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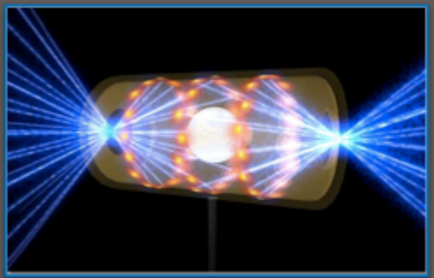
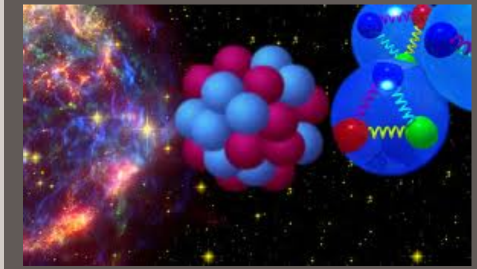
Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

Calculations with chiral forces in no-core shell model with continuum

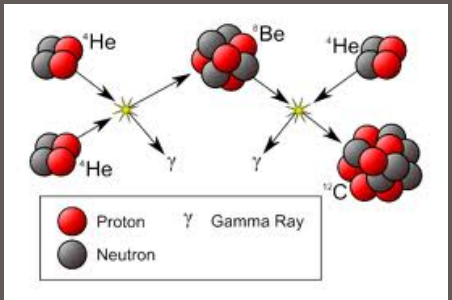


RIBF ULIC Symposium on Perspective in Isospin Physics
~ Role of non-central interactions in structure and dynamics of unstable nuclei ~
27-28th August 2012, RIKEN



Petr Navratil | TRIUMF

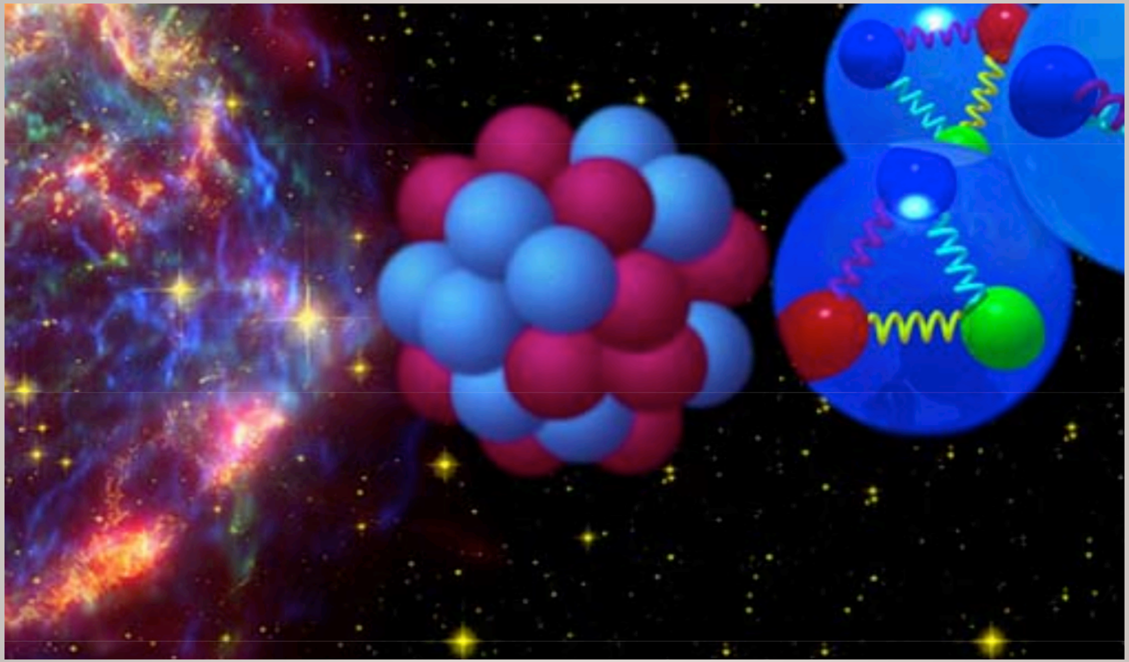
Collaborators: Sofia Quaglioni (LLNL), Robert Roth (TU Darmstadt), S. Baroni (ULB), C. Romero-Redondo (TRIUMF), M. Kruse (UA), J. Langhammer (TU Darmstadt), G. Hupin (LLNL), W. Horiuchi (Hokkaido)



Outline

Ab initio calculations of nuclear structure and reactions

Connection to Astrophysics

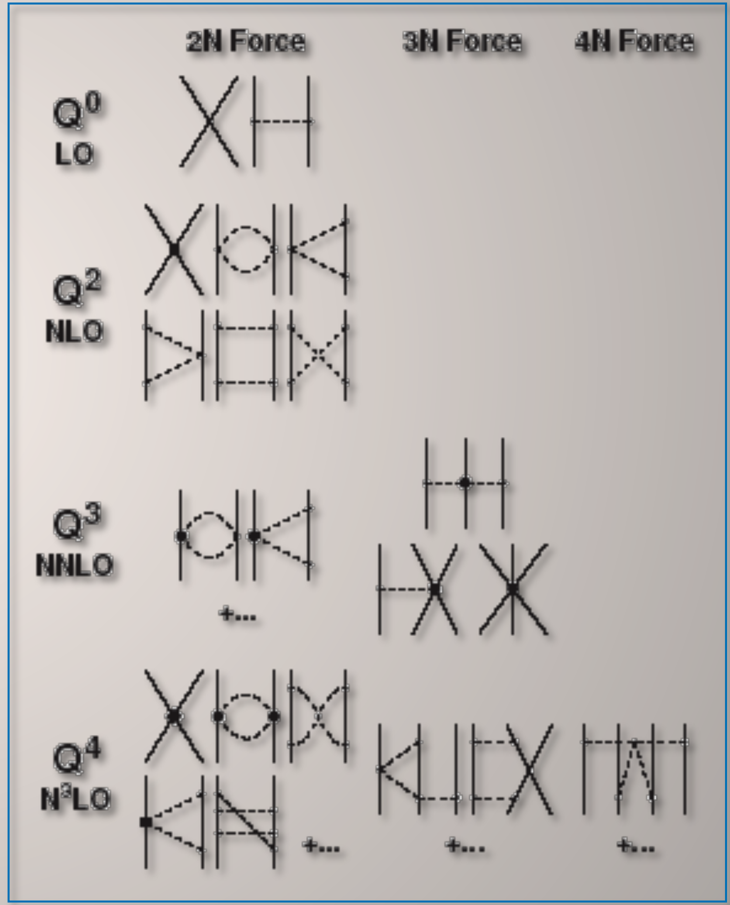


Connection to QCD

- Chiral forces
- No-core shell model, NCSM/RGM
  - Neutron rich He isotopes, N-^{4}He scattering, ^{12}C structure
- No-core shell model with continuum (NCSMC):
  - Unbound ^{7}He

Chiral Effective Field Theory

- **First principles for Nuclear Physics:**
  QCD
  - Non-perturbative at low energies
  - Lattice QCD in the future
- ***For now a good place to start:***
- Inter-nucleon forces from chiral effective field theory
  - Based on the symmetries of QCD
    - Chiral symmetry of QCD ($m_u \approx m_d \approx 0$), spontaneously broken with pion as the Goldstone boson
    - Degrees of freedom: nucleons + pions
  - Systematic low-momentum expansion to a given order (Q/Λ_χ)
  - Hierarchy
  - Consistency
  - Low energy constants (LEC)
    - Fitted to data
    - Can be calculated by lattice QCD

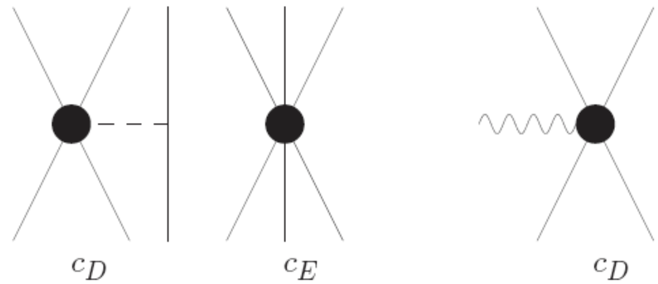


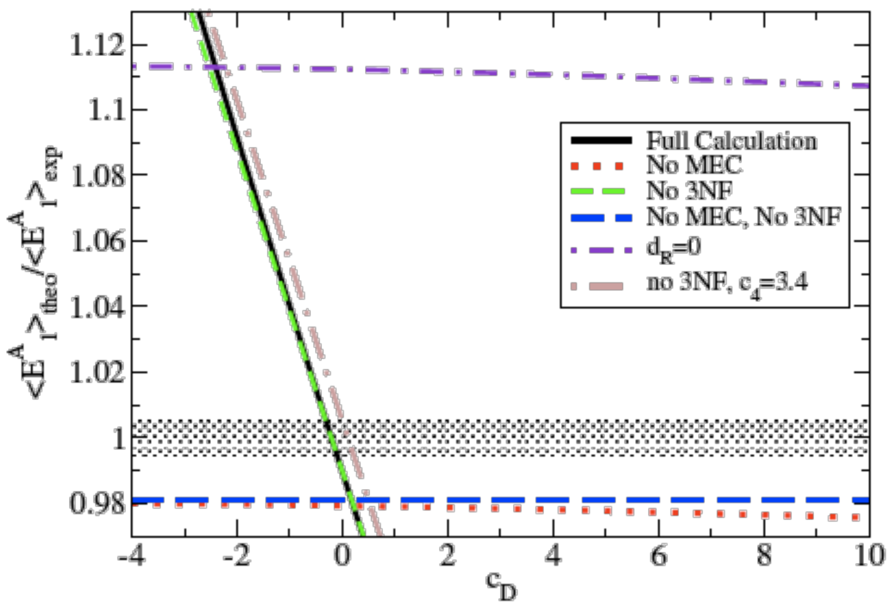
Λ_χ~1 GeV :
Chiral symmetry breaking scale

