TRIUMF

Halo and unbound light nuclei from *ab initio* theory

Nuclear Structure and Dynamics NSD 2019

Venice, Italy, May 13-17, 2019

Petr Navratil

TRIUMF

Collaborators: S. Quaglioni (LLNL), G. Hupin (Orsay), M. Vorabbi, A. Calci (TRIUMF), P. Gysbers (UBC/TRIUMF), M. Gennari (Waterloo), J. Dohet-Eraly (ULB), R. Roth (Darmstadt)

2019-05-18

Discovery, accelerated

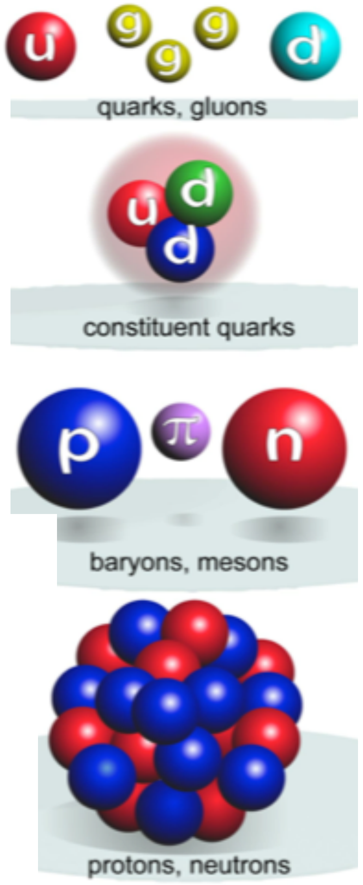
Outline

- Introduction to *ab initio* No-Core Shell Model with Continuum (NCSMC)
- Polarized ^{3}H(d,n)^{4}He fusion
- ^{11}Be parity inversion in low-lying states, photo-dissociation
- Structure of the halo *sd*-shell nucleus ^{15}C & unbound mirror ^{15}F

First principles or *ab initio* nuclear theory

Quantum Chromodynamics (QCD)

Genuine *Ab Initio*



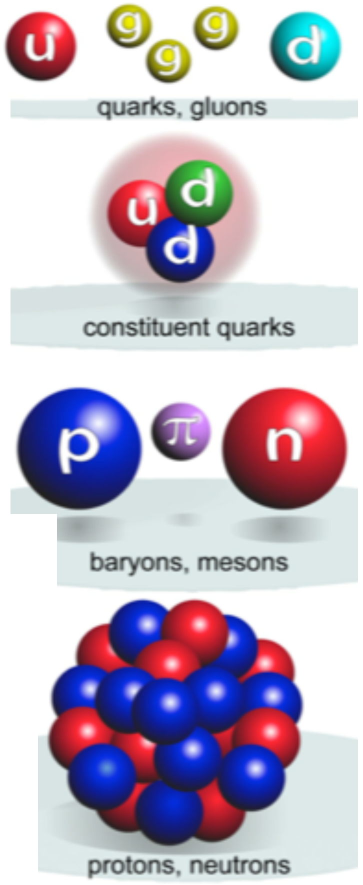
First principles or *ab initio* nuclear theory – what we do at present

Quantum Chromodynamics (QCD)

Chiral Effective Field Theory (parameters fitted to NN data)

Current *ab anitio* nuclear theory

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

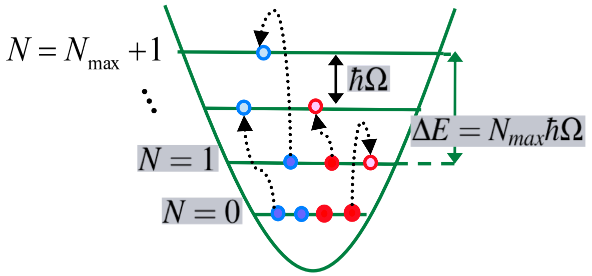


- *Ab initio*
- ✧ Degrees of freedom: Nucleons
- ✧ All nucleons are active
- ✧ Exact Pauli principle
- ✧ Realistic inter-nucleon interactions
  - ✧ Accurate description of NN (and 3N) data
- ✧ Controllable approximations

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

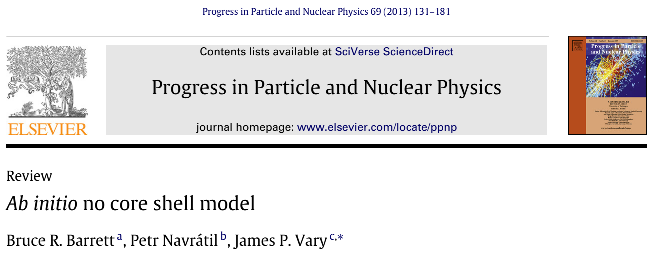
NCSM

- 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



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

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


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

Contents lists available at SciVerse ScienceDirect

Progress in Particle and Nuclear Physics

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

ELSEVIER

Review

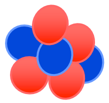
Ab initio no core shell model

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

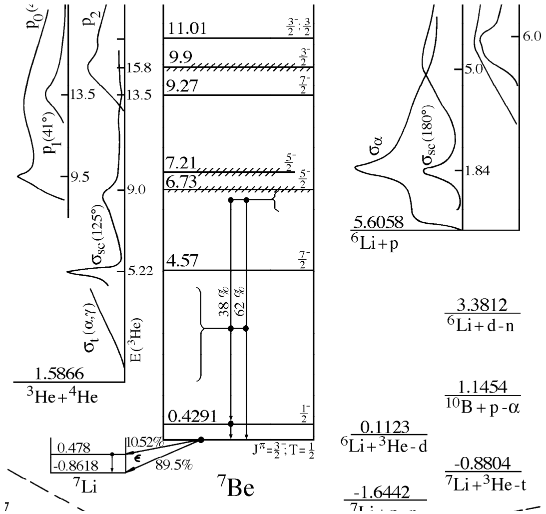
Extending no-core shell model beyond bound states

Include more many nucleon correlations…

NCSM



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

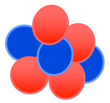


Extending no-core shell model beyond bound states

Include more many nucleon correlations…

NCSM

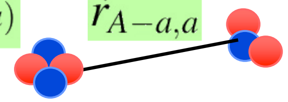
A



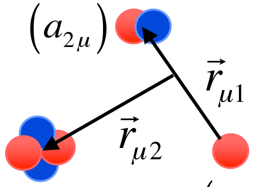
$$\Psi^A = \sum_{N=0}^{N_{max}} \sum_i c_{Ni} \Phi_{Ni}^A$$

+

$(A-a)$ $\vec{r}_{A-a,a}$ (a)



+



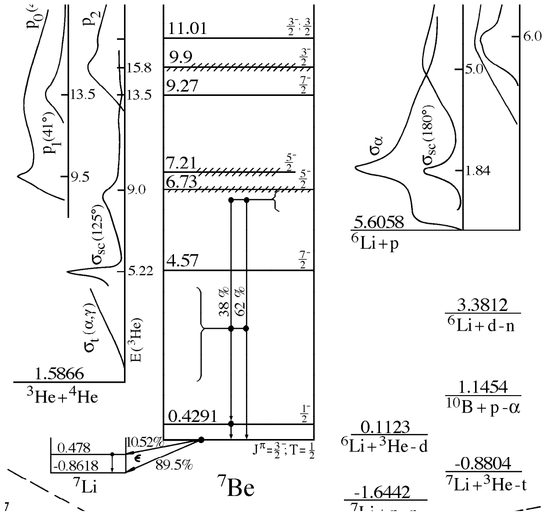
$(a_{2\mu})$ $\vec{r}_{\mu 1}$ $\vec{r}_{\mu 2}$ $(a_{1\mu})$ $(a_{3\mu})$

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

+

…

…using the Resonating Group Method (RGM) ideas

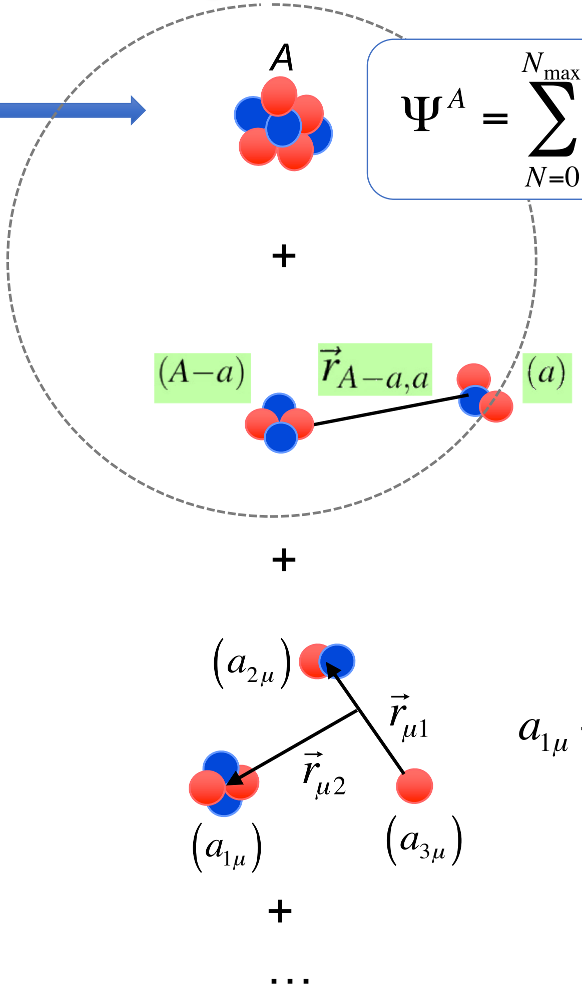


Extending no-core shell model beyond bound states

Include more many nucleon correlations…

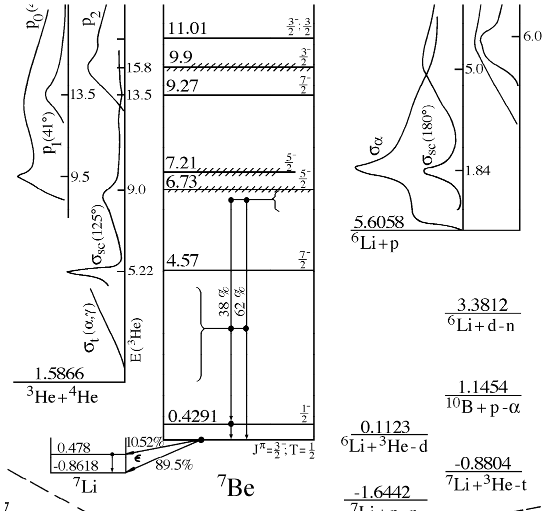
NCSM

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



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

…using the Resonating Group Method (RGM) ideas

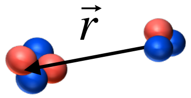


Unified approach to bound & continuum states; to nuclear structure & reactions

- 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

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

Unknowns

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

Coupled NCSMC equations

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

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

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

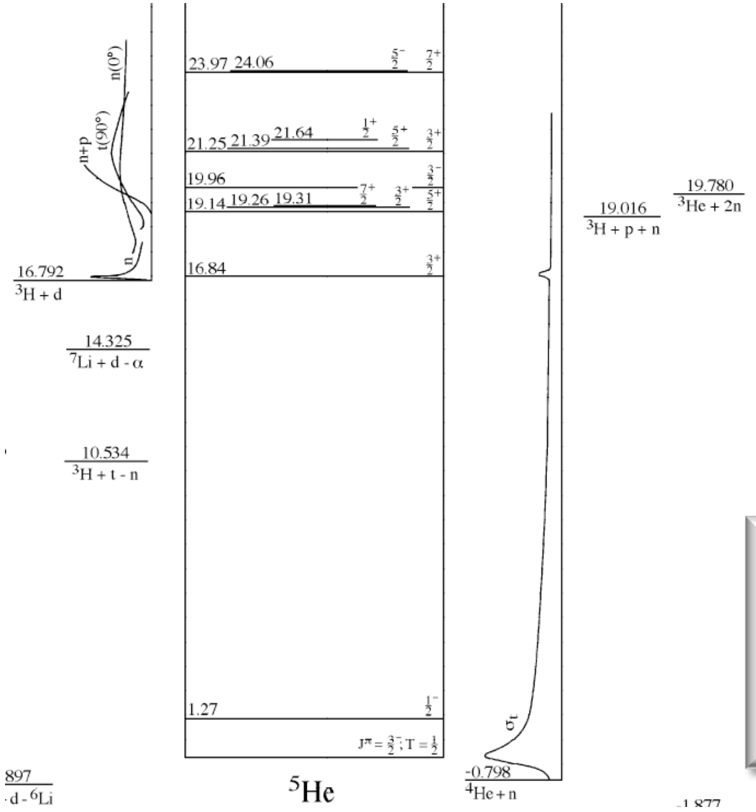
$$\begin{pmatrix} H_{NCSM} & h \\ h & H_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix} = E \begin{pmatrix} 1_{NCSM} & g \\ g & N_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix}$$

