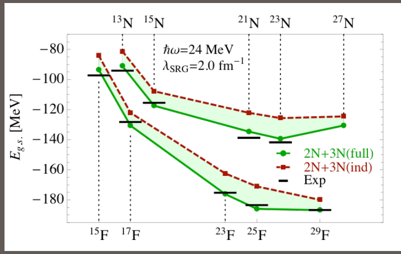
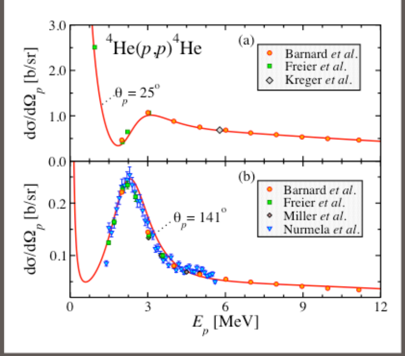
TRIUMF
Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire
et en physique des particules

Ab initio calculations in nuclear physics

International Conference on Science and Technology for FAIR in Europe
Worms, Germany
October 13-17, 2014

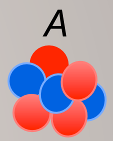


Petr Navratil | TRIUMF

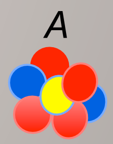


Outline

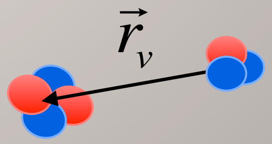
- What is meant by *ab initio* in nuclear physics
- *Ab initio* nuclear structure and reaction approaches
  - Exact few-body calculations (*A*=3,4)
  - Quantum Monte Carlo (*A*≤12)
  - Nuclear Lattice EFT (*A*=4,8,12,16, 20, 24, 28)
  - Coupled Cluster Method (*A*≤132, magic, semi-magic)
  - In-medium Similarity Renormalization Group (*A*≤90, open shells)
  - Self-Consistent Green’s Function Method (*A*≤78, open shells)



- No-core shell model (*A*≤26, hypernuclei)



- Including the continuum with the resonating group method
  - NCSM/RGM
  - NCSM with continuum



- Outlook

TRIUMF

What is meant by *ab initio* in nuclear physics?

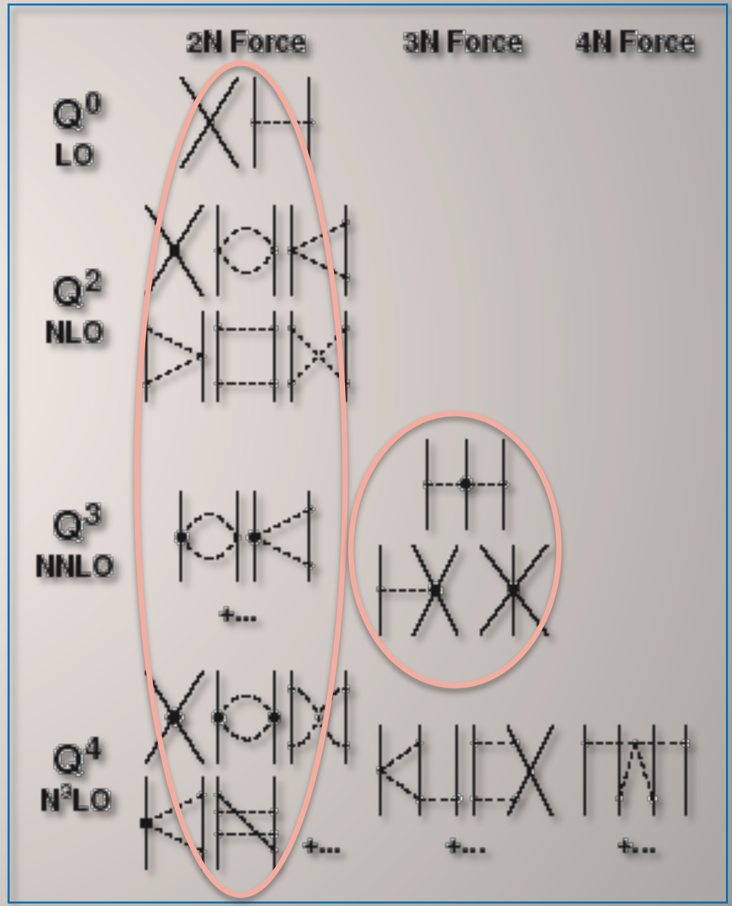
- **First principles for Nuclear Physics:**
  QCD
  - Non-perturbative at low energies
  - Lattice QCD in the future

- Degrees of freedom: NUCLEONS
  - Nuclei made of nucleons
  - Interacting by nucleon-nucleon and three-nucleon potentials

- *Ab initio*
  - ✧ All nucleons are active
  - ✧ Exact Pauli principle
  - ✧ Realistic inter-nucleon interactions
    - ✧ Accurate description of NN (and 3N) data
  - ✧ Controllable approximations

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

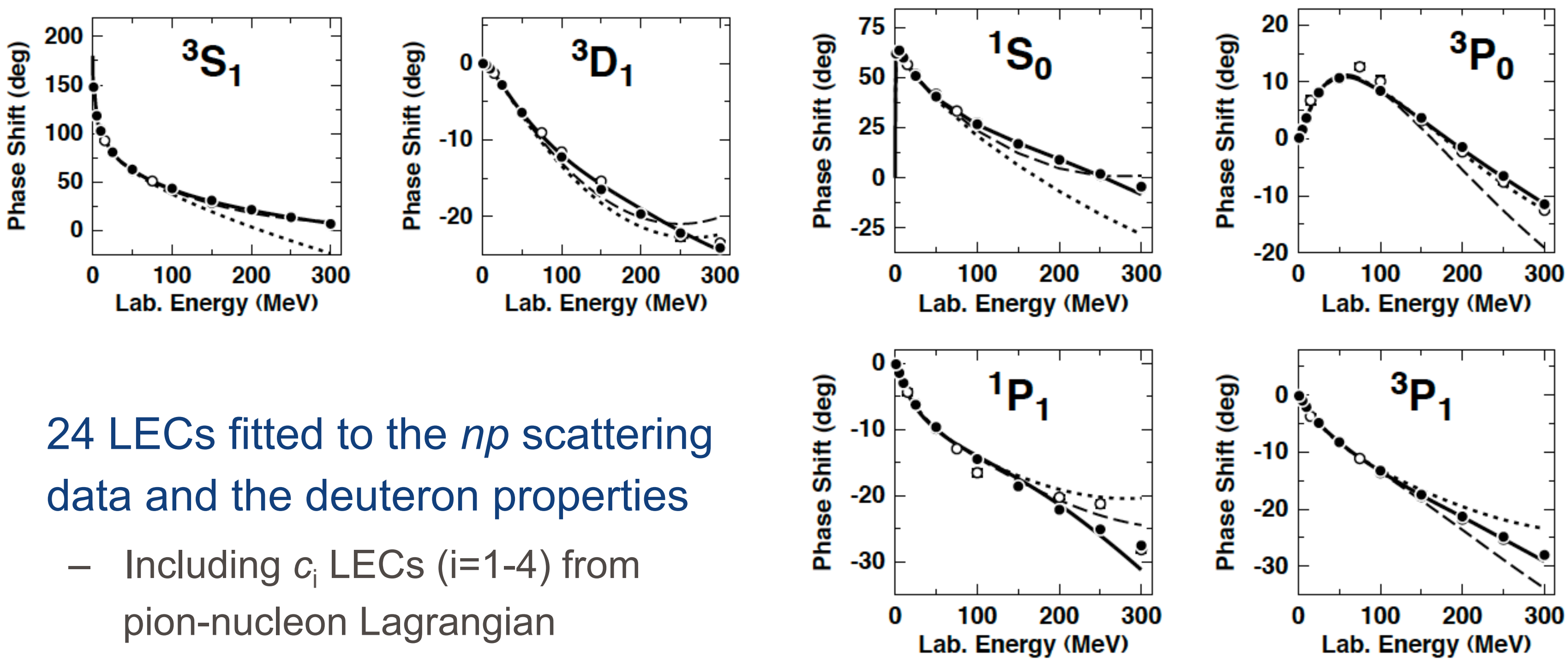
TRIUMF

The NN interaction from chiral EFT

PHYSICAL REVIEW C **68**, 041001(R) (2003)

Accurate charge-dependent nucleon-nucleon potential at fourth order of chiral perturbation theory

D. R. Entem[1,2,*] and R. Machleidt[1,†]



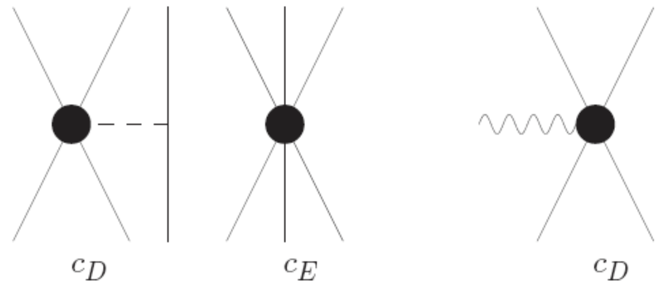
- 24 LECs fitted to the *np* scattering data and the deuteron properties
  - Including c_i LECs (i=1-4) from pion-nucleon Lagrangian

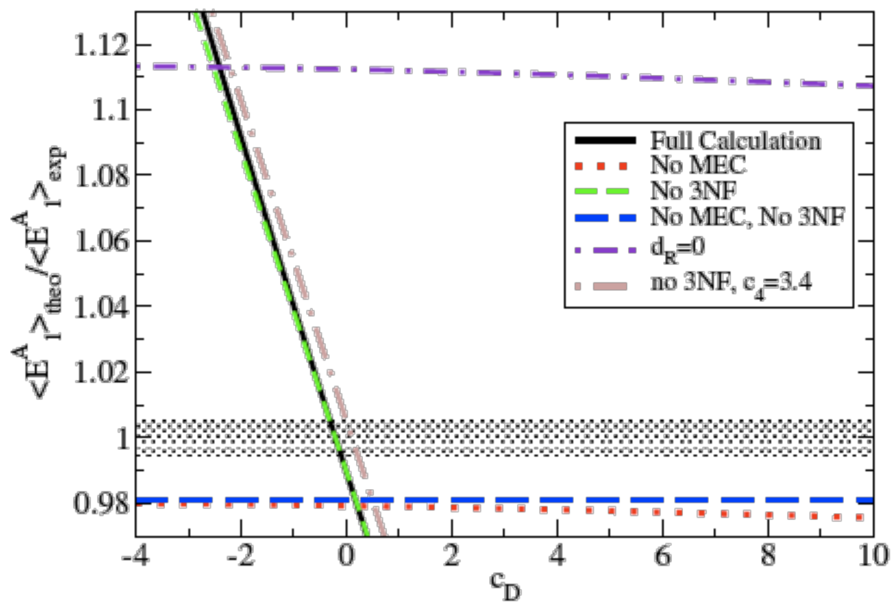
TRIUMF

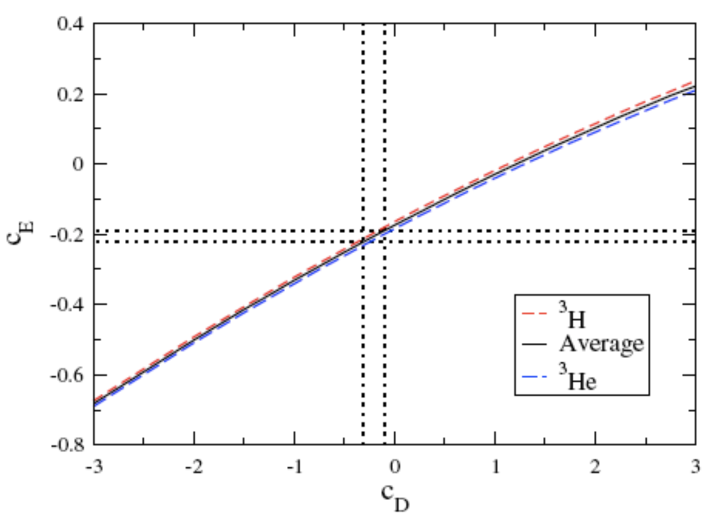
Determination of NNN LECs c_D and c_E from the triton binding energy and the half life

- **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

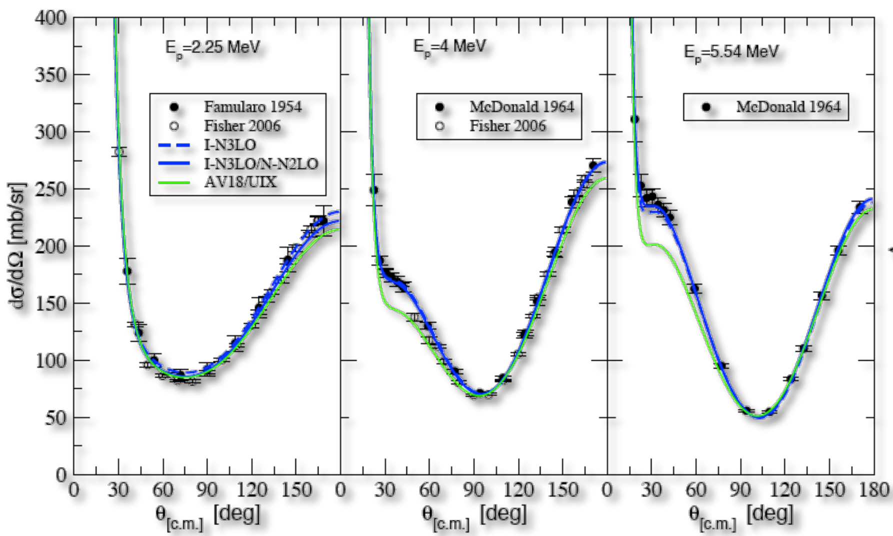
Three-Nucleon Low-Energy Constants from the Consistency of Interactions and Currents in Chiral Effective Field Theory

