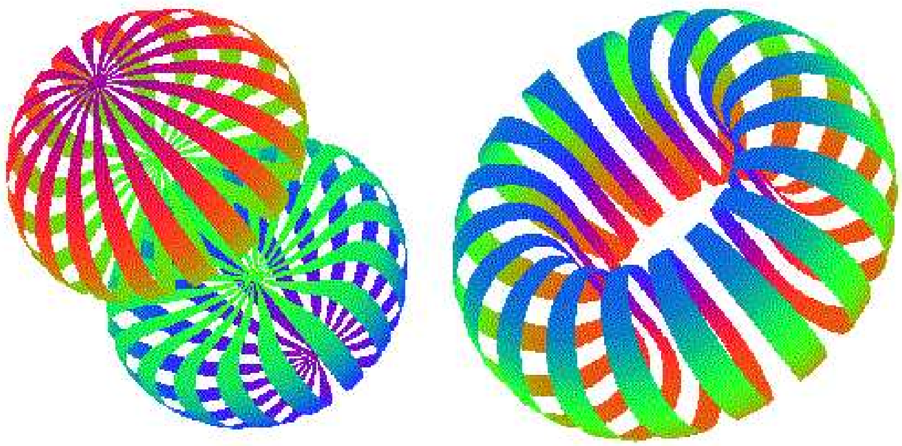
Nuclear Forces and

Ab Initio Calculations of Nuclei

Robert B. Wiringa, *Argonne National Laboratory*



Machleidt, Adv. Nucl. Phys. **19**, 189 (1989)

Carlson & Schiavilla, Rev. Mod. Phys. **70**, 743 (1997)

Pieper & Wiringa, Ann. Rev. Nucl. Part. Sci. **51**, 53 (2002)

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Ab Initio Calculations of Nuclei

Goals

Understand nuclei at the level of elementary interactions between individual nucleons, including

- Binding energies, excitation spectra, relative stability
- Densities, electromagnetic moments, transition amplitudes, cluster-cluster overlaps
- Low-energy NA & AA scattering, asymptotic normalizations, astrophysical reactions

Requirements

- Two-nucleon potentials that accurately describe elastic NN scattering data
- Consistent three-nucleon potentials and electroweak current operators
- Precise methods for solving the many-nucleon Schrödinger equation

Methods

- Faddeev, hyperspherical harmonic, AGS, etc., for $A = 3, 4$ ground states & scattering
- Variational & Green's function Monte Carlo calculations for $A \leq 12$ nuclei
- Auxiliary field diffusion Monte Carlo for $N \leq 40$ neutron drops
- No-core shell model for $A \leq 16+$
- Coupled-cluster for $A = 4, 16, 40$ closed-shell and near closed-shell

PROGRESS IN *Ab Initio* CALCULATIONS

Accurate Representations of Nuclear Forces

Yukawa meson-exchange theory (1935)   Fujita-Miyazawa three-nucleon potential (1957)

First phase-shift analysis of NN scattering data (1957)

Gammel-Thaler, Hamada-Johnston, Reid phenomenological potentials (1957-1968)

Bonn, Nijmegen, Paris field-theoretic models (1970s)

Tucson-Melbourne, Brazil, Urbana NNN potentials (1970s-80s)

Nijmegen partial wave analysis (PWA93) $\rightarrow \chi^2 \sim 1$ (1993)

Nijm I, Nijm II, Argonne v_{18}, CD-Bonn (1990s) χ Effective field theory at N^3LO (2000s)

Accurate Solutions of Many-Body Schrödigner Equation

^{2}H by Numerical Integration (1952)

^{3}H by Faddeev (1975-85)

”The computation takes between 5 and 20 minutes, the printing takes another 5 minutes”

^{4}He by Green’s function Monte Carlo (1988)

$A = 6$ by No-core shell model & GFMC (1994-95)

$A = 7$ by GFMC & NCSM (1997-98)

$A = 8$ by GFMC & NCSM (2000)

^{4}He benchmark by 7 methods to 0.1% (2001)

$A = 9, 10$ by GFMC & NCSM (2002)

^{12}C by GFMC & NCSM (2004-)

^{16}O, ^{40}Ca by coupled-cluster (2005-7)

THE NUCLEAR MANY-BODY PROBLEM

Many-Body Schrödinger Equation (MBSE) for bound states:

$$H\Psi(\mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_A; s_1, s_2, ..., s_A; t_1, t_2, ..., t_A)$$

$$= E\Psi(\mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_A; s_1, s_2, ..., s_A; t_1, t_2, ..., t_A)$$

where

$\mathbf{r}_i$ are the nucleon coordinates in r-space

s_i are the nucleon spins ($= \pm\frac{1}{2}$)

t_i are the nucleon isospins (p or $n = \pm\frac{1}{2}$)

This corresponds to

$2^A \times \binom{A}{Z}$ coupled second-order differential equations equations in 3A dimensions!

which is

96 for ^{4}He

17,920 for ^{8}Be

3,784,704 for ^{12}C

This is a challenging many-body problem!

Variational Monte Carlo

Minimize expectation value of H

$$E_V = \frac{\langle \Psi_V | H | \Psi_V \rangle}{\langle \Psi_V | \Psi_V \rangle} \geq E_0$$

Trial function (s-shell nuclei)

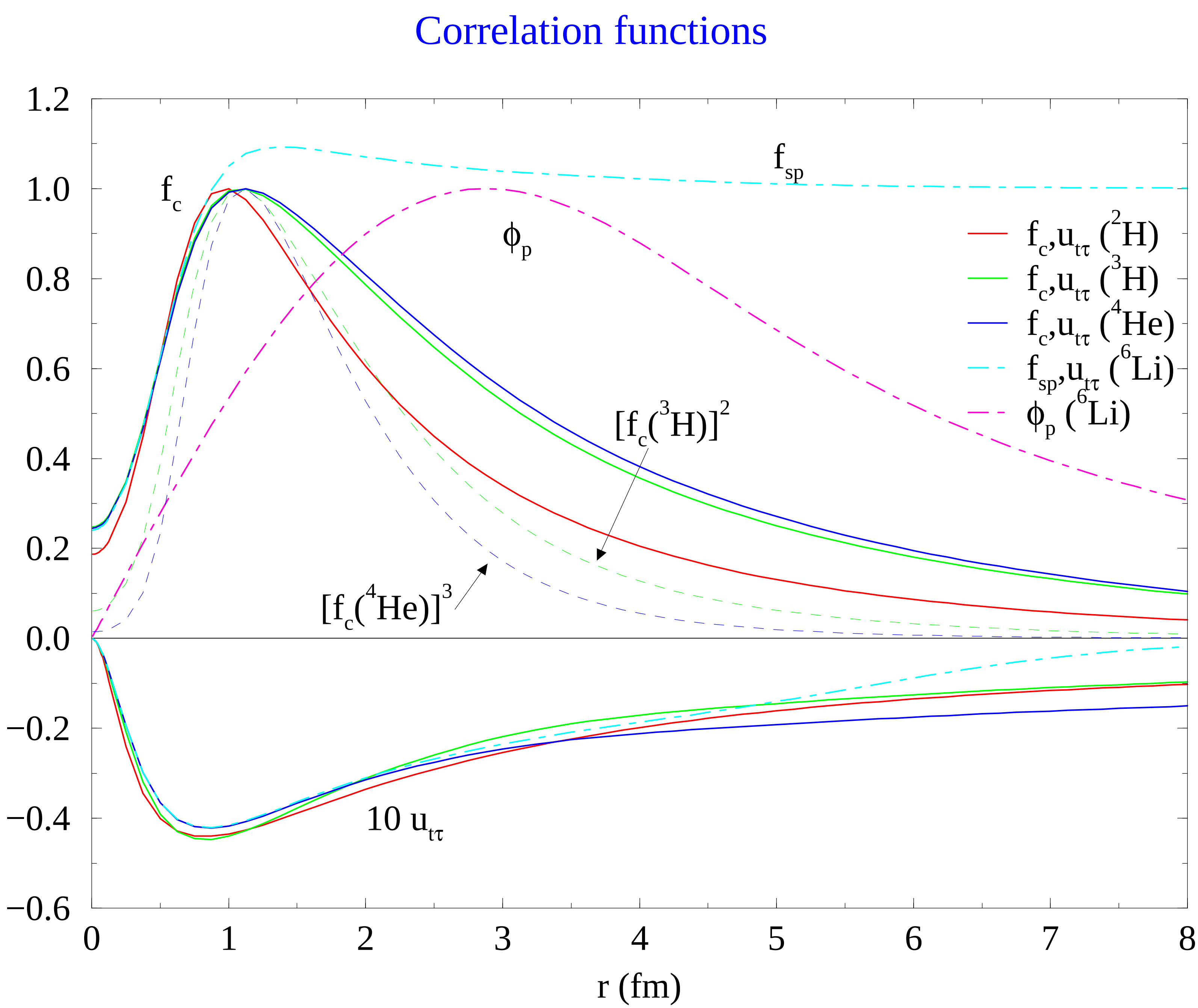
$$|\Psi_V\rangle = \left[\mathcal{S} \prod_{i<j} (1 + U_{ij} + \sum_{k \neq i,j} U_{ijk}) \right] |\Psi_J\rangle$$

$$|\Psi_J\rangle = \left[\prod_{i<j} f_c(r_{ij}) \right] |\Phi_A(JMTT_3)\rangle$$

$$|\Phi_d(1100)\rangle = \mathcal{A} | \uparrow p \uparrow n \rangle \;\; ; \;\; |\Phi_\alpha(0000)\rangle = \mathcal{A} | \uparrow p \downarrow p \uparrow n \downarrow n \rangle$$

$$U_{ij} = \sum_{p=2,6} u_p(r_{ij}) O^p_{ij} \;\; ; \;\; U_{ijk} = -\epsilon V_{ijk}(\tilde{r}_{ij}, \tilde{r}_{jk}, \tilde{r}_{ki})$$

Functions $f_c(r_{ij})$ and $u_p(r_{ij})$ obtained from coupled differential equations with v_{ij} .



Correlation functions
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
0
1
2
3
4
5
6
7
8
r (fm)
f_c
f_{sp}
ϕ_p
$[f_c(^3H)]^2$
$[f_c(^4He)]^3$
$10\ u_{t\tau}$
$f_c, u_{t\tau}$ (^{2}H)
$f_c, u_{t\tau}$ (^{3}H)
$f_c, u_{t\tau}$ (^{4}He)
$f_{sp}, u_{t\tau}$ (^{6}Li)
ϕ_p (^{6}Li)

Trial function (p-shell nuclei)

$$|\Psi_J\rangle = \mathcal{A}\left\{\prod_{i<j\le 4} f_{ss}(r_{ij}) \sum_{LS[n]} \beta_{LS[n]} \prod_{k\le 4<l\le A} f_{sp}(r_{kl}) \prod_{4<l<m\le A} f_{pp}(r_{lm})\right.$$

$$\left.\Big|\Phi_\alpha(0000)_{1234} \prod_{4<l\le A} \phi_p^{LS[n]}(R_{\alpha l}) \left\{[Y_1^{m_l}(\Omega_{\alpha l})]_{LM_L} \otimes [\chi_l(\tfrac{1}{2}m_s)]_{SM_S}\right\}_{JM} [\nu_l(\tfrac{1}{2}t_3)]_{TT_3}\Big\rangle\right\}$$

Diagonalization

in $\beta_{LS[n]}$ basis to produce energy spectra $E(J_x^\pi)$ and orthogonal excited states $\Psi_V(J_x^\pi)$

Expectation values

$\Psi_V(\mathbf{R})$ represented by vector with $2^A \times \binom{A}{Z}$ spin-isospin components (or a little less assuming isospin conservation) for each space configuration $\mathbf{R} = (\mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_A)$; expectation values are evaluated in a Metropolis Monte Carlo random walk, i.e., by a summation over samples drawn from probability distribution $W(\mathbf{R}) = |\Psi_P(\mathbf{R})|^2$:

$$\frac{\langle\Psi_V|O|\Psi_V\rangle}{\langle\Psi_V|\Psi_V\rangle} = \sum \frac{\Psi_V^\dagger(\mathbf{R}) O \Psi_V(\mathbf{R})}{W(\mathbf{R})} \Big/ \sum \frac{\Psi_V^\dagger(\mathbf{R})\Psi_V(\mathbf{R})}{W(\mathbf{R})}$$

$\Psi^\dagger\Psi$ is a dot product and $\Psi^\dagger O\Psi$ a sparse matrix operation.

