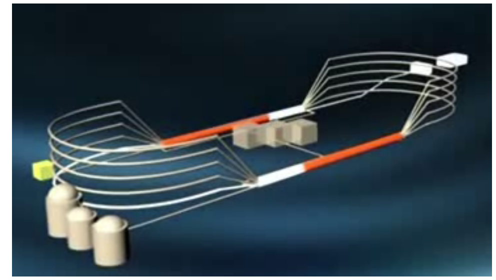
Ab initio nuclear structure – recent developments

"Nuclear Theory in the Supercomputing Era"
Pacific National University

James P. Vary
Iowa State University

June 18-22, 2012

Ab initio nuclear physics – fundamental ?'s



- What controls nuclear saturation?
- How the nuclear shell model emerges from the underlying theory?
- What are the properties of nuclei with extreme neutron/proton ratios?
- Can we predict useful cross sections that cannot be measured?
- Can nuclei provide precision tests of the fundamental laws of nature?
- Under what conditions do we need QCD to describe nuclear structure?

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Blue Gene/P->Q

Hopper

+

K-super.
Blue Waters
Lomonosov

UNEDF SciDAC Collaboration

Universal Nuclear Energy Density Functional

QCD
Theory of strong interactions

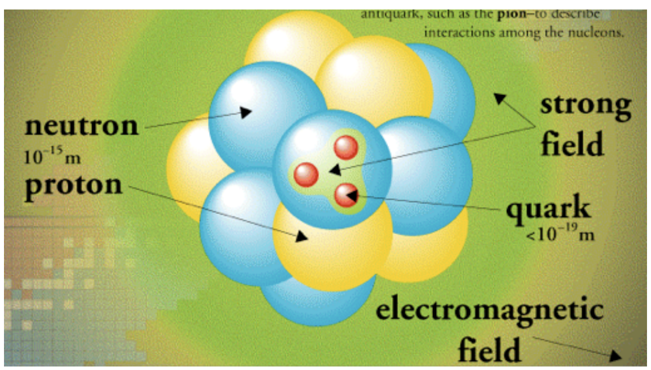
χEFT
Chiral Effective Field Theory

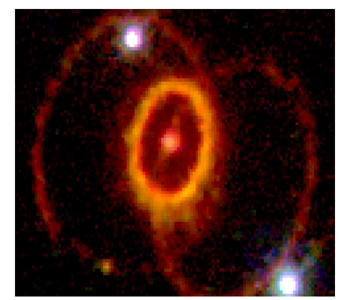
Inter-Nucleon
NN, NNN Interactions
AV18, EFT, $V_{low\text{-}k}$

Theory of Light Nuclei
Spectroscopy and selected reactions
Verification: NCSM=GFMC=CC
Validation: nuclei with A<16

Big Bang
Nucleosynthesis
& Stellar Reactions

Density Functional Theory
improved functionals
remove computationally-imposed constraints
properties for all nuclei with A>16





Dynamic Extensions of DFT
LACM by GCM,TDDFT,QRPA
Level densites

Low-energy Reactions
Hauser-Feshbach
Feshbach-Kerman-Koonin
Fission
mass and energy distributions

r,s processes
& Supernovae

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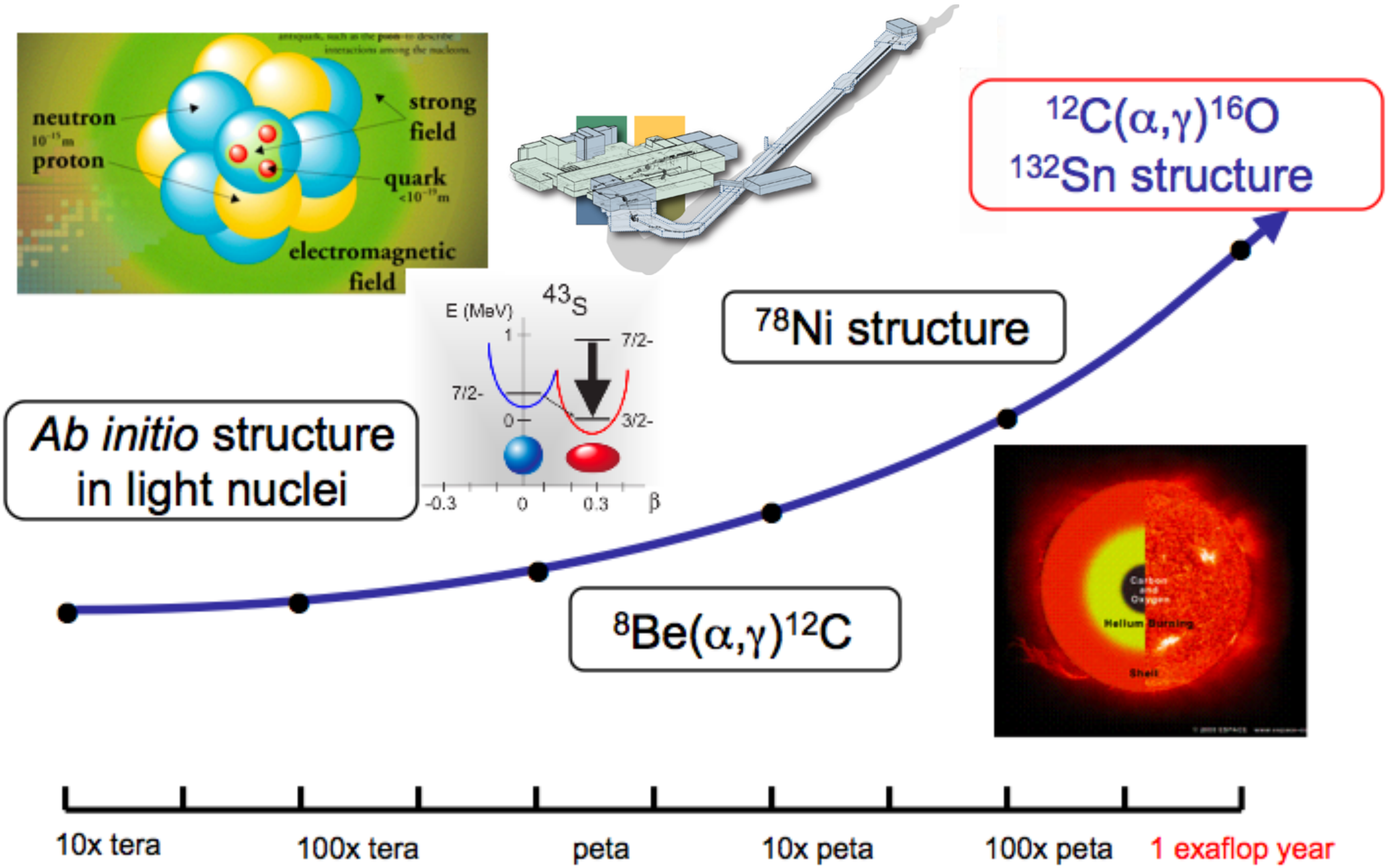

neutron
proton
strong field
quark
electromagnetic field
43S
E (MeV)
1
7/2-
0
7/2-
3/2-
-0.3
0
0.3
β
Ab initio structure in light nuclei
78Ni structure
8Be(α,γ)12C
12C(α,γ)16O
132Sn structure
Carbon and Oxygen
Helium Burning
Shell
10x tera
100x tera
peta
10x peta
100x peta
1 exaflop year

The Nuclear Many-Body Problem

The many-body Schroedinger equation for bound states consists of $2^A \binom{A}{Z}$ coupled second-order differential equations in 3A coordinates using strong (NN & NNN) and electromagnetic interactions.

Successful *ab initio* quantum many-body approaches (A > 6)

Stochastic approach in coordinate space
Greens Function Monte Carlo (**GFMC**)

Hamiltonian matrix in basis function space
No Core Shell Model (**NCSM**)
No Core Full Configuration (**NCFC**)

Cluster hierarchy in basis function space
Coupled Cluster (**CC**)

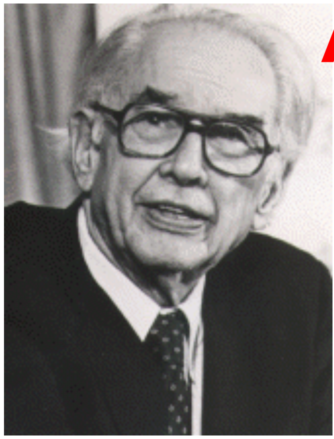
Lattice + EFT approach (New)

Coming - Gorkov Green's Function, . . .

Comments

All work to preserve and exploit symmetries
Extensions of each to scattering/reactions are well-underway
They have different advantages and limitations

Atanasoff-Berry Computer (ABC)



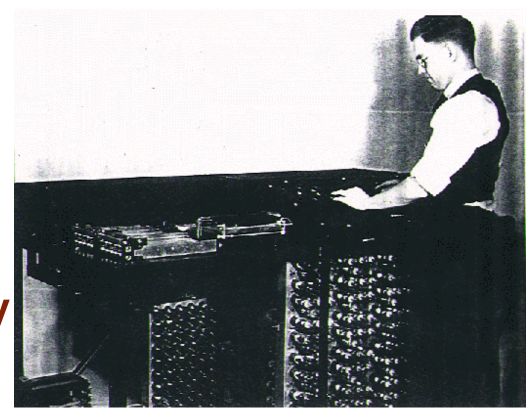
John Vincent Atanasoff
1983 photo

Clifford Berry
1962 photo

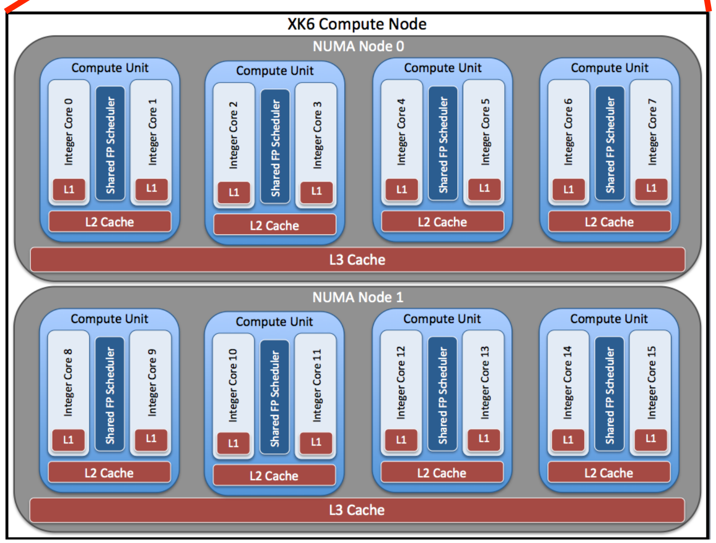
- 1939 - Iowa State Physics Professor Atanasoff invents the electronic digital computer based on binary mathematics with stored program and data along with punch card input. Atanasoff and graduate student Clifford Berry construct the ABC and use ABC to solve simultaneous linear equations
- 1997 - Replica completed and demonstrated in public

1990 - Atanasoff awarded the National Medal of Technology by President George W. Bush

1942 photo of Clifford Berry and the ABC



“Leadership Class” Computational Resources



16 “cores” on one compute “node”
Total: 300,000 cores at present
Titan will have 1GPU/node

& INCITE Award 55M cpu-hrs/yr

All interactions are "effective" until the ultimate theory unifying all forces in nature is attained.

Thus, even the Standard Model, incorporating QCD,
is an effective theory valid below the Planck scale
$\lambda < 10^{19}$ GeV/c

The "bare" NN interaction, usually with derived quantities,
is thus an effective interaction valid up to some scale, typically
the scale of the known NN phase shifts and Deuteron gs properties
$\lambda \sim 600$ MeV/c ($3.0\ fm^{-1}$)

Effective NN interactions can be further renormalized to lower scales
and this can enhance convergence of the many-body applications
$\lambda \sim 300$ MeV/c ($1.5\ fm^{-1}$)

"Consistent" NNN and higher-body forces, as well as electroweak
currents, are those valid to the same scale as their corresponding
NN partner, and obtained in the same renormalization scheme.

ab initio renormalization schemes

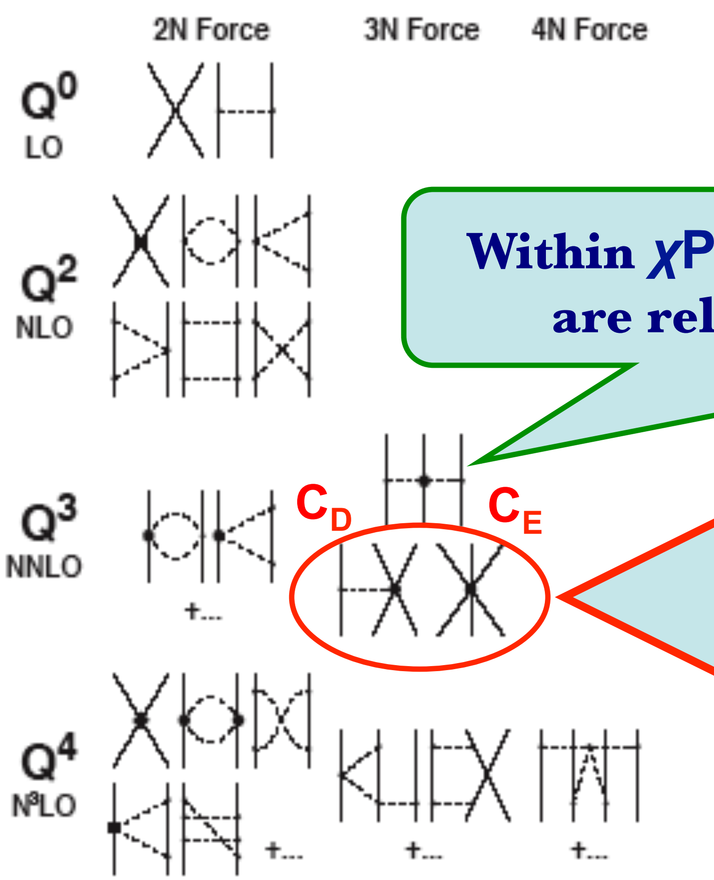
SRG: Similarity Renormalization Group
OLS: Okubo-Lee-Suzuki
Vlowk: V with low k scale limit
UCOM: Unitary Correlation Operator Method
and there are more!

Effective Nucleon Interaction
(Chiral Perturbation Theory)

Chiral perturbation theory (χPT) allows for controlled power series expansion

Expansion parameter : $\left(\frac{Q}{\Lambda_\chi}\right)^{\upsilon}$, $Q-$momentum transfer,

$\Lambda_\chi \approx 1\ GeV$, χ - symmetry breaking scale



R. Machleidt, D. R. Entem, nucl-th/0503025

Within χPT 2π-NNN Low Energy Constants (LEC) are related to the NN-interaction LECs $\{c_i\}$.

