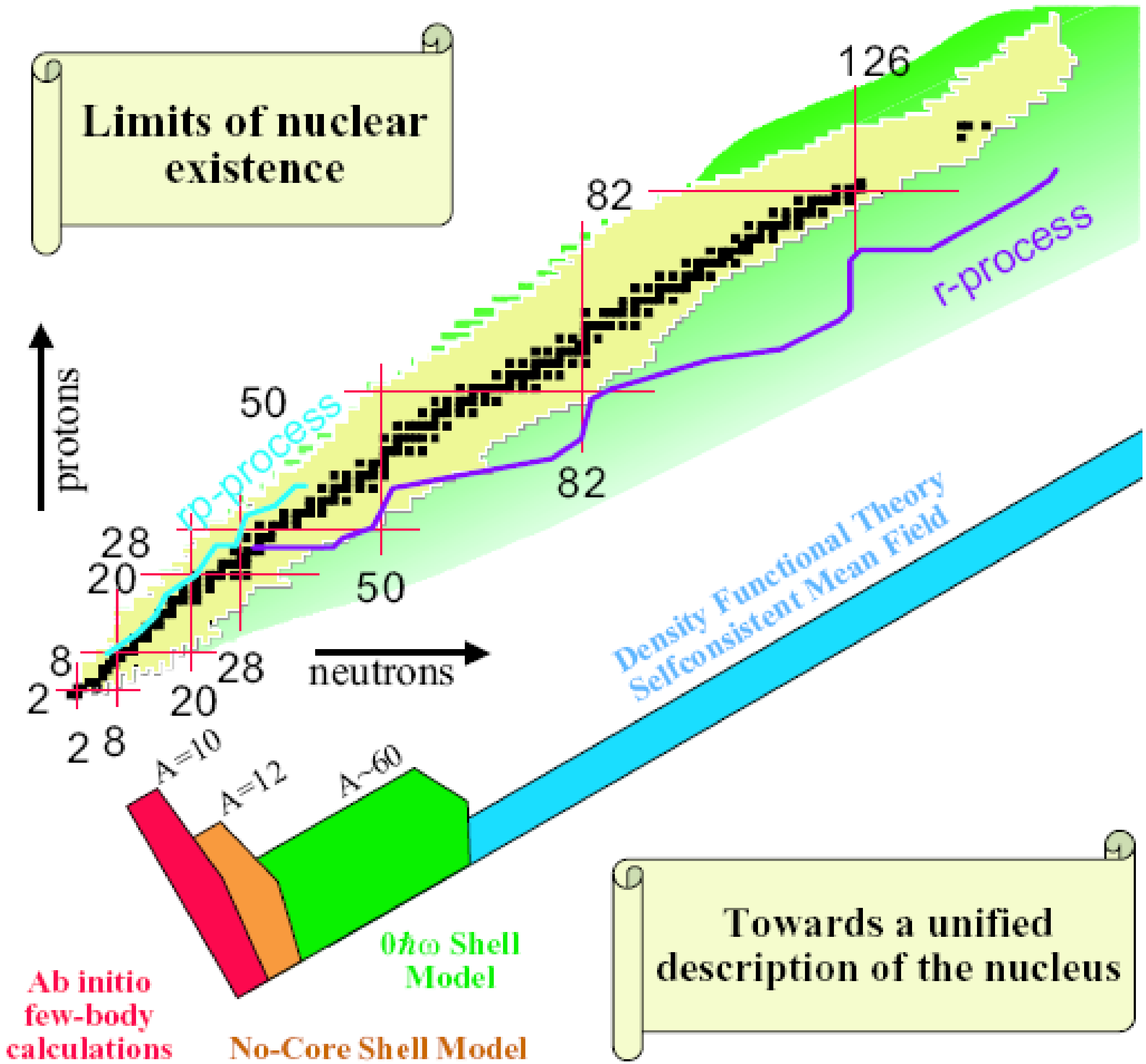
Ab initio Shell Model: With and Without a Core

Bruce R. Barrett
University of Arizona, Tucson

INT

May 13, 2010



Limits of nuclear existence
126
82
50
28
20
8
2
2 8
20
28
50
82
protons
neutrons
rp-process
r-process
Density Functional Theory
Selfconsistent Mean Field
A=10
A=12
A~60
Ab initio few-body calculations
No-Core Shell Model
0ħω Shell Model
Towards a unified description of the nucleus

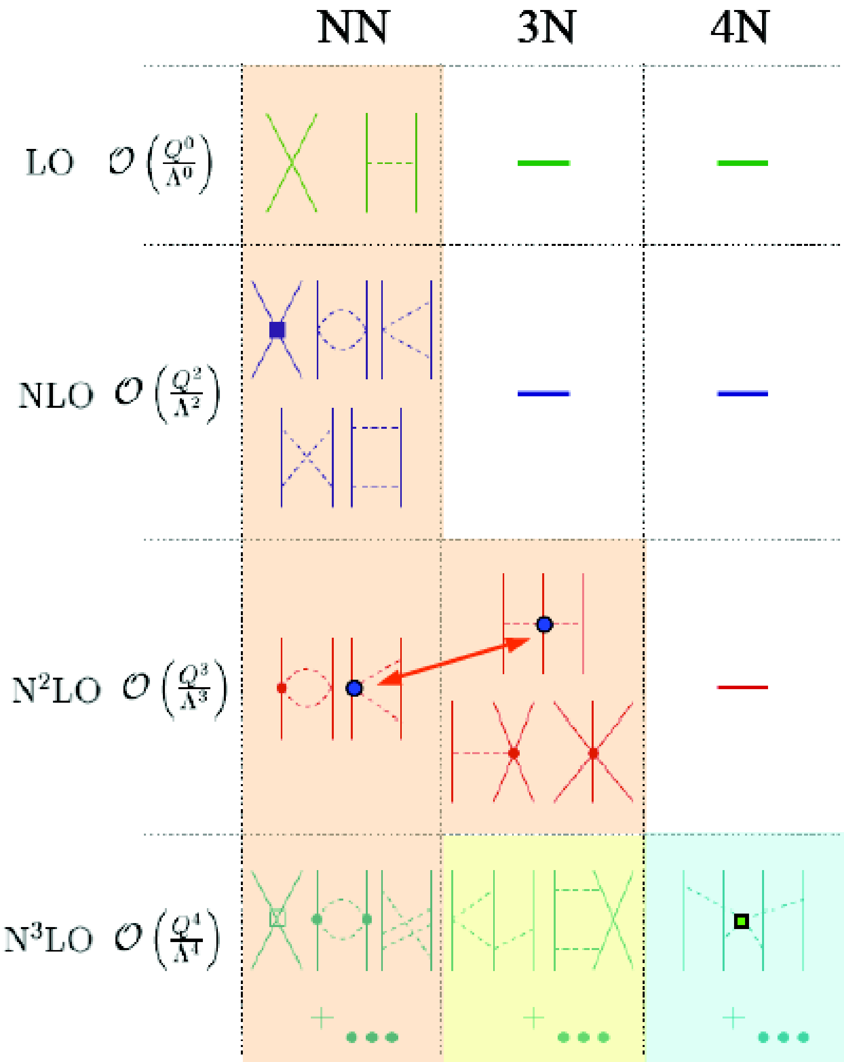
MICROSCOPIC NUCLEAR-STRUCTURE THEORY

1. Start with the bare interactions among the nucleons

2. Calculate nuclear properties using nuclear many-body theory

Chiral effective field theory (EFT) for nuclear forces

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale Λ_b

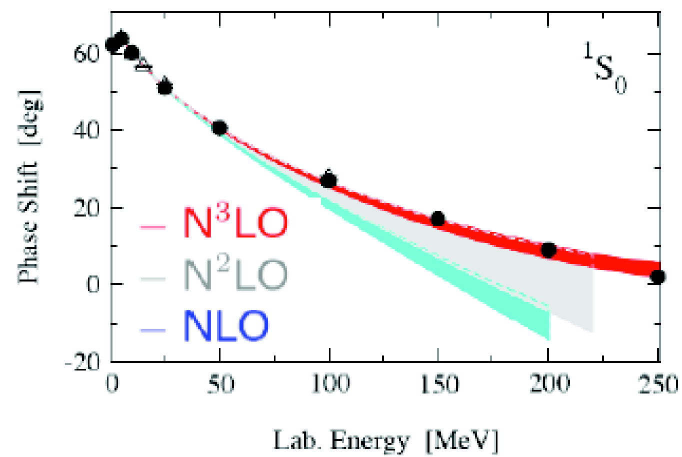


explains pheno hierarchy:
NN > 3N > 4N > …

NN-3N, πN, ππ, electro-weak,… consistency

3N,4N: 2 new couplings to N³LO!

theoretical error estimates



Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Meissner, Nogga, Machleidt,…

A. Schwenk

I. Forces among nucleons

1. QCD ---> EFT ---> CPT --> Self-consistent nucleon interactions

2. Need NN and NNN and perhaps NNNN interactions

	N^3LO	Exp
^3H	7.85 MeV	8.48 MeV
^4He	25.35(5) MeV	28.30 MeV
^6Li	28.5(5) MeV	31.99 MeV

P. Navratil and E. Caurier, Phys. Rev. C 69, 014311 (2004)

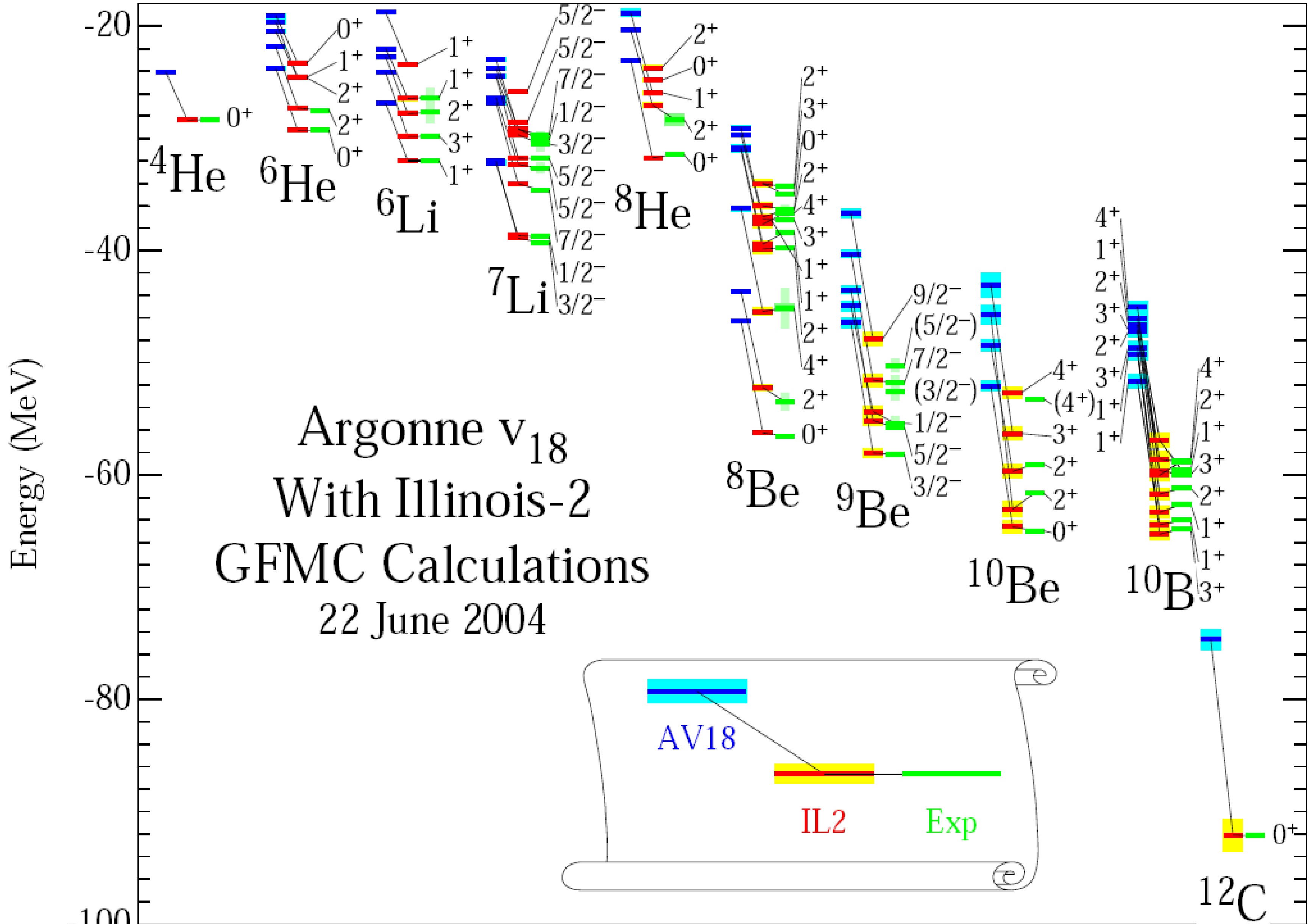
H. Kamada, *et al.*, Phys. Rev. C 64, 044001 (2001)

PHYSICAL REVIEW C, VOLUME 64, 044001

Benchmark test calculation of a four-nucleon bound state

In the past, several efficient methods have been developed to solve the Schrödinger equation for four-nucleon bound states accurately. These are the Faddeev-Yakubovsky, the coupled-rearrangement-channel Gaussian-basis variational, the stochastic variational, the hyperspherical variational, the Green's function Monte Carlo, the no-core shell model, and the effective interaction hyperspherical harmonic methods. In this article we compare the energy eigenvalue results and some wave function properties using the realistic AV8′ *NN* interaction. The results of all schemes agree very well showing the high accuracy of our present ability to calculate the four-nucleon bound state.

$BE_{th} \approx 25.91$ MeV $BE_{exp} \approx 28.296$ MeV

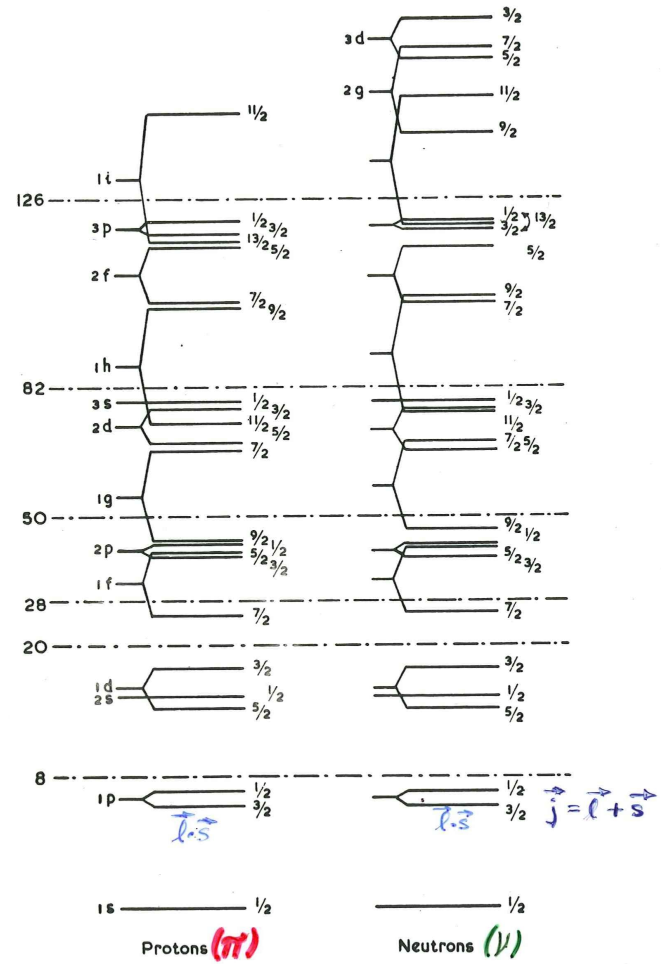


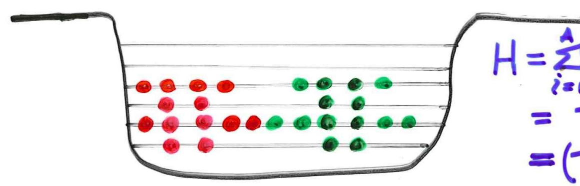
12C results are preliminary.

