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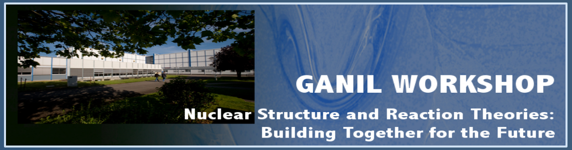
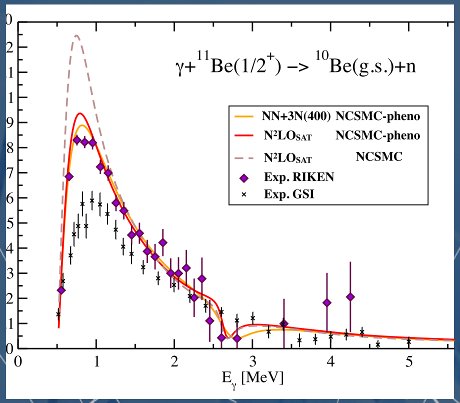
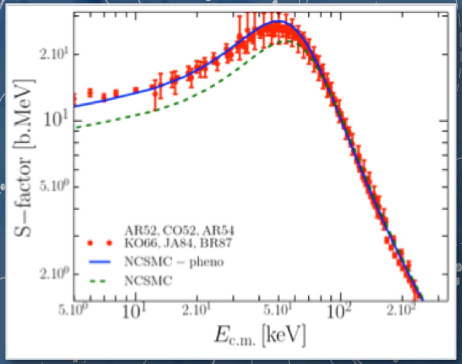


Unifying Nuclear Structure and Reactions: From Light to Medium Mass Nuclei



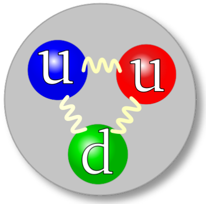
GANIL Topical Meeting
«Nuclear Structure and Reaction Theories: Building Together for the Future»
October 9-13, 2017, GANIL, Caen, France

Petr Navratil | TRIUMF

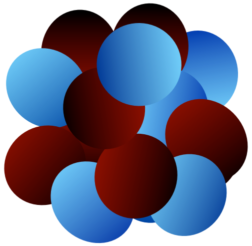


Collabrorators:
Sofia Quaglioni, Carolina Romero-Redondo (LLNL)
Guillaume Hupin (CNRS), **Angelo Calci**, **Matteo Vorabbi** (TRIUMF)
Jeremy Dohet-Eraly (INFN), Klaus Vobig, Robert Roth (TU Darmstadt)

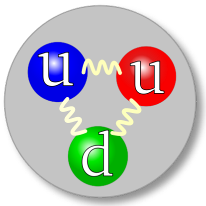
- Nuclear structure and reactions from first principles
- No-Core Shell Model with Continuum (NCSMC) approach
- n-^{4}He scattering, ^{3}H(d,n)^{4}He fusion
- Structure of unbound ^{9}He
- Extension to medium mass nuclei: IM-SRG/RGM
- ^{12}N, ^{11}C(p,p) scattering and ^{11}C(p,γ)^{12}N capture
- ^{11}Be parity inversion in low-lying states, photo-dissociation
- ^{11}N and ^{10}C(p,p) scattering

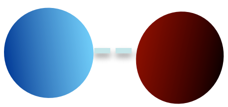


Low-energy QCD



Nuclear structure and reactions

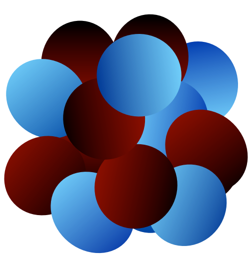




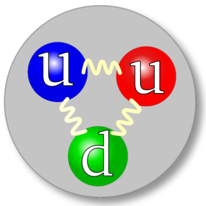
Low-energy QCD

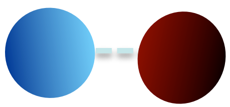
NN+3N interactions from chiral EFT

...or accurate meson-exchange potentials



Nuclear structure and reactions





Low-energy QCD

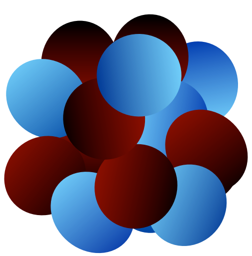
NN+3N interactions from chiral EFT

...or accurate meson-exchange potentials

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

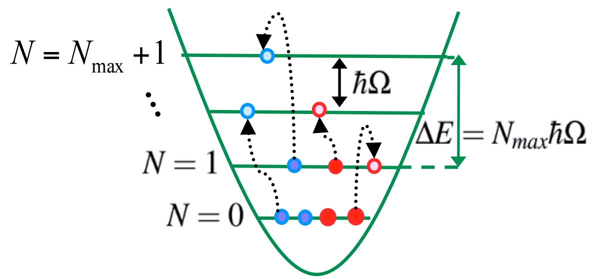
Many-Body methods

NCSM, NCSMC, CCM, IM-SRG, SCGF, GFMC, HH, Nuclear Lattice EFT...

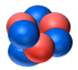


Nuclear structure and reactions

- *Ab initio* no-core shell model
  - Short- and medium range correlations
  - Bound-states, narrow resonances
  - Equivalent description in relative-coordinate and Slater determinant basis



Harmonic oscillator basis



NCSM

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

- *Ab initio* no-core shell model
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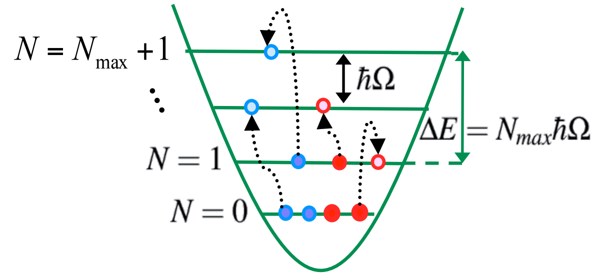
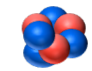


Harmonic oscillator basis



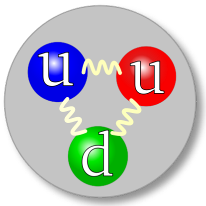
NCSM

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

$$(A) \quad \Psi^A_{\mathrm{SD}} = \sum_{N=0}^{N_{\max}} \sum_j c^{\mathrm{SD}}_{Nj} \Phi^{HO}_{\mathrm{SD}\,Nj}(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A) = \Psi^A \varphi_{000}(\vec{R}_{CM})$$

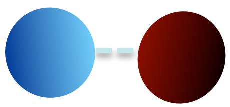
TRIUMF

From QCD to nuclei



Low-energy QCD

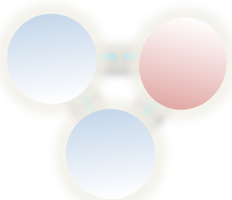
⇩



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

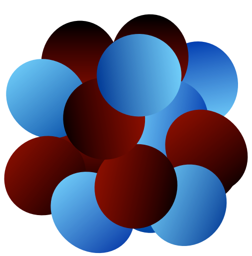
⇩

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

Many-Body methods

NCSM, NCSMC, CCM, IM-SRG, SCGF, GFMC, HH, Nuclear Lattice EFT...

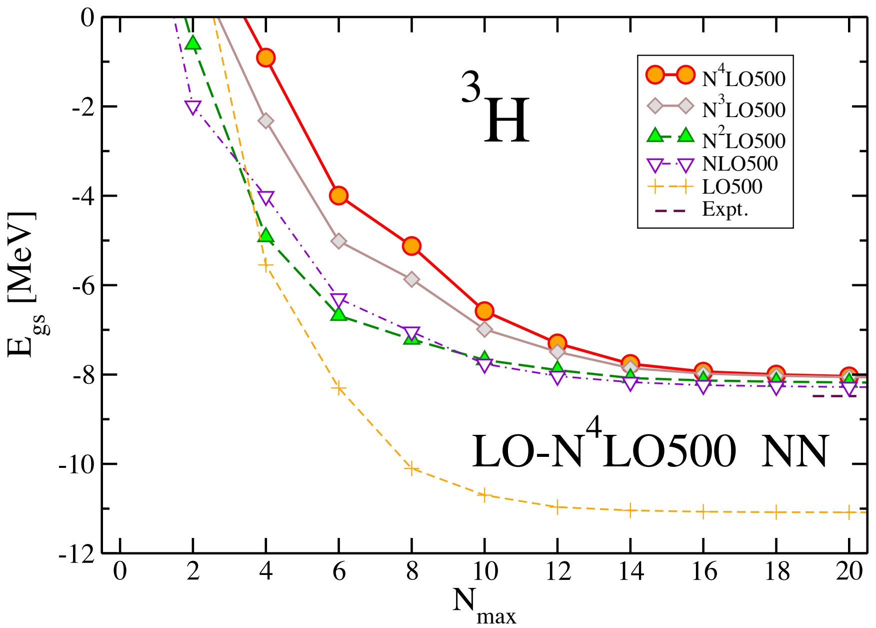
⇩



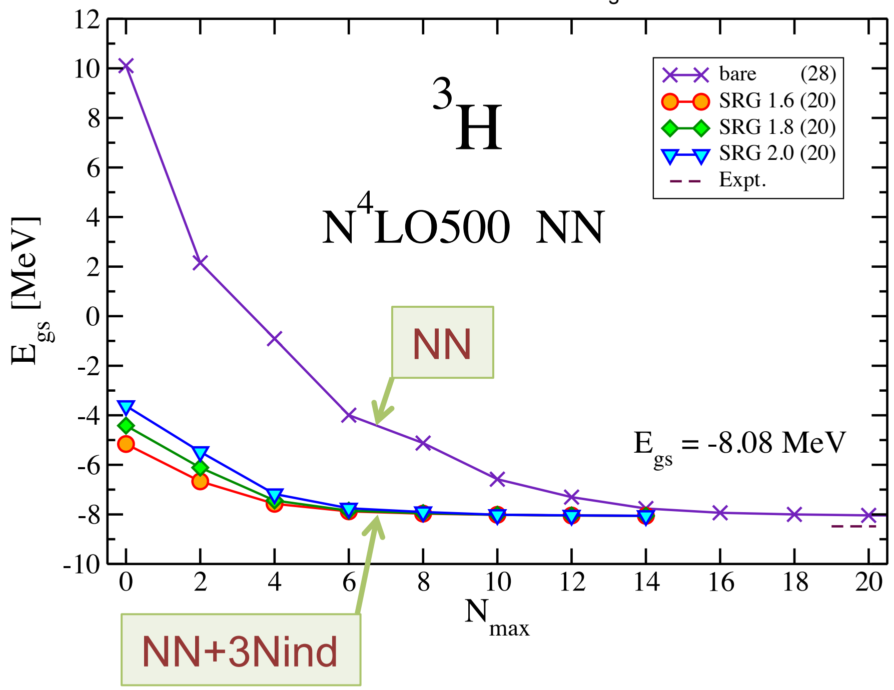
Nuclear structure and reactions

Chiral EFT interactions up to N^4LO

- Systematic from LO to N^4LO
- High precision – χ^2/datum = 1.15
  - D. R. Entem, N. Kaiser, R. Machleidt, and Y. Nosyk, PRC **91**, 014002 (2015)
  - D. R. Entem, R. Machleidt, and Y. Nosyk, PRC **96**, 024004 (2017)



Original EM 2003 N^3LO NN E_{gs}=-7.85 MeV



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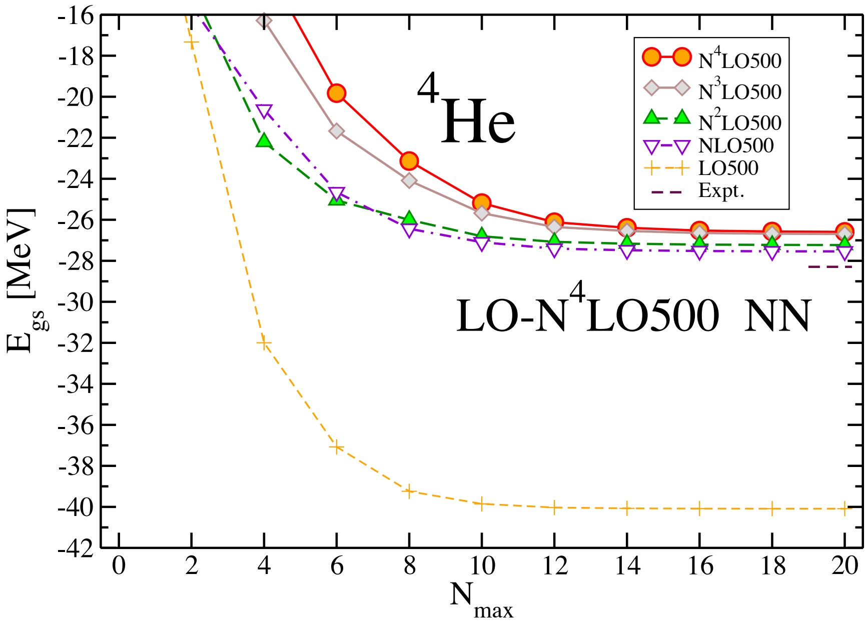
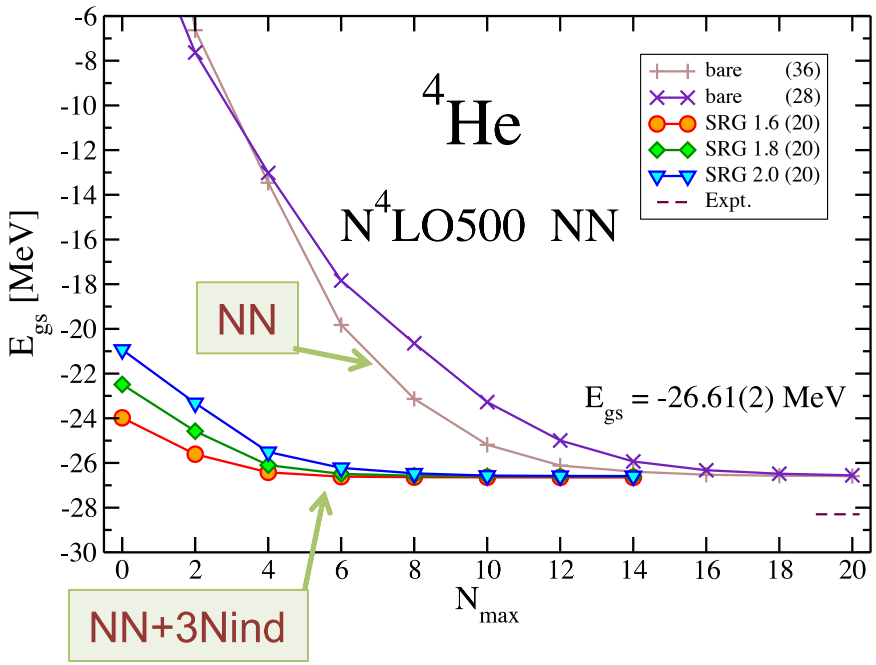
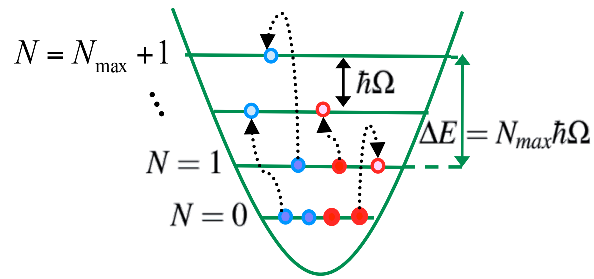


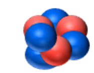
Original EM 2003 N³LO NN E_{gs}=-25.39 MeV



- *Ab initio* no-core shell model
  - Short- and medium range correlations
  - Bound-states, narrow resonances