Terms suggested within the
Chiral Perturbation Theory

Regularization is essential, which is obvious within the Harmonic Oscillator wave function basis.

No Core Shell Model

A large sparse matrix eigenvalue problem

$$H = T_{rel} + V_{NN} + V_{3N} + \bullet\bullet\bullet$$

$$H|\Psi_i\rangle = E_i|\Psi_i\rangle$$

$$|\Psi_i\rangle = \sum_{n=0}^{\infty} A_n^i |\Phi_n\rangle$$

$$\text{Diagonalize } \{\langle\Phi_m|H|\Phi_n\rangle\}$$

- Adopt realistic NN (and NNN) interaction(s) & renormalize as needed - retain induced many-body interactions: Chiral EFT interactions and JISP16
- Adopt the 3-D Harmonic Oscillator (HO) for the single-nucleon basis states, α, β,…
- Evaluate the nuclear Hamiltonian, H, in basis space of HO (Slater) determinants (manages the bookkeeping of anti-symmetrization)
- Diagonalize this sparse many-body H in its "m-scheme" basis where [α =(n,l,j,$m_{j,}$$\tau_z$)]

$$|\Phi_n\rangle = [a_\alpha^+ \bullet\bullet\bullet a_\varsigma^+]_n|0\rangle$$

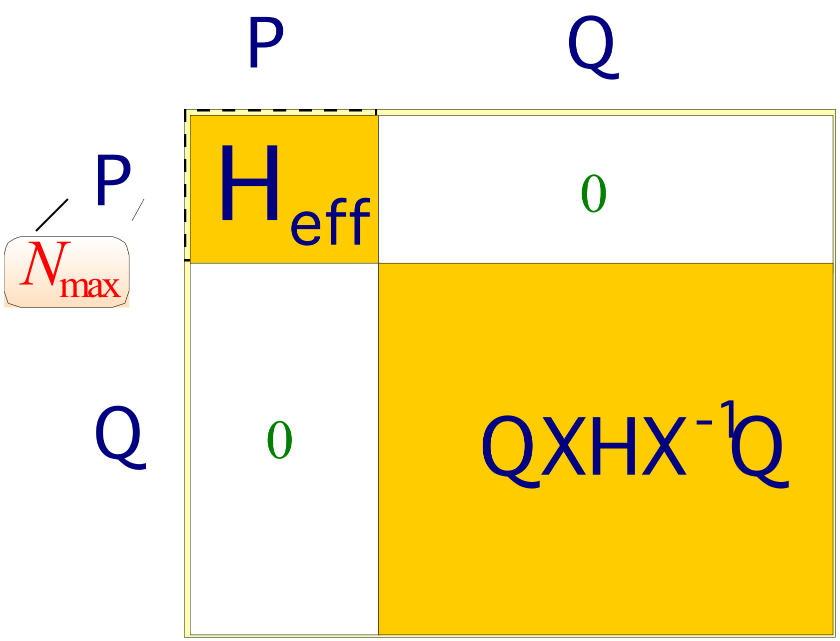
$$n = 1,2,\ldots,10^{10} \text{ or more!}$$

- Evaluate observables and compare with experiment

Comments

- Straightforward but computationally demanding => new algorithms/computers
- Requires convergence assessments and extrapolation tools
- Achievable for nuclei up to A=20 (40) today with largest computers available

Effective Hamiltonian in the NCSM
Okubo-Lee-Suzuki renormalization scheme



$$H: \quad E_1, E_2, E_3, \ldots E_{d_P}, \ldots E_\infty$$

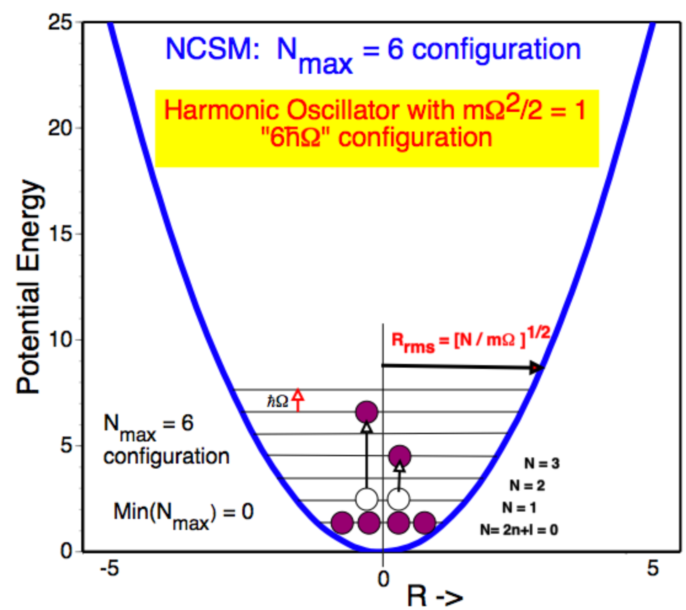
$$H_{eff}: \quad E_1, E_2, E_3, \ldots E_{d_P}$$

model space dimension

$$QXHX^{-1}P = 0$$

$$H_{eff} = PXHX^{-1}P$$

- n-body cluster approximation, $2 \leq n \leq A$
- $H^{(n)}_{eff}$ n-body operator
- Two ways of convergence:
  - For $P \to 1$ $\quad H^{(n)}_{eff} \to H$
  - For $n \to A$ and fixed P: $H^{(n)}_{eff} \to H_{eff}$



Controlling the center-of-mass (cm) motion in order to preserve Galilean invariance

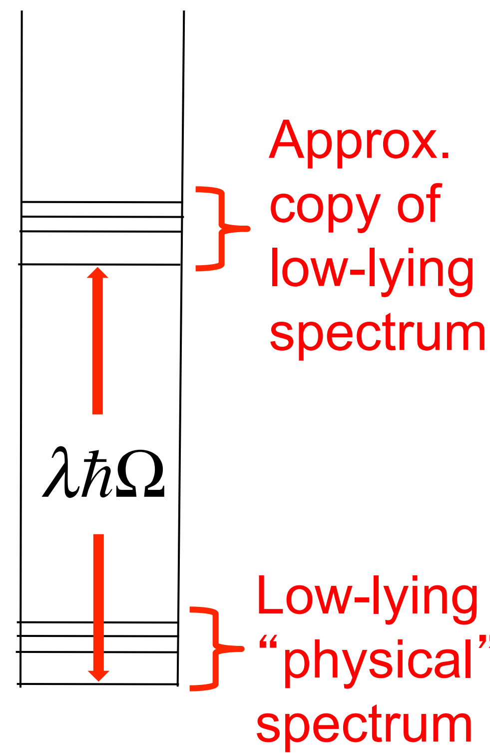
Add a Lagrange multiplier term acting on the cm alone so as not to interfere with the internal motion dynamics

$$H_{eff}(N_{\max},\hbar\Omega) \equiv P[T_{rel}+V^{a}(N_{\max},\hbar\Omega)]P$$

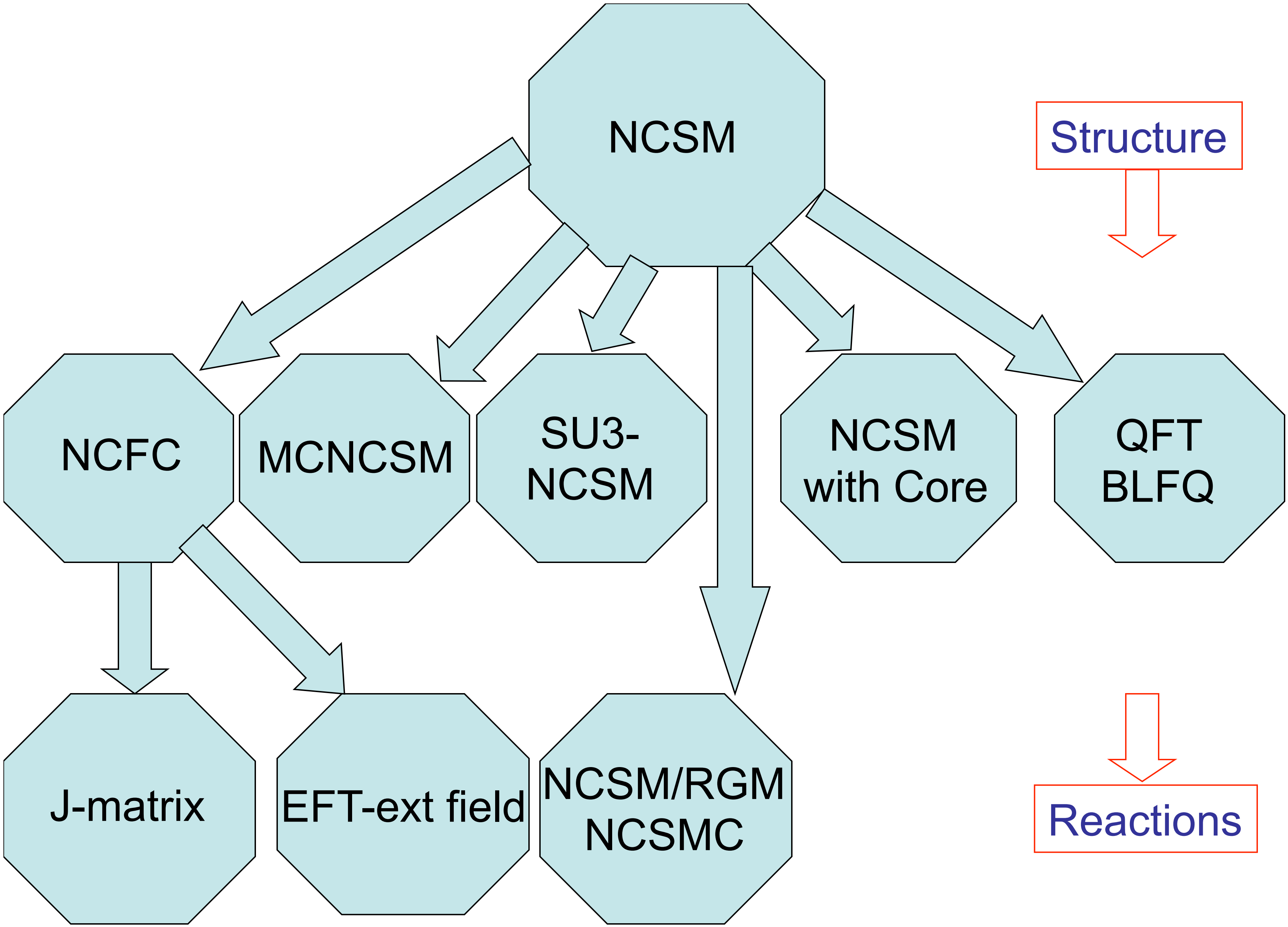
$$H = H_{eff}(N_{\max},\hbar\Omega)+\lambda H_{cm}$$

$$H_{cm}=\frac{P^2}{2M_A}+\frac{1}{2}M_A\Omega^2R^2$$

$$\lambda \sim 10 \quad \text{suffices}$$



Along with the N_{max} truncation in the HO basis, the Lagrange multiplier term guarantees that all low-lying solutions have eigenfunctions that factorize into a 0s HO wavefunction for the cm times a translationaly invariant wavefunction.


NCSM
Structure
NCFC
MCNCSM
SU3-
NCSM
NCSM
with Core
QFT
BLFQ
J-matrix
EFT-ext field
NCSM/RGM
NCSMC
Reactions

PRL 99, 042501 (2007) PHYSICAL REVIEW LETTERS week ending 27 JULY 2007

Structure of $A = 10$–13 Nuclei with Two- Plus Three-Nucleon Interactions from Chiral Effective Field Theory

P. Navrátil,[1] V. G. Gueorguiev,[1,*] J. P. Vary,[1,2] W. E. Ormand,[1] and A. Nogga[3]

Strong correlation between c_D and c_E for exp' l properties of A = 3 & 4

=> Retain this correlation in applications to other systems

Range favored by various analyses & values are "natural"

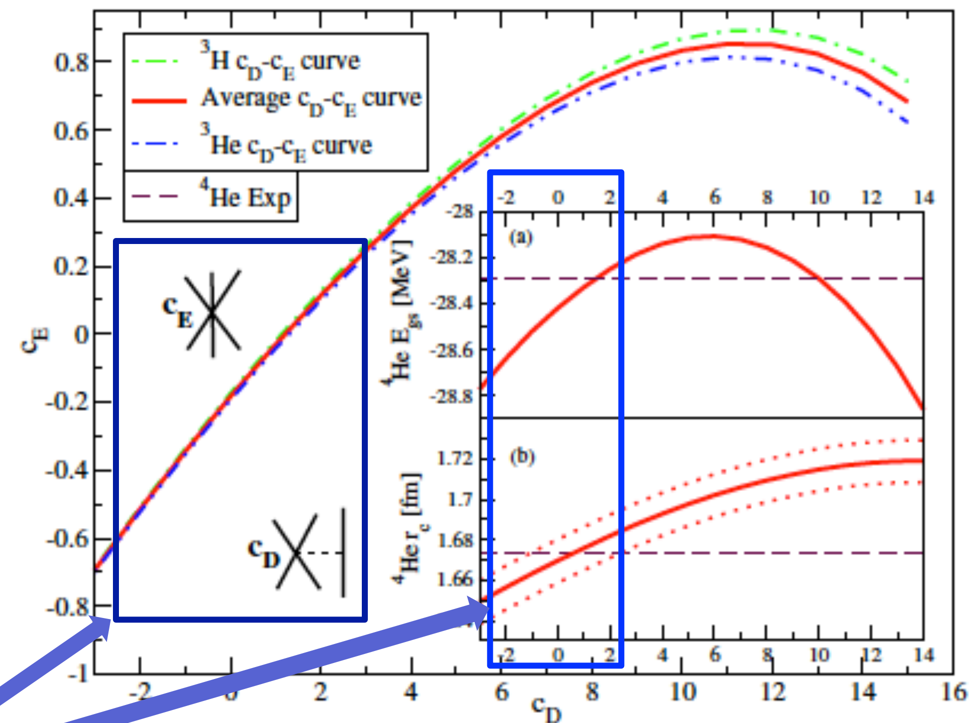
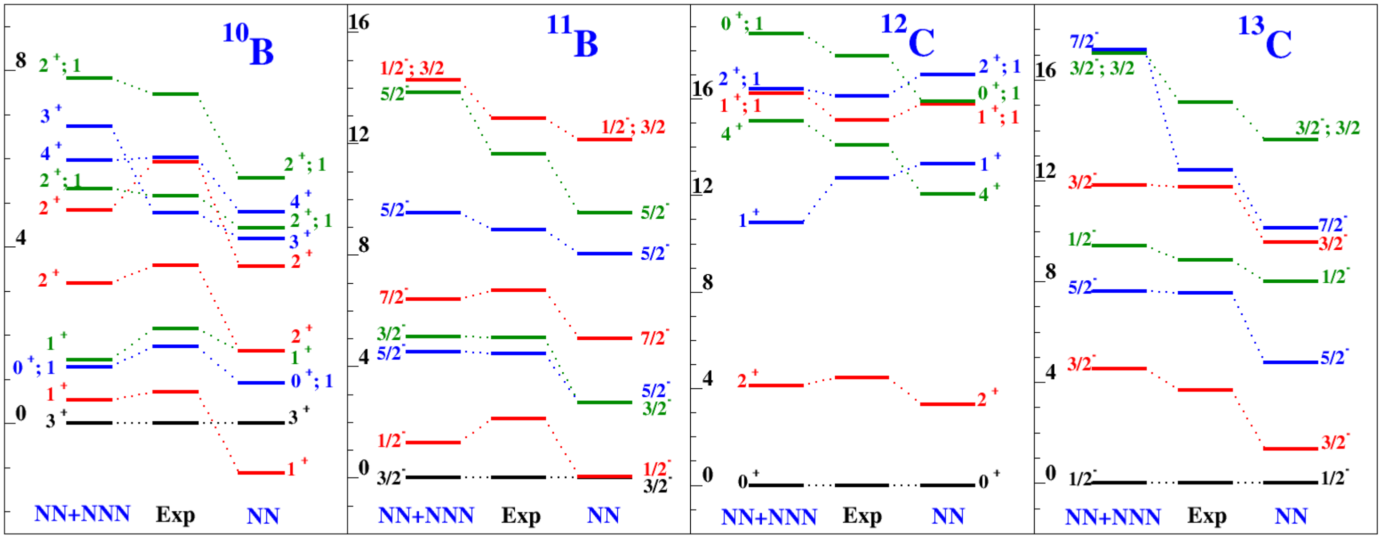