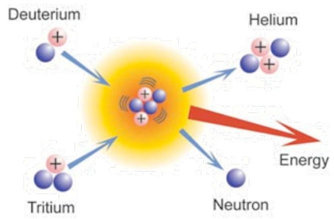
$$\left\langle (A-a)\; r'\;(a) \left| \hat{A}_{\nu'}\,H\,\hat{A}_\nu \right| (a)\; r\;(A-a) \right\rangle \qquad \left\langle (A-a)\; r'\;(a) \left| \hat{A}_{\nu'}\,\hat{A}_\nu \right| (a)\; r\;(A-a) \right\rangle$$

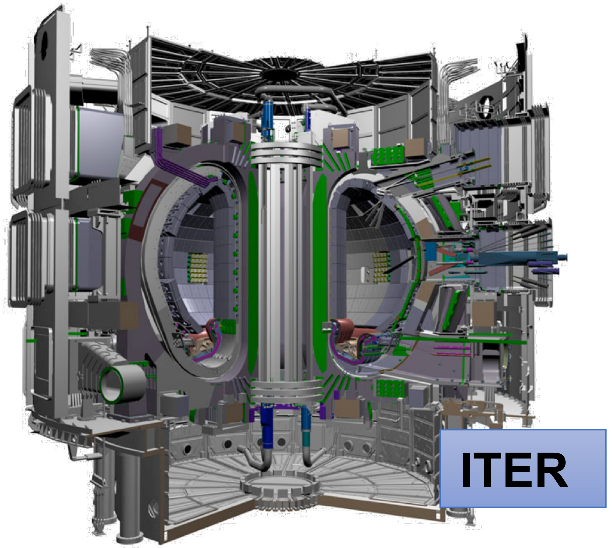
Solved by Microscopic R-matrix theory on a Lagrange mesh – efficient for coupled channels

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

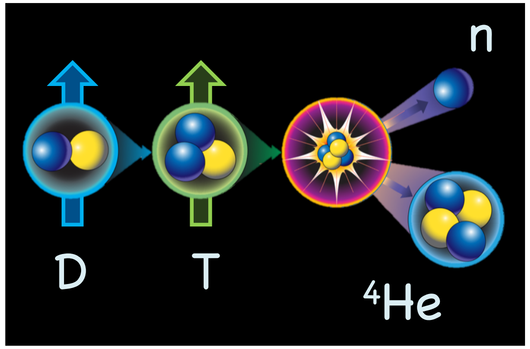
17.64 MeV energy released:
14.1 MeV neutron and 3.5 MeV alpha

NCSMC calculation of the DT fusion

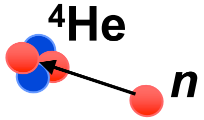
$$|\Psi\rangle = \sum_{\lambda} c_{\lambda} \left| {}^{5}\mathrm{He}, \lambda \right\rangle + \int d\vec{r}\, u_{\nu_{DT}}(\vec{r}) \hat{A}_{DT} \left| \mathrm{T} \overset{\vec{r}}{\longleftarrow} D, \nu_{DT} \right\rangle + \int d\vec{r}\, u_{\nu_{n\alpha}}(\vec{r}) \hat{A}_{n\alpha} \left| \alpha \overset{\vec{r}}{\longleftarrow} n, \nu_{n\alpha} \right\rangle$$

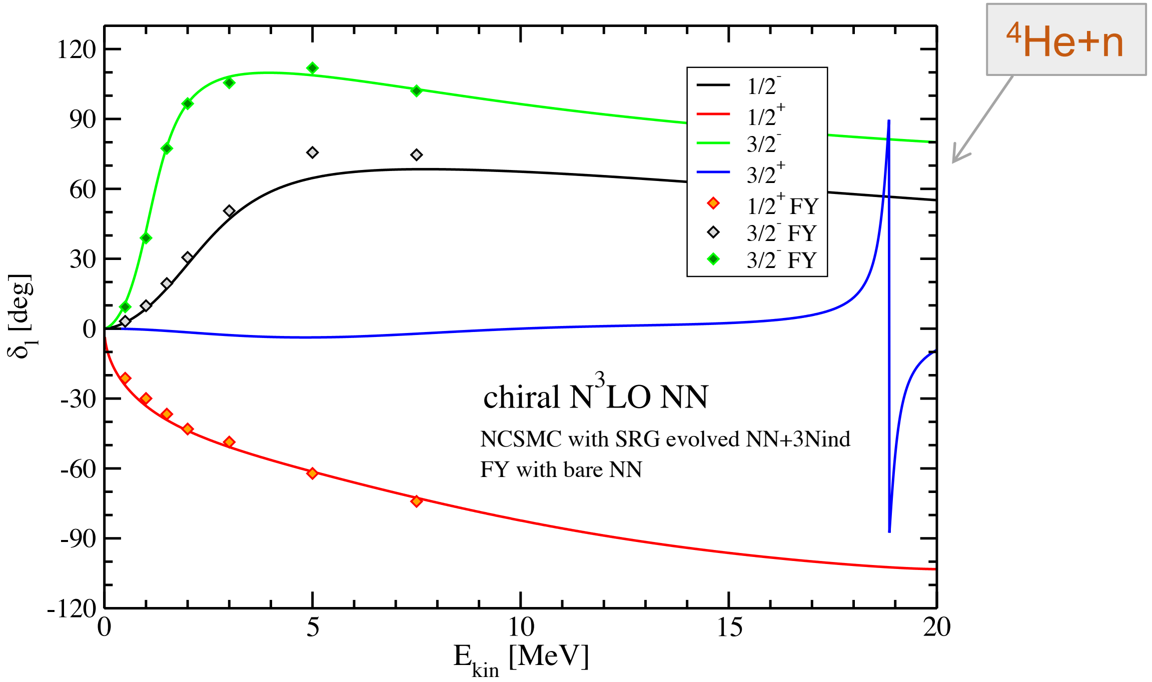
- 2x7 static ^{5}He eigenstates computed with the NCSM
- Continuous D-T(g.s.) cluster states (entrance channel)
  - Including positive-energy eigenstates of D to account for distortion
- Continuous n-^{4}He(g.s.) cluster states (exit channel)
- Chiral NN+3N(500) interaction

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

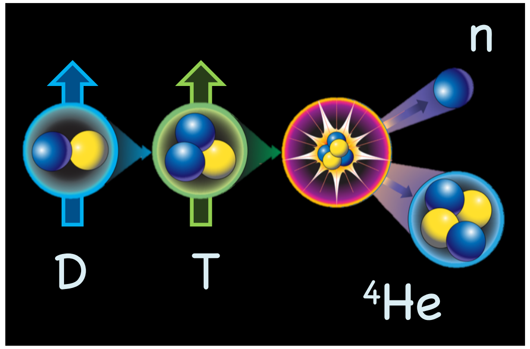


n-^{4}He and *d*+^{3}H scattering phase-shifts





FY: Faddeev-Yakubovsky method - Rimantas Lazauskas

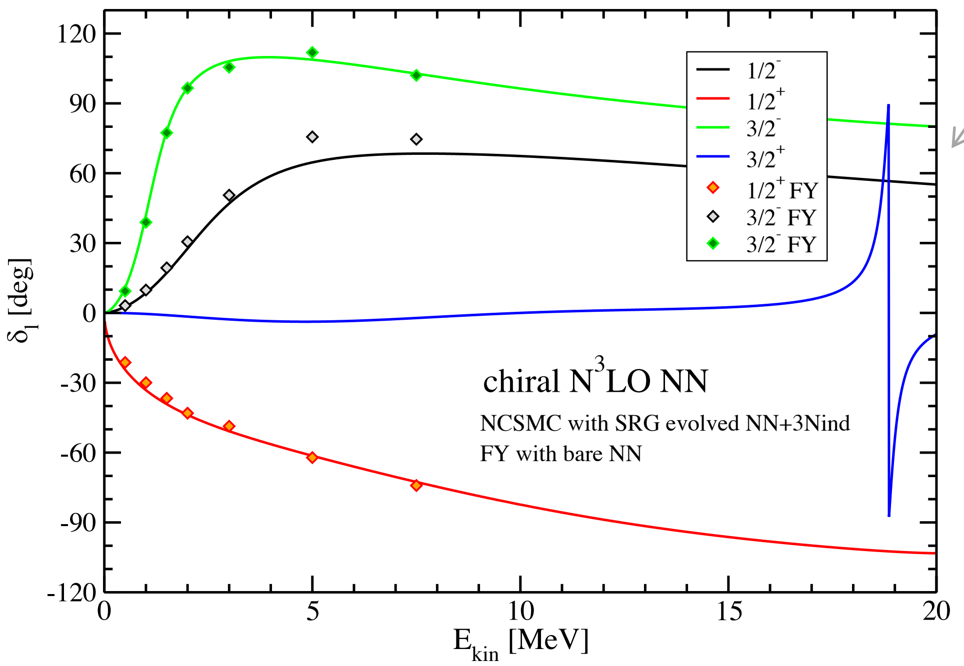


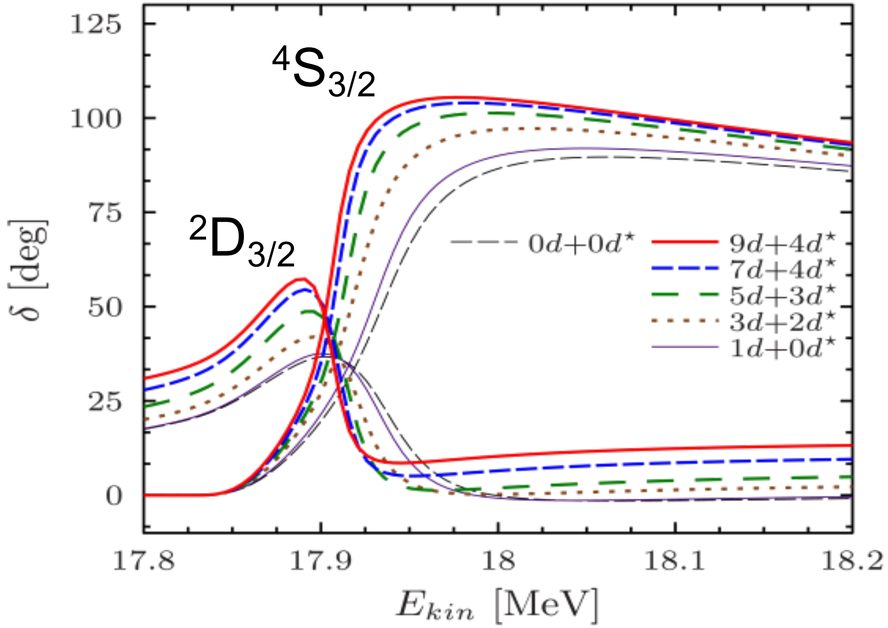
n-^{4}He scattering and ^{3}H+d fusion within NCSMC

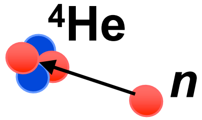
^{4}He+n -> ^{3}H+d

n-^{4}He and *d*+^{3}H scattering phase-shifts

^{4}He+n



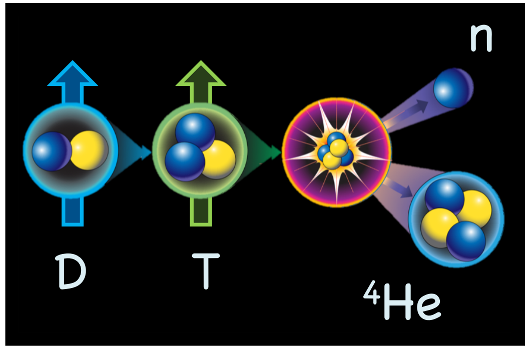




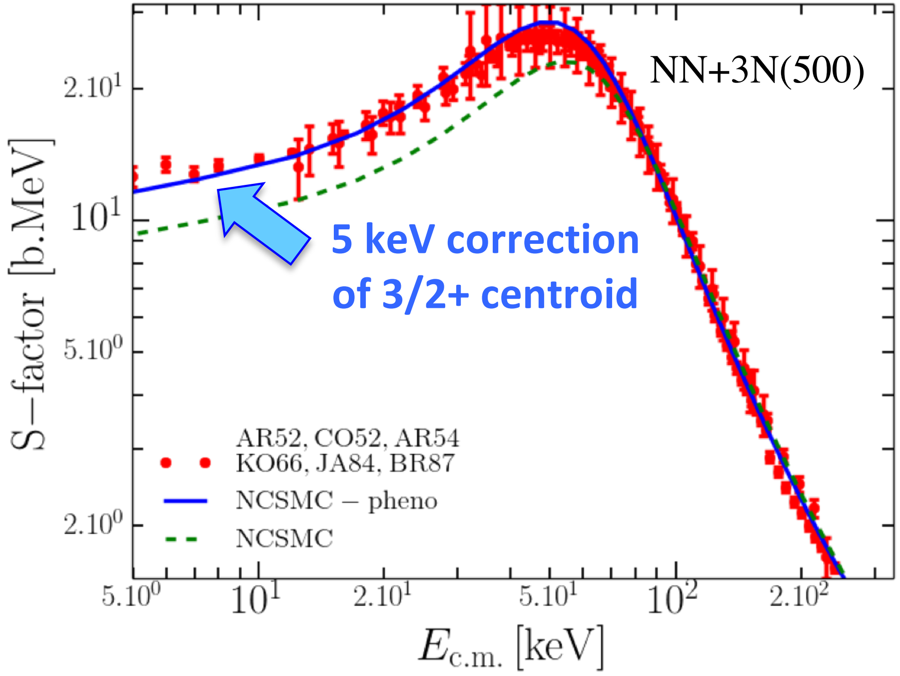
FY: Faddeev-Yakubovsky method - Rimantas Lazauskas