Harmonic oscillator basis



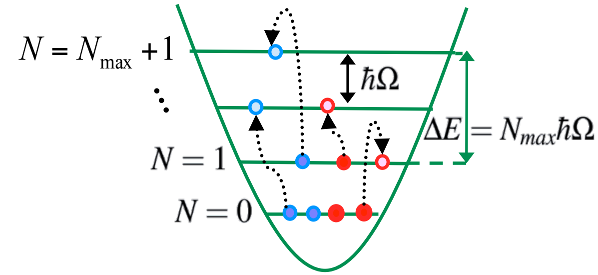
NCSM

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left| {}^{(A)} , \lambda \right\rangle$$

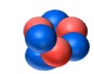
Unknowns

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

- *Ab initio* no-core shell model
  - Short- and medium range correlations
  - Bound-states, narrow resonances

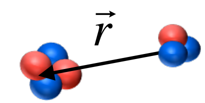


Harmonic oscillator basis



NCSM

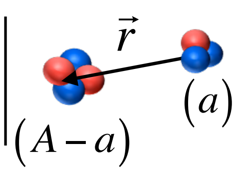
- …with resonating group method
  - Bound & scattering states, reactions
  - Cluster dynamics, long-range correlations



NCSM/RGM

NCSM/RGM channel states

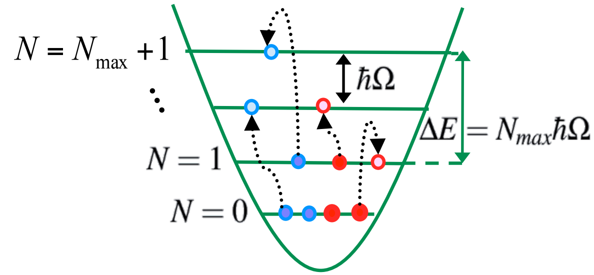
$$\Psi^{(A)} = \sum_{\nu} \int d\vec{r}\; \gamma_{\nu}(\vec{r})\; \hat{A}_{\nu} \underbrace{\left| \quad \right. \quad , \nu \Big\rangle}_{\text{NCSM/RGM channel states}}$$

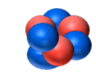


Unknowns

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

- *Ab initio* no-core shell model
  - Short- and medium range correlations
  - Bound-states, narrow resonances





NCSM

- …with resonating group method
  - Bound & scattering states, reactions
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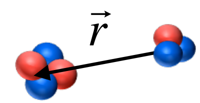


NCSM/RGM

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

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

NCSMC

$$\Psi^{(A)} = \sum_\lambda c_\lambda \overbrace{\left| {}^{(A)}, \lambda \right\rangle}^{\text{NCSM eigenstates}} + \sum_\nu \int d\vec{r}\; \gamma_\nu(\vec{r})\; \hat{A}_\nu \overbrace{\left| {}_{(A-a)} \; \vec{r} \; {}_{(a)}, \nu \right\rangle}^{\text{NCSM/RGM channel states}}$$

Unknowns

Coupled NCSMC equations

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

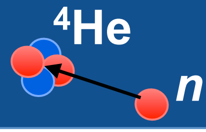
$$\Psi^{(A)} = \sum_\lambda c_\lambda \left| {}^{(A)}, \lambda \right\rangle + \sum_\nu \int d\vec{r}\; \gamma_\nu(\vec{r})\; \hat{A}_\nu \left| {}_{(A-a)} \quad \vec{r} \quad {}_{(a)}, \nu \right\rangle$$

$$E_\lambda^{NCSM}\,\delta_{\lambda\lambda'} \qquad \left\langle {}^{(A)} \right| H\,\hat{A}_\nu \left| {}_{(a)} \quad r \quad {}_{(A-a)} \right\rangle \qquad \delta_{\lambda\lambda'} \qquad \left\langle {}^{(A)} \right| \hat{A}_\nu \left| {}_{(a)} \quad r \quad {}_{(A-a)} \right\rangle$$

$$\begin{pmatrix} H_{NCSM} & h \\ h & H_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix} = E \begin{pmatrix} 1_{NCSM} & g \\ g & N_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix}$$

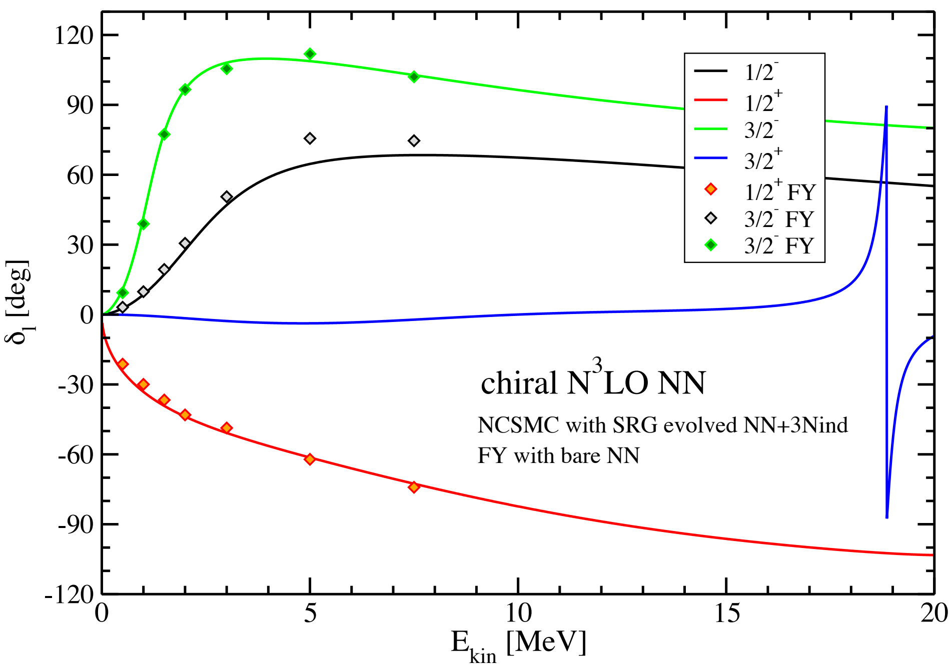
$$\left\langle {}_{(A-a)} \quad r' \quad {}_{(a)} \right| \hat{A}_{\nu'}\, H\, \hat{A}_\nu \left| {}_{(a)} \quad r \quad {}_{(A-a)} \right\rangle \qquad \left\langle {}_{(A-a)} \quad r' \quad {}_{(a)} \right| \hat{A}_{\nu'}\, \hat{A}_\nu \left| {}_{(a)} \quad r \quad {}_{(A-a)} \right\rangle$$

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



n-⁴He scattering within NCSMC

n-⁴He scattering phase-shifts for chiral NN



FY: Faddeev-Yakubovsky method - Rimantas Lazauskas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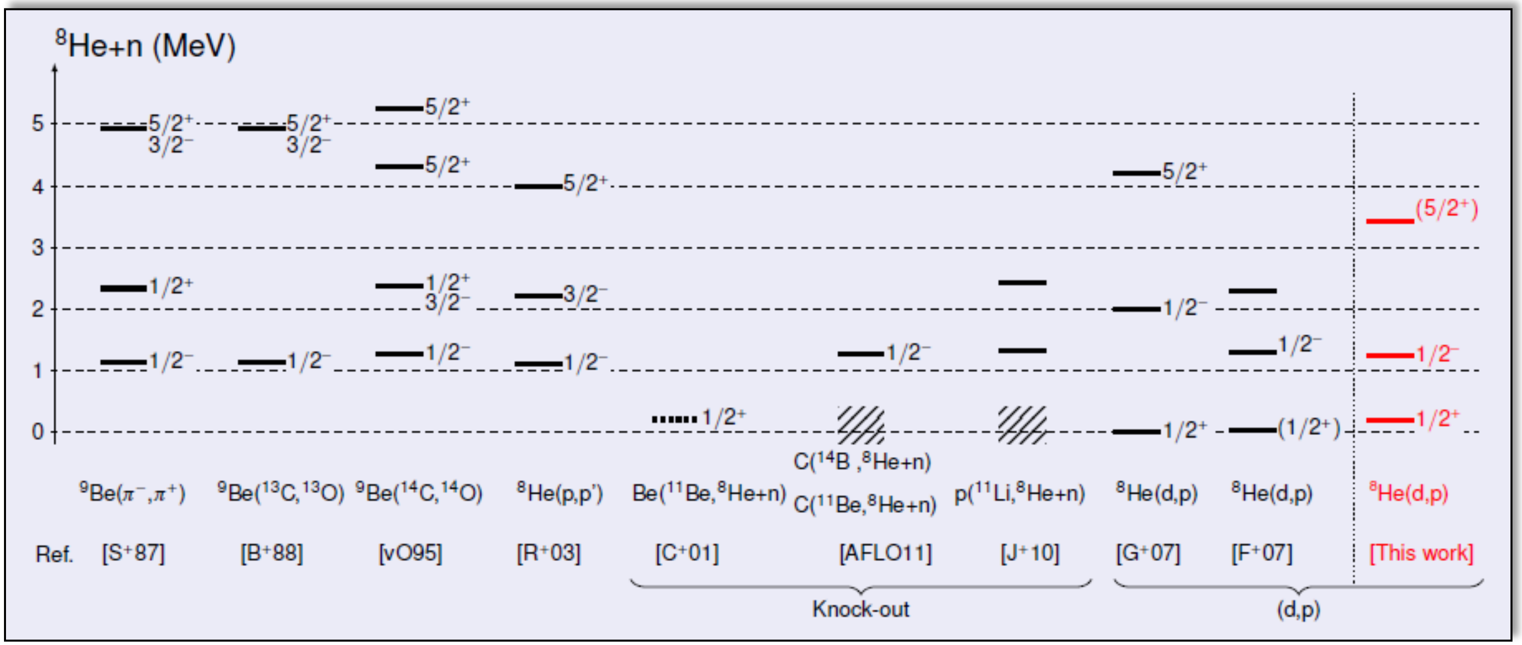
Phys. Scr. 00 (2016) 000000 (37pp)

Invited Comment

Unified *ab initio* approaches to nuclear structure and reactions

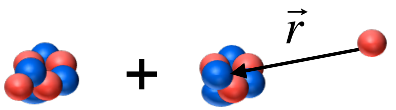
Petr Navrátil[1], Sofia Quaglioni[2], Guillaume Hupin[3,4], Carolina Romero-Redondo[2] and Angelo Calci[1]

- Controversial experimental situation
  - From talk by Nigel Orr at ECT* in 2013



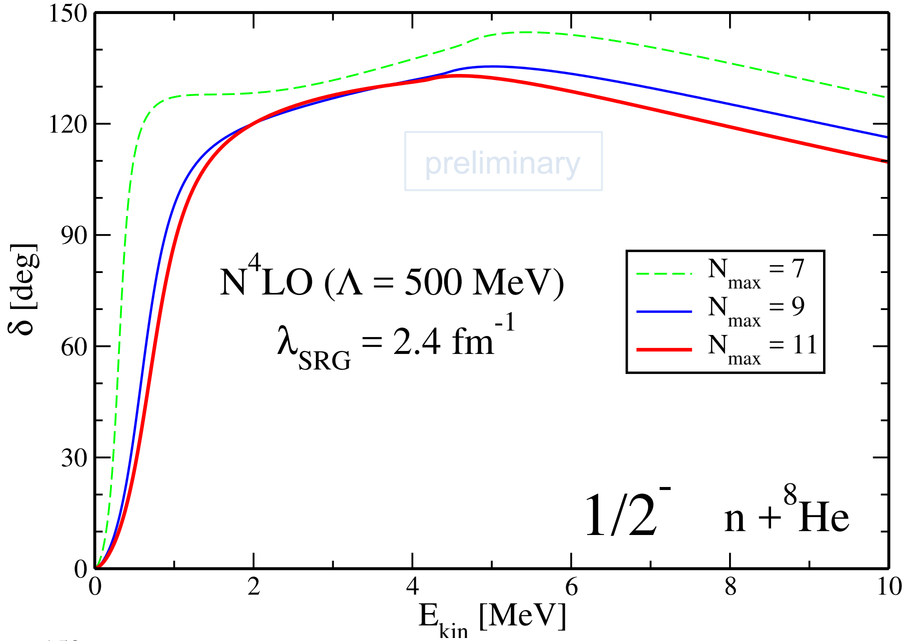
  - Most experiments see 1/2$^-$ resonance ~ 1 MeV
  - Is there a 1/2$^+$ resonance?
    - a_0~ -10 fm (Chen et al.)
    - a_0~ -3 fm (Al Falou, et al.)
  - Any higher-lying resonances?
  - Recent ^{8}He(p,p) measurement at TRIUMF by Rogachev found no T=5/2 resonances (PLB 754 (2016) 323)

- NCSMC calculations with several NN and NN+3N interactions
  - ^{9}He ~ $(^{9}\mathrm{He})_{\mathrm{NCSM}}$ + $(\mathrm{n}\text{-}^{8}\mathrm{He})_{\mathrm{NCSM/RGM}}$

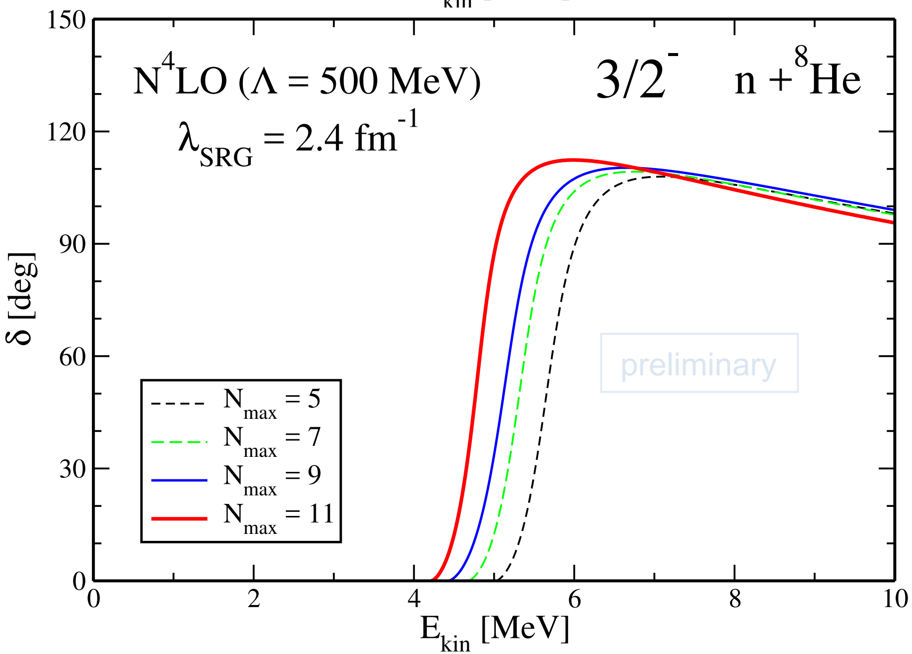


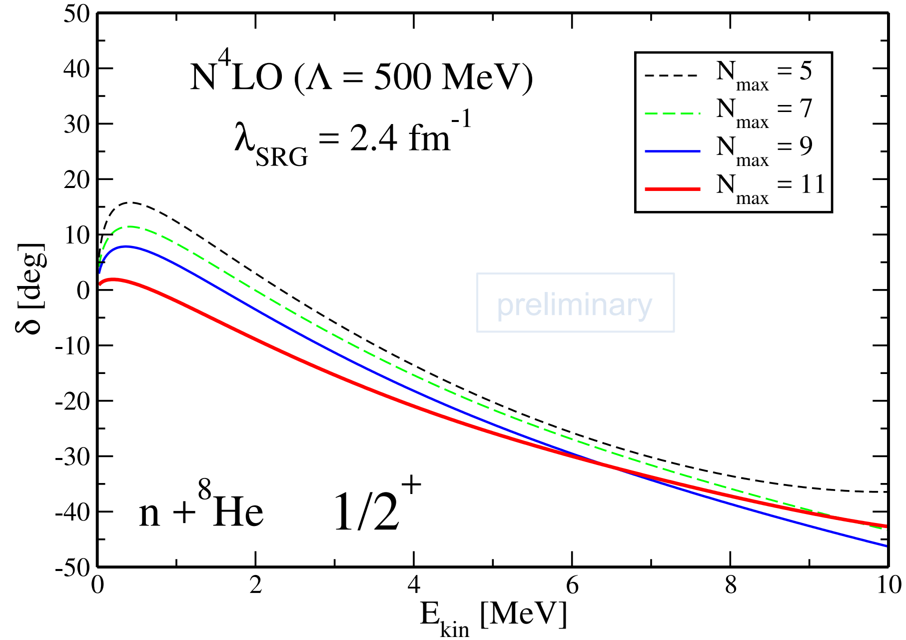
    - ^{8}He: 0^{+} and 2^{+} NCSM eigenstates
    - ^{9}He: ≥4 π = -1 and ≥4 π = +1 NCSM eigenstates
  - Importance of large N_{max} basis:
    - SRG-N^{4}LO500 NN with λ=2.4 fm^{-1}
      - up to N_{max}=11 with ^{9}He NCSM m-scheme basis of 350 million