Standard Shell Model

Maria Goeppert-Mayer
J. Hans D. Jensen (1949)

Nobel Prize for Physics 1963





Mean Field

$$H = \sum_{i=1}^{A} t_i + \sum_{i<j}^{A} v_{ij}$$
$$= T + V$$
$$= (T + U^{sp}) + (V - U^{sp})$$
$$= H_0^{sp} + \overline{V} \text{(residual interaction)}$$

PHENOMENOLOGICAL EFFECTIVE INTERACTIONS

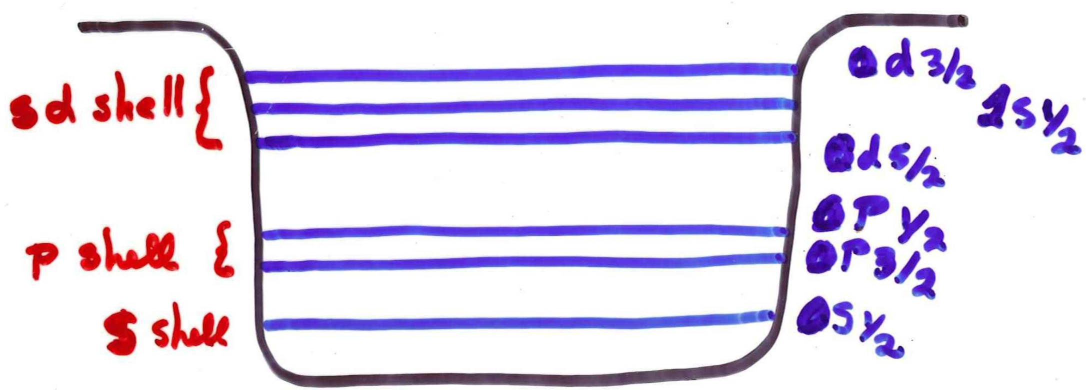
1. Usually constructed for a single major shell

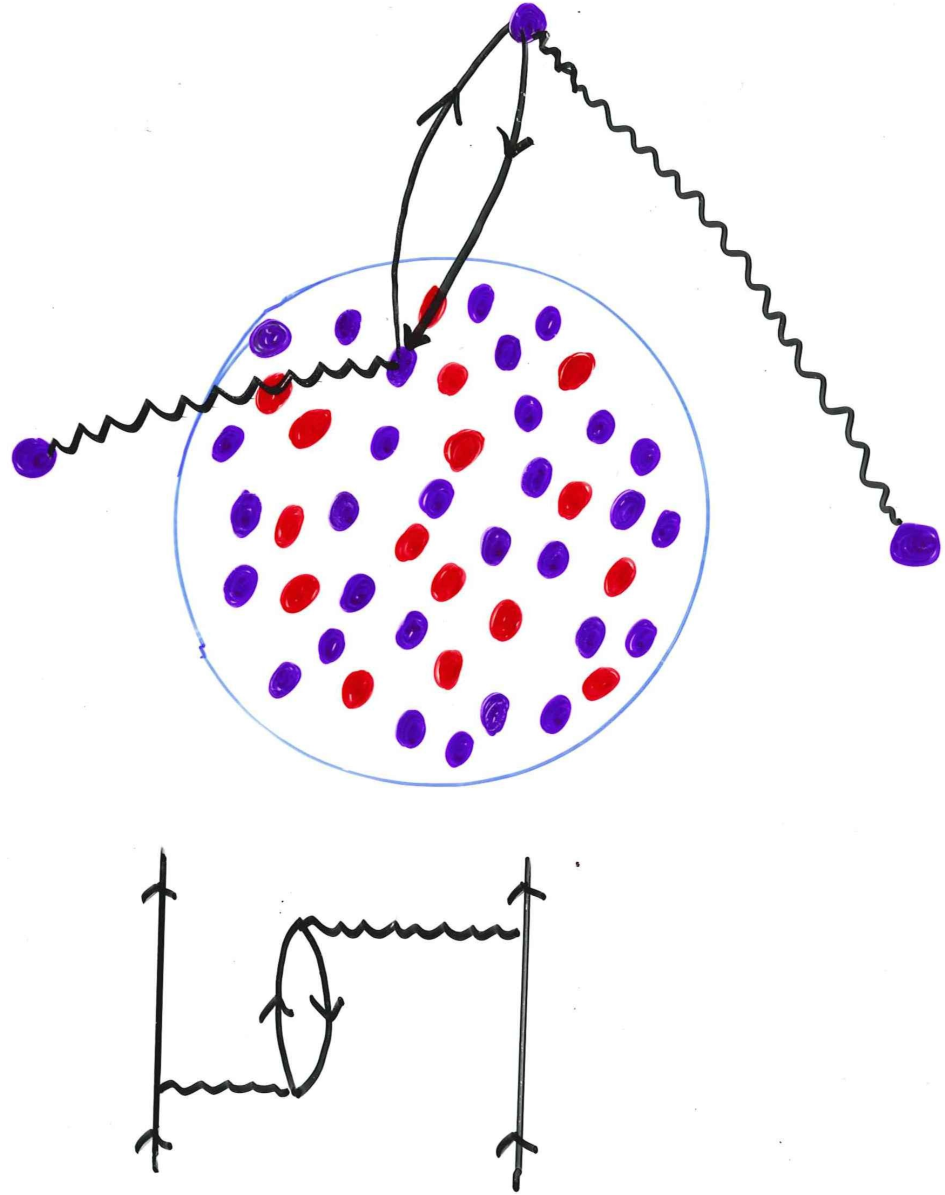
2. Take experimental single-particle energies

3. Determine two-body matrix elements

$$\langle (j_1 j_2) JT | V | (j_3 j_4) JT \rangle$$

by a least-squares fit to some subset of the experimental data





Core-polarization

Some current shell-model references

1. E. Caurier, G. Martinez-Pinedo, F. Nowacki, A. Poves, and A. P. Zuker, “The Shell Model as a Unified View of Nuclear Structure,” *Reviews of Modern Physics* **77**, 427 (2005)

2. B. A. Brown, “The Nuclear Shell Model towards the Drip Lines,” *Progress in Particle and Nuclear Physics* **47**, 517 (2001)

3. I. Talmi, “Fifty Years of the Shell Model-The Quest for the Effective Interaction,” *Advances in Nuclear Physics*, Vol. **27**, ed. J. W. Negele and E. Vogt (Plenum, NY, 2003)

4. B. R. B., “Effective Operators in Shell-Model Calculations,” 10th Indian Summer School of Nuclear Physics:Theory of Many-Fermion Systems, *Czechoslovak Journal of Physics* **49**, 1 (1999)

Effective Interactions and Operators in Nuclei

Barrett, B. R.

Effective Interactions and Operators in Nuclei: Proceedings of the Tucson International Topical Conference on Nuclear Physics Held at the University of Arizona, Tucson, June 2–6,1975. Editor: B. R. Barrett, Lecture Notes in Physics, vol. 40.

Abstract not Available

No Core Shell Model

"*Ab Initio*" approach to microscopic nuclear structure calculations, in which <u>all</u> <u>A</u> nucleons are treated as being active.

Want to solve the A-body Schrödinger equation

$$H_A \Psi^A = E_A \Psi^A$$

R P. Navrátil, J.P. Vary, B.R.B., PRC <u>62,</u> 054311 (2000)
P. Navratil, et al., J. Phys. G: Nucl. Part. Phys. 36, 083101 (2009)

No-Core Shell-Model Approach

- Start with the purely intrinsic Hamiltonian

$$H_A = T_{rel} + \mathcal{V} = \frac{1}{A}\sum_{i<j=1}^{A}\frac{(\vec{p}_i - \vec{p}_j)^2}{2m} + \sum_{i<j=1}^{A} V_{NN} \left(+ \sum_{i<j<k}^{A} V_{ijk}^{3b} \right)$$

Note: There are no phenomenological s.p. energies**!**

Can use any NN potentials

Can use any NN potentials	Coordinate space:	Argonne V8', AV18 Nijmegen I, II
	Momentum space:	CD Bonn, EFT Idaho

No-Core Shell-Model Approach

- Next, add CM harmonic-oscillator Hamiltonian

$$H_{CM}^{HO} = \frac{\vec{P}^{\,2}}{2Am} + \frac{1}{2}Am\Omega^2\vec{R}^{\,2}\,; \quad \vec{R} = \frac{1}{A}\sum_{i=1}^{A}\vec{r}_i\,, \quad \vec{P} = Am\dot{\vec{R}}$$

To H_A, yielding

$$H_A^{\Omega} = \sum_{i=1}^{A}\left[\frac{\vec{p}_i^{\,2}}{2m} + \frac{1}{2}m\Omega^2\vec{r}_i^{\,2}\right] + \underbrace{\sum_{i<j=1}^{A}\left[V_{NN}(\vec{r}_i - \vec{r}_j) - \frac{m\Omega^2}{2A}(\vec{r}_i - \vec{r}_j)^2\right]}_{V_{ij}}$$

Defines a basis (*i.e.* HO) for evaluating V_{ij}

$$H \Psi = E \Psi$$

We cannot, in general, solve the full problem in the complete Hilbert space, so we must truncate to a finite model space

$\Rightarrow$ We must use effective interactions and operators!

Effective Interaction

- Must truncate to a finite model space $V_{ij} \dashrightarrow V_{ij}^{effective}$
- In general, V_{ij}^{eff} is an A-body interaction
- We want to make an a-body cluster approximation

$$\mathcal{H} = \mathcal{H}^{(I)} + \mathcal{H}^{(A)} \underset{a < A}{\gtrapprox} \mathcal{H}^{(I)} + \mathcal{H}^{(a)}$$

$$H\Psi_\alpha = E_\alpha\Psi_\alpha$$ where $$H = \sum_{i=1}^{A} t_i + \sum_{i\leq j}^{A} v_{ij}.$$

$$\mathcal{H}\Phi_\beta = E_\beta\Phi_\beta$$

$$\Phi_\beta = P\Psi_\beta$$

P is a projection operator from S into $\mathcal{S}$

$$< \tilde{\Phi}_\gamma|\Phi_\beta >= \delta_{\gamma\beta}$$

$$\mathcal{H} = \sum_{\beta\epsilon\mathcal{S}} |\Phi_\beta > E_\beta < \tilde{\Phi}_\beta|$$

Effective Hamiltonian for NCSM

Solving $H^{\Omega}_{A,\, a=2}\Psi_{a=2} = E^{\Omega}_{A,\, a=2}\Psi_{a=2}$ in "infinite space" 2n+l = 450 relative coordinates

P + Q = 1; P – model space; Q – excluded space;

$$E^{\Omega}_{A,2} = U_2 H^{\Omega}_{A,2} U_2^{\dagger} \qquad U_2 = \begin{pmatrix} U_{2,P} & U_{2,PQ} \\ U_{2,QP} & U_{2,Q} \end{pmatrix} \qquad E^{\Omega}_{A,2} = \begin{pmatrix} E^{\Omega}_{A,2,P} & 0 \\ 0 & E^{\Omega}_{A,2,Q} \end{pmatrix}$$

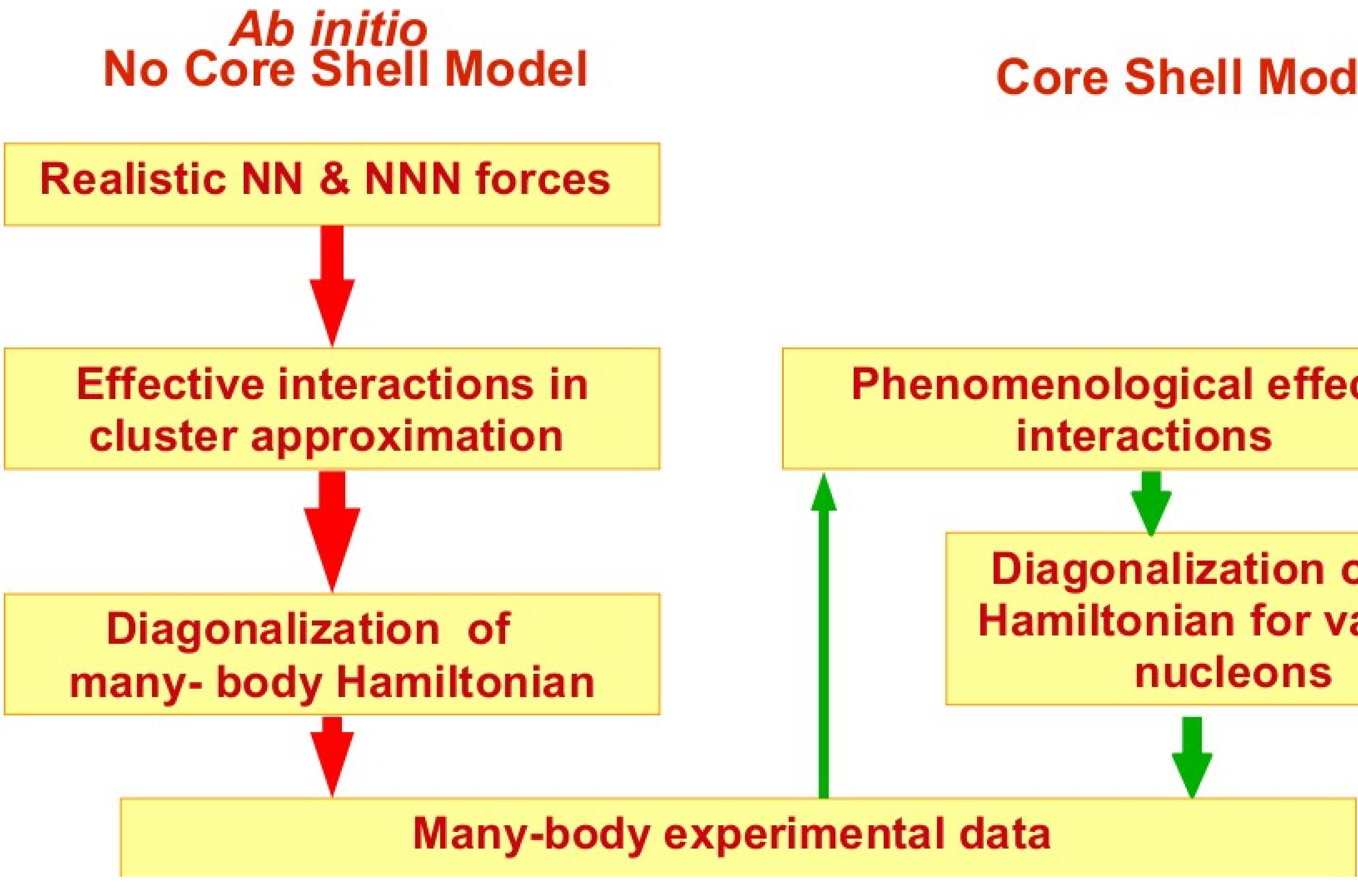
$$H^{N_{\max},\Omega,\mathrm{eff}}_{A,2} = \frac{U^{\dagger}_{2,P}}{\sqrt{U^{\dagger}_{2,P}U_{2,P}}} E^{\Omega}_{A,2,P} \frac{U_{2,P}}{\sqrt{U^{\dagger}_{2,P}U_{2,P}}}$$

Two ways of convergence:

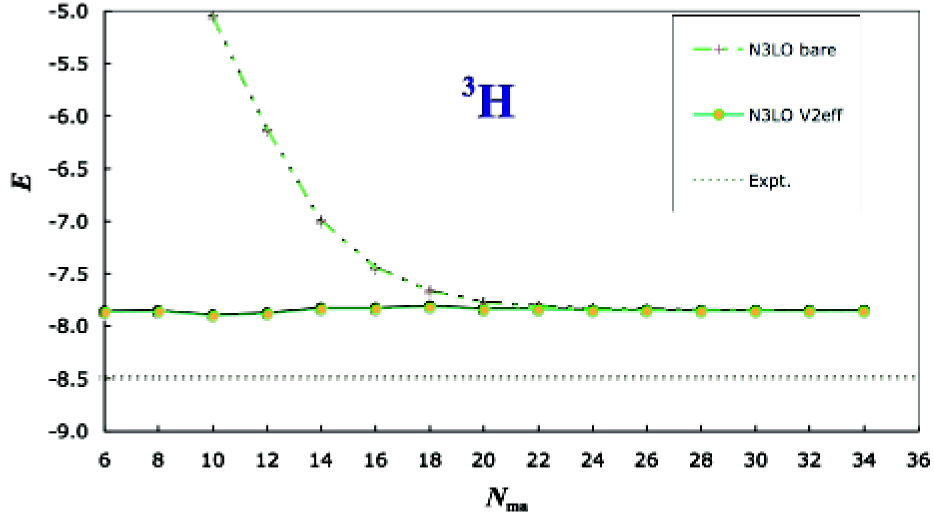
1) For P → 1 and fixed a: $H^{\mathrm{eff}}_{A,a=2} \to H_A$