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**

$^{3}H(d,n)^{4}He$ with chiral NN+3N(500) interaction



Astrophysical S-factor



Astrophysical S-factor:
nuclear contribution

Fusion
cross section

$$\sigma(E) = \frac{\boxed{S(E)}}{E}\exp\left(-\frac{2\pi Z_1 Z_2 e^2}{\hbar\sqrt{2E/m}}\right)$$

'Coulomb'
Contribution
(tunneling)

NCSMC phenomenology

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

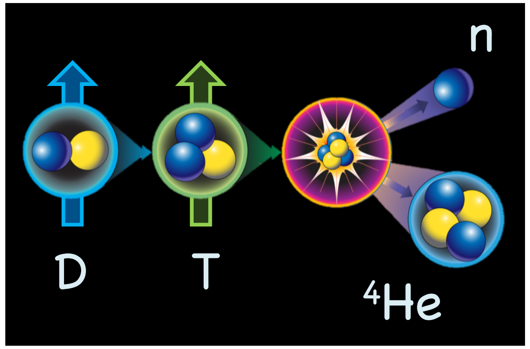
$$E_\lambda^{NCSM}\,\delta_{\lambda\lambda'} \qquad \left\langle (A) \middle| H \hat{A}_\nu \middle| r\;\; (a)\;\; (A-a) \right\rangle \qquad \delta_{\lambda\lambda'} \qquad \left\langle (A) \middle| \hat{A}_\nu \middle| r\;\; (a)\;\; (A-a) \right\rangle$$

E_λ^{NCSM} energies treated as adjustable parameters

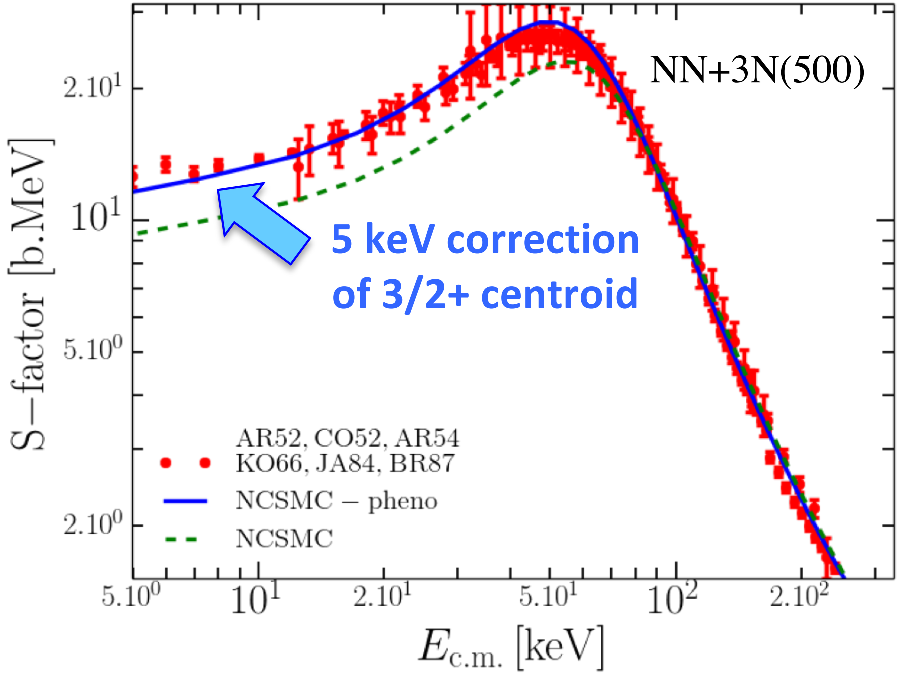
$$\begin{pmatrix} H_{NCSM} & h \\ h & H_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix} = E \begin{pmatrix} 1_{NCSM} & g \\ g & N_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix}$$

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

$^{3}H(d,n)^{4}He$ with chiral NN+3N(500) interaction



Astrophysical S-factor



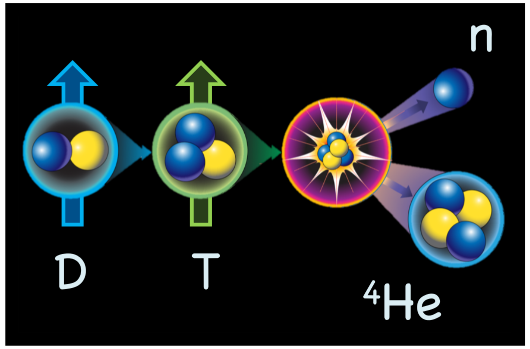
Fusion cross section

Astrophysical S-factor: nuclear contribution

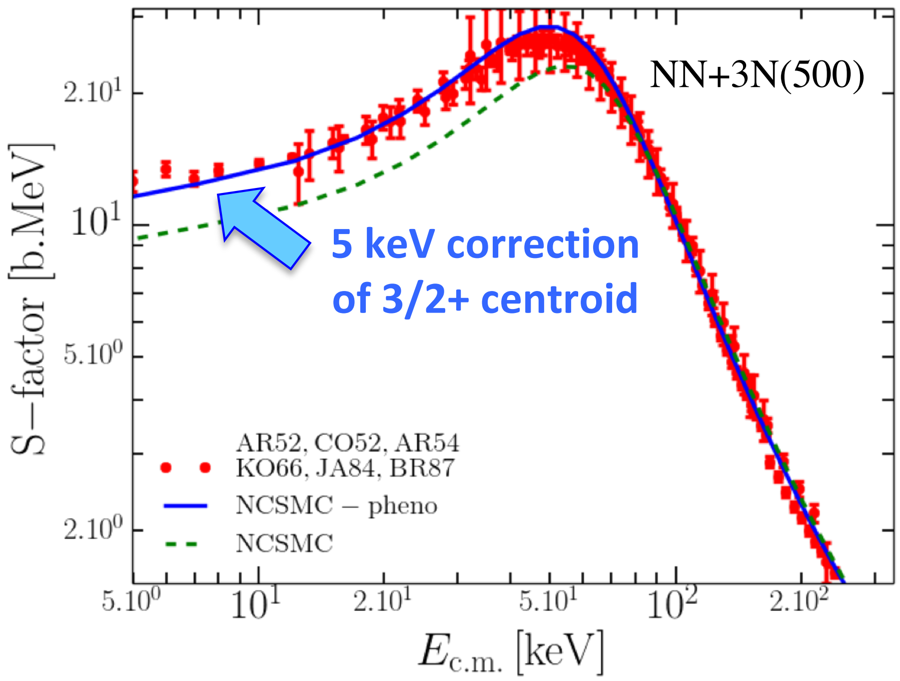
$$\sigma(E) = \frac{\boxed{S(E)}}{E}\exp\left(-\frac{2\pi Z_1 Z_2 e^2}{\hbar\sqrt{2E/m}}\right)$$

'Coulomb' Contribution (tunneling)

$^{3}H(d,n)^{4}He$ with chiral NN+3N(500) interaction



Astrophysical S-factor



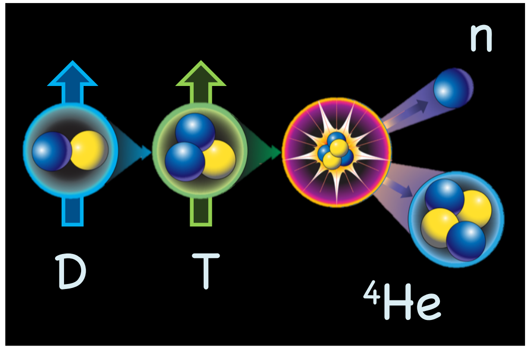
- While the DT fusion rate has been measured extensively, a fundamental understanding of the process is still missing
- Very little is known experimentally of how the polarization of the reactants' spins affects the reaction

$$\sigma_{unpol} = \sum_J \frac{2J+1}{(2I_D+1)(2I_T+1)}\sigma_J$$
$$\approx \frac{1}{3}\cancel{\sigma_{\frac{1}{2}}} + \frac{2}{3}\sigma_{\frac{3}{2}}$$

$$\sigma_{pol} \approx 1.5\,\sigma_{unpol}$$

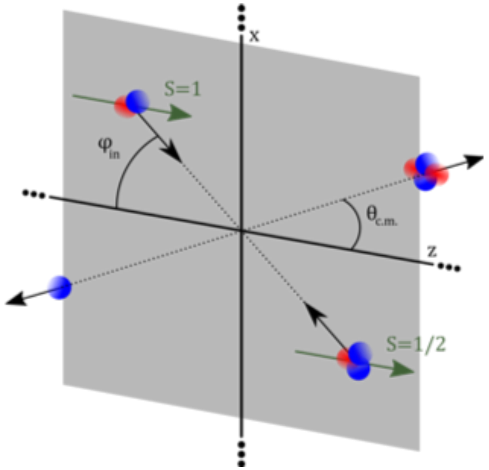
Assuming the fusion proceeds only in S-wave
with spins of D and T completely aligned:
Polarized cross section 50% higher than unpolarized

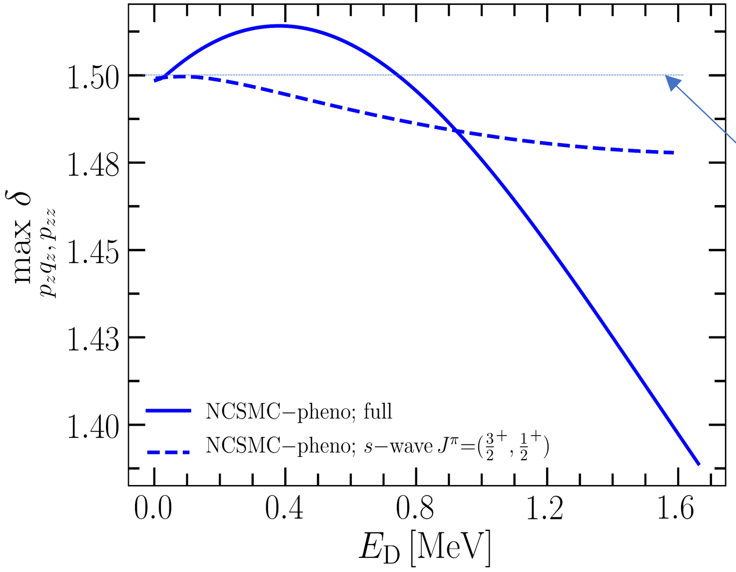
^{3}H(d,n)^{4}He with chiral NN+3N(500) interaction



Polarized fusion

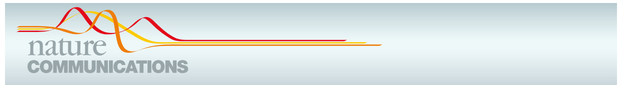
$$\frac{\partial\sigma_{pol}}{\partial\Omega_{c.m.}}(\theta_{\rm c.m.}) = \frac{\partial\sigma_{unpol}}{\partial\Omega_{c.m.}}(\theta_{\rm c.m.})\left(1+\frac{1}{2}p_{zz}A_{zz}^{(b)}(\theta_{\rm c.m.})+\frac{3}{2}p_z q_z C_{z,z}(\theta_{\rm c.m.})\right)$$





$$\sigma_{unpol} = \sum_J \frac{2J+1}{(2I_D+1)(2I_T+1)}\sigma_J \approx \frac{1}{3}\cancel{\sigma_{\frac{1}{2}}} + \frac{2}{3}\sigma_{\frac{3}{2}}$$

$$\sigma_{pol} \approx 1.5\,\sigma_{unpol}$$

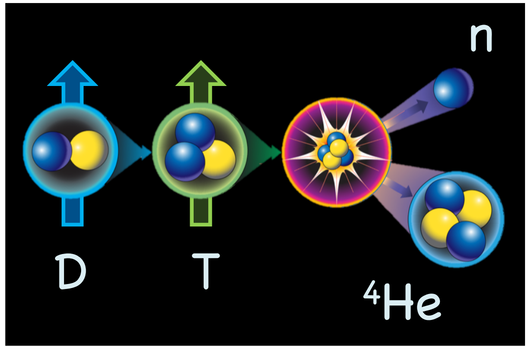


ARTICLE
https://doi.org/10.1038/s41467-018-08052-6 OPEN

Ab initio predictions for polarized deuterium-tritium thermonuclear fusion

Guillaume Hupin[1,2,3], Sofia Quaglioni[3] & Petr Navrátil[4]