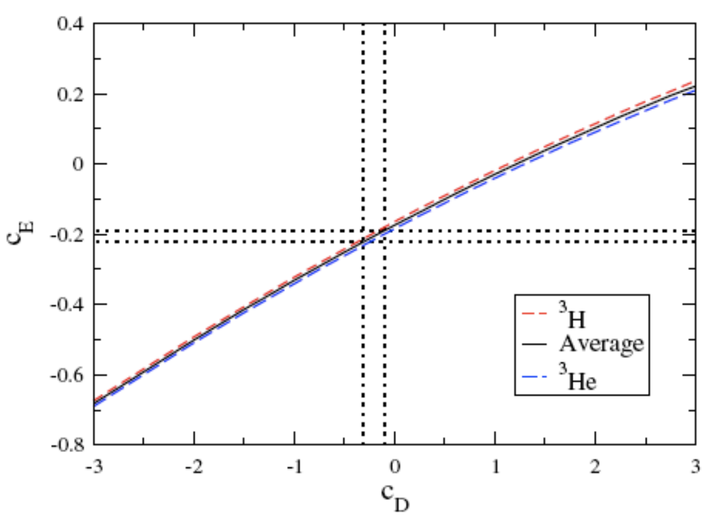
Determination of NNN constants c_D and c_E from the triton binding energy and the half life

- **Chiral EFT**: c_D also in the two-nucleon contact vertex with an external probe
- Calculate $\langle E_1^A \rangle = |\langle {}^3\mathrm{He}||E_1^A||{}^3\mathrm{H}\rangle|$
  - Leading order GT
  - N^2LO: one-pion exchange plus contact
- *A*=3 binding energy constraint:

c_D=-0.2±0.1 c_E =-0.205±0.015







PRL 103, 102502 (2009) PHYSICAL REVIEW LETTERS week ending 4 SEPTEMBER 2009

Three-Nucleon Low-Energy Constants from the Consistency of Interactions and Currents in Chiral Effective Field Theory

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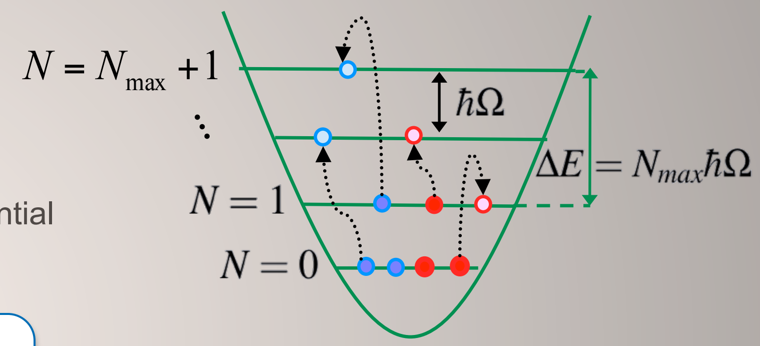
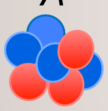
No-core shell model combined with the resonating group method (NCSM/RGM)

- **The NCSM:** An approach to the solution of the A-nucleon bound-state problem
  - Accurate nuclear Hamiltonian
  - Finite harmonic oscillator (HO) basis
    - Complete $N_{max}\hbar\Omega$ model space
  - Effective interaction due to the model space truncation
    - Similarity-Renormalization-Group evolved NN(+NNN) potential
  - Short & medium range correlations
  - No continuum



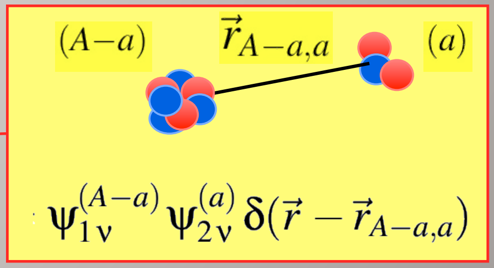
A



$$\Psi^A = \sum_{N=0}^{N_{\max}} \sum_i c_{Ni} \Phi_{Ni}^A$$

- **The RGM:** A microscopic approach to the A-nucleon scattering of clusters
  - Long range correlations, relative motion of clusters

$$\Psi^{(A)} = \sum_\nu \int d\vec{r}\, \varphi_\nu(\vec{r})\, \hat{\mathcal{A}}\, \Phi_{\nu\vec{r}}^{(A-a,a)}$$



***Ab initio* NCSM/RGM**: Combines the best of both approaches
Accurate nuclear Hamiltonian, consistent cluster wave functions
Correct asymptotic expansion, Pauli principle and translational invariance

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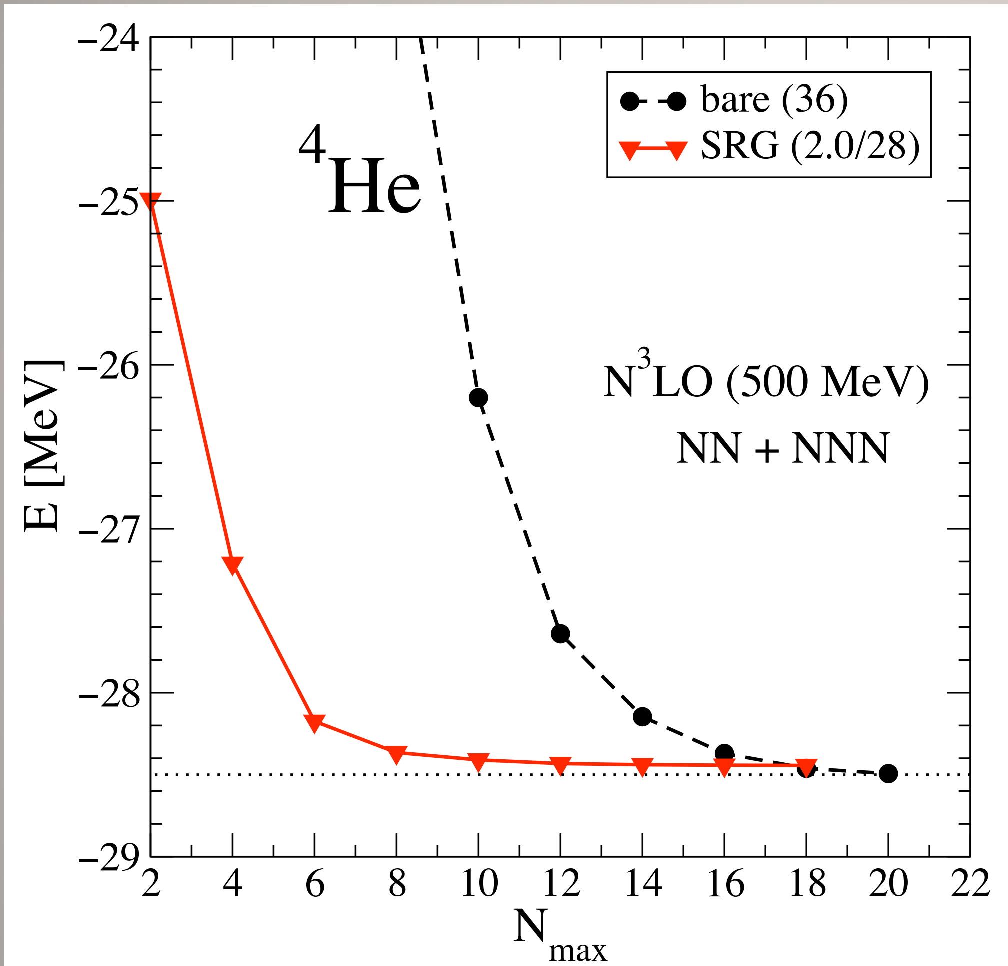
^{4}He from chiral EFT interactions: g.s. energy convergence



PRL 103, 082501 (2009) PHYSICAL REVIEW LETTERS week ending 21 AUGUST 2009

Evolution of Nuclear Many-Body Forces with the Similarity Renormalization Group

E. D. Jurgenson,[1] P. Navrátil,[2] and R. J. Furnstahl[1]

A=3 binding energy and half life constraint
c_D=-0.2, c_E=-0.205, Λ=500 MeV

Chiral N^{3}LO NN plus N^{2}LO NNN potential

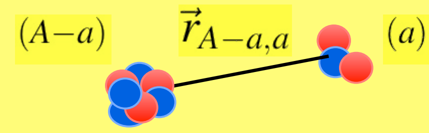
- Bare interaction (black line)
  - Strong short-range correlations
    - Large basis needed
- SRG evolved effective interaction (red line)
  - Unitary transformation

$$H_\alpha = U_\alpha H U_\alpha^+ \Rightarrow \frac{dH_\alpha}{d\alpha} = \left[\left[T, H_\alpha\right], H_\alpha\right] \quad \left(\alpha = 1/\lambda^4\right)$$

  - Two- plus *three*-body components, *four*-body omitted
  - Softens the interaction
    - Smaller basis sufficient

The *ab initio* NCSM/RGM in a snapshot

- Ansatz: $$\Psi^{(A)} = \sum_{\nu} \int d\vec{r}\, \varphi_\nu(\vec{r})\, \hat{\mathcal{A}}\, \Phi^{(A-a,a)}_{\nu\vec{r}}$$



$$\psi^{(A-a)}_{1\nu}\,\psi^{(a)}_{2\nu}\,\delta(\vec{r}-\vec{r}_{A-a,a})$$

eigenstates of $H_{(A-a)}$ and $H_{(a)}$ in the *ab initio* NCSM basis

- Many-body Schrödinger equation:

$$H\Psi^{(A)} = E\Psi^{(A)}$$

$$T_{\rm rel}(r) + \mathcal{V}_{\rm rel} + \bar{V}_{\rm Coul}(r) + H_{(A-a)} + H_{(a)}$$

realistic nuclear Hamiltonian

$$\sum_{\nu} \int d\vec{r} \left[\mathcal{H}^{(A-a,a)}_{\mu\nu}(\vec{r}\,',\vec{r}) - E\mathcal{N}^{(A-a,a)}_{\mu\nu}(\vec{r}\,',\vec{r}) \right] \varphi_\nu(\vec{r}) = 0$$

$$\langle \Phi^{(A-a,a)}_{\mu\vec{r}\,'} | \hat{\mathcal{A}} H \hat{\mathcal{A}} | \Phi^{(A-a,a)}_{\nu\vec{r}} \rangle$$