2) For a → A and fixed P: $H^{\mathrm{eff}}_{A,a} \to H_A$

From few-body to many-body

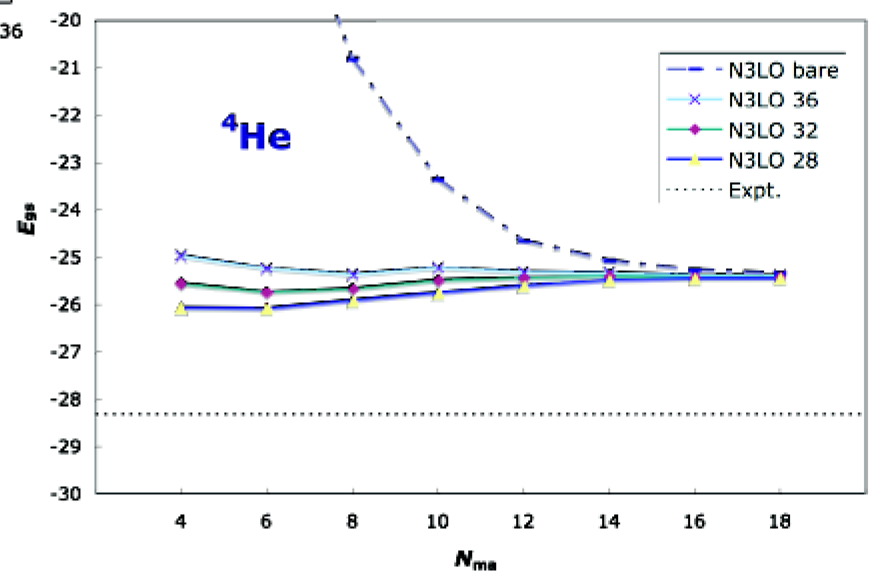


- NCSM convergence test
  - Comparison to other methods

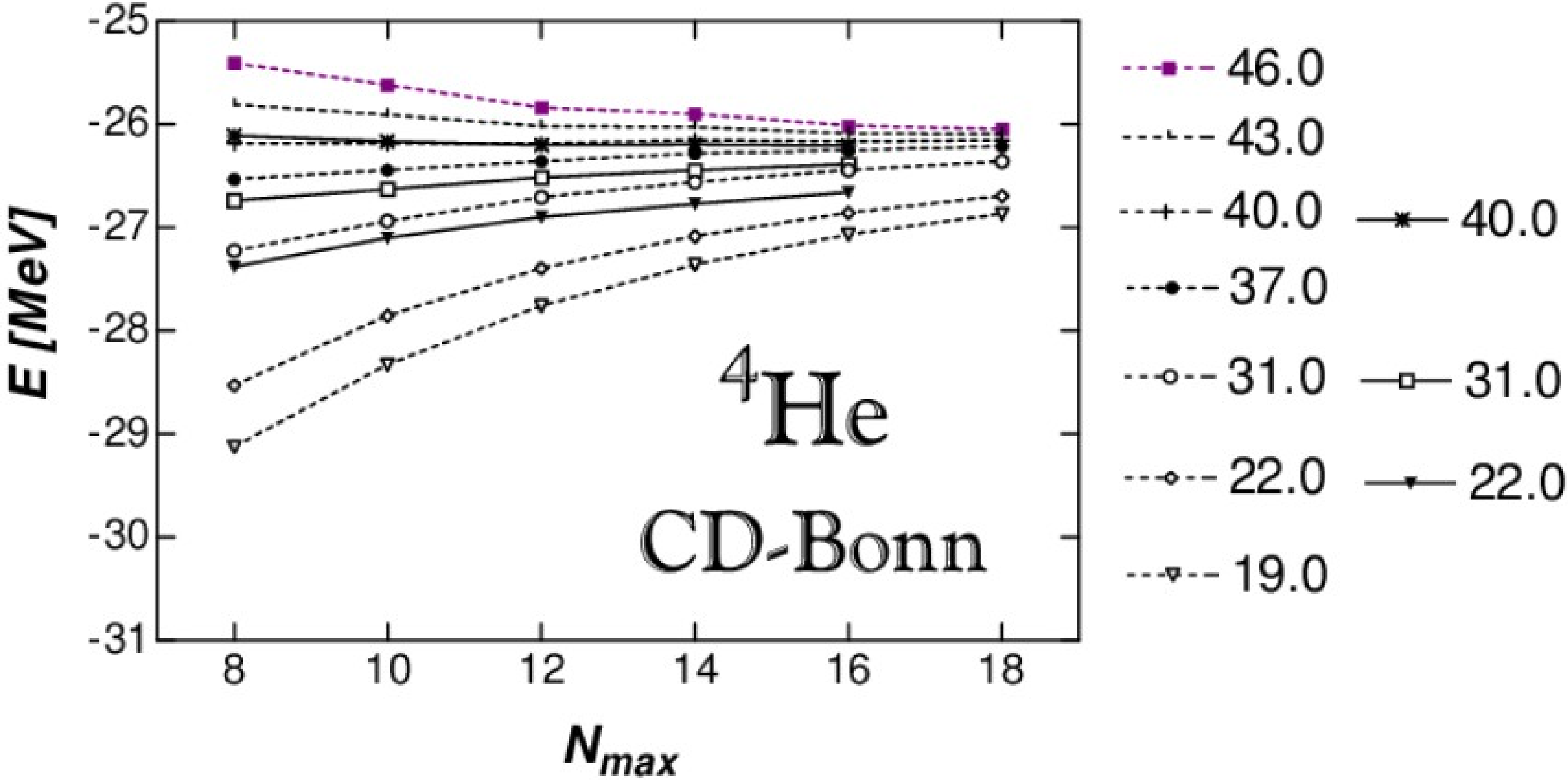


N³LO NN	NCSM	FY	HH
³H	7.852(5)	7.854	7.854
⁴He	25.39(1)	25.37	25.38

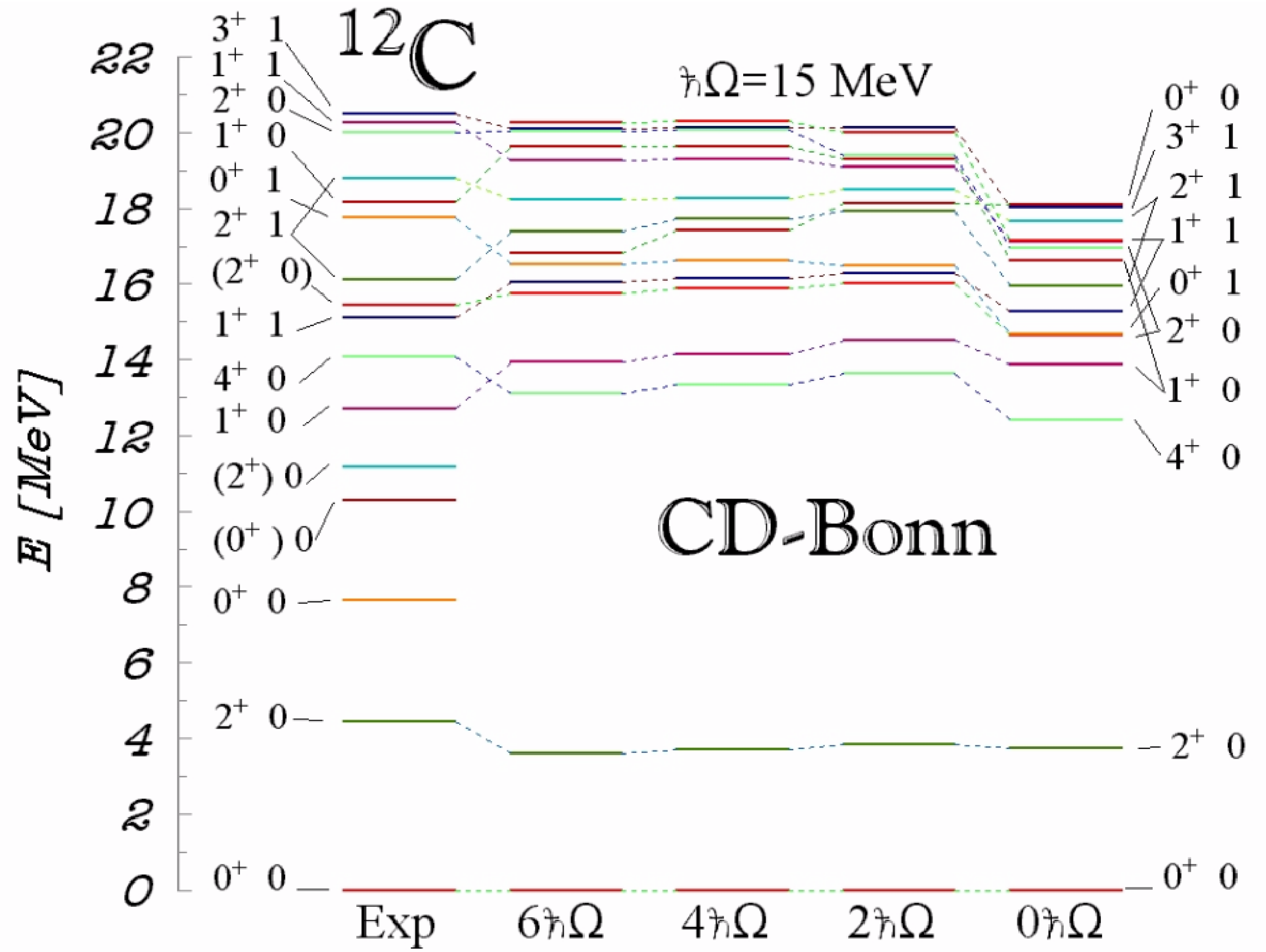
- Short-range correlations ⇒ effective interaction
- Medium-range correlations ⇒ multi-$\hbar\Omega$ model space
- Dependence on
  - size of the model space (N_{max})
  - HO frequency ($\hbar\Omega$)
- Not a variational calculation
- Convergence OK
- NN interaction insufficient to reproduce experiment



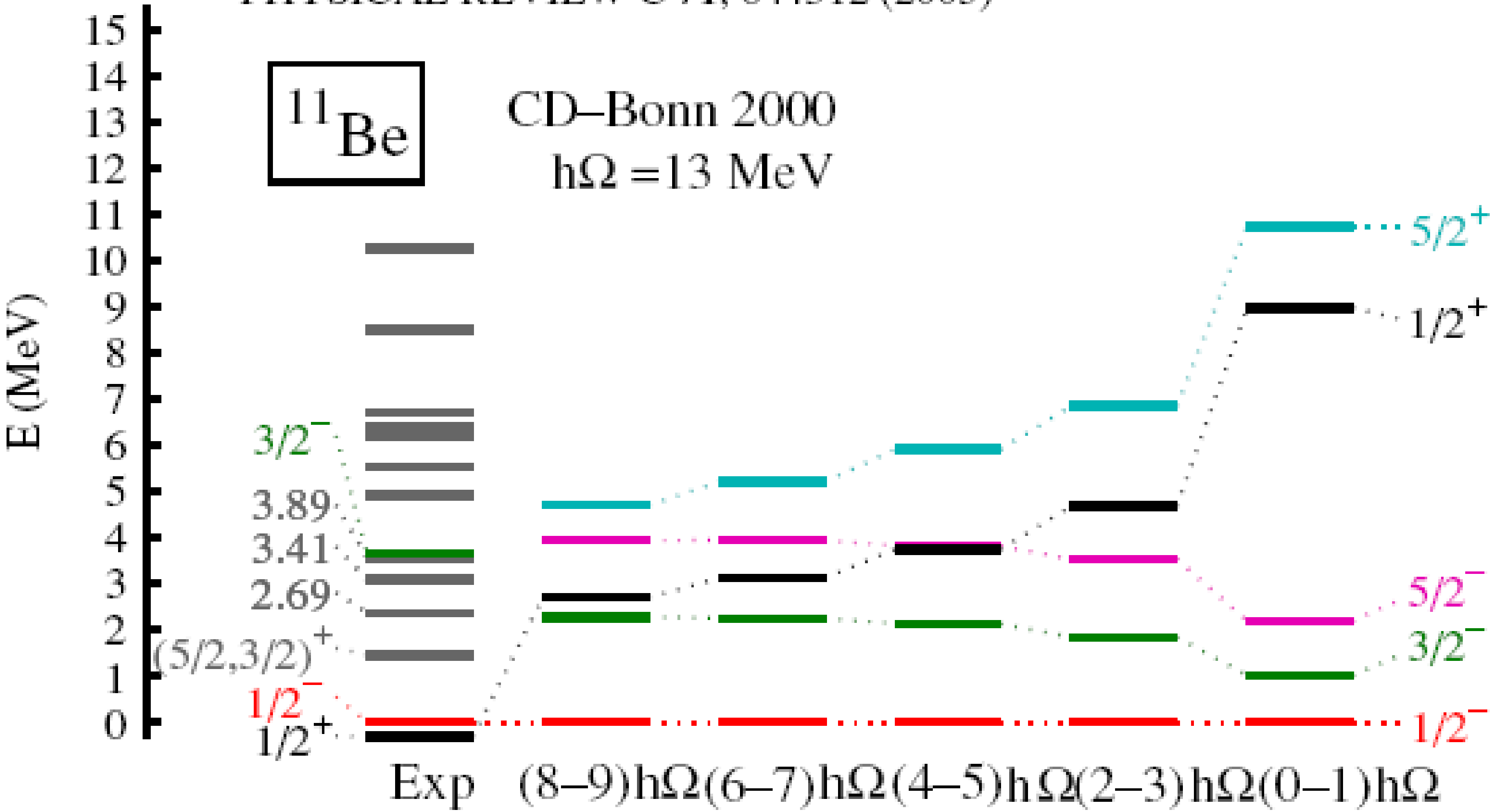
P. Navratil, INT Seminar, November 13, 2007, online



