TRIUMF

Nuclear structure and dynamics from chiral forces

Nuclear Theory in the Supercomputing Era – 2018 (NTSE-2018)

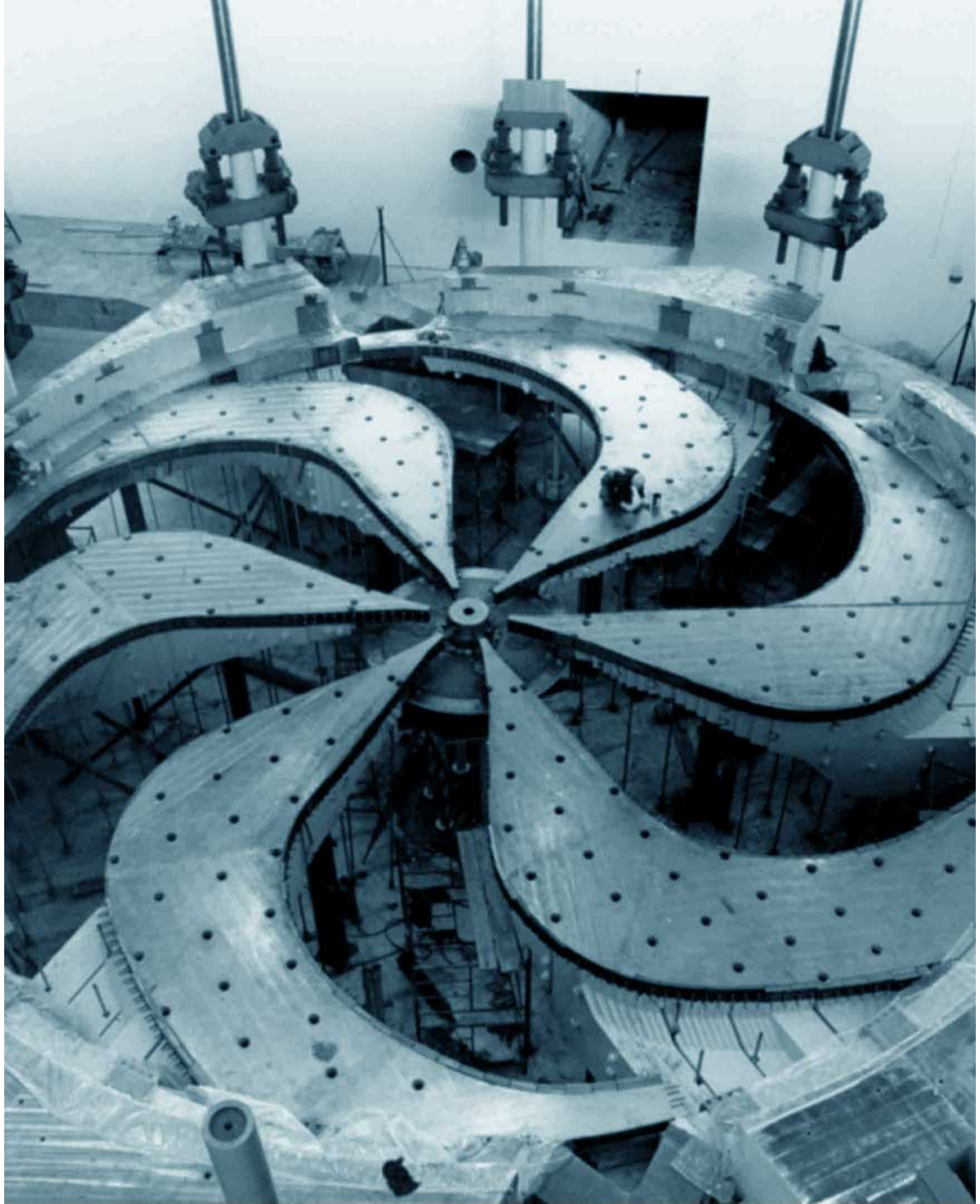
IBS Headquarters, Daejeon, Korea
29 October – 2 November 2018

Petr Navratil

TRIUMF

Collaborators: S. Quaglioni (LLNL), G. Hupin (Orsay), M. Vorabbi, A. Calci (TRIUMF), P. Gysbers (UBC/TRIUMF), M. Gennari (U Waterloo)

2018-10-31

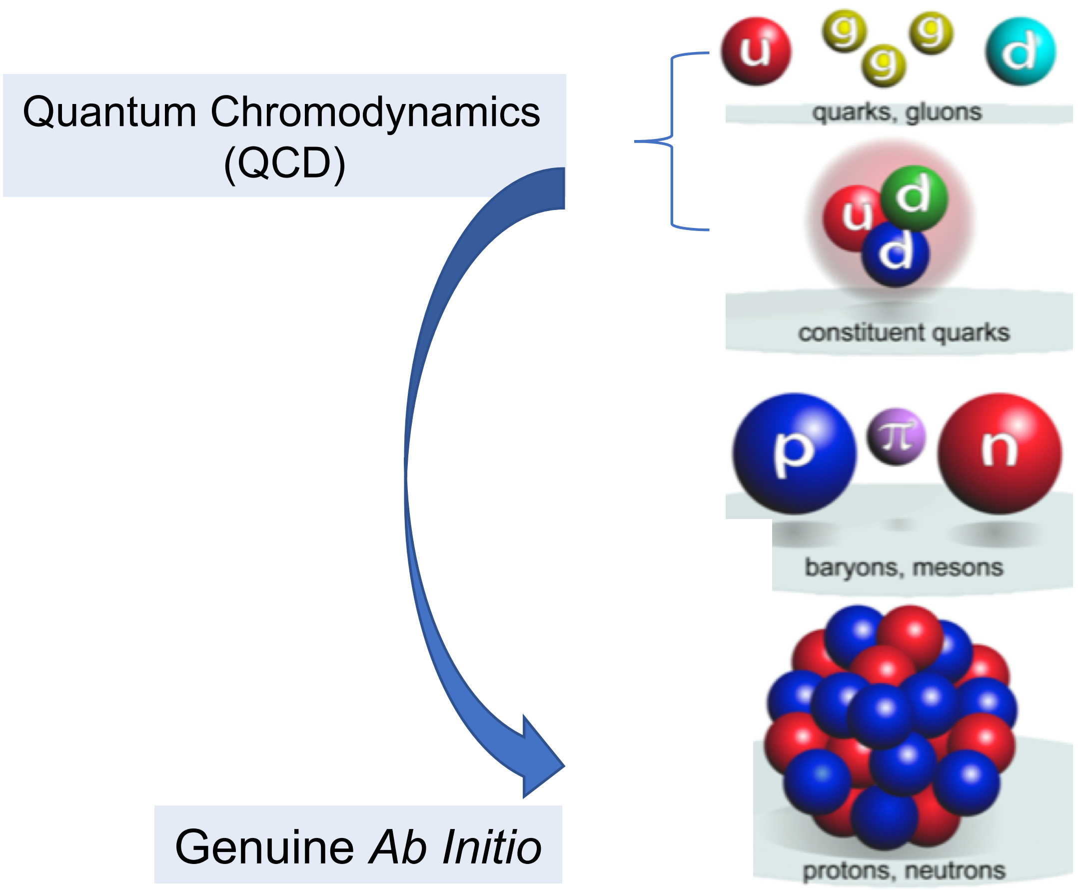


Discovery, accelerated

Outline

- Nuclear structure and reactions from first principles
- New chiral NN N^4LO + 3N
  - Beta decays of light nuclei in NCSM
  - Microscopic optical potentials from NCSM densities
- No-Core Shell Model with Continuum (NCSMC)
- N-^4He scattering and polarized D+T fusion
- Structure of ^7He
- ^{12}N, $^{11}C(p,p)$ scattering and $^{11}C(p,\gamma)^{12}N$ capture
  - Support of approved TRIUMF TUDA experiment

First principles or *ab initio* nuclear theory



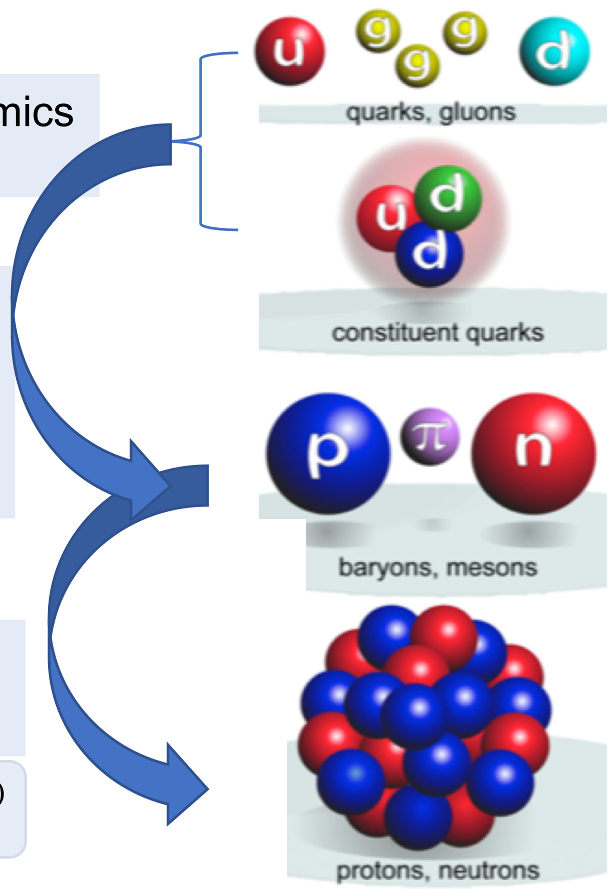
First principles or *ab initio* nuclear theory – what we do at present

Quantum Chromodynamics (QCD)

Chiral Effective Field Theory (parameters fitted to NN data)

Current *ab anitio* nuclear theory

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

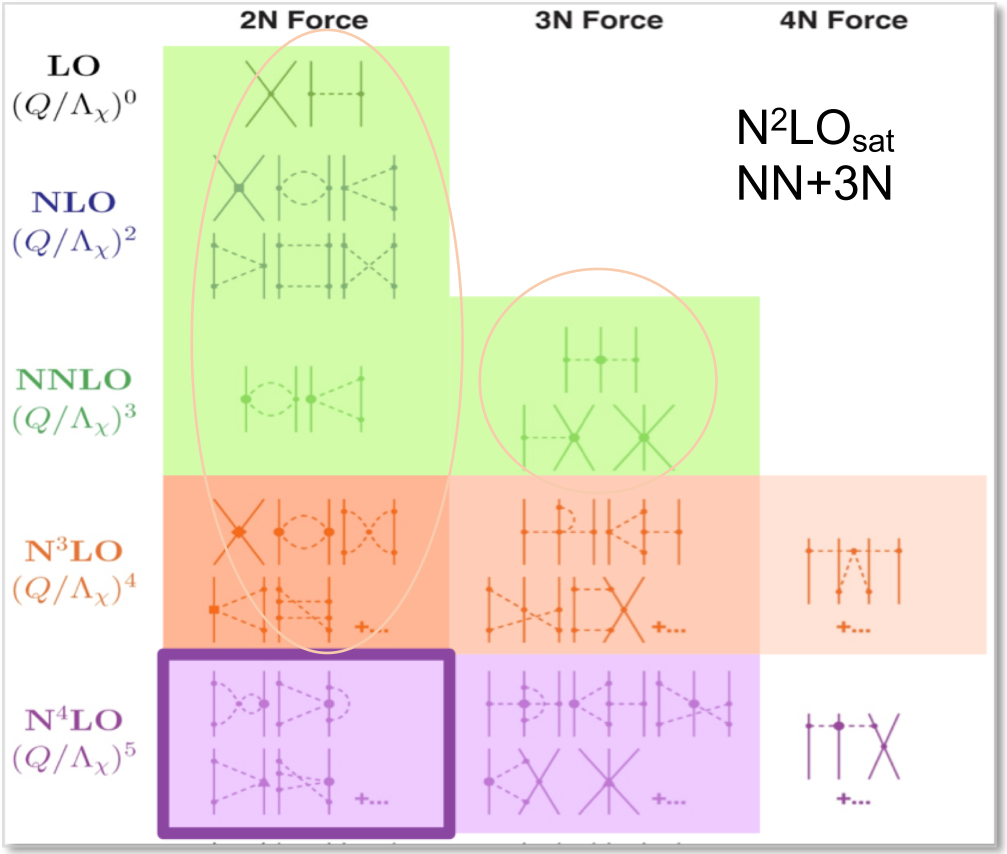


- *Ab initio*
- ✧ Degrees of freedom: Nucleons
- ✧ All nucleons are active
- ✧ Exact Pauli principle
- ✧ Realistic inter-nucleon interactions
  - ✧ Accurate description of NN (and 3N) data
- ✧ Controllable approximations

Chiral Effective Field Theory

- 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



N^3LO NN+N^2LO 3N
(NN+3N400, NN+3N500)

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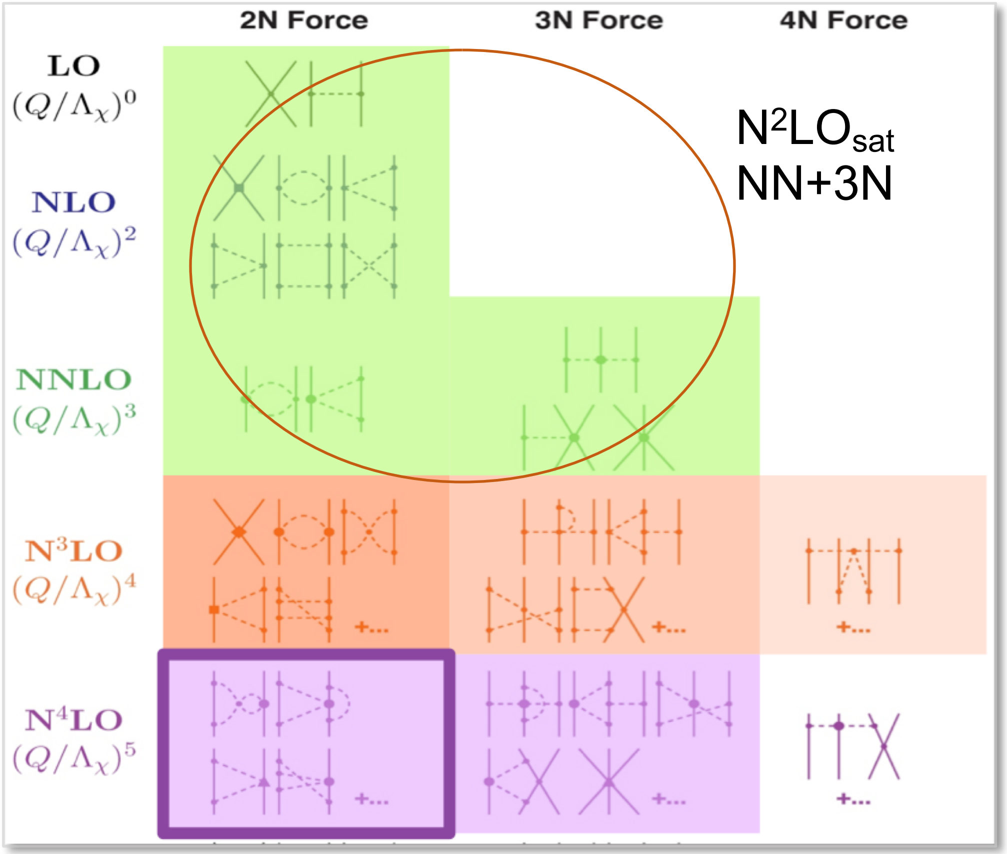