Hamiltonian kernel

$$\langle \Phi^{(A-a,a)}_{\mu\vec{r}\,'} | \hat{\mathcal{A}}^2 | \Phi^{(A-a,a)}_{\nu\vec{r}} \rangle$$

Norm kernel

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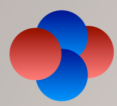
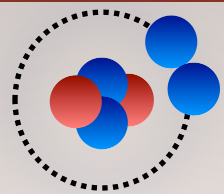
NNN interaction effects in neutron rich nuclei: He isotopes

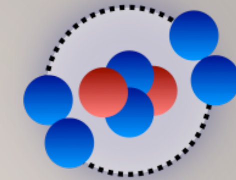
^{4}He



^{6}He



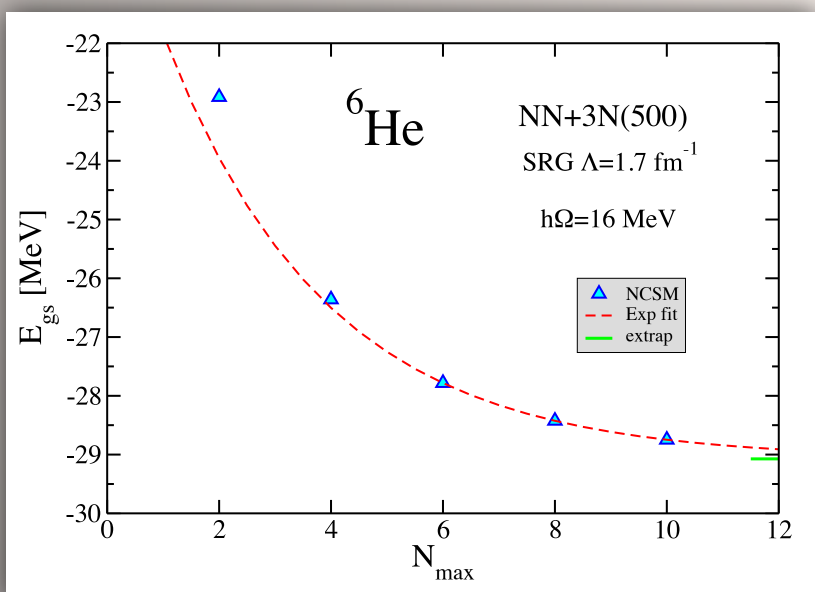
^{8}He

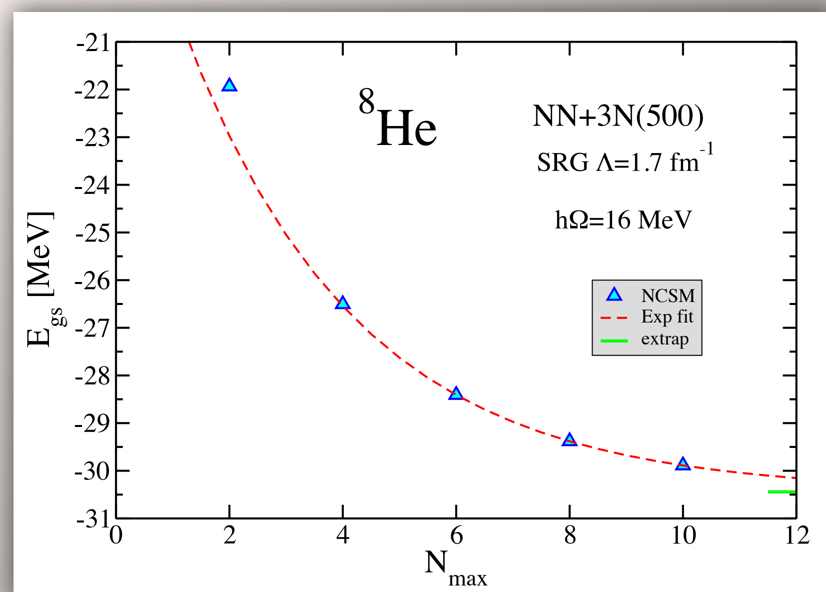


^{6}He and ^{8}He with SRG-evolved chiral N^{3}LO NN + N^{2}LO NNN

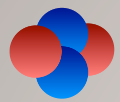
A=3 binding energy & half life constraint
c_D=-0.2, c_E=-0.205, Λ=500 MeV

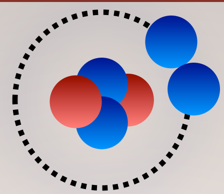
- 3N matrix elements in coupled-*J* single-particle basis:
  - Introduced and implemented by Robert Roth *et al.*
  - Now also in my codes: Jacobi-Slater-Determinant transformation & NCSD code
  - Example: ^{6}He, ^{8}He NCSM calculations up to N_{max}=10 done with moderate resources

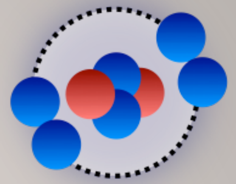




3N interaction effects in neutron rich nuclei: He isotopes

^{4}He 

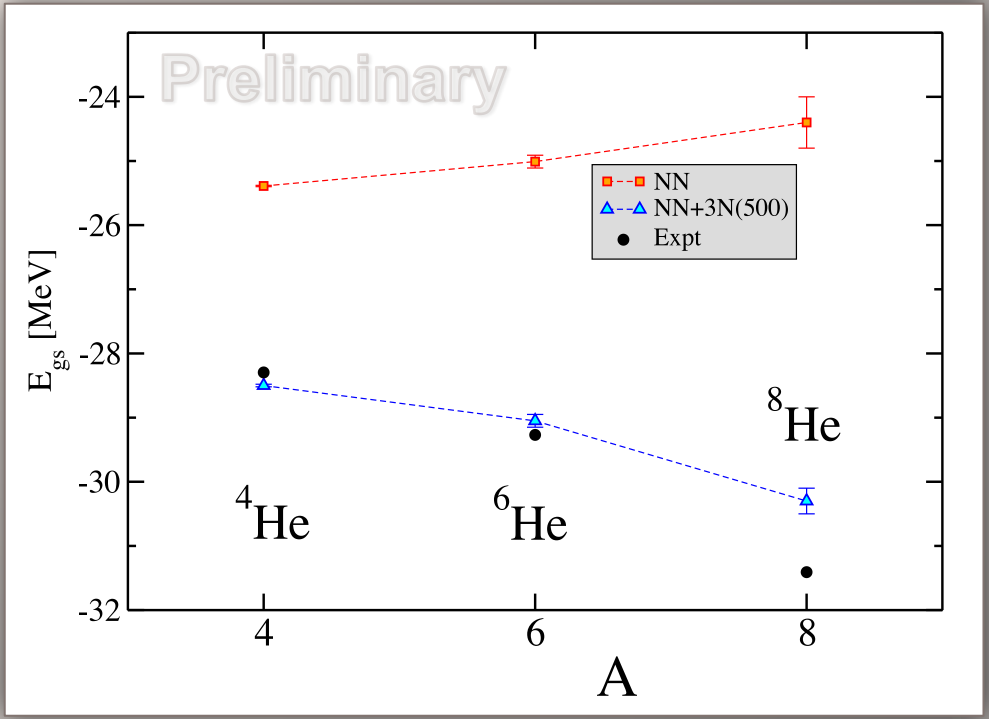
^{6}He 

^{8}He 

- ^{6}He and ^{8}He with SRG-evolved chiral N^{3}LO NN + N^{2}LO 3N
  - chiral N^{3}LO NN: ^{4}He underbound, ^{6}He and ^{8}He unbound
  - chiral N^{3}LO NN + N^{2}LO 3N(500): ^{4}He OK, both ^{6}He and ^{8}He bound

A=3 binding energy & half life constraint
c_D=-0.2, c_E=-0.205, Λ=500 MeV

NNN interaction important to bind neutron rich nuclei



3N interaction effects in neutron rich nuclei: He isotopes

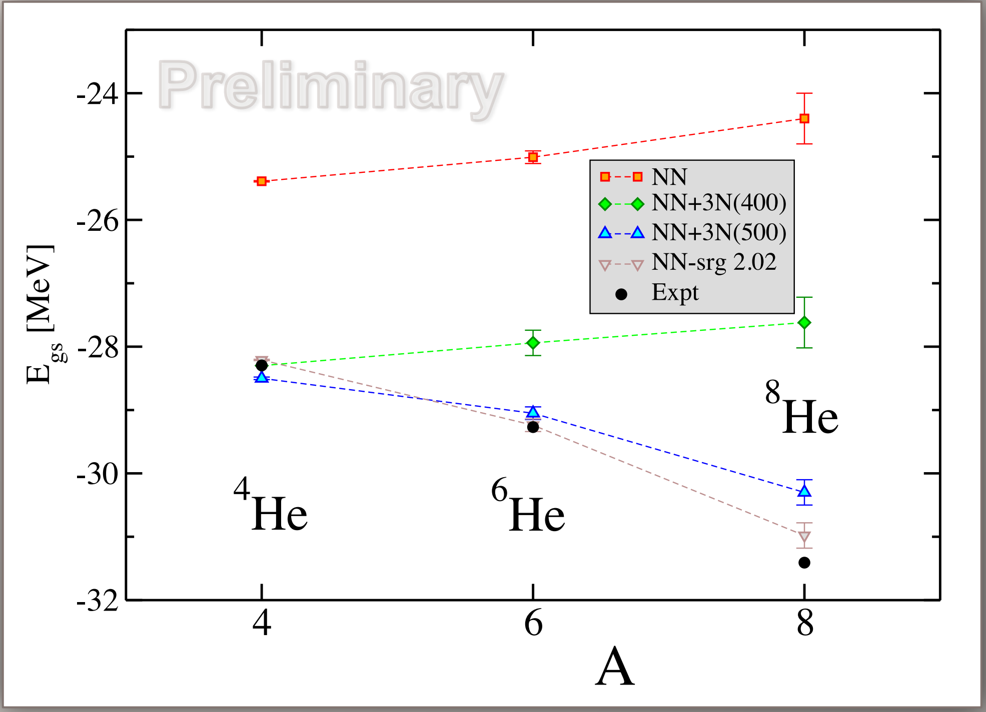
- ^{6}He and ^{8}He with SRG-evolved chiral N^{3}LO NN + N^{2}LO 3N
  - chiral N^{3}LO NN: ^{4}He underbound, ^{6}He and ^{8}He unbound
  - chiral N^{3}LO NN + N^{2}LO 3N(400): ^{4}He fitted, ^{6}He barely unbound, ^{8}He unbound
    - describes quite well binding energies of ^{12}C, ^{16}O, ^{40}Ca, ^{48}Ca
  - chiral N^{3}LO NN + N^{2}LO 3N(500): ^{4}He OK, both ^{6}He and ^{8}He bound
    - does well up to A=10, overbinds ^{12}C, ^{16}O, Ca isotopes
  - SRG-N^{3}LO NN Λ=2.02 fm^{-1}: ^{4}He OK, both ^{6}He and ^{8}He bound
    - ^{16}O, Ca strongly overbound