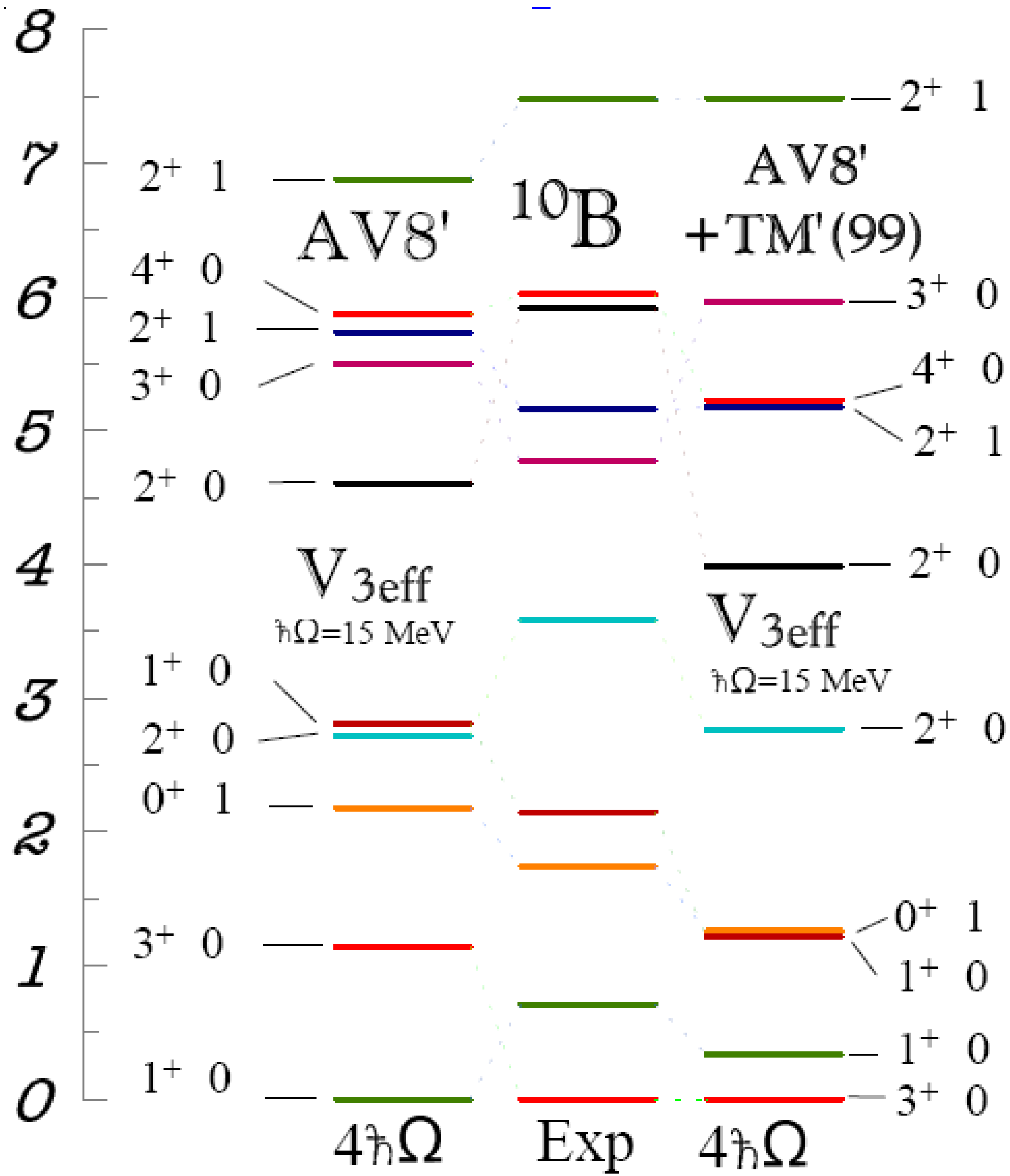
-25
-26
-27
-28
-29
-30
-31
E [MeV]
8
10
12
14
16
18
N_max
⁴He
CD-Bonn
46.0
43.0
40.0
40.0
37.0
31.0
31.0
22.0
22.0
19.0



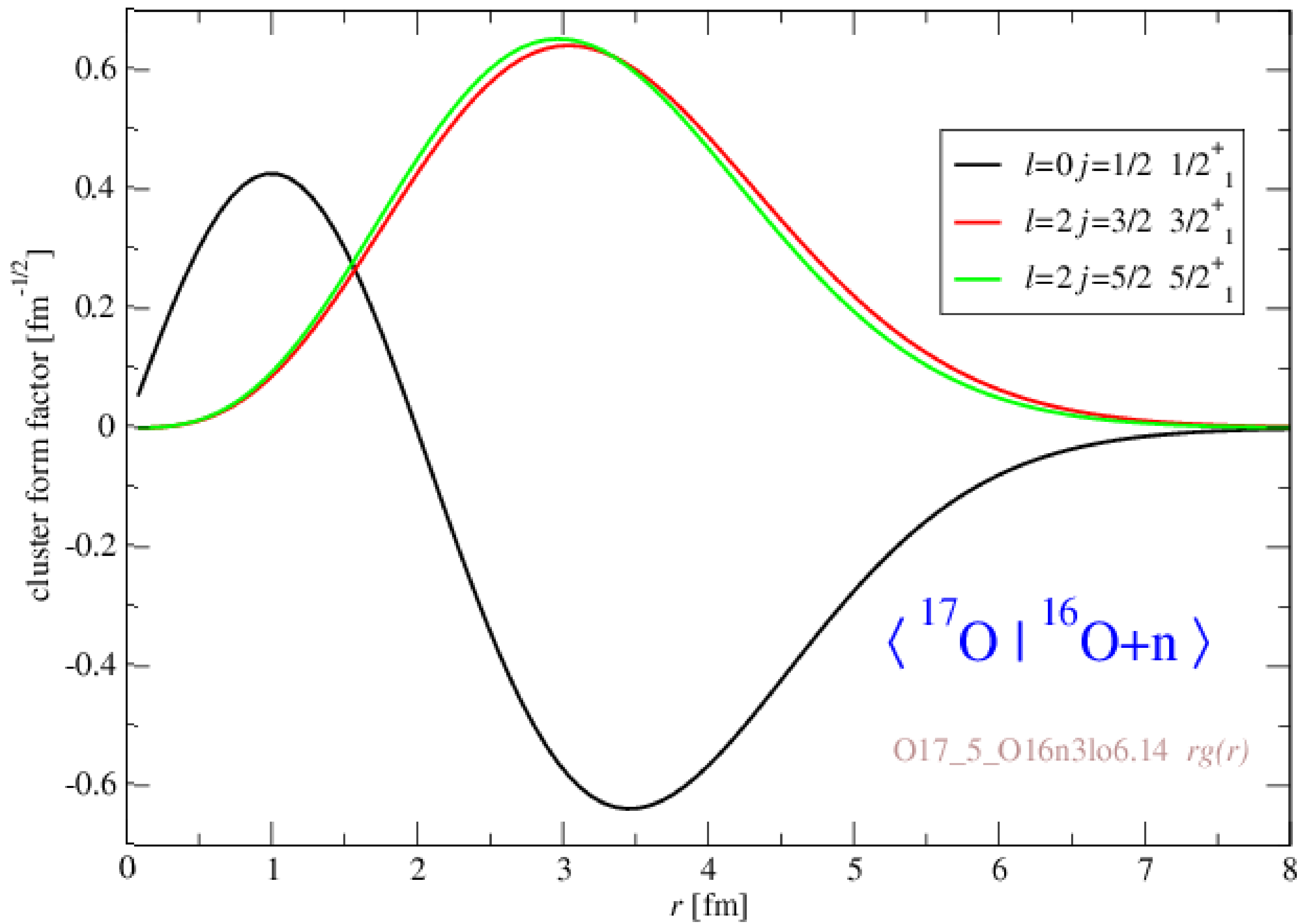
P. Navrátil, J. P. Vary and B. R. B., Phys. Rev. C 62, 054311 (2000)



15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
E (MeV)
11Be
CD–Bonn 2000
hΩ =13 MeV
3/2−
3.89
3.41
2.69
(5/2,3/2)+
1/2−
1/2+
5/2+
1/2+
5/2−
3/2−
1/2−
Exp
(8–9)hΩ
(6–7)hΩ
(4–5)hΩ
(2–3)hΩ
(0–1)hΩ



P. Navrátil and W. E. Ormand, Phys. Rev. C **68**, 034305 (2003)



0.6
0.4
0.2
0
-0.2
-0.4
-0.6
cluster form factor [fm$^{-1/2}$]
0
1
2
3
4
5
6
7
8
r [fm]
l=0 j=1/2 1/2$^+_1$
l=2 j=3/2 3/2$^+_1$
l=2 j=5/2 5/2$^+_1$
⟨ ^{17}O | ^{16}O+n ⟩
O17_5_O16n3lo6.14 rg(r)

P. Navratil

H. Kamada, *et al.*, Phys. Rev. C 64, 044011 (2001)

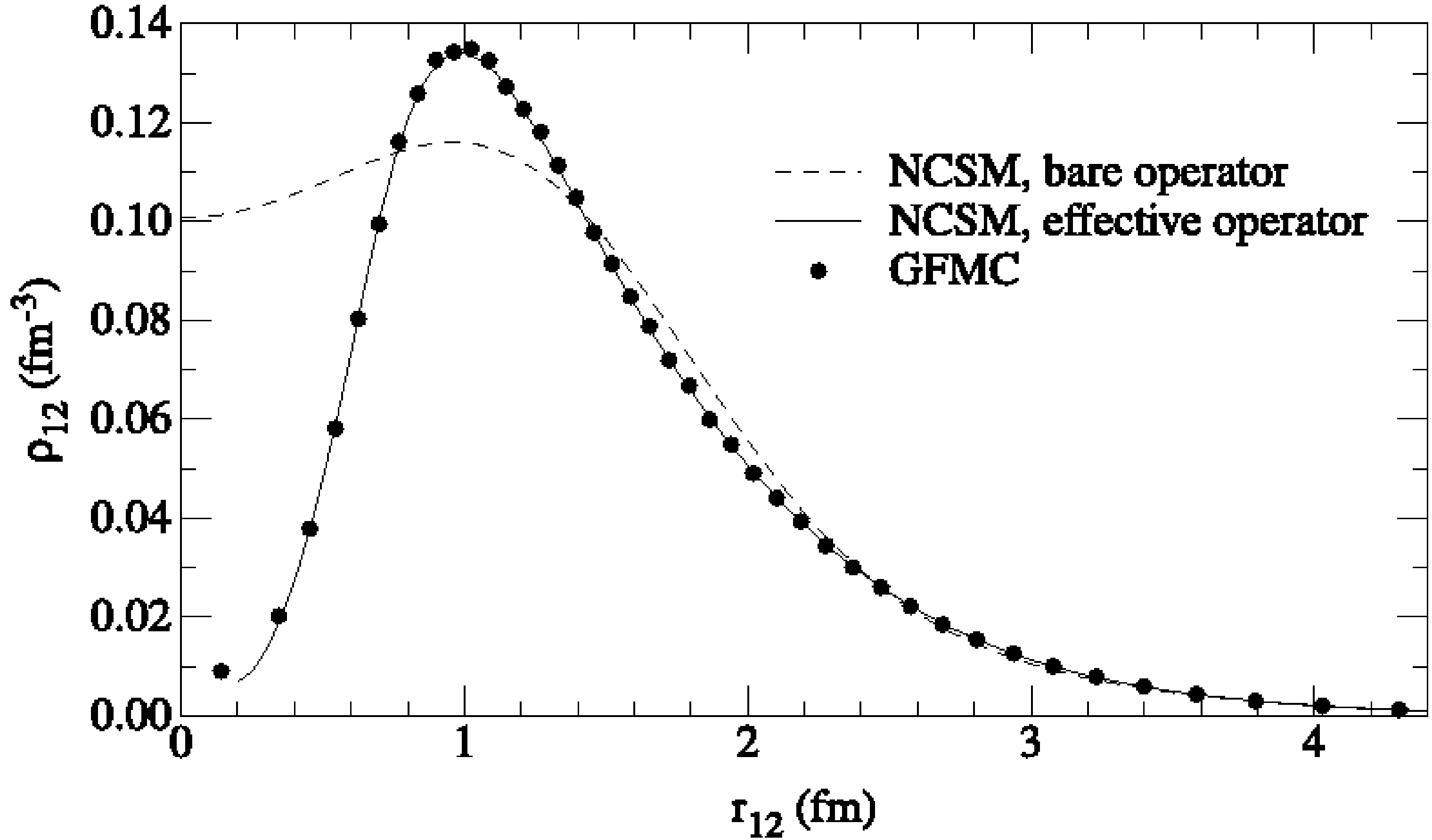
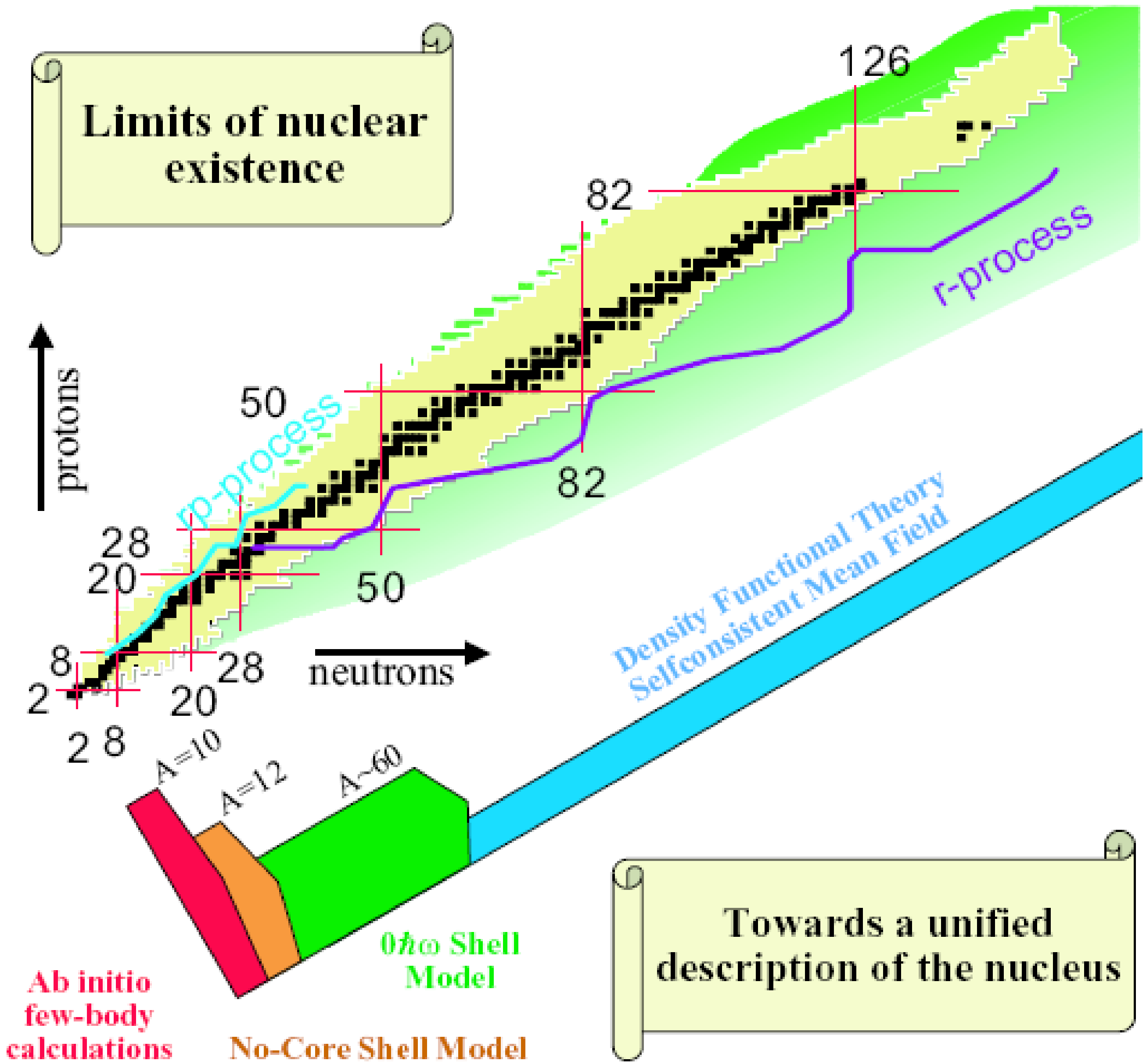


Figure 2. *NCSM and GFMC NN pair density in ^{4}He.*



Limits of nuclear existence
126
82
r-process
protons
50
rp-process
82
28
20
50
Density Functional Theory
Selfconsistent Mean Field
8
28
neutrons
2
20
2 8
A=10
A=12
A~60
0ħω Shell Model
Towards a unified description of the nucleus
Ab initio few-body calculations
No-Core Shell Model

Towards a unified description of the nucleus

The goal of nuclear structure theory:

exact treatment of nuclei based on NN, NNN,... interactions

⇨ need to build a bridge between:

ab initio few-body & light nuclei calculations: $A \lesssim 24$

$0\hbar\Omega$ Shell Model calculations: $16 < A < 120$

Density Functional Theory calculations: $A \geq 100$

PHYSICAL REVIEW C **78**, 044302 (2008)