A Simplified VMC Calculation

- Generate a random position: $\mathbf{R} = \mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_A$
- Make many (1000's) random steps based on the probability $P = |\Psi_V(\mathbf{R})|^2$
- Start integration loop:
  - Make order 10 steps based on P
  - Compute and sum $H_{\text{local}}(\mathbf{R}) = [\Psi_V(\mathbf{R})^\dagger H \Psi_V(\mathbf{R})]/|\Psi_V(\mathbf{R})|^2$
- $\langle\Psi_V|H|\Psi_V\rangle/\langle\Psi_V|\Psi_V\rangle = \text{average}(H_{\text{local}})$

Making a random step

- Use $3A$ uniform random numbers on (0,1), $\{w_j\}$, to make $\triangle\mathbf{R}$; $\triangle x_i = 2\delta r(w_j - 1)$
- $\mathbf{R}' = \mathbf{R} + \triangle\mathbf{R}$; $P(\triangle\mathbf{R}) = |\Psi_V(\mathbf{R}')|^2/|\Psi_V(\mathbf{R})|^2$
- Make another random number on (0,1): p
- If $P > p$, the step is accepted; replace $\mathbf{R}$ with $\mathbf{R}'$
  if $P < p$, the step is rejected; discard $\mathbf{R}'$ and stay at $\mathbf{R}$

Gradients and Laplacians are computed by differences: $6A$ evaluations of $\Psi_V(\mathbf{R} + \delta_j \vec{r}_i)$

SCALING OF VMC CALCULATION TIME WITH NUCLEUS

Scales with # particles (6A w.f. calculations for kinetic energy) $\times$
pairs (operations to construct w.f.) $\times$ spin$\times$isospin (size of w.f. vector):

	A	Pairs	Spin$\times$Isospin	$\prod(/^8$Be)
^{4}He	4	6	16×2	0.001
^{5}He	5	10	32×5	0.010
^{6}Li	6	15	64×5	0.036
^{7}Li	7	21	128×14	0.33
^{8}Be	8	28	256×14	1.
^{9}Be	9	36	512×42	8.7
^{10}Be	10	45	1024×90	52.
^{11}B	11	55	2048×132	200.
^{12}C	12	66	4096×132	530.
^{14}C	14	91	16384×1001	26,000.
^{16}O	16	120	65536×1430	220,000.
^{40}Ca	40	780	$1.1\times10^{12}\times6.6\times10^9$	2.8×10^{20}
^{8}n	8	28	256×1	0.071
^{14}n	14	91	16384×1	26.

Green's Function Monte Carlo

Projects out lowest energy state from variational trial function

$$\Psi(\tau) = \exp[-(H-E_0)\tau]\Psi_V = \sum_n \exp[-(E_n-E_0)\tau]a_n\psi_n$$
$$\Psi(\tau\to\infty) = a_0\psi_0$$

Evaluation of $\Psi(\tau)$ done stochastically in small time steps $\Delta\tau$

$$\Psi(\mathbf{R}_n,\tau) = \int G(\mathbf{R}_n,\mathbf{R}_{n-1})\cdots G(\mathbf{R}_1,\mathbf{R}_0)\Psi_V(\mathbf{R}_0)d\mathbf{R}_{n-1}\cdots d\mathbf{R}_0$$

using the short-time propagator accurate to order $(\Delta\tau)^3$ (V_{ijk} term omitted for simplicity)

$$G_{\alpha\beta}(\mathbf{R},\mathbf{R}') = e^{E_0\delta\tau}G_0(\mathbf{R},\mathbf{R}')\langle\alpha|\left[\mathcal{S}\prod_{i<j}\frac{g_{ij}(\mathbf{r}_{ij},\mathbf{r}'_{ij})}{g_{0,ij}(\mathbf{r}_{ij},\mathbf{r}'_{ij})}\right]|\beta\rangle$$

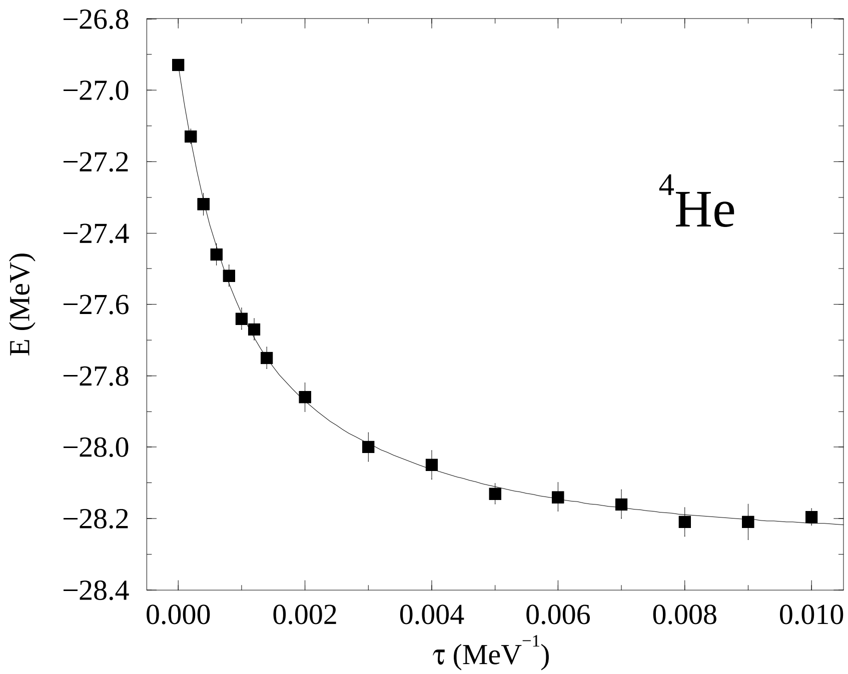
where the free many-body propagator is

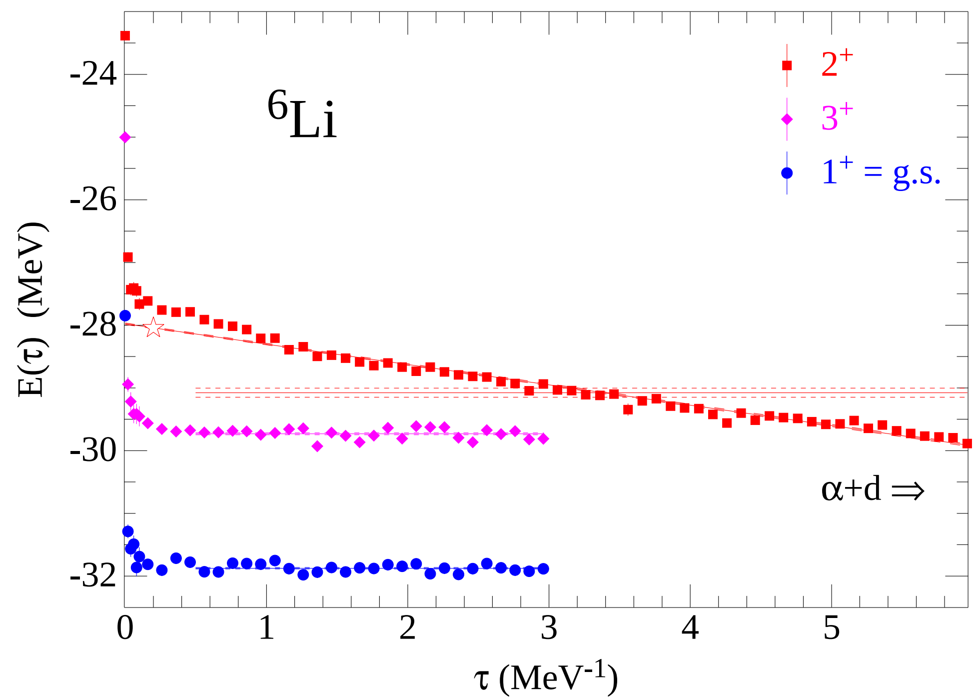
$$G_0(\mathbf{R},\mathbf{R}') = \langle\mathbf{R}|e^{-K\triangle\tau}|\mathbf{R}'\rangle = \left[\sqrt{\frac{m}{2\pi\hbar^2\triangle\tau}}\right]^{3A}\exp\left[\frac{-(\mathbf{R}-\mathbf{R}')^2}{2\hbar^2\triangle\tau/m}\right]$$

and $g_{0,ij}$ and g_{ij} are the free and exact two-body propagators

$$g_{ij}(\mathbf{r}_{ij},\mathbf{r}'_{ij}) = \langle\mathbf{r}_{ij}|e^{-H_{ij}\triangle\tau}|\mathbf{r}'_{ij}\rangle$$

Examples of GFMC Propagation





- Curve has $\exp(-E_i\tau)$ with E_i = 1480, 340 & 20.2 MeV (20.2 MeV is first ^{4}He 0^+ excitation)
- Ψ_V has small amounts of 1.5 GeV contamination
- g.s. (1^+) & 3^+ stable after τ = 0.2 MeV^{-1} 2^+ (a broad resonance) never stable – decaying to separated α & d
- $E(\tau$=0.2) is best GFMC estimate of resonance energy

Mixed estimates

$$\langle O(\tau)\rangle = \frac{\langle\Psi(\tau)|O|\Psi(\tau)\rangle}{\langle\Psi(\tau)|\Psi(\tau)\rangle} \approx \langle O(\tau)\rangle_{\rm Mixed} + [\langle O(\tau)\rangle_{\rm Mixed} - \langle O\rangle_V]$$

$$\langle O(\tau)\rangle_{\rm Mixed} = \frac{\langle\Psi_V|O|\Psi(\tau)\rangle}{\langle\Psi_V|\Psi(\tau)\rangle} \quad ; \quad \langle H(\tau)\rangle_{\rm Mixed} = \frac{\langle\Psi(\tau/2)|H|\Psi(\tau/2)\rangle}{\langle\Psi(\tau/2)|\Psi(\tau/2)\rangle} \geq E_0$$

Propagator cannot contain p^2, L^2, or $(\mathbf{L}\cdot\mathbf{S})^2$ operators:

$G_{\beta\alpha}(\mathbf{R}',\mathbf{R})$ has only v_8'

$\langle v_{18} - v_8'\rangle$ computed perturbatively with extrapolation (small for AV18)

Fermion sign problem limits maximum τ:

$G_{\beta\alpha}(\mathbf{R}',\mathbf{R})$ brings in lower-energy boson solution

$\langle\Psi_V|H|\Psi(\tau)\rangle$ projects back fermion solution. but statistical errors grow exponentially

