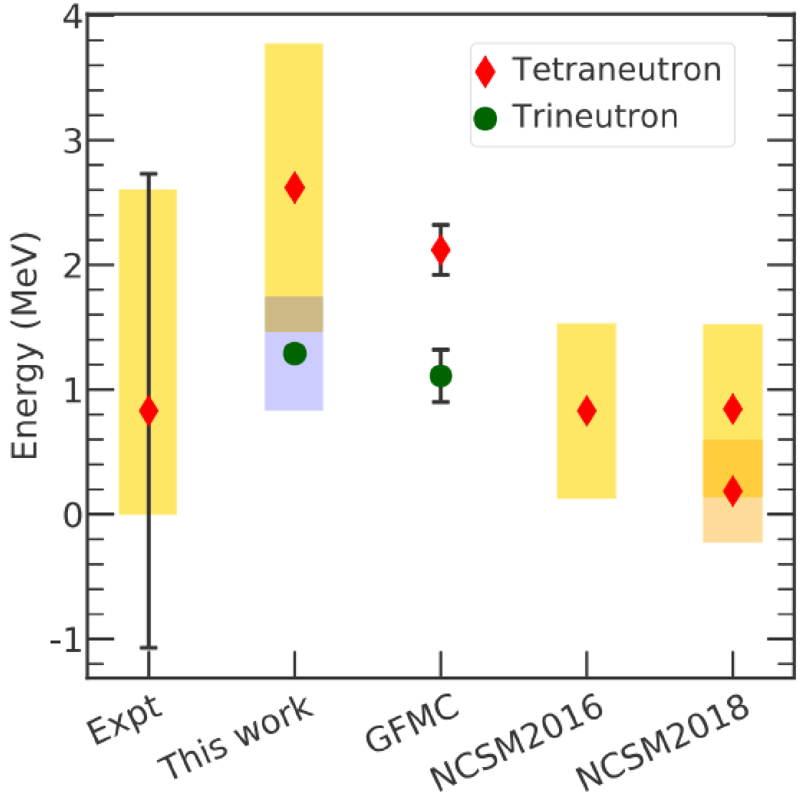
NCGSM for multi-neutron systems

$E(^3n) = 1.29$ MeV $\Gamma(^3n) = 0.91$ MeV
$E(^4n) = 2.64$ MeV $\Gamma(^4n) = 2.38$ MeV