Ab-initio shell model with a core

A. F. Lisetskiy,[1,*] B. R. Barrett,[1] M. K. G. Kruse,[1] P. Navratil,[2] I. Stetcu,[3] and J. P. Vary[4]

[1]*Department of Physics, University of Arizona, Tucson, Arizona 85721, USA*

[2]*Lawrence Livermore National Laboratory, Livermore, California 94551, USA*

[3]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

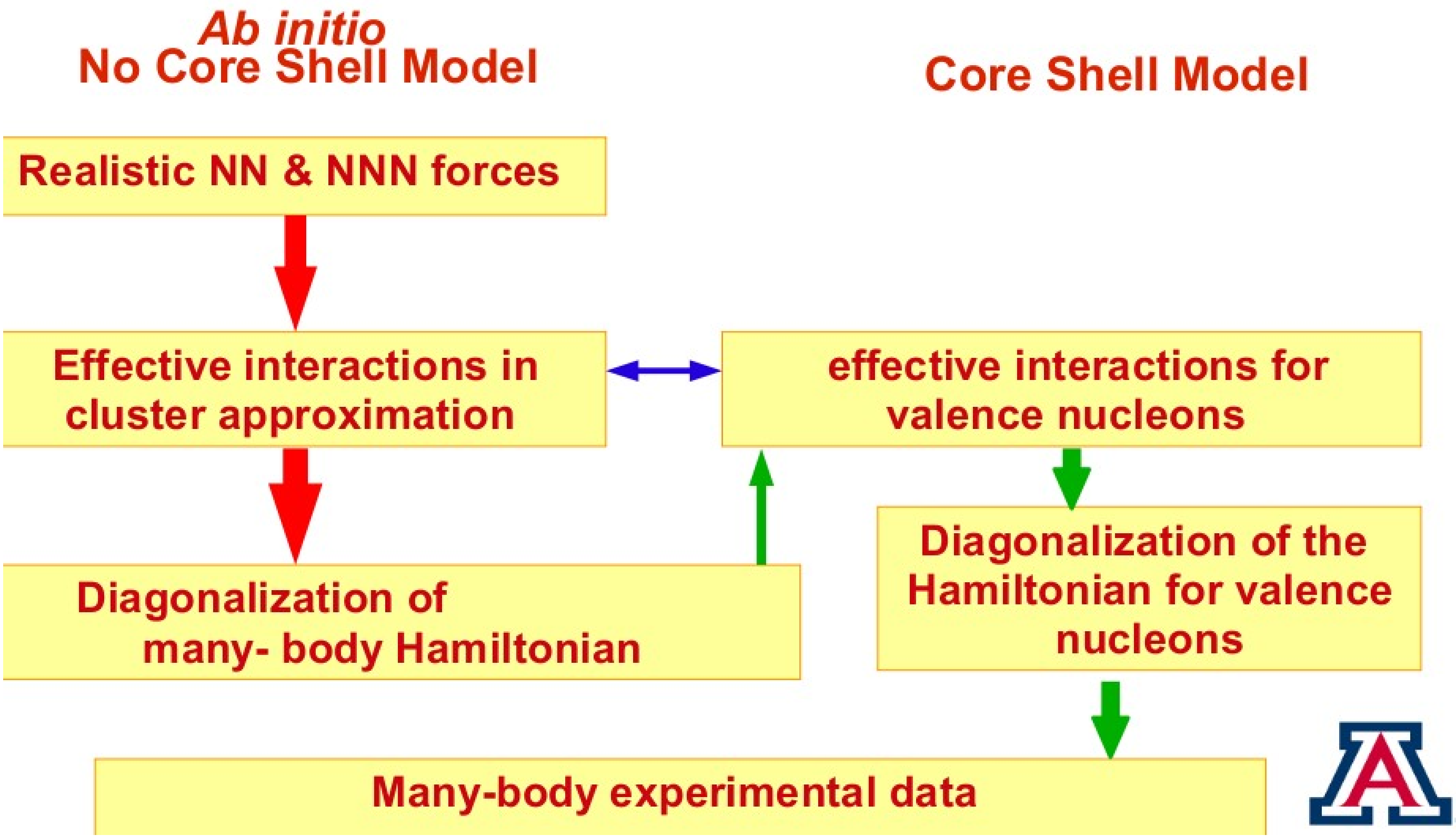
[4]*Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA*

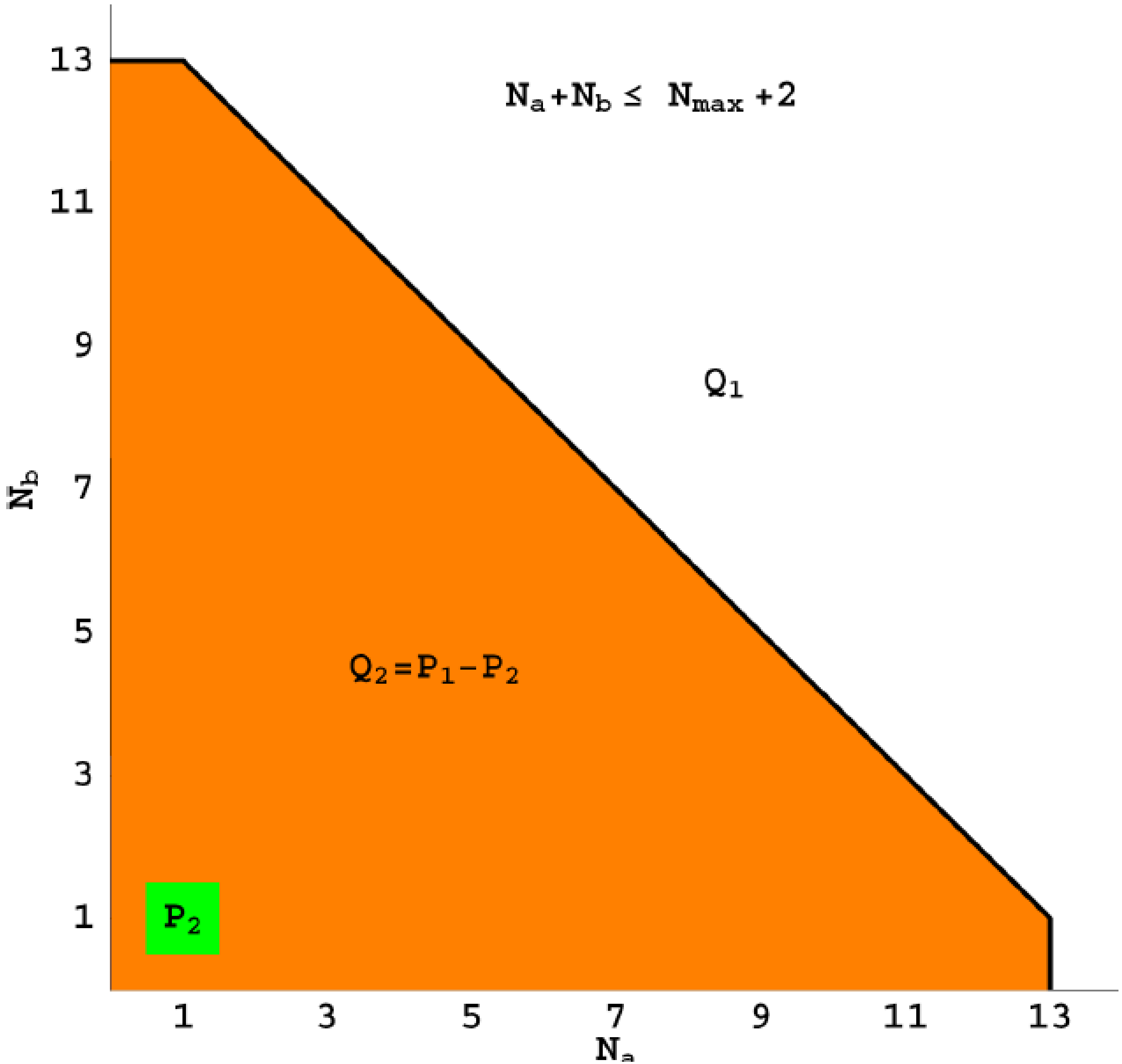
(Received 20 June 2008; published 10 October 2008)

We construct effective two- and three-body Hamiltonians for the p-shell by performing $12\hbar\Omega$ *ab initio* no-core shell model (NCSM) calculations for $A = 6$ and 7 nuclei and explicitly projecting the many-body Hamiltonians onto the $0\hbar\Omega$ space. We then separate these effective Hamiltonians into inert core, one- and two-body contributions (also three-body for $A = 7$) and analyze the systematic behavior of these different parts as a function of the mass number A and size of the NCSM basis space. The role of effective three- and higher-body interactions for $A > 6$ is investigated and discussed.

DOI: 10.1103/PhysRevC.78.044302 PACS number(s): 21.10.Hw, 21.60.Cs, 23.20.Lv, 27.20.+n

From few-body to many-body





$N_a+N_b \leq N_{max}+2$
Q_1
$Q_2=P_1-P_2$
P_2
N_b
N_a
1
3
5
7
9
11
13

Effective Hamiltonian for NCSM

Solving $H^{\Omega}_{A,\, a=2} \Psi_{a=2} = E^{\Omega}_{A,\, a=2} \Psi_{a=2}$ in "infinite space" 2n+l = 450 relative coordinates

P + Q = 1; P – model space; Q – excluded space;

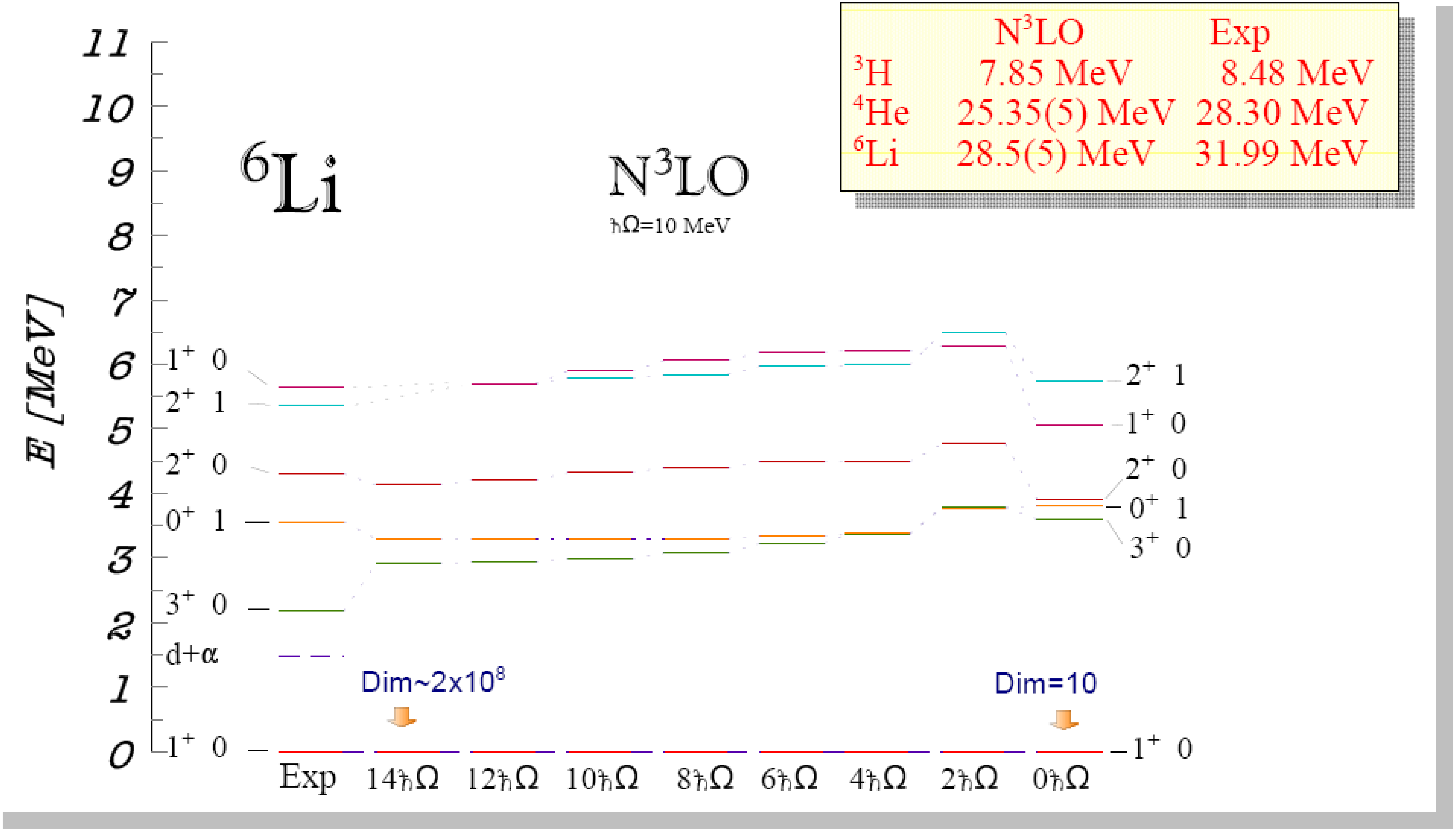
$$E^{\Omega}_{A,2} = U_2 H^{\Omega}_{A,2} U_2^{\dagger} \qquad U_2 = \begin{pmatrix} U_{2,P} & U_{2,PQ} \\ U_{2,QP} & U_{2,Q} \end{pmatrix} \qquad E^{\Omega}_{A,2} = \begin{pmatrix} E^{\Omega}_{A,2,P} & 0 \\ 0 & E^{\Omega}_{A,2,Q} \end{pmatrix}$$

$$H^{N_{\max},\Omega,\mathrm{eff}}_{A,2} = \frac{U^{\dagger}_{2,P}}{\sqrt{U^{\dagger}_{2,P} U_{2,P}}} E^{\Omega}_{A,2,P} \frac{U_{2,P}}{\sqrt{U^{\dagger}_{2,P} U_{2,P}}}$$

Two ways of convergence:

1) For P → 1 and fixed a: $H^{\mathrm{eff}}_{A,a=2} \rightarrow H_A$

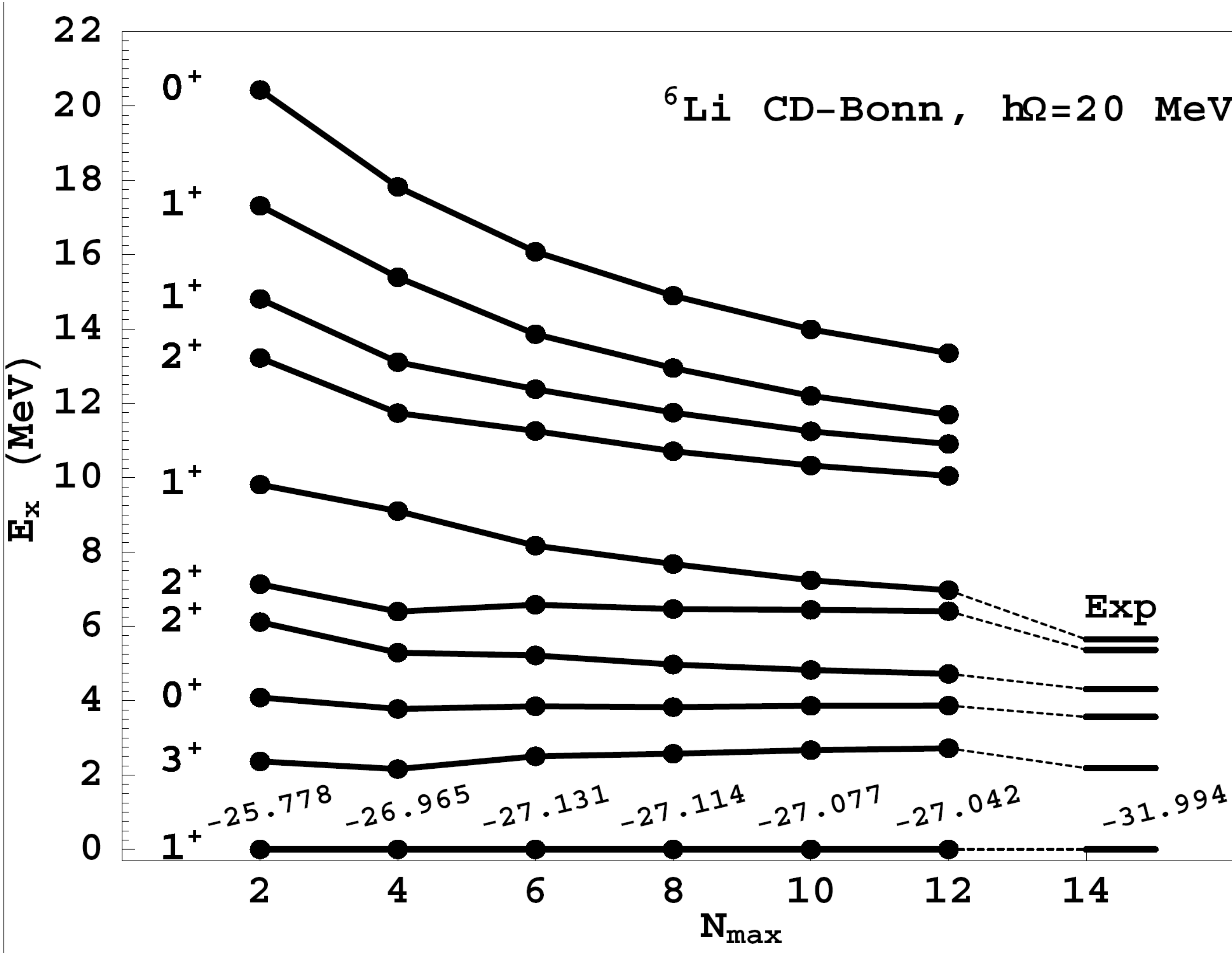
2) For a → A and fixed P: $H^{\mathrm{eff}}_{A,a} \rightarrow H_A$