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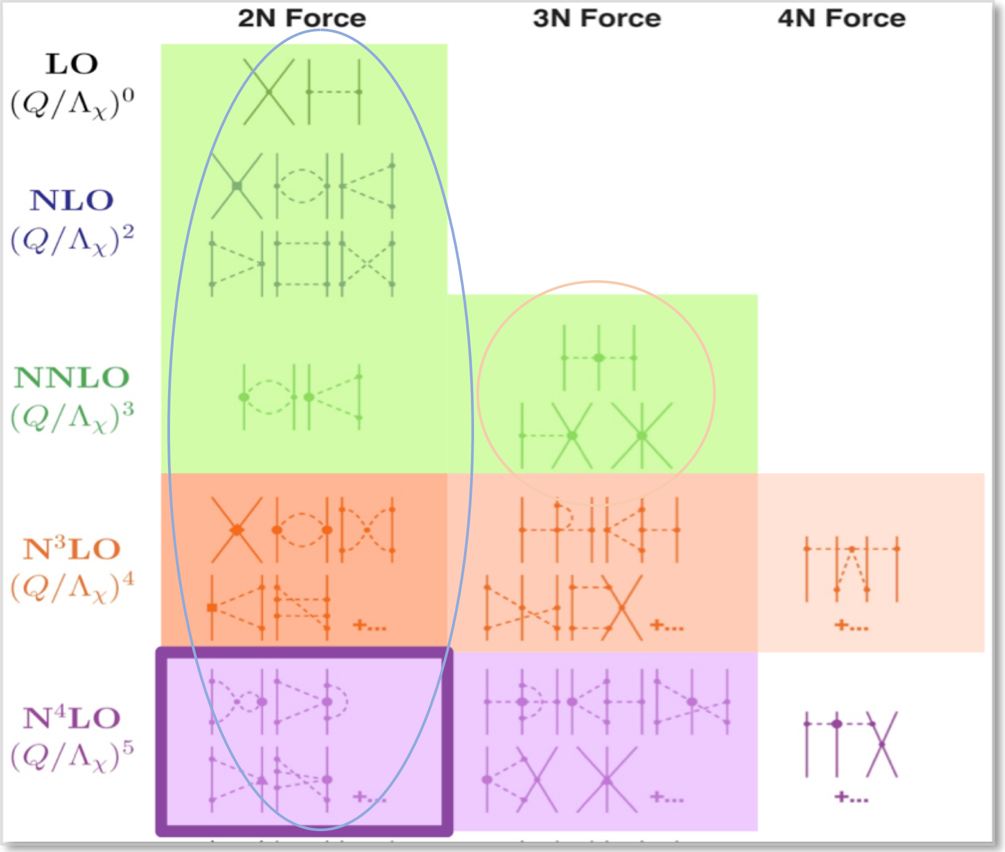


N^{4}LO500 NN

+ N^{2}LO 3N

Currents in chiral EFT

- Meson-exchange current

PHYSICAL REVIEW C **67**, 055206 (2003)

Parameter-free effective field theory calculation for the solar proton-fusion and hep processes

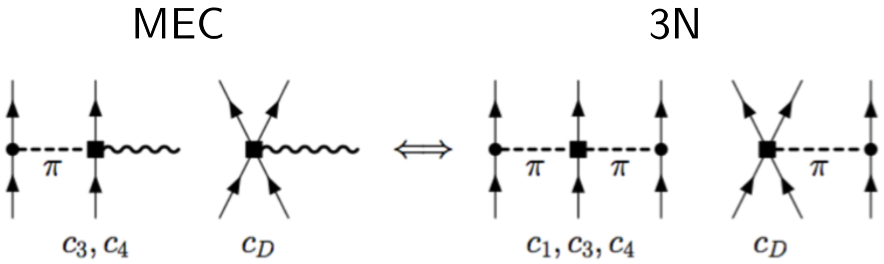
T.-S. Park,[1,2,3] L. E. Marcucci,[4,5] R. Schiavilla,[6,7] M. Viviani,[5,4] A. Kievsky,[5,4] S. Rosati,[5,4] K. Kubodera,[1,2]
D.-P. Min,[8] and M. Rho[1,9]

- weak axial current
  - one-body: LO - Gamow-Teller

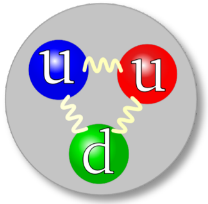
$$\boldsymbol{A}_l = -g_A \tau_l^- e^{-i\boldsymbol{q}\cdot\boldsymbol{r}_l}\left[\boldsymbol{\sigma}_l + \frac{2(\bar{\boldsymbol{p}}_l \boldsymbol{\sigma}_l\cdot\bar{\boldsymbol{p}}_l - \boldsymbol{\sigma}_l \bar{\boldsymbol{p}}_l^2) + i\boldsymbol{q}\times\bar{\boldsymbol{p}}_l}{4m_N^2}\right]$$

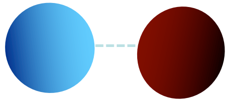
  - two-body: MEC

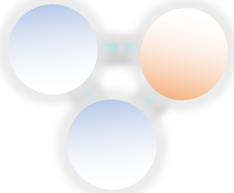
$$\boldsymbol{A}_{12} = \frac{g_A}{2m_N f_\pi^2}\frac{1}{m_\pi^2+\boldsymbol{k}^2}\left[-\frac{i}{2}\tau_\times^- \boldsymbol{p}(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)\cdot\boldsymbol{k} + 4\hat{c}_3 \boldsymbol{k}\boldsymbol{k}\cdot(\tau_1^-\boldsymbol{\sigma}_1+\tau_2^-\boldsymbol{\sigma}_2) + \left(\hat{c}_4+\frac{1}{4}\right)\tau_\times^- \boldsymbol{k}\times[\boldsymbol{\sigma}_\times\times\boldsymbol{k}]\right] + \frac{g_A}{m_N f_\pi^2}[2\hat{d}_1(\tau_1^-\boldsymbol{\sigma}_1+\tau_2^-\boldsymbol{\sigma}_2)+\hat{d}_2\tau_\times^a\boldsymbol{\sigma}_\times],$$



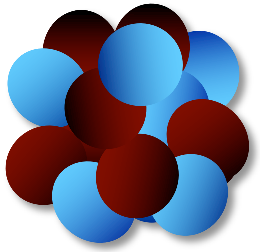
From QCD to nuclei







$$H|\Psi\rangle = E|\Psi\rangle$$



Low-energy QCD

↓

NN+3N interactions from chiral EFT — …or accurate meson-exchange potentials

↓

Unitary/similarity transformations — Identity or SRG or OLS or UCOM … Softens NN, induces 3N

↓

Many-Body methods — NCSM, NCSMC, CCM, SCGF, IM-SRG, GFMC, HH, Nuclear Lattice EFT…

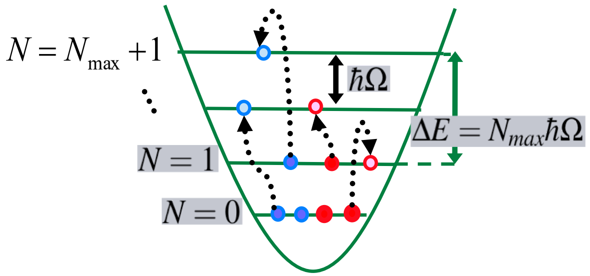
↓

Nuclear structure and reactions

Conceptually simplest *ab initio* method: No-Core Shell Model (NCSM)

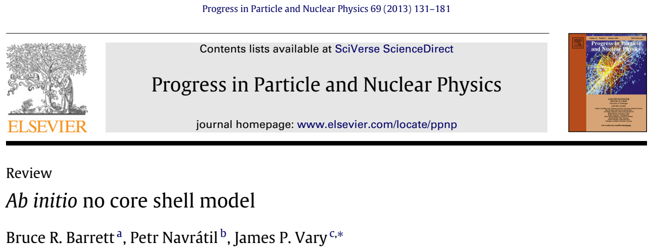
NCSM

- Basis expansion method
  - Harmonic oscillator (HO) basis truncated in a particular way (N_{max})
  - Why HO basis?
    - Lowest filled HO shells match magic numbers of light nuclei (2, 8, 20 – ^{4}He, ^{16}O, ^{40}Ca)
    - Equivalent description in relative-coordinate and Slater determinant basis
- Short- and medium range correlations
- Bound-states, narrow resonances



$$(A) \quad \Psi^{A} = \sum_{N=0}^{N_{max}} \sum_{i} c_{Ni} \Phi_{Ni}^{HO}(\vec{\eta}_1, \vec{\eta}_2, \ldots, \vec{\eta}_{A-1})$$

$$(A) \quad \Psi_{SD}^{A} = \sum_{N=0}^{N_{max}} \sum_{j} c_{Nj}^{SD} \Phi_{SD\,Nj}^{HO}(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A) = \Psi^{A} \varphi_{000}(\vec{R}_{CM})$$


Progress in Particle and Nuclear Physics 69 (2013) 131–181

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journal homepage: www.elsevier.com/locate/ppnp

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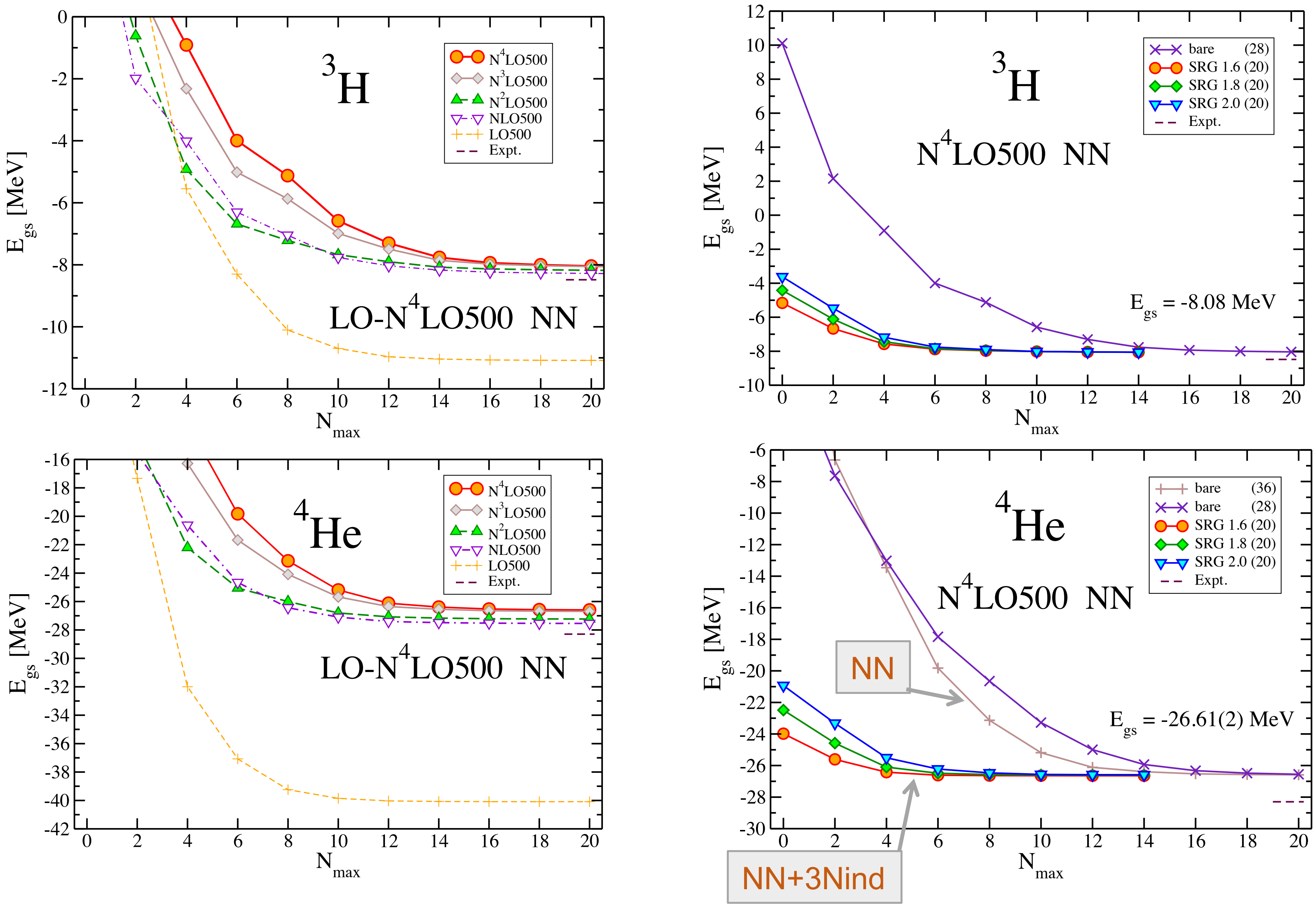
Review

Ab initio no core shell model

Bruce R. Barrett[a], Petr Navrátil[b], James P. Vary[c,*]

^{3}H and ^{4}He with chiral EFT interactions up to N^{4}LO



$^3H \rightarrow {}^3He$ β decay

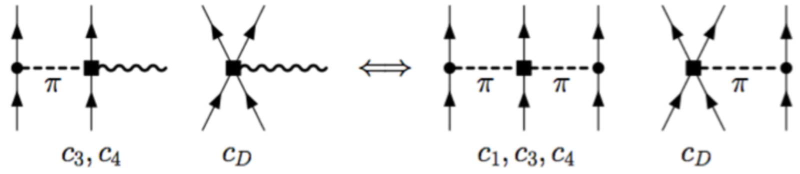
$$\hat{O} = GT^{(1)} + MEC^{(2)} \rightarrow \hat{O}_\alpha = GT^{(1)} + GT^{(2)}_\alpha + MEC^{(2)}_\alpha + \ldots$$

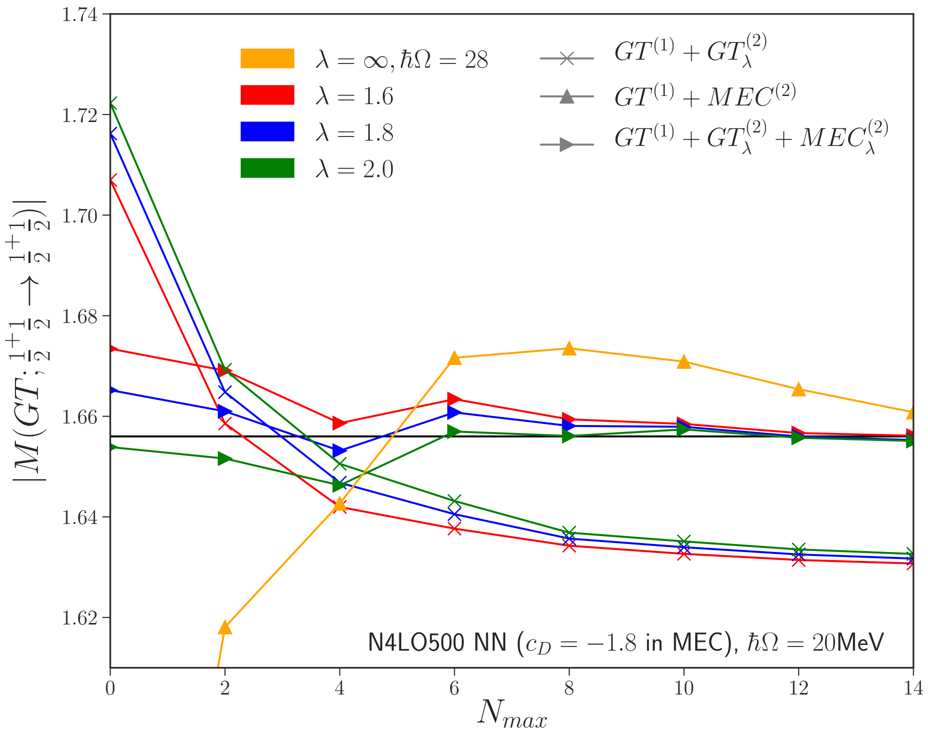
Operator:

Gamow-Teller (1-body) + chiral meson exchange current (2-body) Park (2003)

Potential: "N^{4}LO NN"

- chiral NN @ N^{4}LO, Machleidt PRC96 (2017), 500MeV cutoff
- LEC $c_D = -1.8$ determined





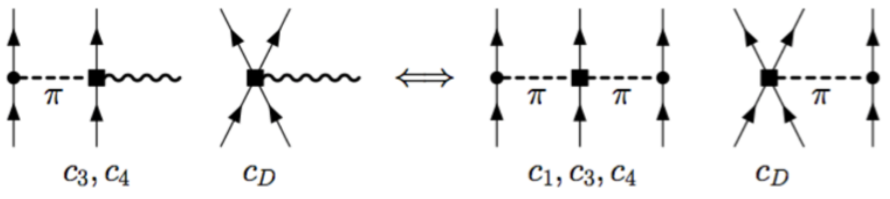
Original EM 2003 N^{3}LO NN c_D=+0.8 (3N repulsive)

Determination of the c_D parameter relevant to chiral 3N force c_D=-1.8 (3N attractive)

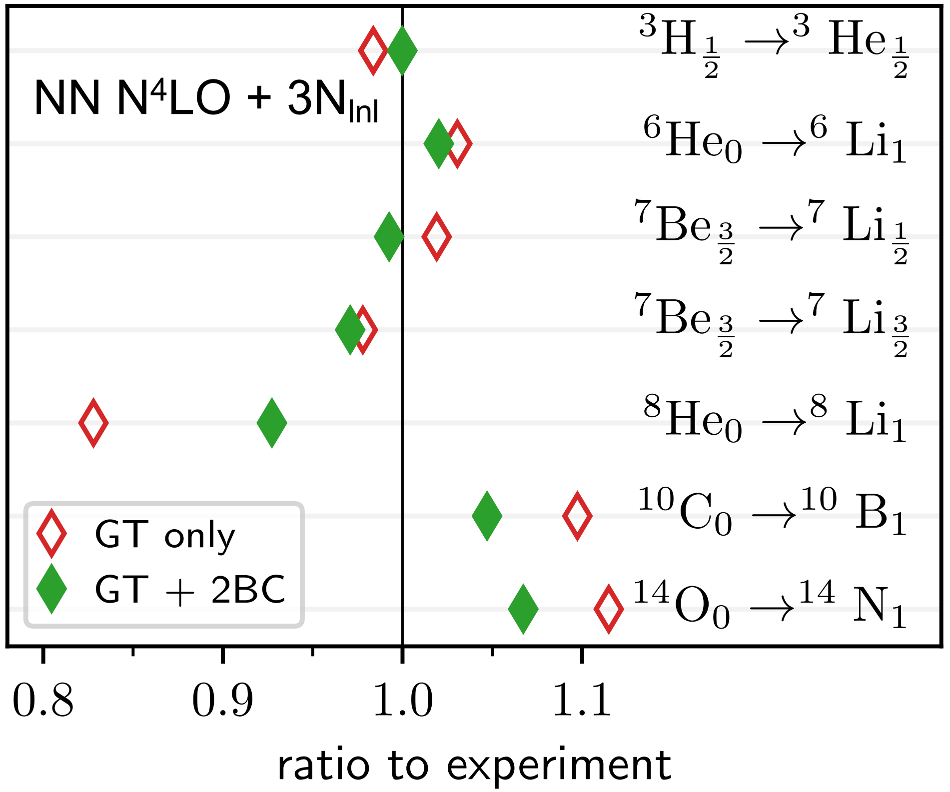
Applications to β decays in p-shell nuclei and beyond

- Does inclusion of the MEC explain g_A quenching?
- In light nuclei correlations present in *ab initio* (NCSM) wave functions explain almost all of the quenching compared to the standard shell model
  - MEC inclusion overall improves agreement with experiment
- The effect of the MEC inclusion is greater in heavier nuclei
- SRG evolved matrix elements used in coupled-cluster and IM-SRG calculations (up to ^{100}Sn)

See talk by Gaute Hagen on Friday



Hollow symbols – GT
Filled symbols – GT+MEC
Both Hamiltonian and operators SRG evolved
Hamiltonian and current consistent parameters



P. Gysbers *et al., "Quenching puzzle of beta decays,"* submitted.

PHYSICAL REVIEW C **97**, 034619 (2018)

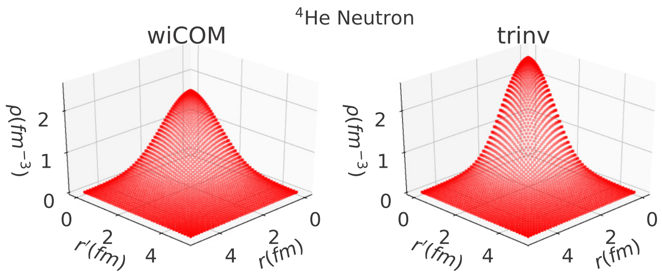
Microscopic optical potentials derived from *ab initio* translationally invariant nonlocal one-body densities

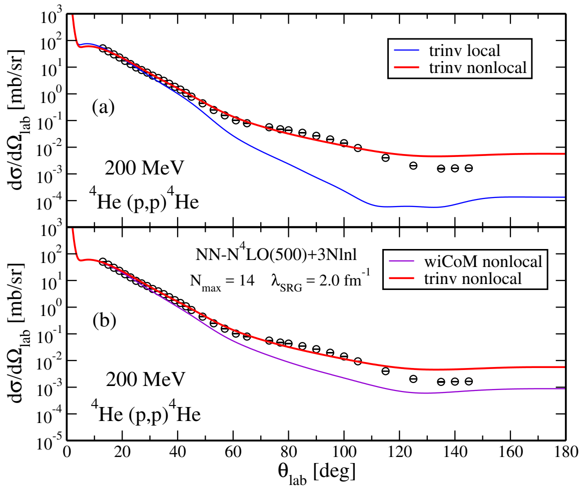
Michael Gennari*
University of Waterloo, 200 University Avenue West Waterloo, Ontario N2L 3G1, Canada and TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada

Matteo Vorabbi,† Angelo Calci, and Petr Navrátil‡
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada

Microscopic optical potentials from NCSM densities

- Translationally-invariant non-local densities from NCSM calculations with chiral NN N^4LO + 3N N^2LO interactions
- High-energy proton-nucleus scattering with microscopic optical potentials from chiral N^4LO NN interaction and NCSM densities





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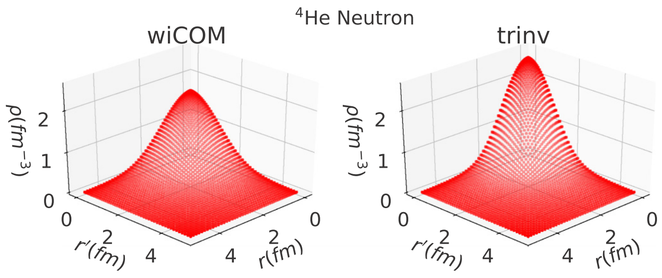
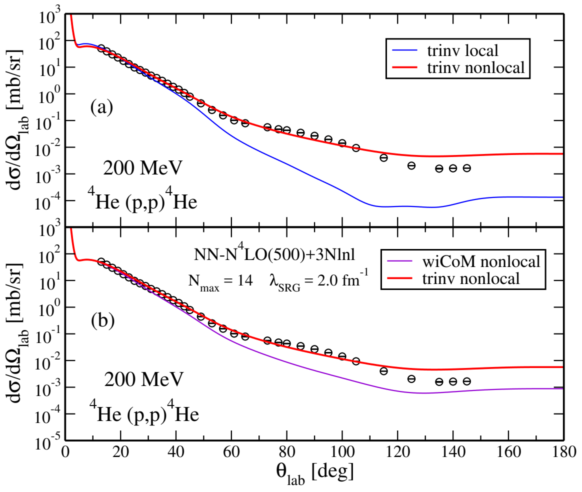
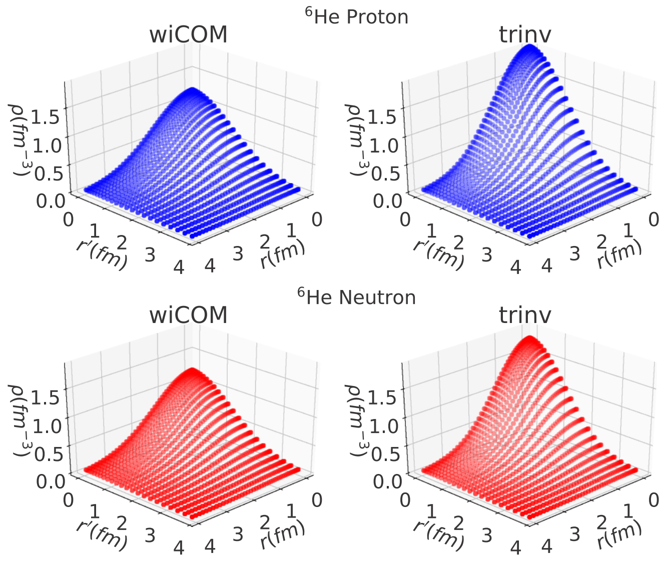
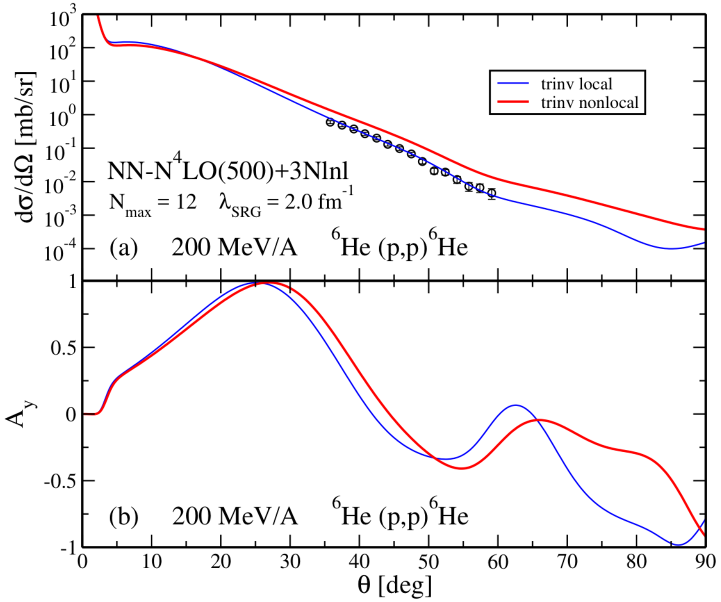
Microscopic optical potentials from NCSM densities

- Translationally-invariant non-local densities from NCSM calculations with chiral NN N⁴LO + 3N N²LO interactions
- High-energy proton-nucleus scattering with microscopic optical potentials from chiral N⁴LO NN interaction and NCSM densities







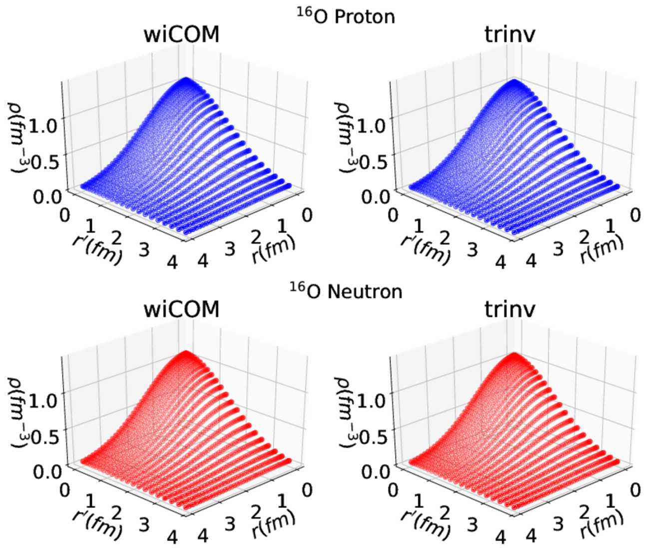


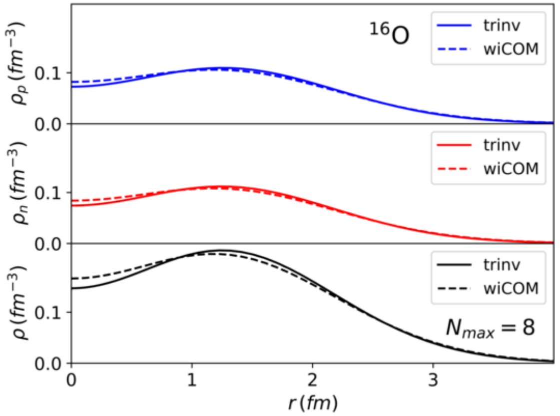
Nuclear kinetic density from NCSM wave functions

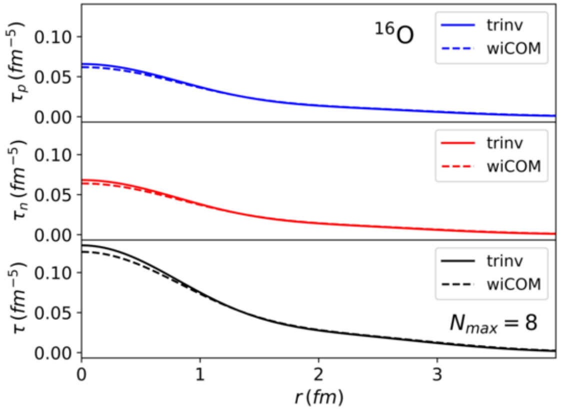
M. Gennari and P. N., arXiv:1808.10537

- DFT calculations include kinetic density
  - Might contain center-of-mass contamination
- Can be calculated for light nuclei in NCSM
  - Translationally invariant

$$\tau_{\mathcal{N}}(\vec{r}) = \left[\vec{\nabla} \cdot \vec{\nabla}'\rho_{\mathcal{N}}(\vec{r},\vec{r}\,')\right]_{\vec{r}=\vec{r}\,'}$$