Constrained-path propagation, removes steps that have

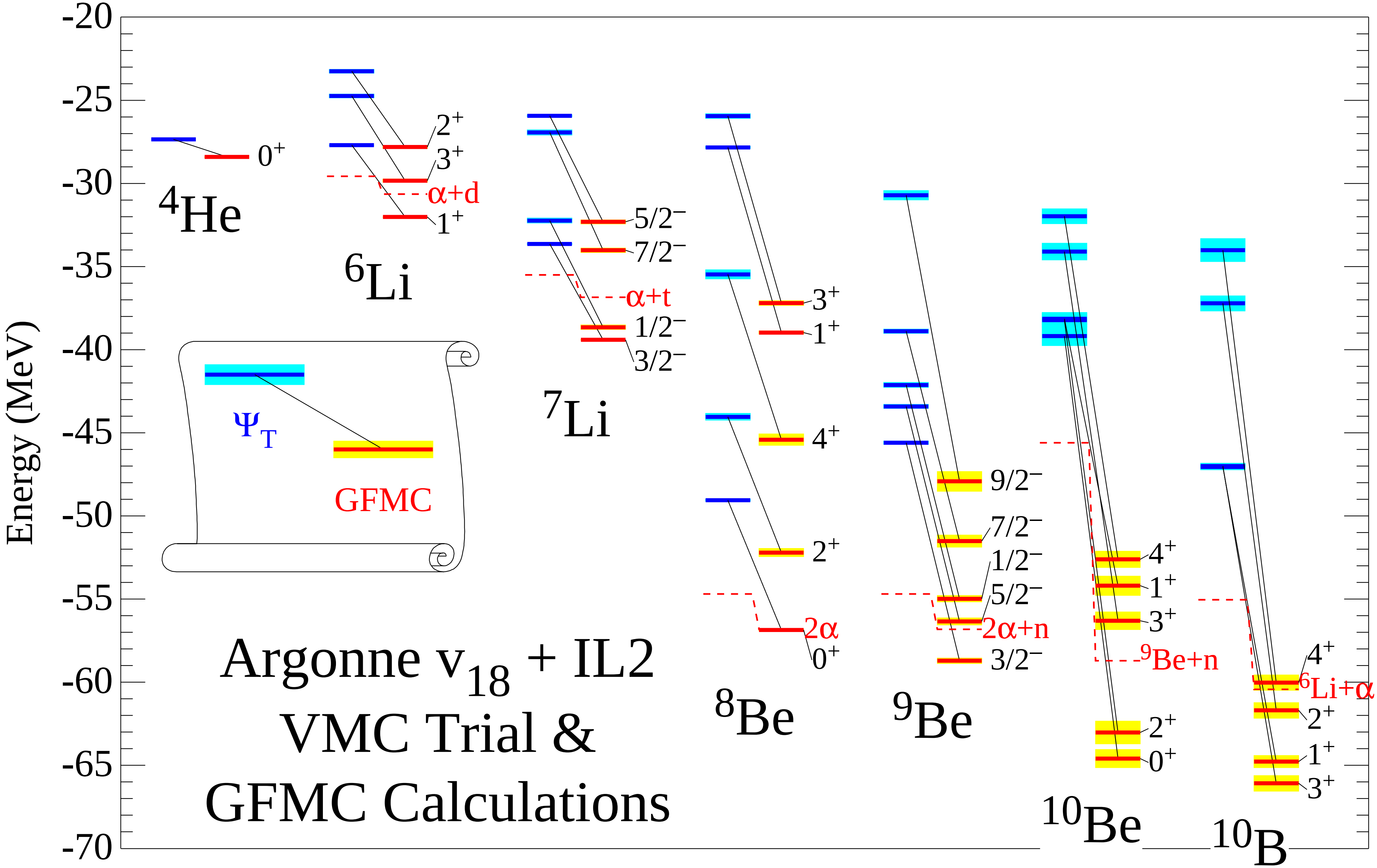
$$\overline{\Psi^\dagger(\tau,\mathbf{R})\Psi(\mathbf{R})} = 0$$

Possible systematic errors rduced by $10-20$ unconstrained steps before evaluating observables.

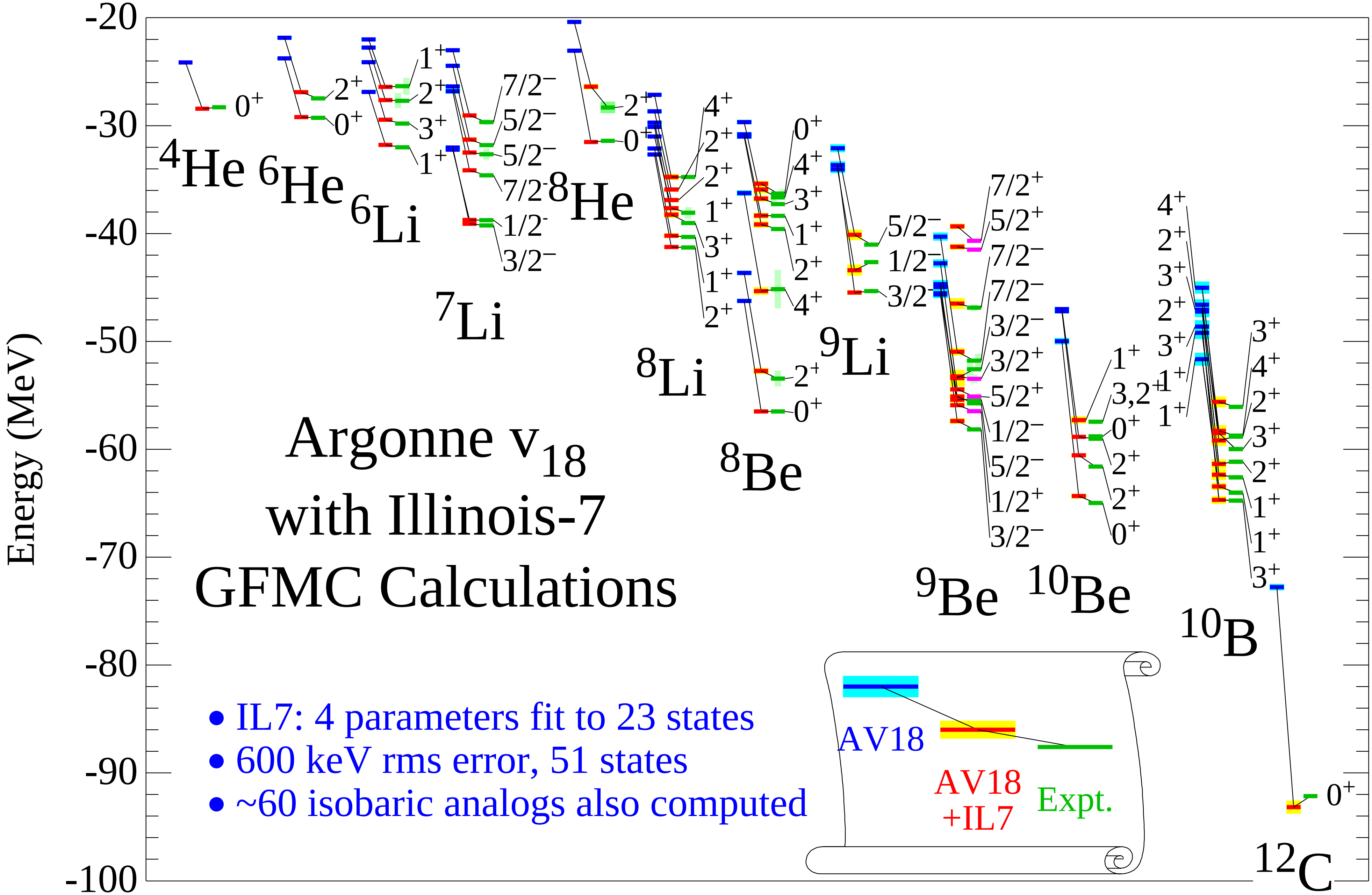
Pudliner, Pandharipande, Carlson, Pieper, & Wiringa, Phys. Rev. C **56**, 1720 (1997)

A SIMPLIFIED GFMC CALCULATION

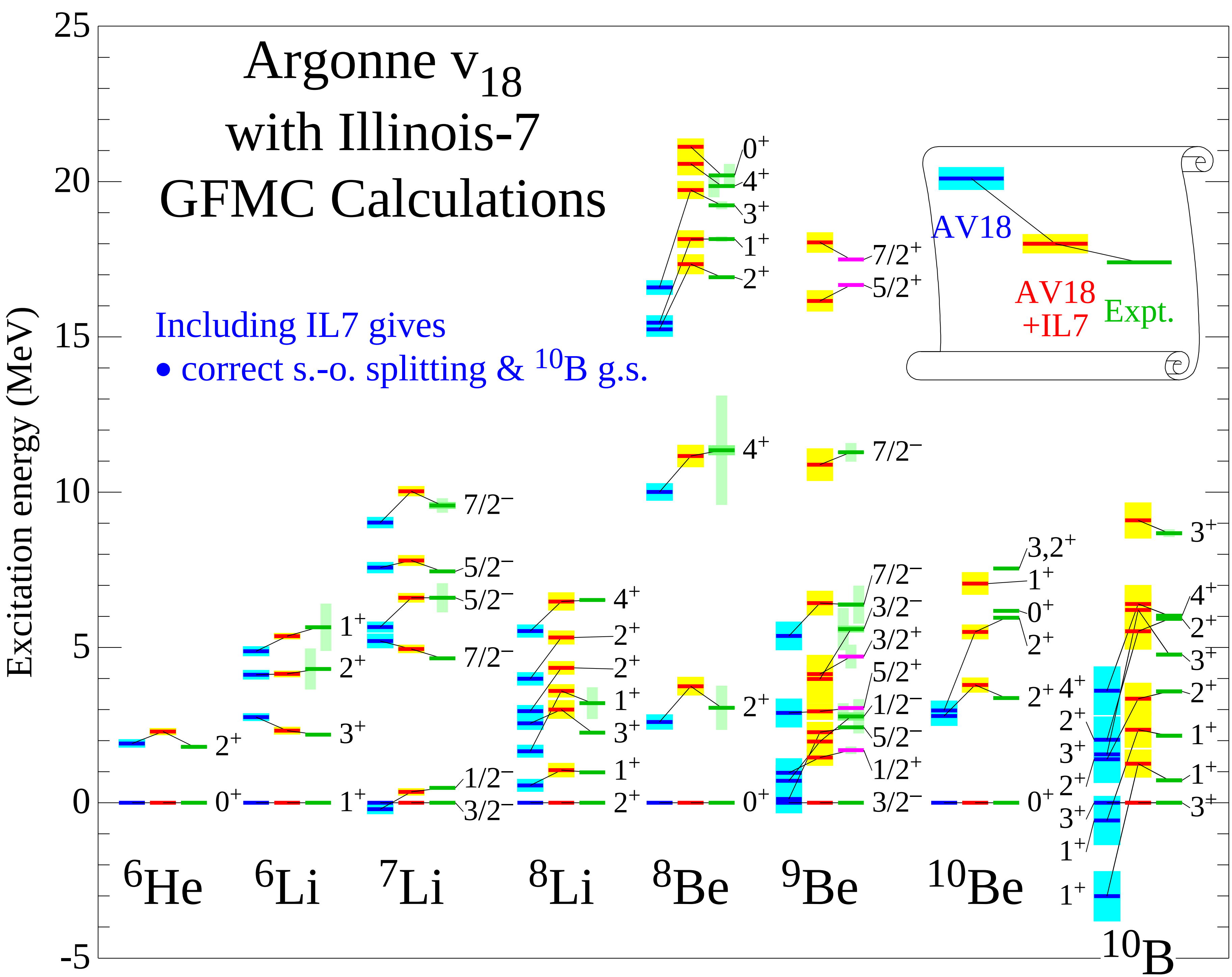
- Start with collection of $\Psi(\tau = 0, \mathbf{R}_j) = \Psi_V(\mathbf{R}_j)$ from VMC calculation
- Loop over time steps $\tau_n = n\triangle\tau$
  - Loop over configurations J
    - Make random step $\mathbf{R}'_j = \mathbf{R}_j + \triangle\mathbf{R}_j$ by sampling the Gaussian $\exp\left[\frac{-(\mathbf{R}'_j - \mathbf{R}_j)^2}{2\hbar^2\triangle\tau/m}\right]$
    - Sample several directions based on simplified Ψ_V and potential
    - Compute $\Psi(\tau_{n+1}, \mathbf{R}'_j) = G(\mathbf{R}'_j, \mathbf{R}_j)\Psi(\tau_n, \mathbf{R}_j)$
    - Possibly mark as killed due to constraint $\Psi^\dagger(\tau_{n+1}, \mathbf{R}'_j) \cdot \Psi_V(\mathbf{R}'_j)$
    - Use importance sampling to kill or replicate the configuration $\Psi(\tau_{n+1}, \mathbf{R}'_j)$
  - Every 20–40 time steps
    - compute $\Psi^\dagger(\tau_n, \mathbf{R}_j) H \Psi^\dagger_V(\tau_n, \mathbf{R}_j)$
    - check that total number of configurations is staying reasonably constant