P. Navrátil and E. Caurier, Phys. Rev. C **69**, 014311 (2004)

NCSM results for ^{6}Li with CD-Bonn NN potential

Dimensions p-space: 10; N_{max}=12: 48 887 665; N_{max} = 14: 211 286 096



$H\Psi_\alpha = E_\alpha \Psi_\alpha$ where $H = \sum_{i=1}^{A} t_i + \sum_{i\leq j}^{A} v_{ij}.$

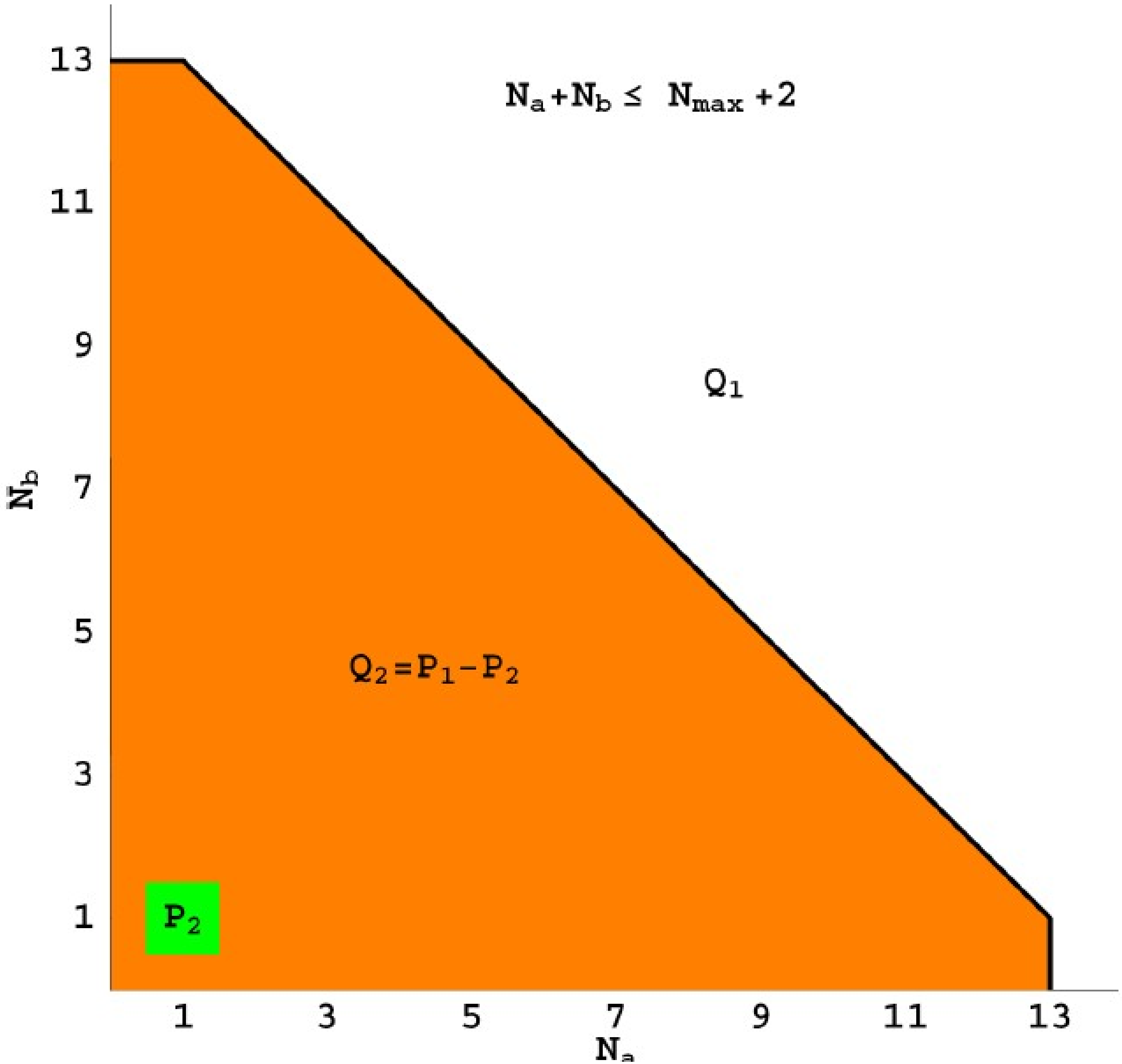
$$\mathcal{H}\Phi_\beta = E_\beta \Phi_\beta$$

$$\Phi_\beta = P\Psi_\beta$$

P is a projection operator from S into $\mathcal{S}$

$$< \tilde{\Phi}_\gamma | \Phi_\beta >= \delta_{\gamma\beta}$$

$$\mathcal{H} = \sum_{\beta \epsilon \mathcal{S}} |\Phi_\beta > E_\beta < \tilde{\Phi}_\beta|$$



$N_a + N_b \leq N_{max} + 2$
Q_1
$Q_2 = P_1 - P_2$
P_2
N_b
N_a
13
11
9
7
5
3
1
1
3
5
7
9
11
13

Effective Hamiltonian for SSM

Two ways of convergence:

1) For $P \rightarrow 1$ and fixed a: $H^{eff}_{A,a=2} \rightarrow H_A$: previous slide

2) For $a_1 \rightarrow A$ and fixed P_1: $H^{eff}_{A,a1} \rightarrow H_A$

$P_1 + Q_1 = P$; P_1 - small model space; Q_1 - excluded space;

$$\mathcal{H}_{A,a_1}^{N_{1,\max},N_{\max}} = \frac{U_{a_1,P_1}^{A,\dagger}}{\sqrt{U_{a_1,P_1}^{A,\dagger} U_{a_1,P_1}^{A}}} E_{A,a_1,P_1}^{N_{\max},\Omega} \frac{U_{a_1,P_1}^{A}}{\sqrt{U_{a_1,P_1}^{A,\dagger} U_{a_1,P_1}^{A}}}$$

Valence Cluster Expansion

$N_{1,max} = 0$ space (p-space) ; $a_1 = A_C + a_V$; a_1 - order of cluster;

A_C - number of nucleons in core; a_V - order of valence cluster;

$$\mathcal{H}_{A,a_1}^{0,N_{\max}} = \sum_{k}^{a_v} V_k^{A,A_c+k}$$

Two-body VCE for ^{6}Li

$$\mathcal{H}^{0,N_{\max}}_{A=6,a_1=6} = V_0^{6,4} + V_1^{6,5} + V_2^{6,6}$$

Need NCSM results in N_{max} space for ^{4}He | ^{5}He ^{5}Li | ^{6}He ^{6}Li ^{6}Be

With effective interaction for A=6 !!! $H^{N_{\max},\Omega,\text{eff}}_{A=6,2}$

Core Energy: $V_0^{6,4}$ = -51.644 MeV

$$V_1^{6,5} = \mathcal{H}^{0,N_{\max}}_{6,5} - V_0^{6,4} \quad \langle ab;JT|V_1^{6,5}|cd;JT\rangle = (\epsilon_a + \epsilon_b)\delta_{a,c}\delta_{b,d}$$

Single Particle Energies: $\varepsilon_{p3/2}$ = 14.574 MeV $\quad \varepsilon_{p1/2}$ = 18.516 MeV

$$V_2^{6,6} = \mathcal{H}^{0,N_{\max}}_{6,6} - \mathcal{H}^{0,N_{\max}}_{6,5}$$

TBMEs:

$\langle p_{3/2}p_{3/2}|V_2^{6,6}|p_{3/2}p_{3/2}\rangle_{J=3,T=0}$ = -1.825 MeV

$\langle p_{3/2}p_{3/2}|V_2^{6,6}|p_{3/2}p_{3/2}\rangle_{J=2,T=1}$ = 2.762 MeV

2-body Valence Cluster approximation for A=6

$$\mathcal{H}^{0,N_{\max}}_{A,a_1=6} = V_0^{A,4} + V_1^{A,5} + V_2^{A,6}$$

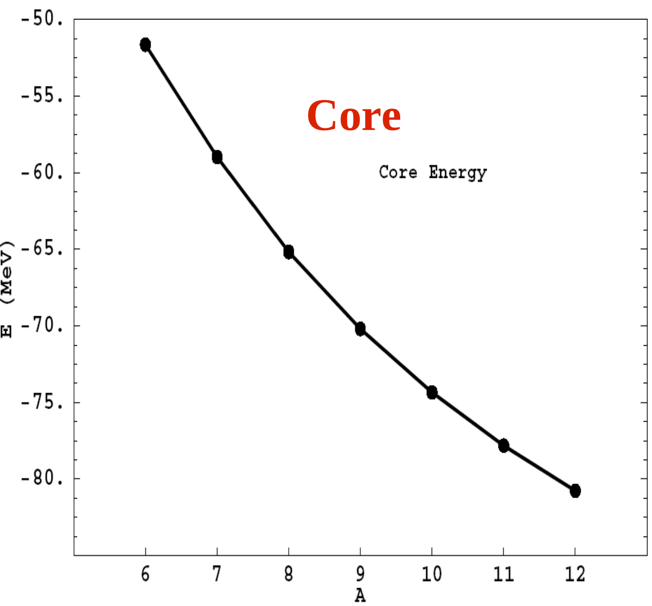
Need NCSM results in N_{max} space for

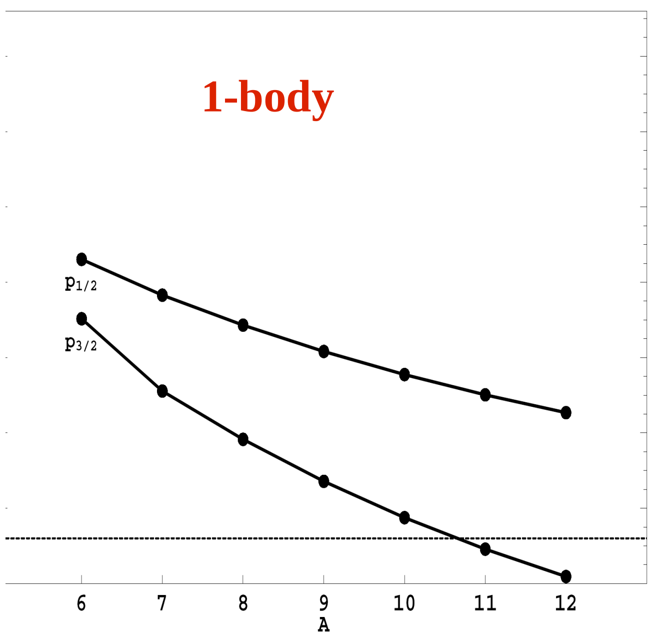
^{4}He **^{5}He ^{5}Li** **^{6}He ^{6}Li ^{6}Be**

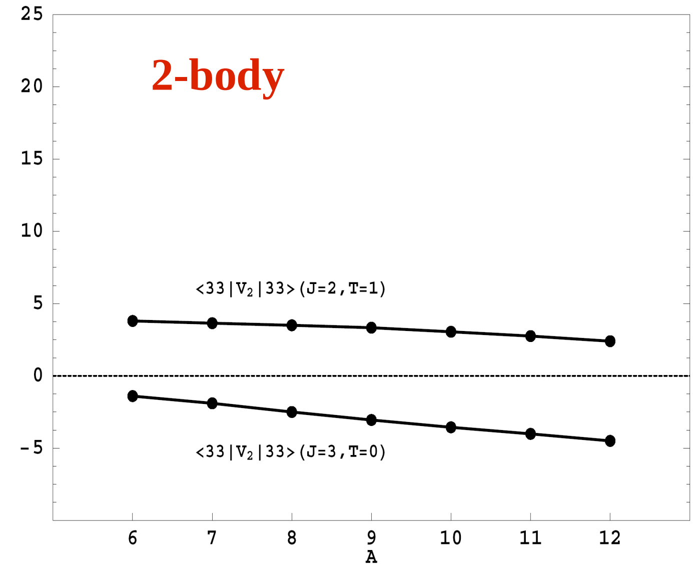
$N_{max} = 6$

With effective interaction for A !!!

$$H^{N_{\max},\Omega,\text{eff}}_{A,2}$$







2-body Valence Cluster approximation for A=7

$$\mathcal{H}^{0,N_{max}}_{A,a_1=6} = V_0^{A,4} + V_1^{A,5} + V_2^{A,6}$$

Need NCSM results in N_{max} space for

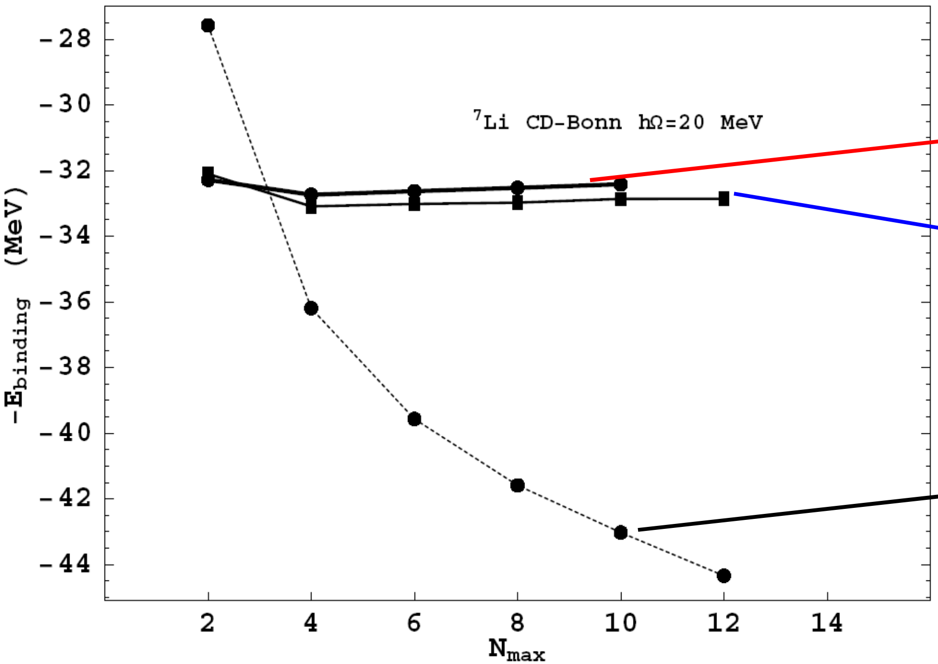
^{4}He

^{5}He ^{5}Li

^{6}He ^{6}Li ^{6}Be

$$H^{N_{max},\Omega,\text{eff}}_{A,2}$$

With effective interaction for A=7 !!!