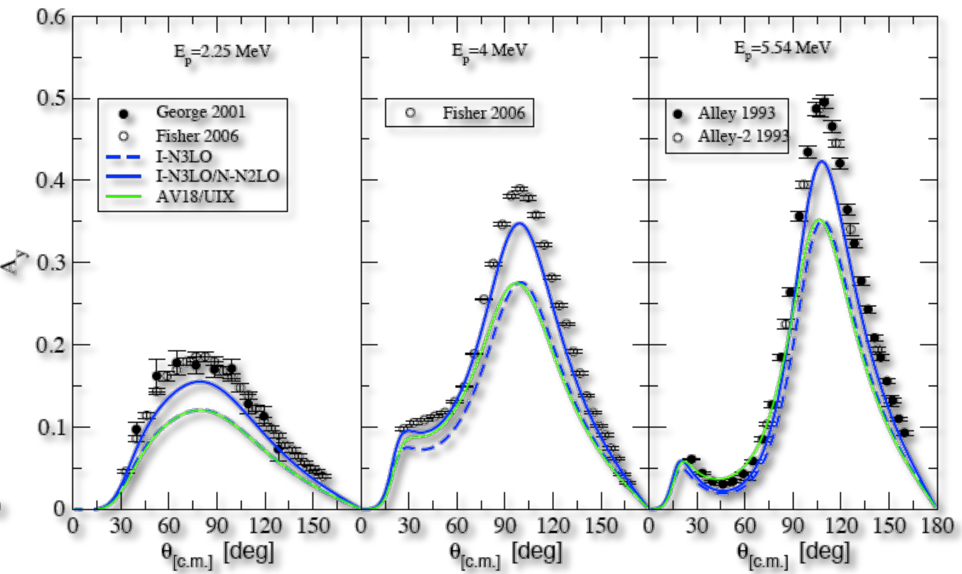
Doron Gazit
Institute for Nuclear Theory, University of Washington, Box 351550, Seattle, Washington 98195, USA

Sofia Quaglioni and Petr Navrátil
Lawrence Livermore National Laboratory, P.O. Box 808, L-414, Livermore, California 94551, USA

Exact few-body calculations (A=3,4)
Proton-^{3}He elastic scattering with χEFT NN+NNN

- **Hypherspherical-harmonics variational calculations**
  - M. Viviani, L. Girlanda, A. Kievski, L. E. Marcucci, and S. Rosati, EPJ Web Conf. **3** (2010) 05011; Few Body Syst. **54** (2013) 885
- ***A_y* puzzle (almost) resolved** with the chiral N^{3}LO NN plus **local chiral N^{2}LO NNN**
  - *used with the NCSM and other methods*





Quantum Monte Carlo

Variational Monte Carlo (VMC): construct Ψ_V that

- Are fully antisymmetric and translationally invariant
- Have cluster structure and correct asymptotic form
- Contain non-commuting 2- & 3-body operator correlations from v_{ij} & V_{ijk}
- Are orthogonal for multiple J^π states
- Minimize $E_V = \langle \Psi_V | H | \Psi_V \rangle \geq E$ integrating by Metropolis Monte Carlo

These are $\sim 2^A \binom{A}{Z}$ component (270,336 for ^{12}C) spin-isospin vectors in $3A$ dimensions

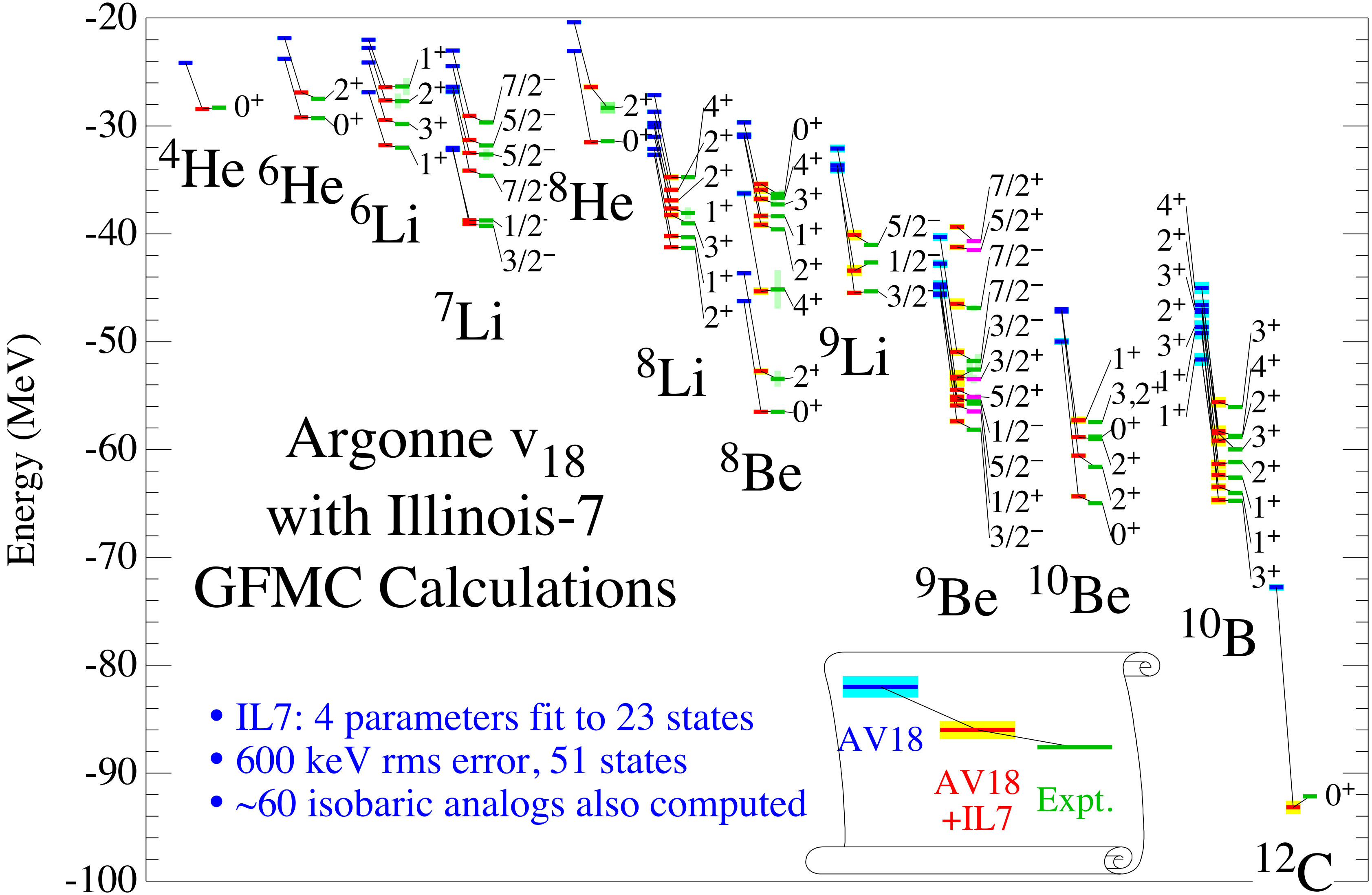
Green's function Monte Carlo (GFMC): project out the exact eigenfunction

- $\Psi(\tau) = \exp[-(H - E_0)\tau]\Psi_V = \sum_n \exp[-(E_n - E_0)\tau] a_n \Psi_n \Rightarrow \Psi_0$ at large τ
- Propagation done stochastically in small time slices $\Delta\tau$
- Exact $\langle H \rangle$ for local potentials; mixed estimates for other $\langle O \rangle$
- Constrained-path propagation controls fermion sign problem for $A \geq 8$
- Multiple excited states for same J^π stay orthogonal

Many tests demonstrate 1–2% accuracy for realistic $\langle H \rangle$

Wiringa, Pieper, Carlson, & Pandharipande, PRC **62**, 014001 (2000)
Pieper, Varga, & Wiringa, PRC **66**, 044310 (2002)
Pieper, Wiringa, & Carlson, PRC **70**, 054325 (2004)
Pieper, NPA **751**, 516c (2005)

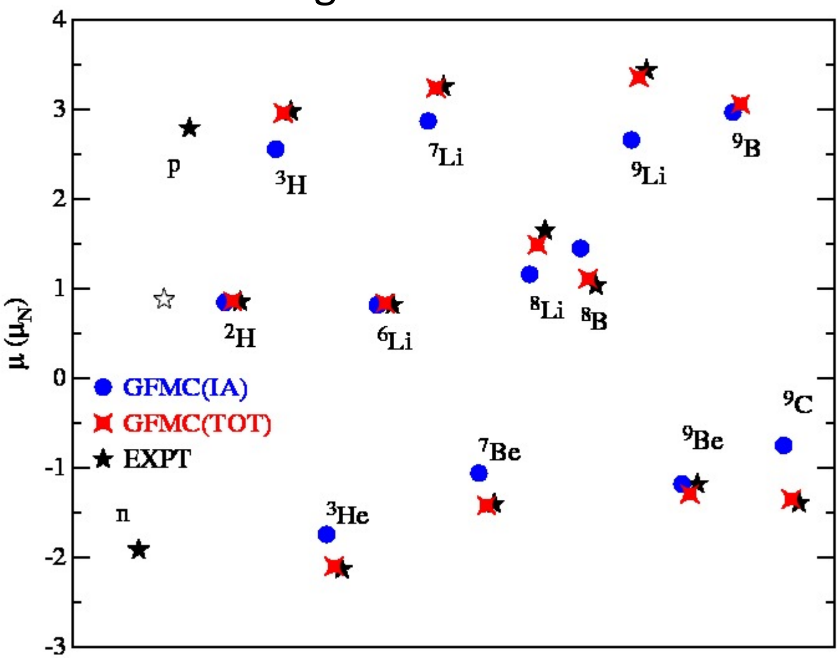
Quantum Monte Carlo: Eigenenergies of light nuclei



TRIUMF

Quantum Monte Carlo: Magnetic moments and transitions light nuclei

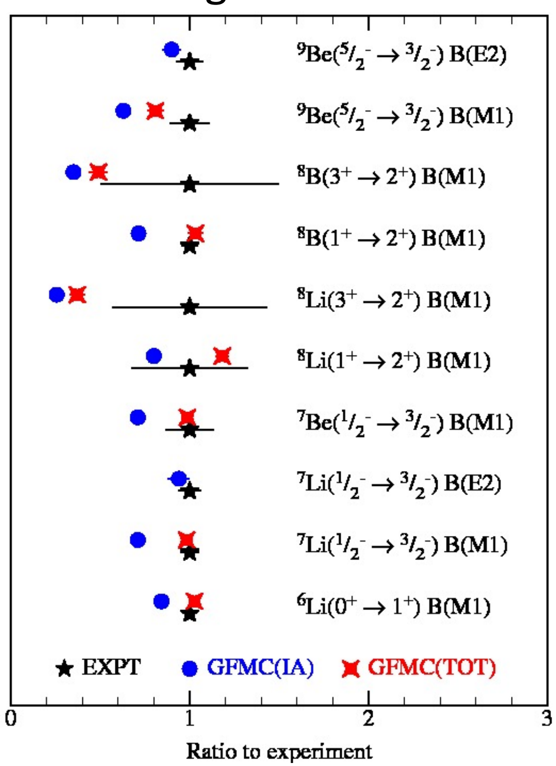
Magnetic Moments



Green's Function Monte Carlo (GFMC) calculations of light nuclei give accurate energies but a lowest-order theory of one-body currents (blue) disagrees with experiment (black).

Including two-nucleon currents based on effective field theory (red) improves all predictions!