The energy of trineutron is lower than tetraneutron.
QMC extrapolations are agree with our calculations



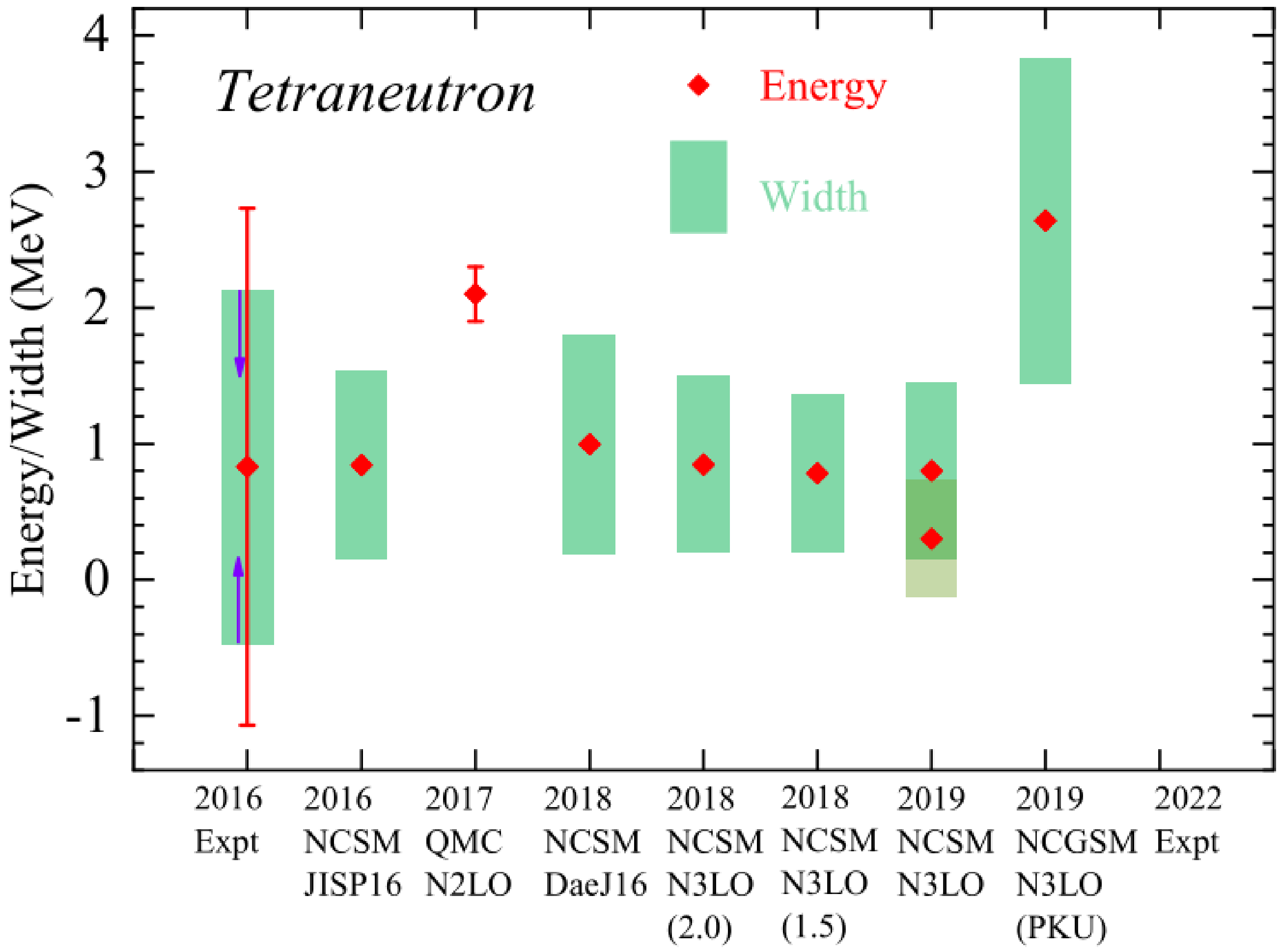
☺The width of trineutron is smaller than tetraneutron.