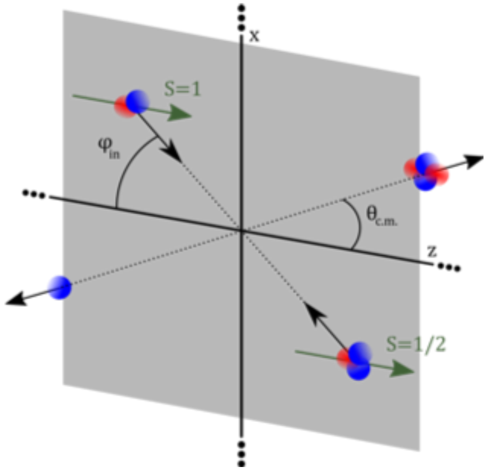
NCSMC calculation demonstrates impact of partial waves with l > 0 as well as the contribution of l = 0 J^π = ½$^+$ channel

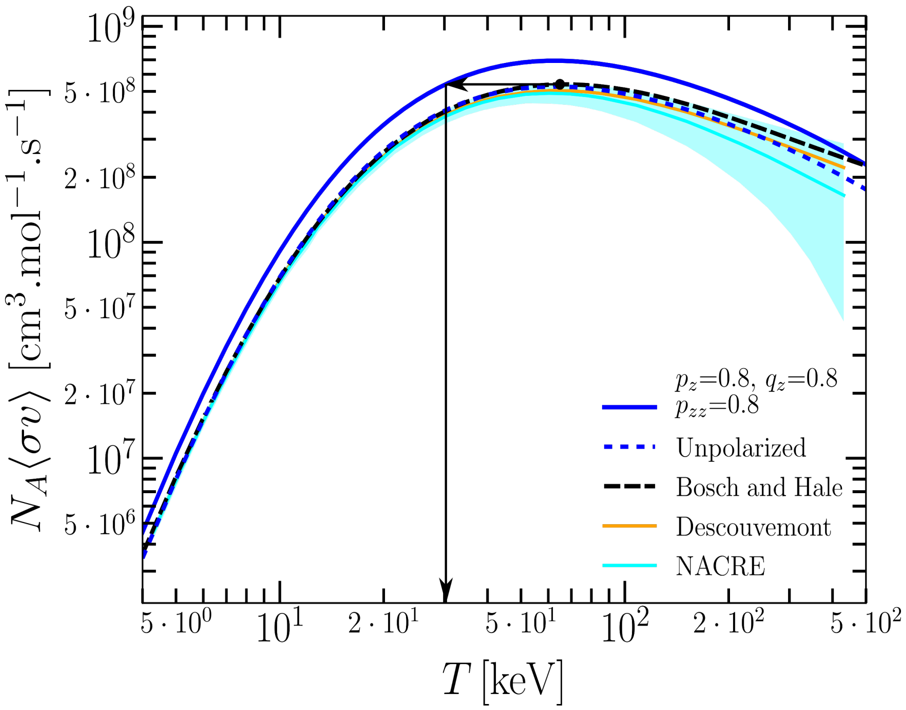


^{3}H(d,n)^{4}He with chiral NN+3N(500) interaction

Polarized fusion

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





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

For a realistic 80% polarization, reaction rate increases by ~32% or the same rate at ~45% lower temperature

nature COMMUNICATIONS

ARTICLE

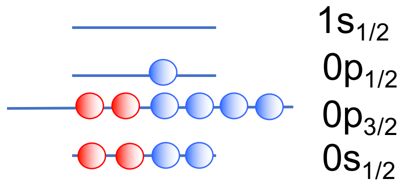
https://doi.org/10.1038/s41467-018-08052-6 OPEN

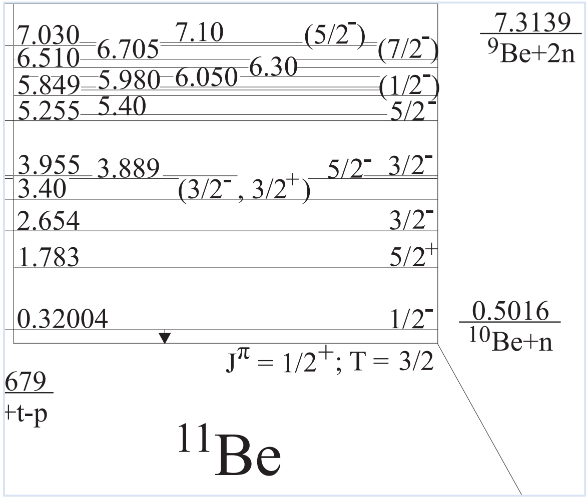
Ab initio predictions for polarized deuterium-tritium thermonuclear fusion

Guillaume Hupin[1,2,3], Sofia Quaglioni[3] & Petr Navrátil[4]

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 **$J^\pi=1/2^+$** - 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?



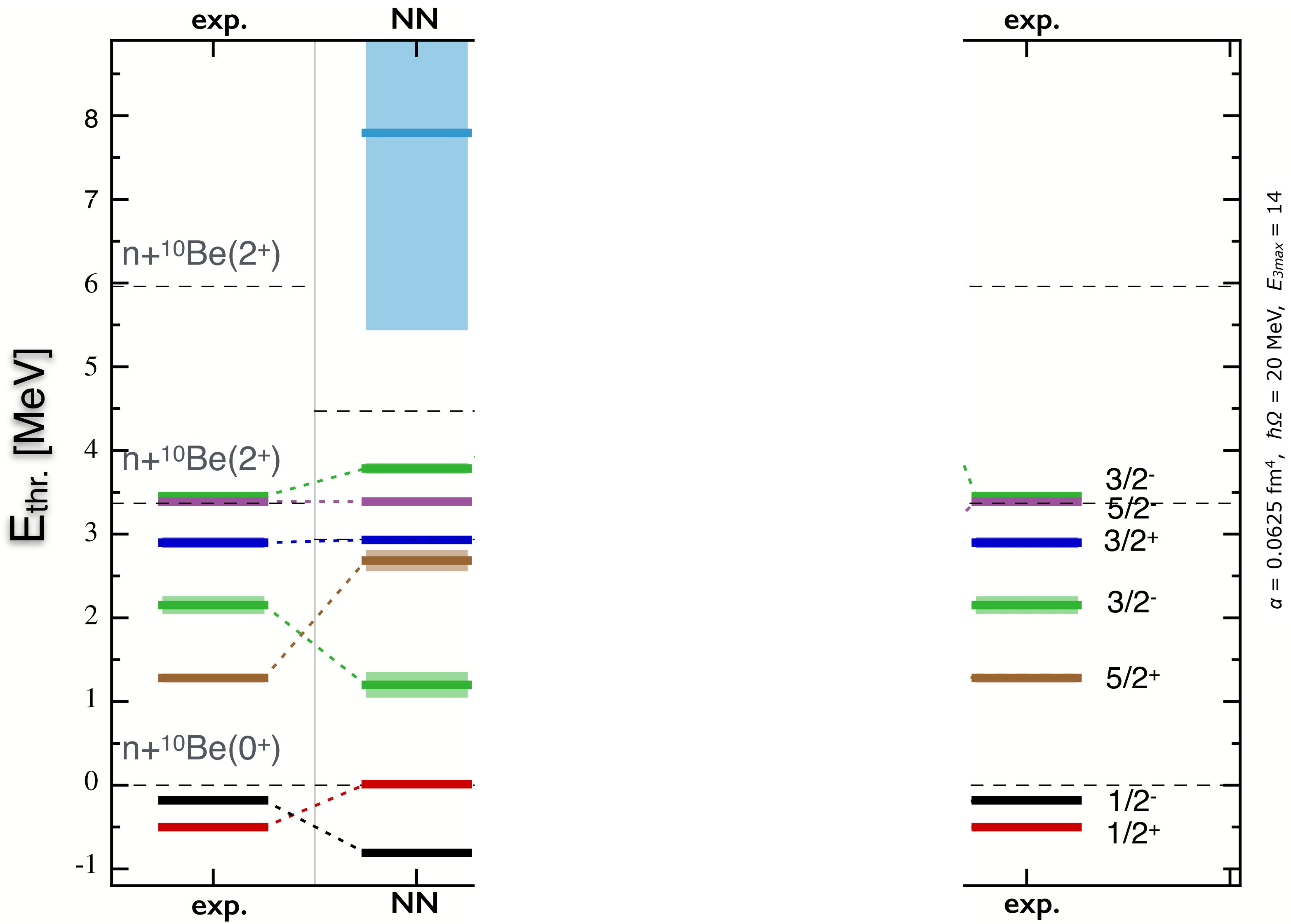


Structure of ^{11}Be from chiral NN+3N forces

- NCSMC calculations **including chiral 3N** (N^3LO NN+N^2LO 3NF400, NNLOsat)
  - n-^{10}Be + ^{11}Be
    - ^{10}Be: 0^+, 2^+, 2^+ NCSM eigenstates
    - ^{11}Be: ≥6 $\pi = -1$ and ≥3 $\pi = +1$ NCSM eigenstates

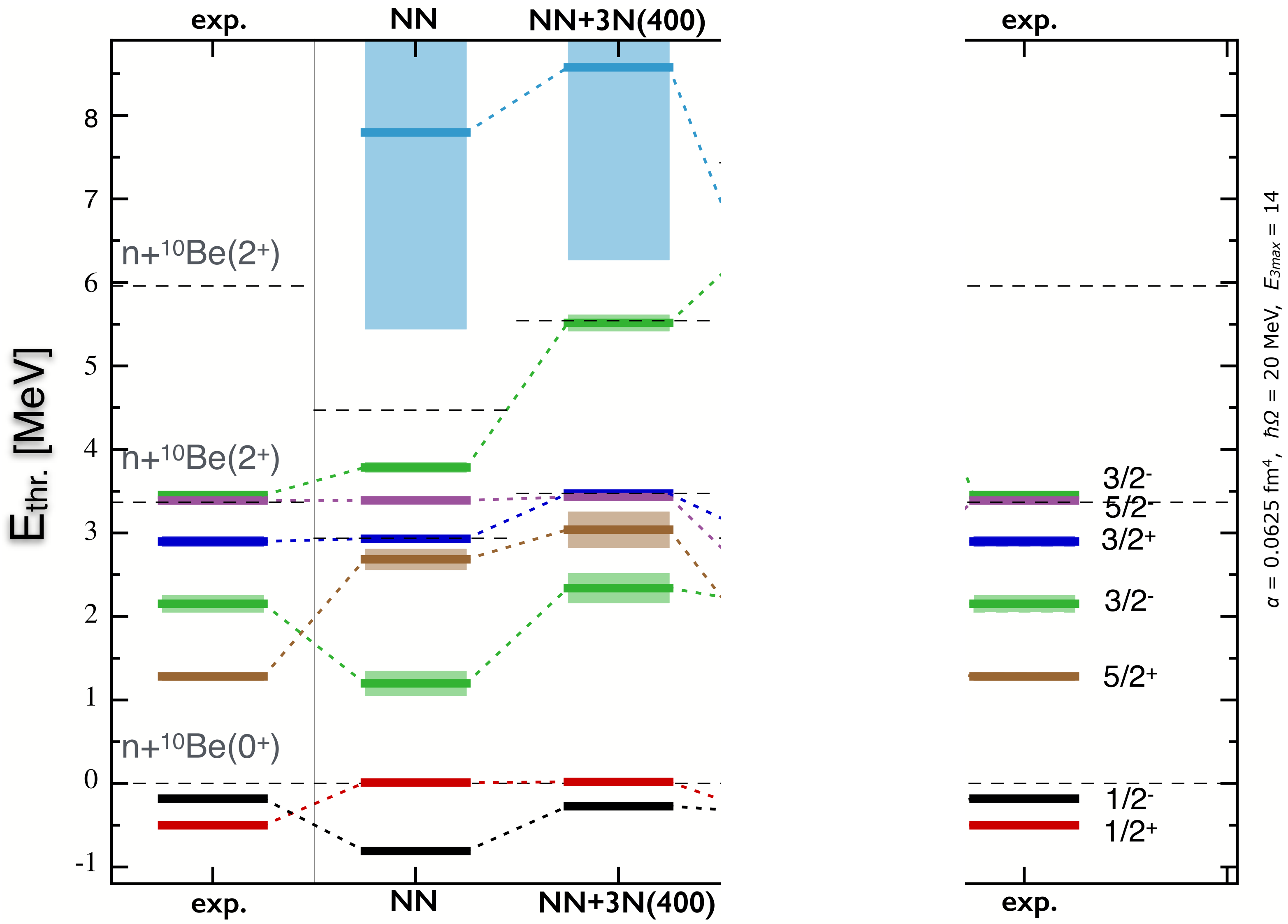
A. Calci, P. Navratil, R. Roth, J. Dohet-Eraly, S. Quaglioni, G. Hupin, PRL 117, 242501 (2016)