G.s. energy [MeV]	^{4}He	^{6}He	^{8}He
SRG-N^{4}LO500 λ=2.4	-28.36	-28.9(2)	-30.1(2)
Expt	-28.30	-29.27	-31.41



Phase shift convergence with SRG-N^{4}LO500 NN λ=2.4 fm^{-1}





NCSMC phenomenology

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

$$E_{\lambda}^{NCSM}\,\delta_{\lambda\lambda'} \qquad \left\langle {}^{(A)} \right| H\,\hat{A}_{\nu} \left| {}_{(a)} \; r \; {}_{(A-a)} \right\rangle \qquad \delta_{\lambda\lambda'} \qquad \left\langle {}^{(A)} \right| \hat{A}_{\nu} \left| {}_{(a)} \; r \; {}_{(A-a)} \right\rangle$$

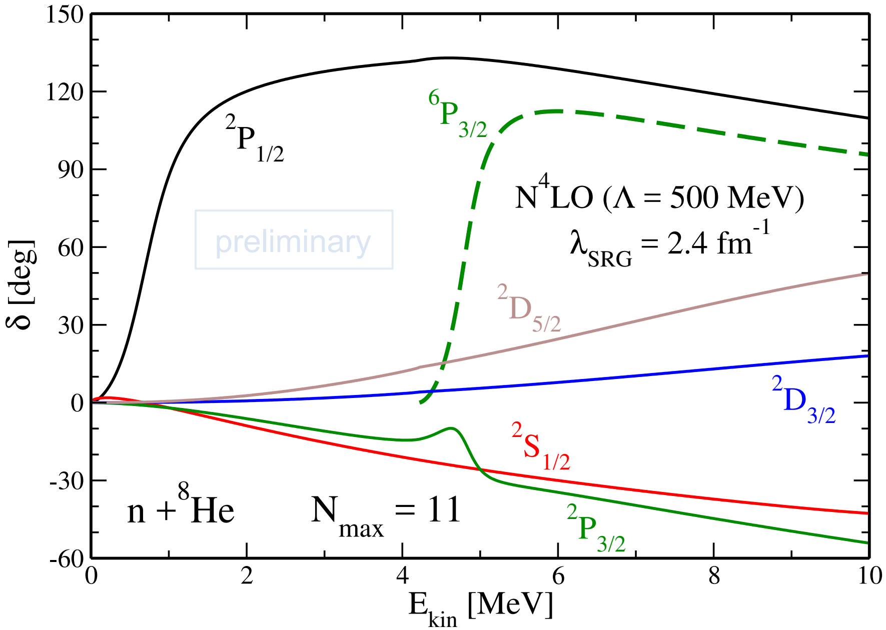
$$\begin{pmatrix} H_{NCSM} & h \\ h & H_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix} = E \begin{pmatrix} 1_{NCSM} & g \\ g & N_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix}$$

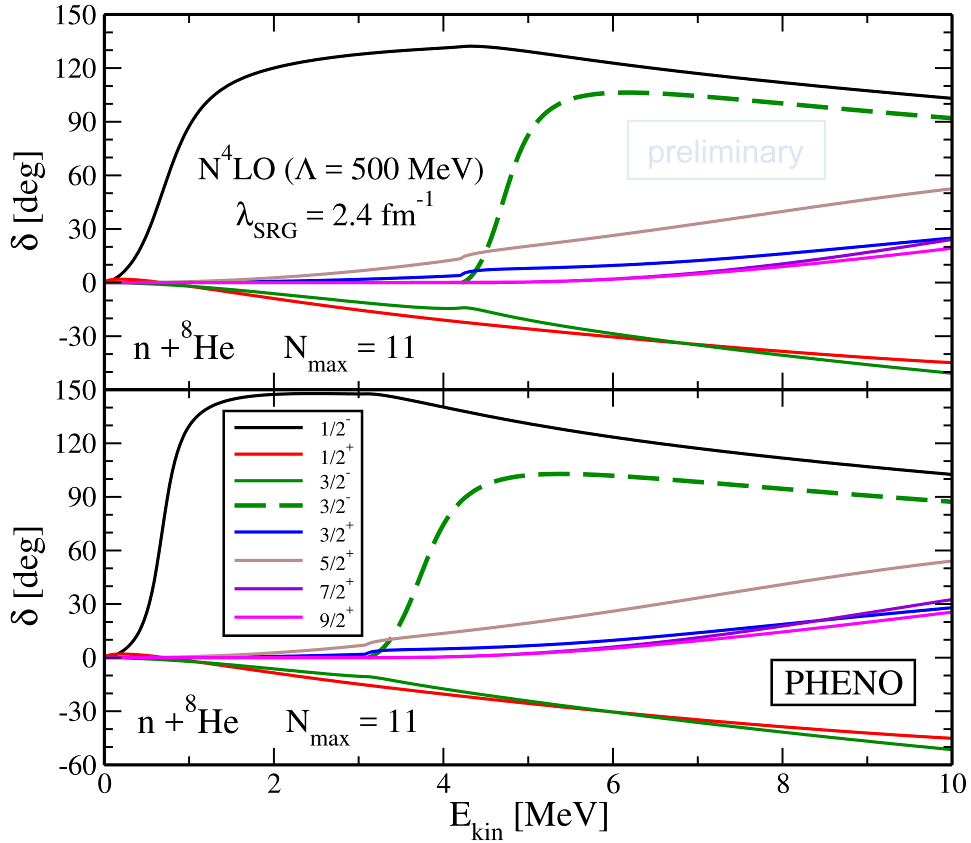
$$\left\langle {}_{(A-a)} \; r' \; {}_{(a)} \right| \hat{A}_{\nu'}\, H\, \hat{A}_{\nu} \left| {}_{(a)} \; r \; {}_{(A-a)} \right\rangle \qquad \left\langle {}_{(A-a)} \; r' \; {}_{(a)} \right| \hat{A}_{\nu'}\, \hat{A}_{\nu} \left| {}_{(a)} \; r \; {}_{(A-a)} \right\rangle$$

$E_{\lambda}^{\mathrm{NCSM}}$ energies treated as adjustable parameters

Cluster excitation energies set to experimental values

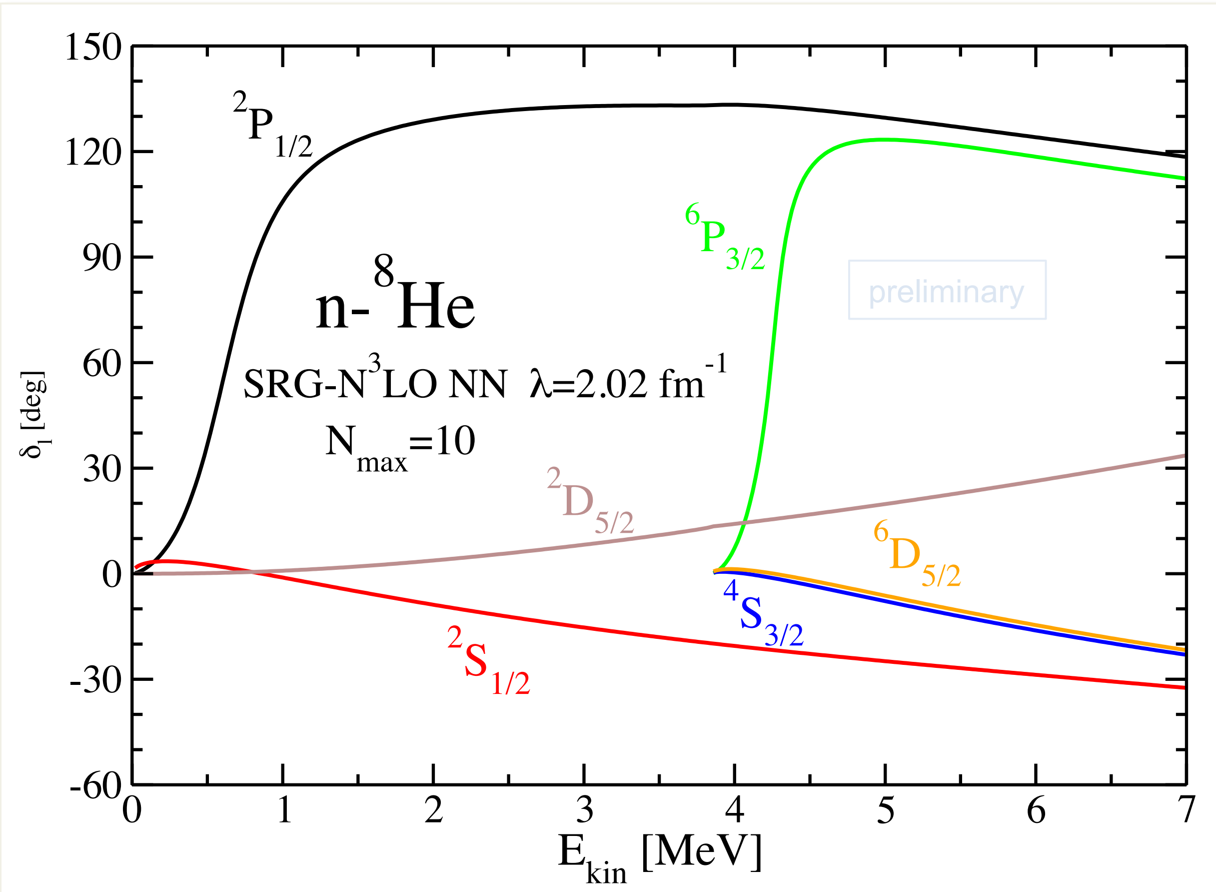
Phase shift and eigenphase shifts with SRG-N^{4}LO500 NN λ=2.4 fm^{-1}

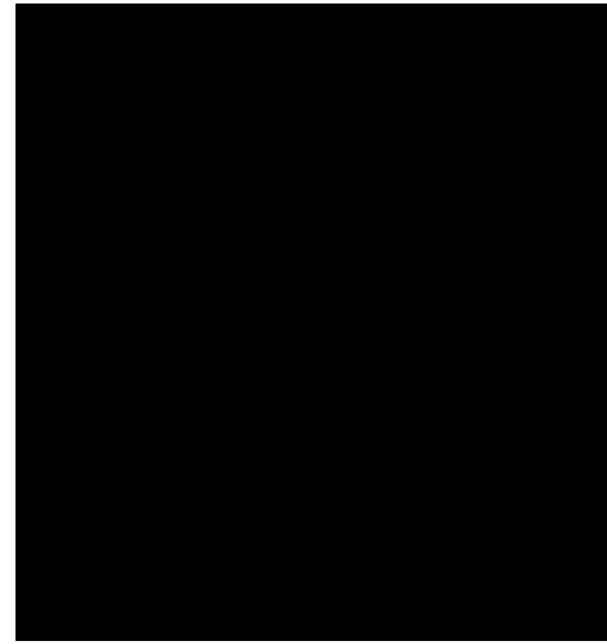




Robust results for **1/2$^-$** (~ 1MeV) and **3/2$^-$** (~4 MeV) **P-wave** resonances
(3/2$^-$ resonance in n-^{8}He(2$^+$) channel)
1/2$^+$ S-wave with vanishing scattering length: a_s= 0 ~ -1 fm
No evidence for other higher lying resonances

^{9}He resonances

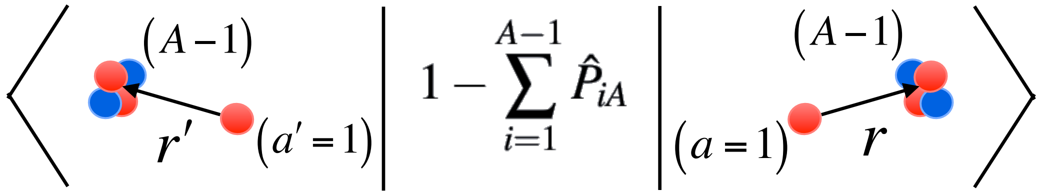




NCSMC with **chiral SRG-N^{3}LO *NN*** potential (lambda=2.02 fm^{-1})
^{8}He 0^{+}_{1} and 2^{+}_{1} included
$1/2^{-}$ and $3/2^{-}$ P-wave resonances found
$1/2^{+}$ S-wave with small scattering length: SRG NN a_s= -1 fm

Norm kernel (Pauli principle): Single-nucleon projectile

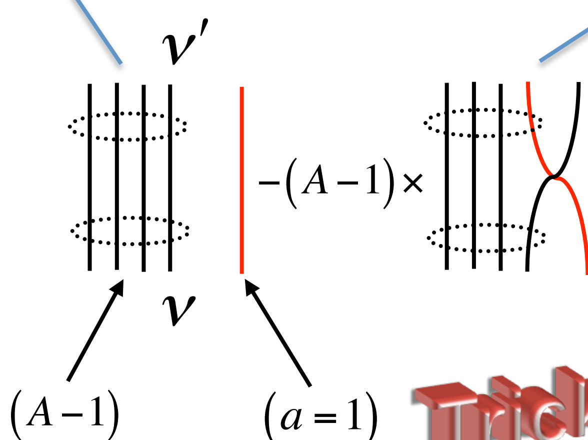
$$\left\langle \Phi^{J^\pi T}_{\nu' r'} \middle| \hat{A}_{\nu'} \hat{A}_{\nu} \middle| \Phi^{J^\pi T}_{\nu r} \right\rangle =$$



$$N^{J^\pi T}_{\nu'\nu}(r',r) = \underbrace{\delta_{\nu'\nu} \frac{\delta(r'-r)}{r'r}} - \underbrace{(A-1) \sum_{n'n} R_{n'\ell'}(r') R_{n\ell}(r) \left\langle \Phi^{J^\pi T}_{\nu' n'} \middle| \hat{P}_{A-1,A} \middle| \Phi^{J^\pi T}_{\nu n} \right\rangle}$$

$${}_{\mathrm{SD}}\left\langle \psi^{(A-1)}_{\mu_1} \middle| a^{+} a \middle| \psi^{(A-1)}_{\nu_1} \right\rangle_{\mathrm{SD}}$$

Direct term:
Treated exactly!
(in the full space)



Exchange term:
Obtained in the model space!
(Many-body correction due to the exchange part of the inter-cluster antisymmetrizer)

Trick #1 $\dfrac{\delta(r - r_{A-a,a})}{r\, r_{A-a,a}} = \sum_n R_{n\ell}(r) R_{n\ell}(r_{A-a,a})$

Trick #2 Target wave functions expanded in the SD basis, the CM motion exactly removed