☺ Trineutron Would be More Possible to be Observed than Tetraneutron

__J. G. Li__, N. Michel, B. S. Hu, W. Zuo, and F. R. Xu, Phys. Rev. C 100, 054313 (2019)*

The History of Tetraneutron



- ✓ 2016 Expt : *Kisamori et al., PRL 116, 044006 (2016)*
- ✓ 2016 NCSM: *A. M. Shirokov,et al, PRL 117,182502 (2016)*
- ✓ 2017 QMC : *S. Gandofi, et al., PRL 118, 232501(2017)*
- ✓ 2018 NCSM : *A. M. Shirokov,et al AIP Conf. proc 020038 (2018)*
- ✓ 2019 NCSM : *A. M. Shirokov Presentation in Nanjing@China 2019*
- ✓ **2019 NCGSM** : ***J. G. Li****, N. Michel, B. S. Hu, W. Zuo, and F. R. Xu*, Phys. Rev. C 100, 054313 (2019)*

Observation of a correlated free four-neutron system

Article

Observation of a correlated free four-neutron system

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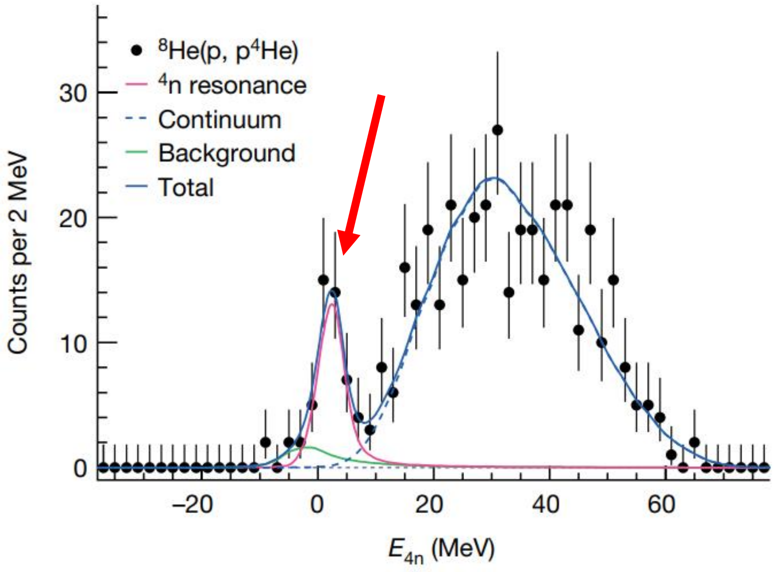
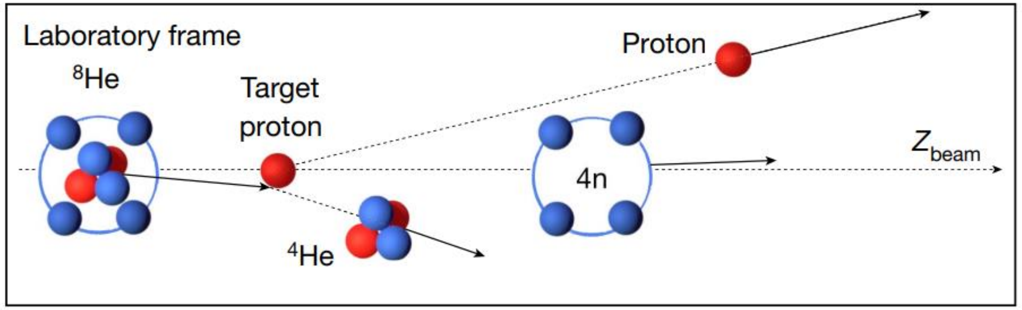
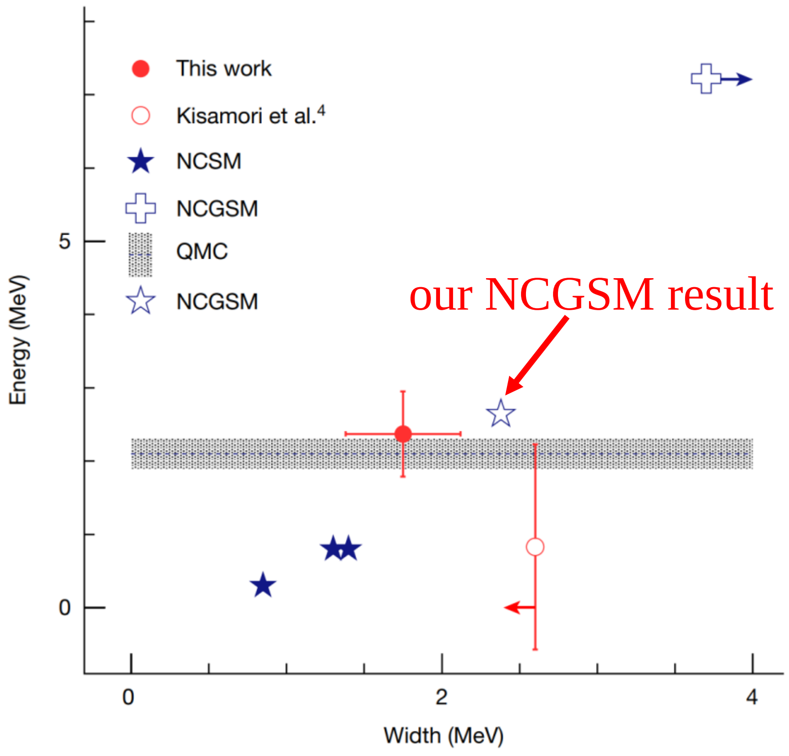
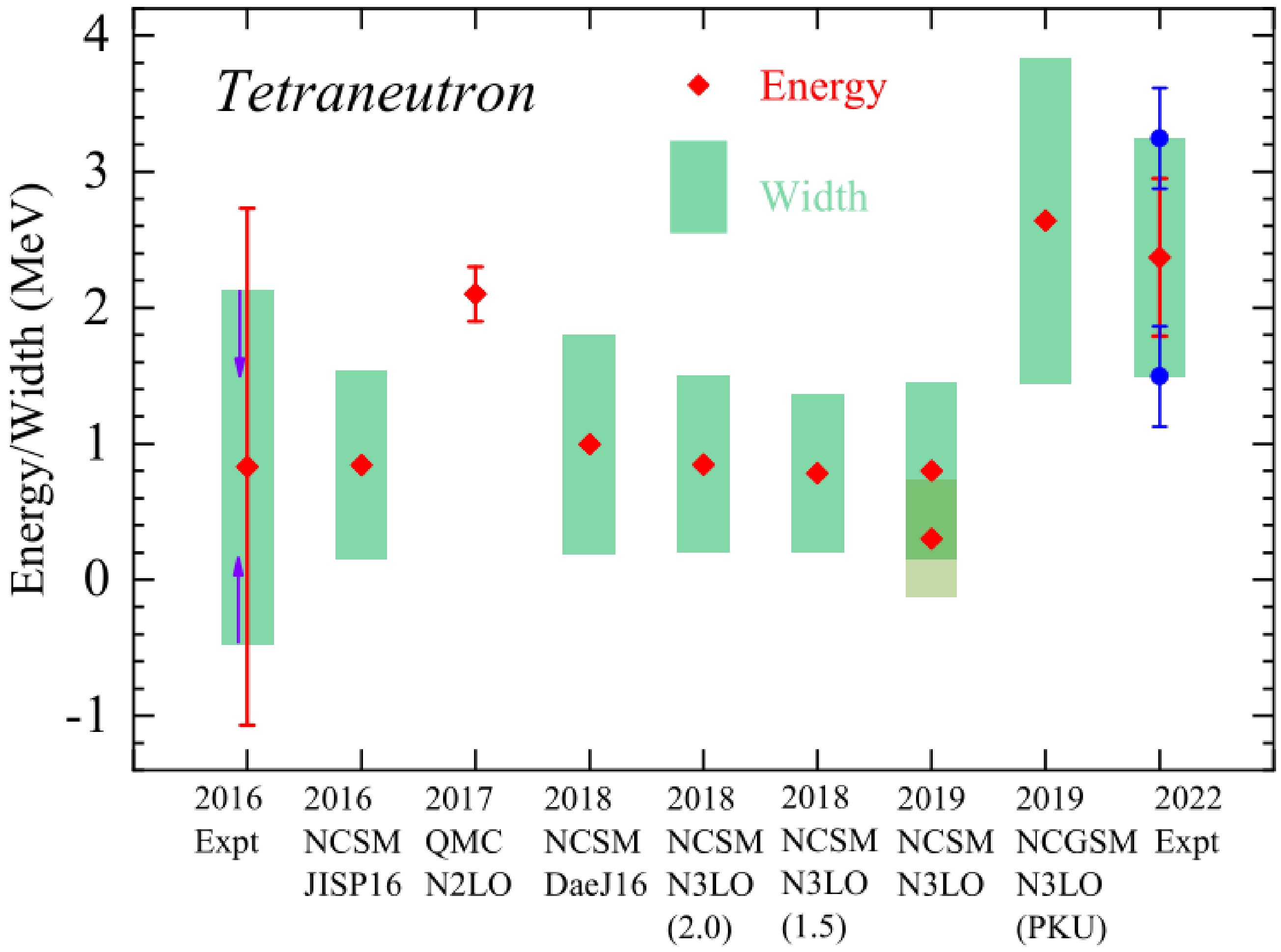