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



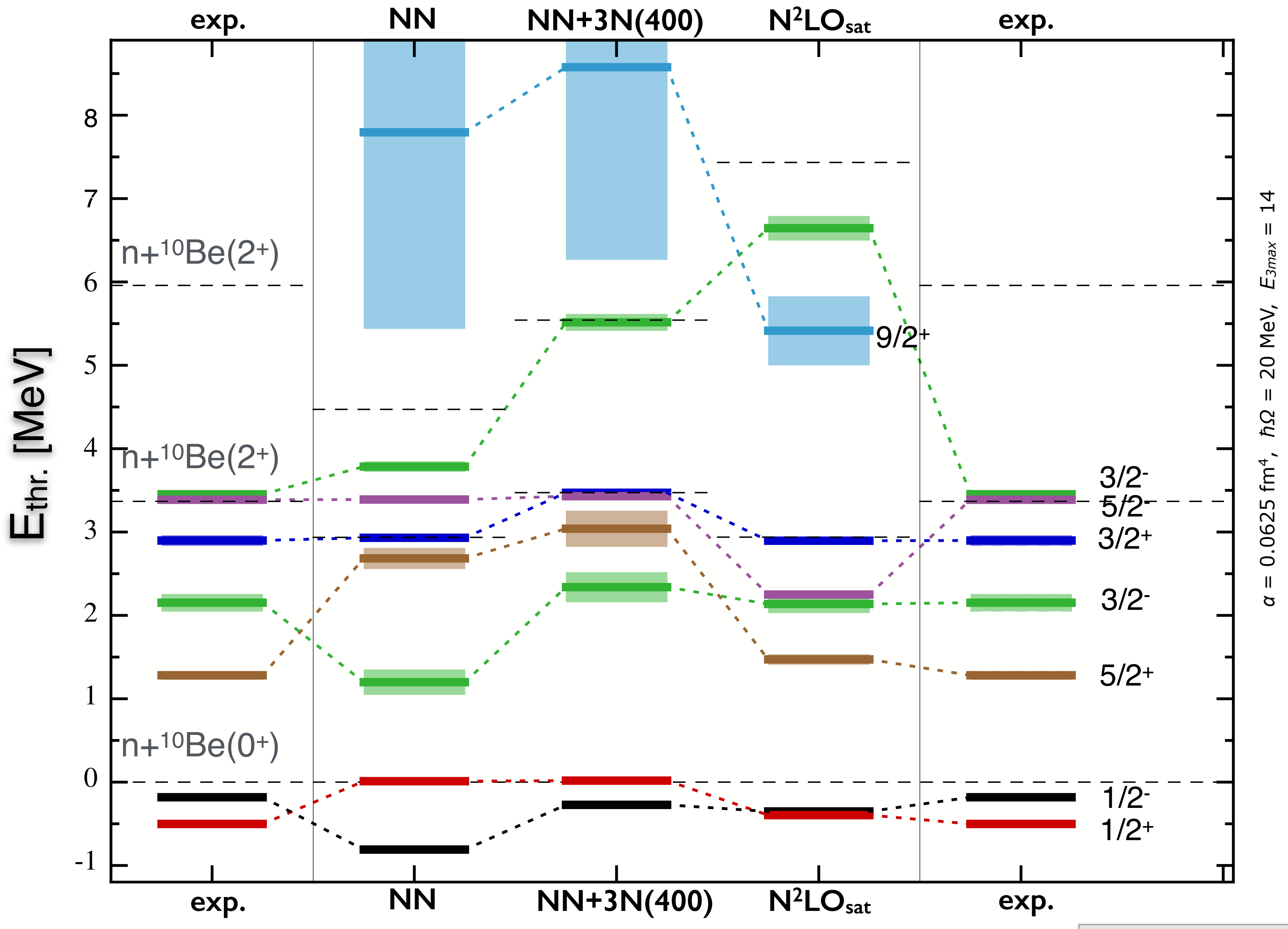
A. Calci, P. Navratil, R. Roth, J. Dohet-Eraly, S. Quaglioni, G. Hupin, PRL 117, 242501 (2016)

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



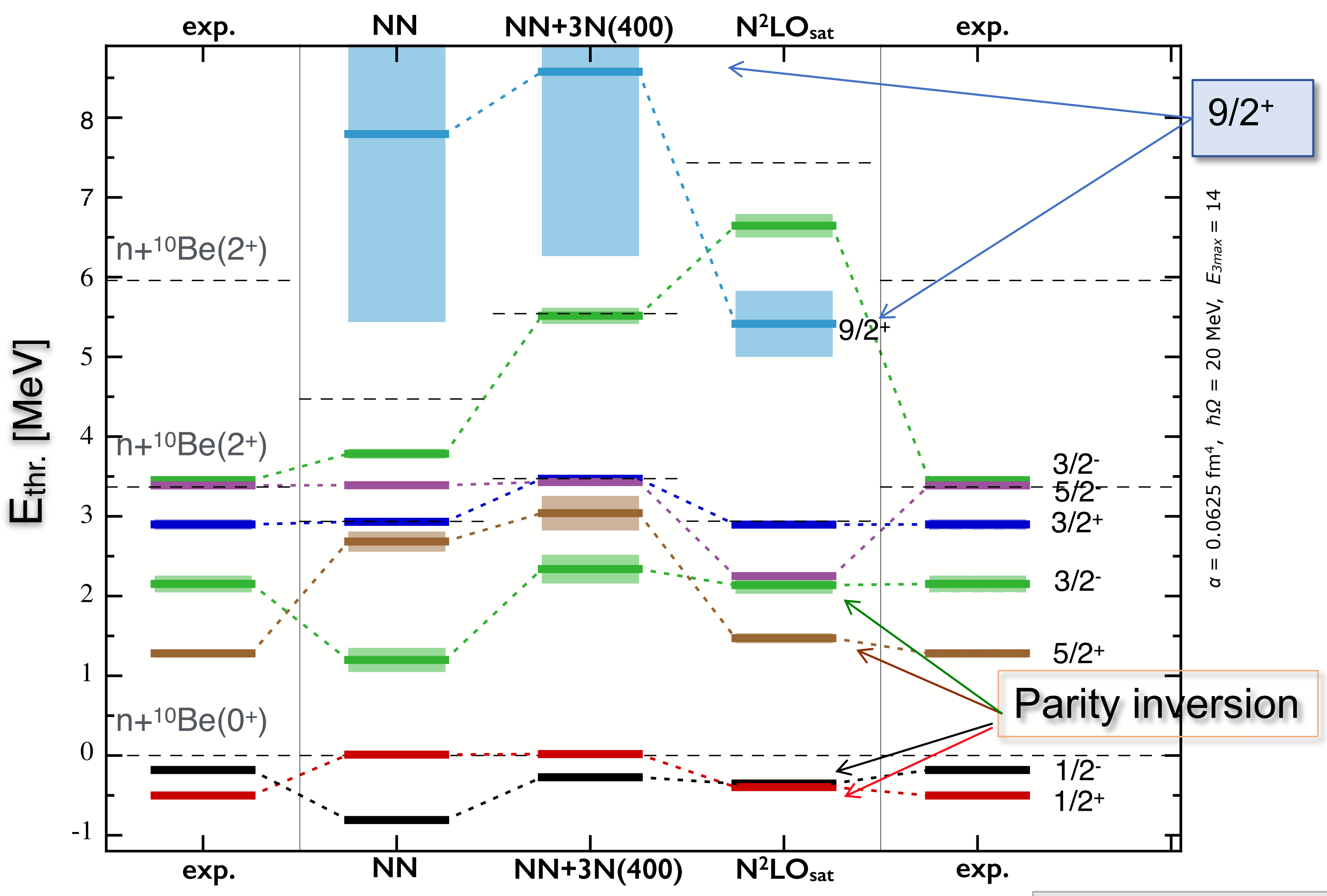
A. Calci, P. Navratil, R. Roth, J. Dohet-Eraly, S. Quaglioni, G. Hupin, PRL 117, 242501 (2016)

^{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)

^{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)

NCSMC phenomenology

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

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

E_λ^{NCSM} energies treated as adjustable parameters

Cluster excitation energies set to experimental values

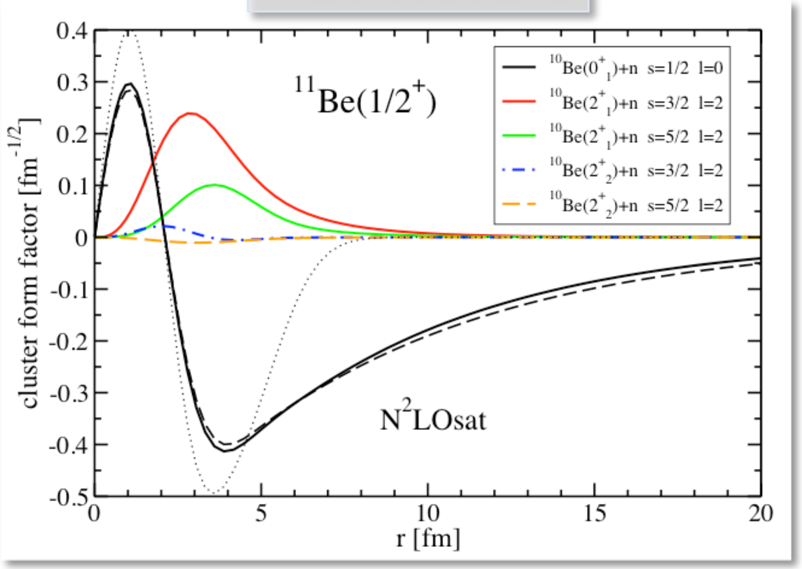
$$\begin{pmatrix} H_{NCSM} & h \\ h & H_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix} = E \begin{pmatrix} 1_{NCSM} & g \\ g & N_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix}$$

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

Photo-disassociation of ^{11}Be

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

Halo structure



cluster form factor

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

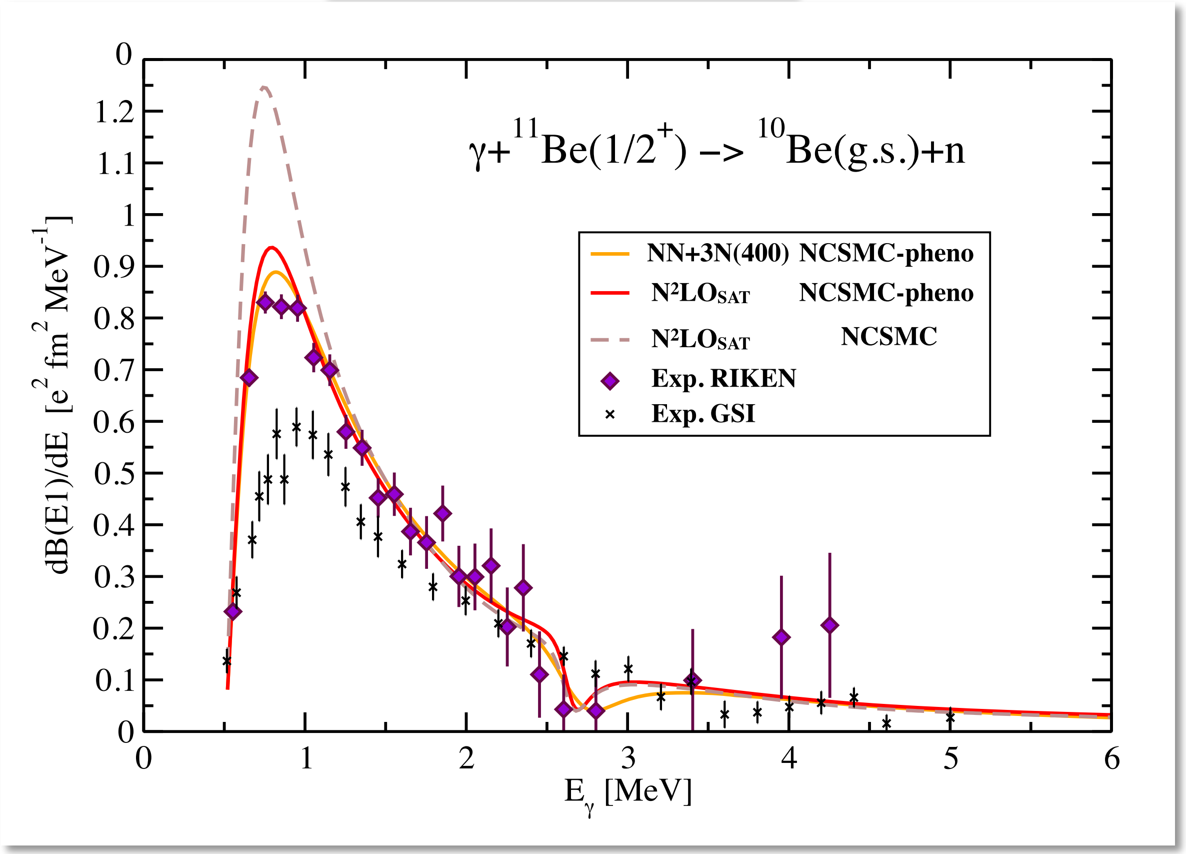
$$\left|\Phi_{\nu r}^{J^\pi T}\right\rangle = \left[\left(\left|{}^{10}\mathrm{Be}\ \alpha_1 I_1^{\pi_1} T_1\right\rangle \left| n\, \tfrac{1}{2}^+ \tfrac{1}{2}\right\rangle\right)^{(sT)} Y_\ell(\hat{r}_{10,1})\right]^{(J^\pi T)} \frac{\delta(r - r_{10,1})}{r r_{10,1}}$$