Introduce SD channels in the HO space

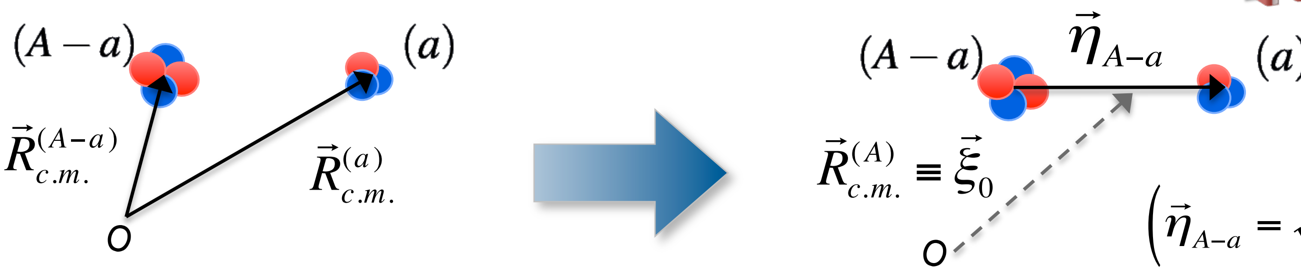
- Define SD channel states in which the eigenstates of the heaviest of the two clusters (target) are described by a SD wave function:

$$\left|\Phi^{J^\pi T}_{\nu n}\right\rangle_{SD} = \Big[\Big(\underbrace{\left|A-a\ \alpha_1 I_1^{\pi_1} T_1\right\rangle_{SD}}_{\left|A-a\ \alpha_1 I_1^{\pi_1} T_1\right\rangle \varphi_{00}\left(\vec{R}^{(A-a)}_{c.m.}\right)} \left|a\ \alpha_2 I_2^{\pi_2} T_2\right\rangle \Big)^{(sT)} Y_\ell\left(\hat{R}^{(a)}_{c.m.}\right)\Big]^{(J^\pi T)} R_{n\ell}\left(R^{(a)}_{c.m.}\right)$$

Vector proportional to the c.m. coordinate of the A-a nucleons

Vector proportional to the c.m. coordinate of the a nucleons

Trick #2



$$\left(\vec{\eta}_{A-a} = \sqrt{\tfrac{(A-a)a}{A}}\,\vec{r}_{A-a,a}\right)$$

$$\left(\varphi_{00}\left(\vec{R}^{(A-a)}_{c.m.}\right)\varphi_{n\ell}\left(\vec{R}^{(a)}_{c.m.}\right)\right)^{\ell} = \sum_{n_r\ell_r,NL} \left\langle 00, n\ell, \ell \middle| n_r\ell_r, NL, \ell\right\rangle_{d=\frac{a}{A-a}} \left(\varphi_{n_r\ell_r}\left(\vec{\eta}_{A-a}\right)\varphi_{NL}\left(\vec{\xi}_0\right)\right)^{\ell}$$

Translationally invariant matrix elements from SD ones

- More in detail:

$$\left|\Phi^{J^\pi T}_{\nu n}\right\rangle_{SD} = \sum_{n_r\ell_r,NL,J_r} \hat{\ell}\hat{J}_r(-1)^{s+\ell_r+L+J} \begin{Bmatrix} s & \ell_r & J_r \\ L & J & \ell \end{Bmatrix} \langle 00,n\ell,\ell | n_r\ell_r,NL,\ell\rangle_{d=\frac{a}{A-a}} \left[\left|\Phi^{J_r^{\pi_r}T}_{\nu_r n_r}\right\rangle \varphi_{NL}(\vec{\xi}_0)\right]^{(J^\pi T)}$$

- The spurious motion of the c.m. is mixed with the intrinsic motion

$$\boxed{{}_{SD}\left\langle \Phi^{J^\pi T}_{\nu' n'}\right|\hat{O}\left|\Phi^{J^\pi T}_{\nu n}\right\rangle_{SD}} = \sum_{n'_r\ell'_r,n_r\ell_r,J_r} \left\langle \Phi^{J_r^{\pi_r}T}_{\nu'_r n'_r}\right|\hat{O}\left|\Phi^{J_r^{\pi_r}T}_{\nu_r n_r}\right\rangle$$

$$\boxed{\begin{aligned}&\times\sum_{NL} \hat{\ell}\hat{\ell}'\hat{J}_r^2(-1)^{s+\ell-s'-\ell'} \begin{Bmatrix} s & \ell_r & J_r \\ L & J & \ell \end{Bmatrix}\begin{Bmatrix} s' & \ell'_r & J_r \\ L & J & \ell' \end{Bmatrix} \\ &\times\langle 00,n\ell,\ell | n_r\ell_r,NL,\ell\rangle_{d=\frac{a}{A-a}} \langle 00,n'\ell',\ell' | n'_r\ell'_r,NL,\ell'\rangle_{d'=\frac{a'}{A-a'}}\end{aligned}}$$

Interested in this

Trick #2

Calculate these

Matrix that can be inverted

- Translational invariance preserved (exactly!) also with SD channels
- Transformation is general: same for different A's or different a's

Advantage of SD channel basis

- SD to Jacobi transformation is general and exact
- Can use powerful second quantization representation
  - Matrix elements of translational invariant operators can be expressed in terms of matrix elements of density operators on the target eigenstates
  - For example, for $a = a' = 1$

$$
{}_{SD}\left\langle \Phi^{J^\pi T}_{\nu' n'} \middle| P_{A-1,A} \middle| \Phi^{J^\pi T}_{\nu n} \right\rangle_{SD} = \frac{1}{A-1} \sum_{jj'K\tau} \hat{s}\hat{s}'\hat{j}\hat{j}'\hat{K}\hat{\tau} (-1)^{I_1'+j'+J} (-1)^{T_1+\frac{1}{2}+T}
$$

$$
\times \begin{Bmatrix} I_1 & \frac{1}{2} & s \\ \ell & J & j \end{Bmatrix} \begin{Bmatrix} I_1' & \frac{1}{2} & s' \\ \ell' & J & j' \end{Bmatrix} \begin{Bmatrix} I_1 & K & I_1' \\ j' & J & j \end{Bmatrix} \begin{Bmatrix} T_1 & \tau & T_1' \\ \frac{1}{2} & T & \frac{1}{2} \end{Bmatrix}
$$

One-body density matrix elements

$$
\times \boxed{ {}_{SD}\left\langle A-1\ \alpha_1' I_1'^{\pi_1'} T_1' \right\| \left(a^{+}_{n\ell j \frac{1}{2}} \tilde{a}_{n'\ell' j' \frac{1}{2}} \right)^{(K\tau)} \left\| A-1\ \alpha_1 I_1^{\pi_1} T_1 \right\rangle_{SD} }
$$

- Given a, a', matrix elements are also general (same for different A's)

- Basic idea: Compute SD densities using a method applicable to medium mass nuclei
  - IM-SRG
  - CCM

- Hypothesis: At convergence

$$\boxed{{}_{SD}\left\langle A-1\ \alpha_1' I_1'^{\pi_1'} T_1' \right\| \left(a^{+}_{n\ell j\frac{1}{2}} \tilde{a}_{n'\ell' j'\frac{1}{2}} \right)^{(K)} \left\| A-1\ \alpha_1 I_1^{\pi_1} T_1 \right\rangle_{SD} \ \text{NCSM}}$$

$$\approx$$

$$\boxed{{}_{SD}\left\langle A-1\ \alpha_1' I_1'^{\pi_1'} T_1' \right\| \left(a^{+}_{n\ell j\frac{1}{2}} \tilde{a}_{n'\ell' j'\frac{1}{2}} \right)^{(K)} \left\| A-1\ \alpha_1 I_1^{\pi_1} T_1 \right\rangle_{SD} \ \text{IM-SRG}}$$

  - Applies also to higher-body densities

- IM-SRG aims at decoupling a reference state $|\phi\rangle$ from its particle-hole excitations
- IM-SRG(Magnus): calculate unitary transformation $\hat{U}(s) \equiv \exp(\hat{\Omega}(s))$ via SRG flow equation approach

$$\frac{d}{ds}\hat{\Omega}(s) = \sum_{k=0} \frac{B_k}{k!}[\hat{\Omega}(s), \hat{\eta}(s)]$$

- one-body density matrix elements formally given as

$$\rho^1_2 = \langle\phi| \hat{U}^\dagger(s)\tilde{a}^1_2\hat{U}(s)|\phi\rangle$$

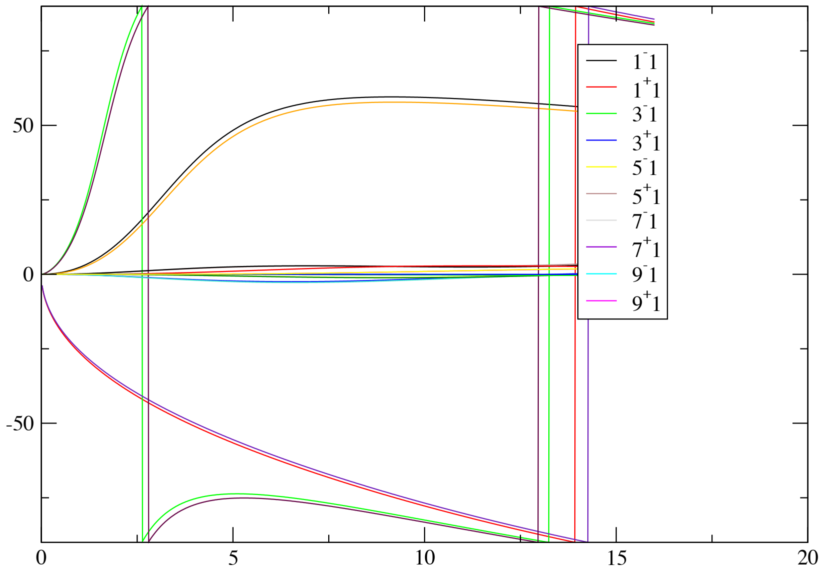
- write unitary transformation via Baker-Campbell-Hausdorff series

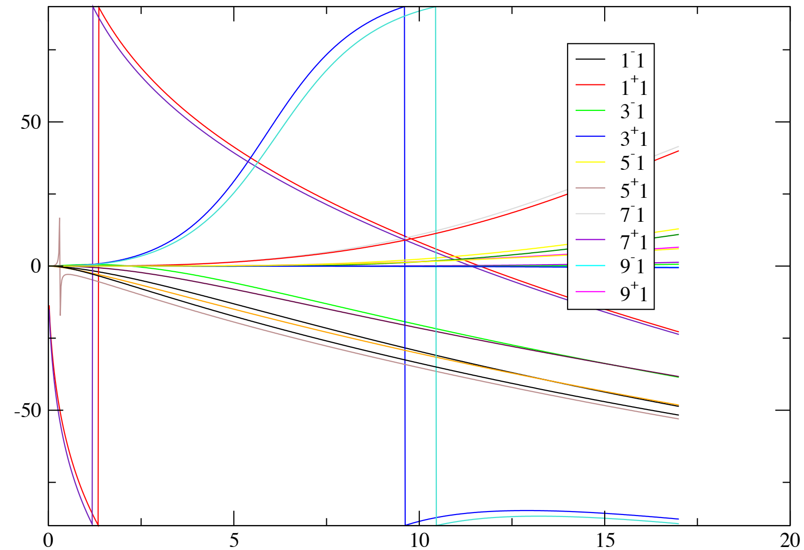
$$\rho^1_2 = \langle\phi| \sum_{k=0}^{\infty}[\hat{\Omega}, \tilde{a}^1_2]_k |\phi\rangle$$
$$= \langle\phi| \tilde{a}^1_2 |\phi\rangle + \langle\phi| [\hat{\Omega}, \tilde{a}^1_2] |\phi\rangle + \langle\phi| [\hat{\Omega}, [\hat{\Omega}, \tilde{a}^1_2]] |\phi\rangle + \ldots$$

- derive equations for density matrix in terms of matrix elements of $\hat{\Omega}(s)$
- complexity of equations scales severely with BCH order $k \rightsquigarrow$ truncate at $k = 2$

Preliminary tests: NCSM/RGM vs. IM-SRG/RGM

- IM-SRG/RGM current status:
  - One-body density from IM-SRG
    - Norm kernel and direct part of NN potential kernel
  - two-body density from NCSM
    - Exchange part of the NN potential kernel
- Benchmarks (model spaces not at convergence yet)
  - n-^{4}He (SRG-N^{3}LO NN, λ=2 fm^{-1})
  - n-^{16}O (SRG-N^{3}LO NN, λ=2.66 fm^{-1})

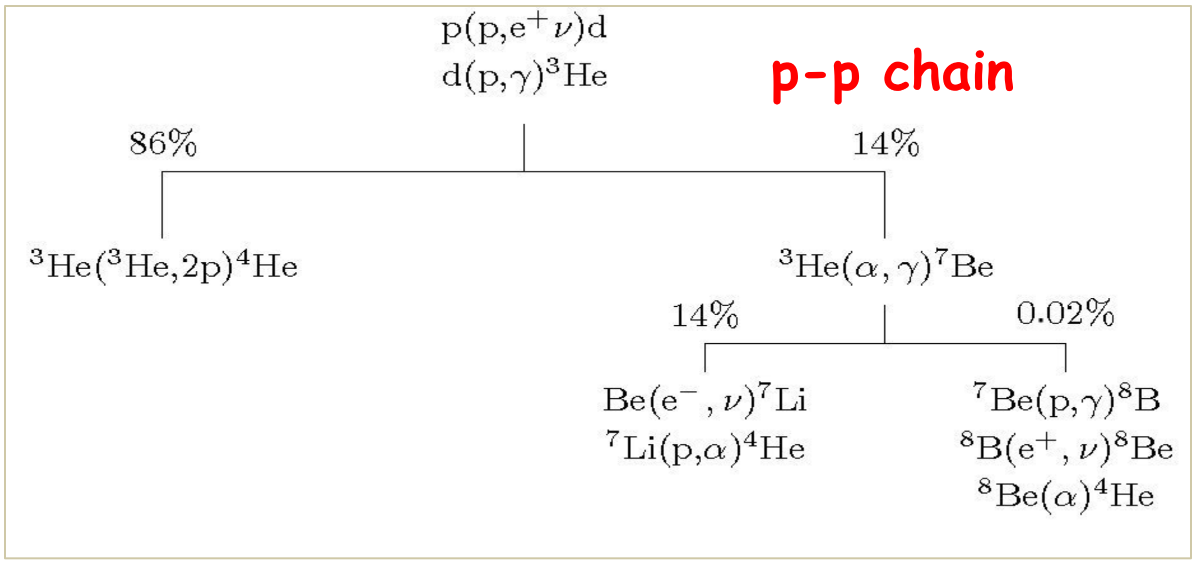




Promising. IM-SRG two-body density calculation under way.
Opens door to calculations of nucleon scattering on medium mass nuclei.