Electromagnetic Transitions



PHYSICAL REVIEW C **87**, 035503 (2013)

Quantum Monte Carlo calculations of electromagnetic moments and transitions in $A \leqslant 9$ nuclei with meson-exchange currents derived from chiral effective field theory

S. Pastore,[1,*] Steven C. Pieper,[1,†] R. Schiavilla,[2,3,‡] and R. B. Wiringa[1,§]

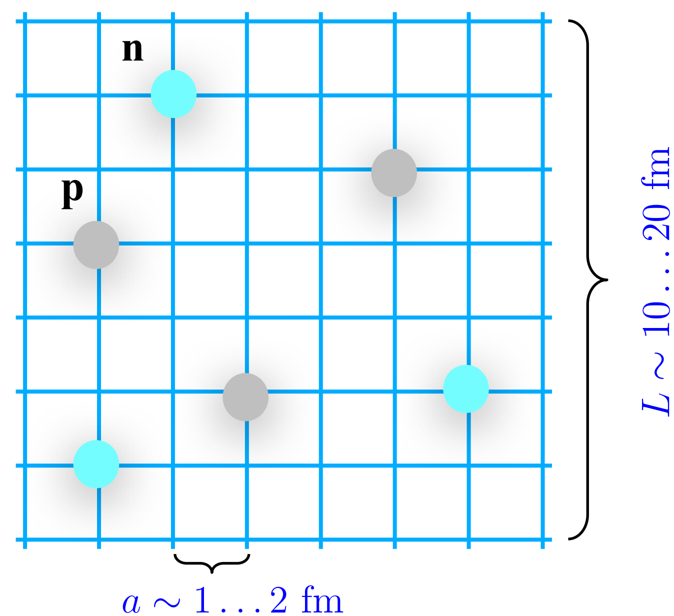
Nuclear Lattice Effective Field Theory Calculations

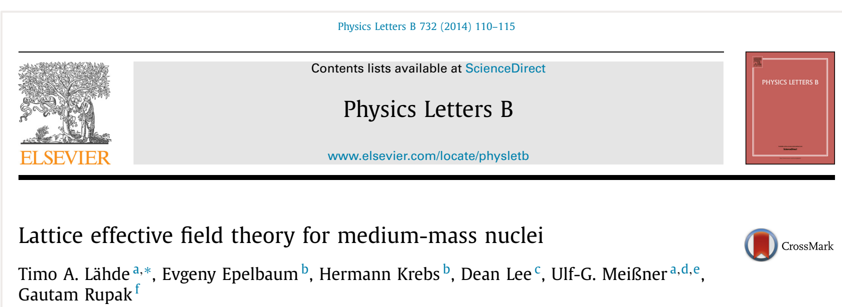
E. Epelbaum, H. Krebs, T. Lahde, D. Lee,U.-G. Meissner

Discretized version of chiral EFT for nuclear dynamics

$$\left[\left(\sum_{i=1}^{A}\frac{-\vec{\nabla}_i^2}{2m_N}+\mathcal{O}(m_N^{-3})\right)+\underbrace{V_{2N}+V_{3N}+V_{4N}+\ldots}_{\text{derivable within in ChPT}}\right]|\Psi\rangle=E|\Psi\rangle$$

Borasoy, E.E., Krebs, Lee, Meißner, Eur. Phys. J. A31 (07) 105,
Eur. Phys. J. A34 (07) 185,
Eur. Phys. J. A35 (08) 343,
Eur. Phys. J. A35 (08) 357,
E.E., Krebs, Lee, Meißner, Eur. Phys. J A40 (09) 199,
Eur. Phys. J A41 (09) 125,
Phys. Rev. Lett 104 (10) 142501,
Eur. Phys. J. 45 (10) 335,
Phys. Rev. Lett. 106 (11) 192501




Physics Letters B 732 (2014) 110–115

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

Lattice effective field theory for medium-mass nuclei

Timo A. Lähde[a,*], Evgeny Epelbaum[b], Hermann Krebs[b], Dean Lee[c], Ulf-G. Meißner[a,d,e], Gautam Rupak[f]

Ground states of alpha nuclei from ^{4}He to ^{28}Si

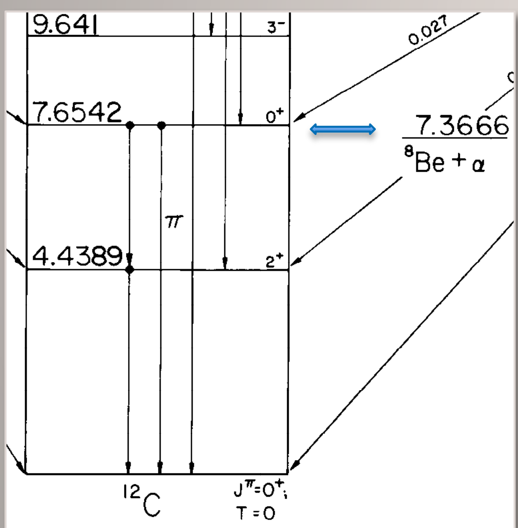
TRIUMF

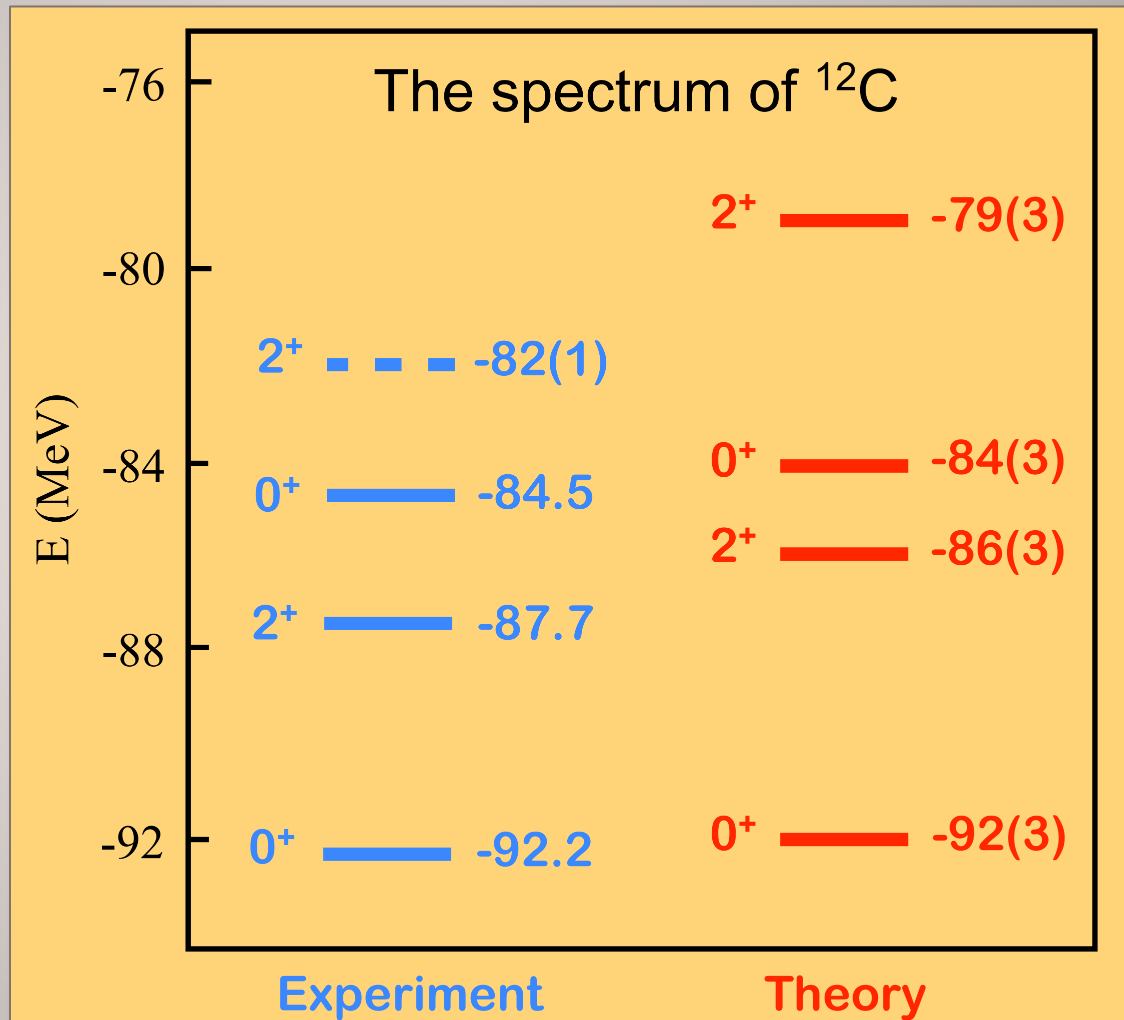
Nuclear Lattice Effective Field Theory Calculations

E. Epelbaum, H. Krebs, T. Lahde, D. Lee,U.-G. Meissner

The Hoyle state

^{12}C production in the Universe



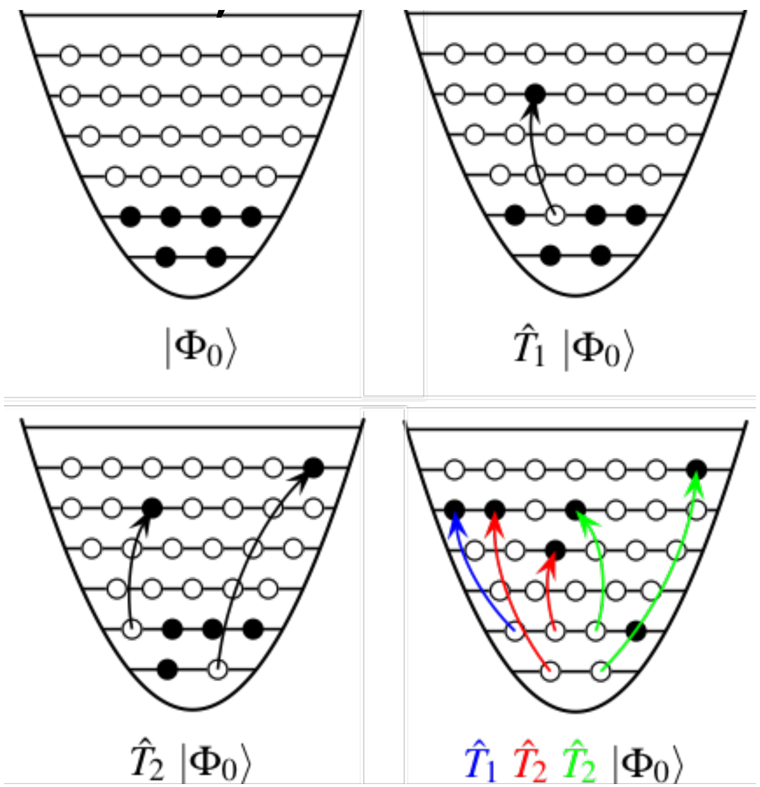


Epelbaum, Krebs, Lee, Meissner, PRL 106, 192501 (2011)

Coupled-Cluster Method

- **exponential Ansatz** for wave operator $|\Psi\rangle = e^{\hat{T}}|\Phi_0\rangle$

- **CCSD**: truncate $\hat{T}$ at the **2p2h excitation** level, $\hat{T} = \hat{T}_1 + \hat{T}_2$

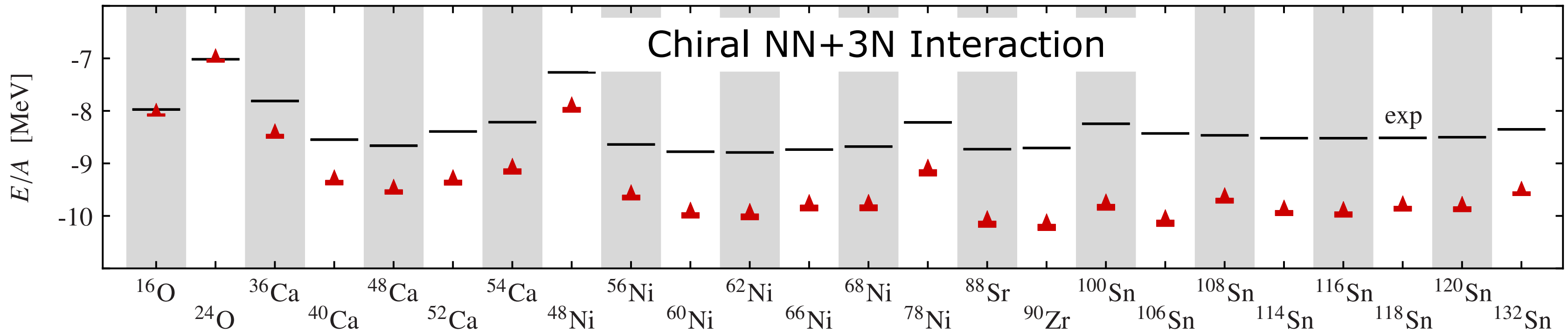


$$\hat{T}_n = \frac{1}{(n!)^2} \sum_{\substack{ijk\ldots \\ abc\ldots}} t_{ijk\ldots}^{abc\ldots} \{\hat{a}_a^\dagger \hat{a}_b^\dagger \hat{a}_c^\dagger \ldots \hat{a}_k \hat{a}_j \hat{a}_i\}$$

- effects of T_3 clusters **included approximately** in ground-state calculations via ΛCCSD(T) or CR-CC(2,3) method

State-of-the-art: Λ-CCSD(T) with 3N interaction

Coupled-Cluster calculations for heavy nuclei with chiral interactions

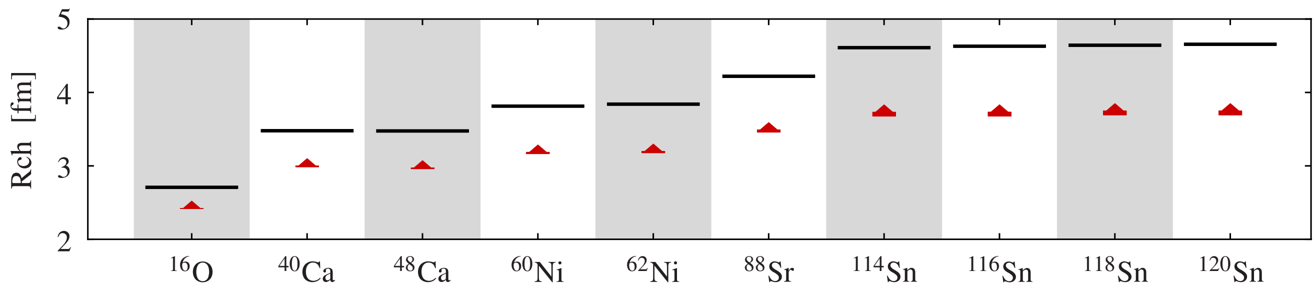


- **current** chiral Hamiltonians capable of describing the **experimental trend** of binding energies