The History of Tetraneutron



- ✓ 2016 Expt : *Kisamori et al., PRL 116, 044006 (2016)*
- ✓ 2016 NCSM: *A. M. Shirokov,et al, PRL 117,182502 (2016)*
- ✓ 2017 QMC : *S. Gandofi, et al., PRL 118, 232501(2017)*
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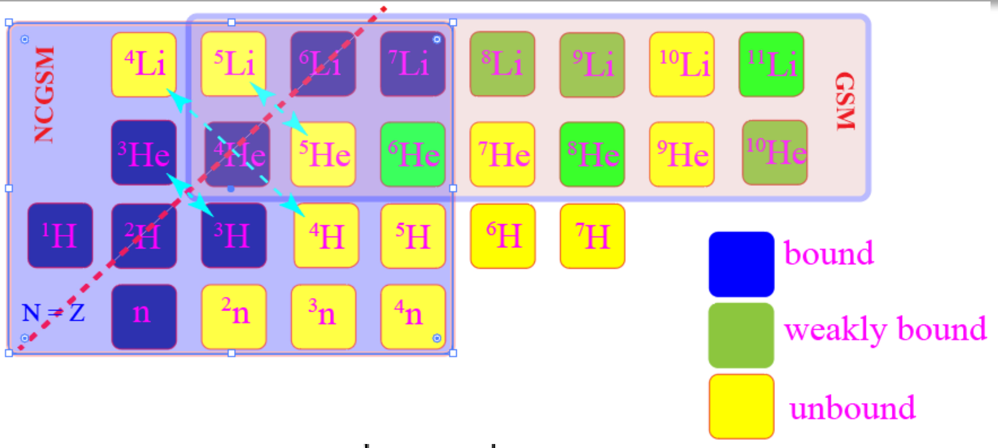
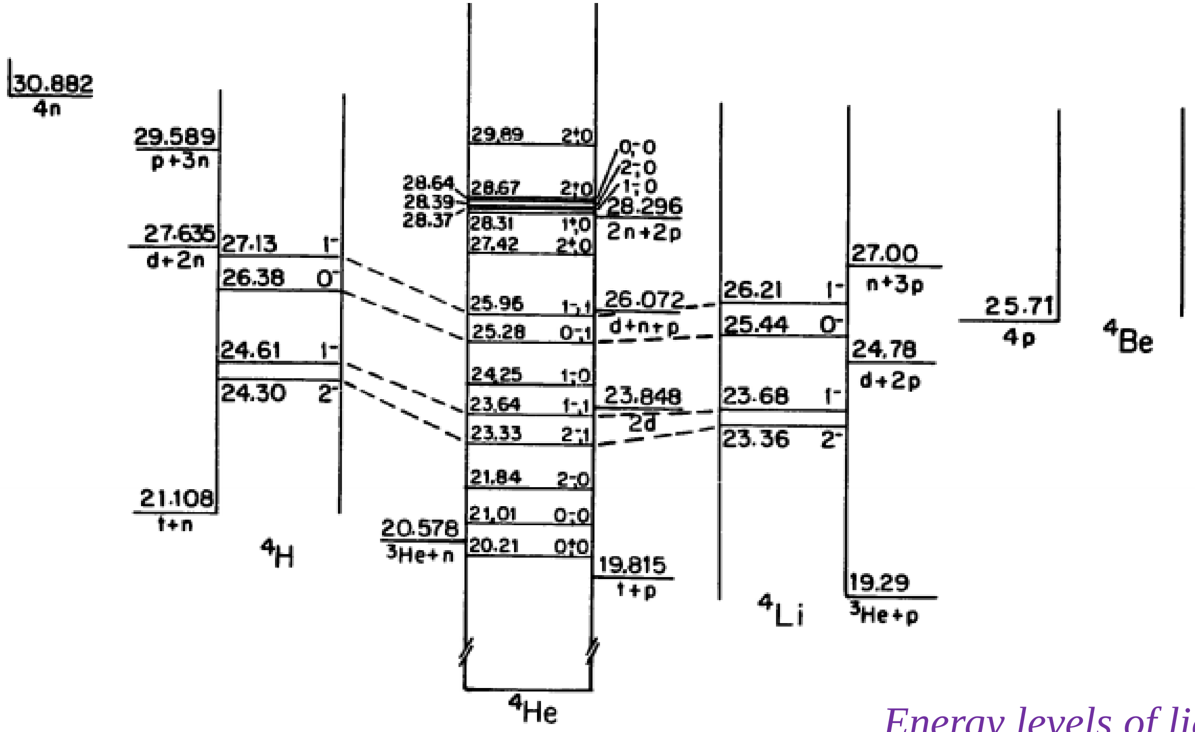
- ✓ 2019 NCSM : *A. M. Shirokov Presentation in Nanjing@China 2019*
- ✓ **2019 NCGSM** : ***J. G. Li****, N. Michel, B. S. Hu, W. Zuo, and F. R. Xu*, Phys. Rev. C 100, 054313 (2019)*
- ✓ 2022 Expt : *M. Duer et al. Nature 606, pages678–682 (2022)*