- Measurement of ${}^{11}C(p,p)$ resonance scattering planned at TRIUMF
  - TUDA facility
  - ${}^{11}C$ beam of sufficient intensity produced
- NCSMC calculations of ${}^{11}C(p,p)$ with chiral NN+3N under way
- Obtained wave functions will be used to calculate ${}^{11}C(p,\gamma){}^{12}N$ capture relevant for astrophysics

- ^{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



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

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

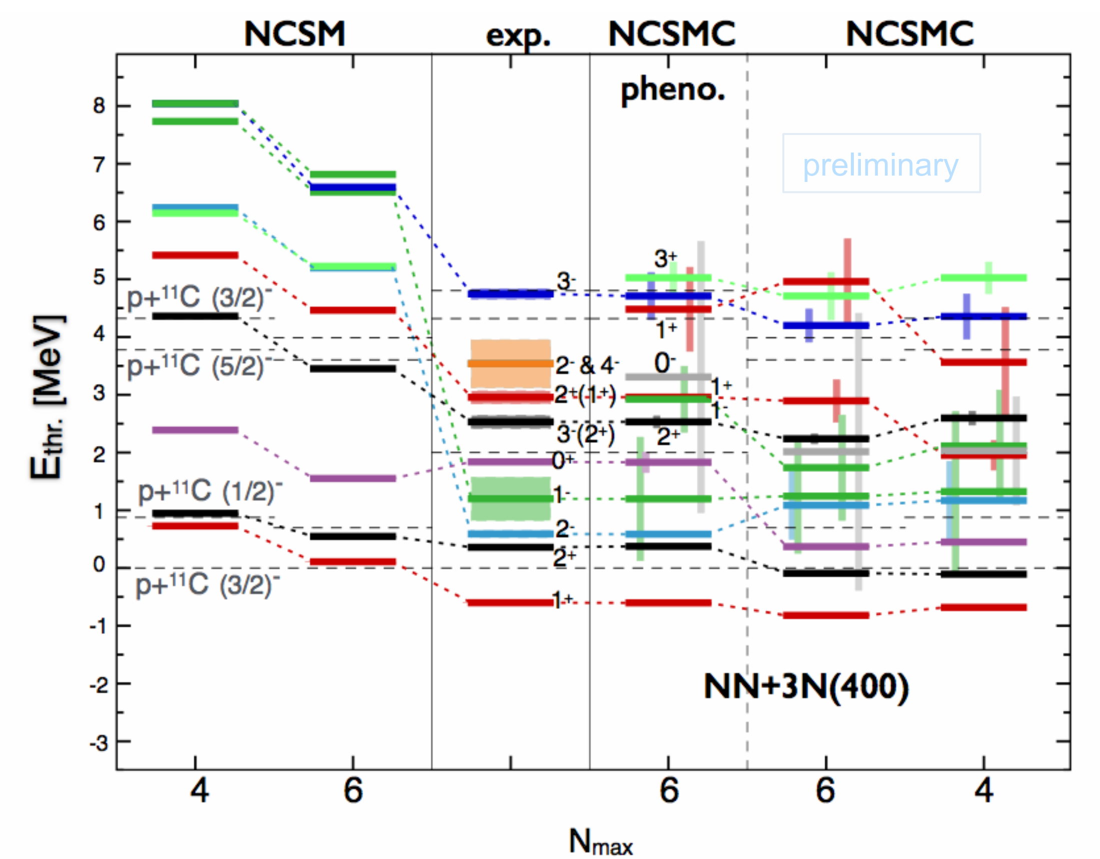
$$^{11}\mathrm{C}(\beta^{+}\ \nu)^{11}\mathrm{B}(p,\alpha)^{8}\mathrm{Be}(^{4}\mathrm{He},^{4}\mathrm{He})$$

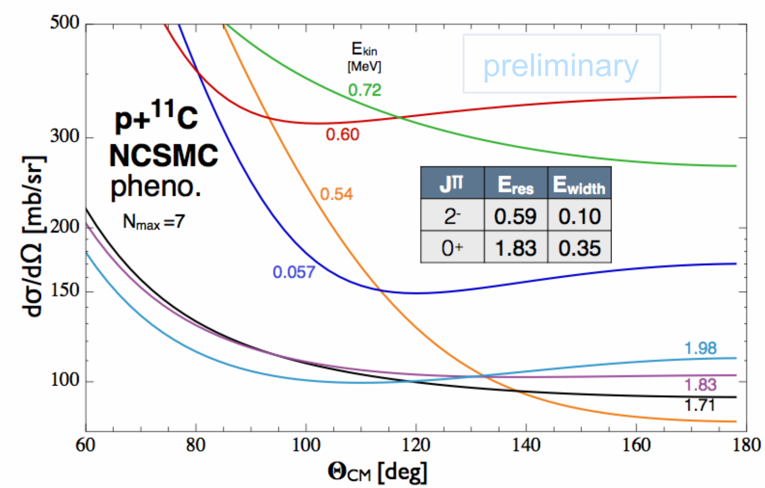
talk by H. Yamaguchi (CNS)

TRIUMF

Next: 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

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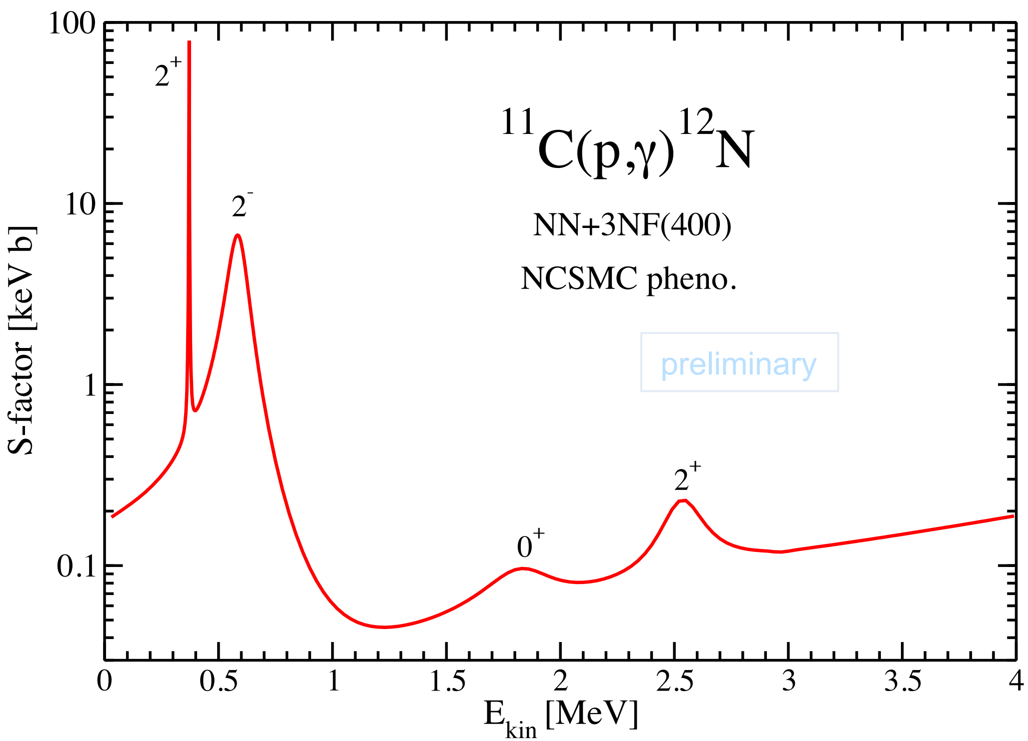
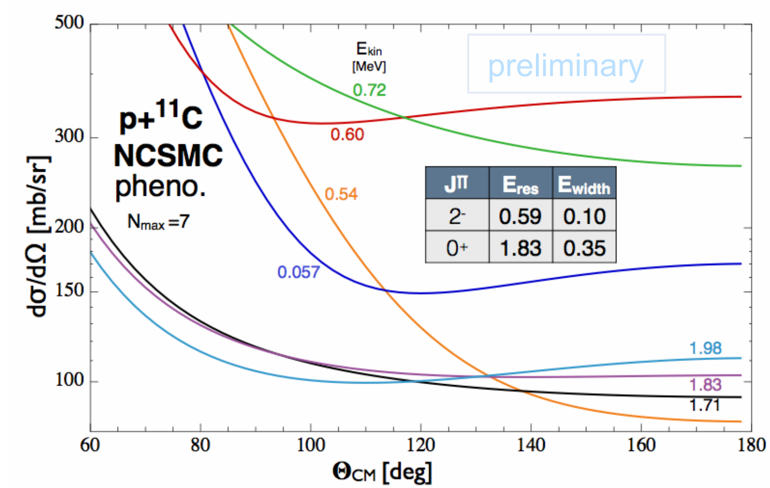
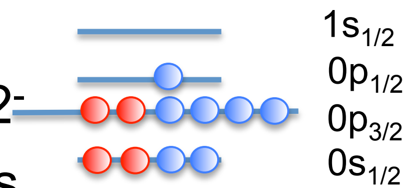




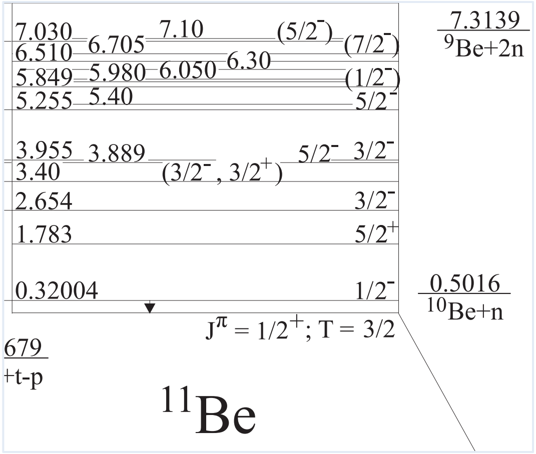
NCSMC calculations to be validated by measured cross sections and applied to calculate the ^{11}C(p,γ)^{12}N capture

Neutron-rich halo nucleus ^{11}Be

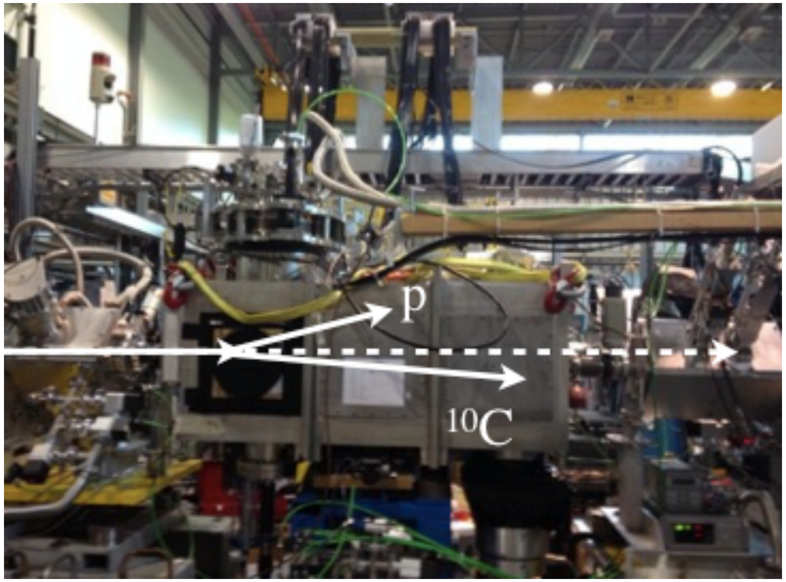


- Z=4, N=7
  - In the shell model picture g.s. expected to be $J^\pi=1/2^-$
    - Z=6, N=7 ^{13}C and Z=8, N=7 ^{15}O have $J^\pi=1/2^-$ g.s.
  - In reality, ^{11}Be g.s. is $\mathbf{J^\pi=1/2^+}$ - parity inversion
  - Very weakly bound: E_{th}=-0.5 MeV
    - Halo state – dominated by ^{10}Be-n in the *S*-wave
  - The $1/2^-$ state also bound – only by 180 keV

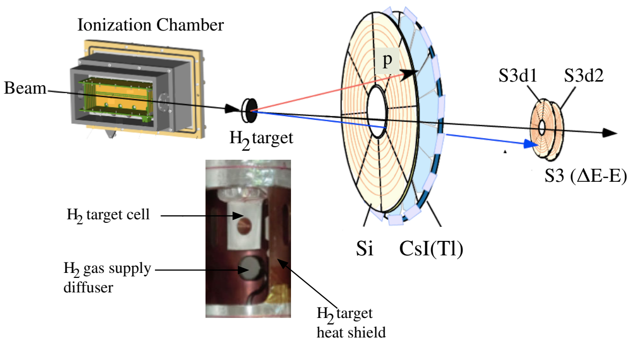
- Can we describe ^{11}Be in *ab initio* calculations?
  - Continuum must be included
  - Does the 3N interaction play a role in the parity inversion?



- Experiment at TRIUMF with the novel IRIS solid H_2 target
  - First re-accelerated ^{10}C beam at TRIUMF
  - $^{10}C(p,p)$ angular distributions measured at E_{CM} ~ 4.15 MeV and 4.4 MeV



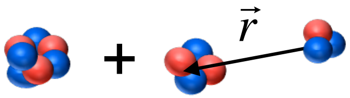
^{11}N ~ ^{10}C+p unbound mirror system of ^{11}Be ~ ^{10}Be+n

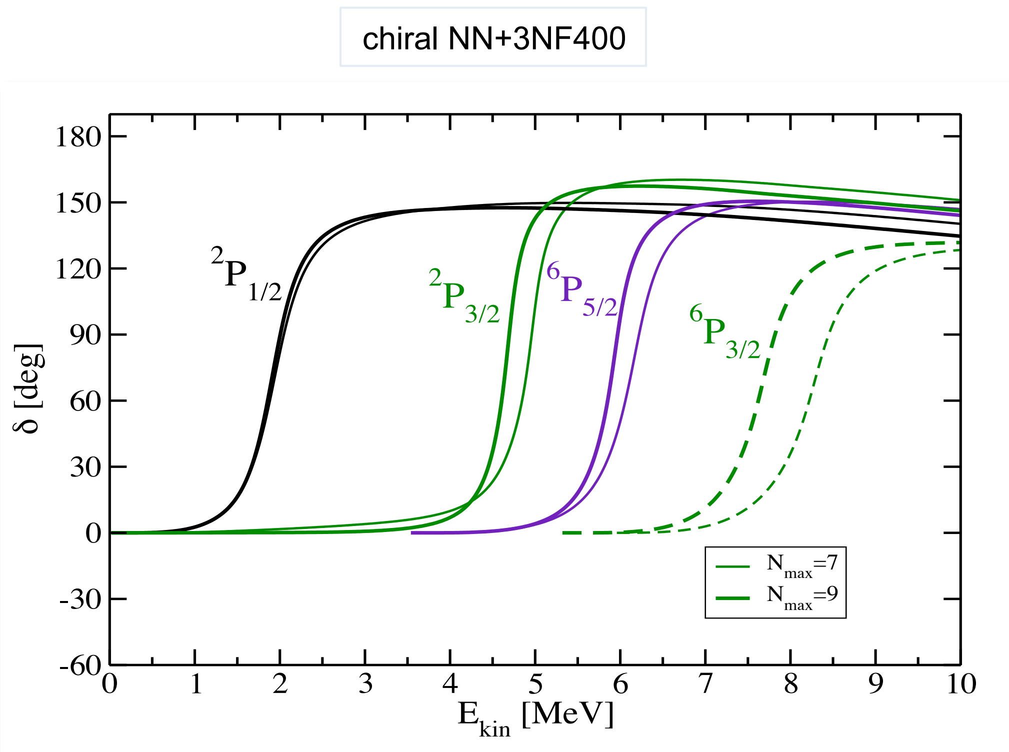


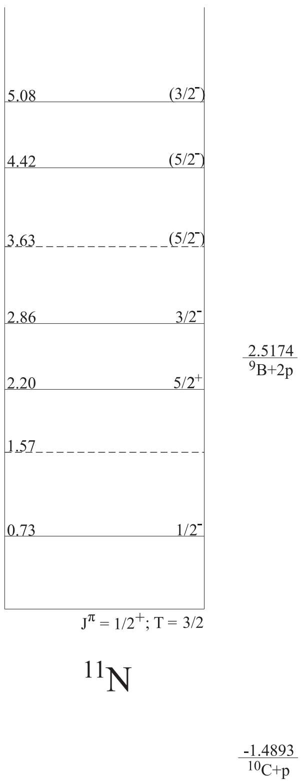
IRIS collaboration:
A. Kumar, R. Kanungo, A. Sanetullaev *et al.*

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

- NCSMC calculations with **chiral NN+3N** (N^{3}LO NN+N^{2}LO 3NF400, NNLOsat)
  - p-^{10}C + ^{11}N
    - ^{10}C: 0^+, 2^+, 2^+ NCSM eigenstates
    - ^{11}N: ≥4 π = -1 and ≥3 π = +1 NCSM eigenstates







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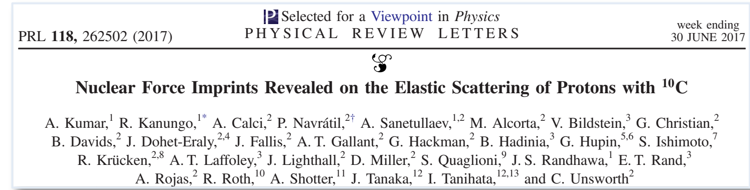