- systematic overbinding indicates that there are still **deficiencies**

  ➡ **consistent 3N** interaction at N^3LO, and **4N** interactions

- **charge radii** are considerably **too small**

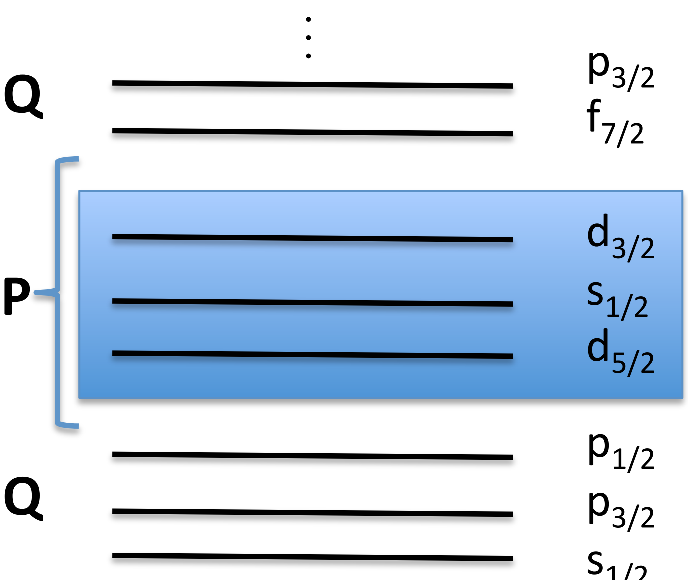


S. Binder et al., PLB 736, 119 (2014)

Coupled-cluster effective interactions (CCEI) for the shell model

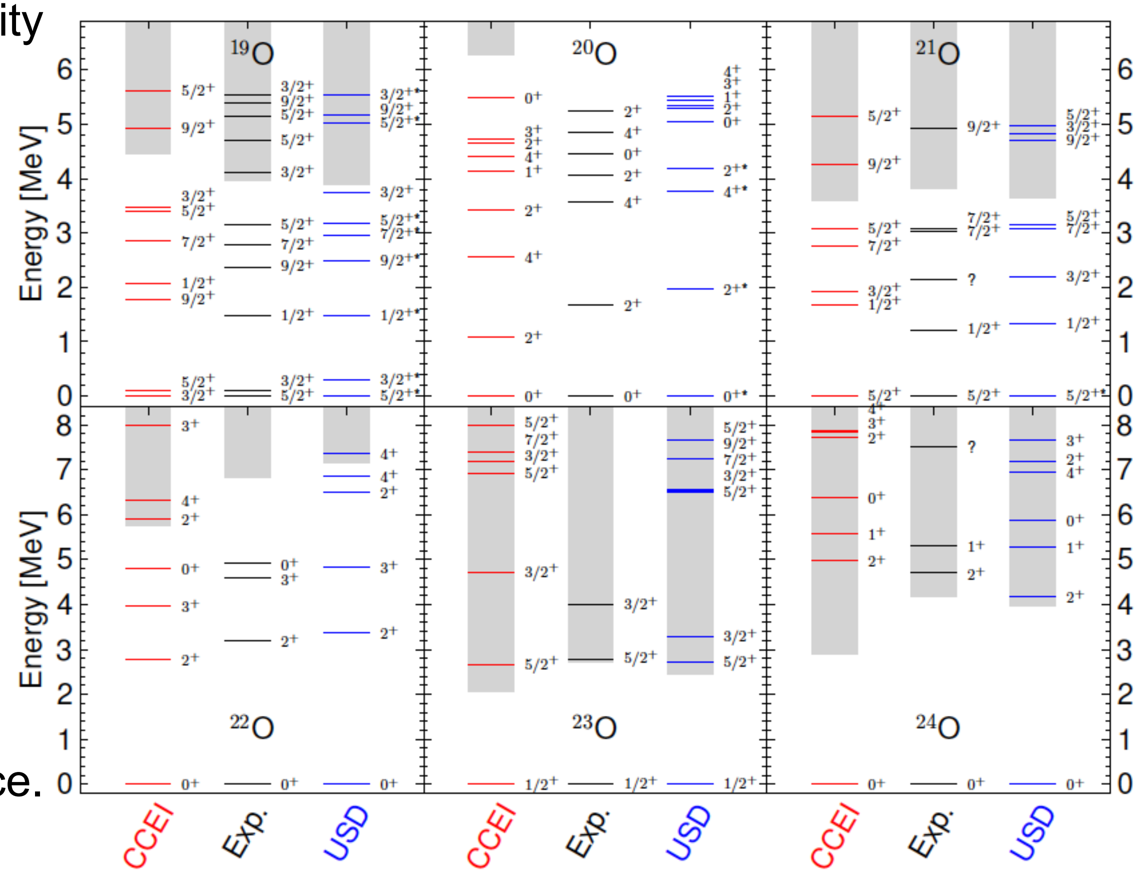
G. R. Jansen, J. Engel, G. Hagen, P. Navratil, A. Signoracci, Phys. Rev. Lett. **113**, 142502 (2014).

- Start from chiral NN($N3LO_{EM}$) + 3NF(N2LO) interactions
- Solve for A+1 and A+2 using CC. Project A+1 and A+2 CC wave functions onto the *s-d* model space using Lee-Suzuki similarity transformation.

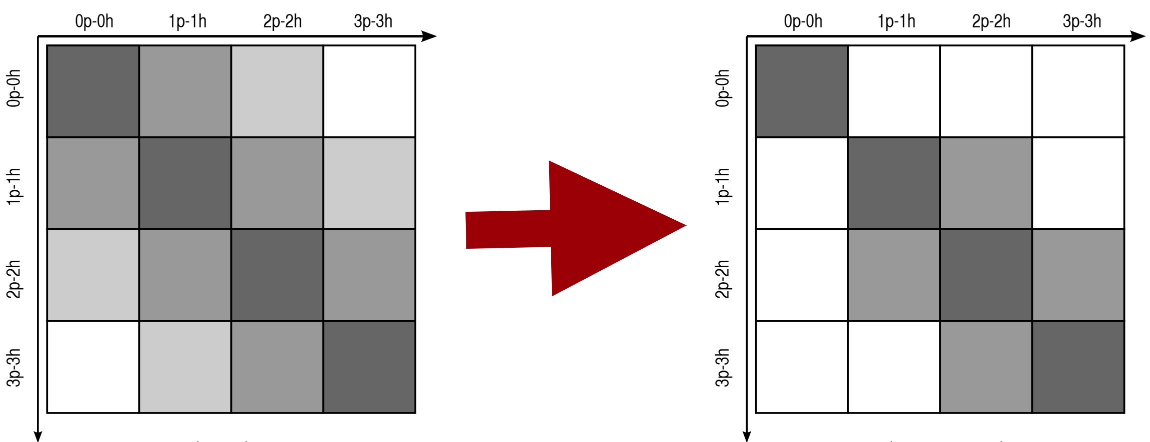


- Diagonalize the effective hamiltonian in the valence space.

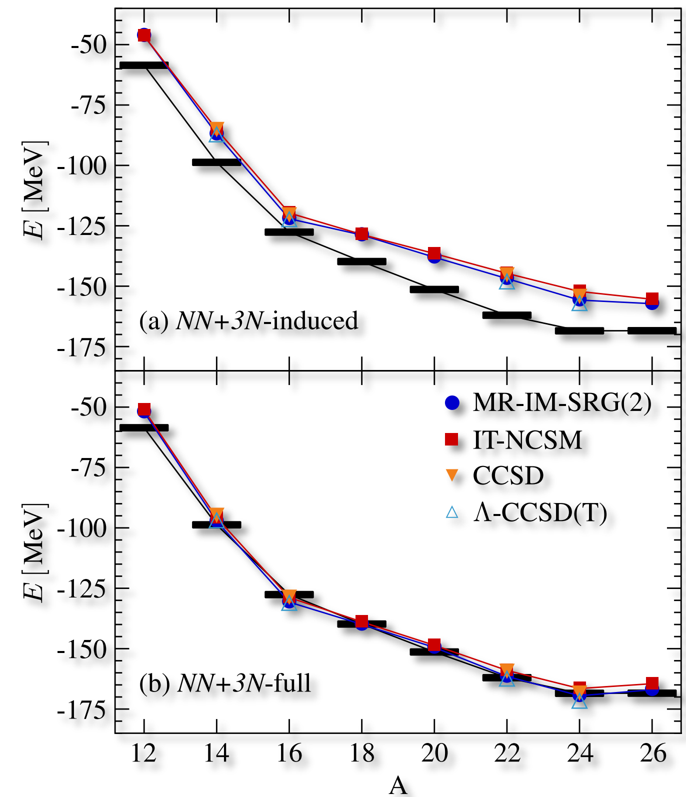
Spectra of oxygen isotopes computed with coupled-cluster effective interaction (CCEI), and compared to experimental data and the phenomenological USD shell model interaction.



In-medium SRG approach: Application to Oxygen isotopes



$$\langle i | H | j \rangle \qquad\qquad \langle i | H(\infty) | j \rangle$$



aim: decouple reference state (0p-0h) from excitations

$$\frac{d}{ds}H(s) = \left[\eta(s), H(s)\right], \quad \eta(s) = \frac{dU(s)}{ds}U^\dagger(s) = -\eta^\dagger(s)$$

- Wegner

$$\eta^I = [H^d, H^{od}]$$

- White (J. Chem. Phys. 117, 7472)

$$\eta^{II} = \sum_{ph} \frac{f_h^p}{E_p - E_h} :A_h^p: + \sum_{pp'hh'} \frac{\Gamma_{hh'}^{pp'}}{E_{pp'} - E_{hh'}} :A_{hh'}^{pp'}: + \text{H.c.}$$

$E_p - E_h, E_{pp'} - E_{hh'}$: approx. 1p1h, 2p2h excitation energies

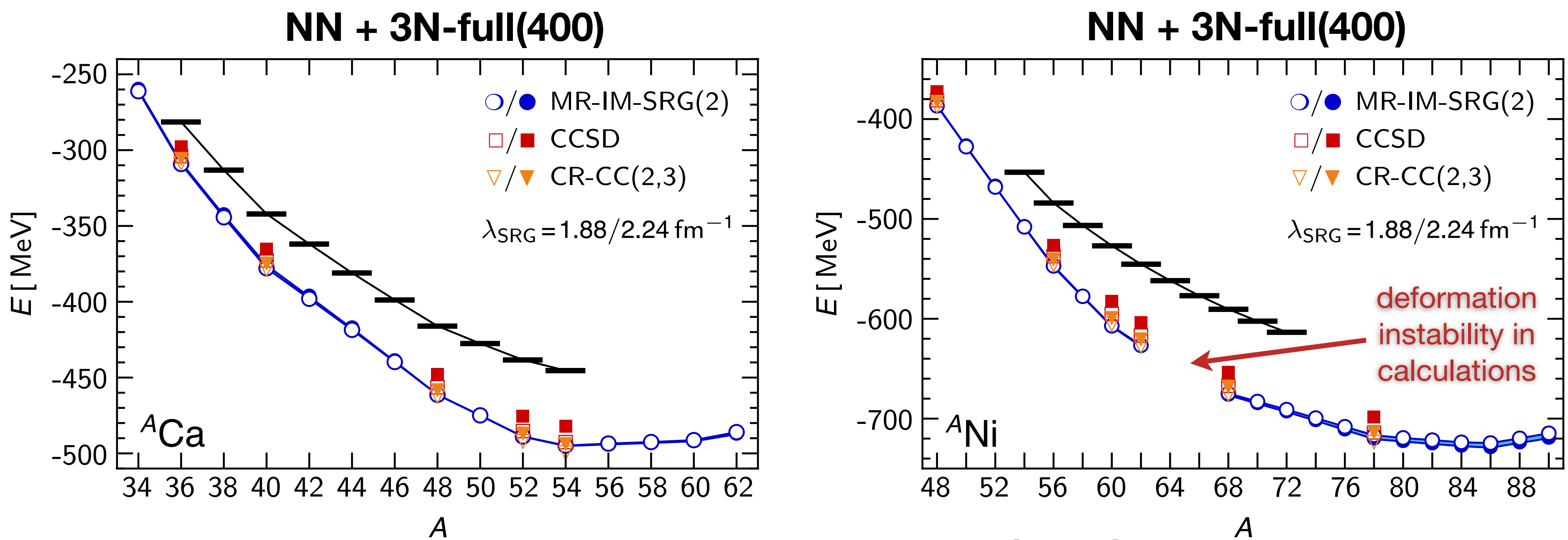
PRL 110, 242501 (2013) PHYSICAL REVIEW LETTERS week ending 14 JUNE 2013

***Ab Initio* Calculations of Even Oxygen Isotopes with Chiral Two-Plus-Three-Nucleon Interactions**

H. Hergert,[1,*] S. Binder,[2] A. Calci,[2] J. Langhammer,[2] and R. Roth[2]

Magic, semi-magic and open-shell nuclei

In-medium SRG approach: Application to Ca and Ni isotopes



H. Hergert et al., arXiv:1408.6555 [nucl-th]

- IM-SRG calculations for A~100 are routine, tin isotopes in progress
- controlled uncertainties & consistent results for different ab-intio methods
- systematic overbinding due to current chiral Hamiltonians - results for new generation of chiral Hamiltonians soon