Energy (MeV)
-20
-25
-30
-35
-40
-45
-50
-55
-60
-65
-70
4He
0+
6Li
2+
3+
α+d
1+
7Li
5/2−
7/2−
α+t
1/2−
3/2−
8Be
3+
1+
4+
2+
2α
0+
9Be
9/2−
7/2−
1/2−
5/2−
2α+n
3/2−
10Be
4+
1+
3+
9Be+n
2+
0+
10B
4+
6Li+α
2+
1+
3+
ΨT
GFMC
Argonne v18 + IL2
VMC Trial &
GFMC Calculations



Argonne v18
with Illinois-7
GFMC Calculations
Energy (MeV)
-20
-30
-40
-50
-60
-70
-80
-90
-100
4He
6He
6Li
7Li
8He
8Li
8Be
9Li
9Be
10Be
10B
12C
• IL7: 4 parameters fit to 23 states
• 600 keV rms error, 51 states
• ~60 isobaric analogs also computed
AV18
AV18
+IL7
Expt.



Argonne v18
with Illinois-7
GFMC Calculations
Including IL7 gives
• correct s.-o. splitting & 10B g.s.
AV18
AV18
+IL7
Expt.
Excitation energy (MeV)
25
20
15
10
5
0
-5
6He
6Li
7Li
8Li
8Be
9Be
10Be
10B
0+
2+
1+
3+
3/2−
1/2−
7/2−
5/2−
4+
1/2+
5/2+
7/2+
3,2+

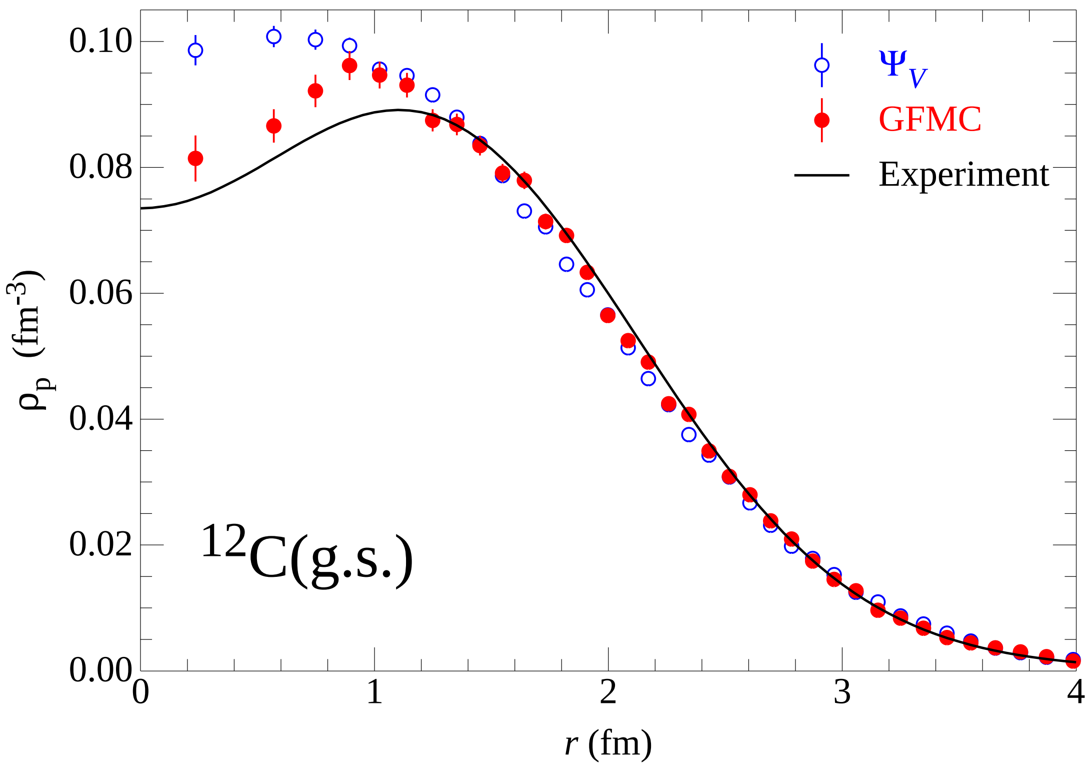
MAKING GFMC WORK ON 131,072 PROCESSORS AND ^{12}C

UNEDF SciDAC grant to develop general-purpose load-balancing library (ADLB) to run under MPI on 32,768 nodes with OpenMP for 4 cores/node

INCITE grant of Argonne BG/P time used for ^{12}C calculations

- AV18+IL7 Hamiltonian
- Ψ_V has 3-α structure and complete set of 0^+ p-shell states
- Extensive convergence studies made
- GFMC generates central density dip

	VMC	GFMC	Expt.
E (MeV)	–65.8(2)	–93.2(6)	–92.16
$\langle r^2\rangle^{1/2}$ (fm)	2.36	2.35	2.33



Lusk, Pieper, & Butler, SciDAC Review Spring 2010

CHARGE SYMMETRY BREAKING

GFMC isovector and isotensor energy coefficients $a^{(n)}_{A,T}$

$$E_{A,T}(T_z) = \sum_{n\leq 2T} a^{(n)}_{A,T} Q_n(T,T_z)$$

$$Q_0 = 1\,; \quad Q_1 = T_z\,;\text{ and } \quad Q_2 = \tfrac{1}{2}(3T_z^2 - T^2)$$

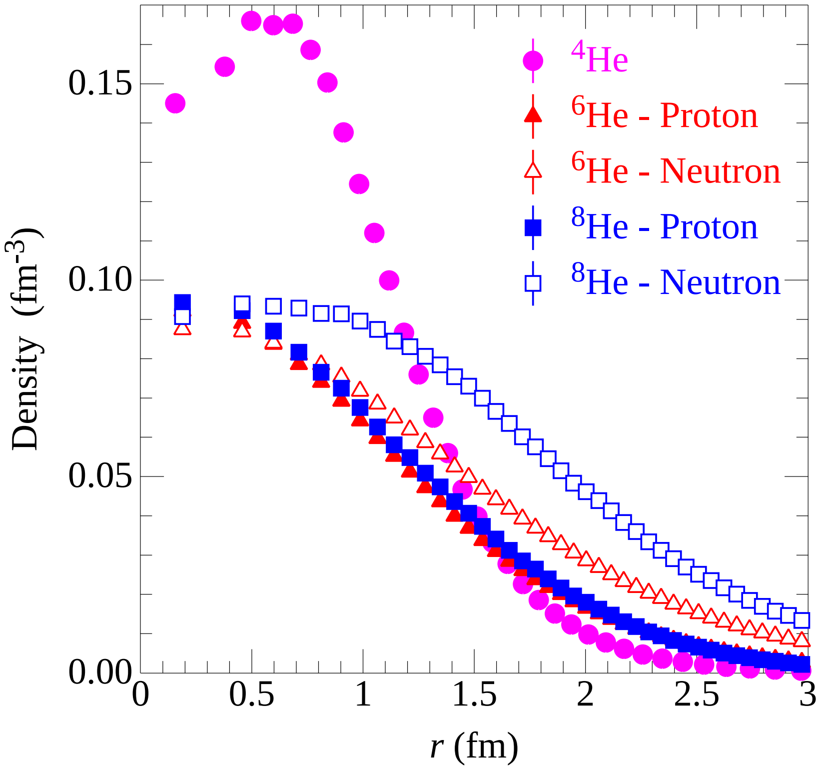
Argonne v_{18} + IL7 (keV)

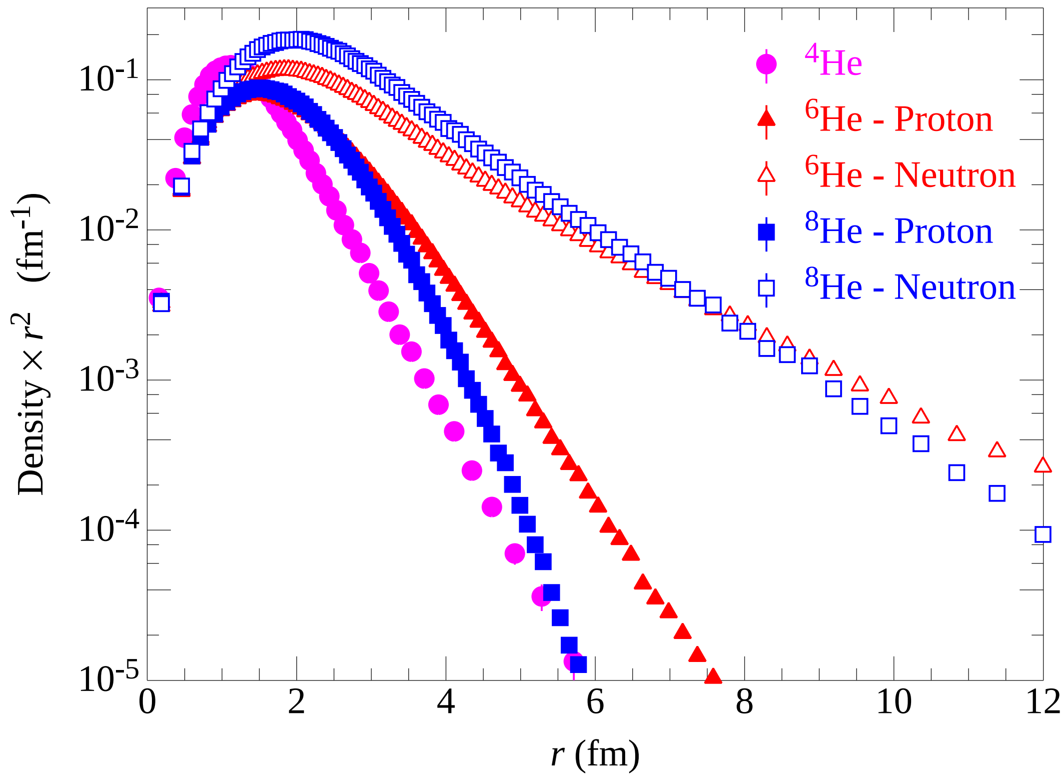
	T	n	$v^{\rm Coul}$	$v^{\rm MM+}$	$v^{\rm CSB+CD}$	$K^{\rm CSB}$	Total	Expt.
^{3}H–^{3}He	$\frac{1}{2}$	1	650	28	65	14	757	764
^{7}Li–^{7}Be	$\frac{1}{2}$	1	1446	36	86	23	1592	1644
^{7}He,^{7}Li,^{7}Be,^{7}B	$\frac{3}{2}$	1	1270	9	52	17	1348	1376
	$\frac{3}{2}$	2	129	7	38		174	174
^{8}Li,^{8}Be,^{8}B	1	1	1660	19	78	23	1780	1770
	1	2	137	4	−10		132	127
^{8}He,^{8}Li,^{8}Be,^{8}B,^{8}C	2	1	1624	8	71	22	1726	1659
	2	2	144	6	39		189	153