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PRL **118,** 262502 (2017) PHYSICAL REVIEW LETTERS week ending 30 JUNE 2017

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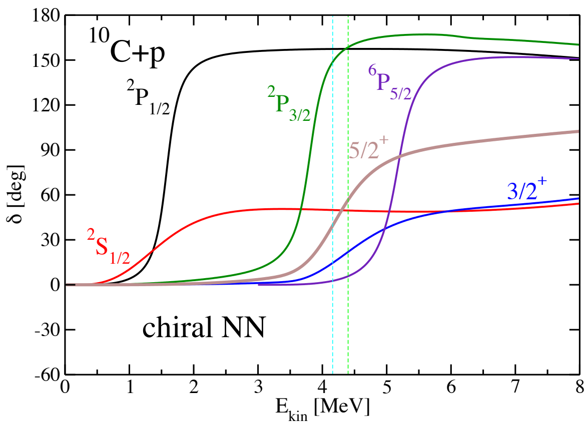

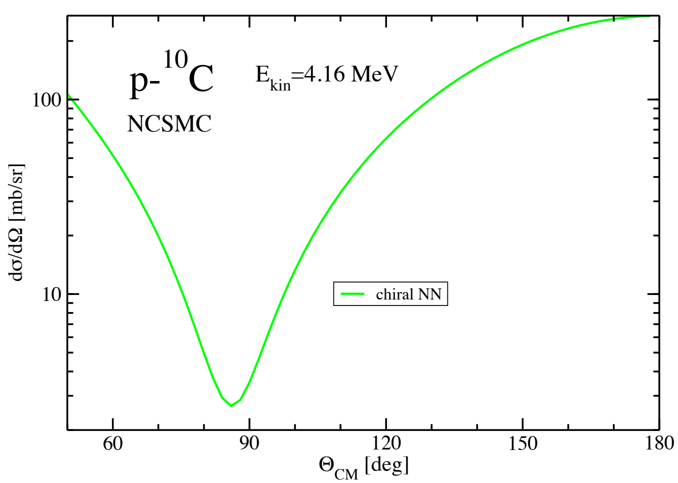

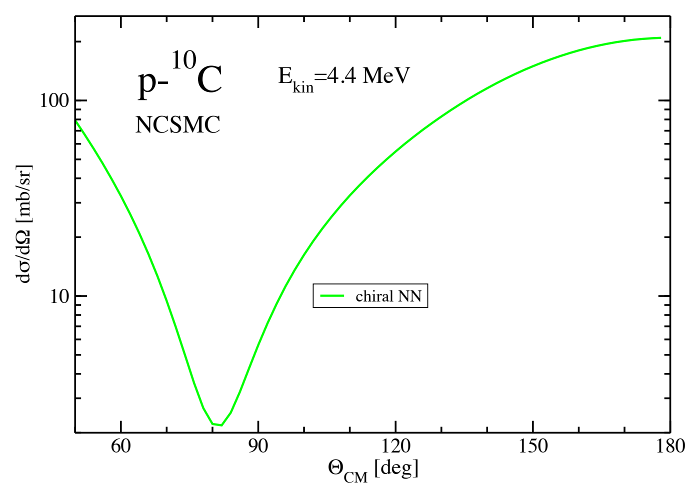

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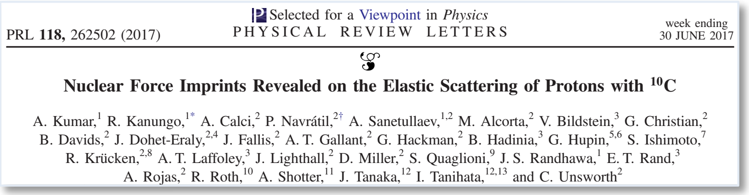

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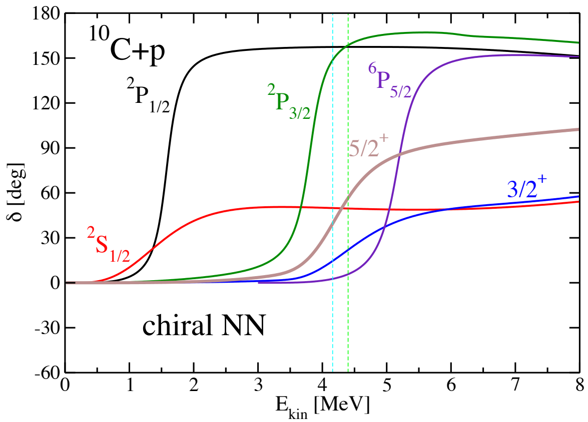

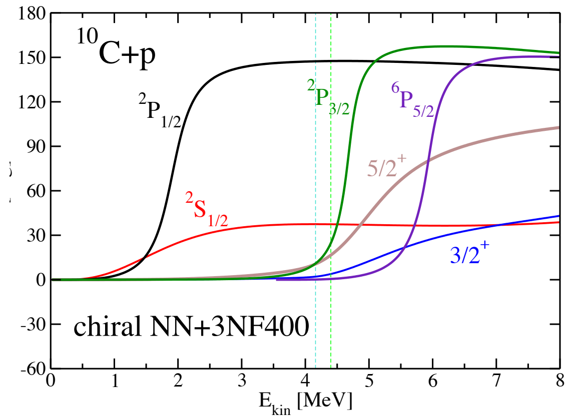

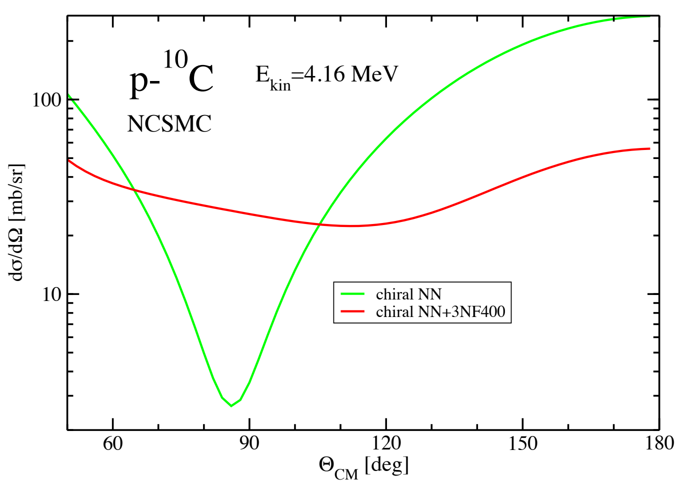

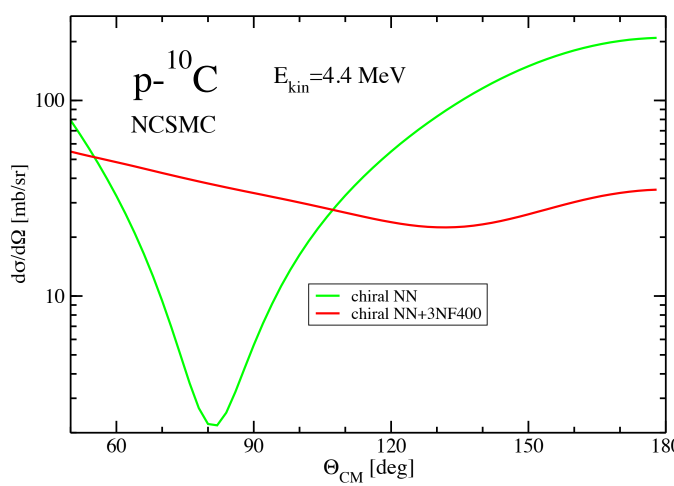

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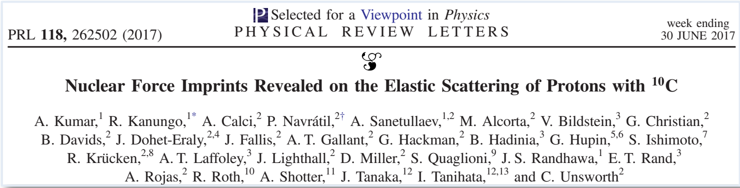

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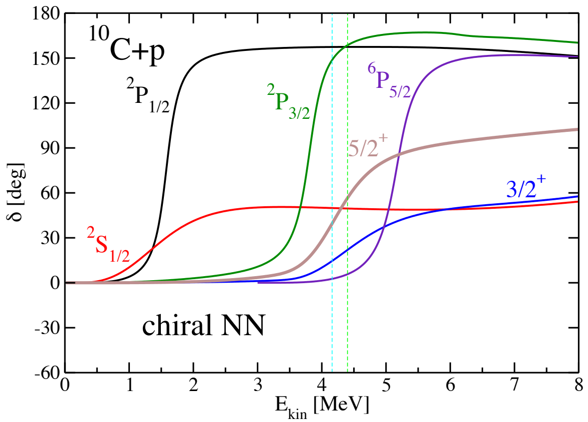
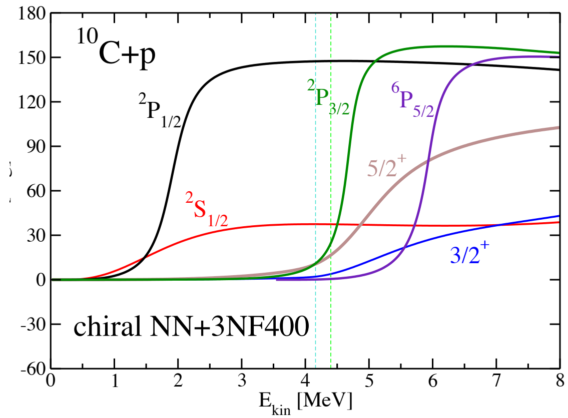
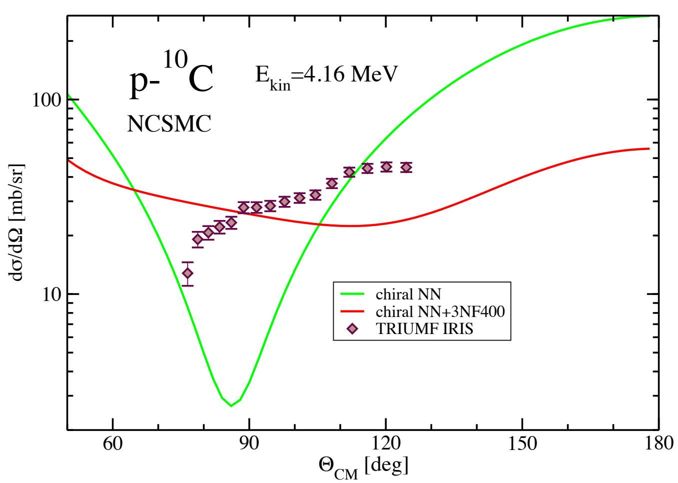
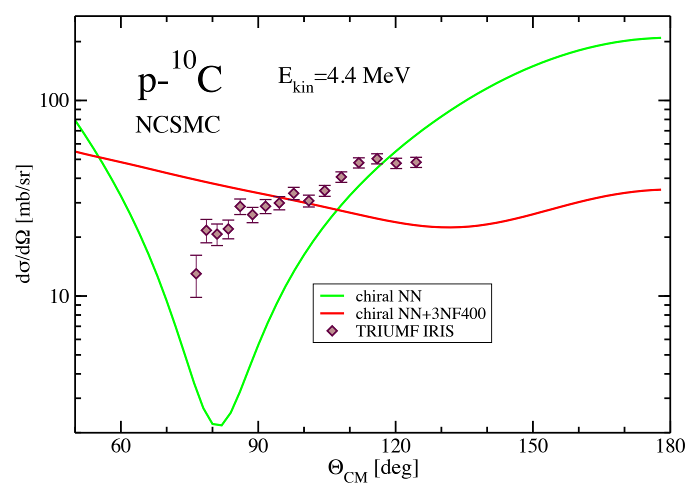
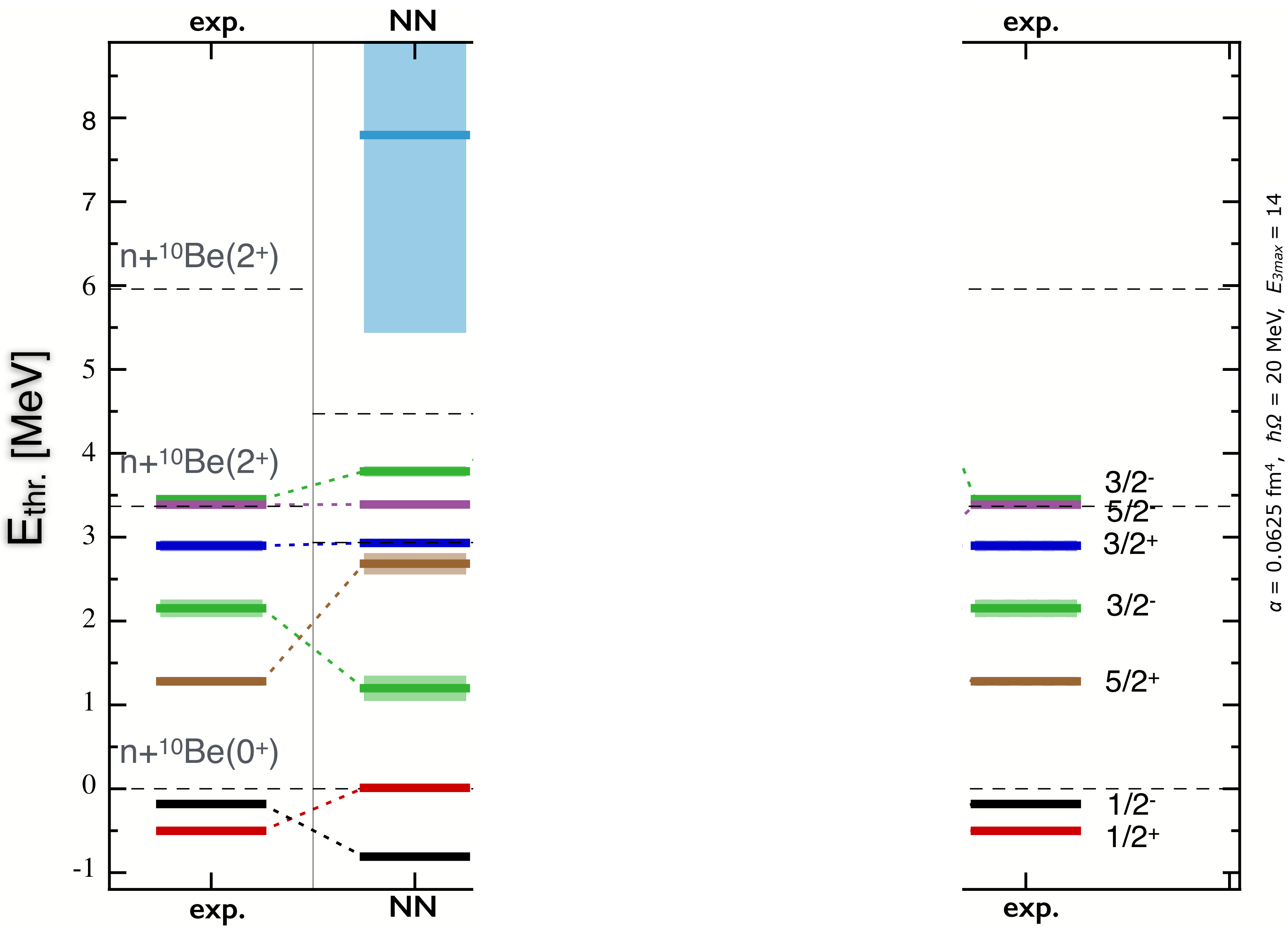