TRIUMF

Self-Consistent Green's Function Method: Oxygen, Fluorine, Nitrogen isotopes

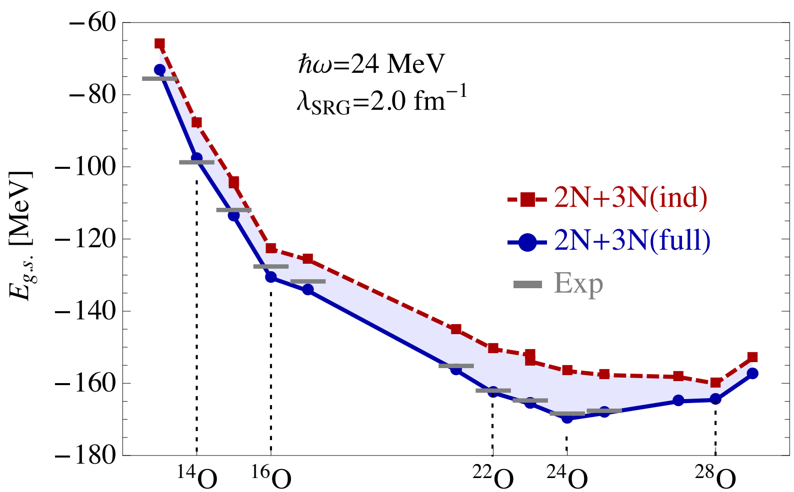
$$g_{\alpha\beta}(\omega) = \sum_n \frac{\langle \Psi_0^A | c_\alpha | \Psi_n^{A+1} \rangle \langle \Psi_n^{A+1} | c_\beta^\dagger | \Psi_0^A \rangle}{\omega - \varepsilon_n^{A+1} + i\eta} + \sum_k \frac{\langle \Psi_0^A | c_\beta^\dagger | \Psi_k^{A-1} \rangle \langle \Psi_k^{A-1} | c_\alpha | \Psi_0^A \rangle}{\omega - \varepsilon_k^{A-1} - i\eta},$$

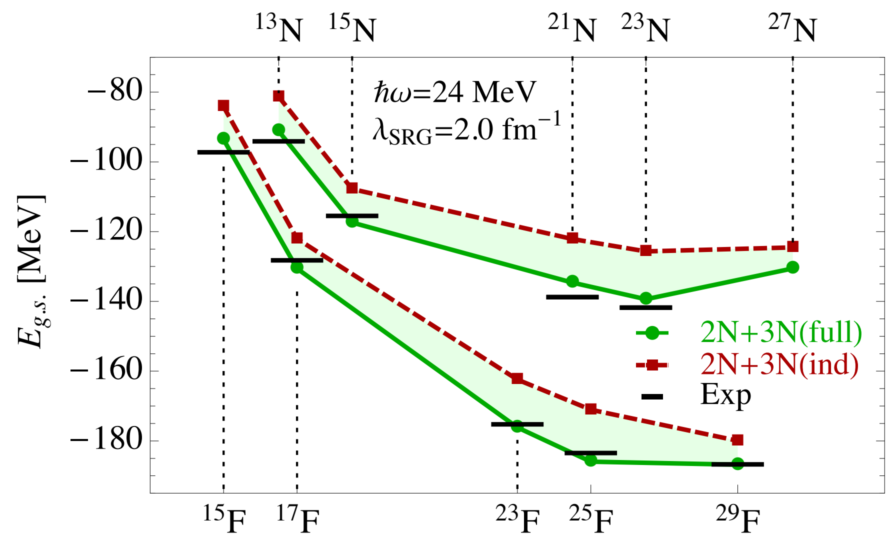
Magic and semi-magic nuclei

PRL 111, 062501 (2013) PHYSICAL REVIEW LETTERS week ending 9 AUGUST 2013

Isotopic Chains Around Oxygen from Evolved Chiral Two- and Three-Nucleon Interactions

A. Cipollone,[1] C. Barbieri,[1,*] and P. Navrátil[2]





→ 3NF crucial for reproducing binding energies and driplines around oxygen

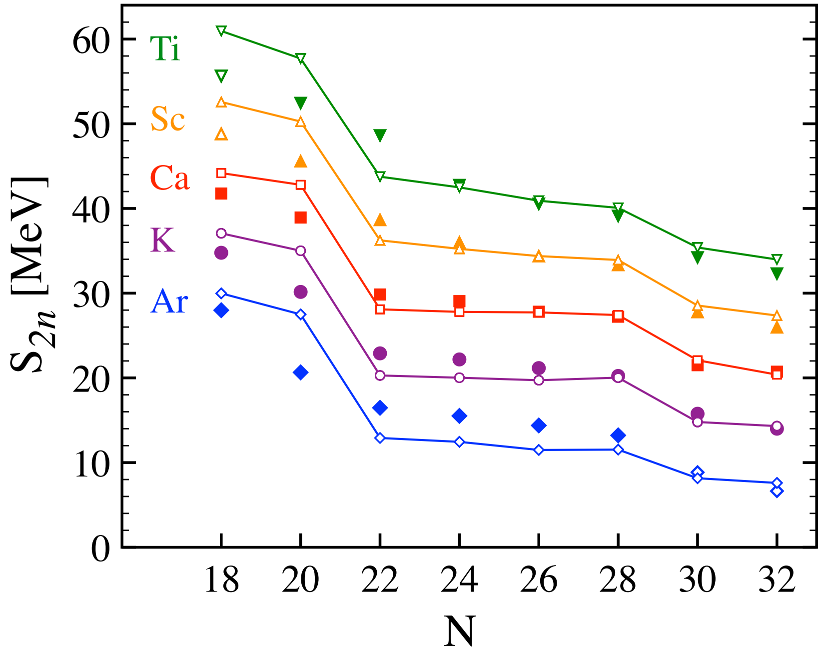
→ *$d_{3/2}$ raised* by genuine 3NF

TRIUMF

Green's functions in medium-mass nuclei

Gorkov GF go beyond standard expansion schemes and are not limited to doubly closed-shells

- ○ Expansion around a Bogoliubov vacuum
- ○ From few tens to hundreds of medium-mass open-shell systems (→ complete chains)



Open shell nuclei

PHYSICAL REVIEW C **89**, 061301(R) (2014)

Chiral two- and three-nucleon forces along medium-mass isotope chains

V. Somà,[1,2,3,*] A. Cipollone,[4] C. Barbieri,[4,†] P. Navrátil,[5] and T. Duguet[3,6,‡]

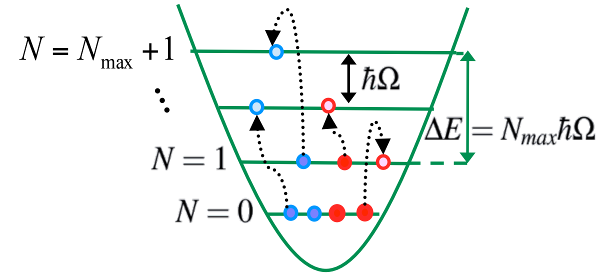
→ Systematic overbinding of medium-mass nuclei (in agreement with other ab initio methods)

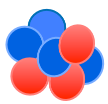
→ initial (full) 3NF are necessary to reproduce relative trends

→ Relative energies (S_{2n}) well reproduced

No-core shell model

- No-core shell model (NCSM)
  - *A*-nucleon wave function expansion in the harmonic-oscillator (HO) basis
  - short- and medium range correlations
  - Bound-states, narrow resonances

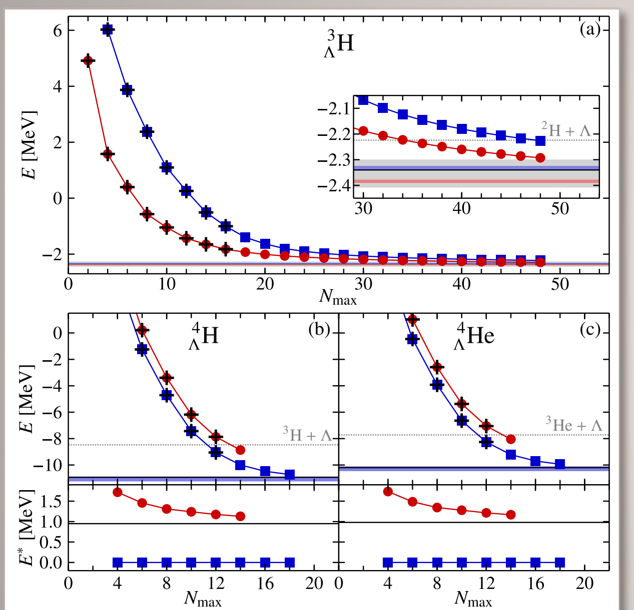




$$\Psi^A = \sum_{N=0}^{N_{\max}} \sum_i c_{Ni} \Phi_{Ni}^A$$

NCSM calculations for light nuclei and *hypernuclei*

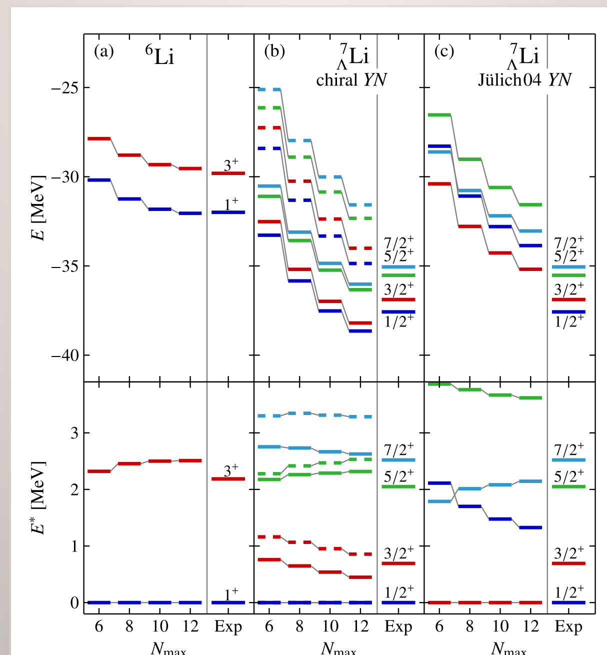
- Flexible approach capable performing exact calculations for few-nucleon systems and accurate calculations for nuclei with A≤24 & **hypernuclei**

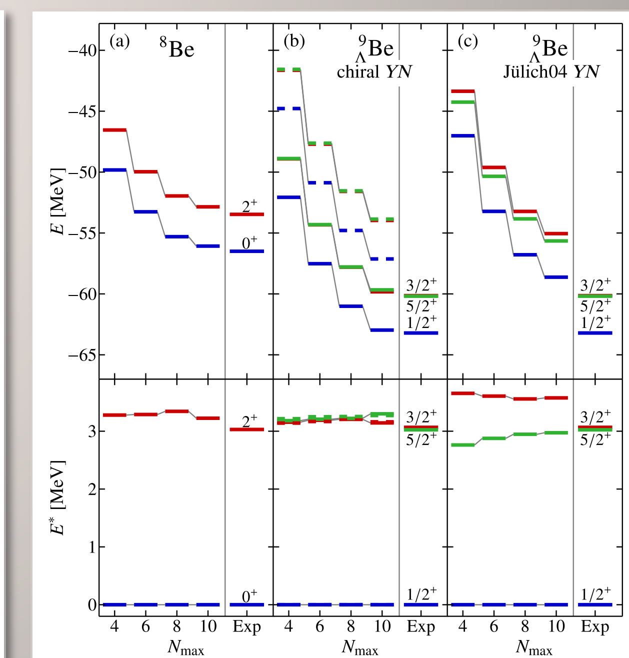


PHYSICAL REVIEW LETTERS

Ab Initio Description of _p_-Shell Hypernuclei

Roland Wirth,[1,*] Daniel Gazda,[2,3] Petr Navrátil,[4] Angelo Calci,[1] Joachim Langhammer,[1] and Robert Roth[1,†]



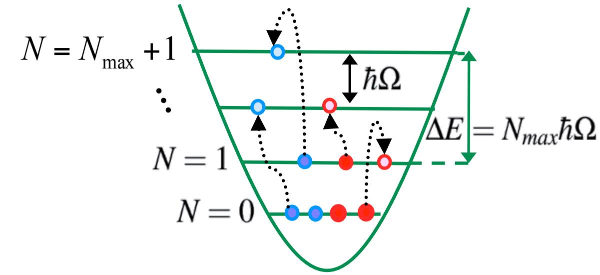


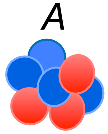
Testing chiral LO NY potentials with Λ-Σ mixing included

…outperform the Julich ’04 YN potential

No-core shell model with continuum

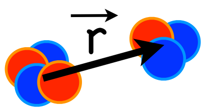
- No-core shell model (NCSM)
  - *A*-nucleon wave function expansion in the harmonic-oscillator (HO) basis
  - short- and medium range correlations
  - Bound-states, narrow resonances





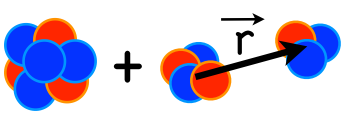
$$\Psi^A = \sum_{N=0}^{N_{max}} \sum_i c_{Ni} \Phi^A_{Ni}$$