Wiringa, AIP Conf. Proc. **1128**, 1 (2009)

SINGLE-NUCLEON DENSITIES

$$\rho_{p,n}(r) = \sum_i \langle \Psi | \delta(r - r_i) \frac{1 \pm \tau_i}{2} | \Psi \rangle$$





RMS radii

	r_n	r_p	r_c	Expt
^{4}He	1.45(1)	1.45(1)	1.67(1)	1.681(4)*
^{6}He	2.86(6)	1.92(4)	2.06(4)	2.072(9)†
^{8}He	2.79(3)	1.82(2)	1.94(2)	1.961(16)‡

*Sick, PRC **77**, 041302(R) (2008)

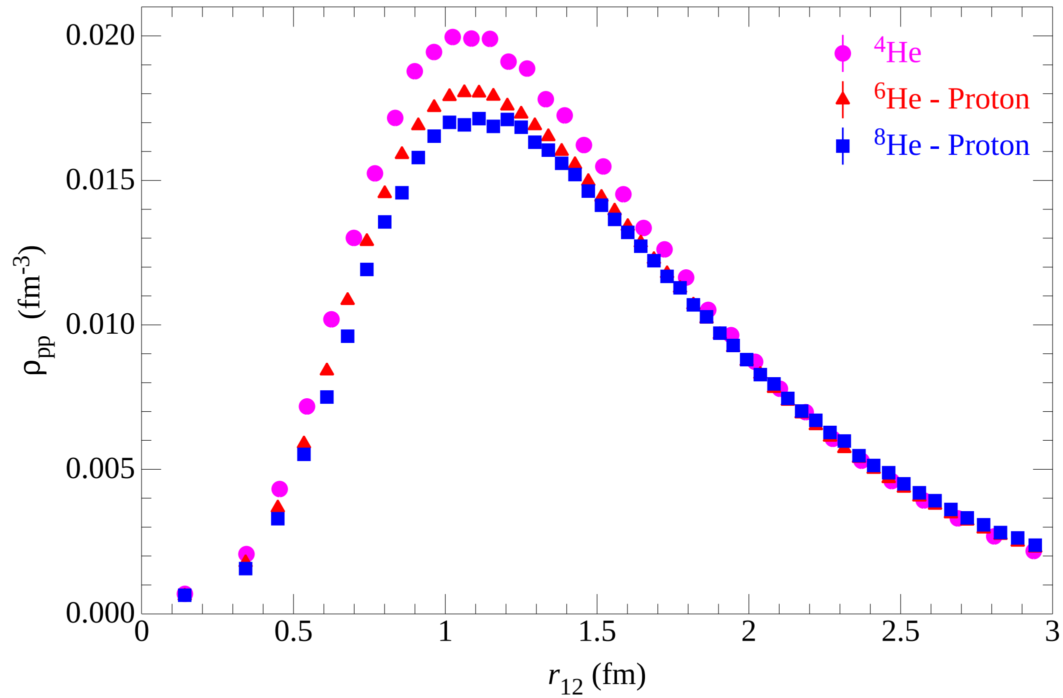
†Wang, *et al.*, PRL **93**, 142501 (2004)

‡Mueller, *et al.*, PRL **99**, 252501 (2007)

IS AN ALPHA PARTICLE IN A SEA OF NEUTRONS STILL AN ALPHA PARTICLE?

The α core of ^{6,8}He is pushed around by the neutrons
— rms charge radius changed just by C.M. effects

$\rho_{pp}(r_{12})$ is probability of two protons separated by r_{12}
— not effected by C.M. motion of the α.
Only pp pair in ^{4,6,8}He is "in" the α core
–$\rho_{pp}(r_{12})$ measures size of α core
ρ_{pp} less peaked in ^{6,8,10}He
— Core polarization
— Charge-exchange correlations
with valence neutrons
— Implies 80−350 keV excitation of α or
0.4−2% admixture of 20 MeV excited state



Intrinsic Density of ^{8}Be

^{8}Be w.f.: ^{4}He core + 4 p-shell nucleons + pair corr.

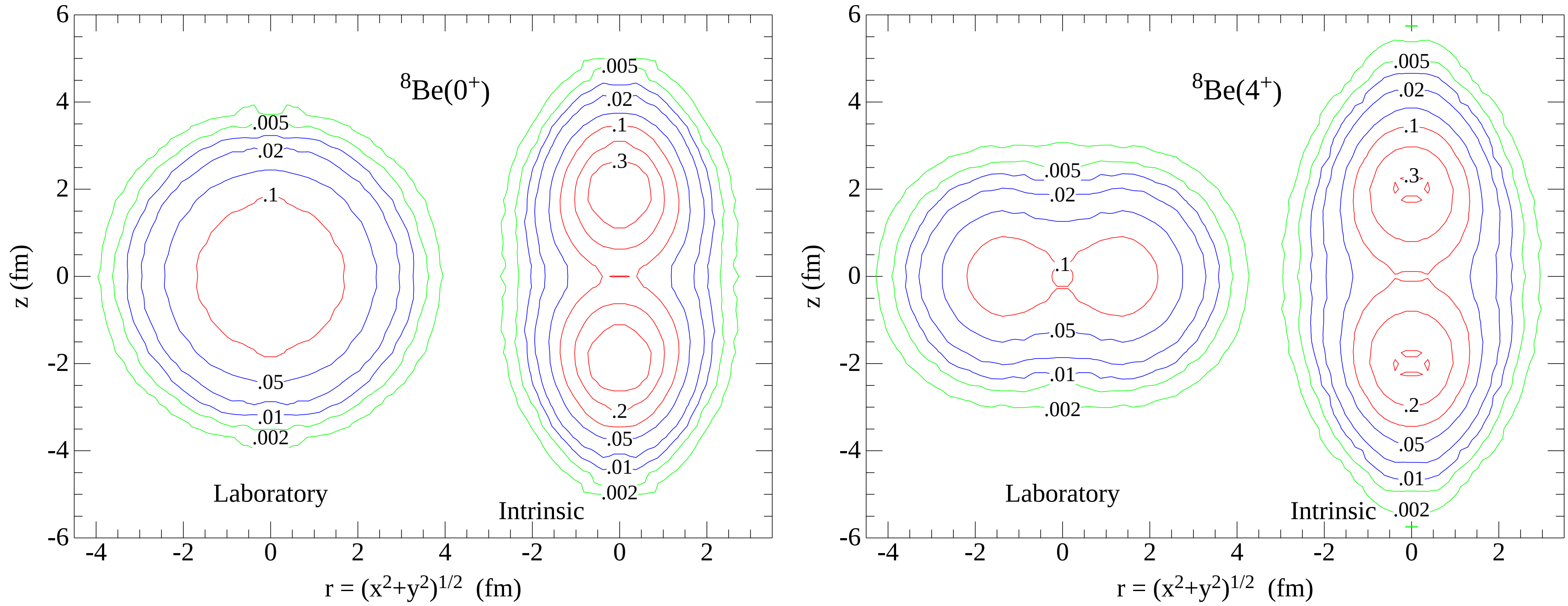
M. C. $\rho(\mathbf{r})$: random walk in $|\Psi(\mathbf{r}_1, \mathbf{r}_2, \cdots, \mathbf{r}_8)|^2$ & periodically for each set $(\mathbf{r}_1, \mathbf{r}_2, \cdots, \mathbf{r}_8)$

Lab $\rho(\mathbf{r})$: bin $\mathbf{r}_1, \mathbf{r}_2, \cdots, \mathbf{r}_8$

Intrinsic $\rho(\mathbf{r})$: find eigenvectors of moment of inertia matrix:

$$\mathcal{M} = \sum_i \begin{pmatrix} x_i^2 & x_i y_i & x_i z_i \\ y_i x_i & y_i^2 & y_i z_i \\ z_i x_i & z_i y_i & z_i^2 \end{pmatrix} ,$$

rotate to them, and bin $\mathbf{r}'_1, \mathbf{r}'_2, \cdots, \mathbf{r}'_8$.



Wiringa, Pieper, Carlson, & Pandharipande, Phys. Rev. C **62**, 014001 (2000)

$M1$, $E2$, F, GT transitions

NO EFFECTIVE CHARGES!

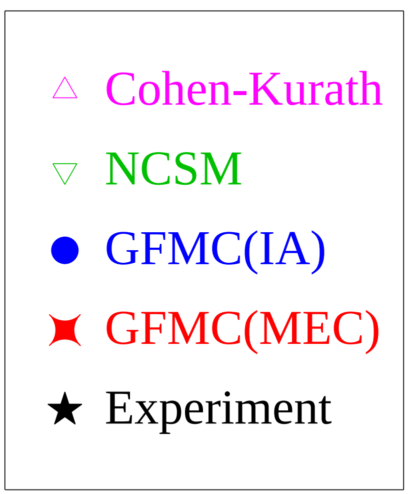
$$E2 = e\sum_k \tfrac{1}{2}\left[r_k^2 Y_2(\hat{r}_k)\right](1+\tau_{kz})$$