^{4}He binding energy & ^{3}H half life constraint
c_D=-0.2, c_E=+0.098, Λ=400 MeV

A=3 binding energy & half life constraint
c_D=-0.2, c_E=-0.205, Λ=500 MeV

NNN interaction important to bind neutron rich nuclei

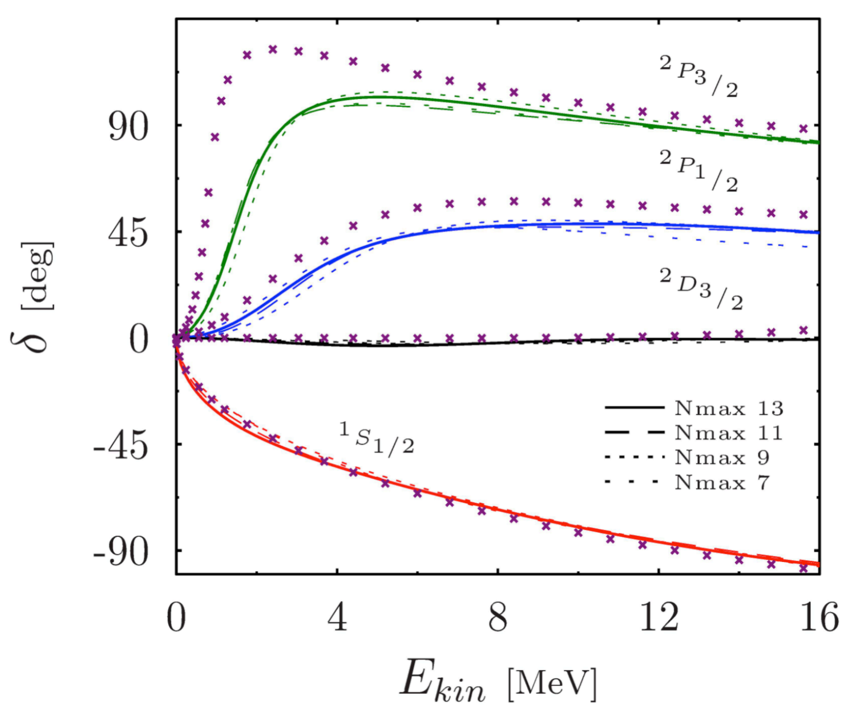
Our knowledge of the 3N interaction is incomplete



N-^{4}He scattering with NN+NNN interactions

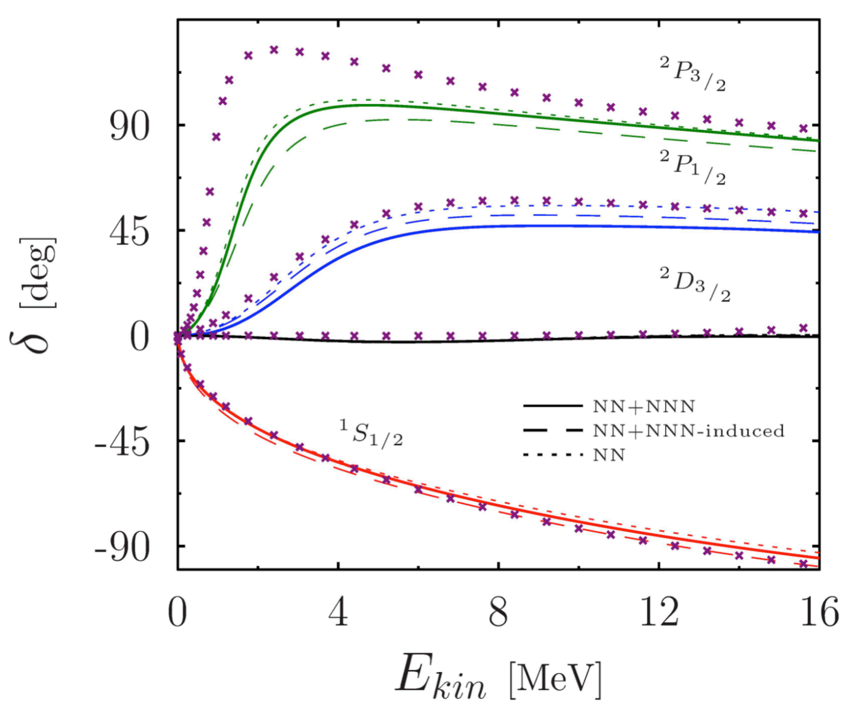
G. Hupin, J. Langhammer, S. Quaglioni, P. Navratil, R. Roth, work in progress

^{4}He(n,n)^{4}He phase shifts



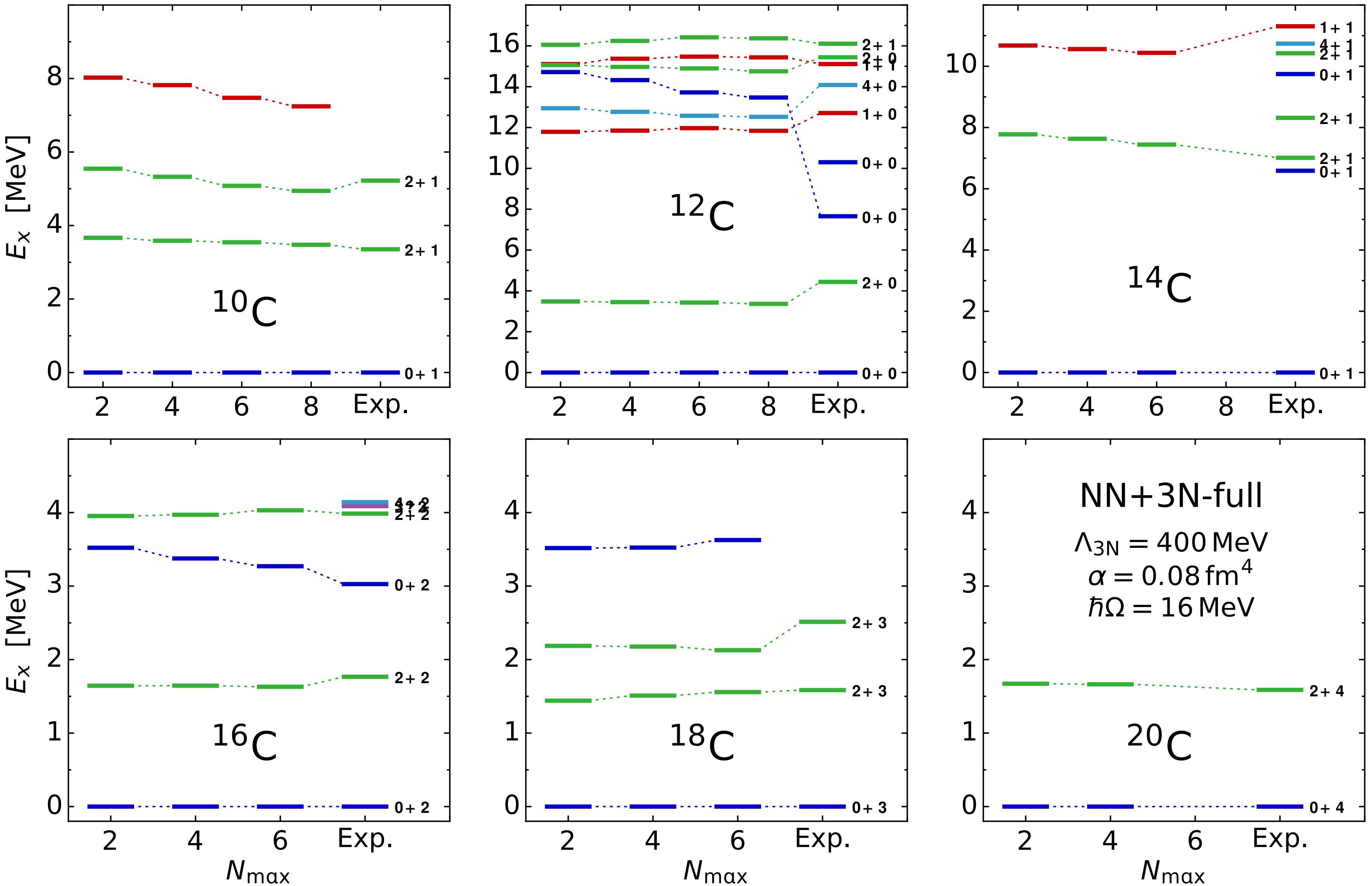
Here:
n + ^{4}He(g.s.), SRG-(N^{3}LO NN + N^{2}LO NNN) potential with (λ=2 fm^{-1}). Convergence with respect to HO basis size (N_{max})