- NCSM with Resonating Group Method (NCSM/RGM)
  - cluster expansion
  - proper asymptotic behavior
  - long-range correlations



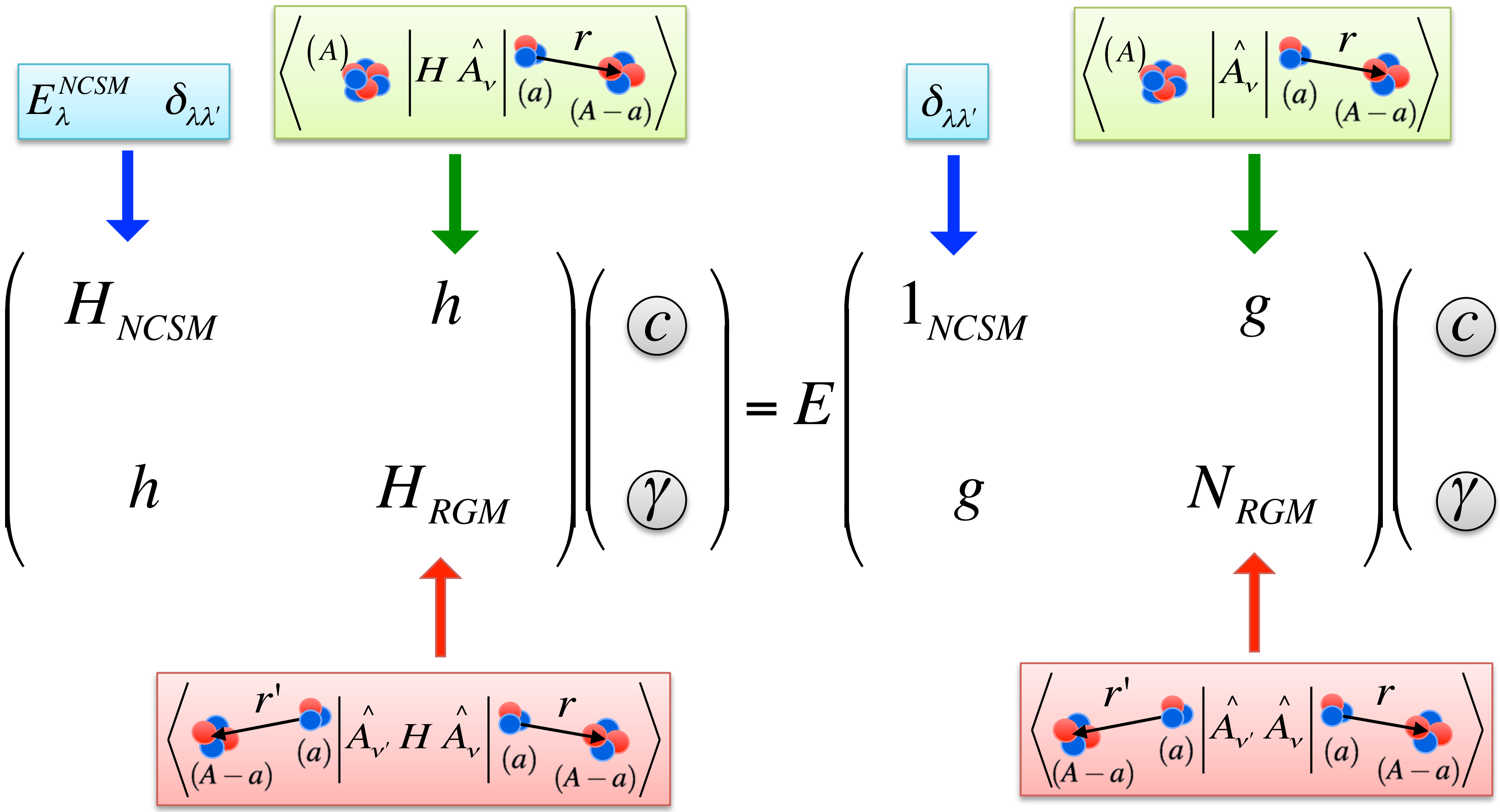
$$\Psi^A = \sum_\nu \int d\vec{r} \varphi_\nu(\vec{r}) \mathcal{A}_\nu \Phi^{(A-a)}_{1\nu} \Phi^{(a)}_{2\nu} \delta(\vec{r} - \vec{r}_{A-a,a})$$

- NCSM with continuum (NCSMC)
  - unified description of bound and unbound states



S. Baroni, P. N., and S. Quaglioni,
PRL **110**, 022505 (2013); PRC **87**, 034326 (2013).

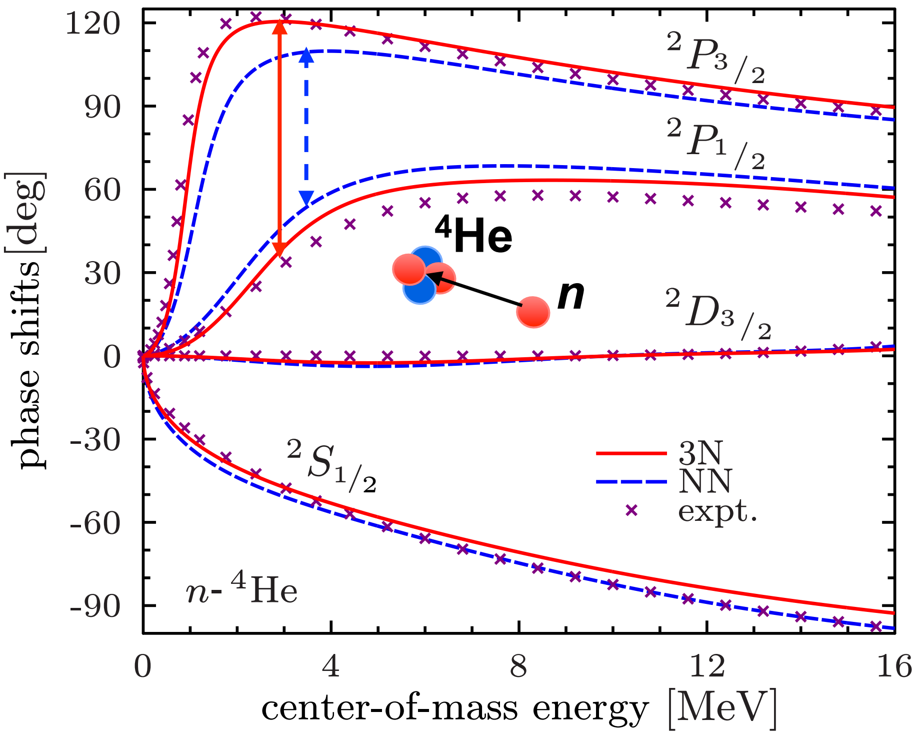
Coupled NCSMC equations



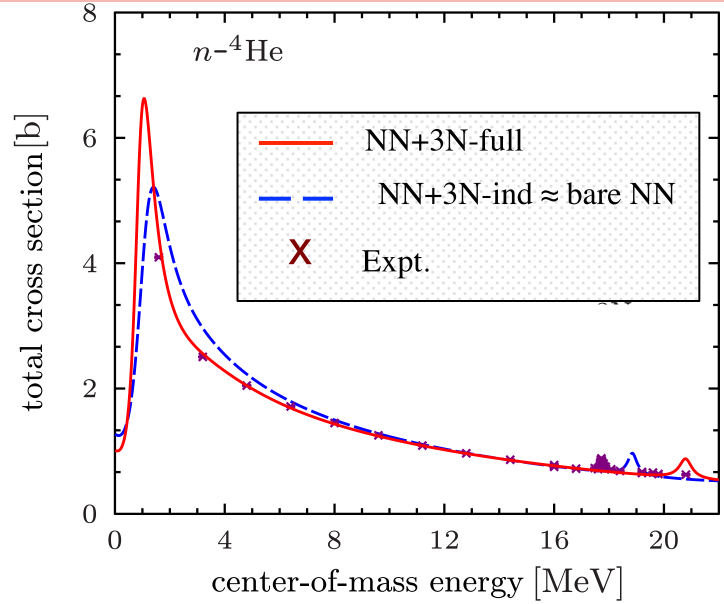
Scattering matrix (and observables) from matching solutions to known asymptotic with microscopic *R*-matrix on Lagrange mesh

n-^{4}He & p-^{4}He scattering within NCSMC

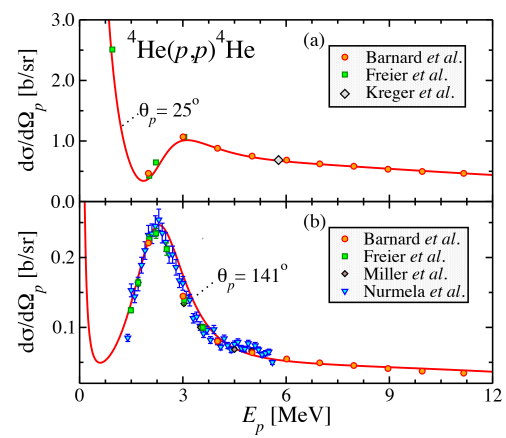
n-^{4}He scattering phase-shifts for chiral NN and NN+3N potential



Total n-^{4}He cross section with NN and NN+3N potentials



3N force enhances $1/2^- \leftarrow\rightarrow 3/2^-$ splitting; essential at low energies!



Differential p-^{4}He cross section with NN+3N potentials

G. Hupin, S. Quaglioni and P. Navrátil, arXiv:1409.0892 [nucl-th]

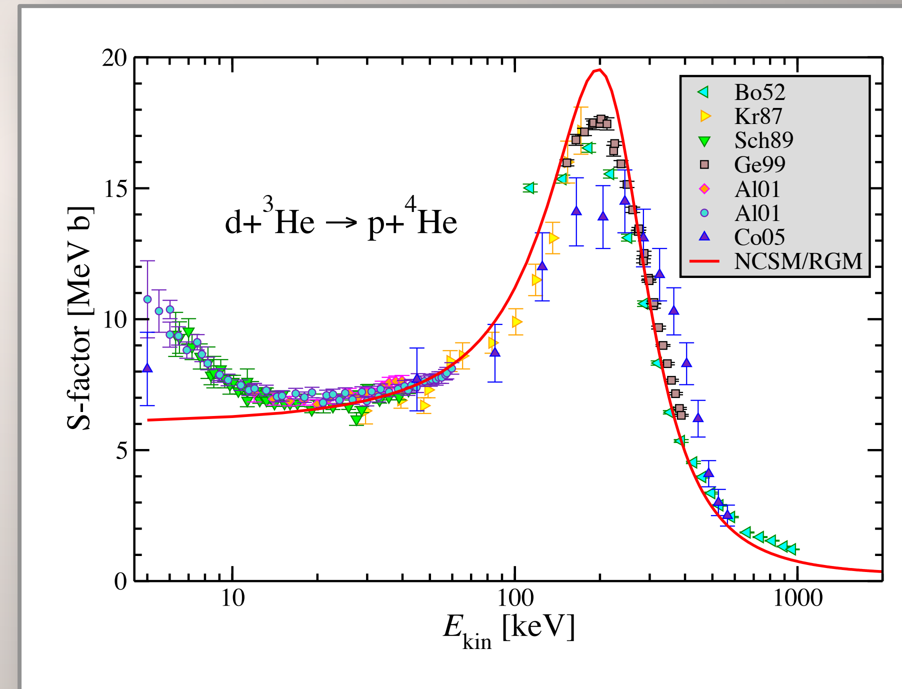
NCSM/RGM calculations of transfer reactions

$$\int dr\, r^2 \begin{pmatrix} \left\langle r'\; n\;\alpha \right| \hat{A}_1 (H-E) \hat{A}_1 \left| \alpha\; n\; r \right\rangle & \left\langle r'\; n\;\alpha \right| \hat{A}_1 (H-E) \hat{A}_2 \left| {}^3\mathrm{H}\; d\; r \right\rangle \\ \left\langle r'\; d\;{}^3\mathrm{H} \right| \hat{A}_2 (H-E) \hat{A}_1 \left| \alpha\; n\; r \right\rangle & \left\langle r'\; d\;{}^3\mathrm{H} \right| \hat{A}_2 (H-E) \hat{A}_2 \left| {}^3\mathrm{H}\; d\; r \right\rangle \end{pmatrix} \begin{pmatrix} \frac{g_1(r)}{r} \\ \frac{g_2(r)}{r} \end{pmatrix} = 0$$