FIG. 1 (color online). Relations between c_D and c_E for which the binding energy of ^{3}H (8.482 MeV) and ^{3}He (7.718 MeV) are reproduced. (a) ^{4}He ground-state energy along the averaged curve. (b) ^{4}He charge radius r_c along the averaged curve. Dotted lines represent the r_c uncertainty due to the uncertainties in the proton charge radius.

ab initio NCSM with χ_{EFT} Interactions

- *Only method capable to apply the χ_{EFT} NN+NNN interactions to all p-shell nuclei*
- *Importance of NNN interactions for describing nuclear structure and transition rates*

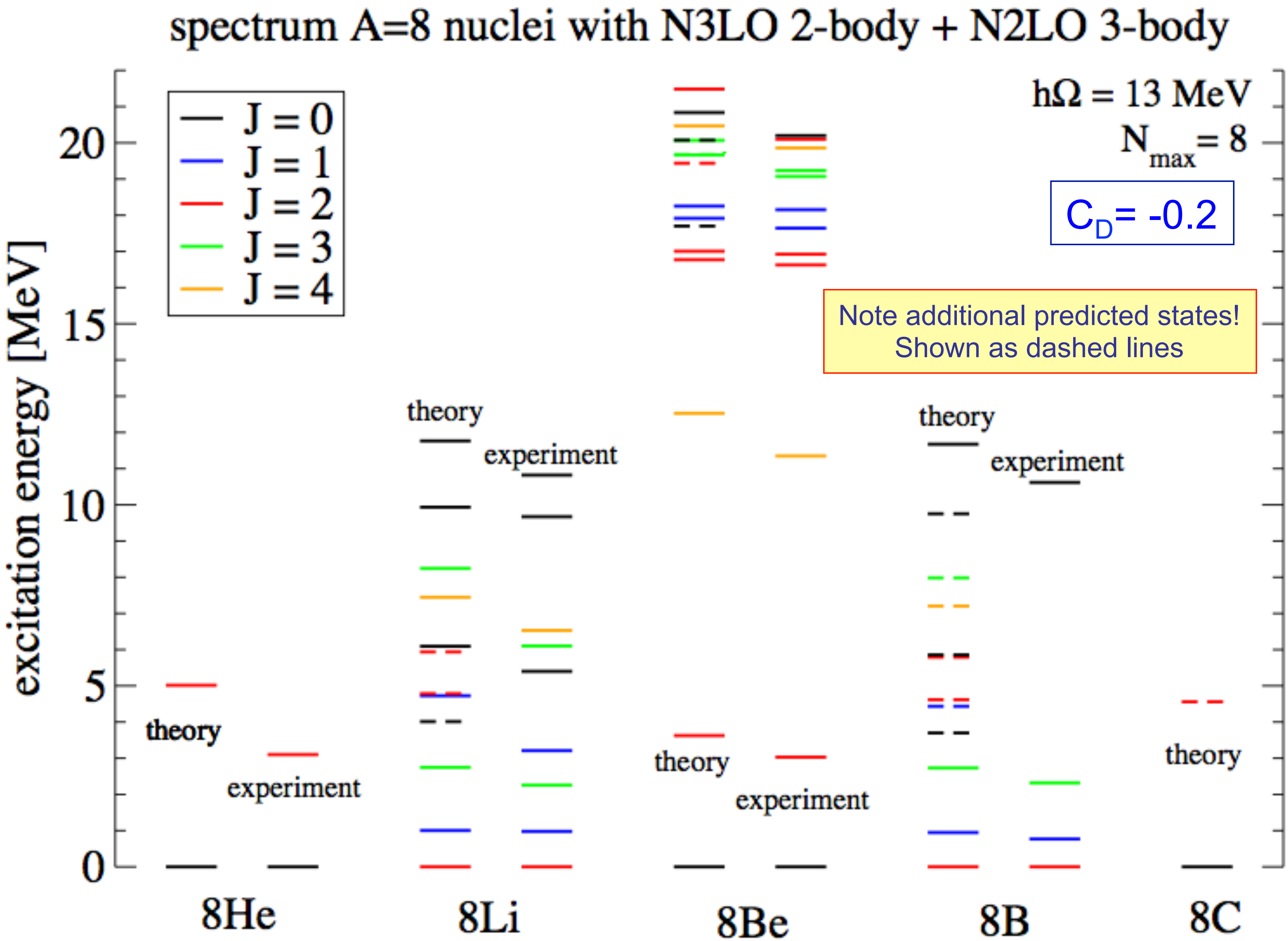


P. Navratil, V.G. Gueorguiev, J. P. Vary, W. E. Ormand and A. Nogga, PRL 99, 042501(2007); ArXiV: nucl-th 0701038.

$c_D = -1$

Extensions and work in progress

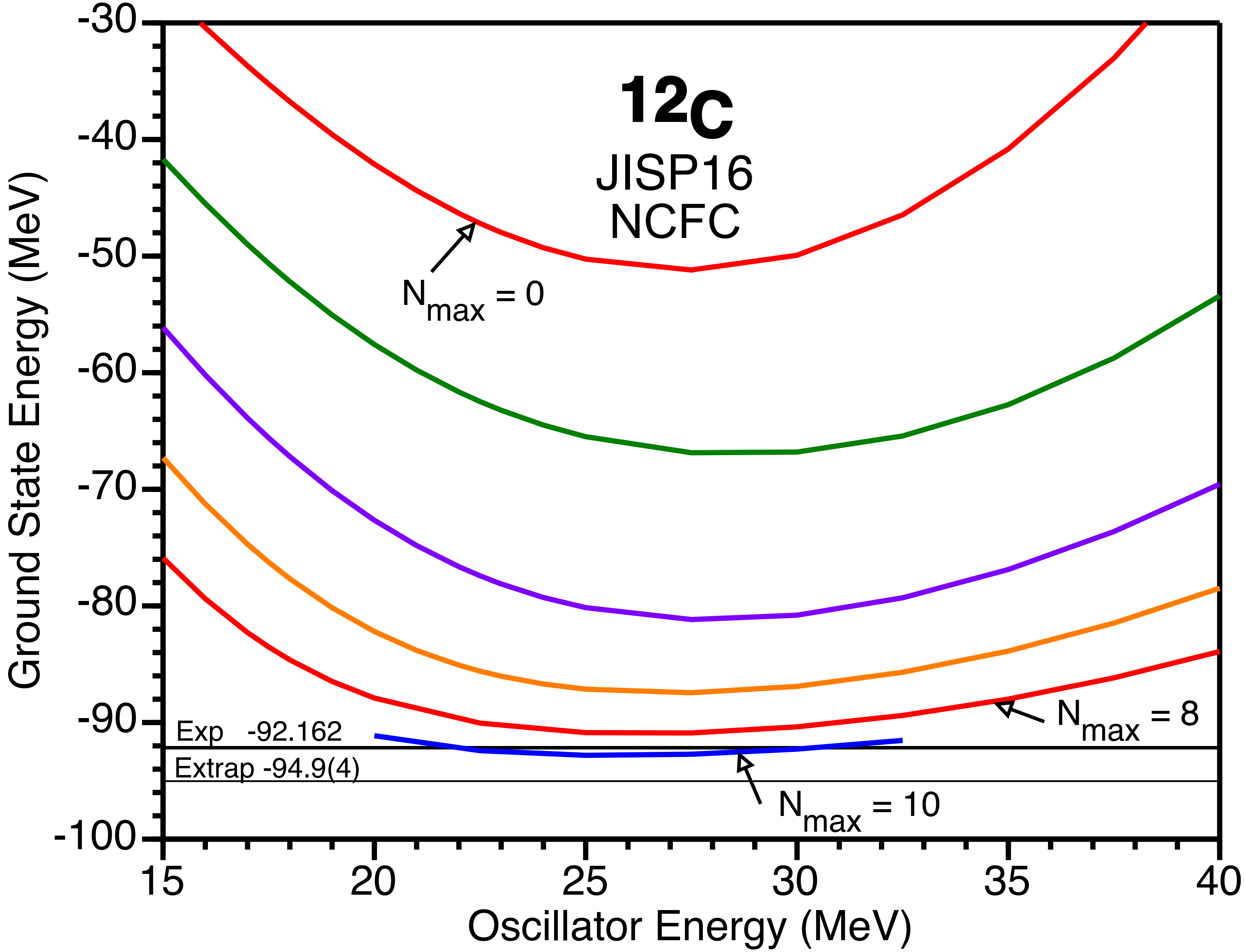
- *Better determination of the NNN force itself, feedback to χ_{EFT}* (LLNL, OSU, MSU, TRIUMF/GSI)
- *Implement Vlowk & SRG renormalizations (Bogner, Furnstahl, Maris, Perry, Schwenk & Vary, NPA 801, 21(2008); ArXiv 0708.3754)*
- *Response to external fields - bridges to DFT/DME/EDF (SciDAC/UNEDF)*
  - *- Axially symmetric quadratic external fields - in progress*
  - *- Triaxial and spin-dependent external fields - planning process*
- *Cold trapped atoms (Stetcu, Barrett, van Kolck & Vary, PRA 76, 063613(2007); ArXiv 0706.4123) and applications to other fields of physics (e.g. quantum field theory)*
- *Effective interactions with a core (Lisetsky, Barrett, Navratil, Stetcu, Vary)*
- *Nuclear reactions-scattering (Forssen, Navratil, Quaglioni, Shirokov, Mazur, Luu, Savage,Schwenk,Vary)*



P. Maris, P. Navratil, J. P. Vary, to be published

Assessing Convergence

- Independence of basis space parameters ($N_{\max}, \hbar\Omega$)
- Each observable must be investigated separately
- Standard approach for gs energy (next slide)
- Newest approach (Sid Coon's talk at this meeting)



12C
JISP16
NCFC
N_{max} = 0
N_{max} = 8
N_{max} = 10
Exp -92.162
Extrap -94.9(4)
Ground State Energy (MeV)
Oscillator Energy (MeV)
-30
-40
-50
-60
-70
-80
-90
-100
15
20
25
30
35
40

Convergence and Uncertainty Assessments: Recent Highlight

Convergence properties of *ab initio* calculations of light nuclei in a harmonic oscillator basis

arXiv:1205.3230

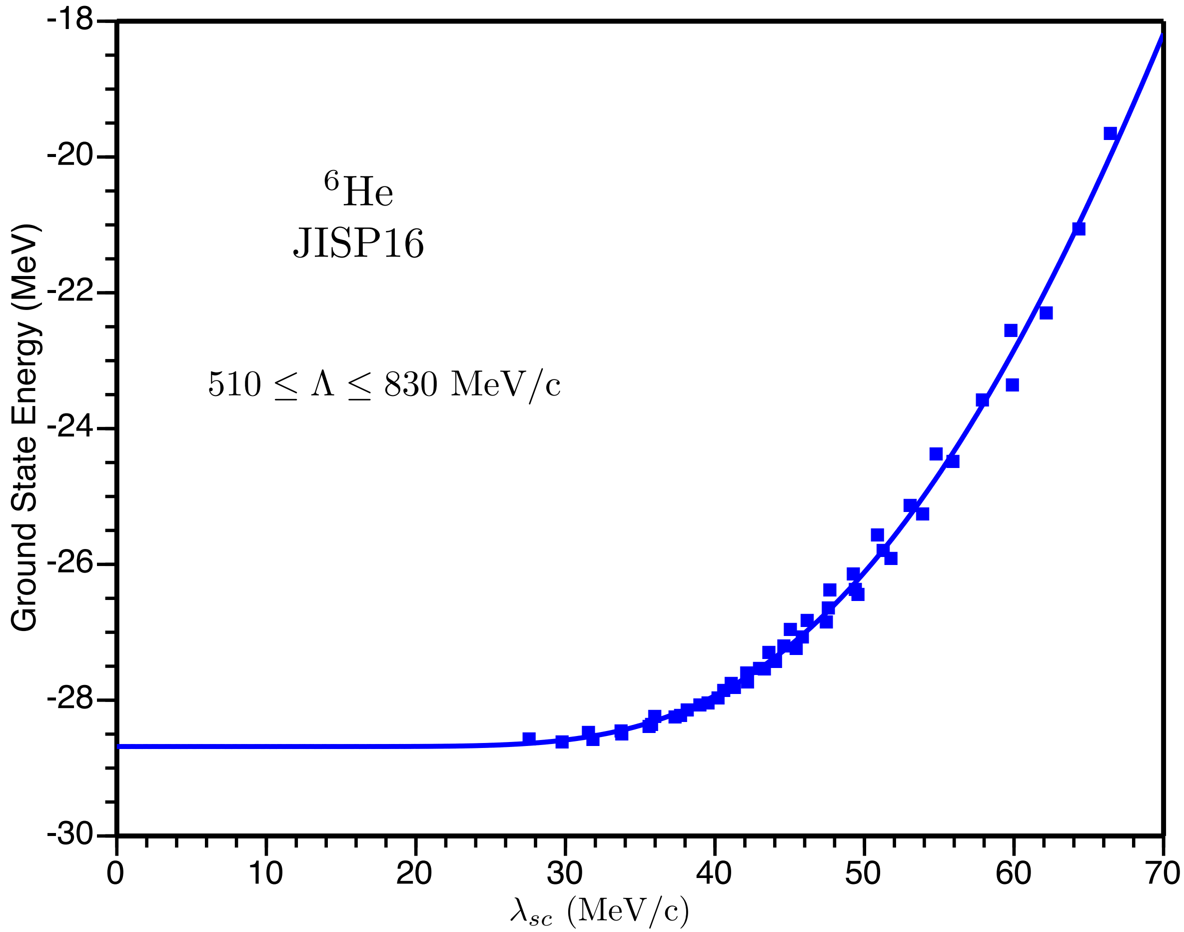
S. A. Coon[a], M. I. Avetian[a], M. K. G. Kruse[a], U. van Kolck[a,b], P. Maris[c], J. P. Vary[c]