A = 4 (^{4}H, ^{4}He and ^{4}Li) nuclear systems





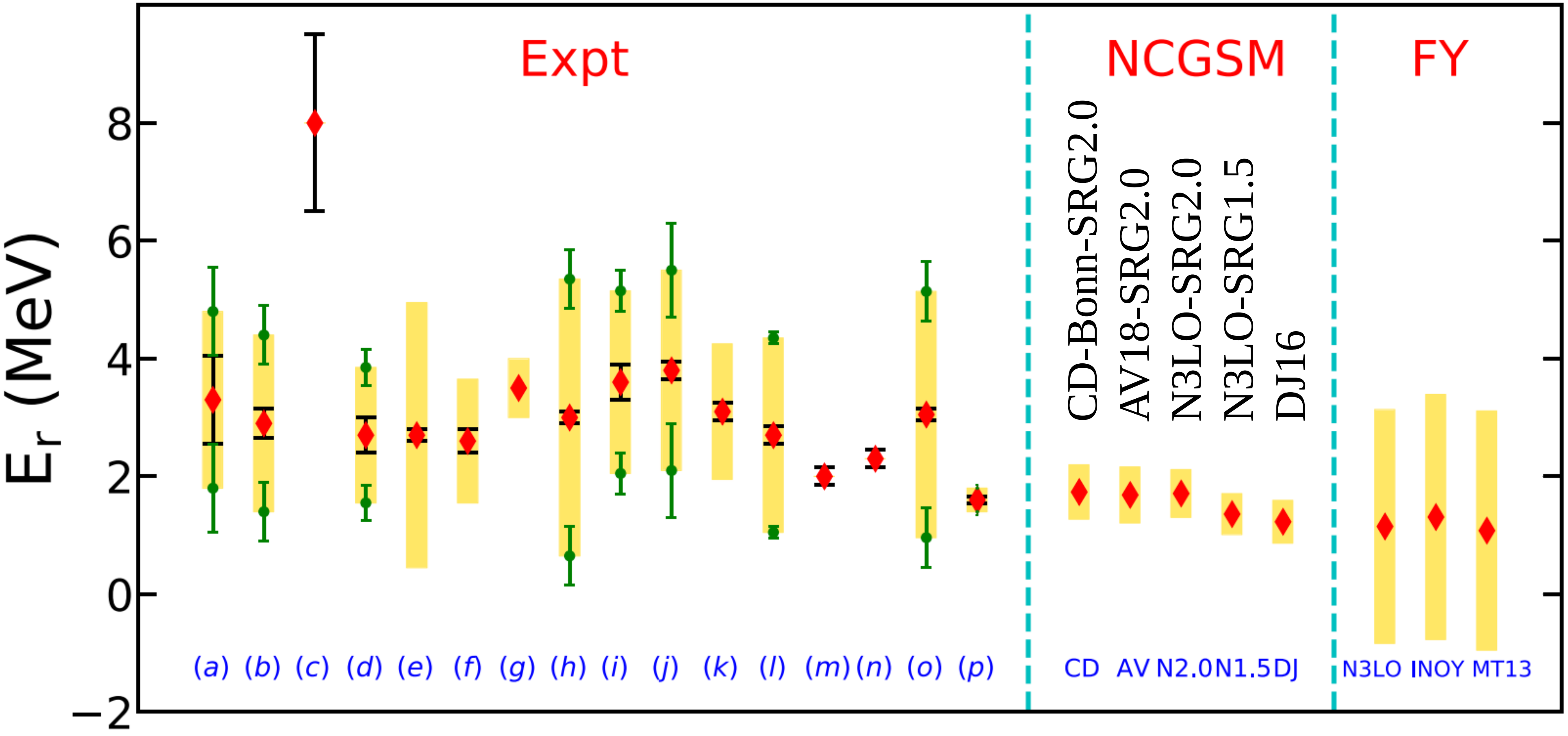
- ✓ ^{4}Li, ^{4}He and ^{4}H, all the states, except the ground state of ^{4}He, are unbound bearing broad widths.

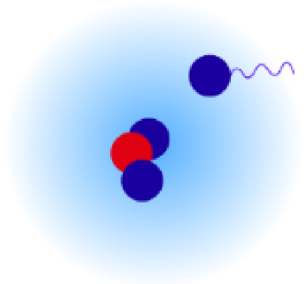
- ✓ The experimental energies and widths of the ground state of ^{4}H and ^{4}Li are either not very conclusive or even contraction.

- ✓ The T = 1 isospin multiplet states: the ground states of ^{4}Li and ^{4}H, and the excietd state of ^{4}He → Isospin symmetry breaking

Energy levels of light nuclei A =4 D.R. Tilley et al. Nucl. Phys. A541 (1992) 1-104