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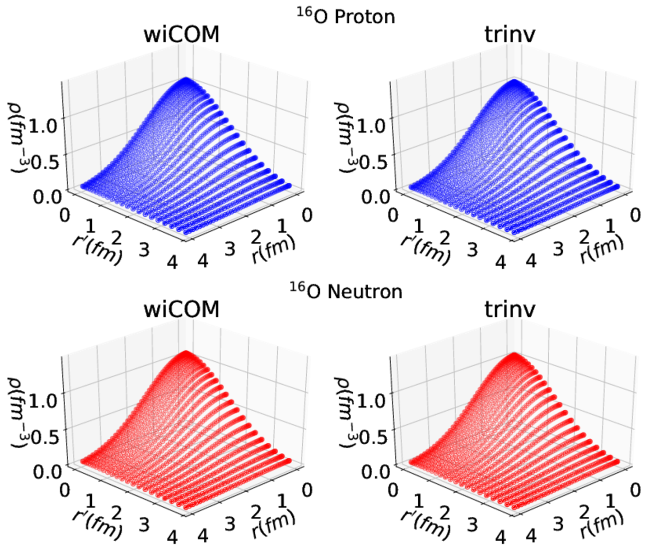
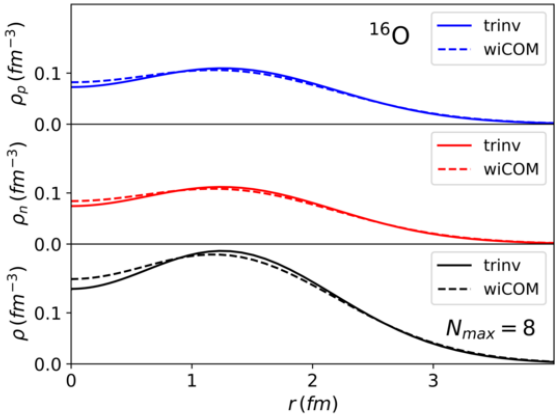
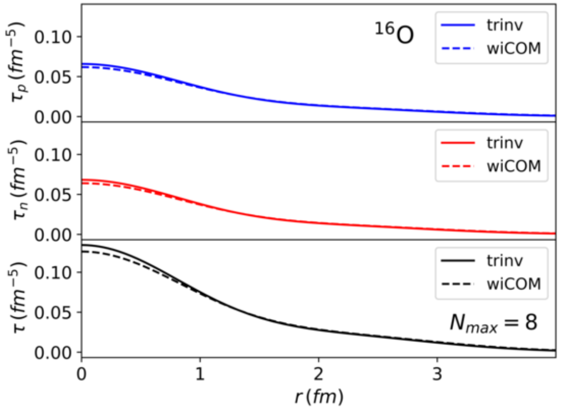
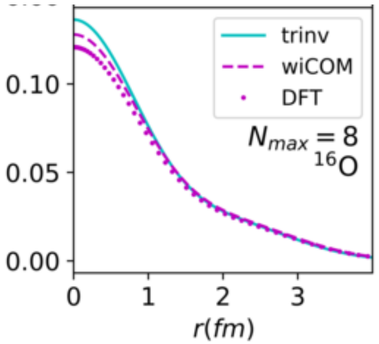
$$\tau_{DFT}(\vec{r}) = \left(1-\frac{1}{A}\right)\tau_{wiCOM}(\vec{r})$$





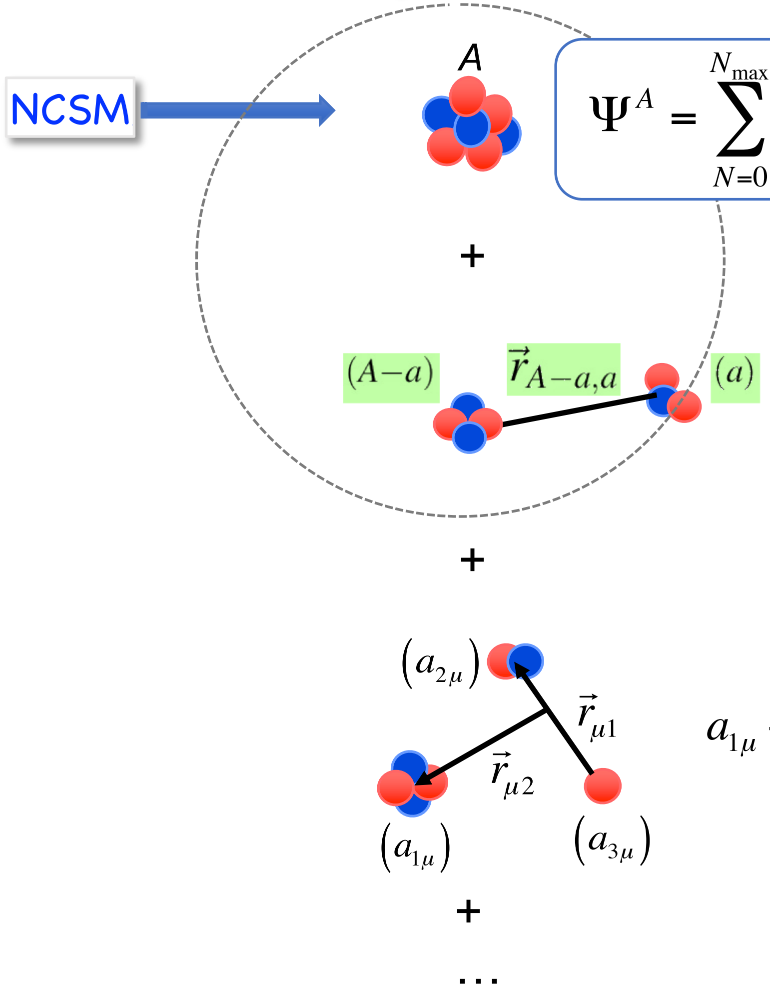


Nucleus	$N_{\max}$	$\langle T_{int}\rangle$	$\langle T_{wiCOM}\rangle$	$\langle T_{DFT}\rangle$
^{4}He	14	51.91	66.91	50.18
^{6}He	12	78.26	93.26	77.72
^{8}He	10	116.30	131.30	114.89
^{12}C	8 IT	219.84	234.84	215.27
^{16}O	8 IT	301.69	316.69	296.90



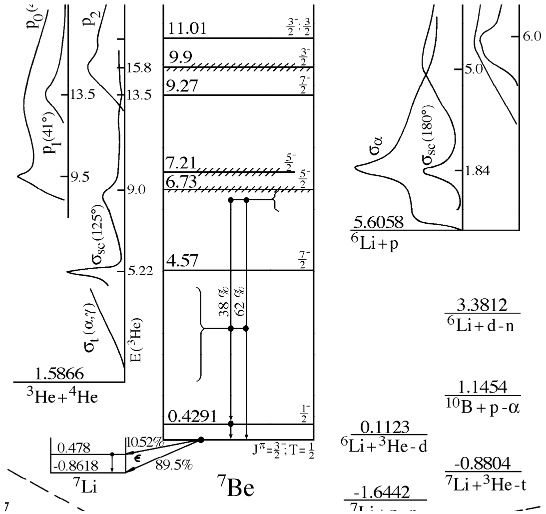
Extending no-core shell model beyond bound states

Include more many nucleon correlations…



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

$$a_{1\mu} + a_{2\mu} + a_{3\mu} = A$$



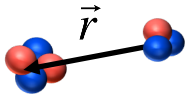
…using the Resonating Group Method (RGM) ideas

Unified approach to bound & continuum states; to nuclear structure & reactions

- 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

NCSM

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



NCSM/RGM

- Most efficient: *ab initio* no-core shell model with continuum (NCSMC)

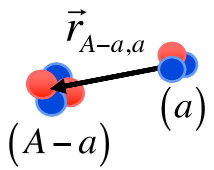
NCSMC

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left|^{(A)}, \lambda\right\rangle + \sum_{\nu} \int d\vec{r}\; \gamma_{\nu}(\vec{r})\; \hat{A}_{\nu} \left|_{(A-a)} \;\vec{r}\; (a), \nu\right\rangle$$

Unknowns

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

Binary cluster basis



- Working in partial waves ($\nu \equiv \{A-a\ \alpha_1 I_1^{\pi_1} T_1; a\ \alpha_2 I_2^{\pi_2} T_2; s\ell\}$)

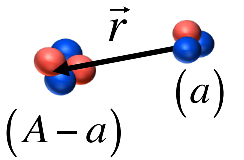
$$\left|\psi^{J^\pi T}\right\rangle = \sum_\nu \hat{A}_\nu \left[\left(\underbrace{\left|A-a\ \alpha_1 I_1^{\pi_1} T_1\right\rangle}_{\text{Target}} \underbrace{\left|a\ \alpha_2 I_2^{\pi_2} T_2\right\rangle}_{\text{Projectile}} \right)^{(sT)} Y_\ell(\hat{r}_{A-a,a}) \right]^{(J^\pi T)} \frac{g_\nu^{J^\pi T}(r_{A-a,a})}{r_{A-a,a}}$$

- Introduce a dummy variable $\vec{r}$ with the help of the delta function

$$\left|\psi^{J^\pi T}\right\rangle = \sum_\nu \int \frac{g_\nu^{J^\pi T}(r)}{r} \hat{A}_\nu \left[\left(\left|A-a\ \alpha_1 I_1^{\pi_1} T_1\right\rangle \left|a\ \alpha_2 I_2^{\pi_2} T_2\right\rangle \right)^{(sT)} Y_\ell(\hat{r}) \right]^{(J^\pi T)} \delta(\vec{r} - \vec{r}_{A-a,a})\ r^2 dr\, d\hat{r}$$

  - Allows to bring the wave function of the relative motion in front of the antisymmetrizer

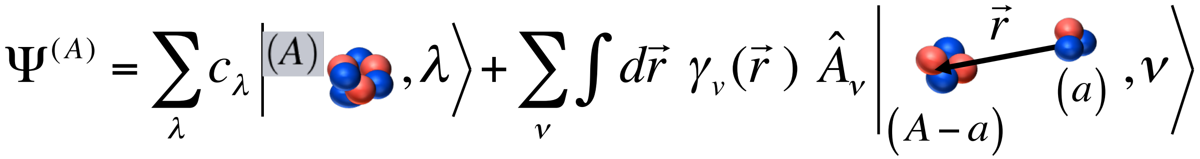
$$\sum_\nu \int d\vec{r}\ \gamma_\nu(\vec{r}\,)\ \hat{A}_\nu \Big|$$

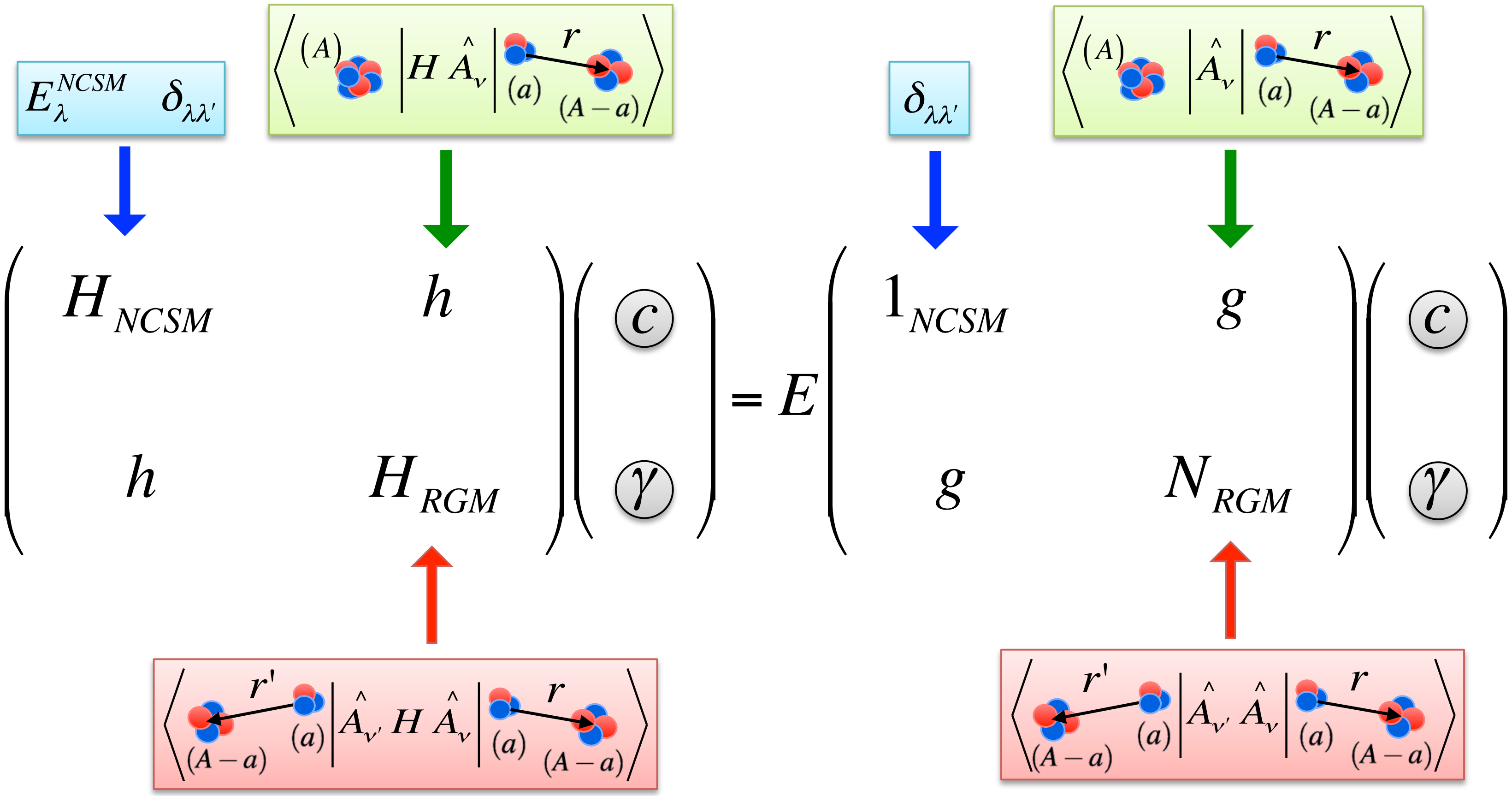


$$, \nu \Big\rangle$$

Coupled NCSMC equations

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



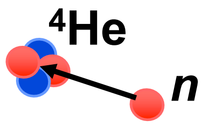


Solved by Microscopic R-matrix theory on a Lagrange mesh – efficient for coupled channels

Computational aspects of NCSMC

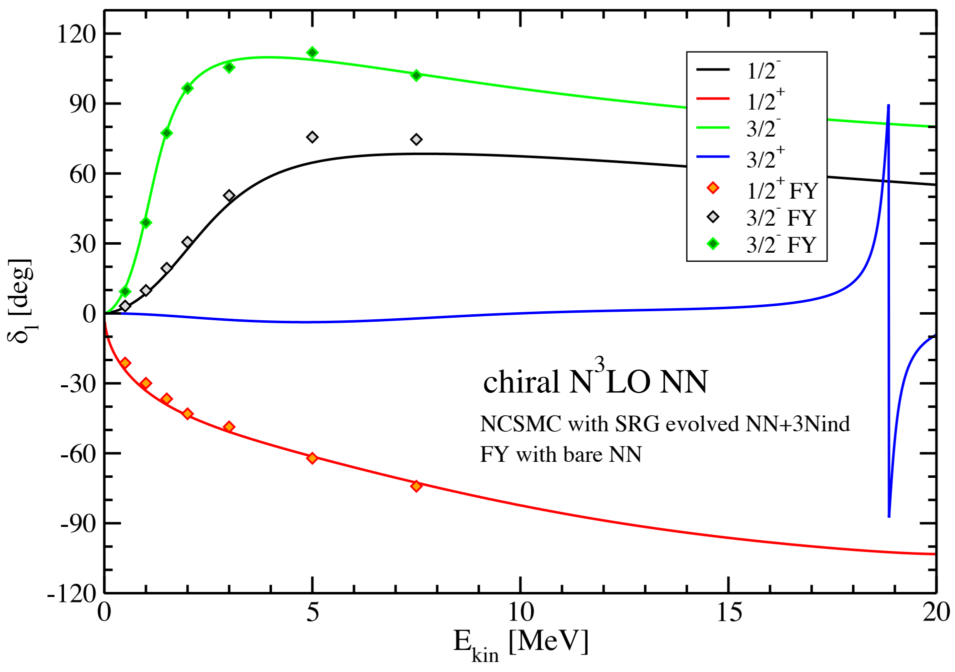
- NN matrix elements
  - Choice of various potentials – chiral N^3LO, LO-N^4LO…
  - SRG (also for one and two-body operators)
  - Transformation to s.p. basis (up to N_{12max}~30)
  - ncsmv2b - Fortran90 with OpenMP
- 3N matrix elements
  - Choice of various NN (chiral N^3LO, LO-N^4LO) and 3N (N^2LO with local or local/non-local regulators, N^4LO contacts) potentials
  - SRG (also for one, two- and three-body operators)
  - Transformation to s.p. basis (up to N_{123max}~17)
  - manyeff, v3trans (op3trans) – Fortran90 with OpenMP
- NCSM diagonalization
  - NN, NN+3N or NN+3N(NO2b) interactions
  - Calculations of N_{max} sequence (0(1),2(3),…Nmax)
  - Importance truncation
  - ncsd – Lanczosh algorithm, bit operations, hashing, partial or full storing of non-zero matrix elements, Fortran 90 with MPI, ~12,000 MPI tasks
- Transition densities and/or RGM and coupling kernels
  - One- and two-body transition densities for wave functions of the same or different nuclei (three- and four-body for *A*=3,4 nuclei)
    - Coordinate space local and nonlocal translationally invariant one-body densities
  - RGM and coupling kernel calculation for the NCSMC (including the 3N interaction)
  - Normal ordering of 3N interaction
  - trdens – bit operations, hashing, Fortran90 with MPI, ~8,000 MPI tasks
- NCSMC calculation
  - RGM and coupling kernels either input or calculated from densities
  - Solves NCSMC coupled equations, calculates the S-matrix and scattering/reaction observables
  - ncsmc – Fortran90 with OpenMP and MPI

n-^{4}He scattering within NCSMC



n-^{4}He scattering phase-shifts for

chiral NN



FY: Faddeev-Yakubovsky method - Rimantas Lazauskas

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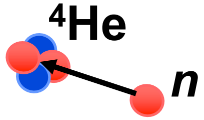
Phys. Scr. 00 (2016) 000000 (37pp)