Straightforward to couple different mass partitions in the NCSM/RGM formalism

Applications to (d,p) and (d,n) reactions
Example: ^{3}**He(d,p)**^{4}**He**

Work in progress:
^{7}Li(d,p)^{8}Li & ^{8}Li(d,p)^{9}Li

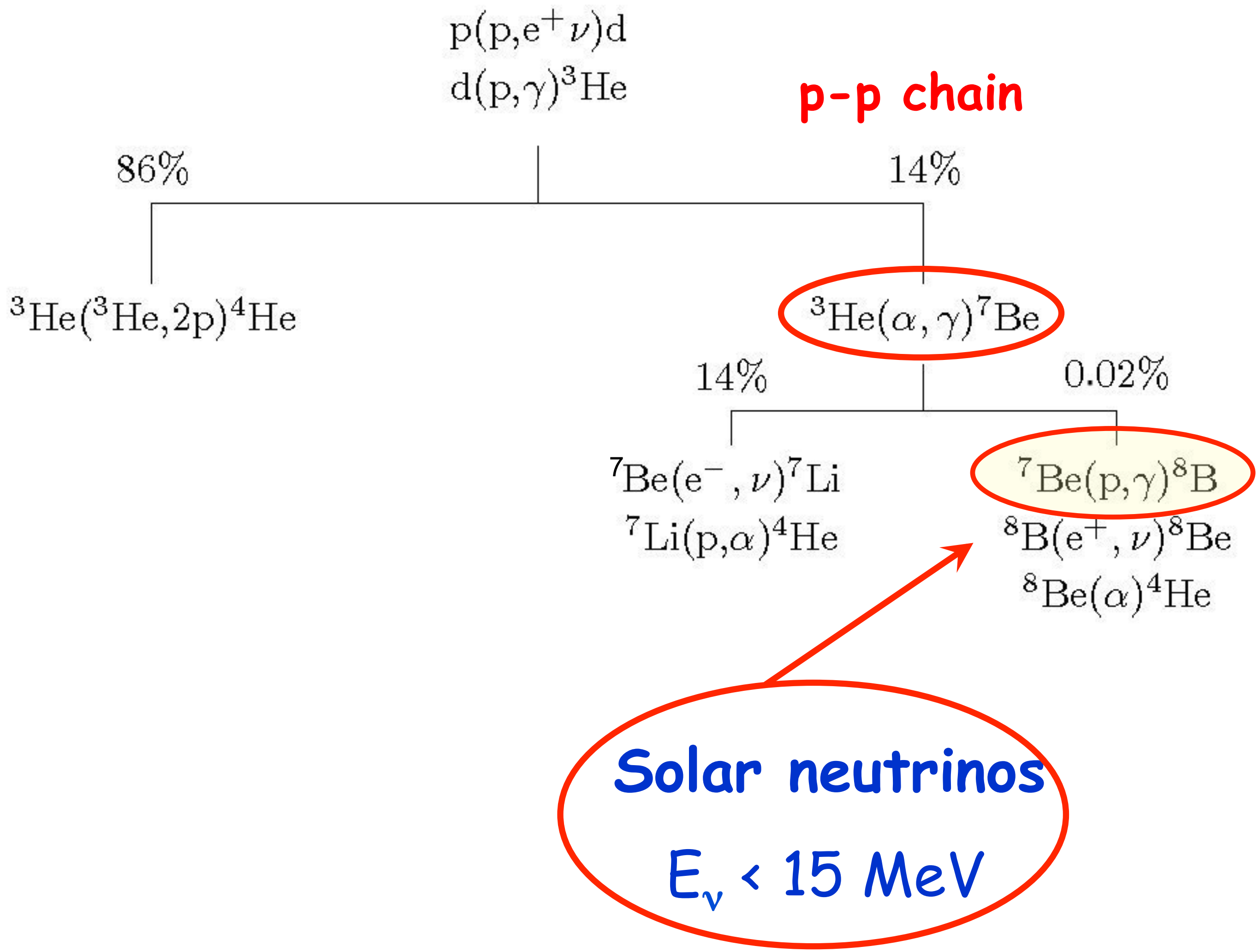


PRL 108, 042503 (2012) PHYSICAL REVIEW LETTERS week ending 27 JANUARY 2012

Ab Initio Many-Body Calculations of the ^{3}H(*d*, *n*)^{4}He and ^{3}He(*d*, *p*)^{4}He Fusion Reactions

Petr Navrátil[1,2] and Sofia Quaglioni[2]

Solar *p-p* chain

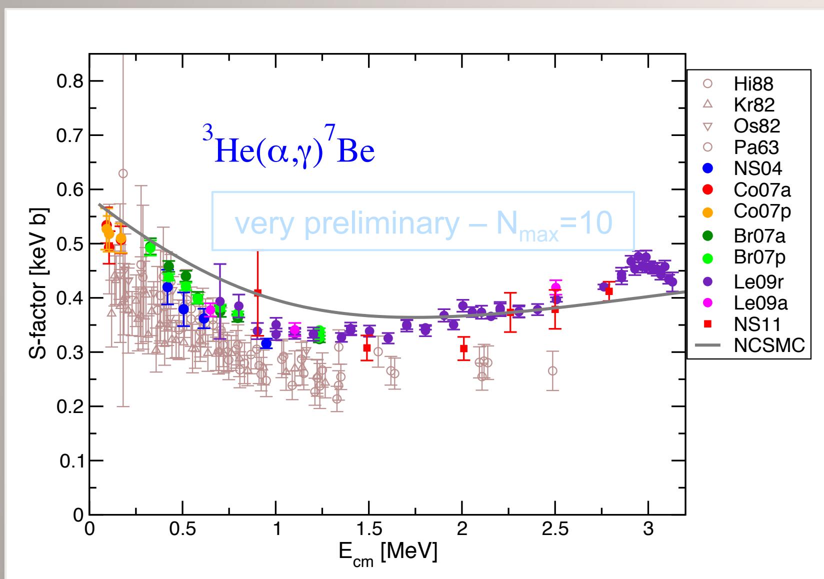


TRIUMF

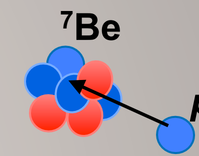
$^{3}He(^{4}He,\gamma)^{7}Be$ & $^{7}Be(p,\gamma)^{8}B$ radiative capture

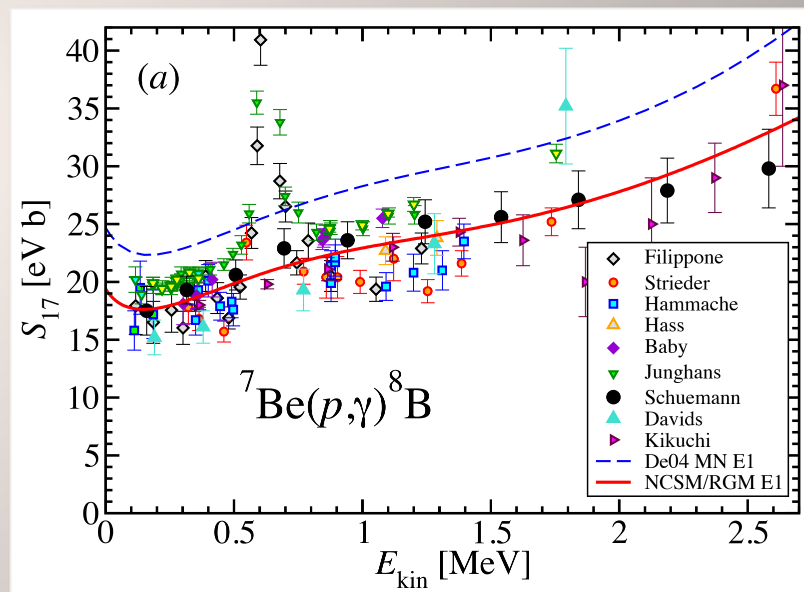
- NCSMC & NCSM/RGM calculations
  - Soft NN potential (chiral SRG-N^{3}LO with with Λ = 2.1 fm^{-1} & Λ = 1.86 fm^{-1})

In progress
J. Dohet-Eraly, P.N., S. Quaglioni, W. Horiuchi, G. Hupin



P.N., R. Roth, S. Quaglioni,
Physics Letters B 704 (2011) 379



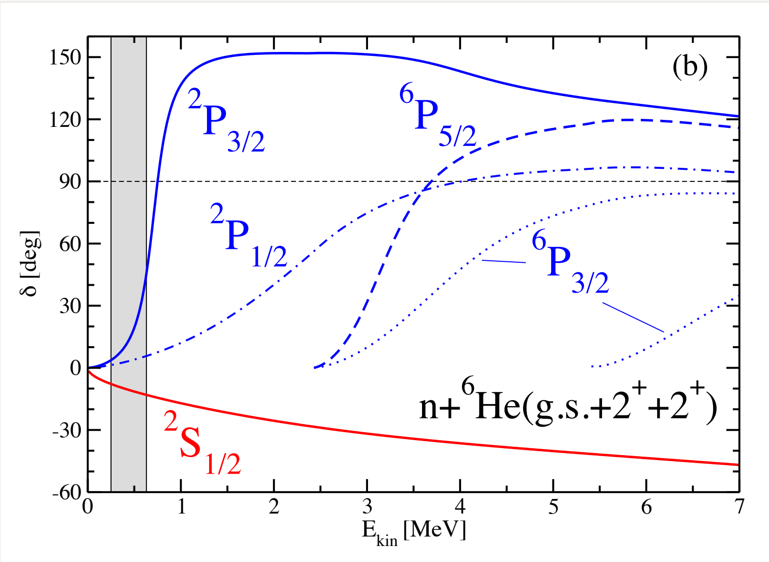


Preliminary: N_{max}=10
$E_{th}(^{7}Be)$=-1.32 MeV (Expt. -1.59 MeV)

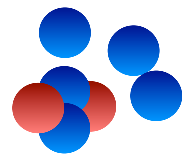
^{8}B 2^{+} g.s. **bound** by 136 keV (expt. 137 keV)
S(0) ~ 19.4(0.7) eV b

Current data evaluation: S(0)=20.8(2.1) eV b

NCSM with continuum: ^{7}He $\leftrightarrow$ ^{6}He+*n*



^{7}He

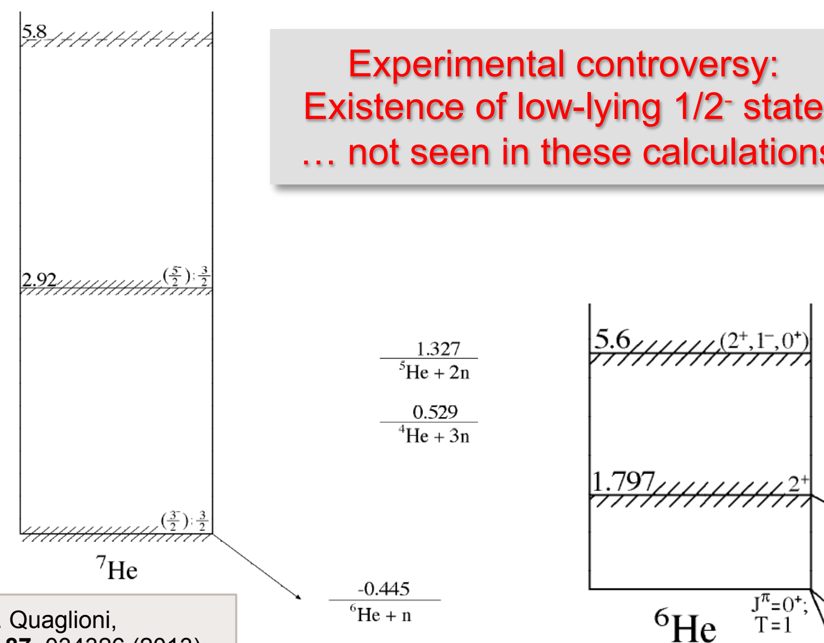


unbound

J^π	experiment			NCSMC	
	E_R	Γ	Ref.	E_R	Γ
$3/2^-$	0.430(3)	0.182(5)	[2]	0.71	0.30
$5/2^-$	3.35(10)	1.99(17)	[40]	3.13	1.07
$1/2^-$	3.03(10)	2	[11]	2.39	2.89
	3.53	10	[15]		
	1.0(1)	0.75(8)	[5]		

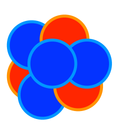
[11] A. H. Wuosmaa *et al.*, Phys. Rev. C **72**, 061301 (2005).