^{4}He(n,n)^{4}He phase shifts

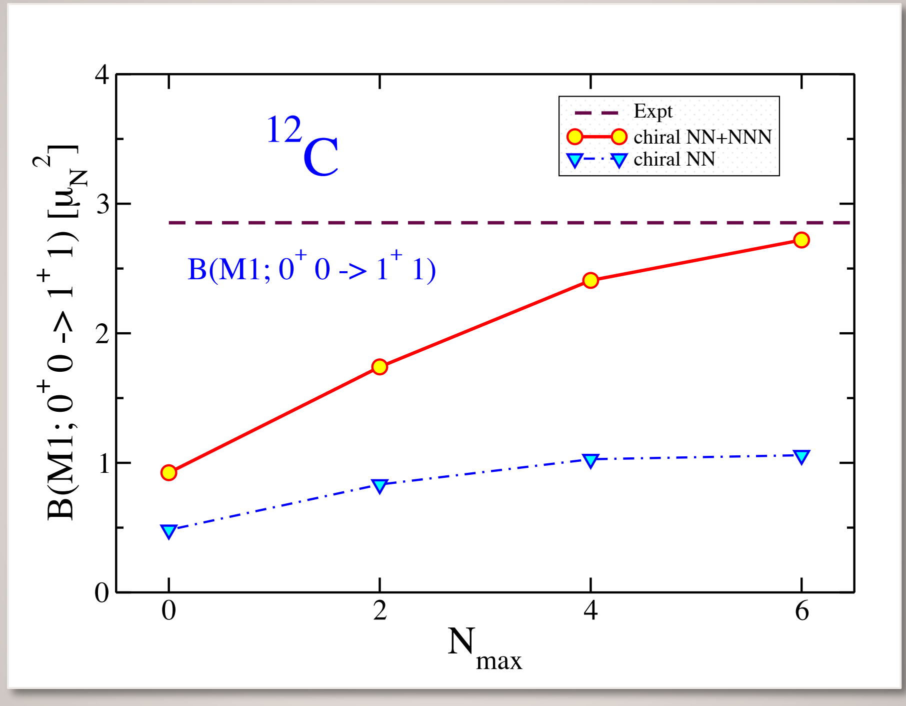


Largest splitting between *P* waves obtained with NN+NNN. Need ^{4}He exited states and study with respect to SRG λ

Neutron rich Carbon isotopes from chiral NN+NNN interactions (IT-NCSM, R. Roth *et al.*)



M1 transitions in ^{12}C sensitive to 3N interaction



Chiral 3N interaction changes occupations of the $p_{3/2}$ and $p_{1/2}$ orbits
("increases the gap" between them)
Enhances the M1 transition from the g.s. to 1^+ 1 state

Similar increase of the Gamow-Teller transition between g.s. of $^{12}B(^{12}N)$ and ^{12}C

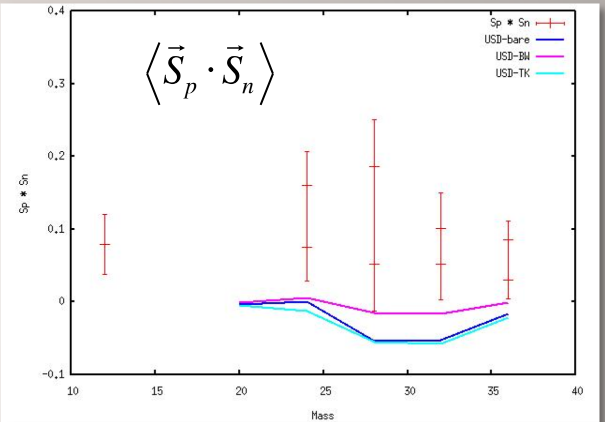
Tensor correlations and 3N effects in ground states of ^{4}He and ^{12}C

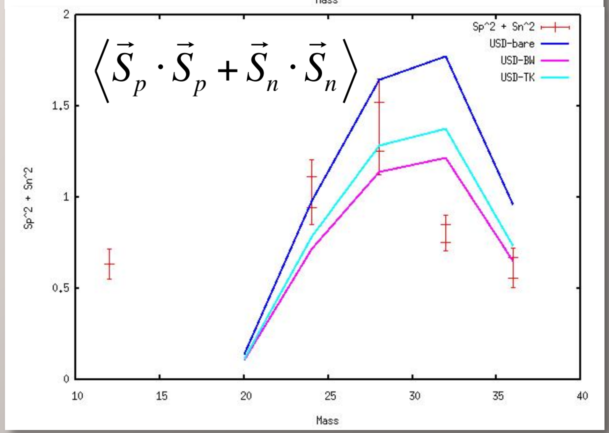
- Tensor correlations related to $\langle \vec{S}_p \cdot \vec{S}_n \rangle$ and $\langle \vec{S}_p \cdot \vec{S}_p + \vec{S}_n \cdot \vec{S}_n \rangle$
  - $\vec{S}_p = \frac{1}{2}\sum_{i=1}^{A}(\frac{1}{2}+t_{z,i})\,\vec{\sigma}_i \quad , \quad \vec{S}_n = \frac{1}{2}\sum_{i=1}^{A}(\frac{1}{2}-t_{z,i})\,\vec{\sigma}_i$ … spin operators

- Experiment: Atsushi Tamii *et al.*

- *Ab initio* NCSM:
  - ^{12}C N_{max}=6 only

	$\langle \vec{S}_p \cdot \vec{S}_p + \vec{S}_n \cdot \vec{S}_n \rangle$	$\langle \vec{S}_p \cdot \vec{S}_n \rangle$	$\langle \vec{S}^2 \rangle$
^{4}He Minnesota NN	0.04	-0.02	0
^{4}He chiral NN	0.19	0.04	0.27
^{4}He chiral NN+3N(500)	0.22	0.05	0.32
^{12}C chiral NN	0.50	0.065	0.63
^{12}C chiral NN+3N(400)	0.68	0.061	0.80
^{12}C chiral NN+3N(500)	1.01	0.065	1.14

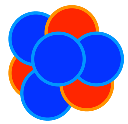




^{12}C: chiral NN+3N(400)
the best agreement with experiment

New developments: NCSM with continuum

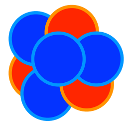
NCSM



$$\left|\Psi_A^{J^\pi T}\right\rangle = \sum_{Ni} c_{Ni} \left|ANiJ^\pi T\right\rangle$$

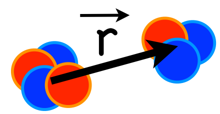
New developments: NCSM with continuum

NCSM



$$\left|\Psi_A^{J^\pi T}\right\rangle = \sum_{Ni} c_{Ni} \left|ANiJ^\pi T\right\rangle$$

NCSM/RGM



$$|\Psi_A^{J^\pi T}\rangle = \sum_\nu \int d\vec{r} \chi_\nu(\vec{r}) \hat{A} \Phi_{\nu\vec{r}}^{J^\pi T(A-a,a)}$$

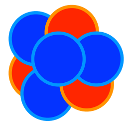
$$\mathcal{H}\chi = E\mathcal{N}\chi$$

$$\bar{\chi} = \mathcal{N}^{+\frac{1}{2}}\chi$$

$$\boxed{(\mathcal{N}^{-\frac{1}{2}}\mathcal{H}\mathcal{N}^{-\frac{1}{2}})\bar{\chi} = E\bar{\chi}}$$

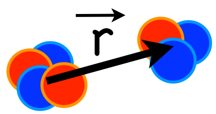
New developments: NCSM with continuum

NCSM



$$\left|\Psi_A^{J^\pi T}\right\rangle = \sum_{Ni} c_{Ni} \left|ANiJ^\pi T\right\rangle$$

NCSM/RGM



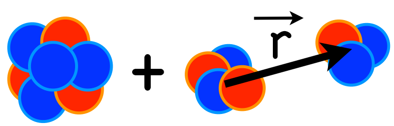
$$|\Psi_A^{J^\pi T}\rangle = \sum_\nu \int d\vec{r} \chi_\nu(\vec{r}) \hat{A} \Phi_{\nu\vec{r}}^{J^\pi T(A-a,a)}$$

$$\mathcal{H}\chi = E\mathcal{N}\chi$$

$$\bar{\chi} = \mathcal{N}^{+\frac{1}{2}}\chi$$

$$(\mathcal{N}^{-\frac{1}{2}}\mathcal{H}\mathcal{N}^{-\frac{1}{2}})\bar{\chi} = E\bar{\chi}$$

NCSMC



$$|\Psi_A^{J^\pi T}\rangle = \sum_\lambda c_\lambda |A\lambda J^\pi T\rangle + \sum_\nu \int d\vec{r} \left(\sum_{\nu'} \int d\vec{r}\,' \mathcal{N}_{\nu\nu'}^{-\frac{1}{2}}(\vec{r},\vec{r}\,')\bar{\chi}_{\nu'}(\vec{r}\,') \right) \hat{A}\Phi_{\nu\vec{r}}^{J^\pi T(A-a,a)}$$

$$\begin{pmatrix} H_{NCSM} & \bar{h} \\ \bar{h} & \mathcal{N}^{-\frac{1}{2}}\mathcal{H}\mathcal{N}^{-\frac{1}{2}} \end{pmatrix} \begin{pmatrix} c \\ \bar{\chi} \end{pmatrix} = E \begin{pmatrix} 1 & \bar{g} \\ \bar{g} & 1 \end{pmatrix} \begin{pmatrix} c \\ \bar{\chi} \end{pmatrix}$$

NCSMC formalism

Start from
$$\begin{pmatrix} H_{NCSM} & \bar{h} \\ \bar{h} & \bar{\mathcal{H}} \end{pmatrix} \begin{pmatrix} c \\ \chi \end{pmatrix} = E \begin{pmatrix} 1 & \bar{g} \\ \bar{g} & 1 \end{pmatrix} \begin{pmatrix} c \\ \chi \end{pmatrix}$$

NCSM sector:
$$(H_{NCSM})_{\lambda\lambda'} = \langle A\lambda J^\pi T|\hat{H}|A\lambda' J^\pi T\rangle = \varepsilon_\lambda^{J^\pi T}\delta_{\lambda\lambda'}$$