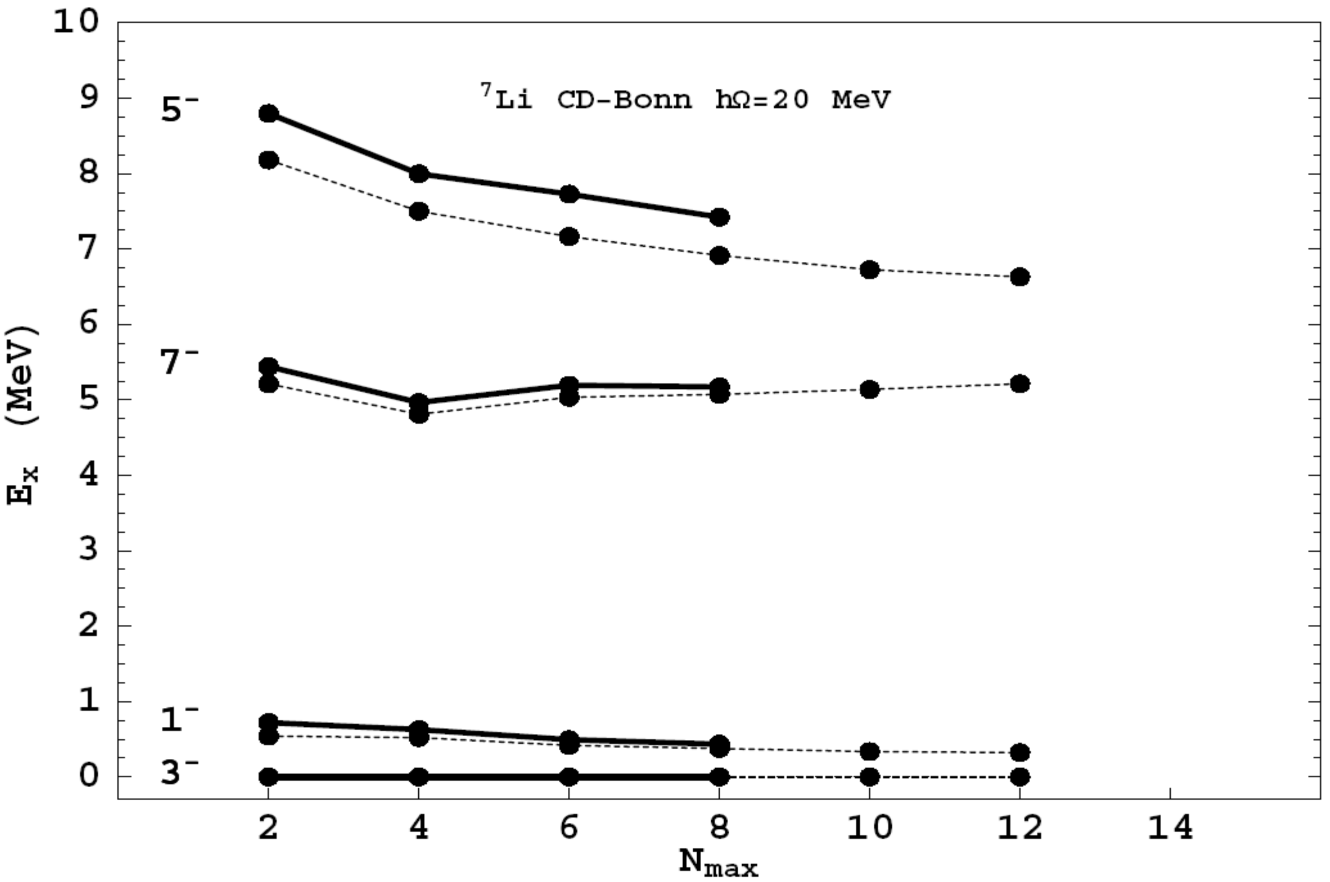
Exact NCSM

SSM with A-dependent core

SSM with inert core

2-body Valence Cluster approximation for A=7

$$\mathcal{H}_{A\ \ \ ,a_1=6}^{0,N_{\max}} = V_0^{A,4} + V_1^{A,5} + V_2^{A,6}$$



3-body Valence Cluster approximation for A>6

$$\mathcal{H}^{0,N_{\max}}_{A,a_1=7} = V_0^{A,4} + V_1^{A,5} + V_2^{A,6} + V_3^{A,7}$$

Need NCSM results in N_{max} space for

^{4}He | ^{5}He ^{5}Li | ^{6}He ^{6}Li ^{6}Be | ^{7}He ^{7}Li ^{7}B ^{7}Be

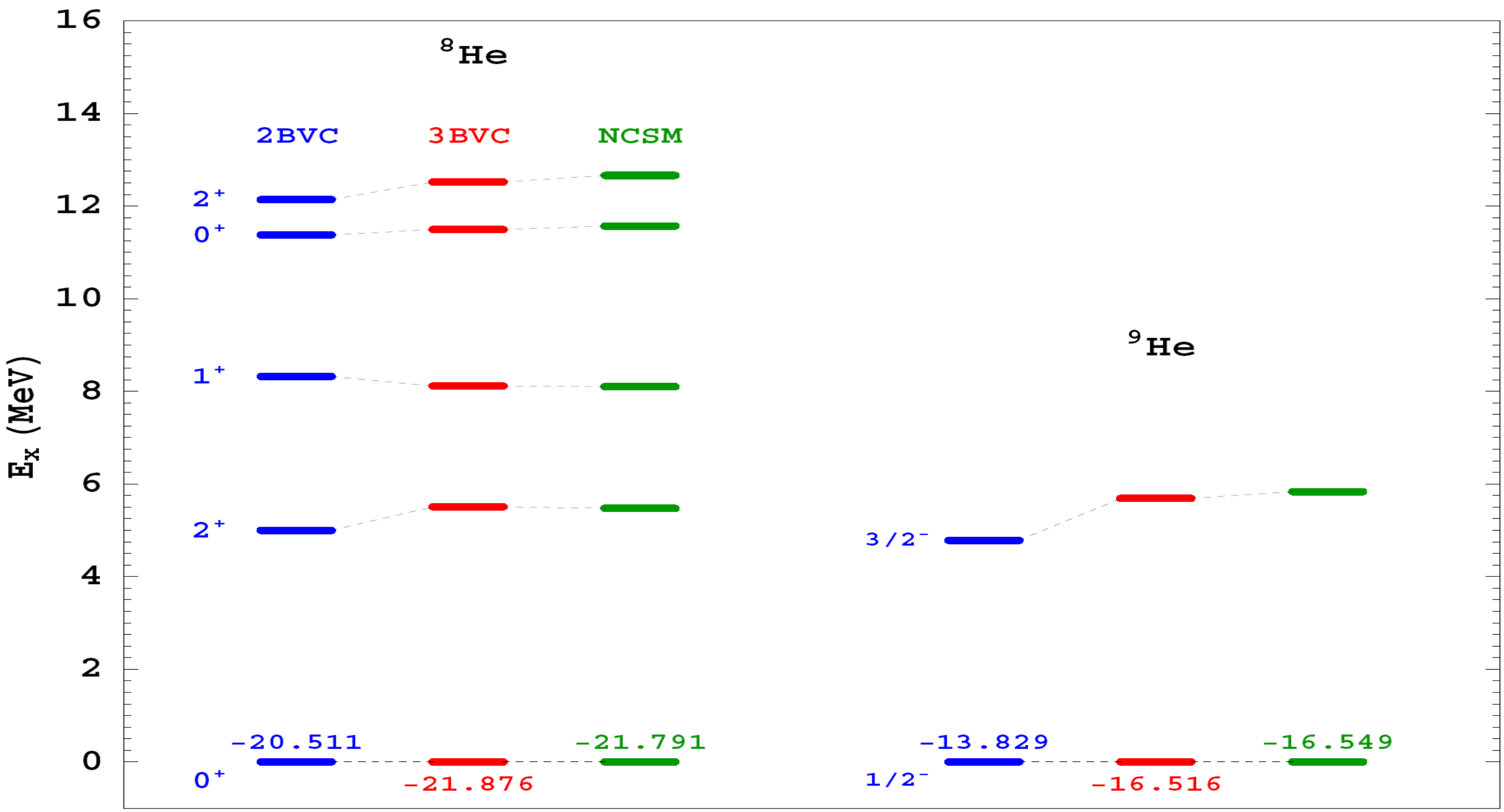
With effective interaction for A !!!

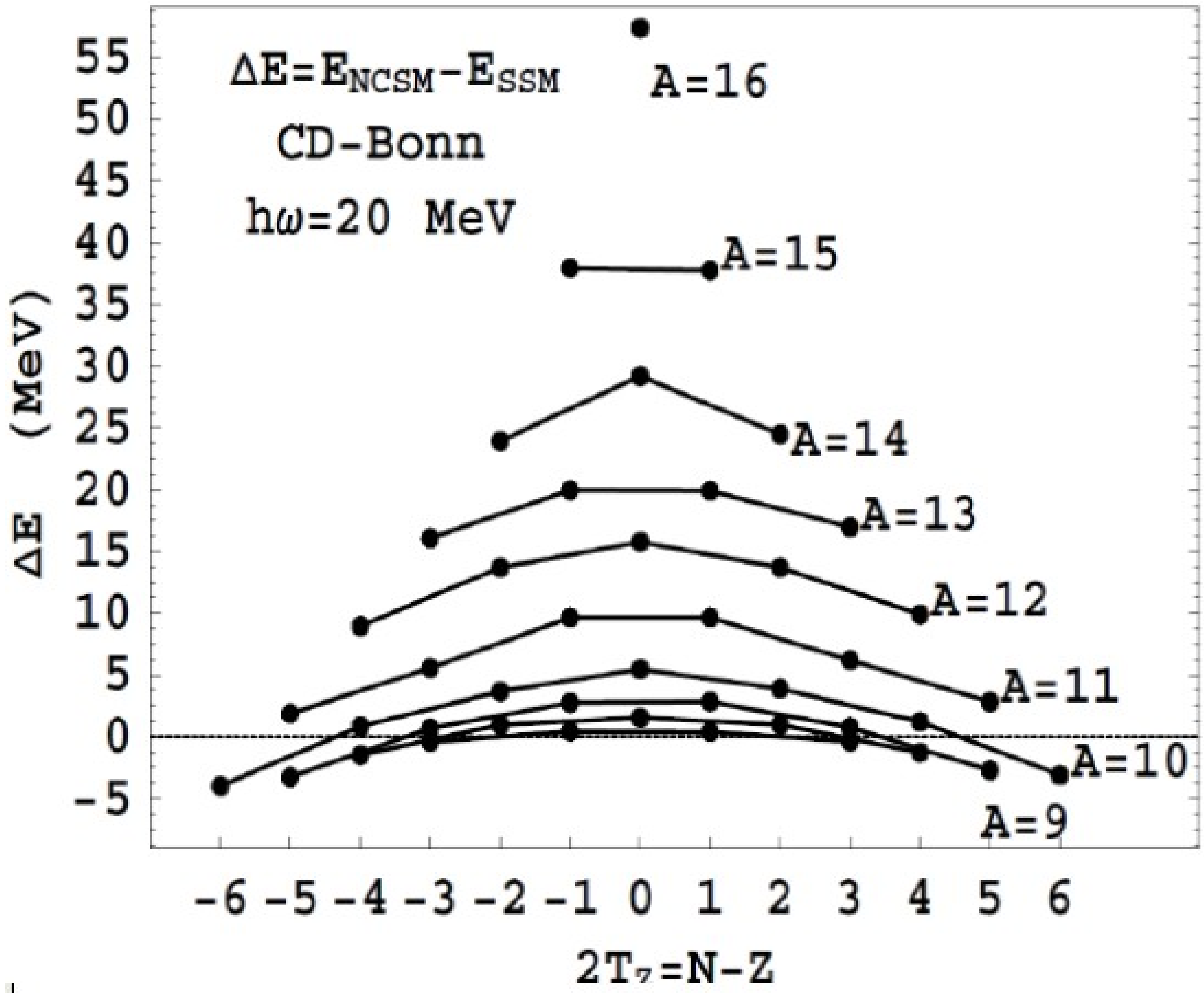
$$H^{N_{\max},\Omega,\mathrm{eff}}_{A\ \ \ ,2}$$

Construct 3-body interaction in terms of 3-body matrix elements: Yes

$$V_3^{A,7} = \mathcal{H}^{0,N_{\max}}_{A,7} - \mathcal{H}^{0,N_{\max}}_{A,6}$$

3-body Valence Cluster approximation for A>6





ΔE=E_NCSM−E_SSM
CD-Bonn
hω=20 MeV
A=16
A=15
A=14
A=13
A=12
A=11
A=10
A=9
ΔE (MeV)
55
50
45
40
35
30
25
20
15
10
5
0
-5
-6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6
2T_z=N-Z

PHYSICAL REVIEW C **80**, 024315 (2009)

Effective operators from exact many-body renormalization

A. F. Lisetskiy,[1,2,*] M. K. G. Kruse,[1] B. R. Barrett,[1] P. Navratil,[3] I. Stetcu,[4] and J. P. Vary[5]
[1]*Department of Physics, University of Arizona, Tucson, Arizona 85721, USA*
[2]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824-1321, USA*
[3]*Lawrence Livermore National Laboratory, Livermore, California 94551, USA*
[4]*Department of Physics, University of Washington, P. O. Box 351560, Seattle, Washington 98195-1560, USA*
[5]*Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA*
(Received 15 June 2009; published 28 August 2009)

We construct effective two-body Hamiltonians and $E2$ operators for the p shell by performing $16\hbar\Omega$ *ab initio* no-core shell model (NCSM) calculations for $A = 5$ and $A = 6$ nuclei and explicitly projecting the many-body Hamiltonians and $E2$ operator onto the $0\hbar\Omega$ space. We then separate the effective $E2$ operator into one-body and two-body contributions employing the two-body valence cluster approximation. We analyze the convergence of proton and neutron valence one-body contributions with increasing model space size and explore the role of valence two-body contributions. We show that the constructed effective $E2$ operator can be parametrized in terms of one-body effective charges giving a good estimate of the NCSM result for heavier p-shell nuclei.

DOI: 10.1103/PhysRevC.80.024315 PACS number(s): 27.20.+n, 21.10.Hw, 21.60.Cs, 23.20.Lv

$$E_J = \mathcal{U}_J \mathcal{H}_J \mathcal{U}_J^\dagger. \tag{4}$$

This same eigenstate matrix $\mathcal{U}_J$ can also be used to calculate the matrix elements of other effective operators, $\mathcal{O}^{\text{eff}}_{A,a_1}(\lambda k; JJ')$, between basis states with spins J and J' in the $0\hbar\Omega$ space:

$$\mathcal{M}^{\text{eff}}_{A,a_1}(\lambda k; JJ') = \mathcal{U}_J \mathcal{O}^{\text{eff}}_{A,a_1}(\lambda k; JJ') \mathcal{U}_{J'}^\dagger, \tag{5}$$

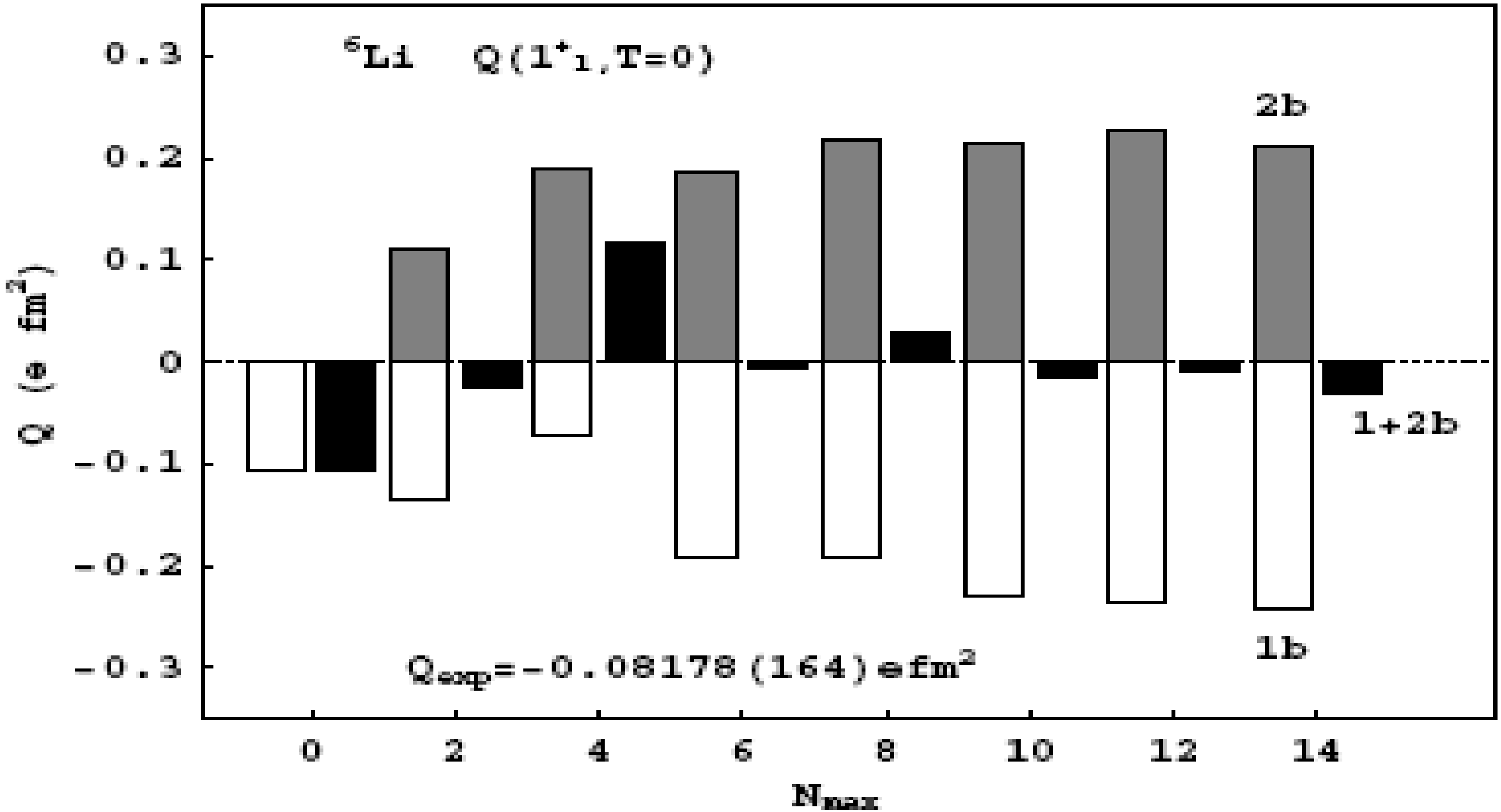


FIG. 6: The quadrupole moment of the ground state for ^{6}Li ($1^+(T = 0)$) is shown in terms of one- and two-body contributions as a function of increasing model space size.