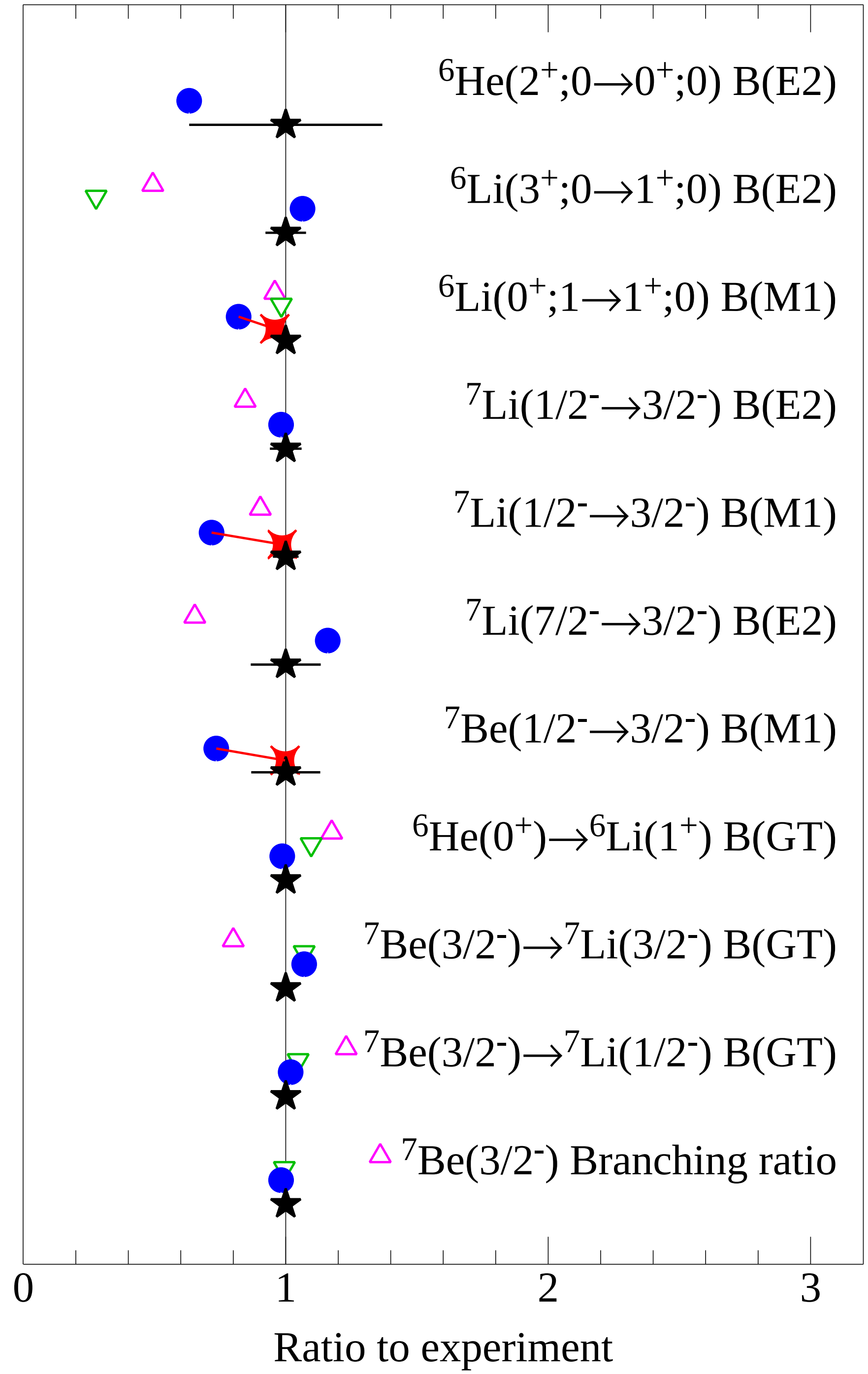
$$M1 = \mu_N \sum_k [\,(L_k + g_p S_k)(1+\tau_{kz})/2 + g_n S_k\ (1-\tau_{kz})/2\,]$$

$$\mathrm{F} = \sum_k \tau_{k\pm}\ ;\ \mathrm{GT} = \sum_k \sigma_k \tau_{k\pm}$$

Pervin, Pieper & Wiringa, PRC **76**, 064319 (2007)

Marcucci, *et al.*, PRC **78**, 065501 (2008)





Radiative Capture Reactions

$$\sigma(E_{cm}) = \frac{8\pi}{3} \frac{\alpha}{v_{\rm rel}} \frac{q}{1+q/m_{\rm Li}} \sum_{LSJ\ell} \left[\left| E_\ell^{LSJ}(q) \right|^2 + \left| M_\ell^{LSJ}(q) \right|^2 \right]$$

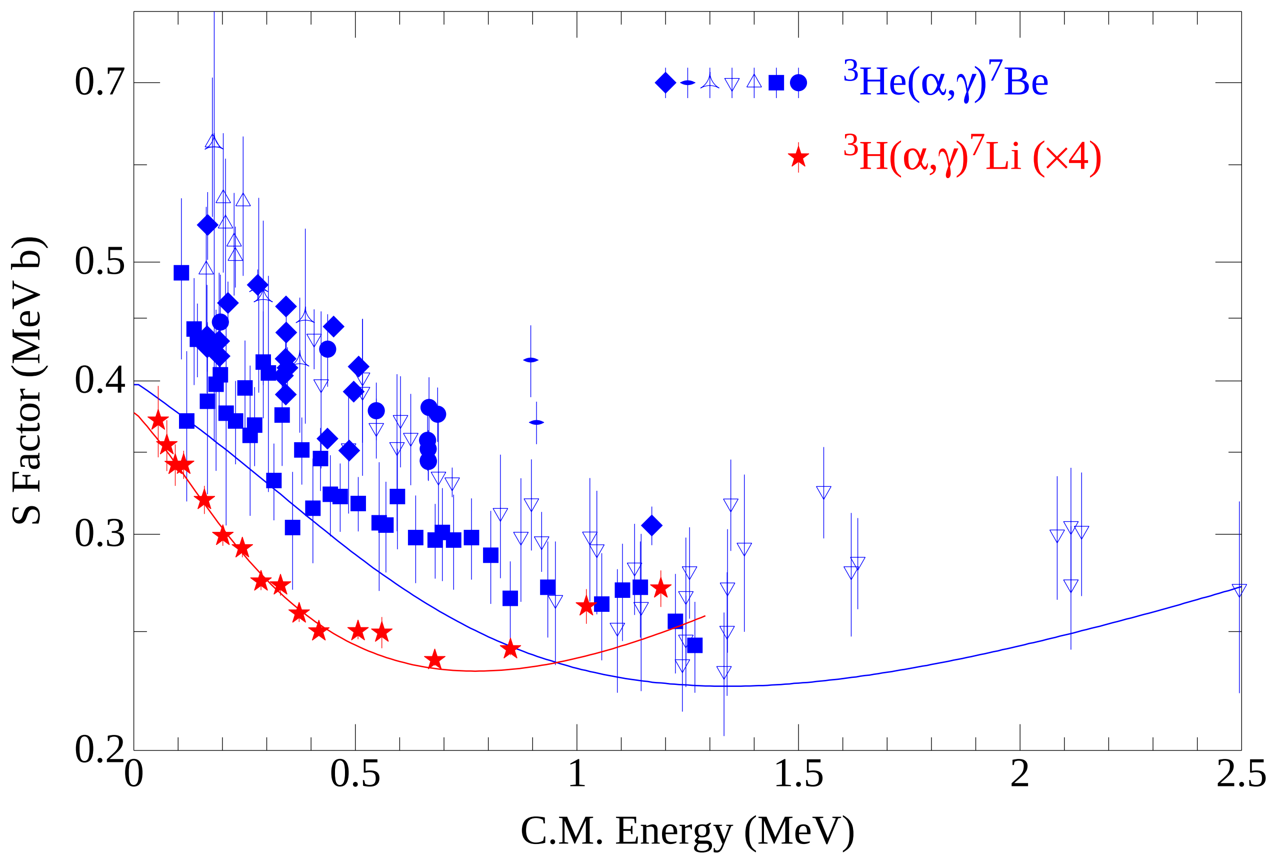
^{3}H$(\alpha,\gamma)^7$Li ^{3}He$(\alpha,\gamma)^7$Be

Sources of ^{7}Li in big bang
(20-500 keV)

^{7}Be key to solar ν_e production
(20 keV)

Full A=7 VMC calculation
except 3+4 scattering w.f.
from optical potential

We want to do everything including
the 3+4 scattering in full GFMC



Nollett, Phys. Rev. C **63**, 054002 (2001)

GFMC FOR SCATTERING STATES

GFMC treats nuclei as particle-stable system – should be good for energies of narrow resonances

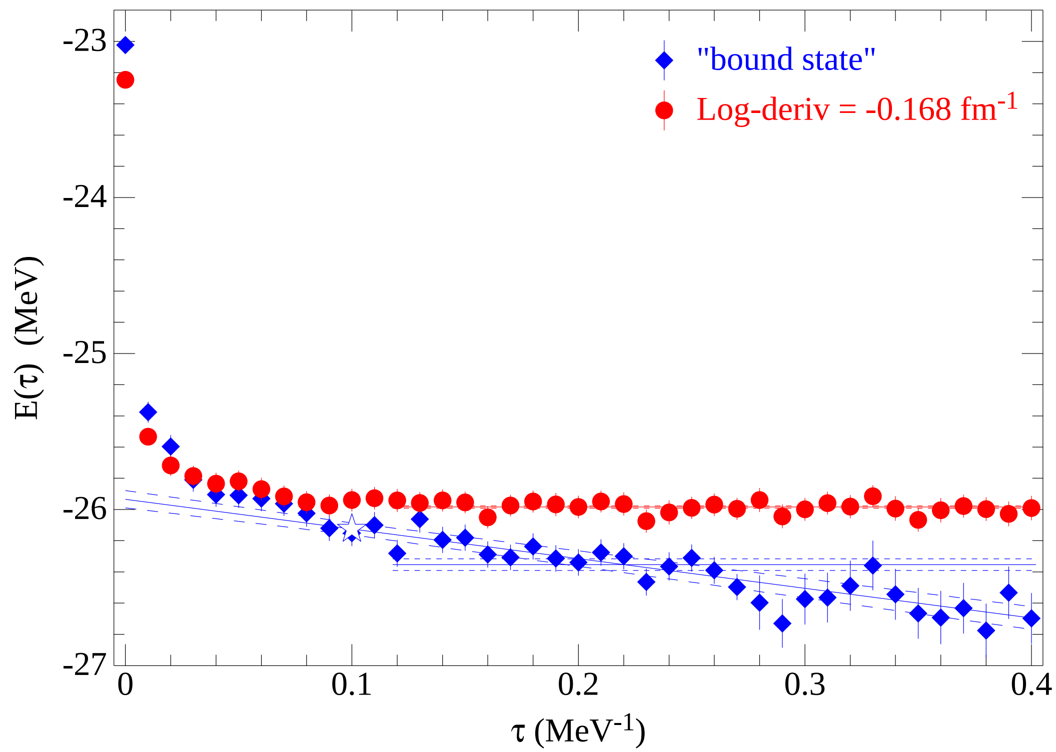
Need better treatment for locations and widths of wide states and for capture reactions

METHOD

- Pick a logarithmic derivative, χ, at some large boundary radius ($R_B \approx 9$ fm)
- GFMC propagation, using method of images to preserve χ at R, finds $E(R_B, \chi)$
- Phase shift, $\delta(E)$, is function of R_B, χ, E
- Repeat for a number of χ until $\delta(E)$ is mapped out
- need E accurate to $\sim 1/3\%$

Example for ^{5}He($\frac{1}{2}^-$)

- "Bound-state" boundary condition does not give stable energy; Decaying to n+^{4}He threshold
- Scattering boundary condition produces stable energy.