^{11}Be within NCSMC: Discrimination among chiral nuclear forces



A. Calci, P. Navratil, R. Roth, J. Dohet-Eraly, S. Quaglioni, G. Hupin, PRL 117, 242501 (2016)

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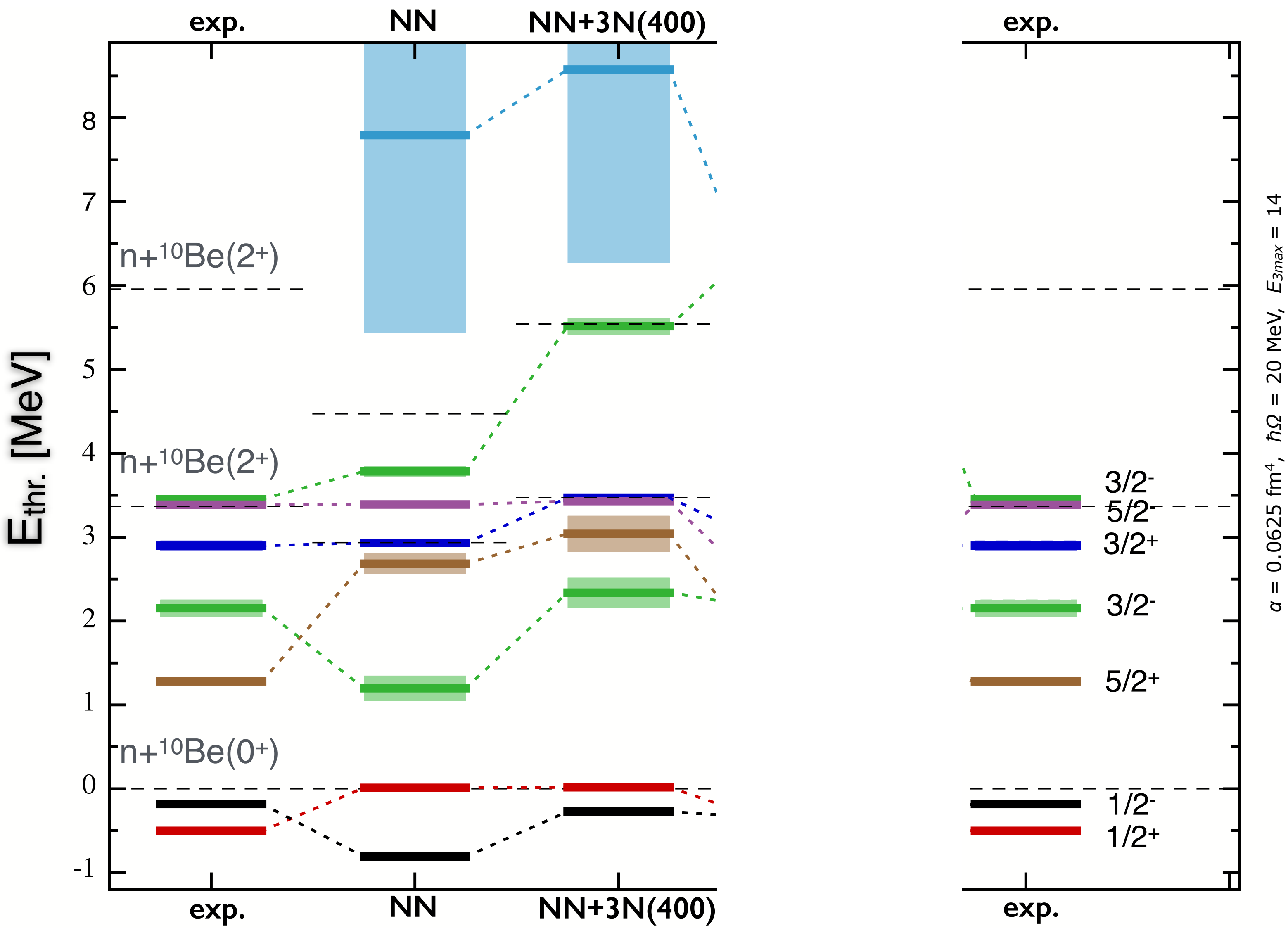

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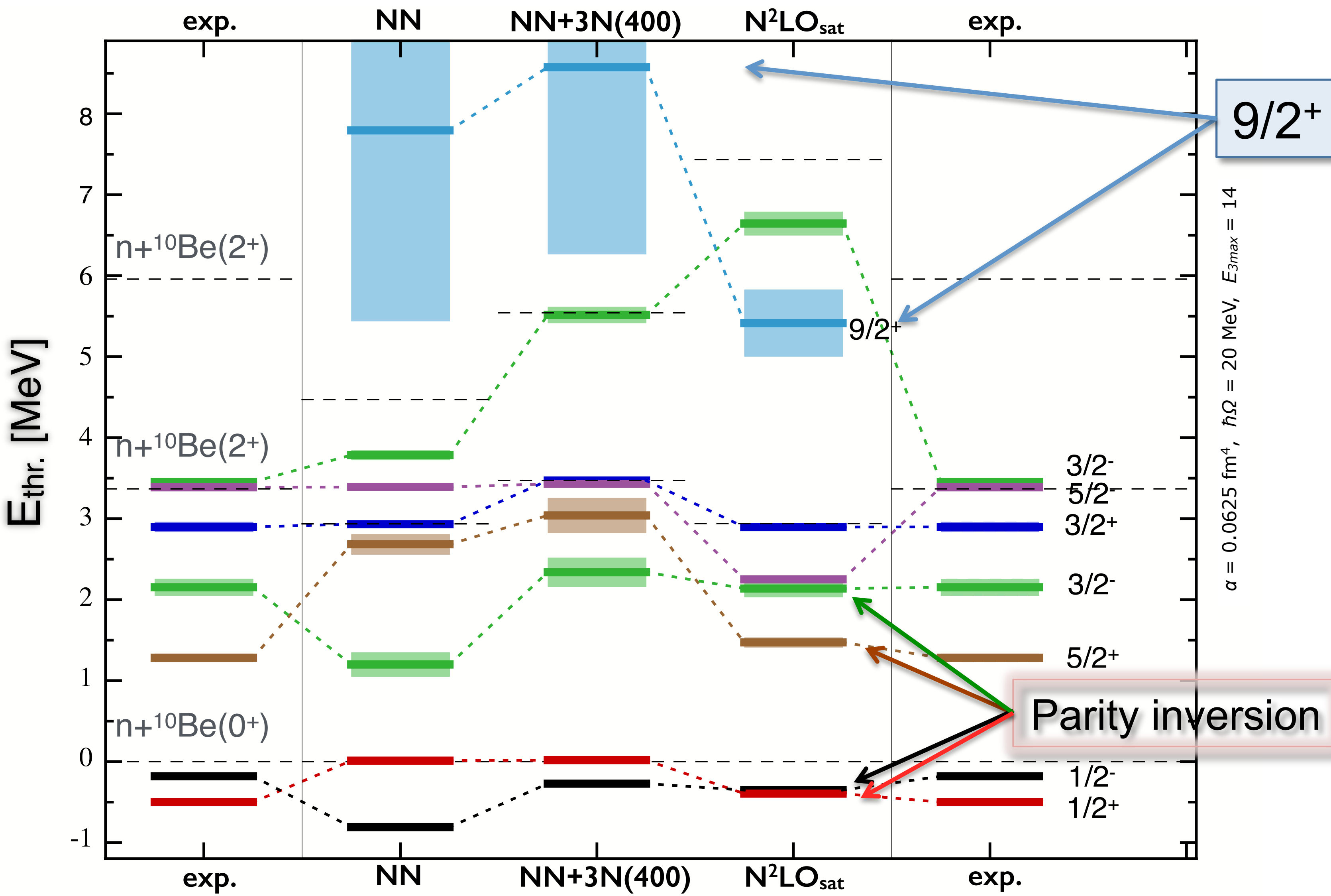

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p+^{10}C scattering: structure of ^{11}N resonances

Selected for a Viewpoint in *Physics*
PRL **118**, 262502 (2017) PHYSICAL REVIEW LETTERS week ending 30 JUNE 2017

Nuclear Force Imprints Revealed on the Elastic Scattering of Protons with ^{10}C

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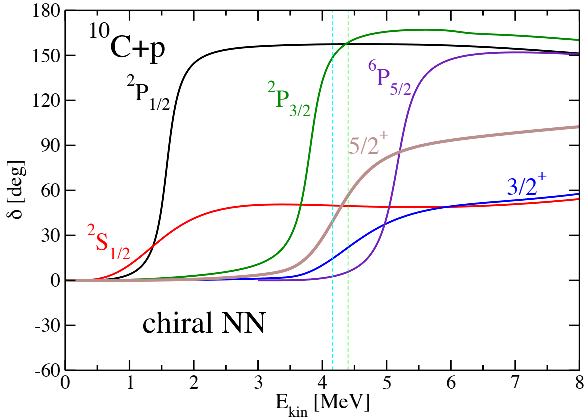

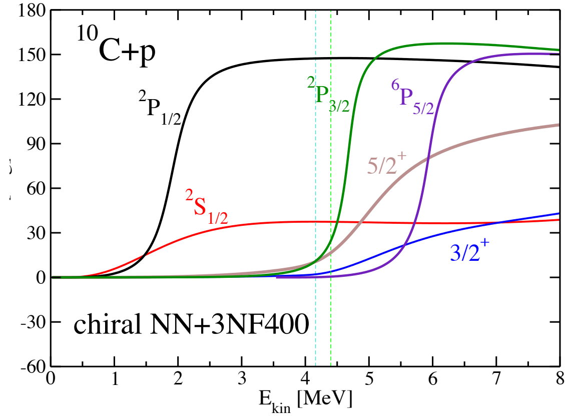

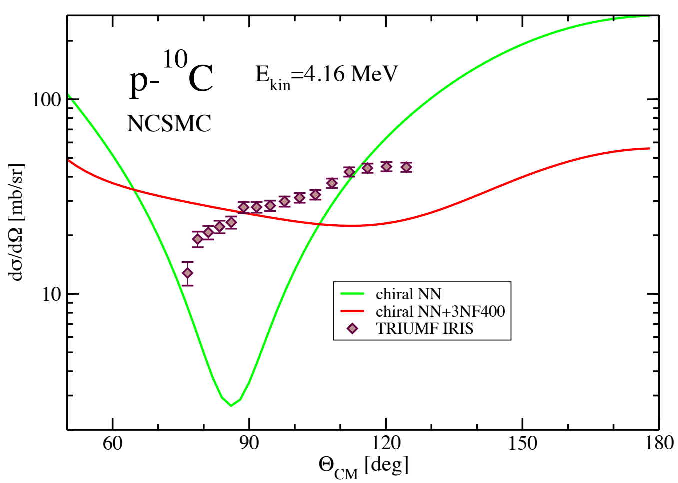

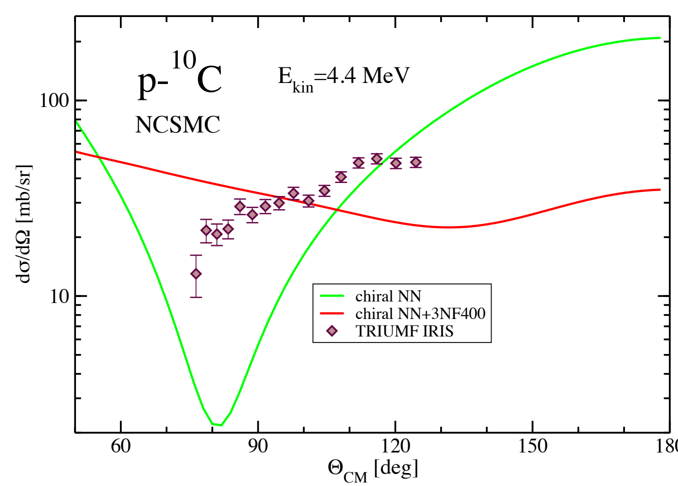

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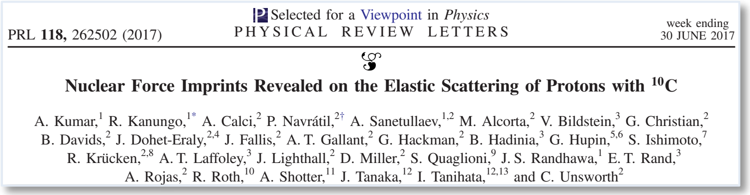
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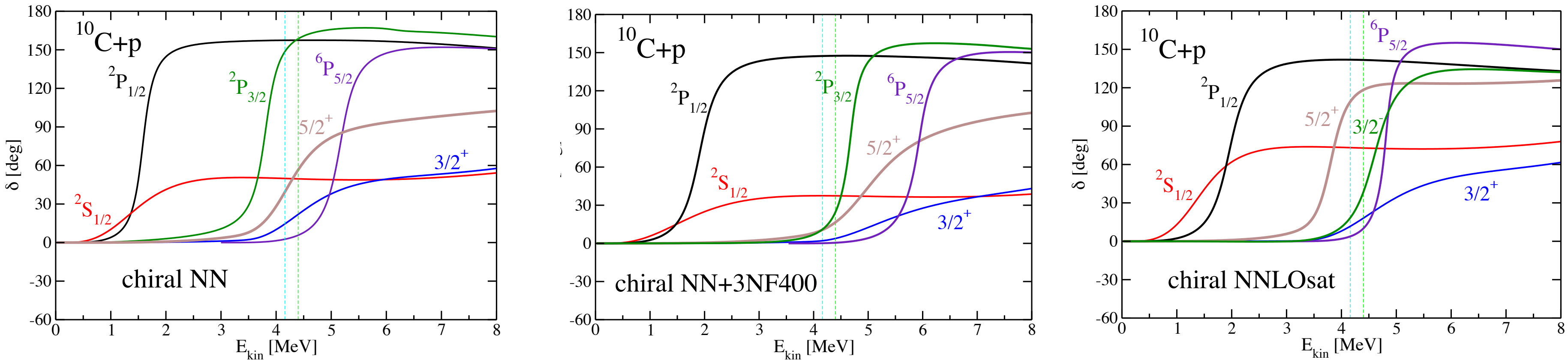