NCSM/RGM sector:
$$\overline{\mathcal{H}}_{\nu\nu'}(r,r') = \sum_{\mu\mu'}\int\int dy dy' y^2 y'^2 \mathcal{N}_{\nu\mu}^{-\frac{1}{2}}(r,y)\mathcal{H}_{\mu\mu'}(y,y')\mathcal{N}_{\mu'\nu'}^{-\frac{1}{2}}(y',r')$$

Coupling:
$$\bar{g}_{\lambda\nu}(r) = \sum_{\nu'}\int dr' r'^2 \langle A\lambda J^\pi T|\hat{\mathcal{A}}_{\nu'}\Phi_{\nu' r'}^{J^\pi T}\rangle\, \mathcal{N}_{\nu'\nu}^{-\frac{1}{2}}(r',r)$$

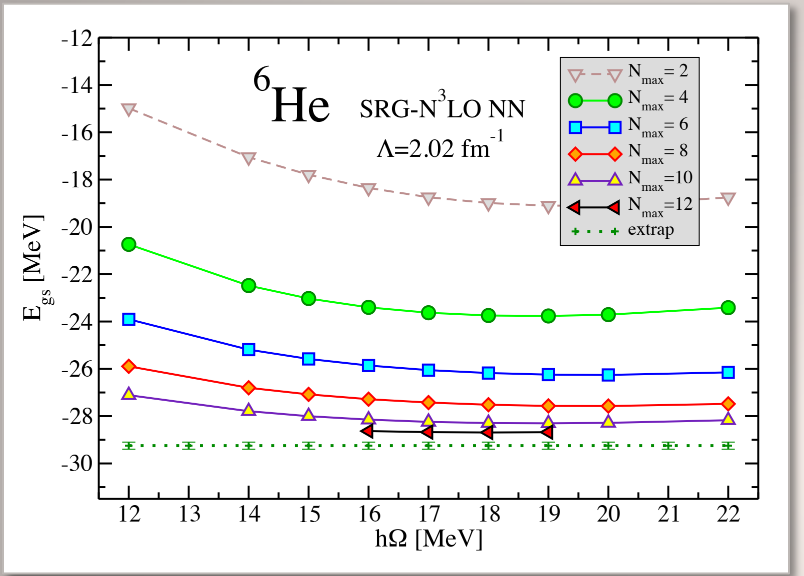
$$\bar{h}_{\lambda\nu}(r) = \sum_{\nu'}\int dr' r'^2 \langle A\lambda J^\pi T|\hat{H}\hat{\mathcal{A}}_{\nu'}|\Phi_{\nu' r'}^{J^\pi T}\rangle\, \mathcal{N}_{\nu'\nu}^{-\frac{1}{2}}(r',r)$$

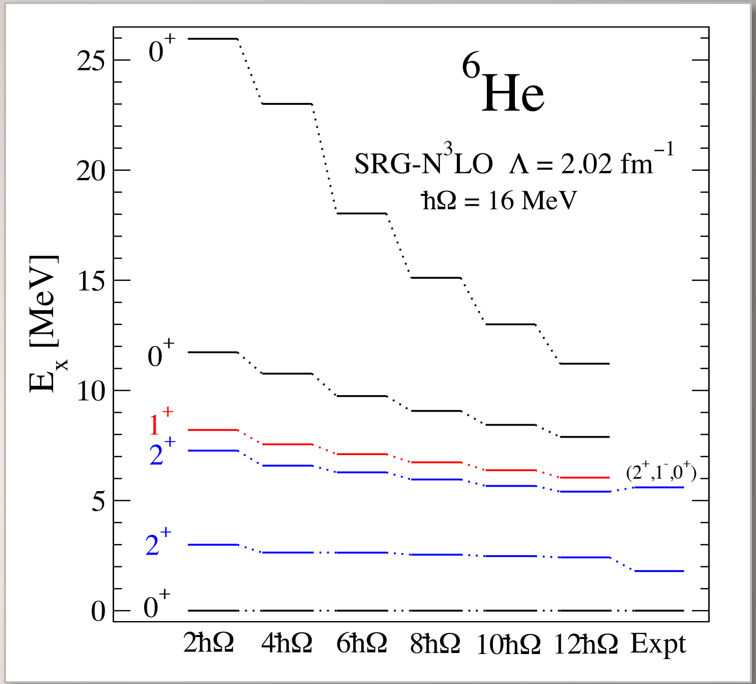
Orthogonalization:
$$N_{\nu r\nu' r'}^{\lambda\lambda'} = \begin{pmatrix} \delta_{\lambda\lambda'} & \bar{g}_{\lambda\nu'}(r') \\ \bar{g}_{\lambda'\nu}(r) & \delta_{\nu\nu'}\frac{\delta(r-r')}{rr'} \end{pmatrix} \qquad \overline{H} = N^{-\frac{1}{2}}\begin{pmatrix} H_{NCSM} & \bar{h} \\ \bar{h} & \mathcal{H} \end{pmatrix} N^{-\frac{1}{2}} \qquad \begin{pmatrix} \bar{c} \\ \bar{\chi} \end{pmatrix} = N^{+\frac{1}{2}}\begin{pmatrix} c \\ \chi \end{pmatrix}$$

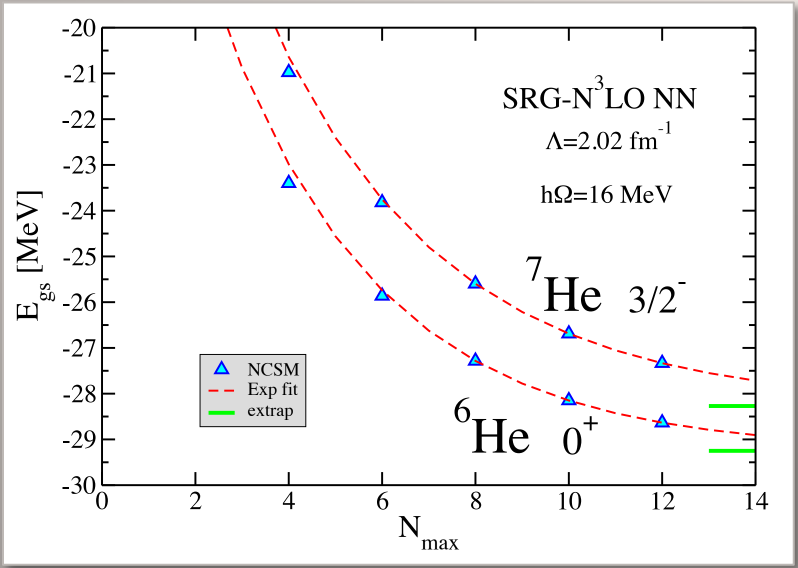
Solve with generalized microscopic R-matrix
$$(\hat{\overline{H}} + \hat{L} - E)\begin{pmatrix} \bar{c} \\ \bar{\chi} \end{pmatrix} = \hat{L}\begin{pmatrix} \bar{c} \\ \bar{\chi} \end{pmatrix}$$

Bloch operator →
$$\hat{L}_\nu = \begin{pmatrix} 0 & 0 \\ 0 & \frac{1}{2}\delta(r-a)(\frac{d}{dr} - \frac{B_\nu}{r}) \end{pmatrix}$$

NCSM calculations of ^{6}He and ^{7}He energies

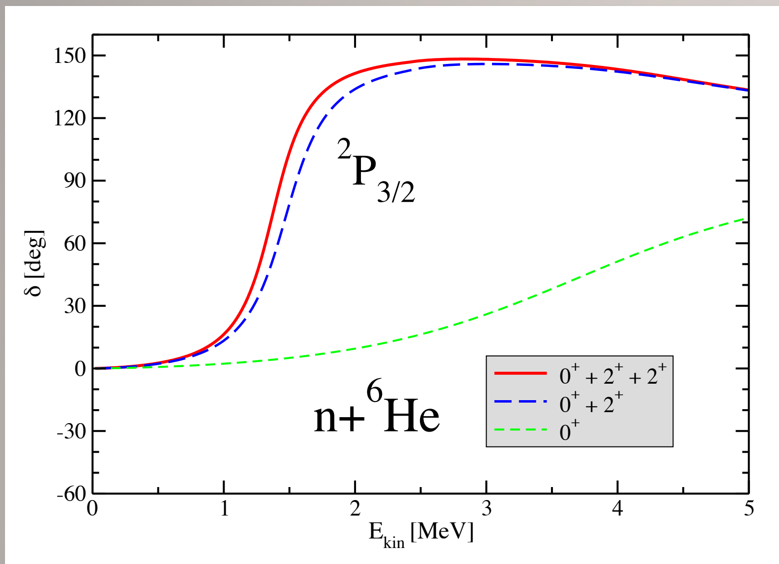


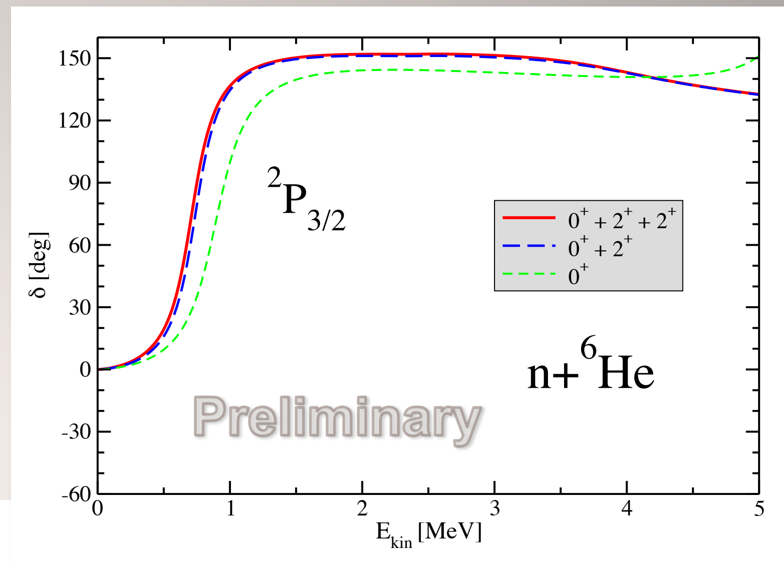




- ✓ N_{max} convergence OK
- ✓ Extrapolation feasible
  - ^{6}He: E_{gs}=-29.25(15) MeV (Expt. -29.269 MeV)
  - ^{7}He: E_{gs}=-28.27(25) MeV (Expt. -28.82(30) MeV)
- ^{7}He unbound (+0.44(3) MeV), width 0.16(3) MeV
  - NCSM: no information about the width
- All ^{6}He excited states above 2^+_1 broad resonances or states in continuum