UV regulator:

$$\Lambda = \sqrt{(N + 3/2) m\hbar\Omega}$$

IR regulator:

$$\lambda_{sc} = \sqrt{\frac{m\hbar\Omega}{(N + 3/2)}}$$

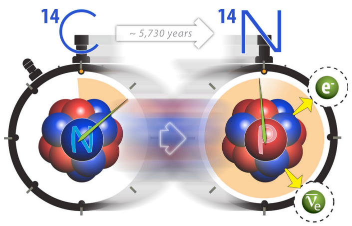


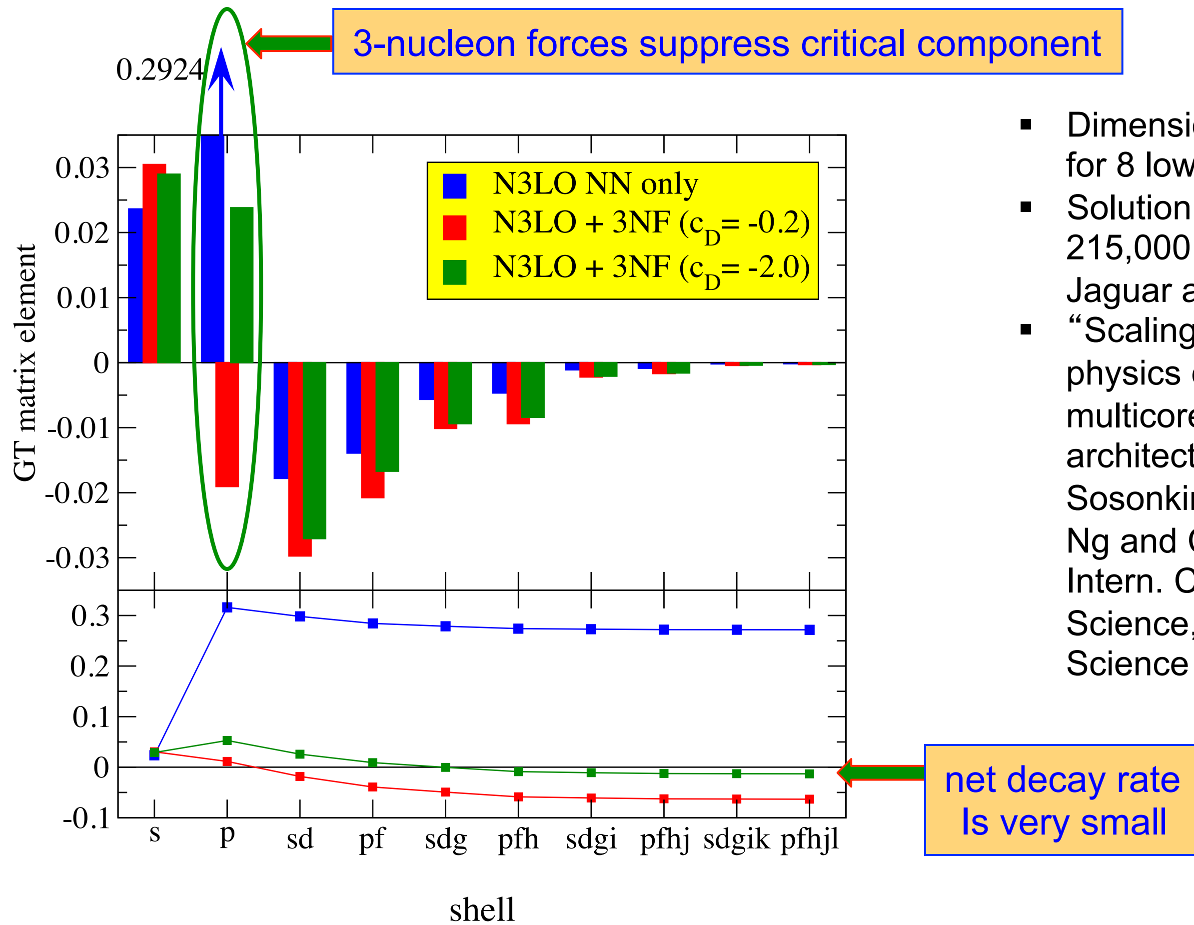
PRL 106, 202502 (2011) PHYSICAL REVIEW LETTERS week ending 20 MAY 2011

Origin of the Anomalous Long Lifetime of ^{14}C

P. Maris,[1] J.P. Vary,[1] P. Navrátil,[2,3] W.E. Ormand,[3,4] H. Nam,[5] and D. J. Dean[5]

- Solves the puzzle of the long but useful lifetime of ^{14}C
- Establishes a major role for strong 3-nucleon forces in nuclei
- Strengthens foundation for guiding DOE-supported experiments





- Dimension of matrix solved for 8 lowest states ~ 1x10^9
- Solution takes ~ 6 hours on 215,000 cores on Cray XT5 Jaguar at ORNL
- "Scaling of *ab initio* nuclear physics calculations on multicore computer architectures," P. Maris, M. Sosonkina, J. P. Vary, E. G. Ng and C. Yang, 2010 Intern. Conf. on Computer Science, Procedia Computer Science 1, 97 (2010)

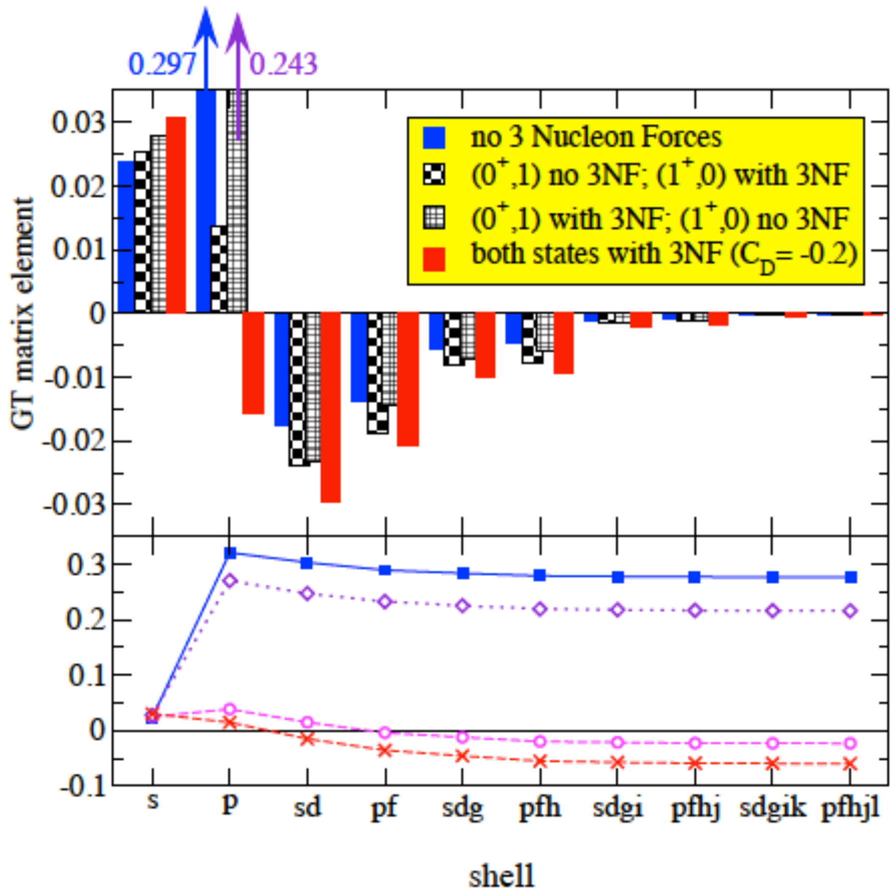


Figure 10. GT matrix element between the $(1^+, 0)$ ground state and the lowest $(0^+, 1)$ excited state of ^{14}N, using the $(1^+, 0)$ wavefunction obtained with three-body forces, but the $(0^+, 1)$ wavefunction obtained without three-body forces, and vice versa. For comparison, we also include the results with and without three-body forces for both wavefunctions.

Innovations underway to improve the NCSM with aims:
(1) improve treatment of clusters and intruders
(2) enable *ab initio* solutions of heavier nuclei
Initially, all follow the NCFC approach = extrapolations

SU(3) No Core Shell Model
Add symmetry-adapted many-body basis states
Preserve exactly the CM factorization
Talk by Thomas Dytrych at this meeting

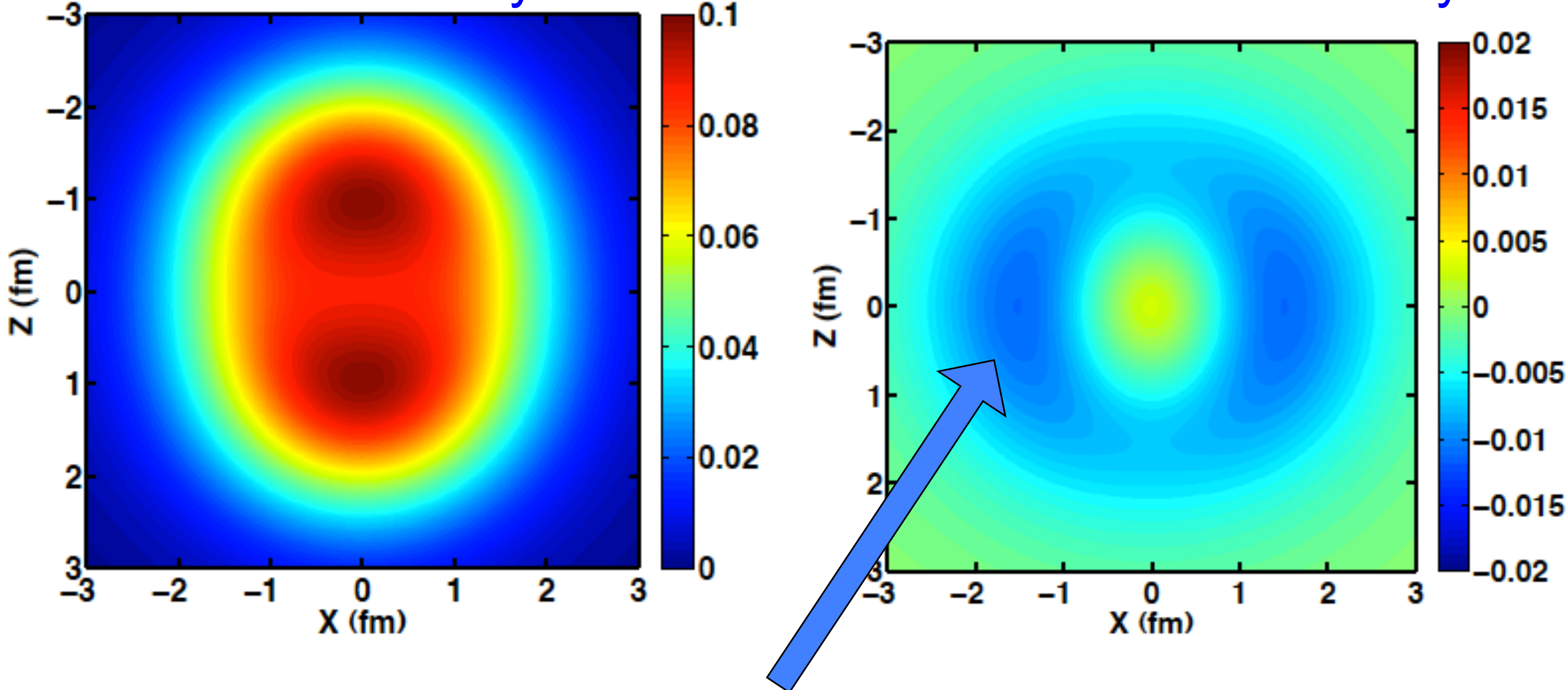
No Core Monte Carlo Shell Model
Invokes single particle basis (FCI) truncation
Separate spurious CM motion in same way as CC approach
Scales well to larger nuclei
Talks by Yutaka Utsuno and Takashe Abe at this meeting

Importance Truncated – NCSM
Extrapolate full basis at each Nmax using a sequence with improving tolerance
Robert Roth and collaborators

"Realistic" single-particle basis - Woods-Saxon example
Control the spurious CM motion with Lagrange multiplier term
A.Negoita, ISU PhD thesis
Alternative sp basis spaces – Mark Caprio collaboration

9Be Translationally invariant gs density
Full 3D densities = rotate around the vertical axis

Total density | Neutron – Proton density



Shows that one neutron provides a "ring" cloud around two alpha clusters binding them together