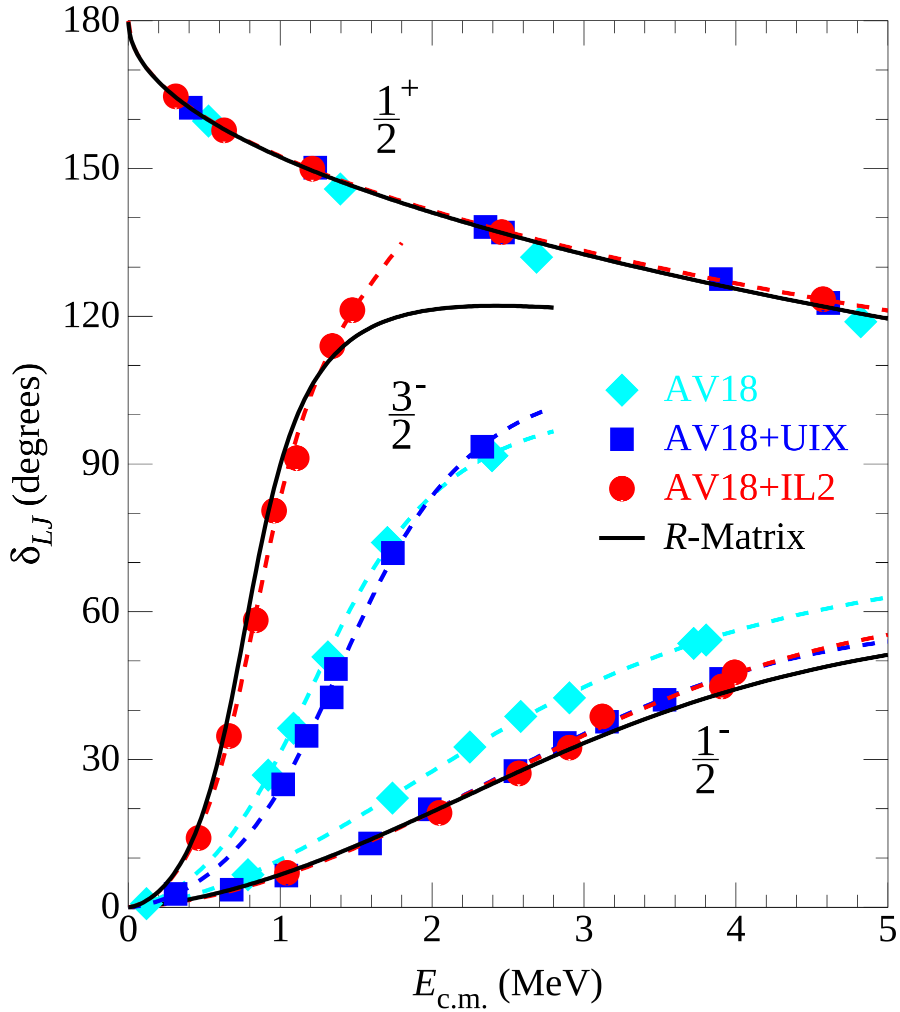
^{5}He AS n+^{4}He SCATTERING

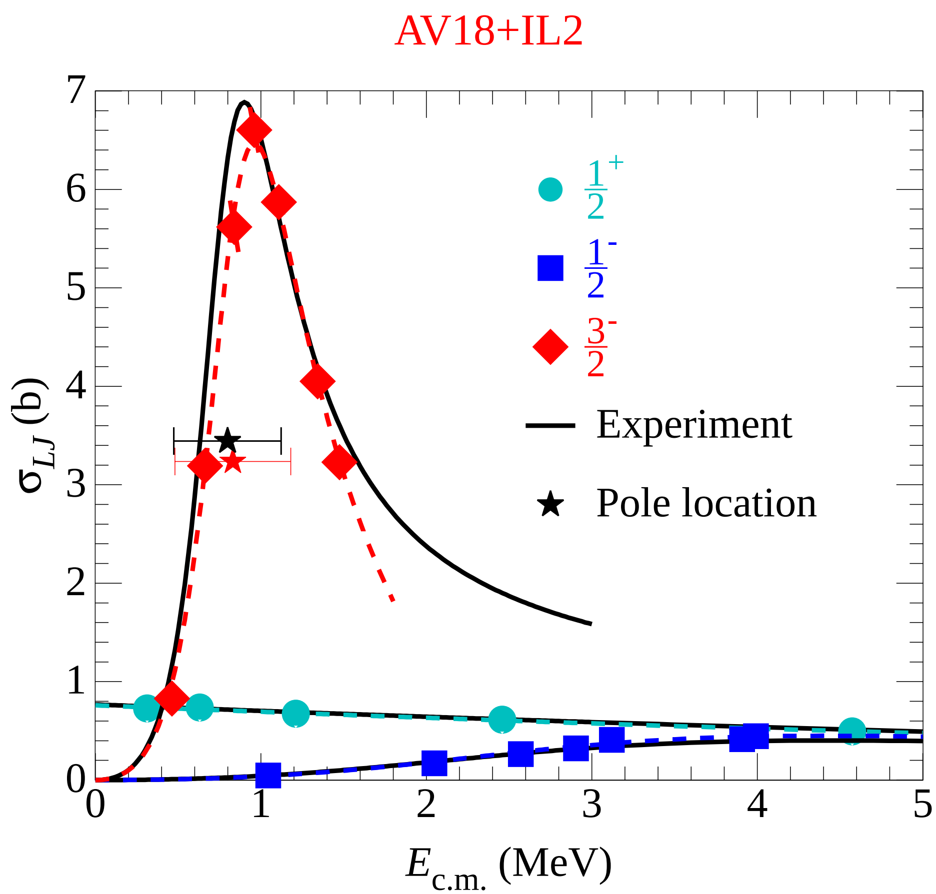
Black curves: Hale phase shifts from R-matrix analysis up to $J = \frac{9}{2}$ of data

AV18 with no V_{ijk} underbinds ^{5}He($3/2^-$) & overbinds ^{5}He($1/2^-$)

AV18+UIX improves ^{5}He($1/2^-$) but still too small spin-orbit splitting

AV18+IL2 reproduces locations and widths of both P-wave resonances





Nollett, Pieper, Wiringa, Carlson, & Hale, Phys. Rev. Lett. **99**, 022502 (2007)

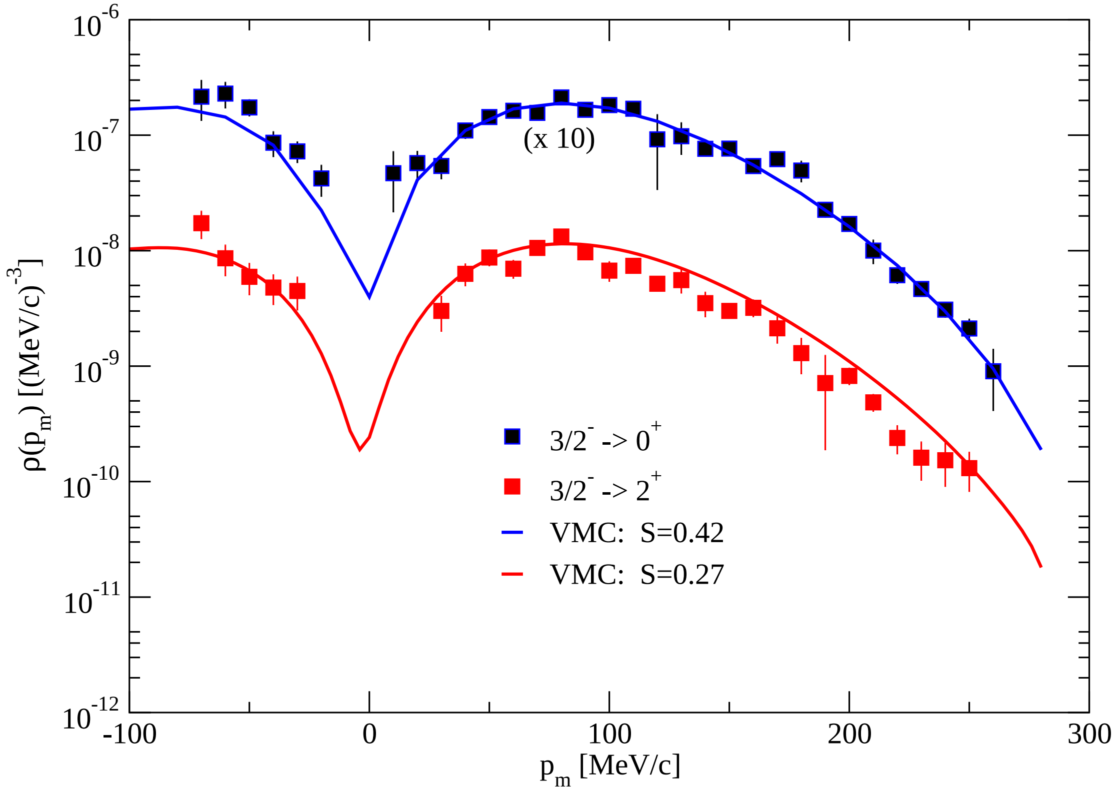
Absolute Spectroscopic Factors

$^{7}Li(e,e'p)^{6}He$

Variational ^{7}Li and ^{6}He wave functions used to compute one-nucleon quasi-particle w.f.

Normalization (Spectroscopic Factor $< 50\%$) is a result of many-nucleon correlations.

Standard (e,e′p) CDWIA used for cross sections.



Lapikás, Wesseling & Wiringa, Phys. Rev. Lett. **82**, 4404 (1999)

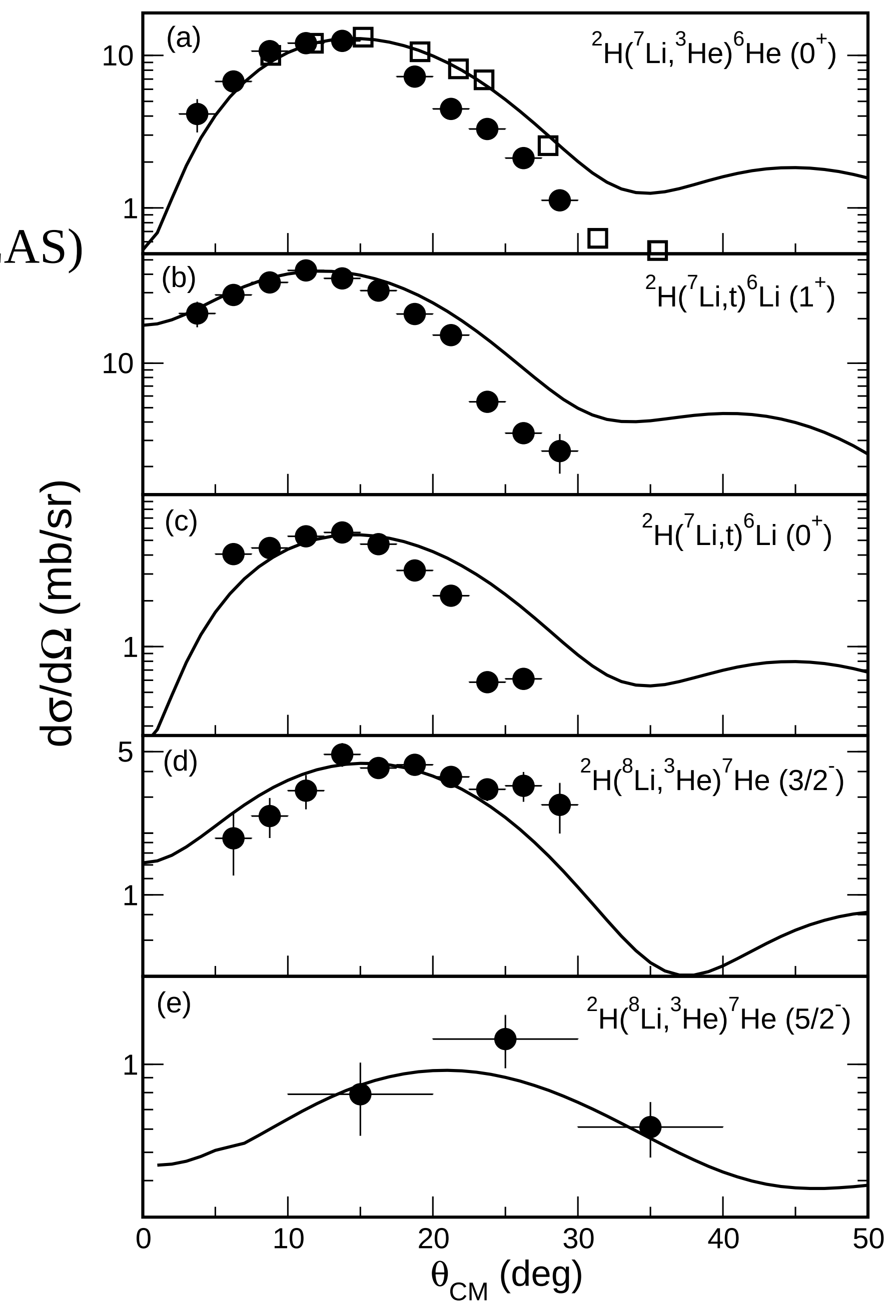
New GFMC calculations give same spectroscopic factors, better asymptotic tail