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

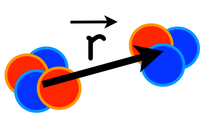


Experimental controversy:
Existence of low-lying $1/2^-$ state
… not seen in these calculations

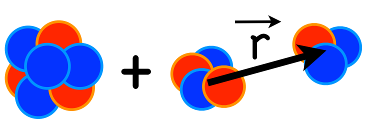
NCSM



NCSM/RGM

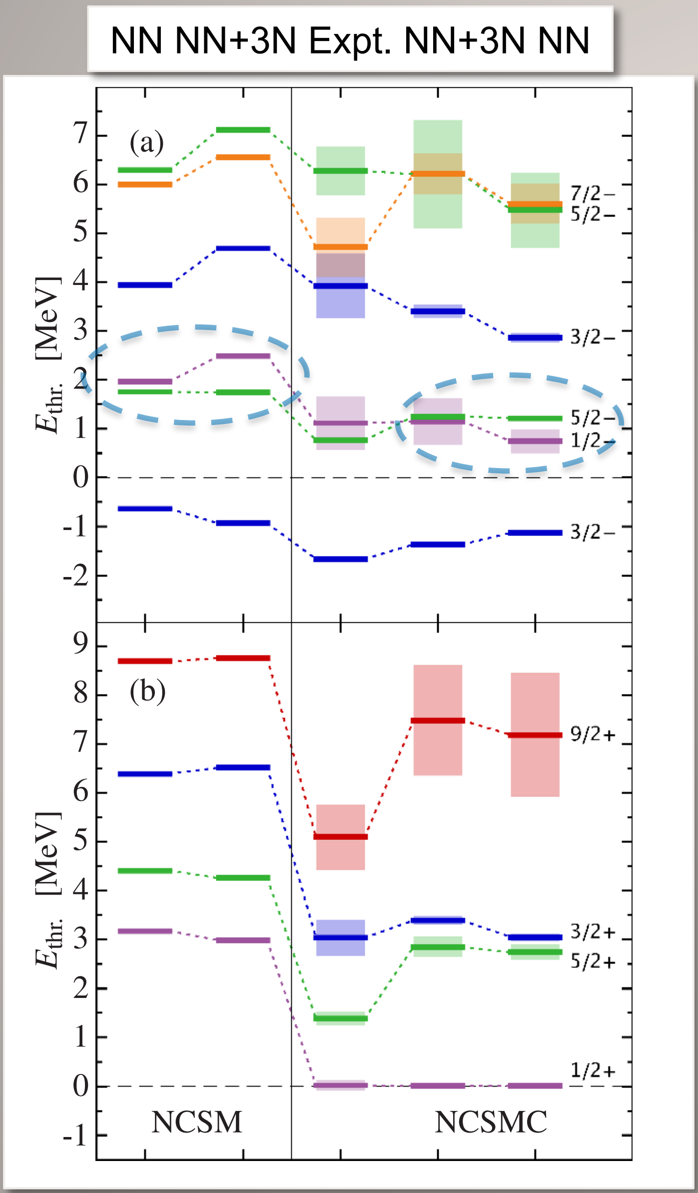


NCSMC



S. Baroni, P. N., and S. Quaglioni,
PRL **110**, 022505 (2013); PRC **87**, 034326 (2013).

Structure of ^{9}Be: bound states and resonances



^{9}Be is a stable nucleus
… but all its excited states unbound
A proper description requires to include effects of continuum

Three-nucleon interaction *and* continuum improve agreement with experiment for negative parity states

Continuum crucial for the description of positive-parity states

J. Langhammer, P. N., G. Hupin, S. Quaglioni, A. Calci, R. Roth, in preparation

TRIUMF

p+^{10}C scattering: structure of ^{11}N resonances

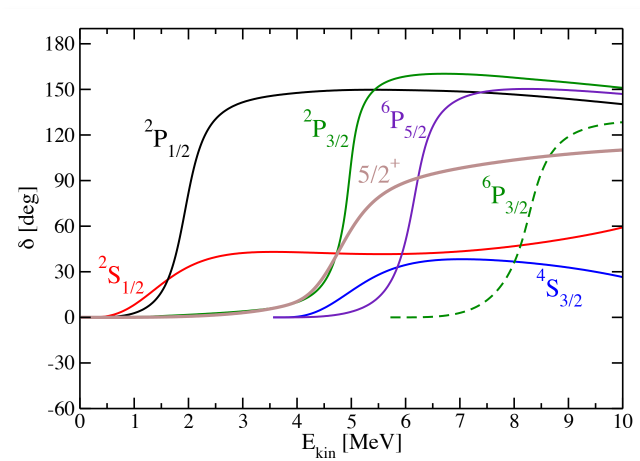
^{11}N from chiral NN+3N within NCSMC

– Preliminary

	J^π	T	E_{res} [MeV]	E_x [MeV]	Γ [keV]
	$1/2^+$	3/2	1.35	0	"4100"
✓	$1/2^-$	3/2	1.94	0.59	580
✓	$3/2^-$	3/2	4.69	3.34	280
	$5/2^+$	3/2	4.75	3.40	1790
	$3/2^+$	3/2	4.95	3.60	"4760"
	$5/2^-$	3/2	5.95	4.60	470
	$3/2^-$	3/2	7.68	6.33	620

^{11}N Expt. (TUNL evaluation)

$E_{\rm res}$ (MeV ± keV)	$E_{\rm x}$ (MeV ± keV)	$J^\pi; T$	Γ (keV)
1.49 ± 60	0	$\frac{1}{2}^+; \frac{3}{2}$	830 ± 30
2.22 ± 30	0.73 ± 70	$\frac{1}{2}^-$	600 ± 100
3.06 ± 80	(1.57 ± 80)		< 100
3.69 ± 30	2.20 ± 70	$\frac{5}{2}^+$	540 ± 40
4.35 ± 30	2.86 ± 70	$\frac{3}{2}^-$	340 ± 40
5.12 ± 80	(3.63 ± 100)	$(\frac{5}{2}^-)$	< 220
5.91 ± 30	4.42 ± 70	$(\frac{5}{2}^-)$	
6.57 ± 100	5.08 ± 120	$(\frac{3}{2}^-)$	100 ± 60



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

Negative parity $1/2^-$ and $3/2^-$ resonances in a good agreement with the current evaluation

Positive parity resonances too broad – N_{max} convergence

p+^{10}C scattering: structure of ^{11}N resonances

^{11}N from chiral NN+3N within NCSMC

– Preliminary

	J^π	T	E_{res} [MeV]	E_x [MeV]	Γ [keV]
	$1/2^+$	3/2	1.35	0	"4100"
✓	$1/2^-$	3/2	1.94	0.59	580
✓	$3/2^-$	3/2	4.69	3.34	280
	$5/2^+$	3/2	4.75	3.40	1790
	$3/2^+$	3/2	4.95	3.60	"4760"
	$5/2^-$	3/2	5.95	4.60	470
	$3/2^-$	3/2	7.68	6.33	620

^{11}N Expt. (TUNL evaluation)

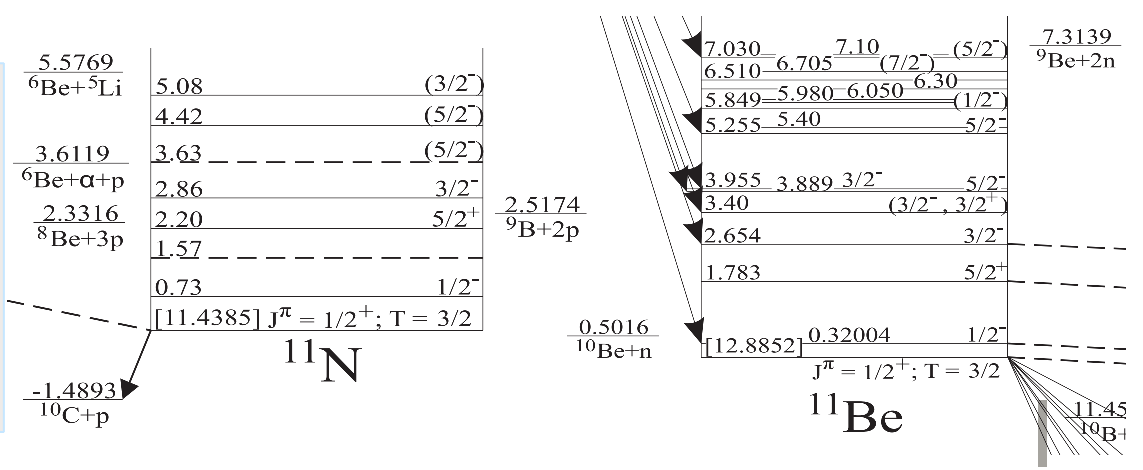
	$E_{\rm res}$ (MeV ± keV)	$E_{\rm x}$ (MeV ± keV)	$J^\pi; T$	Γ (keV)
	1.49 ± 60	0	$\frac{1}{2}^+; \frac{3}{2}$	830 ± 30
	2.22 ± 30	0.73 ± 70	$\frac{1}{2}^-$	600 ± 100
➔	3.06 ± 80	(1.57 ± 80)		< 100
	3.69 ± 30	2.20 ± 70	$\frac{5}{2}^+$	540 ± 40
	4.35 ± 30	2.86 ± 70	$\frac{3}{2}^-$	340 ± 40
➔	5.12 ± 80	(3.63 ± 100)	$(\frac{5}{2}^-)$	< 220
➔	5.91 ± 30	4.42 ± 70	$(\frac{5}{2}^-)$	
	6.57 ± 100	5.08 ± 120	$(\frac{3}{2}^-)$	100 ± 60

No candidate for 3.06 MeV resonance

We predict only one $5/2^-$ resonance below the $3/2^-_2$

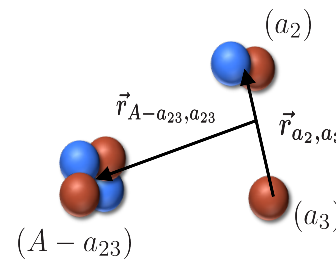
Calculations suggest that either 5.12 MeV or 5.91 MeV resonance might be $3/2^+$ instead

NCSMC resonance predictions more in line with assignments in ^{11}Be



NCSM/RGM for three-body clusters: Structure of ^{6}He

^{4}He + n + n



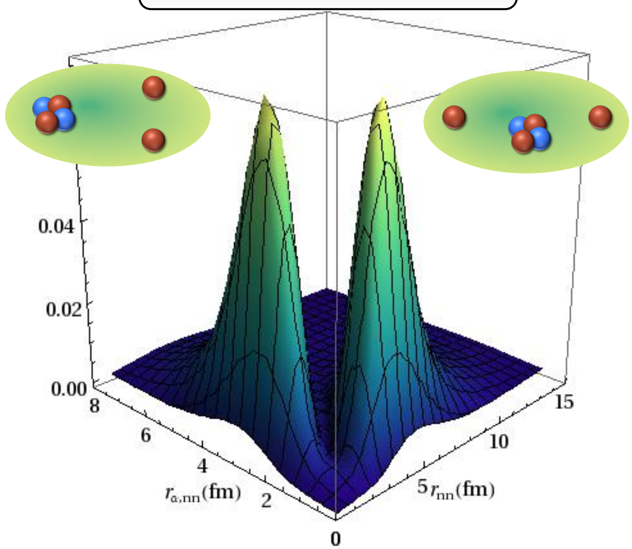
PRL **113,** 032503 (2014) PHYSICAL REVIEW LETTERS week ending 18 JULY 2014

^{4}He + n + n Continuum within an *Ab initio* Framework

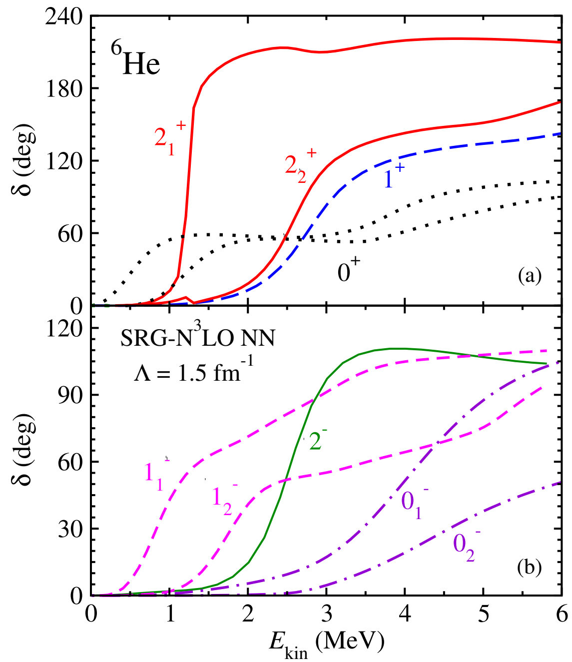
Carolina Romero-Redondo,[1,*] Sofia Quaglioni,[2,†] Petr Navrátil,[1,‡] and Guillaume Hupin[2,§]
[1]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*
[2]*Lawrence Livermore National Laboratory, P.O. Box 808, L-414, Livermore, California 94551, USA*

^{6}He bound 0$^+$ ground state

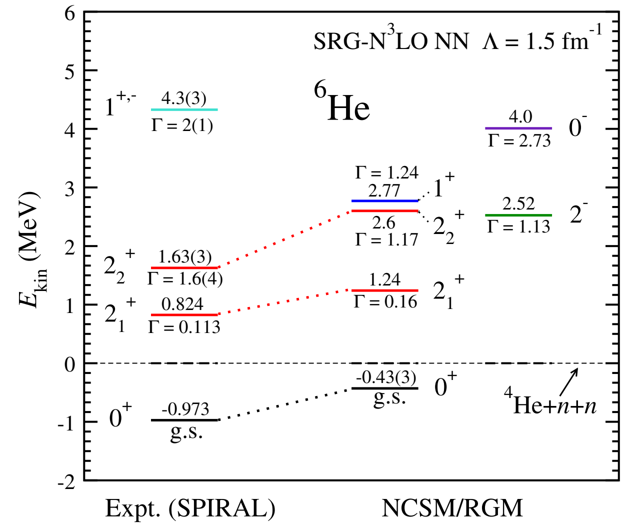
$$\ell_x = \ell_y = L = S_{nn} = 0$$



^{6}He resonances and continuum



Comparison to recent experiment



^{5}H ≈ ^{4}He + n + n in progress

TRIUMF

Conclusions and Outlook

- *Ab initio* calculations of nuclear structure & reactions is a dynamic field with rapid advances
- Several exact methods applicable to few-nucleon systems (A=3,4)
- Significant progress in *ab initio* approaches for *p*-shell nuclei
- New very successful approaches to medium mass nuclei
- We developed a new unified approach to nuclear bound and unbound states
  - Merging of the NCSM and the NCSM/RGM = **NCSMC**

- **Outlook:**
  - Applications to astrophysics
    - nuclear reactions important for astrophysics (and fusion energy generation)
    - equation of state, symmetry energy
  - Neutrino physics
    - neutrino-nucleus cross sections
    - double beta decay nuclear matrix elements
  - Fundamental symmetries
    - nuclear corrections (CKM unitarity…)
  - Strangeness
    - hypernuclei