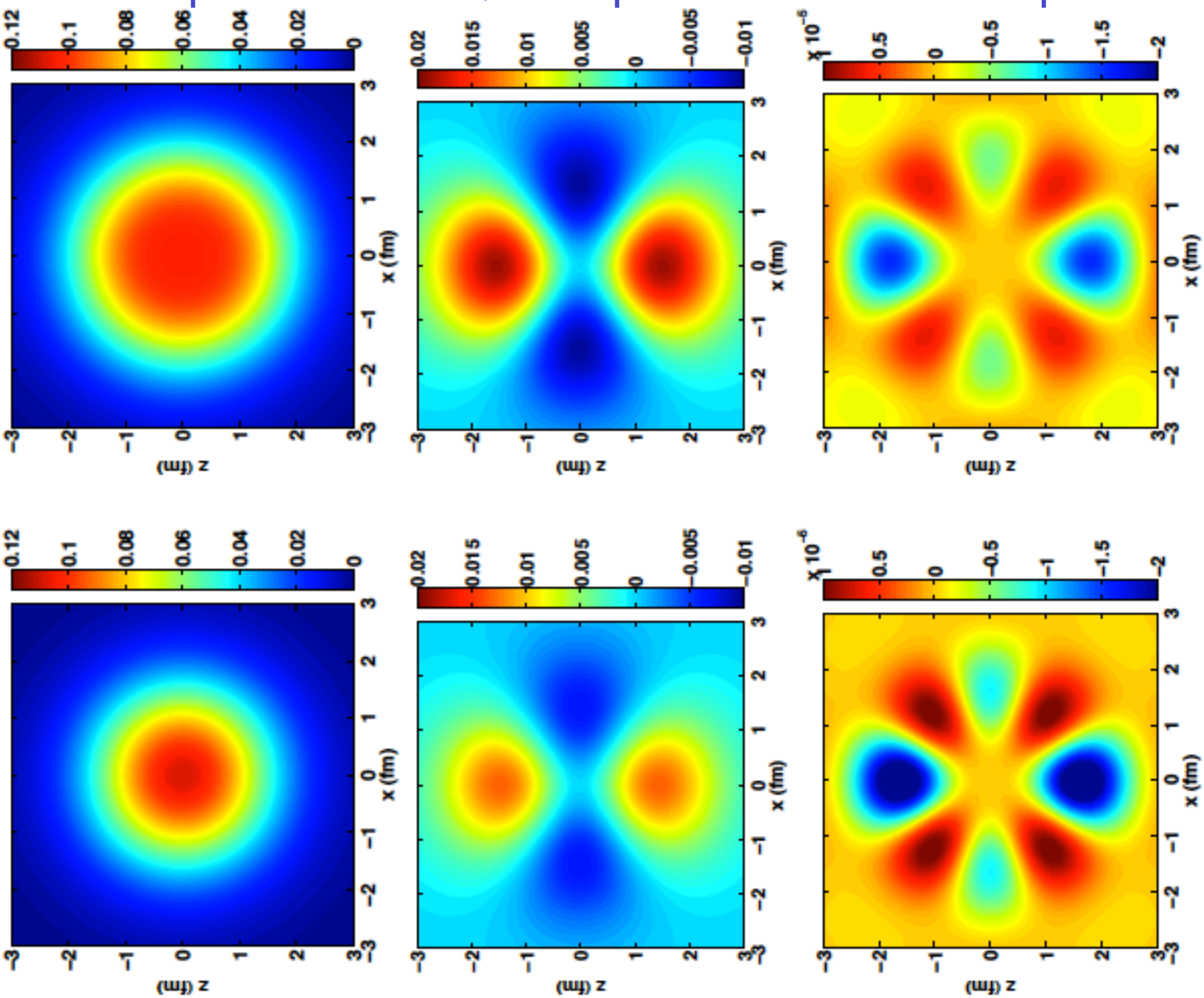
C. Cockrell, J.P. Vary, P. Maris, ArXiv 1201.0724; C. Cockrell, PhD, Iowa State University

^{8}Li gs
J=2

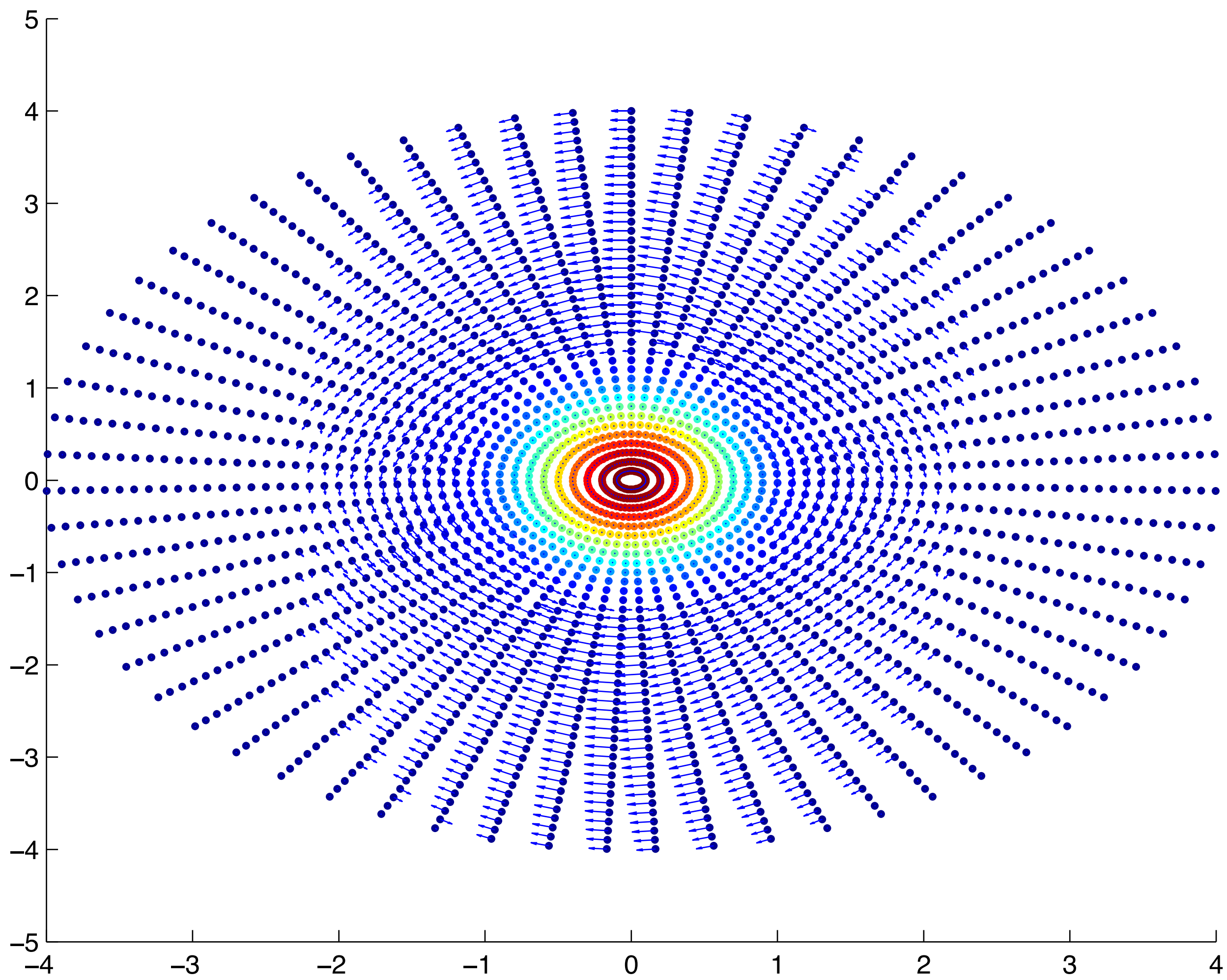
Monopole | Quadrupole | Hexadecapole

Neutrons

Protons



Wigner Distribution in 6LI – Demonstration/Preliminary



C. Cockrell, PhD Thesis, Iowa State 2012

Descriptive Science

Predictive Science

"Proton-Dripping Fluorine-14"

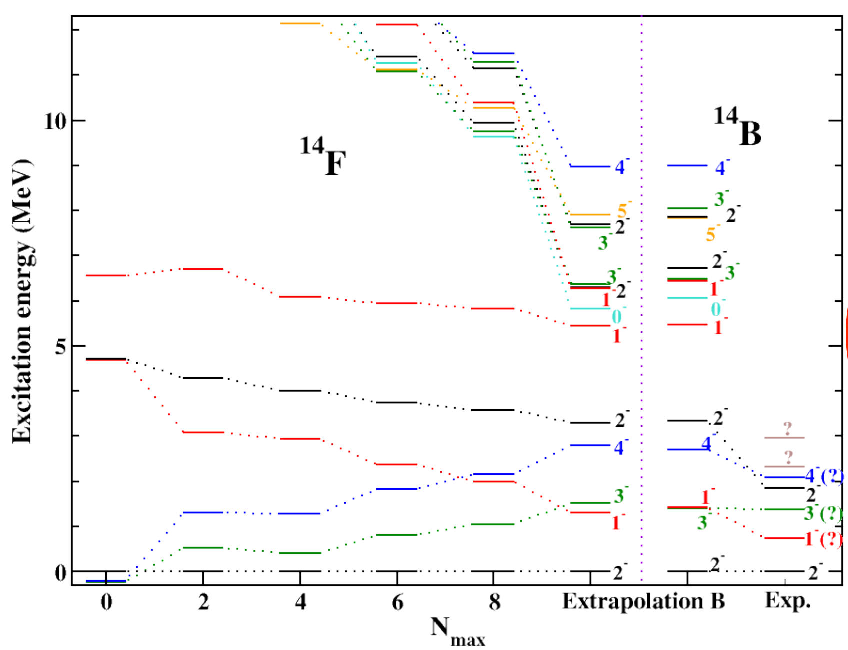
Objectives

- Apply *ab initio* microscopic nuclear theory's predictive power to major test case

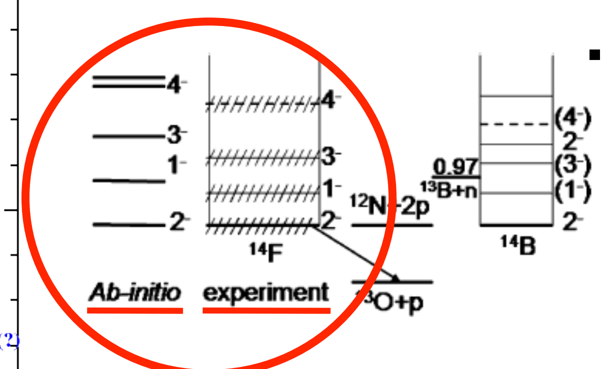
Impact

- Deliver robust predictions important for improved energy sources
- Provide important guidance for DOE-supported experiments
- Compare with new experiment to improve theory of strong interactions

P. Maris, A. Shirokov and J.P. Vary, Phys. Rev. C 81 (2010) 021301(R)



Experiment confirms our published predictions!



V.Z. Goldberg et al., Phys. Lett. B 692, 307 (2010)

- Dimension of matrix solved for 14 lowest states ~ $2x10^9$
- Solution takes ~ 2.5 hours on 30,000 cores (Cray XT4 Jaguar at ORNL)
- "Scaling of ab-initio nuclear physics calculations on multicore computer architectures," P. Maris, M. Sosonkina, J. P. Vary, E. G. Ng and C. Yang, 2010 Intern. Conf. on Computer Science, Procedia Computer Science 1, 97 (2010)

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UNEDF SciDAC Collaboration Universal Nuclear Energy Density Functional

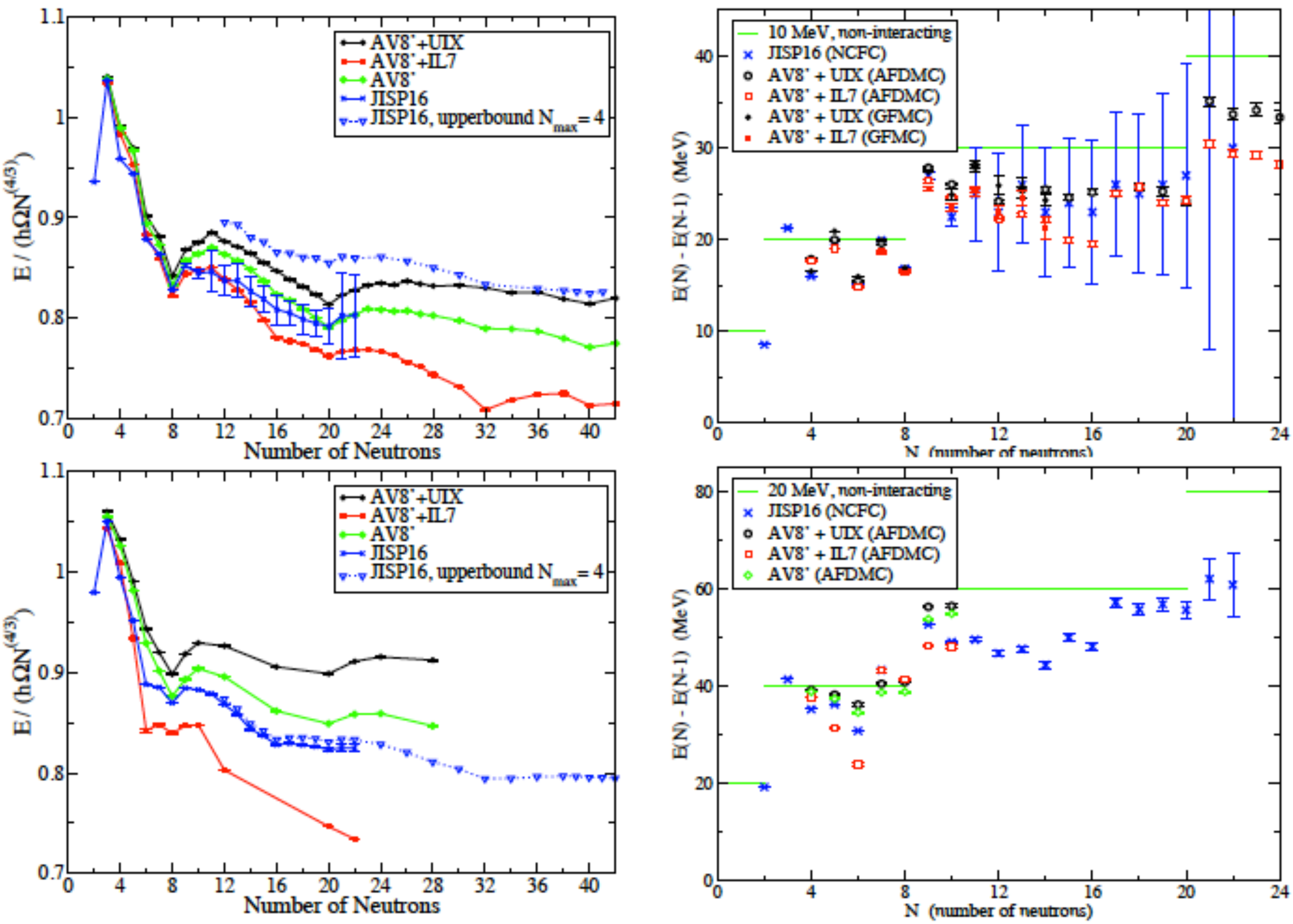
Properties of trapped neutrons interacting with realistic nuclear Hamiltonians