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

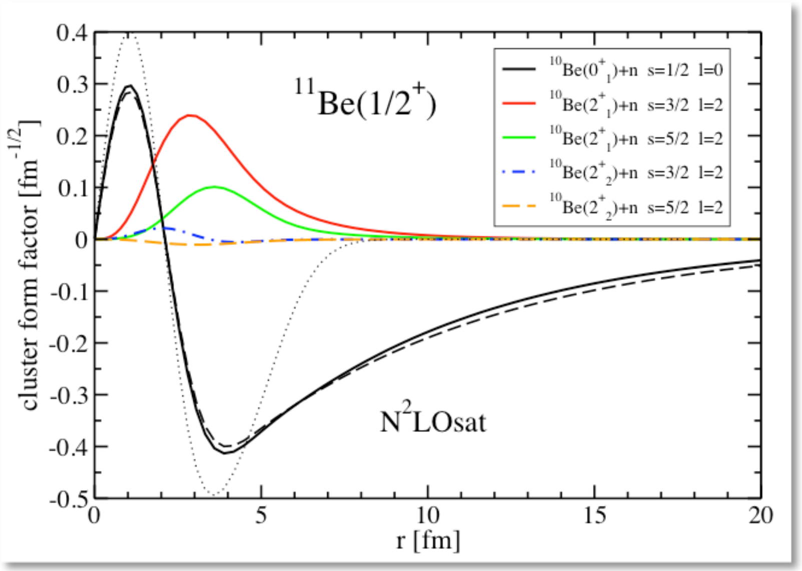
Can *Ab Initio* Theory Explain the Phenomenon of Parity Inversion in ^{11}Be?

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

Bound to continuum



NCSMC wave functions of ^{11}Be used as input for other studies



PHYSICAL REVIEW C **98**, 054602 (2018)

Systematic analysis of the peripherality of the ^{10}Be$(d,p)^{11}$Be transfer reaction and extraction of the asymptotic normalization coefficient of ^{11}Be bound states

J. Yang[1,2,*] and P. Capel[1,3,†]

PHYSICAL REVIEW C **98**, 034610 (2018)

Dissecting reaction calculations using halo effective field theory and *ab initio* input

P. Capel,[1,2,3,4,*] D. R. Phillips,[5,3,4,†] and H.-W. Hammer[3,4,‡]

Physics Letters B 790 (2019) 367–371

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

Reliable extraction of the $dB(\mathrm{E1})/dE$ for ^{11}Be from its breakup at 520 MeV/nucleon

L. Moschini[a,*], P. Capel[b,a]

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

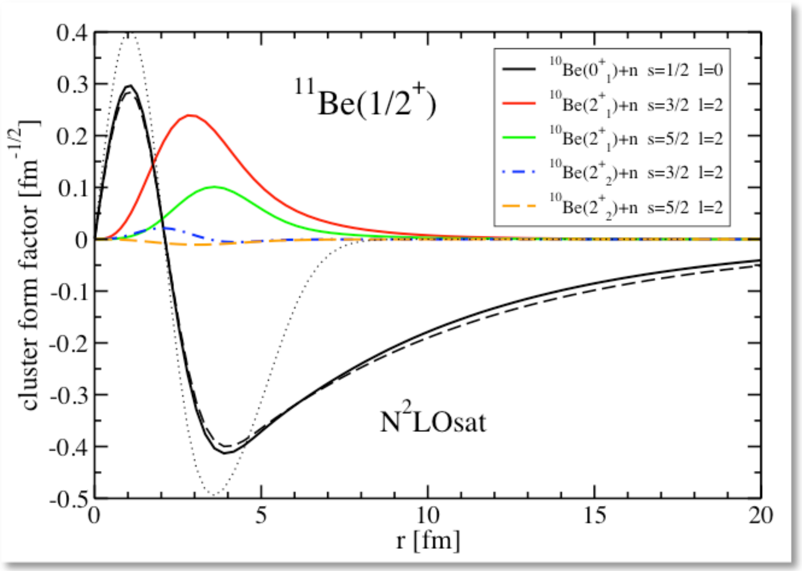
Can *Ab Initio* Theory Explain the Phenomenon of Parity Inversion in ^{11}Be?

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

Neutron transfer reactions in halo effective field theory

M. Schmidt,[1,2] L. Platter,[2,3] and H.-W. Hammer[1,4] arXiv:1812.09152

NCSMC wave functions of ^{11}Be used as input for other studies



IOP Publishing Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. **46** (2019) 025104 (15pp) https://doi.org/10.1088/1361-6471/aaf55b

Neutron disappearance inside the nucleus

H Ejiri[1] and J D Vergados[2]

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

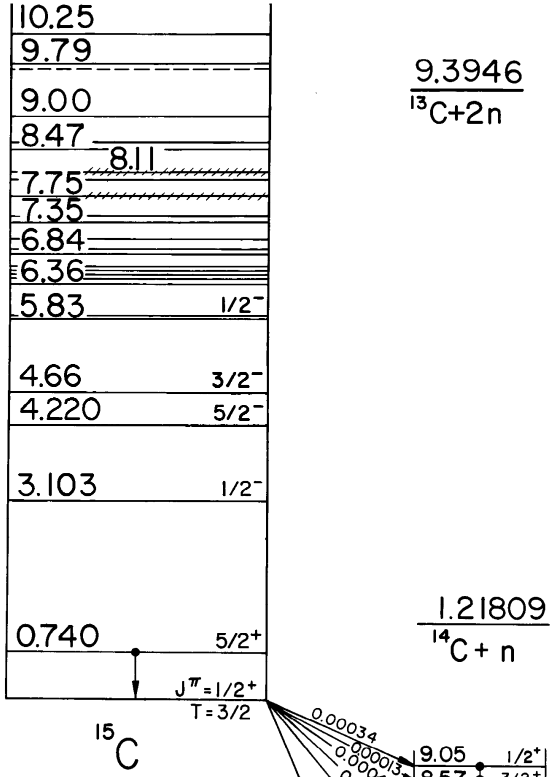
Can *Ab Initio* Theory Explain the Phenomenon of Parity Inversion in ^{11}Be?

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

Halo *sd*-shell nucleus ^{15}C and its unbound mirror ^{15}F

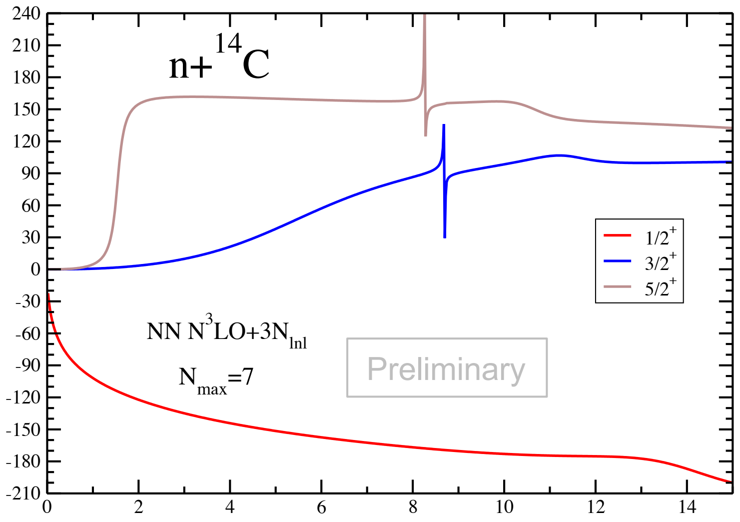
- Motivation:
  - Halo ½+ *S*-wave and 5/2⁺ *D*-wave bound states
  - $^{14}C(n,\gamma)^{15}C$ capture relevant for astrophysics
  - Unbound ^{15}F mirror – very narrow unnatural parity resonances embedded in continuum predicted in $^{14}O(p,p)^{14}O$
    - measured at GANIL

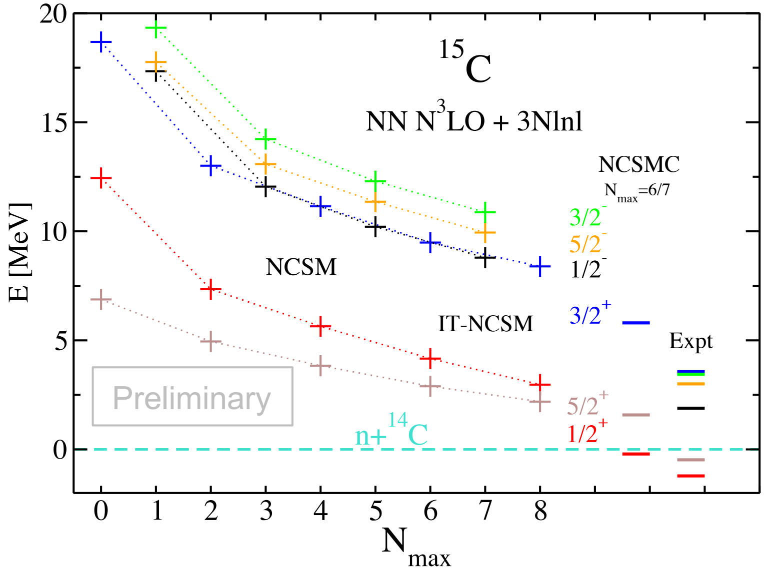
- Calculations in progress – all results preliminary
- NN chiral interaction – N^{3}LO Entem & Machleidt 2003, SRG evolved with λ = 2.0 fm^{-1}
- 3N chiral interaction – N^{2}LO with local/non-local regulator, SRG evolved with λ = 2.0 fm^{-1}

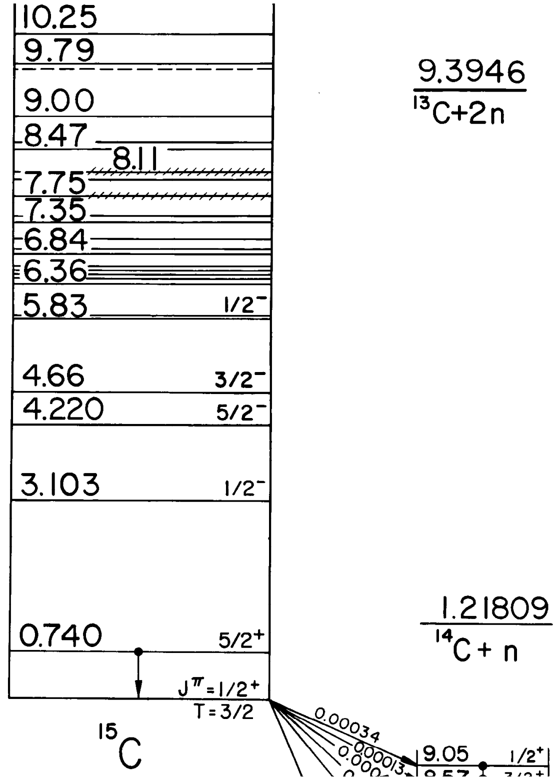


Halo *sd*-shell nucleus ^{15}C

- NCSMC
  - ^{14}C (^{14}O) 0^+ and 2^+ eigenstates
  - ^{15}C (^{15}F) lowest 7 positive and 3 negative parity eigenstates