Invited Comment

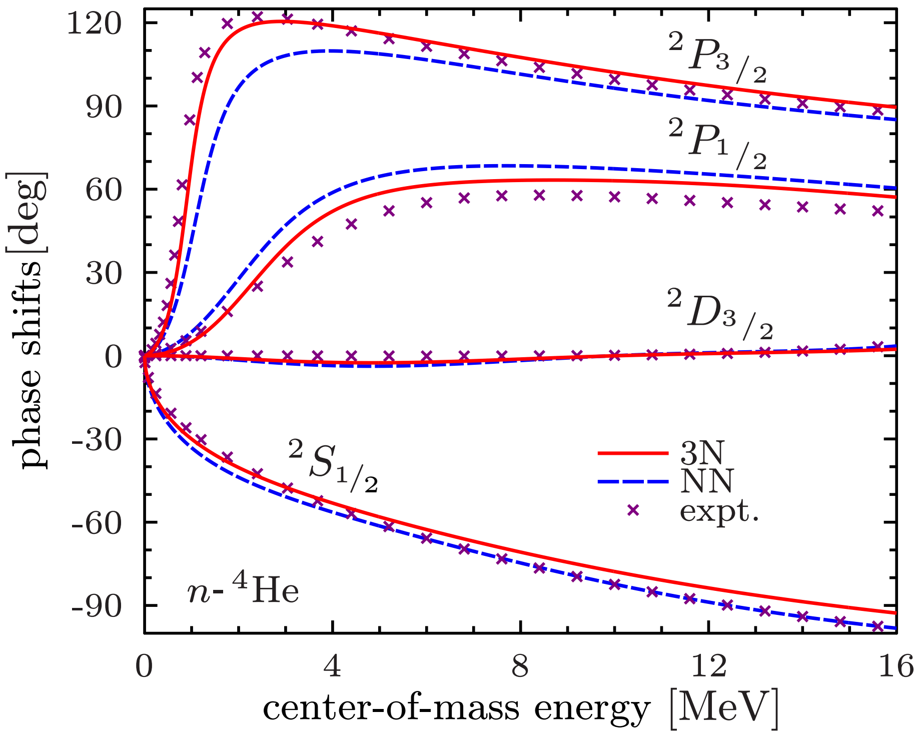
Unified *ab initio* approaches to nuclear structure and reactions

Petr Navrátil[1], Sofia Quaglioni[2], Guillaume Hupin[3,4], Carolina Romero-Redondo[2] and Angelo Calci[1]

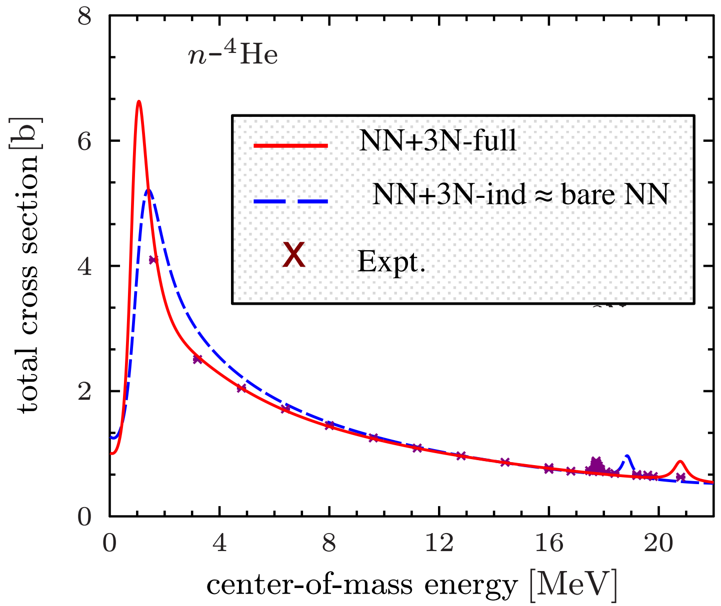
n-^{4}He scattering within NCSMC



n-^{4}He scattering phase-shifts for chiral NN and NN+3N500 potential



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



3N force enhances $1/2^- \leftrightarrow 3/2^-$ splitting: Essential at low energies!

PHYSICAL REVIEW C **88**, 054622 (2013)

***Ab initio* many-body calculations of nucleon-^{4}He scattering with three-nucleon forces**

Guillaume Hupin,[1,*] Joachim Langhammer,[2,†] Petr Navrátil,[3,‡] Sofia Quaglioni,[1,§] Angelo Calci,[2,∥] and Robert Roth[2,¶]

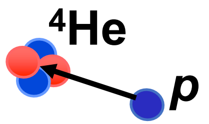
IOP Publishing | Royal Swedish Academy of Sciences Physica Scripta
Phys. Scr. 00 (2016) 000000 (37pp)

Invited Comment

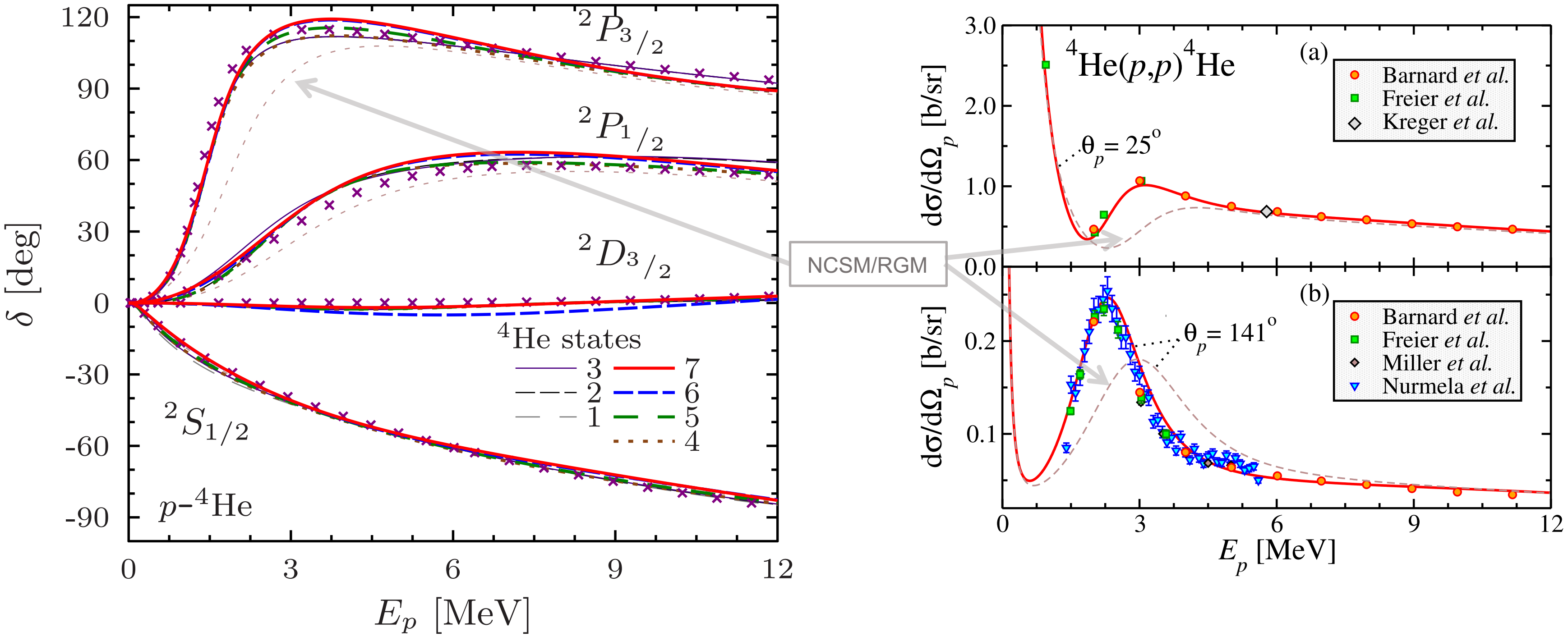
Unified *ab initio* approaches to nuclear structure and reactions

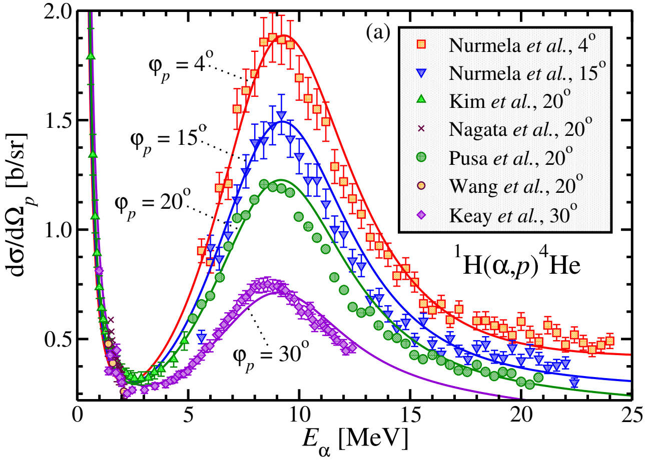
Petr Navrátil[1], Sofia Quaglioni[2], Guillaume Hupin[3,4], Carolina Romero-Redondo[2] and Angelo Calci[1]

p-^{4}He scattering within NCSMC



p-^{4}He scattering phase-shifts for NN+3N500 potential: Convergence	Differential p-^{4}He cross section with NN+3N potentials





PHYSICAL REVIEW C **90**, 061601(R) (2014)

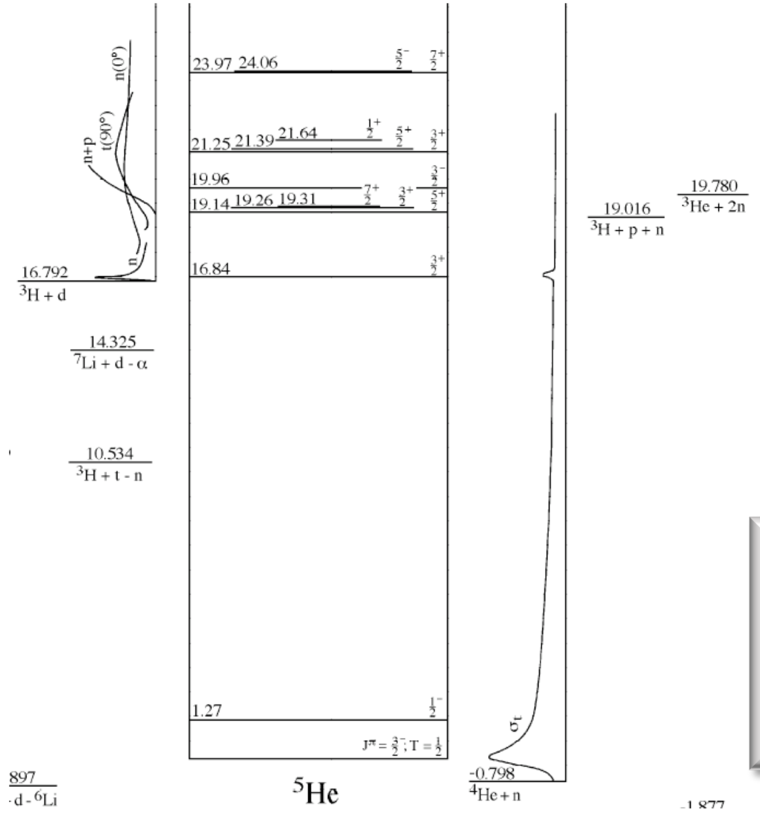
Predictive theory for elastic scattering and recoil of protons from ^{4}He

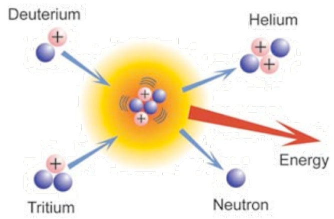
Guillaume Hupin,[1,*] Sofia Quaglioni,[1,†] and Petr Navrátil[2,‡]

Predictive power in the 3/2$^-$ resonance region:
Applications to material science

Deuterium-Tritium fusion

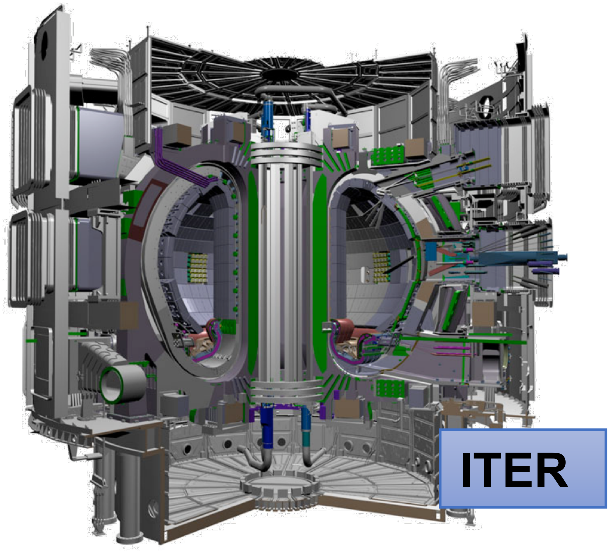
- The $d+{}^3H \rightarrow n+{}^4He$ reaction
  - The most promising for the production of fusion energy in the near future
  - Used to achieve inertial-confinement (laser-induced) fusion at NIF, and magnetic-confinement fusion at ITER
  - With its mirror reaction, $^3He(d,p)^4He$, important for Big Bang nucleosynthesis



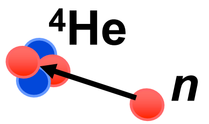


Resonance at E_{cm} =48 keV (E_d=105 keV) in the $J=3/2^+$ channel
Cross section at the peak: 4.88 b