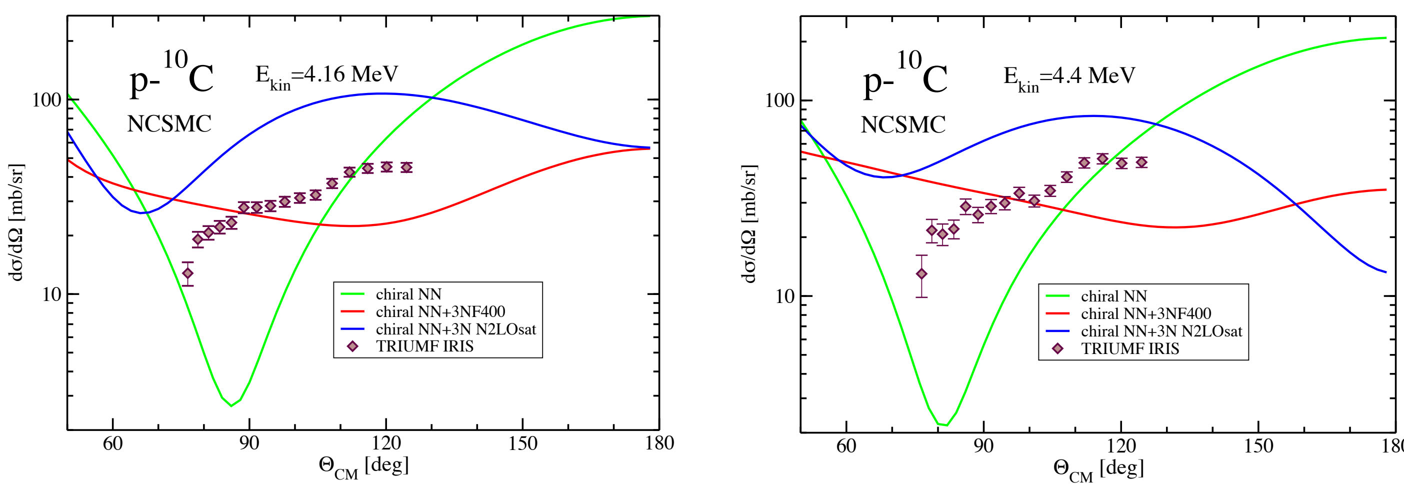

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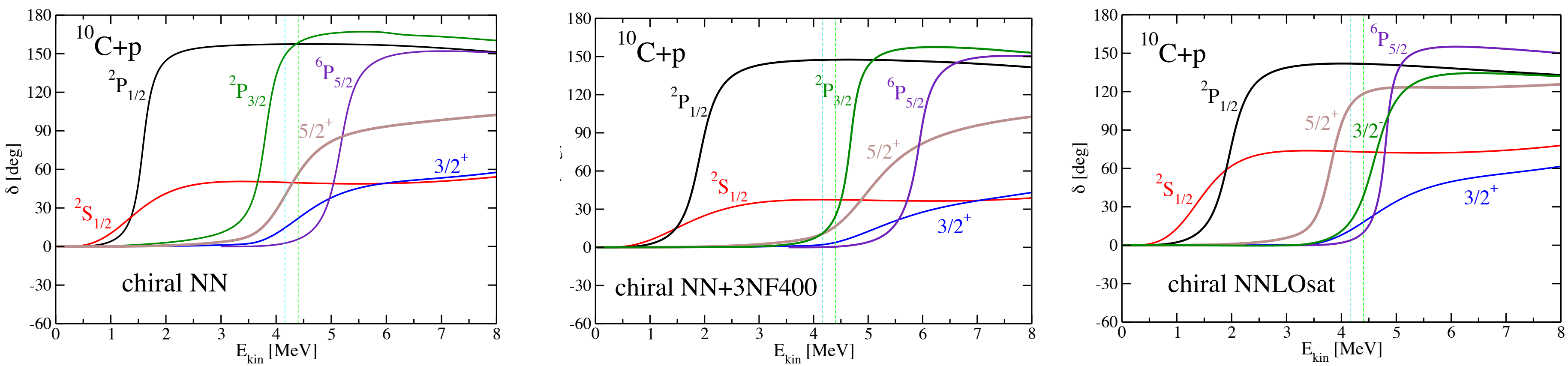
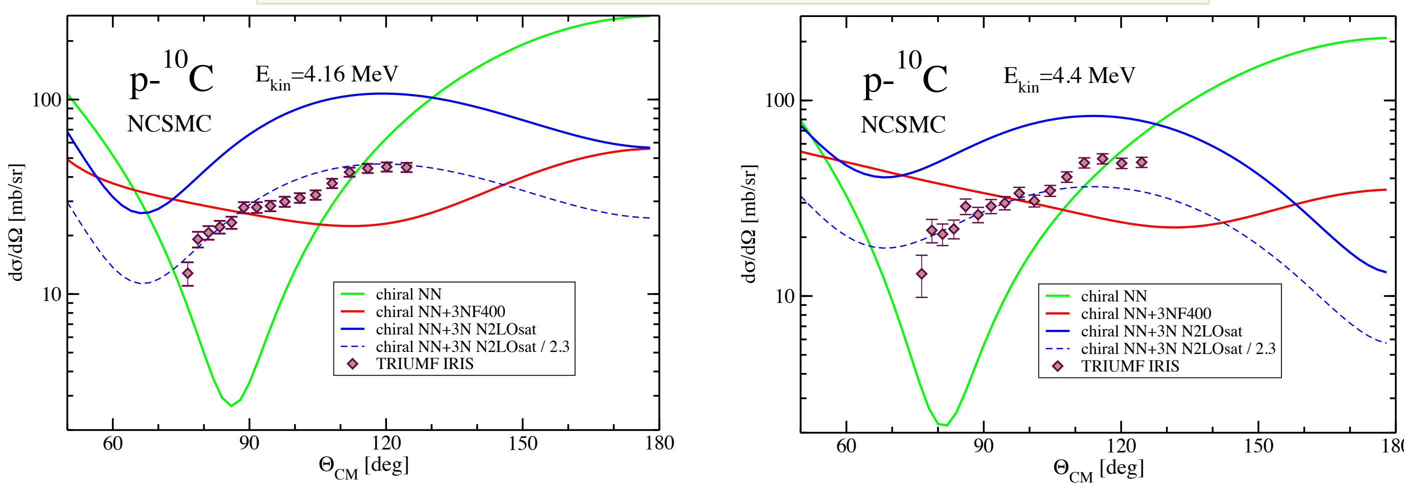


Discrimination among chiral nuclear forces



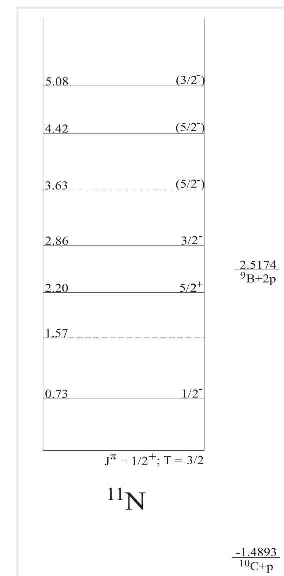


Photo-disassociation of ^{11}Be

Bound to bound	NCSM	NCSMC-phenom	Expt.
B(E1; $1/2^+ \rightarrow 1/2^-$) [e^2 fm^2]	0.0005	0.117	0.102(2)

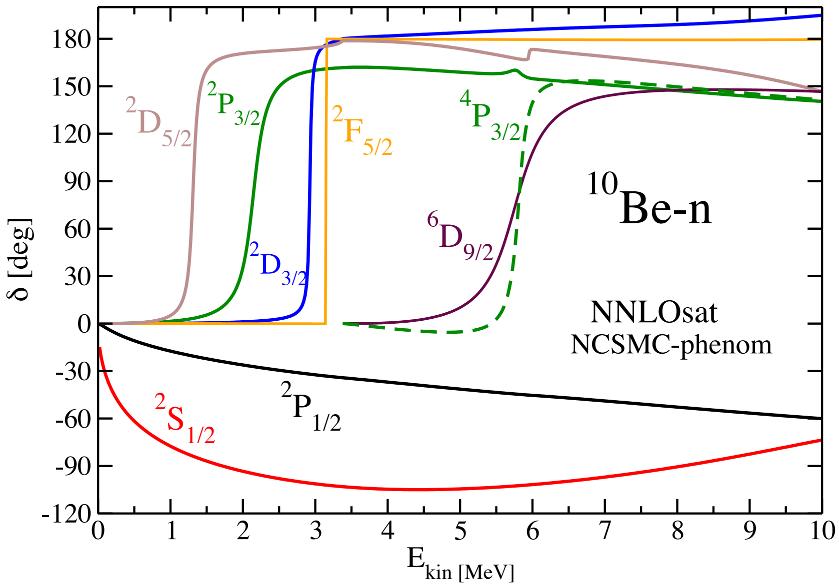
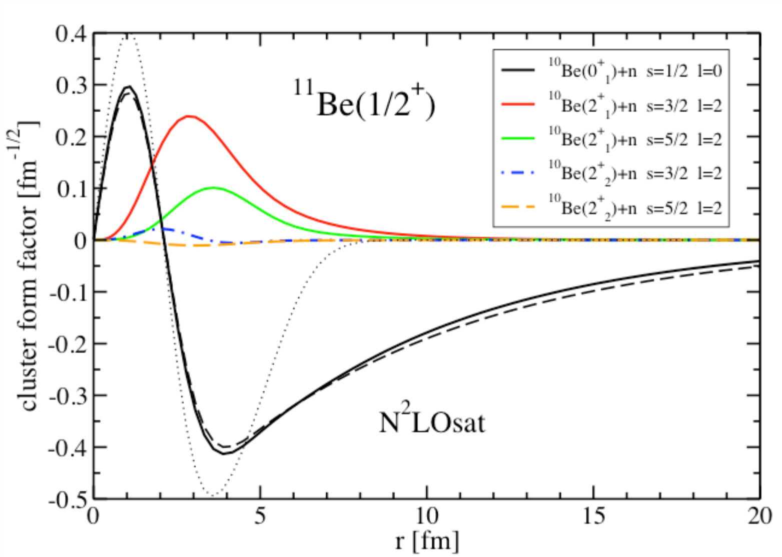
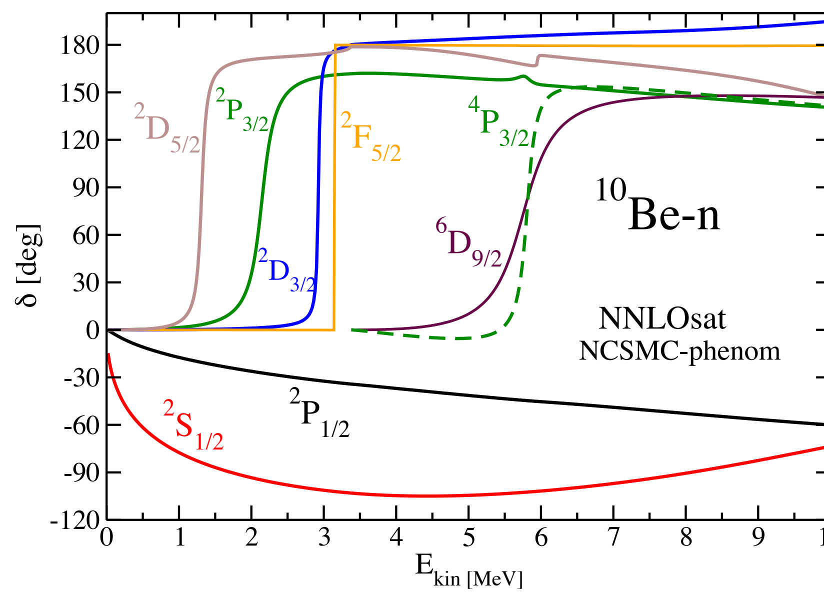


Photo-disassociation of ^{11}Be

Halo structure

Bound to bound	NCSM	NCSMC-phenom	Expt.
B(E1; $1/2^+ \rightarrow 1/2^-$) [e^2 fm^2]	0.0005	0.117	0.102(2)





cluster form factor

$$= r\left\langle \Phi_{\nu r}^{J^\pi T} \middle| \hat{A}_\nu \middle| \psi^{J^\pi T} \right\rangle$$

$$\left|\Phi_{\nu r}^{J^\pi T}\right\rangle = \left[\left(\left|{}^{10}\mathrm{Be}\ \alpha_1 I_1^{\pi_1} T_1\right\rangle \left|n\ \tfrac{1}{2}^+\ \tfrac{1}{2}\right\rangle\right)^{(sT)} Y_\ell(\hat{r}_{10,1})\right]^{(J^\pi T)} \frac{\delta(r - r_{10,1})}{r r_{10,1}}$$

PRL 117, 242501 (2016) PHYSICAL REVIEW LETTERS week ending 9 DECEMBER 2016

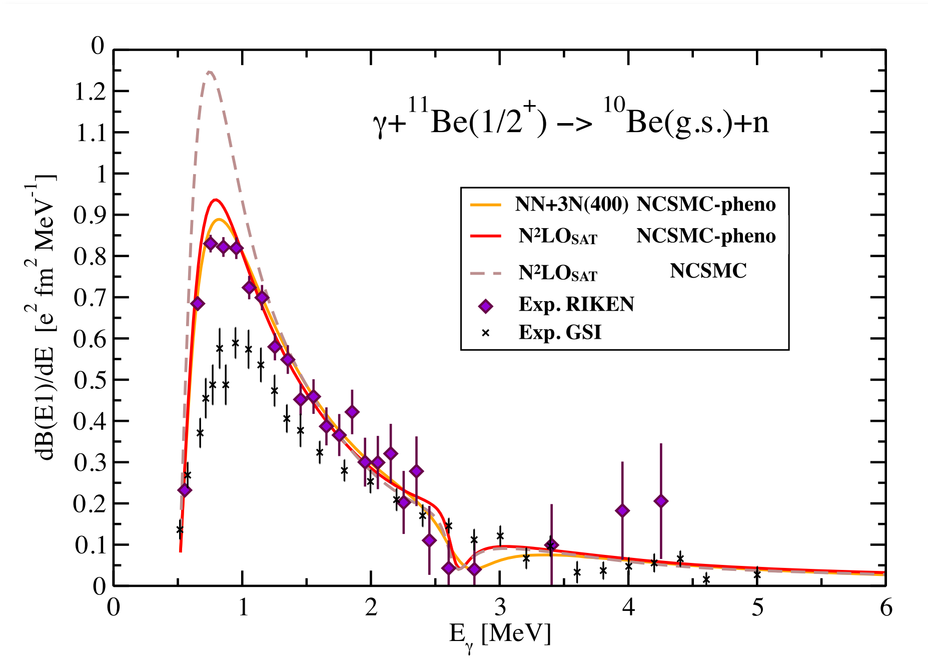
Can *Ab Initio* Theory Explain the Phenomenon of Parity Inversion in ^{11}Be?

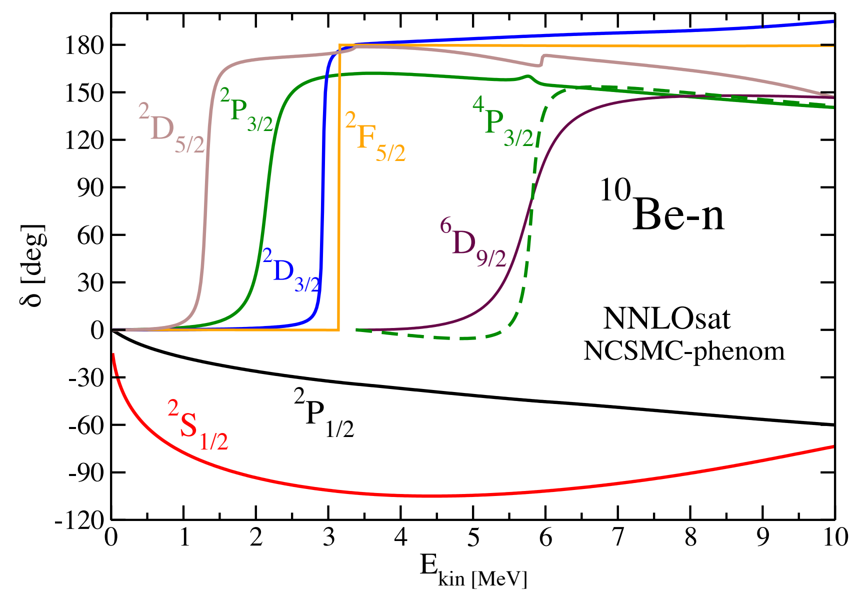
Angelo Calci,[1,*] Petr Navrátil,[1,†] Robert Roth,[2] Jérémy Dohet-Eraly,[1,‡] Sofia Quaglioni,[3] and Guillaume Hupin[4,5]

Photo-disassociation of ^{11}Be

Bound to continuum

Bound to bound	NCSM	NCSMC-phenom	Expt.
B(E1; $1/2^+ \rightarrow 1/2^-$) [e^2 fm^2]	0.0005	0.117	0.102(2)





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Conclusions and Outlook

- *Ab initio* calculations of nuclear structure and reactions is a dynamic field with significant advances

- We developed a new unified approach to nuclear bound and unbound states
  - Merging of the NCSM and the NCSM/RGM = **NCSMC**
  - Inclusion of three-nucleon interactions in reaction calculations for A>5 systems
  - Extension to three-body clusters (^{6}He ~ ^{4}He+n+n)

- Ongoing projects:
  - Transfer reactions
    - Polarized ^{3}H(d,n)^{4}He fusion
  - Applications to capture reactions important for astrophysics
    - ^{11}C(p,γ)^{12}N
  - Structure of unbound ^{9}He
  - Extension to medium mass nuclei with IM-SRG/RGM

- Outlook
  - Alpha-clustering (^{4}He projectile)
    - ^{12}C and Hoyle state: ^{8}Be+^{4}He
    - ^{16}O: ^{12}C+^{4}He