NCGSM calculation of ^4H



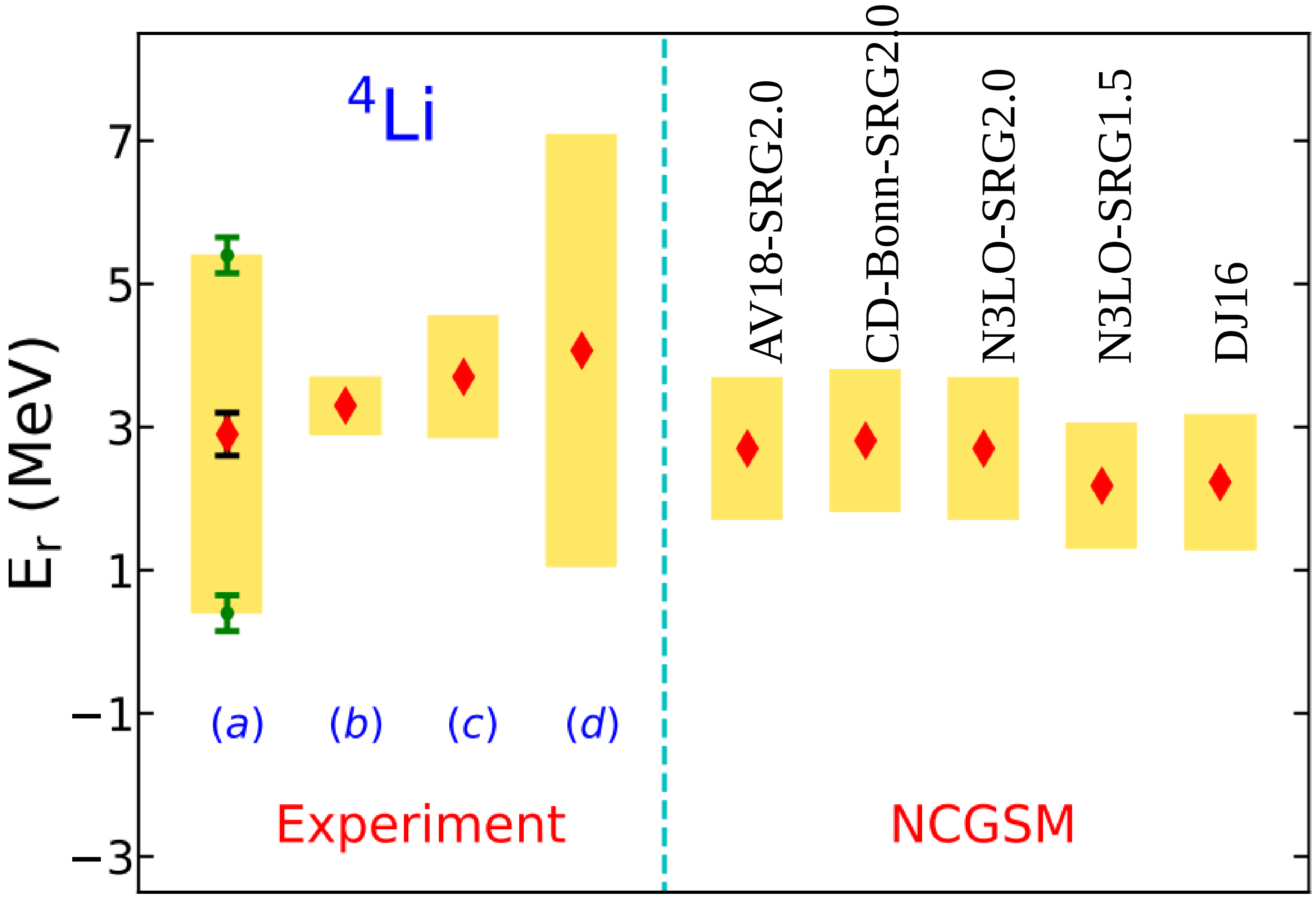


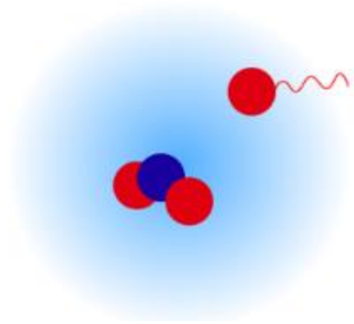
No coulomb force.