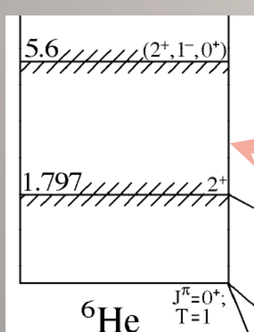
NCSM with continuum: ^{7}He ↔ ^{6}He+n



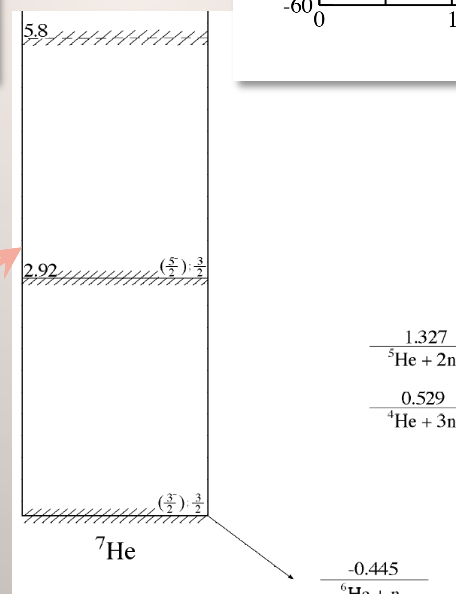


NCSM/RGM
with up to three ^{6}He states

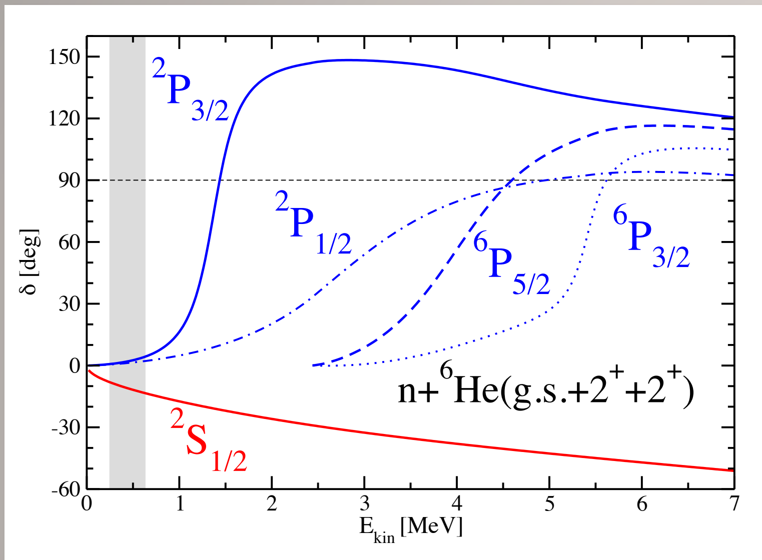
NCSMC
with up to three ^{6}He states
and three ^{7}He eigenstates
More **7-nucleon correlations**
Fewer target states needed



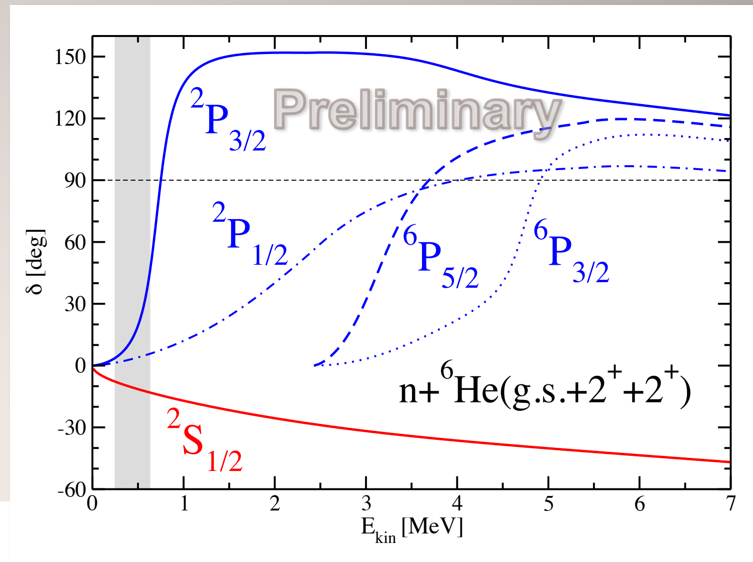
Expt.



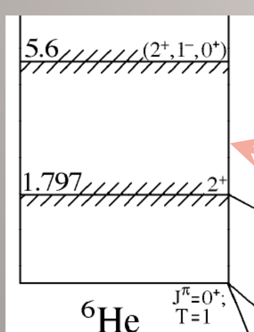
NCSM with continuum: ^{7}He ↔ ^{6}He+n



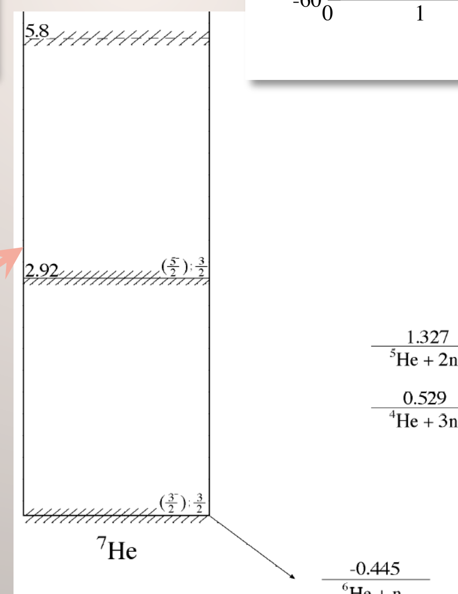
NCSM/RGM
with three ^{6}He states



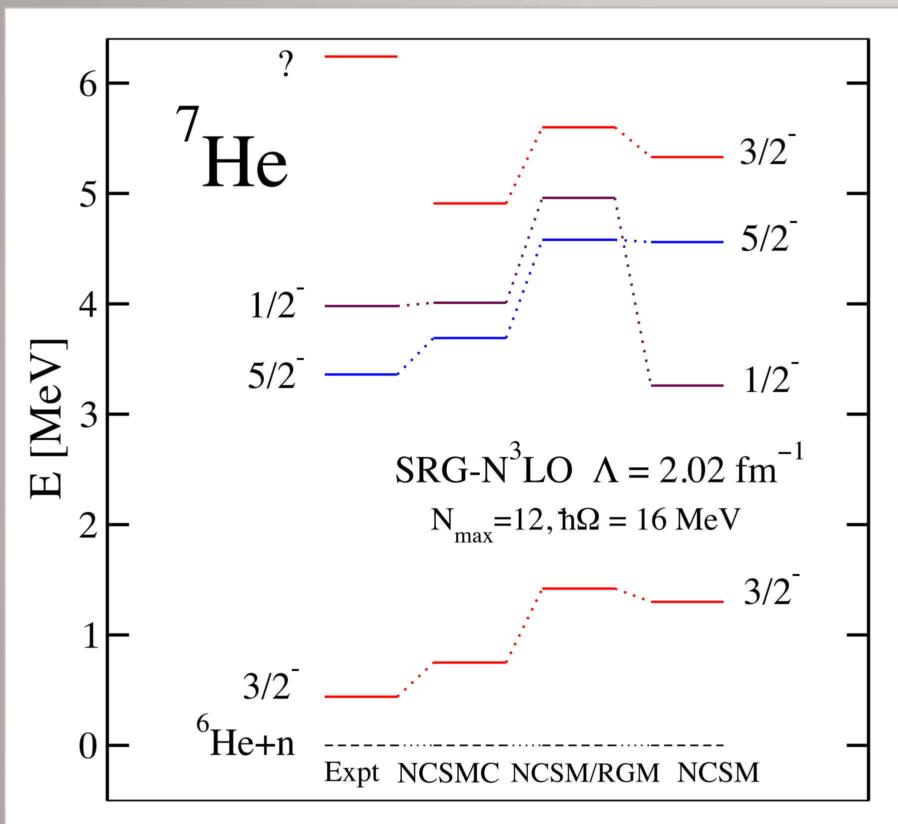
NCSMC
with three ^{6}He states
and three ^{7}He eigenstates
More **7-nucleon correlations**
Fewer target states needed



Expt.