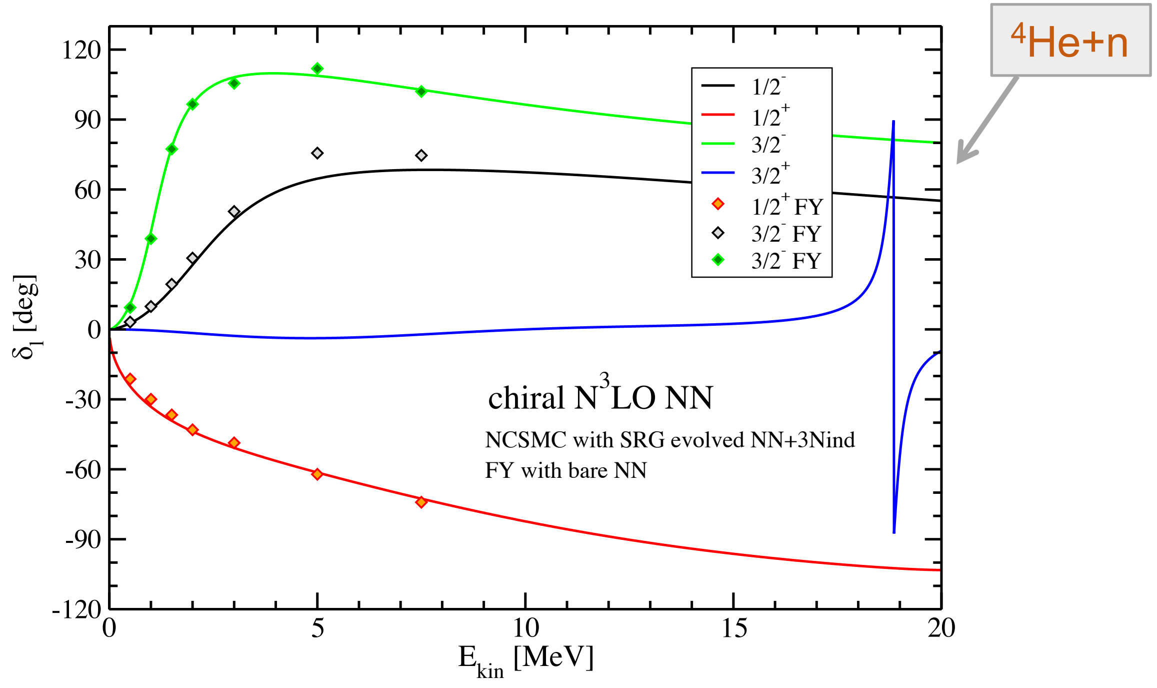
17.64 MeV energy released:
14.1 MeV neutron and 3.5 MeV alpha



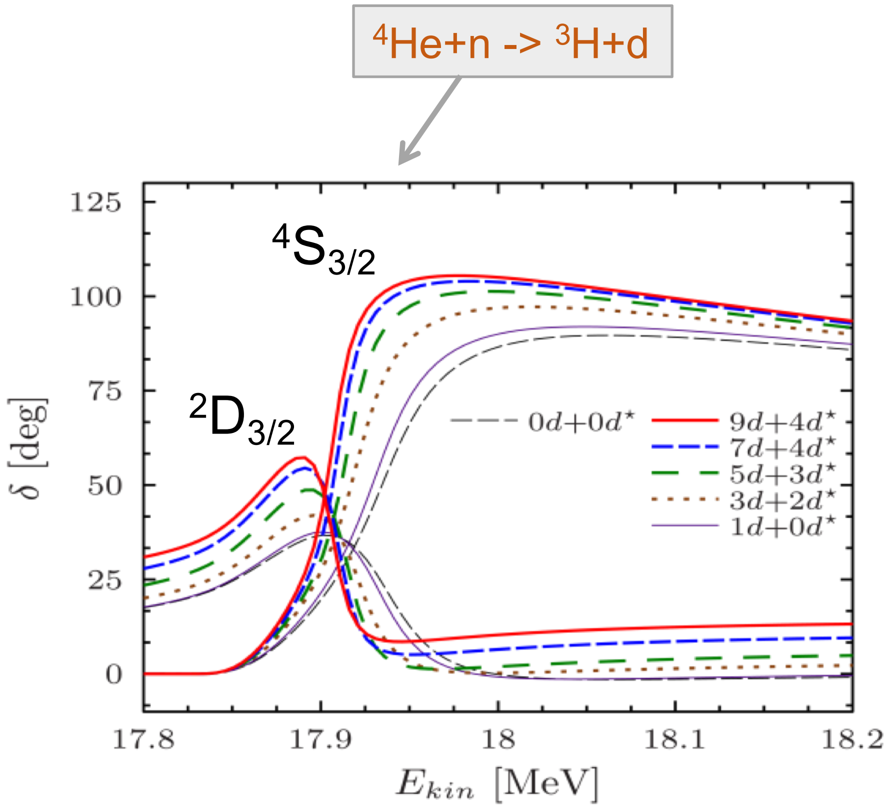
n-^{4}He scattering and ^{3}H+d fusion within NCSMC



n-^{4}He scattering phase-shifts for chiral NN

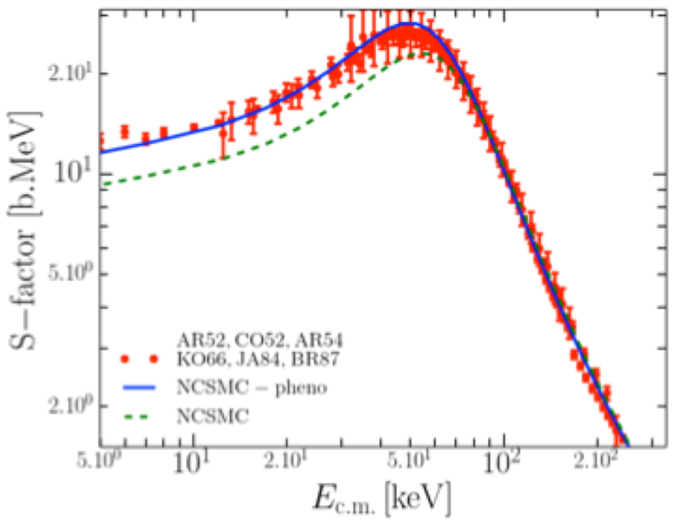


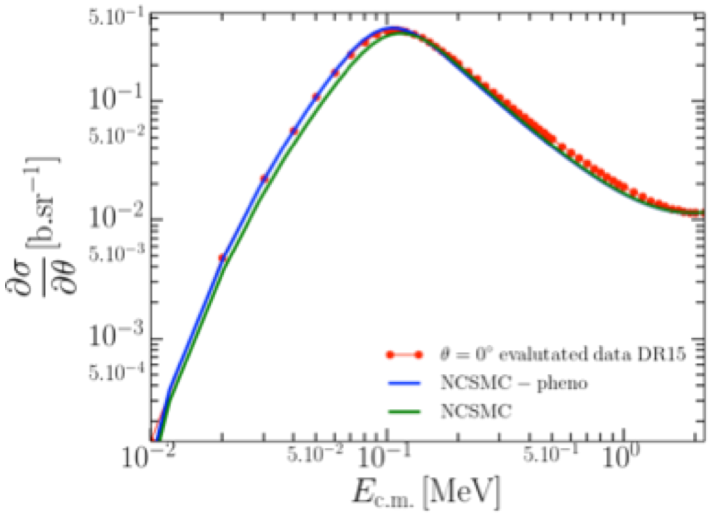
FY: Faddeev-Yakubovsky method - Rimantas Lazauskas



The *d*-^{3}H fusion takes place through a transition of *d*+^{3}H is *S*-wave to *n*+^{4}He in *D*-wave: Importance of the **tensor and 3N force**

$^3H(d,n)^4He$ with chiral NN+3N500 interaction



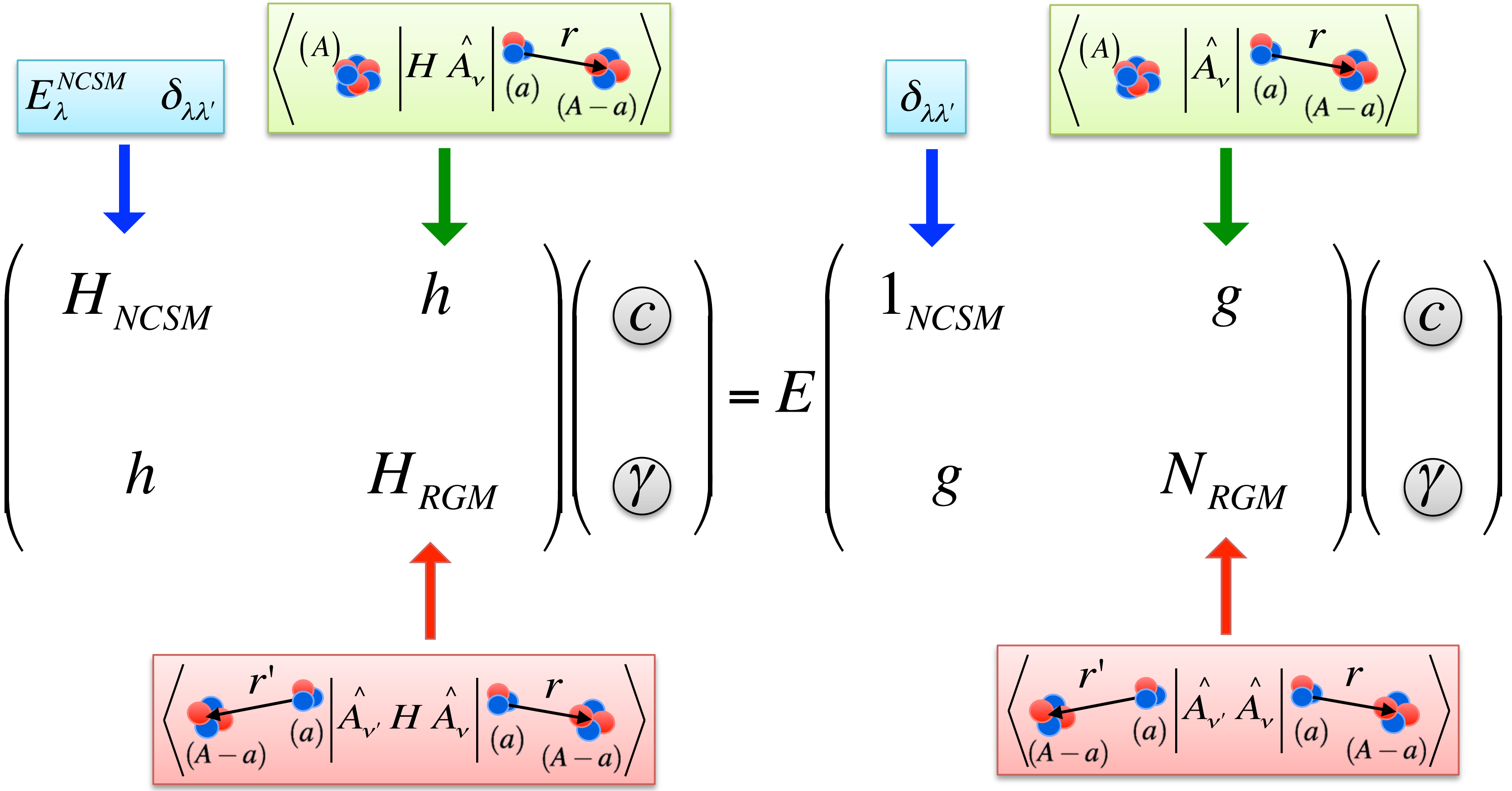


$$S(E) = E\sigma(E)\exp[2\pi\eta(E)]$$

$$\eta(E) = Z_{A-a}Z_a e^2 / \hbar v_{A-a,a}$$

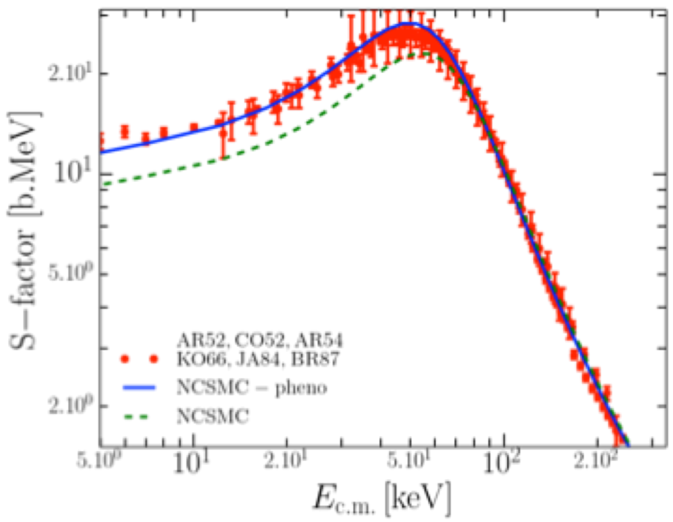
NCSMC phenomenology

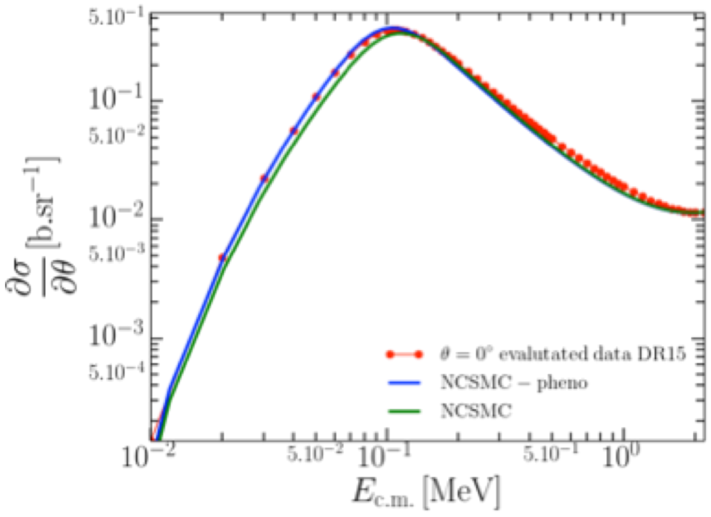
$$H\,\Psi^{(A)} = E\,\Psi^{(A)} \qquad \Psi^{(A)} = \sum_\lambda c_\lambda \left| (A), \lambda \right\rangle + \sum_\nu \int d\vec{r}\, \gamma_\nu(\vec{r})\, \hat{A}_\nu \left| (A-a)\ \vec{r}\ (a), \nu \right\rangle$$



E_λ^{NCSM} energies treated as adjustable parameters

$^3H(d,n)^4He$ with chiral NN+3N500 interaction





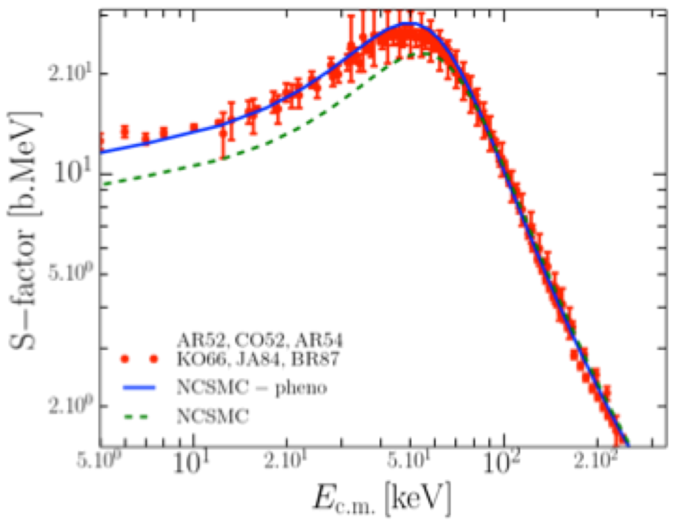
$$S(E) = E\sigma(E)\exp[2\pi\eta(E)]$$

$$\eta(E) = Z_{A-a}Z_a e^2 / \hbar v_{A-a,a}$$

***Ab initio* predictions for *polarized* DT thermonuclear fusion**
Nature Communications (accepted); arXiv:1803.11378
Guillaume Hupin[1,2,3], Sofia Quaglioni[3] and Petr Navrátil[4]