Er ~ 1.23-1.74 MeV
Γ ~ 725-951 keV

J.G. Li, *N. Michel, W. Zuo and F.R. Xu*, Phys. Rev. C 104, 024319 (2021)*

Ab initio NCGSM calculation of ^{4}Li



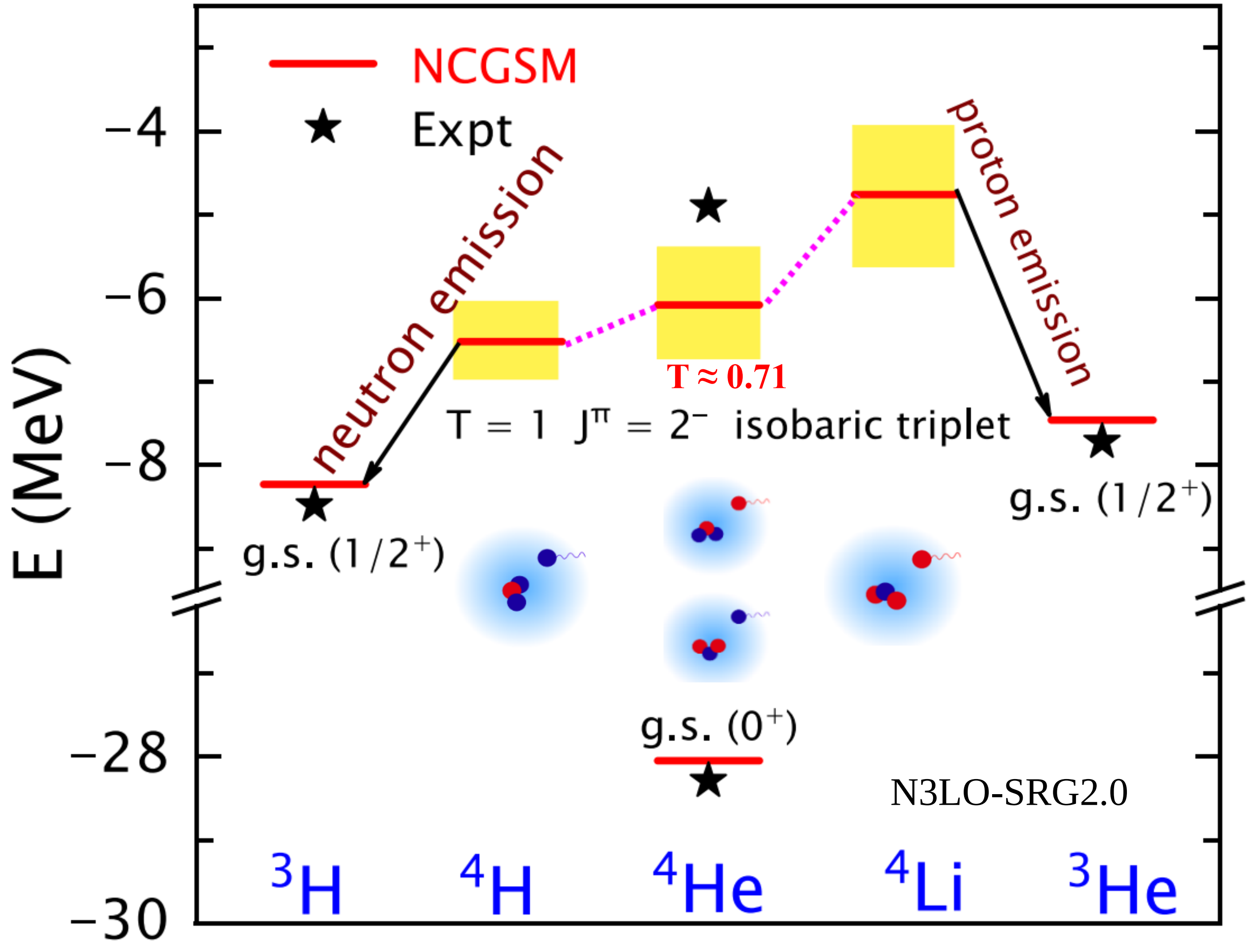


Coulomb force (long-range) need to be well treated.

Er ~ 2.23-2.70 MeV
Γ ~ 1881-1972 keV

J.G. Li, N. Michel, W. Zuo and F.R. Xu, Phys. Rev. C 104, 024319 (2021)*

A = 4 (^{4}H, ^{4}He and ^{4}Li) T = 1 state



- ✓ Comparing the calculated spectra of the A = 4 systems , the ground states ^{4}Li (T= 1), ^{4}H (T=1) (2- and 1-) with the ground state of ^{4}He (T = 0) and 2^- (T= 1) excited states.
- ✓ The isospin breaking is mainly caused by the Coulomb force.
- ✓ The energies and widths are both different due to the isospin breaking.
- ✓ The splitting of the T =2 isobaric triplet states.

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Summary

1. The Energy and Width of the Multi-neutron systems (Trineutron and Tetraneutron) are calculated with *ab initio* no-core Gamow shell model (NCGSM).

   ✓ The calculated Energy and Width of the Tetraneutron in NCGSM are both close to the recent experimental data (*Nature 606, 678 (2022)*).
   ✓ The energy and width of Trineutron are both smaller than Tetraneutron in our NCGSM, suggesting that Trineutron would be more possible to be observed than Tetraneutron.

2. The resonant $T = 1$ $J^{\pi} = 2^{-}$ isobaric triplet states of A = 4 nuclei (^{4}H, ^{4}He and ^{4}Li) are investigated with NCGSM.

   ✓ More precise experimental measurements are urgently needed.

Thank you for your attention