J. Carlson and S. Gandolfi
Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545

Pieter Maris and James Vary
Iowa State University, Ames, Iowa, 50011

Steven C. Pieper
Physics Division, Argonne National Laboratory, Argonne, IL 61801
(Dated: April 20, 2011)

Preliminary



NCSM/RGM

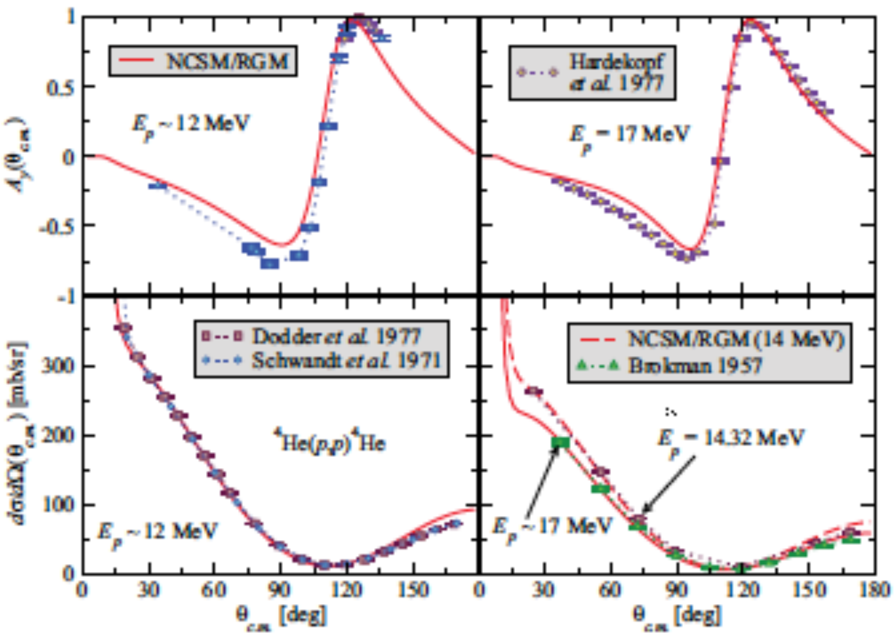


Figure 7. *Calculated p-^{4}He differential cross section (bottom panels) and analyzing power (top panels) for proton laboratory energies Ep = 12, 14.32 and 17 MeV compared to experimental data from Refs. [29, 30, 31, 32]. The SRG-N^{3}LO NN potential with $\lambda = 2.02$ fm^{-1} was used.*

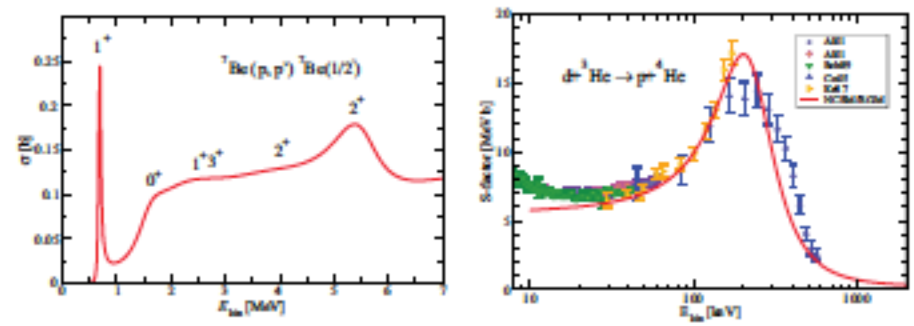
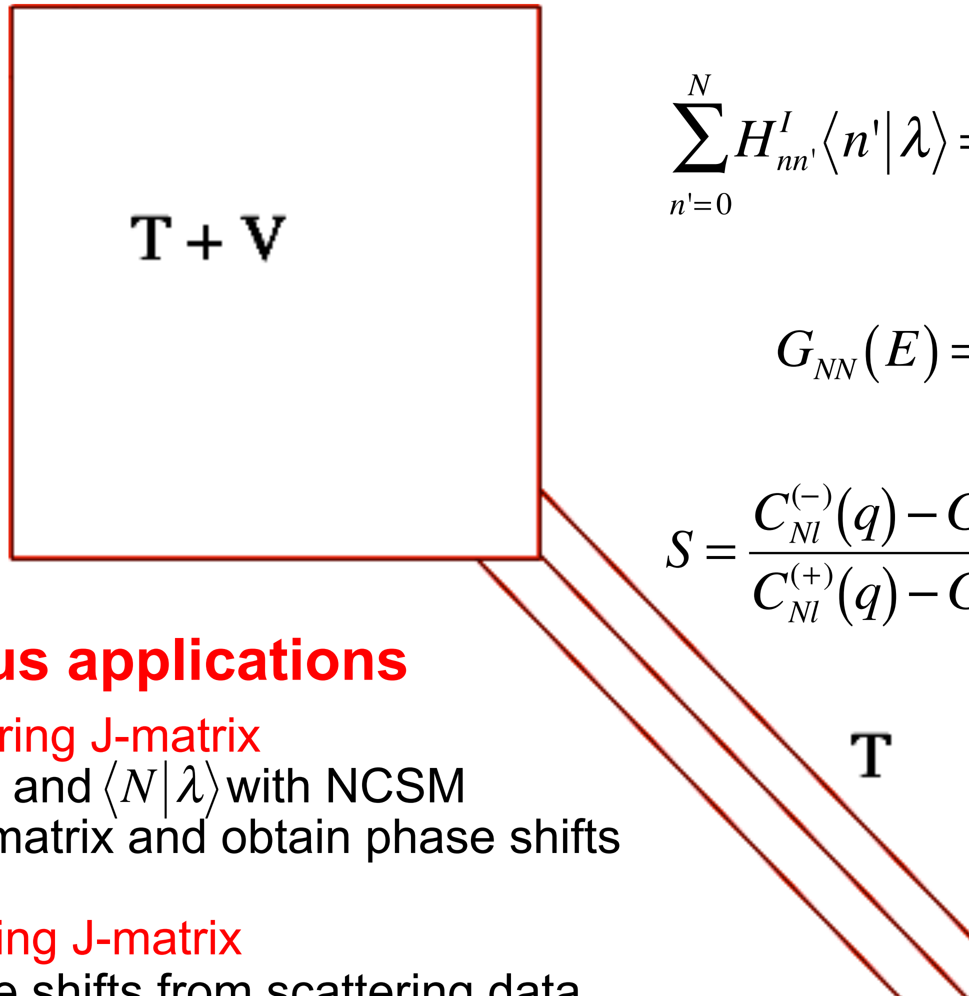


Figure 8. *Calculated inelastic ^{7}Be(p,p′)^{7}Be(1/2$^-$) cross section with indicated positions of the P-wave resonances (left figure). Calculated S-factor of the ^{3}He(d,p)^{4}He fusion reaction compared to experimental data (right figure). Energies are in the center of mass. The SRG-N^{3}LO NN potential with λ = 1.85 fm^{-1} (λ = 1.5 fm^{-1}) was used, respectively.*

P. Navrátil, R. Roth, and S. Quaglioni, *Phys. Rev. C 82 (2010)* 034609

J-matrix formalism:

scattering in the oscillator basis



$$\sum_{n'=0}^{N} H^{I}_{nn'} \langle n' | \lambda \rangle = E_{\lambda} \langle n | \lambda \rangle, \qquad n \le N$$

$$G_{NN}(E) = -\sum_{\lambda=0}^{N} \frac{\langle N | \lambda \rangle^2}{E_{\lambda} - E}$$

$$S = \frac{C^{(-)}_{Nl}(q) - G_{NN}(E) T^{I}_{N,N+1} C^{(-)}_{N+1,l}(q)}{C^{(+)}_{Nl}(q) - G_{NN}(E) T^{I}_{N,N+1} C^{(+)}_{N+1,l}(q)}$$

n(p)+nucleus applications

<u>Forward</u> scattering J-matrix

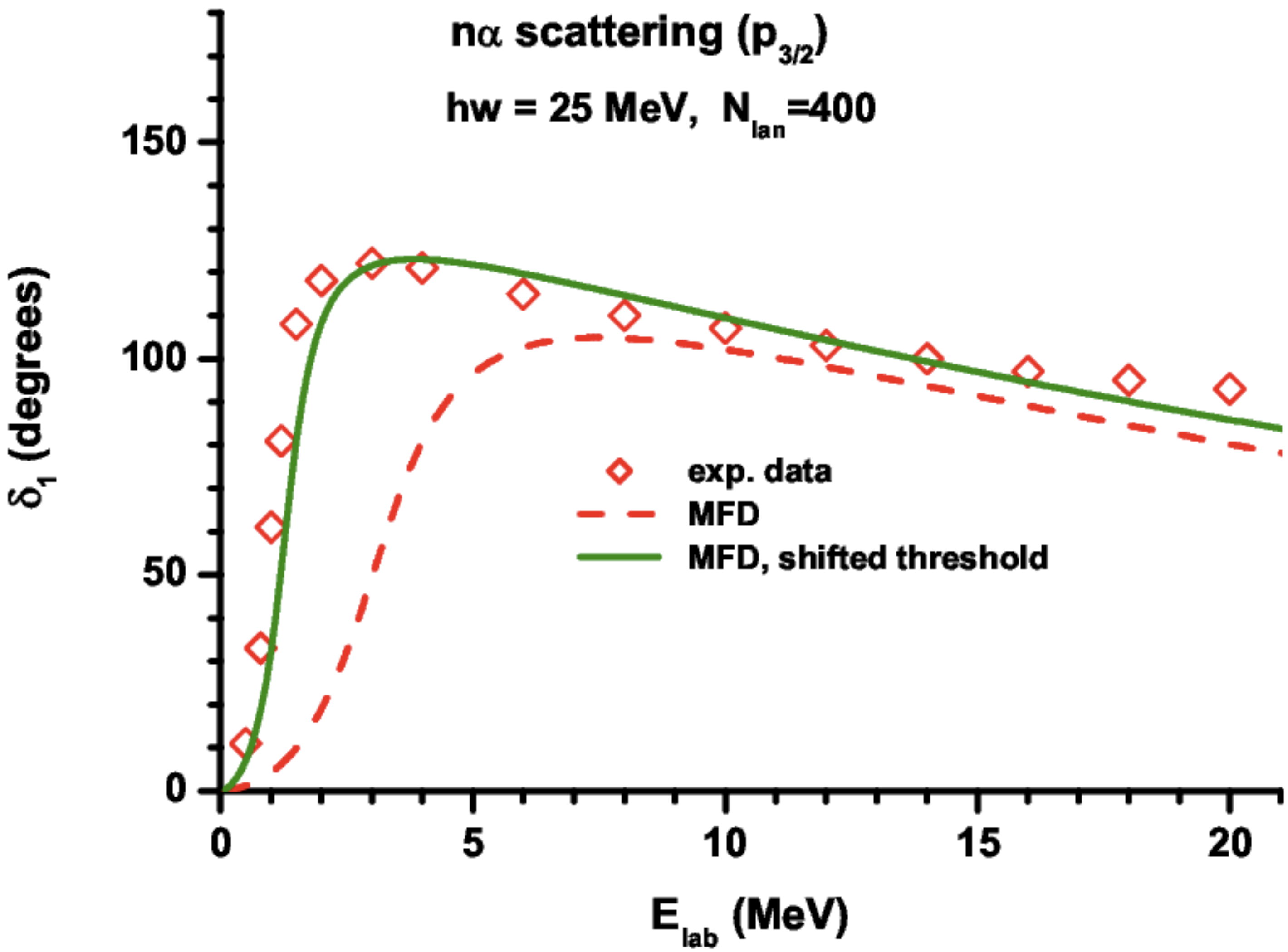
1. Calculate E_{λ} and $\langle N | \lambda \rangle$ with NCSM
2. Solve for S-matrix and obtain phase shifts

<u>Inverse</u> scattering J-matrix

1. Obtain phase shifts from scattering data
2. Solve for n(p)+nucleus potential, resonance params

A.M. Shirokov, A.I. Mazur, J.P. Vary, and E.A. Mazur, Phys. Rev. C. 79, 014610 (2009), arXiv:0806.4018; and references therein

*n*α scattering

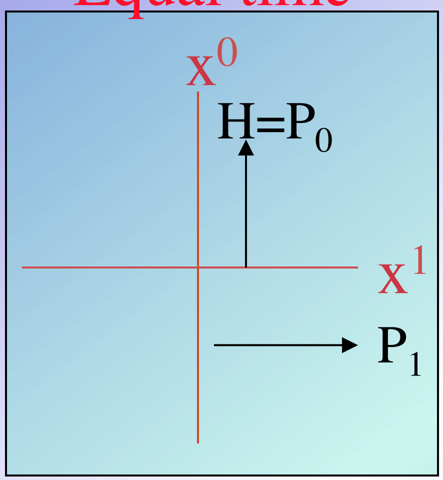


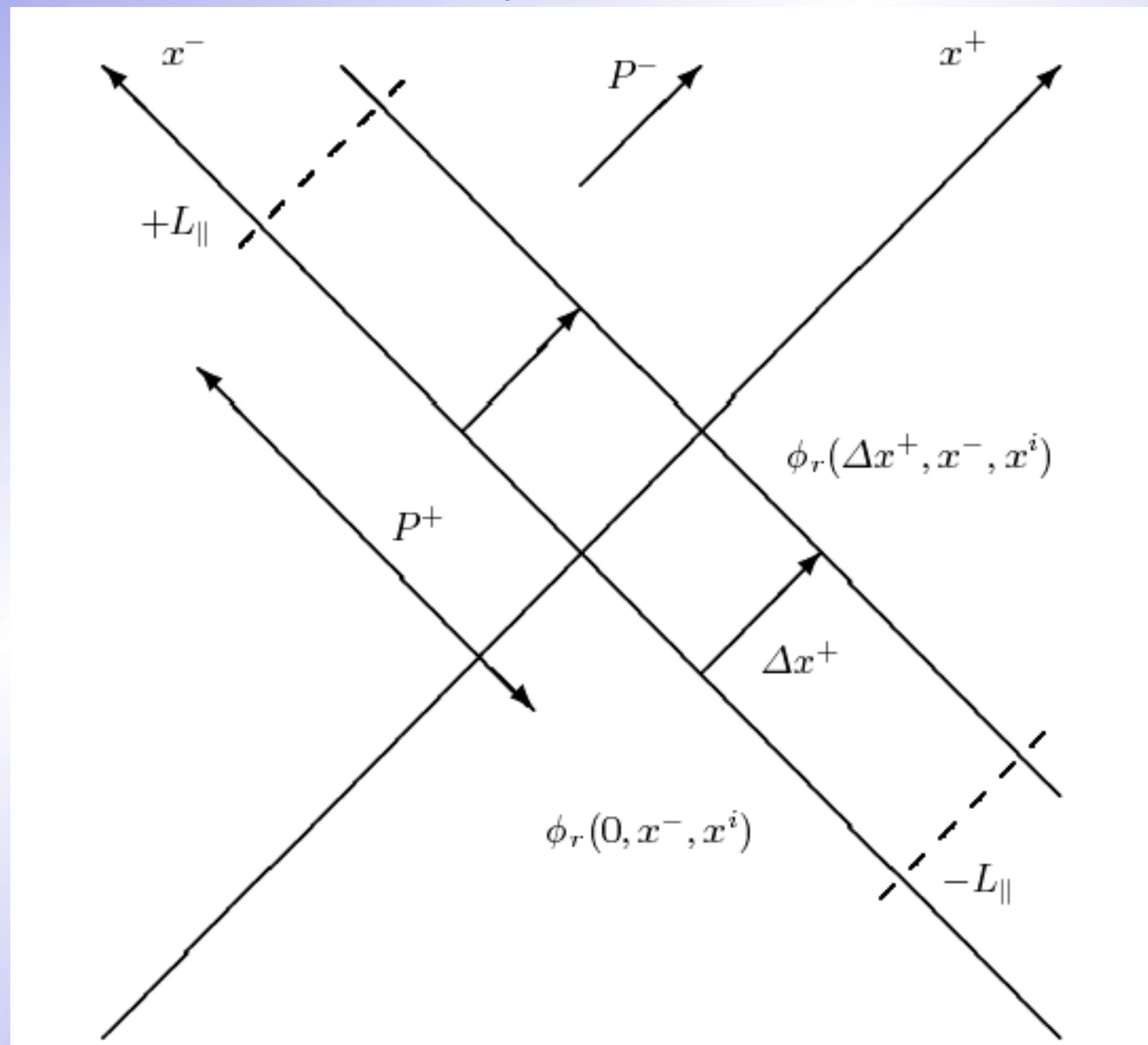
A. M. Shirokov, A. I. Mazur, J. P. Vary and E. A. Mazur, Phys. Rev. C. 79, 014610 (2009), arXiv 0806.4018