^{3}H(d,n)^{4}He with chiral NN+3N500 interaction

Polarized fusion

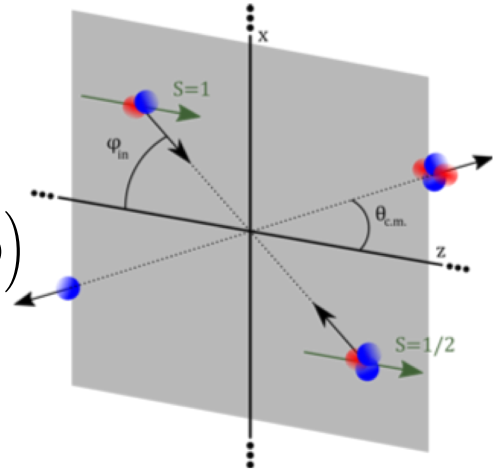


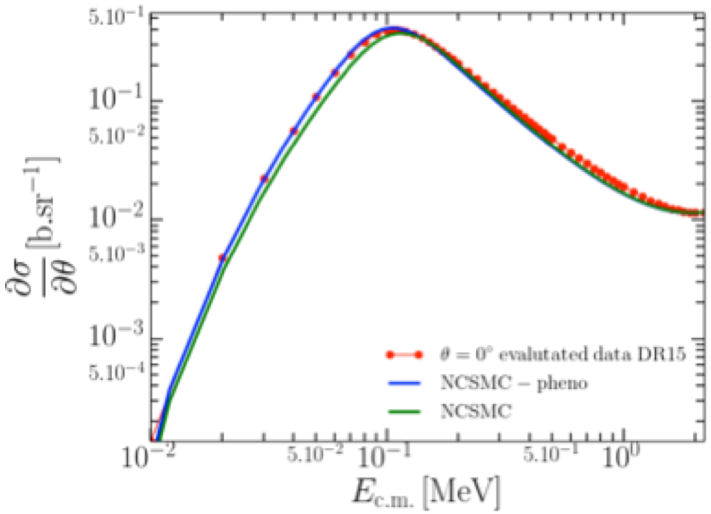
$$S(E) = E\sigma(E)\exp[2\pi\eta(E)]$$

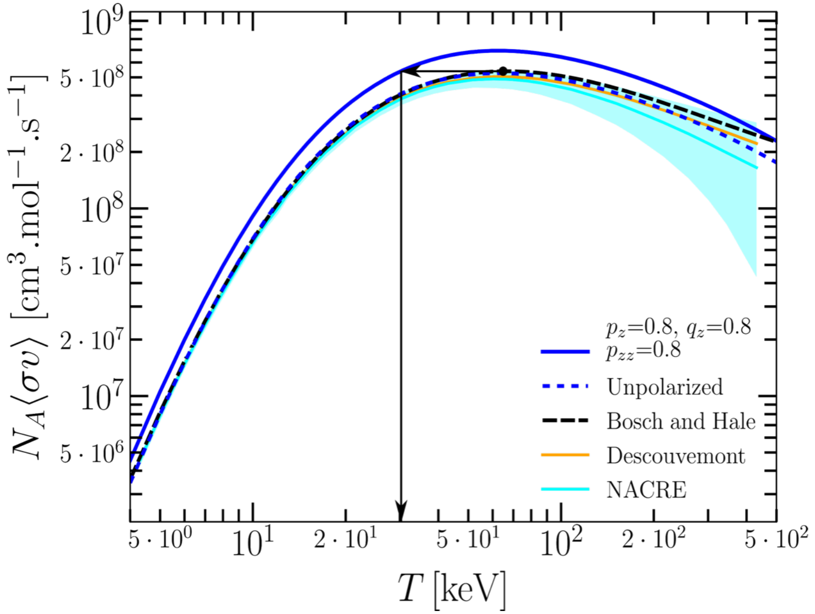
$$\eta(E) = Z_{A-a} Z_a e^2 / \hbar v_{A-a,a}$$

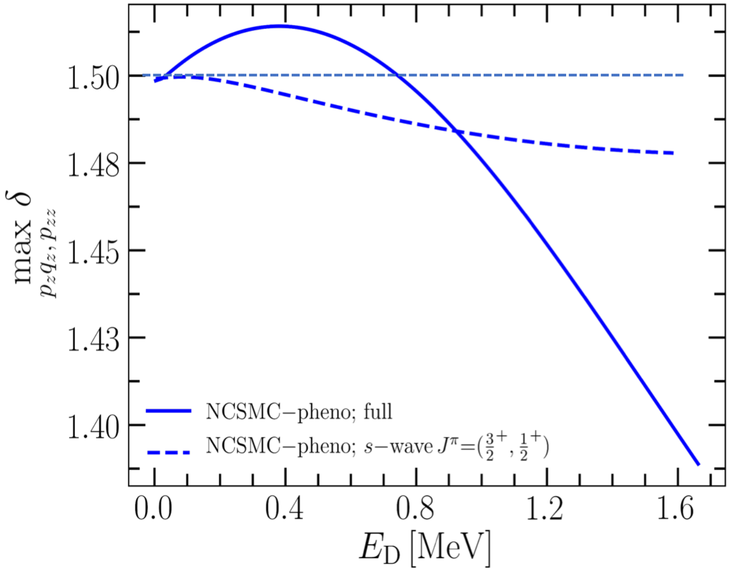
$$\frac{\partial\sigma_{pol}}{\partial\Omega_{c.m.}}(\theta_{\rm c.m.}) = \frac{\partial\sigma_{unpol}}{\partial\Omega_{c.m.}}(\theta_{\rm c.m.})\left(1+\frac{1}{2}p_{zz}A_{zz}^{(b)}(\theta_{\rm c.m.})+\frac{3}{2}p_z q_z C_{z,z}(\theta_{\rm c.m.})\right)$$

$$\langle\sigma v\rangle = \sqrt{\frac{8}{\pi\mu(k_bT)^3}}\int_0^\infty S(E)\; exp\left(-\frac{E}{k_bT}-\sqrt{\frac{E_g}{E}}\right)dE,$$



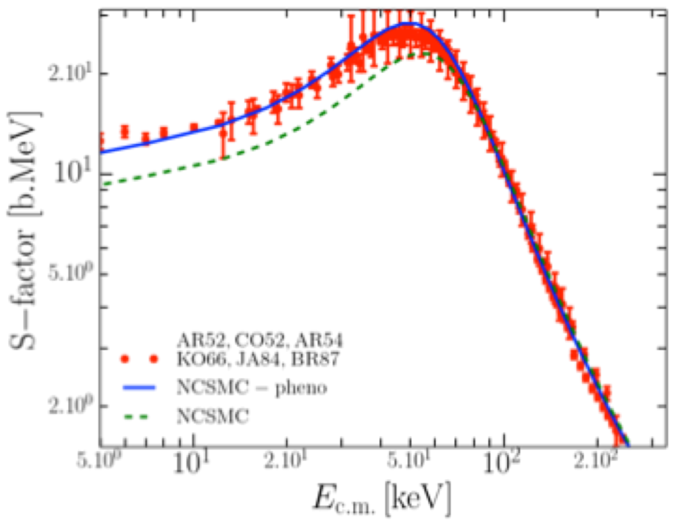






^{3}H(d,n)^{4}He with chiral NN+3N500 interaction

Polarized fusion

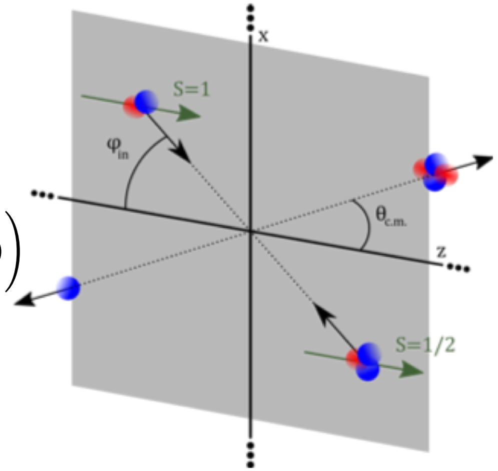


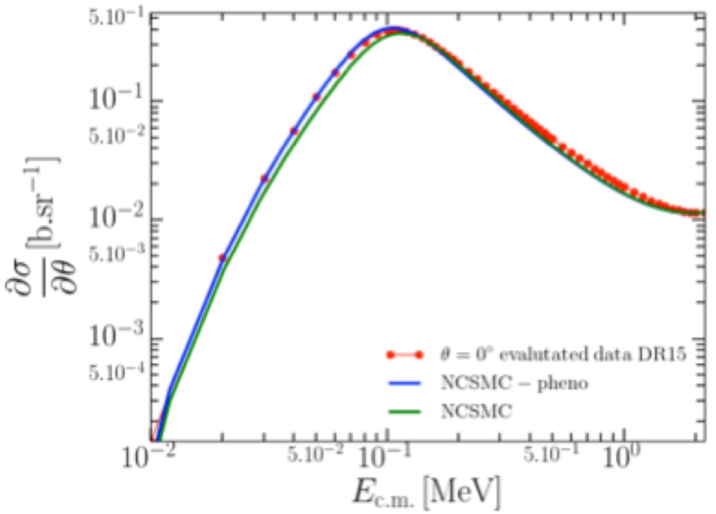
$$S(E) = E\sigma(E)\exp[2\pi\eta(E)]$$

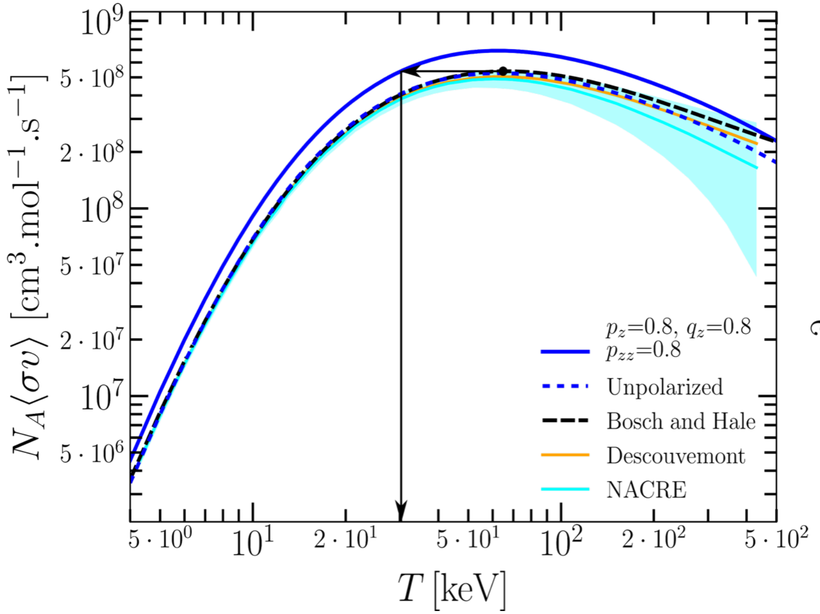
$$\eta(E) = Z_{A-a}Z_a e^2/\hbar v_{A-a,a}$$

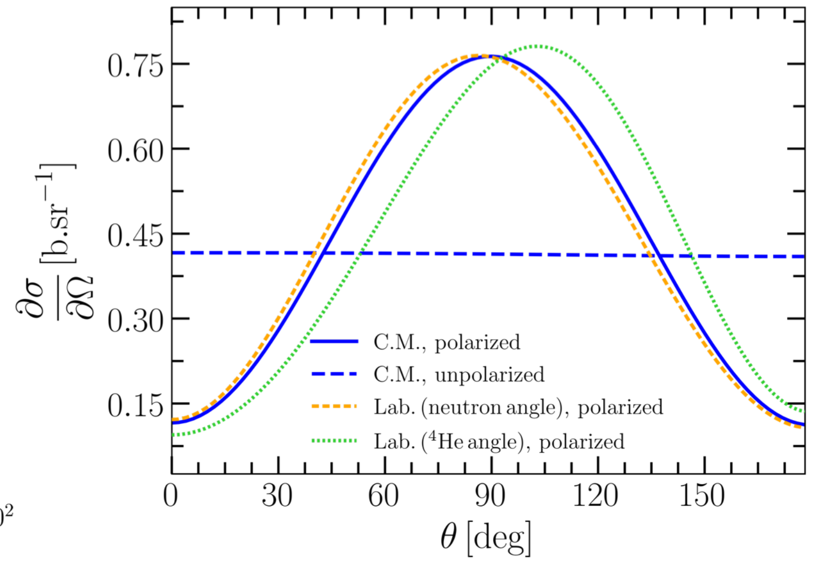
$$\frac{\partial\sigma_{pol}}{\partial\Omega_{c.m.}}(\theta_{\rm c.m.}) = \frac{\partial\sigma_{unpol}}{\partial\Omega_{c.m.}}(\theta_{\rm c.m.})\left(1+\frac{1}{2}p_{zz}A_{zz}^{(b)}(\theta_{\rm c.m.})+\frac{3}{2}p_z q_z C_{z,z}(\theta_{\rm c.m.})\right)$$

$$\langle\sigma v\rangle = \sqrt{\frac{8}{\pi\mu(k_bT)^3}}\int_0^\infty S(E)\ exp\left(-\frac{E}{k_bT}-\sqrt{\frac{E_g}{E}}\right)dE,$$