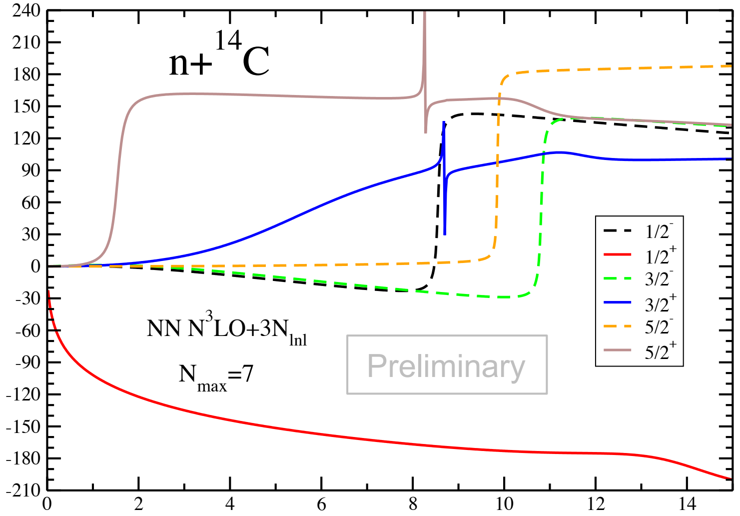


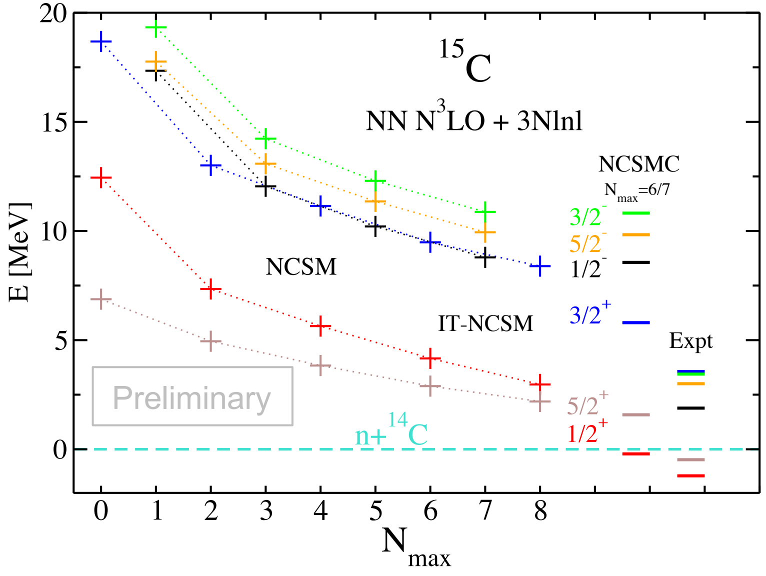


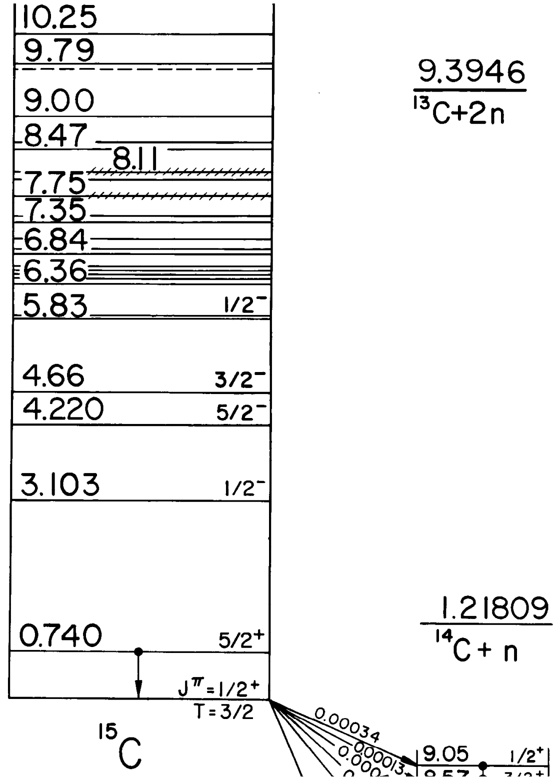


Halo *sd*-shell nucleus ^{15}C

- NCSMC
  - ^{14}C (^{14}O) 0^+ and 2^+ eigenstates
  - ^{15}C (^{15}F) lowest 7 positive and 3 negative parity eigenstates

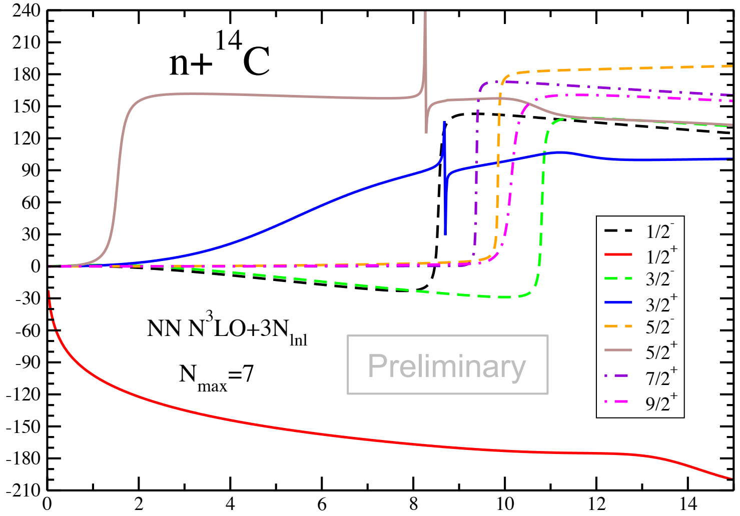


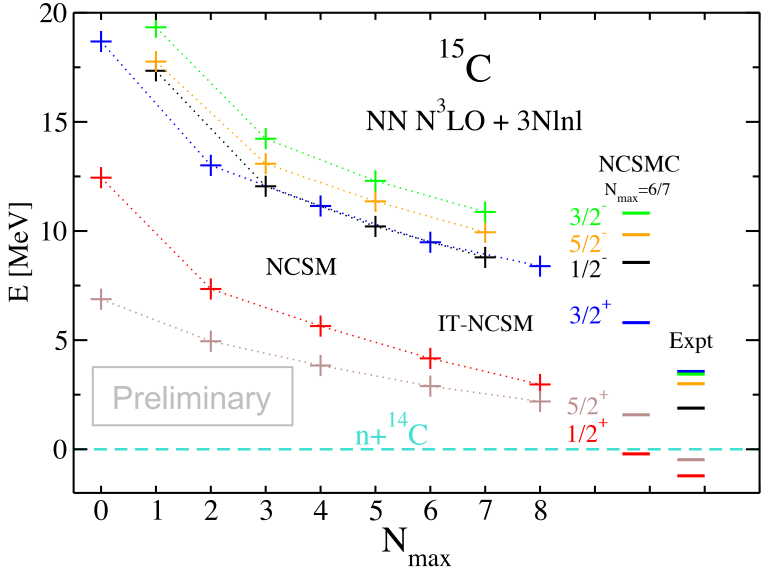


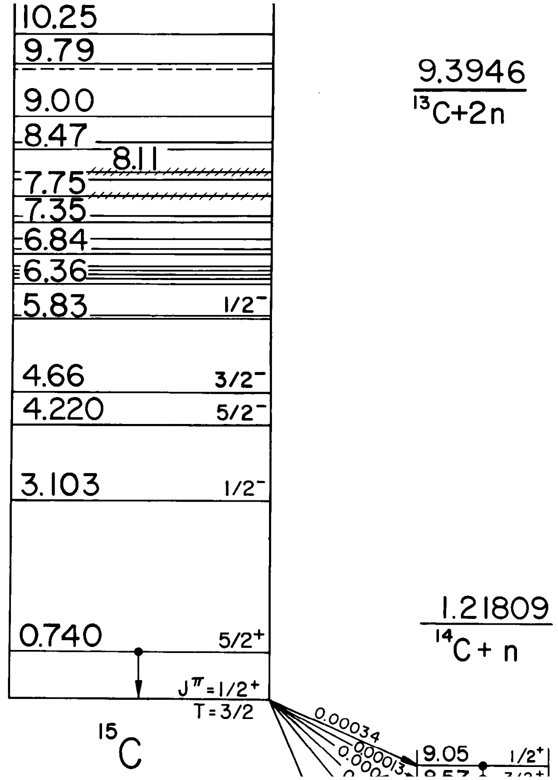


Halo *sd*-shell nucleus ^{15}C

- NCSMC
  - ^{14}C (^{14}O) 0^+ and 2^+ eigenstates
  - ^{15}C (^{15}F) lowest 7 positive and 3 negative parity eigenstates



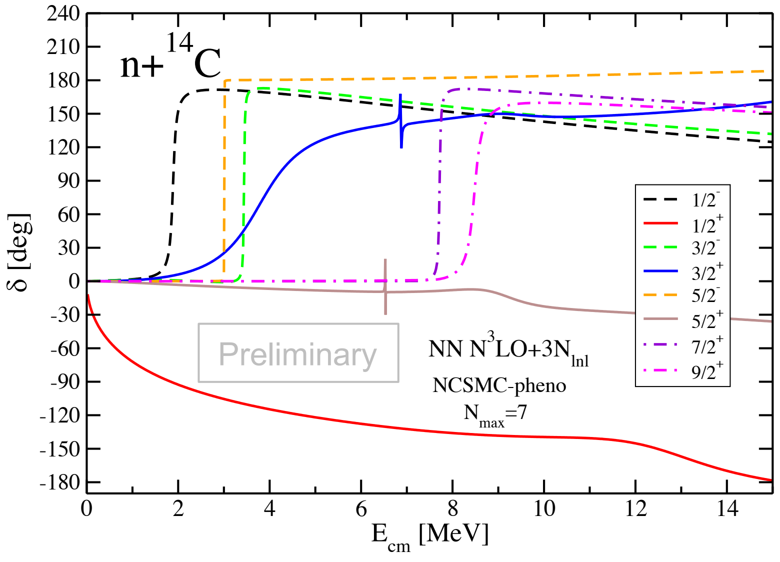




Halo *sd*-shell nucleus ^{15}C

- NCSMC
  - ^{14}C (^{14}O) 0^+ and 2^+ eigenstates
  - ^{15}C (^{15}F) lowest 7 positive and 3 negative parity eigenstates

NCSMC-pheno



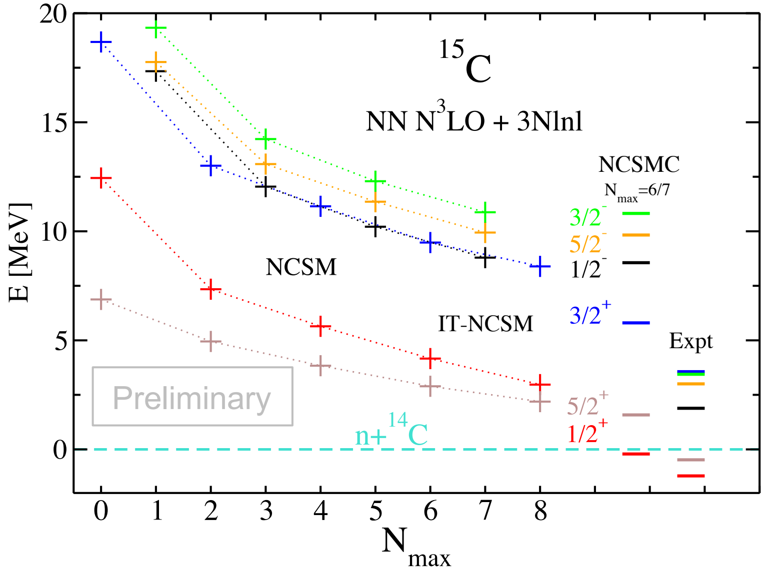
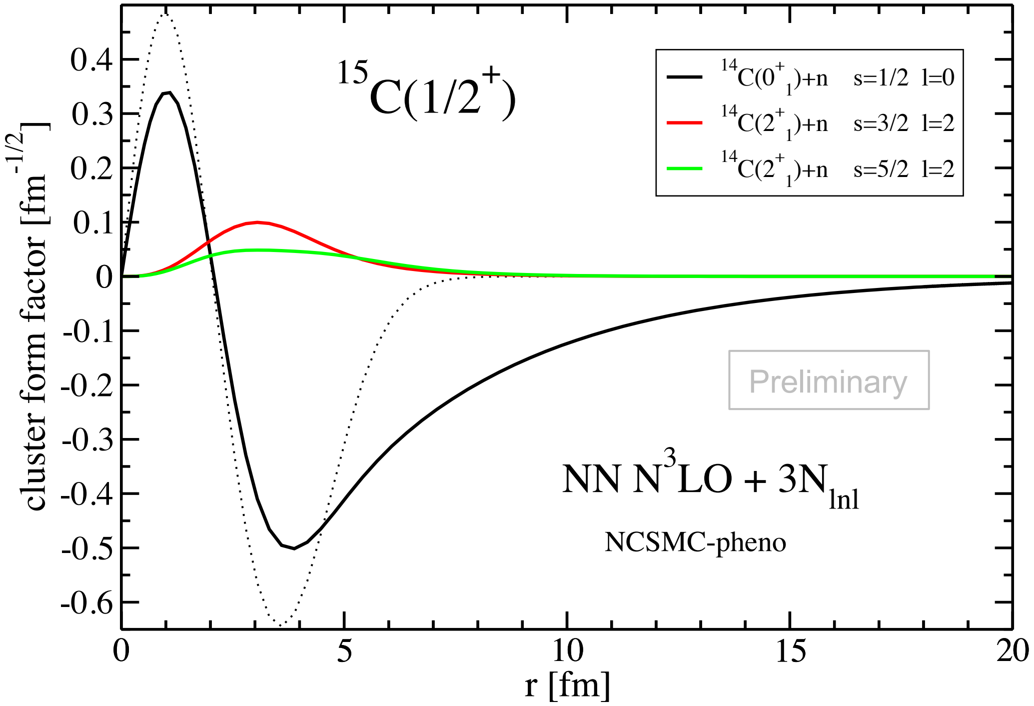