Light cone coordinates and generators

$$M^2 = P^0 P_0 - P^1 P_1 = (P^0 - P^1)(P_0 + P_1) = P^+ P^- = KE$$

Equal time





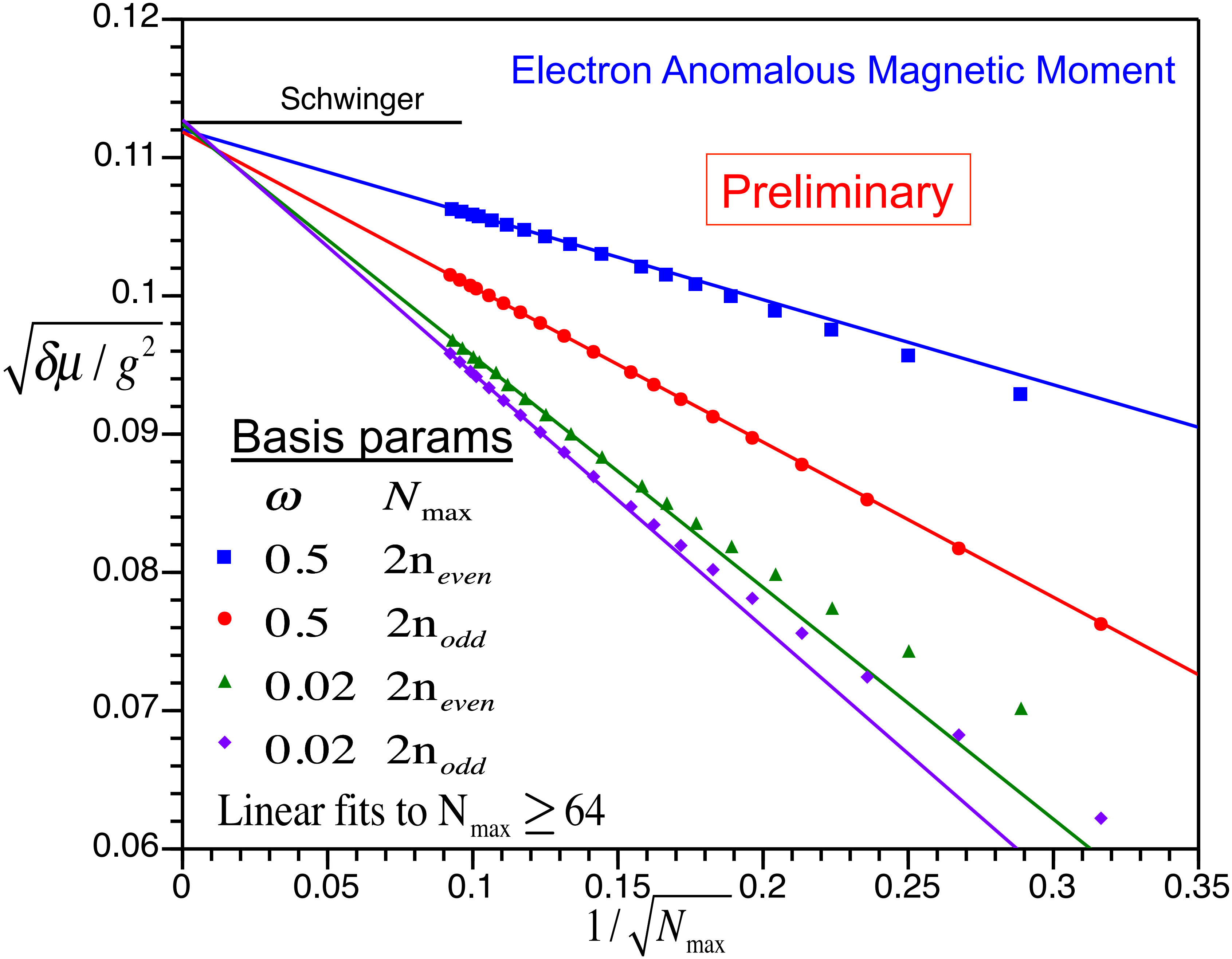
Applications to Relativistic Quantum Field Theory
QED (new) and QCD (under development)

J. P. Vary, H. Honkanen, Jun Li, P. Maris, S. J. Brodsky, A. Harindranath,
G. F. de Teramond, P. Sternberg, E. G. Ng and C. Yang,
"Hamiltonian light-front field theory in a basis function approach",
Phys. Rev. C 81, 035205 (2010); arXiv nucl-th 0905.1411

H. Honkanen, P. Maris, J. P. Vary and S. J. Brodsky,
"Electron in a transverse harmonic cavity",
Phys. Rev. Lett. 106, 061603 (2011); arXiv: 1008.0068

Basis Light Front Quantization (BLFQ) in brief

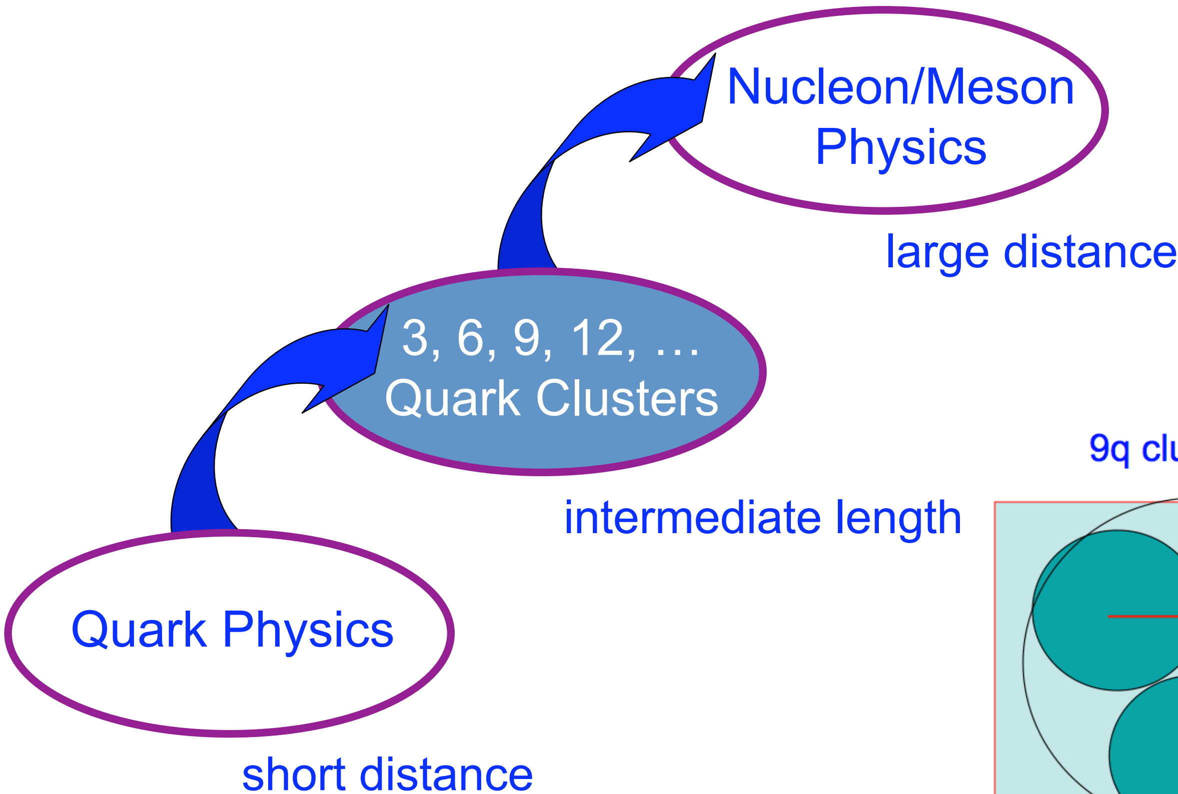
Derive LF Hamiltonian density from Lagrangian density
Invoke canonical quantization
Evaluate H (kinetic term + vertices) in transverse 2D HO basis
with longitudinal plane waves
Setup associated multi-parton Fock space basis
Diagonalize -> invariant mass spectra and LF amplitudes
Evaluate suite of observables and compare with experiment



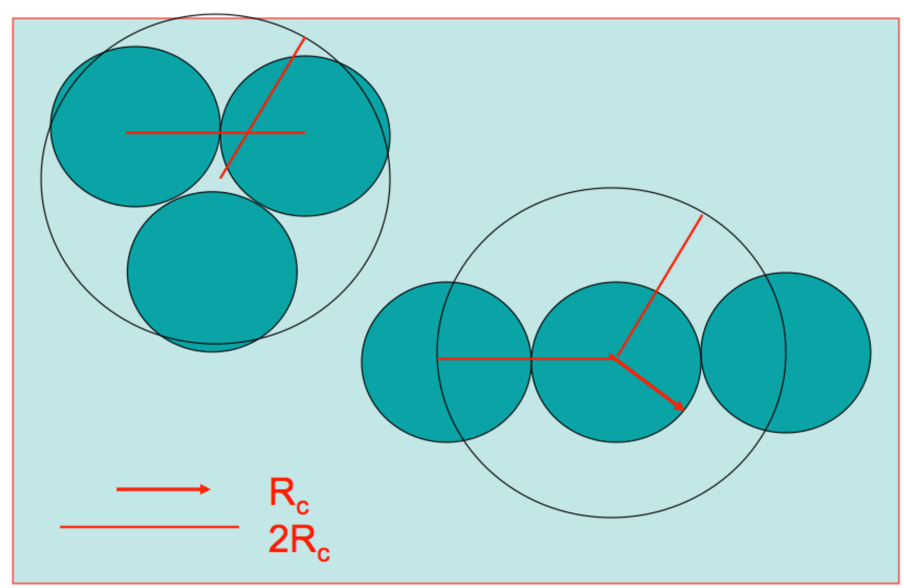
X. Zhao, H. Honkanen, P. Maris, J.P. Vary, S.J. Brodsky, in preparation

Under what conditions do we require a quark-based description on nuclear structure?

"Quark Percolation in Cold and Hot Nuclei"



9q cluster at geometrical limits of formation



H.J. Pirner and J.P. Vary,
Phys. Rev. C. **84**, 015201(2011);
arXiv: nucl-th/1008.4962

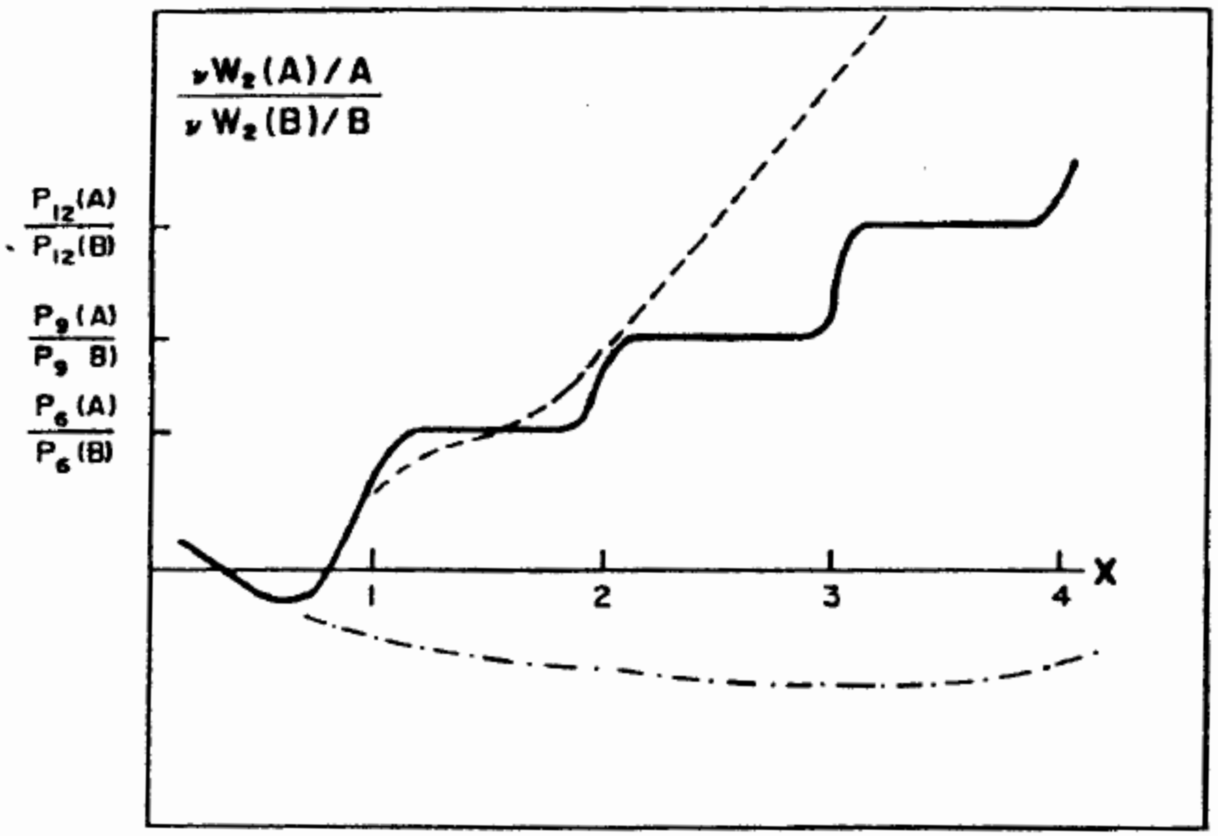


Fig. 2. Characteristic behaviour of the ratio of nuclear structure functions per nucleon for different models over a wide kinematic range of x. The QCM gives the solid curve. The dashed curve is due to the model of reference 22. The dashed-dot curve approximates the predictions of references 23 and 24.