^{7}He: NCSMC vs. NCSM/RGM vs. NCSM



Preliminary

J^π	experiment E	experiment Γ	Ref.	NCSMC E	NCSMC Γ	NCSM/RGM E	NCSM/RGM Γ	NCSM E
$3/2^-$	0.44(3)	0.16(3)	[29]	0.75	0.31	1.42	0.52	1.30
$5/2^-$	3.36(10)	2.2(3)	[30]	3.69	2.57	4.58	3.06	4.56
$1/2^-$	3.98	10	[42]	4.01	15.15	4.96	14.95	3.26
	3.48	2	[38]					

- NCSMC and NSCM/RGM energies from phase shifts at 90 degrees
- NCSMC and NSCM/RGM widths from the derivatives of phase shifts (preliminary)

$$\Gamma = \left.\frac{2}{\partial\delta(E_{kin})/\partial E_{kin}}\right|_{E_{kin}=E_R}$$

Experimental controversy:
Existence of low-lying 1/2$^-$ state
… not seen in these calculations

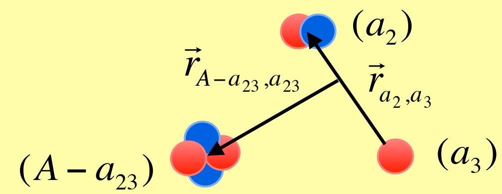
Three-cluster NCSM/RGM

- The starting point:

$$\Psi^{(A)}_{RGM} = \sum_{a_2 a_3 \nu} \int d\vec{x}\, d\vec{y}\; G_\nu^{(A-a_{23},a_2,a_3)}(x,y)$$

$$\times\, \hat{A}^{(A-a_{23},a_2,a_3)} \left| \Phi^{(A-a_{23},a_2,a_3)}_{\nu \vec{x} \vec{y}} \right\rangle$$

$$\rho^{5/2} \sum_K \chi_{\nu K}^{(A-a_{23},a_2,a_3)}(\rho)\, \phi_K^{\ell x \ell y}(\alpha)$$



$$\psi_{\alpha_1}^{(A-a_{23})} \psi_{\alpha_2}^{(a_2)} \psi_{\alpha_3}^{(a_3)} Y^{\ell x, \ell y}(\hat{x},\hat{y})$$

$$\times\, \delta\left(\vec{x} - \vec{r}_{a_2,a_3}\right) \delta\left(\vec{y} - \vec{r}_{A-a_{23},a_{23}}\right)$$

- Solves:

$$\sum_{a_2 a_3 \nu K} \int d\rho\; \rho^5 \left[H^{K',K}_{a'\nu',a\nu}(\rho',\rho) - E\, N^{K',K}_{a'\nu',a\nu}(\rho',\rho) \right] \rho^{-5/2} \chi_{\nu K}^{(A-a_{23},a_2,a_3)}(\rho) = 0$$

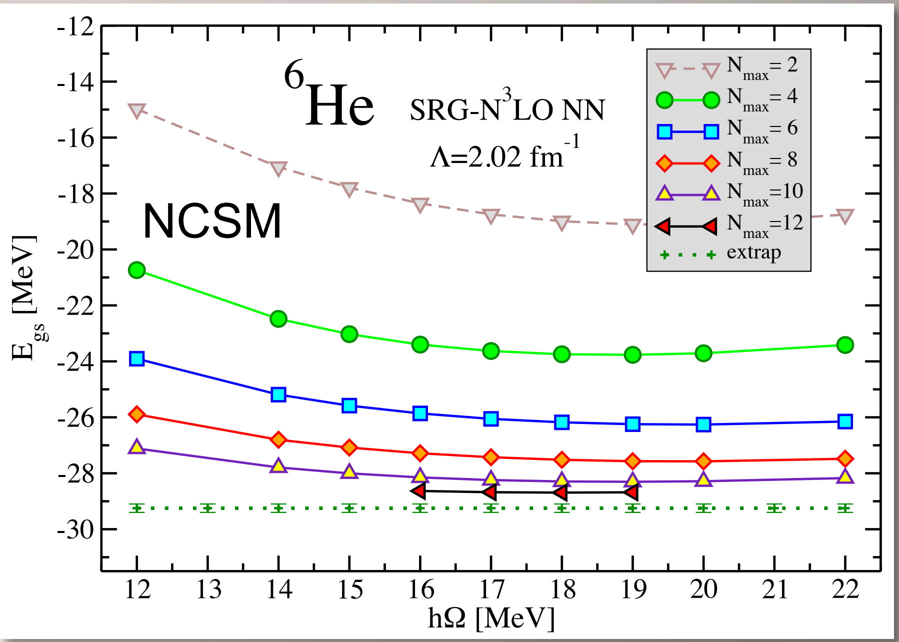
  – Where the hyperspherical coordinates are given by:

$$\rho = \sqrt{x^2 + y^2}, \quad \alpha = \arctan\left(\frac{y}{x}\right) \qquad \left(x = \rho\cos\alpha, \quad y = \rho \sin\alpha \right)$$

First results for ^{6}He ground state

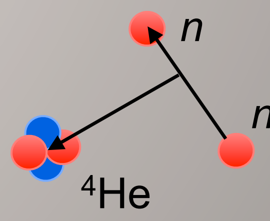
S. Quaglioni, C. Romero-Redondo, P. Navratil, work in progress

- Preliminary NCSM/RGM results for up to N_{max} = 8 model space (hΩ=16 MeV)
  - n+n+^{4}He(g.s.)
  - SRG-NN chiral with λ=2.02 fm^{-1}
- Results compared with NCSM: Gain in binding due to the coupling to continuum
  - At N_{max}=8 ^{6}He unbound within the NCSM, bound in the three-cluster NCSM/RGM by ~1 MeV
  - Extrapolated NCSM beyond N_{max}=12: ^{6}He bound by ~ 1MeV

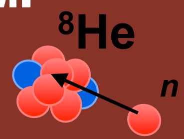


HO model space	$E_{g.s.}$ (^{4}He) [MeV] (NCSM)	$E_{g.s.}$ (^{6}He) [MeV] (NCSM)	$E_{g.s.}$ (^{6}He) [MeV] (NCSM/RGM)
N_{max} = 8	-27.32	-27.28	-28.38

PRELIMINARY

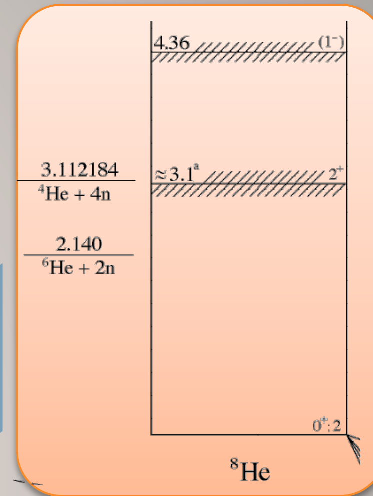


TRIUMF

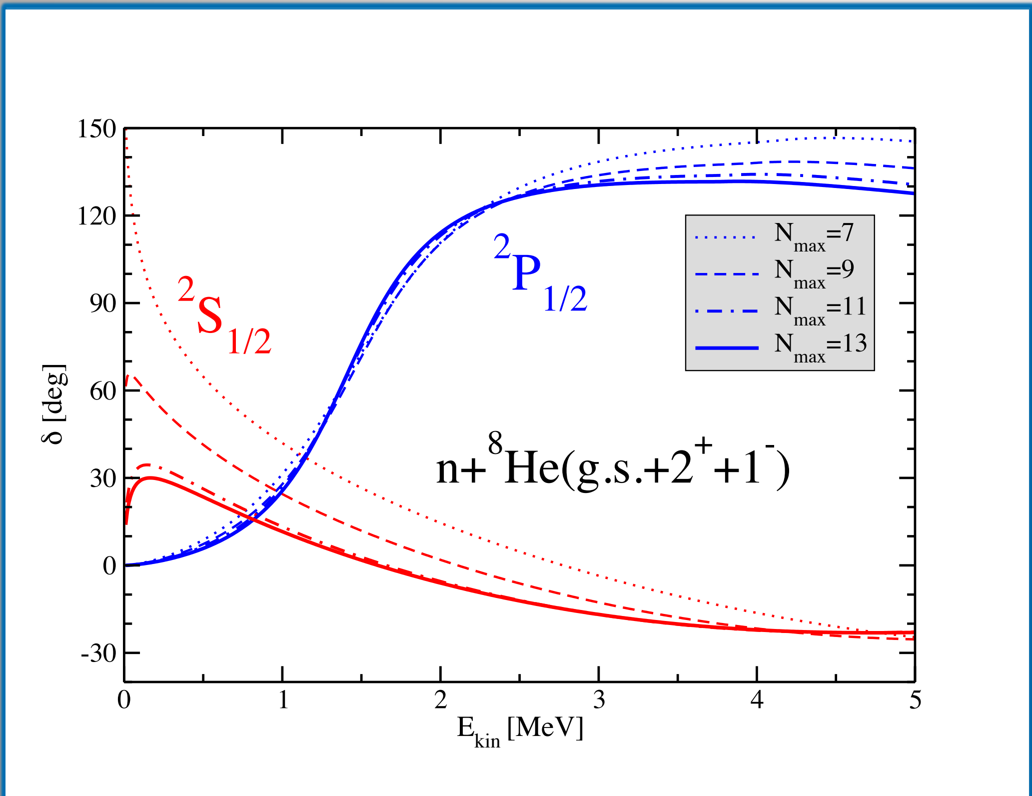


Structure of the exotic ^{9}He nucleus

- NCSM/RGM calculation of *n*-^{8}He
  - SRG-N^{3}LO *NN* potential with Λ = 2.02 fm^{-1}
  - ^{8}He 0$^+$ g.s. and 2$^+$, 1$^-$ excited states included
  - Up to N_{max}= 13



exotic nuclei



Experiment:
P-wave resonance at
Expt. ~ 1.27(10) MeV (Bohlen *et al.*)
S-wave attraction
Expt. a_0~ -10 fm (Chen *et al.*)
a_0~ -3 fm (Al Falou, *et al.*)

Calculation (preliminary):
No bound state
P-wave resonance at ~1.6 MeV
Attraction in the *S*-wave, a_0 ~ -13 fm
SRG-N^{3}LO *NN* too attractive? 3N needed…

TRIUMF

Conclusions and Outlook

- With the NCSM/RGM approach we are extending the *ab initio* effort to describe low-energy reactions and weakly-bound systems
- The first ^{7}Be(p,γ)^{8}B *ab initio* S-factor calculation

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- Deuteron-projectile results with SRG-N^{3}LO *NN* potentials:
  - *d*-^{4}He scattering
  - First *ab initio* study of ^{3}H(d,n)^{4}He & ^{3}He(d,p)^{4}He fusion

PRC **83**, 044609 (2011)

PRL **108**, 042503 (2012)

- Under way:
  - *n*-^{8}He scattering and ^{9}He structure
  - ^{3}He-^{4}He and ^{3}He-^{3}He scattering calculations
  - *Ab initio* NCSM with continuum (NCSMC)
  - Three-cluster NCSM/RGM and treatment of three-body continuum
  - Inclusion of NNN force
- To do:
  - Alpha clustering: ^{4}He projectile