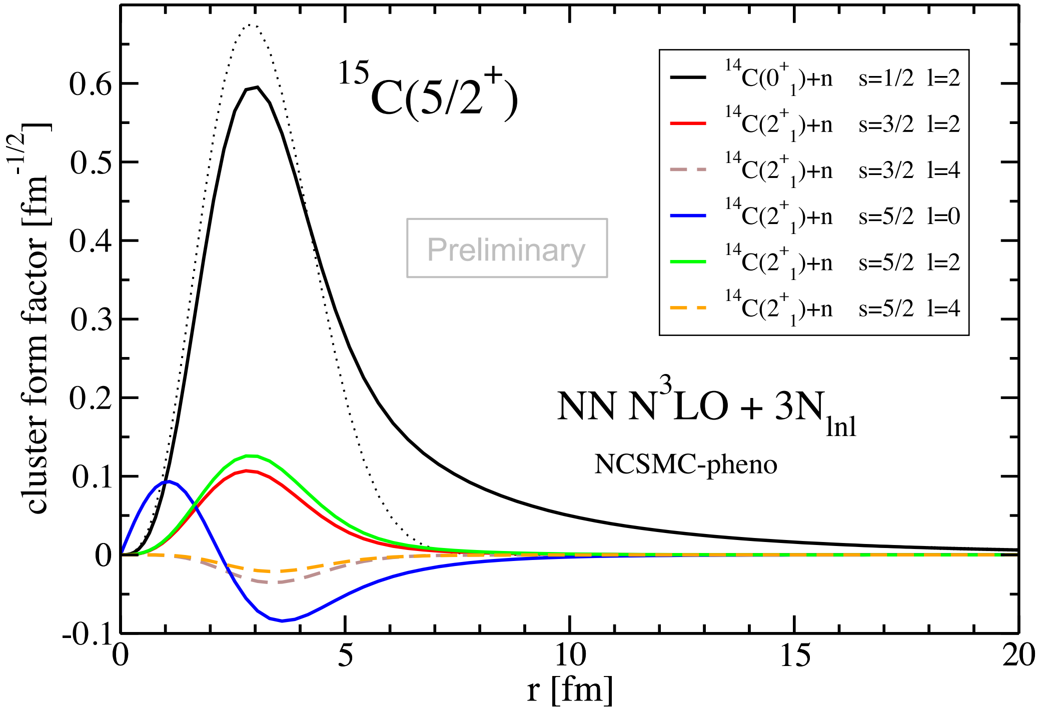
Table 15.1 from (1991AJ01): Energy levels of ^{15}C [a]

E_x (MeV ± keV)	$J^\pi; T$	τ or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
g.s.	$\frac{1}{2}^+; \frac{3}{2}$	$\tau_{1/2} = 2.449 \pm 0.005$ s	β^-	1, 2, 3, 4, 6, 7, 9
		$\lvert g \rvert = 2.63 \pm 0.14$		
0.7400 ± 1.5	$\frac{5}{2}^+$	$\tau_m = 3.76 \pm 0.10$ ns	γ	2, 3, 4, 7, 8
		$g = -0.703 \pm 0.012$		
3.103 ± 4	$\frac{1}{2}^-$	$\Gamma_{c.m.} \leq 40$		2, 3, 9
4.220 ± 3	$\frac{5}{2}^-$	< 14		2, 3
4.657 ± 9	$\frac{3}{2}^-$			2, 3
4.78 ± 100	$\frac{3}{2}^+$	1740 ± 400		6
5.833 ± 20	$(\frac{3}{2}^+)$	64 ± 8		2, 6
5.866 ± 8	$\frac{1}{2}^-$			2, 3
6.358 ± 6	$(\frac{5}{2}, \frac{7}{2}^+, \frac{9}{2}^+)$	< 20		2, 3
6.417 ± 6	$(\frac{3}{2} \rightarrow \frac{7}{2})$	≈ 50		2, 3
6.449 ± 7	$(\frac{9}{2}^-, \frac{11}{2})$	< 14		2, 3
6.536 ± 4	[a]	< 14		2, 3
6.626 ± 8	$(\frac{3}{2})$	20 ± 10		2, 3
6.841 ± 4	[a]	< 14		2, 3
6.881 ± 4	$(\frac{9}{2})$ [a]	< 20		2, 3
7.095 ± 4	$(\frac{3}{2})$	< 15		2, 3
7.352 ± 6	$(\frac{9}{2}, \frac{11}{2})$	20 ± 10		2, 4
7.414 ± 20				2
7.75 ± 30 [b]				2
8.01 ± 30				2

^{15}C cluster form factors

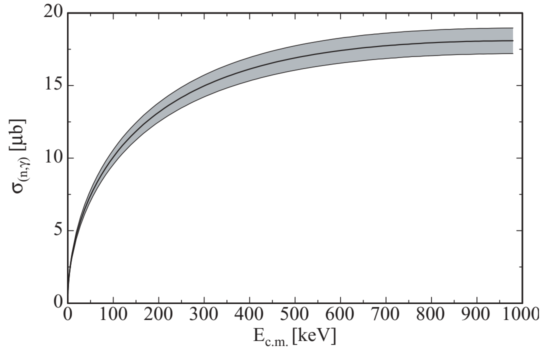
- $1/2^+$ *S*-wave and $5/2^+$ *D*-wave ANCs
  - $C_{1/2+} = 1.282$ fm$^{-1/2}$ - compare to Moschini & Capel inferred from transfer data: 1.26(2) fm$^{-1/2}$
  - $C_{5/2+} = 0.048$ fm$^{-1/2}$ 0.056(1) fm$^{-1/2}$
  - Spectroscopic factors: 0.96 for $1/2^+$ and 0.90 for $5/2^+$ - experiments 0.95(5) and 0.69, resp.

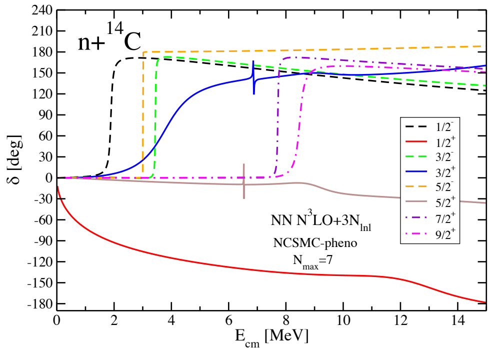


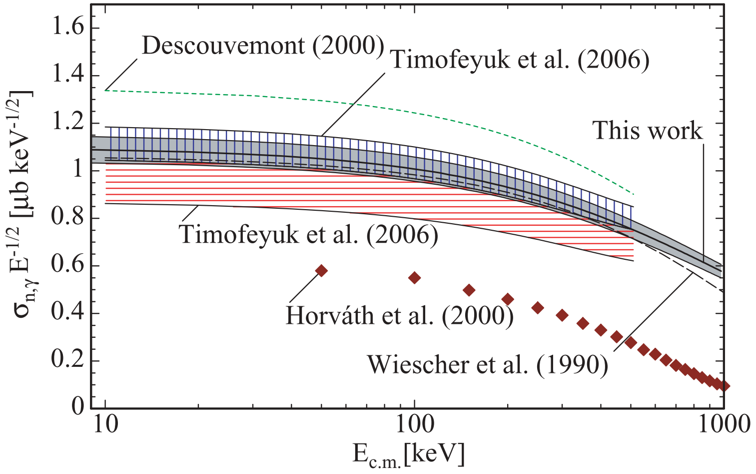


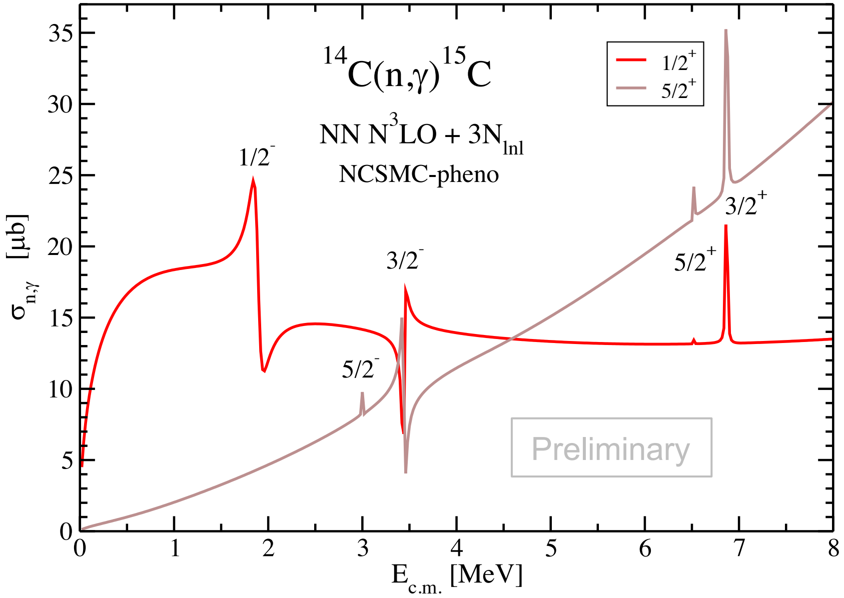
$^{14}C(n,\gamma)^{15}C$ capture cross section

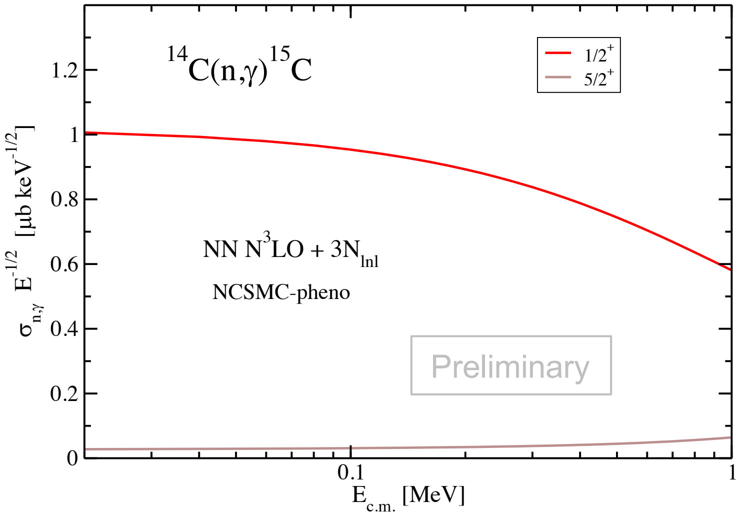
- Comparison to Karlsruhe experiment – Phys. Rev. C 77, 015804 (2008)











Relevant for

Inhomogeneous Big Bang models

Neutron induced CNO cycles

Neutrino driven wind models for the r-process

Validation of Coulomb dissociation method

Conclusions

- *Ab initio* calculations of nuclear structure and reactions becoming feasible beyond the lightest nuclei
  - Make connections between the low-energy QCD, many-body systems, and nuclear astrophysics

- Polarized DT fusion investigated within NCSMC
  - Sheds light on importance of l>0 partial waves

- ^{11}Be parity inversion explained with chiral NN+3N N^2LO_{sat} interaction

- NCSMC calculations of ^{15}C *sd*-shell halo nucleus in progress
  - Capture cross section, cluster form factors, ANCs

- Study of the unbound ^{15}F (mirror of ^{15}C) in progress
  - Structure of resonances

TRIUMF

Thank you!

Merci!

Grazie!

Discovery,
accelerated