Summary

3-step technique to construct effective Hamiltonian for SSM with a core :

#1 2-body UT of bare NN Hamiltonian (2-body cluster approximation)

#2 NCSM diagonalization in large N_{max} space for A = 4,5,6,7

#3 many-body UT of NCSM Hamiltonian (up to 3-body valence cluster approximation)

Results:

1) strong mass dependence of core & one-body parts of H^{eff}

2) 3-body effective interaction plays crucial role

3) negligible role of 4-body and higher-order interactions for identical nucleons

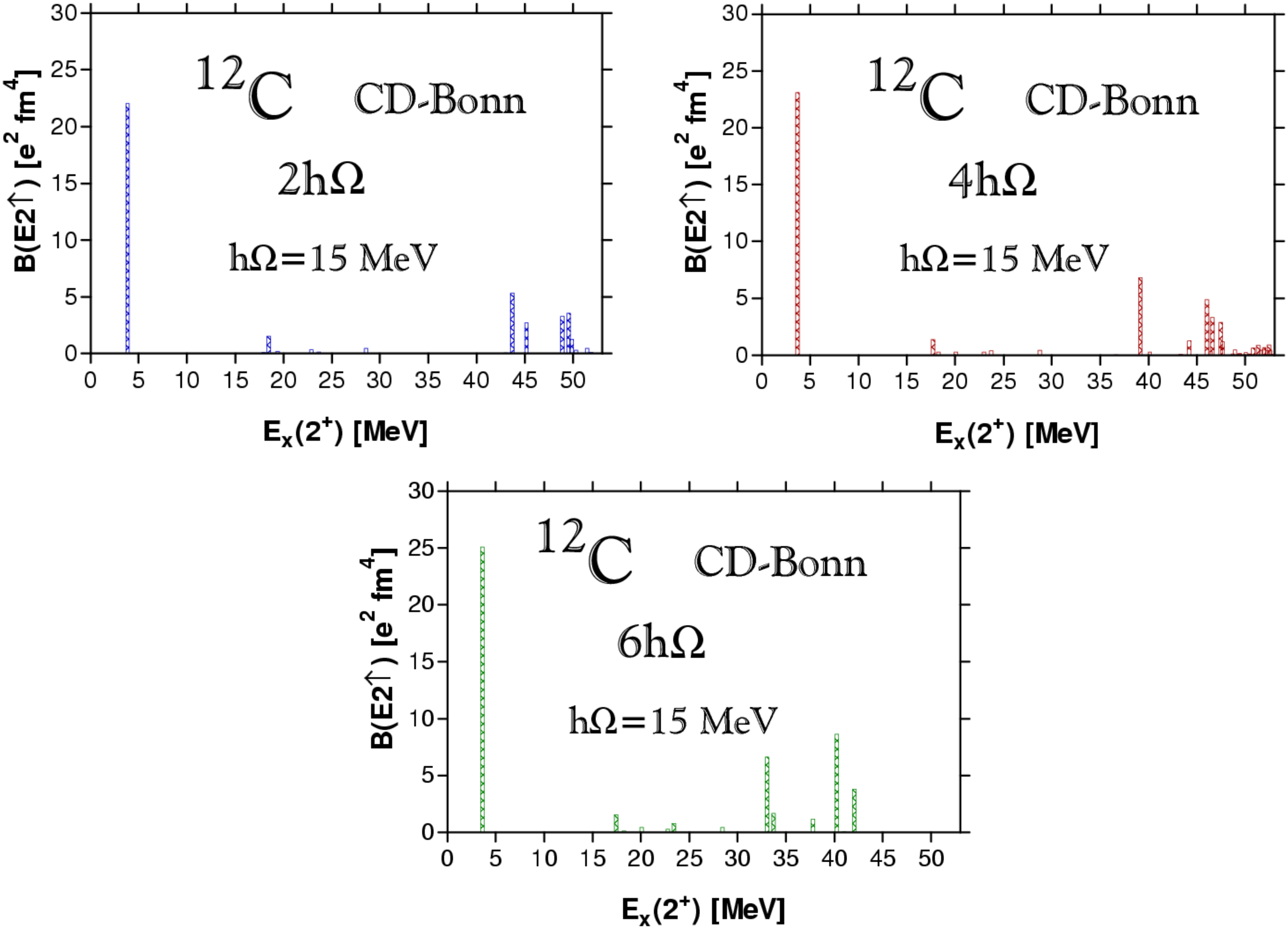
4) similar approach can be applied for calculating effective operators for other physical quantities

COLLABORATORS

Sybil de Clark, University of Arizona
Michael Kruse, University of Arizona
Alexander Lisetskiy, University of Arizona
Petr Navratil, Lawrence Livermore National Laboratory
Erich Ormand, Lawrence Livermore National Laboratory
Sofia Quaglioni, Lawrence Livermore National Laboratory
Jimmy Rotureau, University of Arizona
Ionel Stetcu, University of Washington
Ubirajara van Kolck, University of Arizona
James P. Vary, Iowa State University

SOME REMAINING CHALLENGES

1. Understanding the fundamental interactions among the nucleons in terms of QCD, e.g., NN, NNN, ...
2. Determination of the mean field (the monopole effect).
3. Microscopic calculations of medium- to heavy-mass nuclei:
   a.) How to use the advances for light nuclei to develop techniques for heavier nuclei.
   b.) Building in more correlations among the nucleons in small model spaces, e.g., effective interactions for heavier nuclei.
4. Extensions of these microscopic advances for nuclear structure to nuclear reactions.



^{12}C CD-Bonn
2hΩ
hΩ=15 MeV
^{12}C CD-Bonn
4hΩ
hΩ=15 MeV
^{12}C CD-Bonn
6hΩ
hΩ=15 MeV
B(E2↑) [e^2 fm^4]
$E_x(2^+)$ [MeV]

Available online at www.sciencedirect.com

ScienceDirect

PHYSICS LETTERS B

Physics Letters B 653 (2007) 358–362

www.elsevier.com/locate/physletb

No-core shell model in an effective-field-theory framework

I. Stetcu [a,b,*], B.R. Barrett [a], U. van Kolck [a]

[a] *Department of Physics, University of Arizona, Tucson, AZ 85721, USA*
[b] *Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

Received 5 March 2007; received in revised form 8 July 2007; accepted 31 July 2007

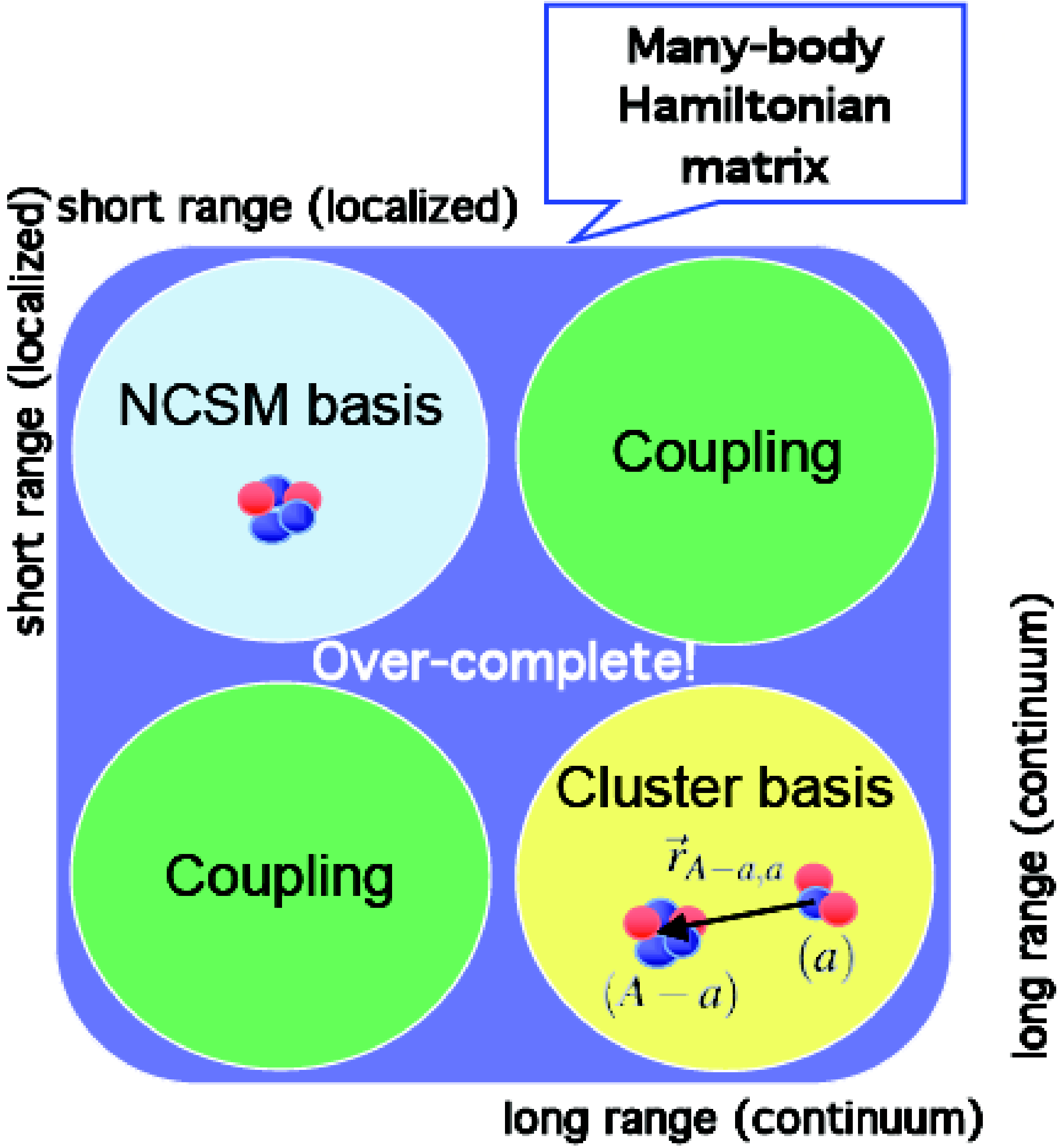
Available online 9 August 2007

Editor: W. Haxton

Abstract

We present a new approach to the construction of effective interactions suitable for many-body calculations by means of the no-core shell model (NCSM). We consider an effective field theory (EFT) with only nucleon fields directly in the NCSM model spaces. In leading order, we obtain the strengths of the three contact interactions from the condition that in each model space the experimental ground-state energies of ^{2}H, ^{3}H and ^{4}He be exactly reproduced. The first $(0^+; 0)$ excited state of ^{4}He and the ground state of ^{6}Li are then obtained by means of NCSM calculations in several spaces and frequencies. After we remove the harmonic-oscillator frequency dependence, we predict for ^{4}He an energy level for the first $(0^+; 0)$ excited state in remarkable agreement with the experimental value. The corresponding ^{6}Li binding energy is about 70% of the experimental value, consistent with the expansion parameter of the EFT.

PACS: 21.30.-x; 21.60.Cs; 24.10.Cn; 45.50.Jf



S. Quaglioni and P. Navratil, Phys. Rev. Lett. 101, 092501 (2008)

I. Forces among nucleons

1. QCD ---> EFT ---> CPT --> Self-consistent nucleon interactions

2. Need NN and NNN and perhaps NNNN interactions

3. Which approach is best?
   a) Chiral Effective Field Theory
   b) Find NN interaction which minimizes the NNN interaction and
      then treat the NNN interaction perturbatively.
   c) Contract the NNN interaction into the nuclear medium as
      0-, 1-, and 2-body density dependent parts + a small residual
      NNN force.
   d) Other approaches: V_low-k, Similarity Renormalization Group (SRG),
      Unitary Correlation Operator Method (UCOM), INOY,...

PROCEEDINGS
OF THE
INTERNATIONAL CONFERENCE
ON
NUCLEAR STRUCTURE

KINGSTON, CANADA

AUGUST 29 - SEPTEMBER 3
1960

EDITED BY

D.A. BROMLEY
E.W. VOGT

UNIVERSITY OF TORONTO PRESS: TORONTO
NORTH HOLLAND PUBLISHING COMPANY: AMSTERDAM

1960

how matter came about, and they add a great deal of significance and importance to nuclear physics and to certain experiments in nuclear physics which would have only little importance to the problems we have discussed here. Perhaps in the next conference we should have a session where we discuss these things; it is not enough just to go to Mr. Cameron or Mr. Fowler and ask him what shall we measure, we ought to know why we do it.

The second and last point I would like to raise is this. To round up the conference I come back to the first remark of Peierls, when he opened up the conference and asked the question, why are we interested in nuclear structure. May I add my own little verse to this. I have heard many people say that Nuclear Structure is not a fundamental problem, the real thing is high energy physics; the object of nuclear structure is after all nothing else but solving a Schroedinger equation for A particles. I strongly disagree with this point of view. The discovery and the understanding of phenomena hidden in a many-body problem can be a task of fundamental importance, if the object itself is of central interest.

Physics inquires into the nature of things. The nucleus, our nucleus, is an essential part of nature, it is the centre of the atom. It is not just a little phenomenon, it is the most prominent constituent of matter. The understanding of the phenomena occurring in this nucleus is therefore of paramount importance. Hence Nuclear Physics is an essential part of physics. I found out that some theorists, both in the east and in the west, consider the only thing worth doing is elementary particle physics. Experimentalists usually don't say so because they work with real matter and hence they know that the nucleus is an important thing. These theorists, however, worship the theory of elementary particles, a theory which in fact doesn't even exist. They knock their heads daily against a wall of dispersion-relations, Mandelstam representations and the like. Let them do it. After all the proton and the meson are also an important part of nature. In fact we should give them all the moral support they need. They are a brave lot who fight a very difficult fight and some day they will find the theory. But don't let yourself be talked into believing that the nucleus is not interesting. It is so small and it has so few parts and still it shows a tremendous variety of phenomena. Its investigation requires the whole arsenal of presently available experimental techniques and its understanding makes use of almost all branches of theoretical physics. What a marvellous invention! It is worth devoting a lifetime to it.