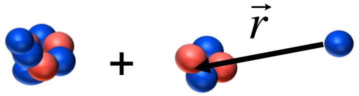


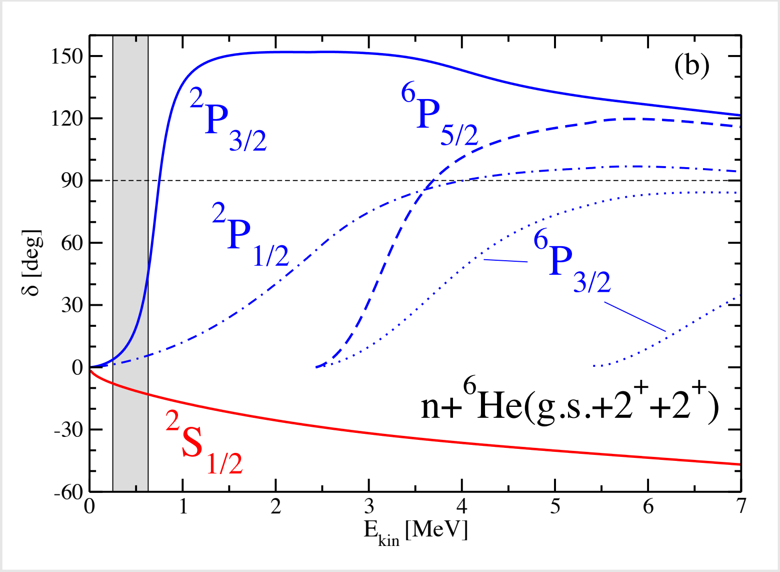






NCSM with continuum: ^{7}He ⟷ ^{6}He+n





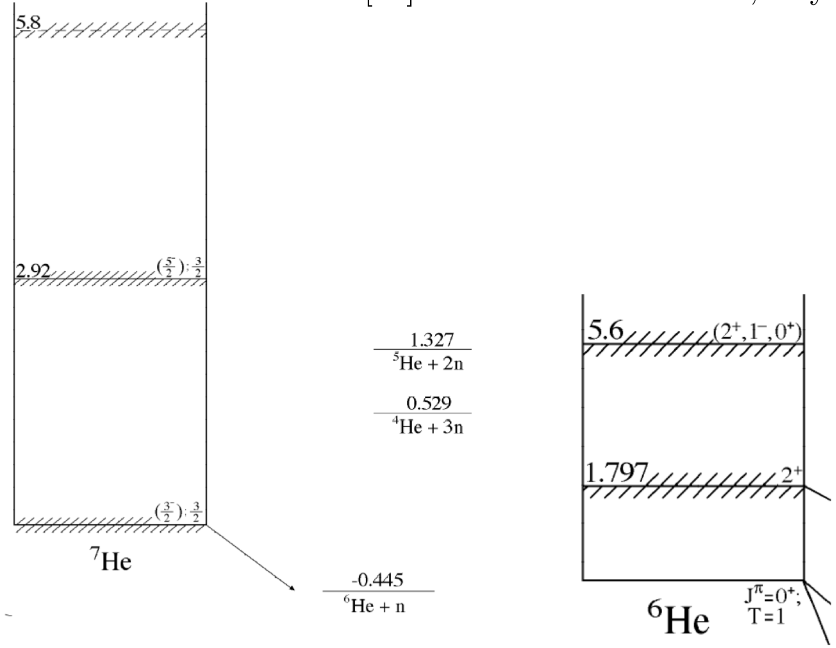
J^π	experiment			NCSMC	
	E_R	Γ	Ref.	E_R	Γ
$3/2^-$	0.430(3)	0.182(5)	[2]	0.71	0.30
$5/2^-$	3.35(10)	1.99(17)	[40]	3.13	1.07
$1/2^-$	3.03(10)	2	[11]	2.39	2.89
	3.53	10	[15]		
	1.0(1)	0.75(8)	[5]		

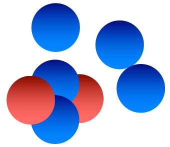
Experimental controversy:
Existence of low-lying 1/2$^-$ state
… not seen in these calculations

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

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

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



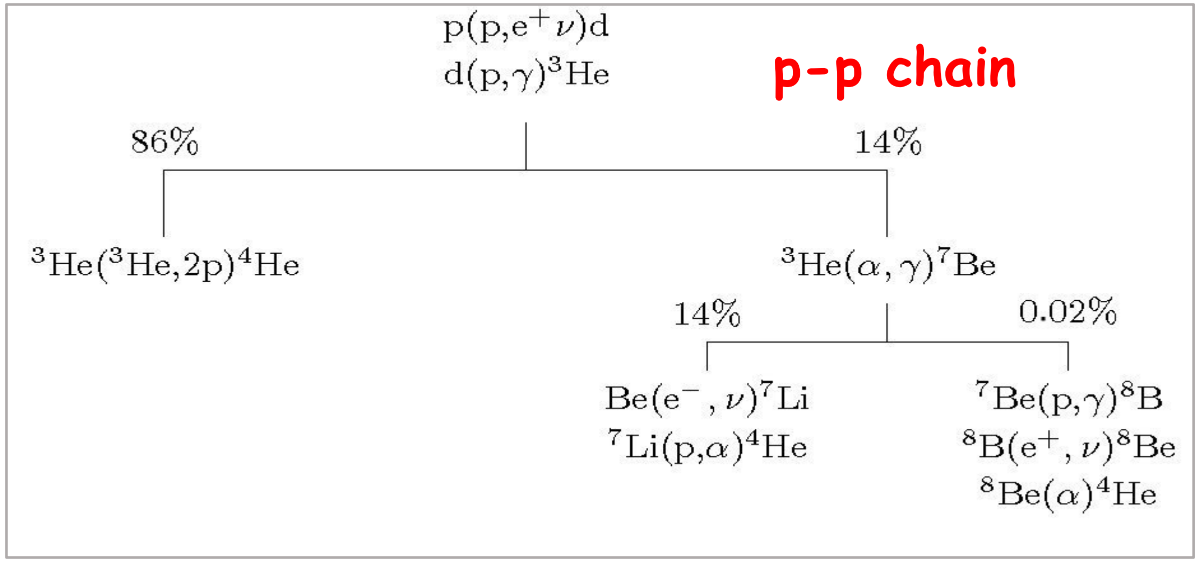


^{7}He unbound

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

p+^{11}C scattering and ^{11}C(p,γ)^{12}N capture

- ^{11}C(p,γ)^{12}N capture relevant in hot *p-p* chain: Link between pp chain and the CNO cycle - bypass of slow triple alpha capture ^{4}He(αα,γ)^{12}C



$$^{3}He(\alpha,\gamma)^{7}Be(\alpha,\gamma)^{11}C(p,\gamma)^{12}N(p,\gamma)^{13}O(\beta^{+},\nu)^{13}N(p,\gamma)^{14}O$$

$$^{3}He(\alpha,\gamma)^{7}Be(\alpha,\gamma)^{11}C(p,\gamma)^{12}N(\beta^{+},\nu)^{12}C(p,\gamma)^{13}N(p,\gamma)^{14}O$$

$$^{11}\mathrm{C}(\beta^{+}\ \nu)^{11}\mathrm{B}(p,\alpha)^{8}\mathrm{Be}(^{4}\mathrm{He},^{4}\mathrm{He})$$

p+^{11}C scattering and ^{11}C(p,γ)^{12}N capture

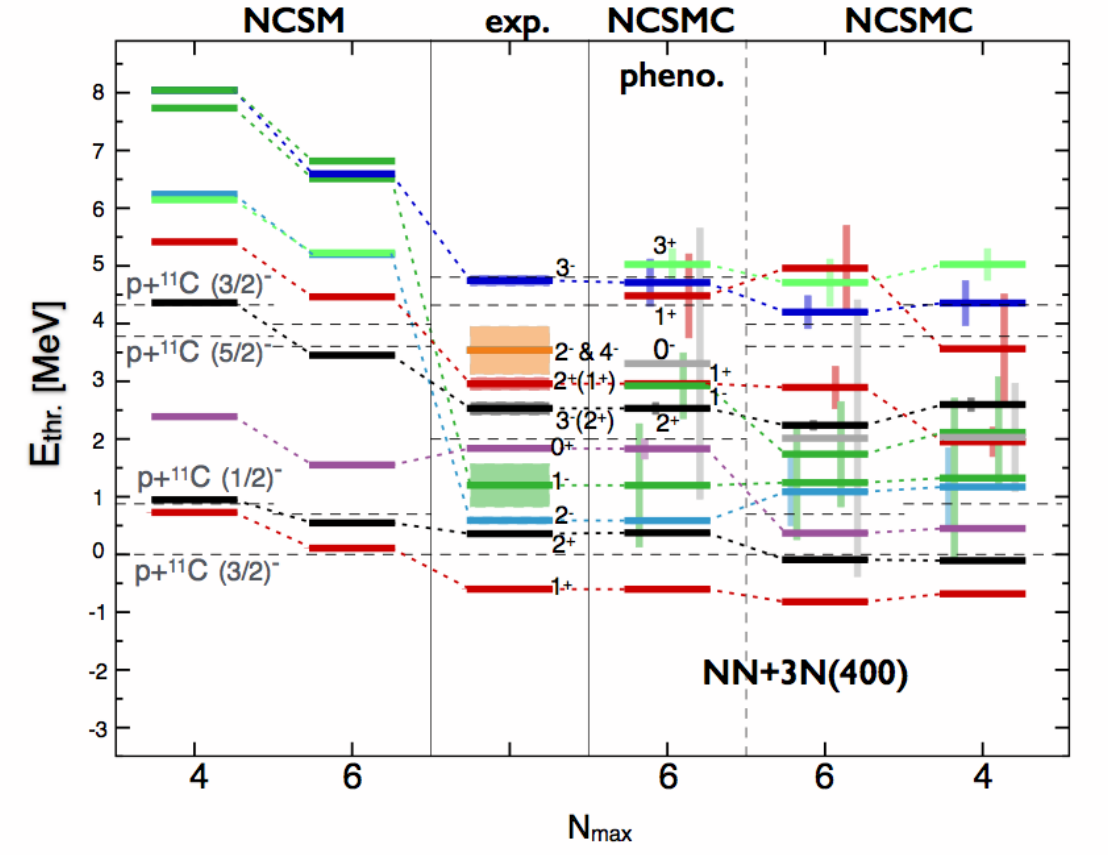
- Measurement of ^{11}C(p,p) resonance scattering planned at TRIUMF
  - TUDA facility
  - ^{11}C beam of sufficient intensity produced
  - Experiment approved with high priority

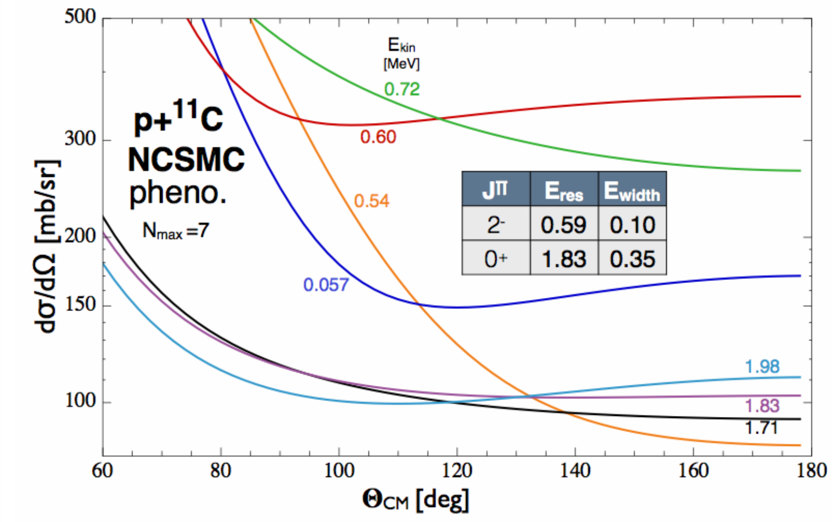
- NCSMC calculations of ^{11}C(p,p) with chiral NN+3N under way

- Obtained wave functions will be used to calculate ^{11}C(p,γ)^{12}N capture relevant for astrophysics

p+^{11}C scattering and ^{11}C(p,γ)^{12}N capture

- NCSMC calculations of ^{11}C(p,p) with chiral NN+3N under way
  - ^{11}C: 3/2$^-$, 1/2$^-$, 5/2$^-$, 3/2$^-$ NCSM eigenstates
  - ^{12}N: ≥6 π = +1 and ≥4 π = -1 NCSM eigenstates

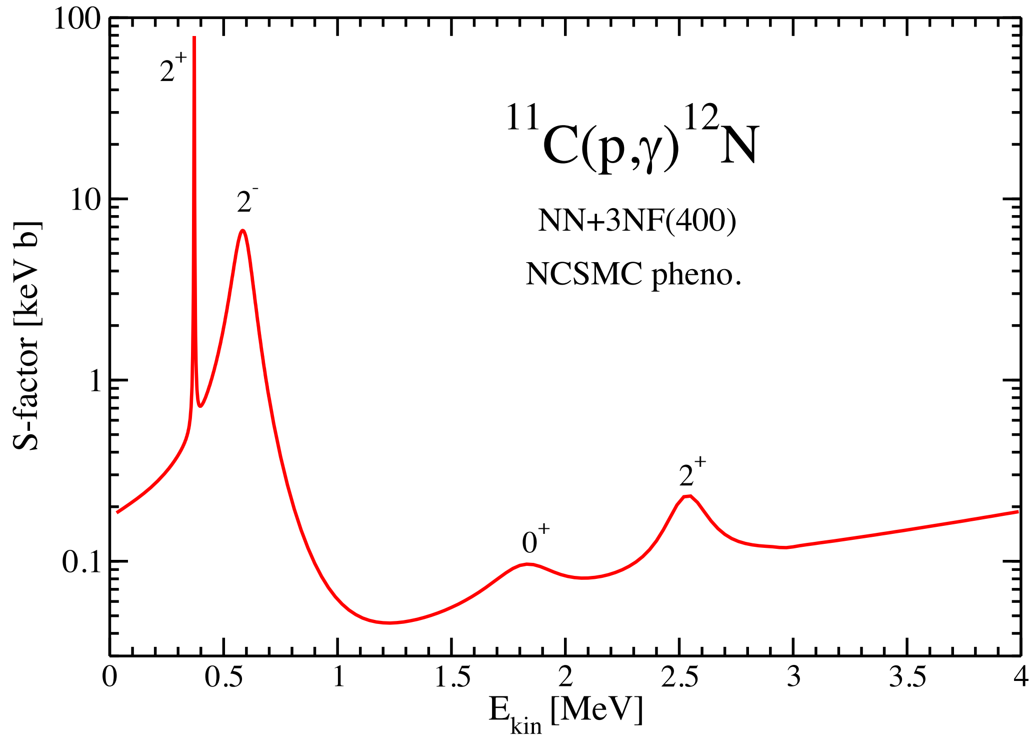


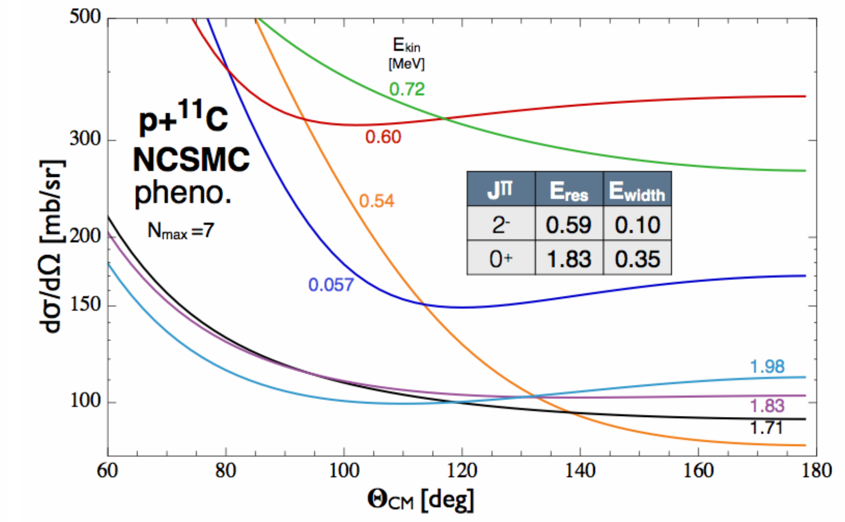


NCSMC calculations to be validated by measured cross sections and applied to calculate the ^{11}C(p,γ)^{12}N capture

p+^{11}C scattering and ^{11}C(p,γ)^{12}N capture

- NCSMC calculations of ^{11}C(p,p) with chiral NN+3N under way
  - ^{11}C: 3/2$^-$, 1/2$^-$, 5/2$^-$, 3/2$^-$ NCSM eigenstates
  - ^{12}N: ≥6 π = +1 and ≥4 π = -1 NCSM eigenstates





NCSMC calculations to be validated by measured cross sections and applied to calculate the ^{11}C(p,γ)^{12}N capture

Conclusions

- *Ab initio* calculations of nuclear structure and reactions with predictive power becoming feasible beyond the lightest nuclei
- *Ab initio* structure calculations can even reach (selected) medium & medium-heavy mass nuclei
- These calculations make connections between the low-energy QCD, many-body systems, and nuclear astrophysics

TRIUMF

Thank you!
Merci!
고맙습니다

Discovery,
accelerated