J.P. Vary, Proc. VII Int'l Seminar on High Energy Physics Problems, "Quark Cluster Model of Nuclei and Lepton Scattering Results," Multiquark Interactions and Quantum Chromodynamics, V.V. Burov, Ed., Dubna #D-1, 2-84-599 (1984) 186 [staircase function for x > 1]

See also: Proceedings of HUGS at CEBAF1992, & many conf. proceedings

New Measurements of High-Momentum Nucleons and Short-Range Structures in Nuclei

N. Fomin,[1,2,3] J. Arrington,[4] R. Asaturyan,[5,*] F. Benmokhtar,[6] W. Boeglin,[7] P. Bosted,[8] A. Bruell,[8] M. H. S. Bukhari,[9] M. E. Christy,[8] E. Chudakov,[8] B. Clasie,[10] S. H. Connell,[11] M. M. Dalton,[3] A. Daniel,[9] D. B. Day,[3] D. Dutta,[12,13] R. Ent,[8] L. El Fassi,[4] H. Fenker,[8] B. W. Filippone,[14] K. Garrow,[15] D. Gaskell,[8] C. Hill,[3] R. J. Holt,[4] T. Horn,[6,8,16] M. K. Jones,[8] J. Jourdan,[17] N. Kalantarians,[9] C. E. Keppel,[8,18] D. Kiselev,[17] M. Kotulla,[17] R. Lindgren,[3] A. F. Lung,[8] S. Malace,[18] P. Markowitz,[7] P. McKee,[3] D. G. Meekins,[8] H. Mkrtchyan,[5] T. Navasardyan,[5] G. Niculescu,[19] A. K. Opper,[20] C. Perdrisat,[21] D. H. Potterveld,[4] V. Punjabi,[22] X. Qian,[13] P. E. Reimer,[4] J. Roche,[20,8] V. M. Rodriguez,[9] O. Rondon,[3] E. Schulte,[4] J. Seely,[10] E. Segbefia,[18] K. Slifer,[3] G. R. Smith,[8] P. Solvignon,[8] V. Tadevosyan,[5] S. Tajima,[3] L. Tang,[8,18] G. Testa,[17] R. Trojer,[17] V. Tvaskis,[18] W. F. Vulcan,[8] C. Wasko,[3] F. R. Wesselmann,[22] S. A. Wood,[8] J. Wright,[3] and X. Zheng[3,4]

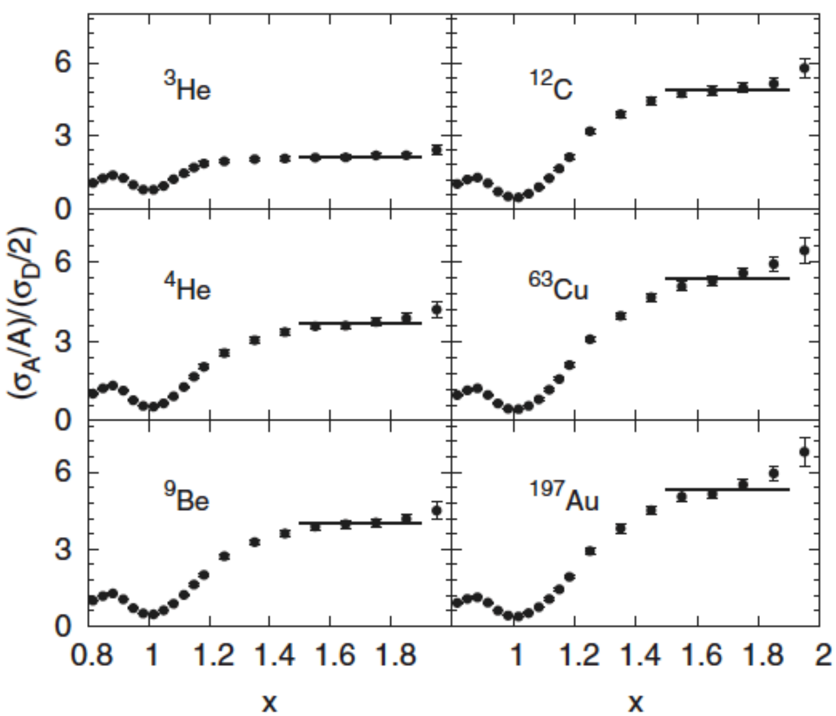


FIG. 2. Pernucleon cross section ratios vs x at $\theta_e = 18°$.

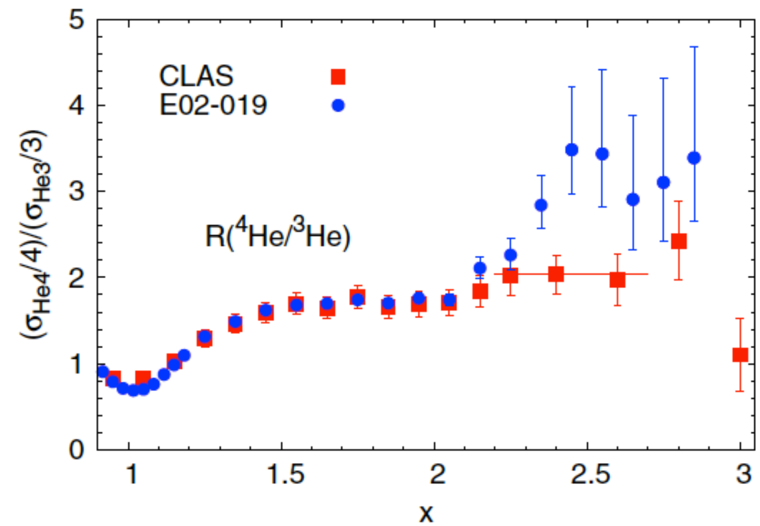
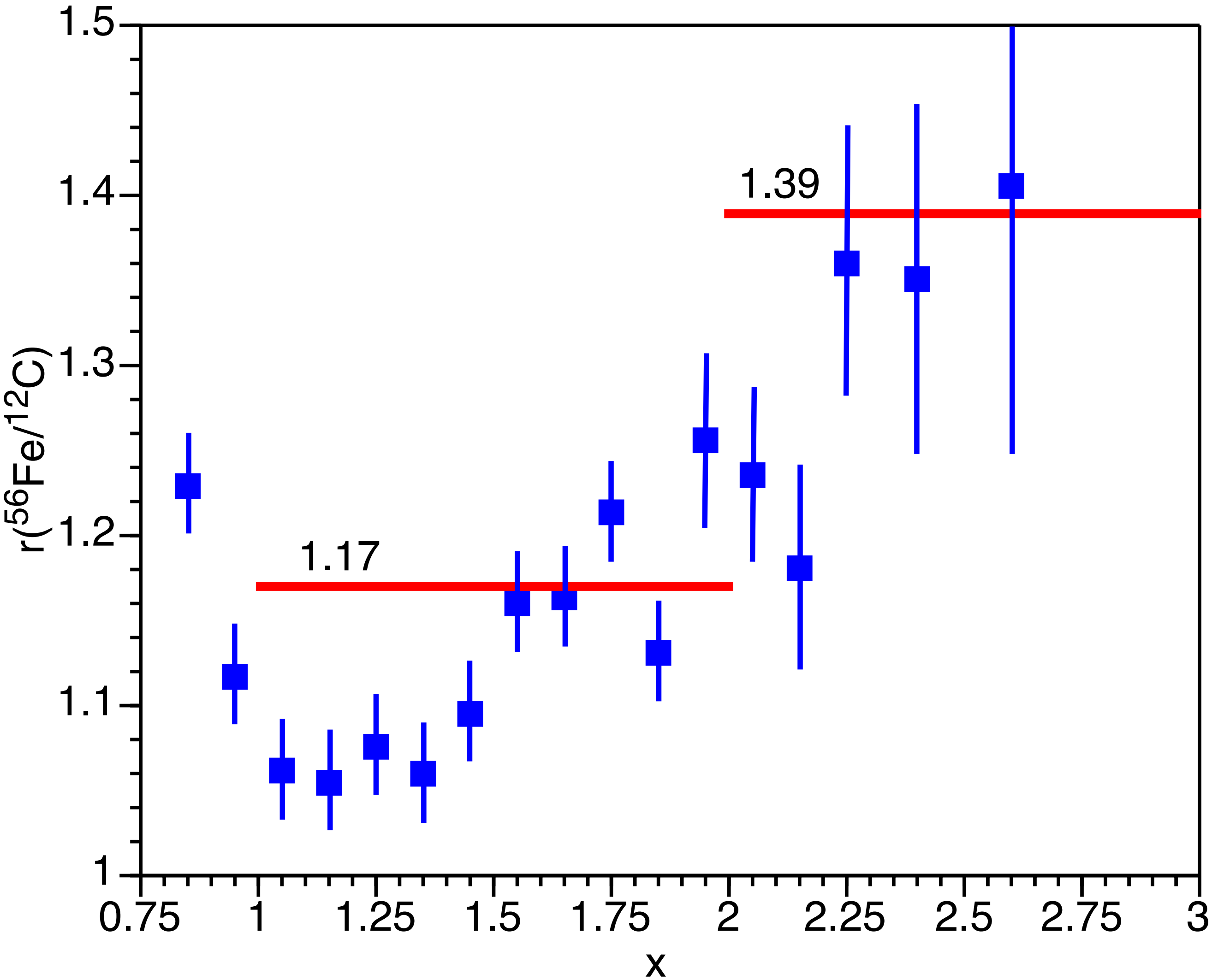


FIG. 3 (color online). The ^{4}He/^{3}He ratios from E02-019 ($Q^2 \approx 2.9$ GeV^2) and CLAS ($\langle Q^2 \rangle \approx 1.6$ GeV^2); errors are combined statistical and systematic uncertainties. For $x > 2.2$, the uncertainties in the ^{3}He cross section are large enough that a one-sigma variation of these results yields an asymmetric error band in the ratio. The error bars shown for this region represent the central 68% confidence level region.

Comparison between Quark-Cluster Model and JLAB data



Data: K.S. Egiyan, et al., Phys. Rev. Lett. **96**, 082501 (2006)

Theory: H.J. Pirner and J.P. Vary, Phys. Rev. Lett. **46**, 1376 (1981)
and Phys. Rev. C **84**, 015201 (2011); nucl-th/1008.4962;
M. Sato, S.A. Coon, H.J. Pirner and J.P. Vary, Phys. Rev. C **33**, 1062 (1986)

Recent accomplishments of the *ab initio* no core shell model (NCSM) and no core full configuration (NCFC)

- Described the anomaly of the nearly vanishing quadrupole moment of ^{6}Li
- Established need for NNN potentials to explain neutrino -^{12}C cross sections
- Explained quenching of Gamow-Teller transitions (beta-decays) in light nuclei
- Obtained successful description of A=10-13 nuclei with chiral NN+NNN potentials
- Explained ground state spin of ^{10}B by including chiral NNN potentials
- Successful prediction of low-lying ^{14}F spectrum (resonances) before experiment
- Developed/applied methods to extract phase shifts (J-matrix, external trap)
- Explained the anomalous long lifetime of ^{14}C with chiral NN+NNN potentials
- Solved systems of trapped neutrons for improved density functionals in isospin extremes

Conclusions

We have entered an era of first principles, high precision,
nuclear structure and nuclear reaction theory

Linking nuclear physics and the cosmos
through the Standard Model is well underway

Applications underway to Light Front QCD
and strong time-dependent QED

Pioneering collaborations between Physicists, Computer Scientists
and Applied Mathematicians have become essential to progress

Recent Collaborators

Nuclear Physics

ISU: Pieter Maris, Alina Negoita, Chase Cockrell, Miles Aronnax
LLNL: Erich Ormand, Tom Luu, Eric Jurgenson
SDSU: Calvin Johnson, Plamen Krastev
ORNL/UT: David Dean, Hai Ah Nam, Markus Kortelainen, Mario Stoitsov, Witek Nazarewicz, Gaute Hagen, Thomas Papenbrock
OSU: Dick Furnstahl, students
MSU: Scott Bogner, Heiko Hergert
WMU: Mihai Horoi
Notre Dame: Mark Caprio
ANL: Harry Lee, Steve Pieper
LANL: Joe Carlson, Stefano Gandolfi
UA: Bruce Barrett, Sid Coon, Bira van Kolck, Michael Kruse, Matthew Avetian
LSU: Jerry Draayer, Tomas Dytrych, Kristina Sviratcheva, Chairul Bahri
UW: Martin Savage, Ionel Stetcu

International

Canada: Petr Navratil
Russia: Andrey Shirokov, Alexander Mazur, Eugene Mazur, Sergey Zaytsev, Vasily Kulikov
Sweden: Christian Forssen
Japan: Takashi Abe, Takaharu Otsuka, Yutaka Utsuno Noritaka Shimizu
Germany: Achim Schwenk, Robert Roth, Javier Menendez, students

Computer Science/Applied Math

Ames Lab: Masha Sosonkina, Fang (Cherry) Liu, students
LBNL: Esmond Ng, Chao Yang, Metin Aktulga
ANL: Stefan Wild, Rusty Lusk
OSU: Umit Catalyurek, Eric Saule

Quantum Field Theory

ISU: Heli Honkanen, Xingbo Zhao, Pieter Maris, Paul Wiecki, Yang Li, Kirill Tuchin
Stanford: Stan Brodsky
Germany: Hans-Juergen Pirner
Costa Rica: Guy de Teramond
India: Avaroth Harindranath, Usha Kulshreshtha, Daya Kulshreshtha, Asmita Mukherjee