ANALYSIS OF LIGHT-ION REACTIONS

The study of nuclei far from stability has renewed interest in (d,p) and related experiments

Calculations performed for four RIB experiments:
^{8}Li$(d,p)^{9}$Li & ^{6}He$(d,p)^{7}$He & ^{8}Li$(d,{}^{3}$He$)^{7}$He (ATLAS)
^{9}Li$(d,t)^{8}$Li (TRIUMF)

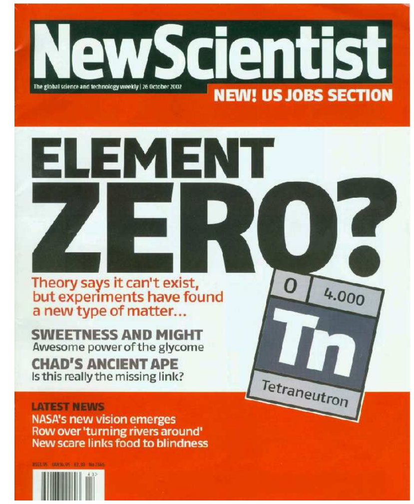
- PTOLEMY DWBA calculations
- (d,p) vertex from AV18
- $(^{8}$Li$,^{9}$Li$)$, $(^{7}$He$,^{8}$Li$)$, $(^{6}$He$,^{7}$He$)$, (d,t) & $(d,{}^{3}$He$)$ vertices computed as A-body overlaps using VMC $\langle\Psi_V(A\text{-}1)|a|\Psi_V(A)\rangle$
- Spin assignments for ^{9}Li* clarified
- Strong rejection of previously claimed 560 keV $\frac{1}{2}^-$ state in ^{7}He



Wuosmaa *et al.*, PRL **94**, 082502 (2005)
Wuosmaa *et al.*, PRC **72**, 061301(R) (2005)
Wuosmaa *et al.*, PRC **78**, 041302(R) (2008)
Kanungo *et al.*, PLB **660**, 26 (2008)

Macfarlane & Pieper, PTOLEMY, ANL-76-11, Rev. 1 (1978)

Can Modern Nuclear Hamiltonians Tolerate a Bound Tetraneutron?



AV18 + IL2 does not bind ^{4}n; $E \sim +2.$ MeV

Attempt minimal modifications to AV18+IL2 to give E(^{4}n) ~ -0.5 MeV

Check effects for other nuclei

Modify $^1S_0$ or ^3P_J part of AV18

- $^1S_0$ binds ^{2}n
- ^3P_J must be insanely strong

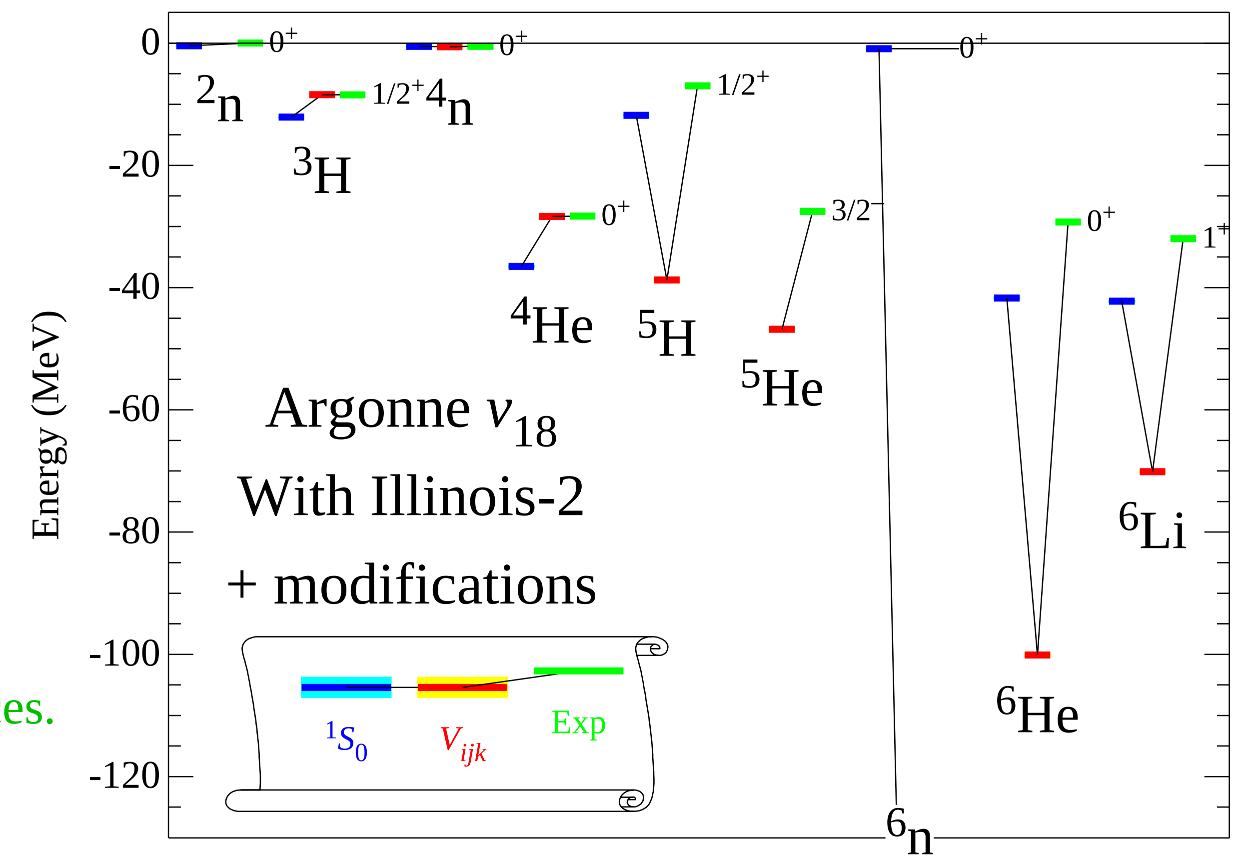
Add $V_{ijk}(T = \frac{3}{2})$ attraction

- No effect on NN scattering
- No effect on ^{3}H, ^{3}He, ^{4}He
- Huge effects elsewheres

Add $V_{ijkl}(T = 2)$ attraction (not shown)

- No effect on ^{4}H, ^{5}He, ^{6}Li
- Extreme (GeV scale) binding of ^{5,6,8}n, ^{6}He, etc.

A bound ^{4}n is incompatible with our understanding of nuclear forces.



Pieper, Phys. Rev. Lett. **90**, 252501 (2003)

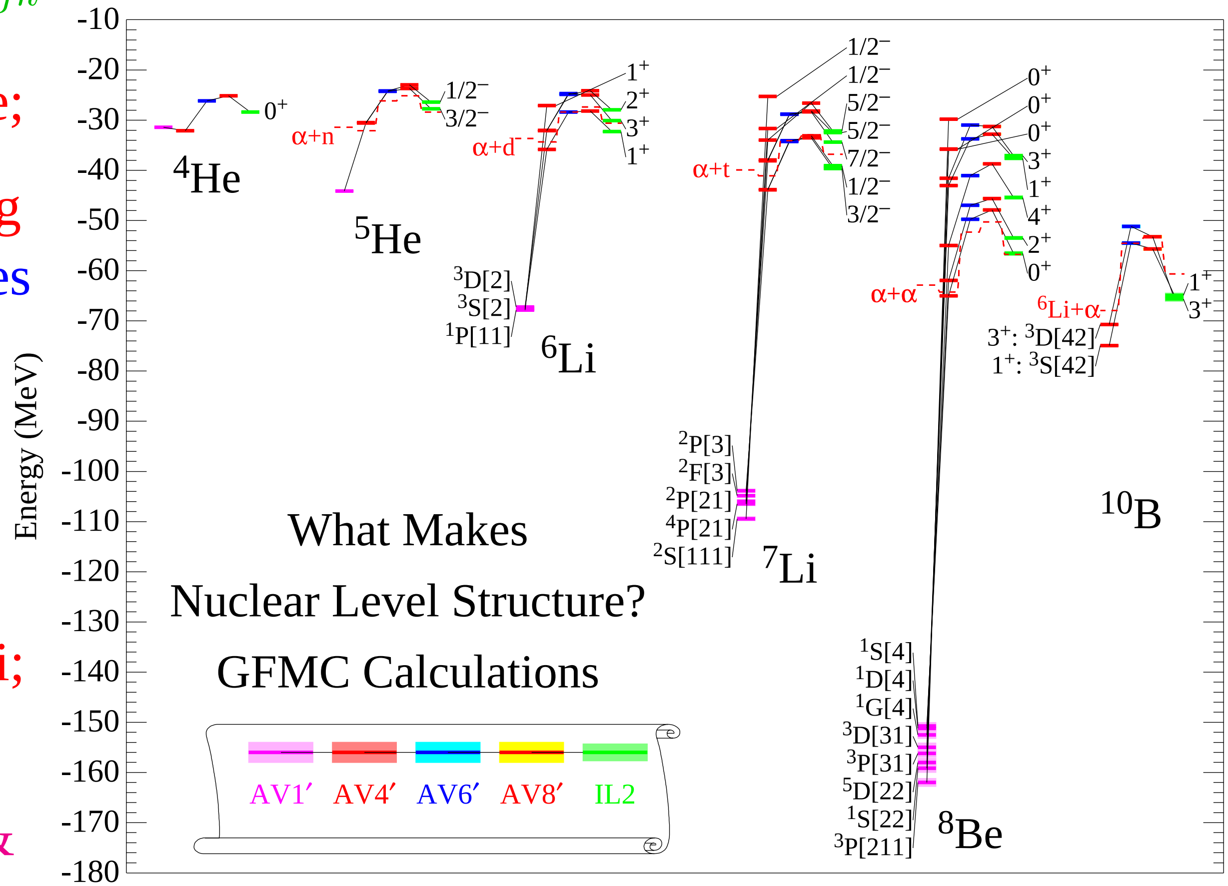
WHAT MAKES NUCLEAR STRUCTURE?

We have a very complicated nuclear Hamiltonian – is it all necessary?

Systematically remove features from nuclear Hamiltonian and look at effects on nuclear level energies

Physical Review Focus

- Full AV18 v_{ij} + Illinois V_{ijk} reproduces experiment
- AV8′ - basic level structure; relative stability correct; some level orderings wrong
- AV6′ - Removing $L\cdot S$ gives no SO splittings; has A=5,8 gaps but weak A=6,7 binding
- AV4′ - Removing tensor force introduces spurious degeneracies; somewhat overbinds nuclei; A=8 bound
- AV1′ - Pure central force "upside-down" spectrum & no nuclear saturation



Need (almost) full, complicated, Hamiltonian to do realistic nuclear physics

Wiringa & Pieper, Phys. Rev. Lett. **89**, 182501 (2002)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