TRIUMF

Nuclear scattering and reactions from *ab initio* no-core shell model with continuum

Open Quantum Systems: From atomic nuclei to ultracold atoms and quantum optics

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TRIUMF

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2019-10-04

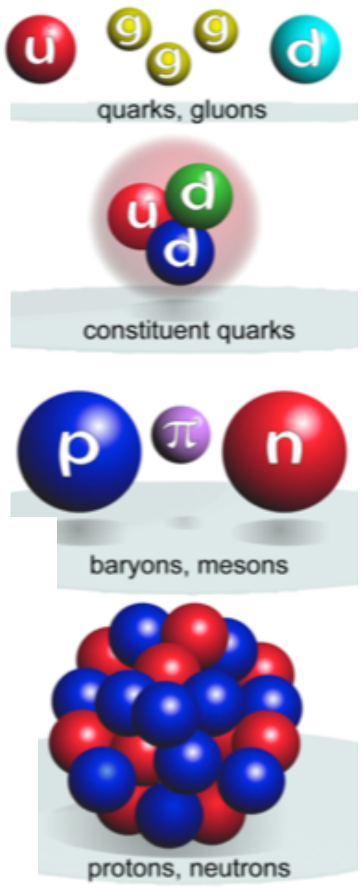
Discovery, accelerated

Outline

- Introduction to *ab initio* No-Core Shell Model with Continuum (NCSMC)
- Polarized ^{3}H(d,n)^{4}He fusion
- Structure of ^{7}Be and ^{7}Li from different binary-mass partitions
- ^{11}C(p,γ)^{12}N capture
- Structure of the halo *sd*-shell nucleus ^{15}C

First principles or *ab initio* nuclear theory

Quantum Chromodynamics (QCD)



Genuine *Ab Initio*

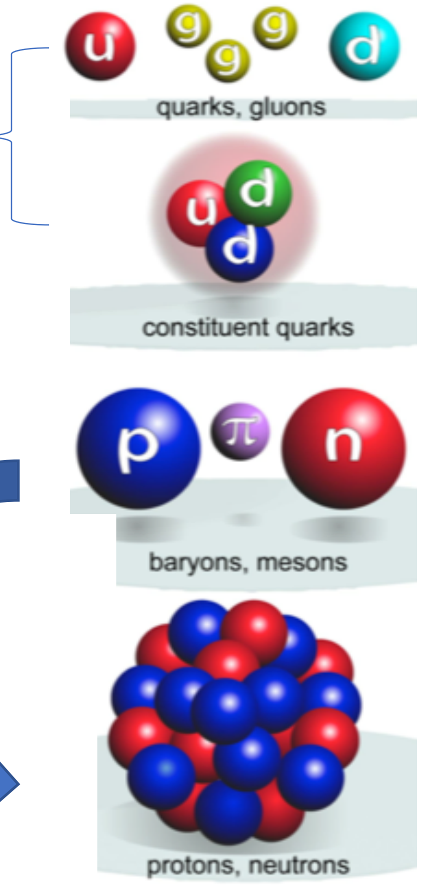
First principles or *ab initio* nuclear theory – what we do at present

Quantum Chromodynamics (QCD)

Chiral Effective Field Theory (parameters fitted to NN data)

Current *ab anitio* nuclear theory

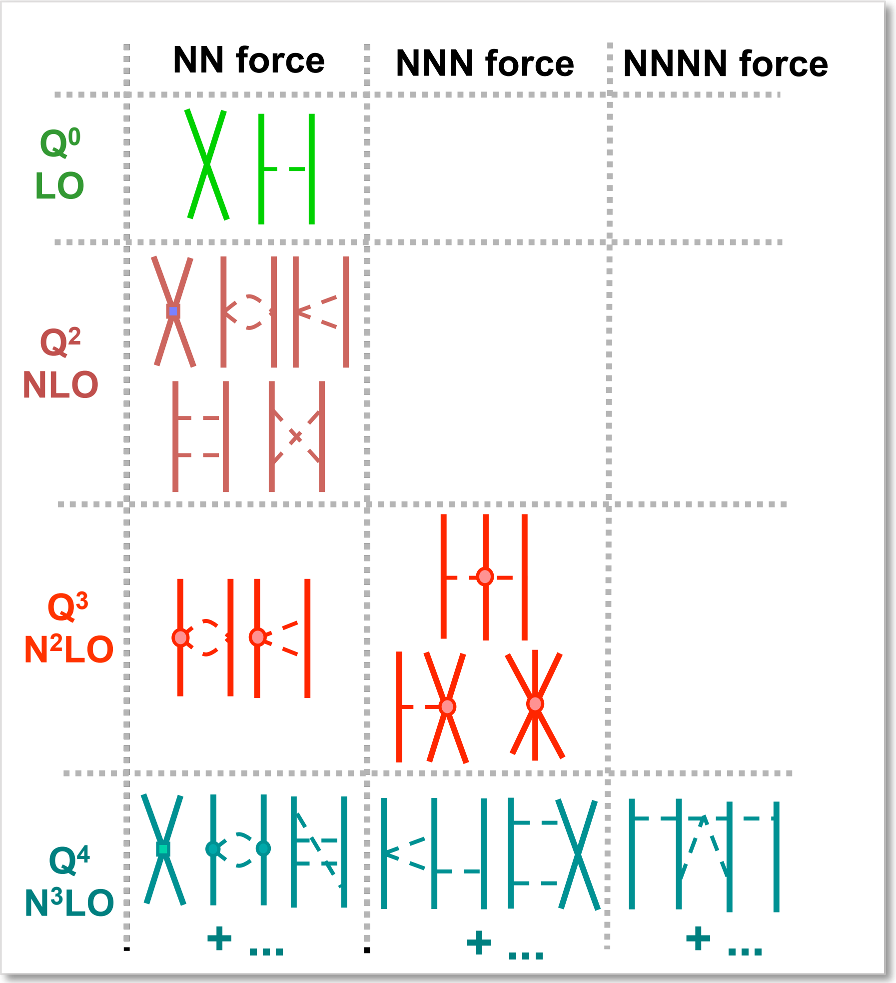
$$H\,\Psi^{(A)} = E\,\Psi^{(A)}$$



- *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

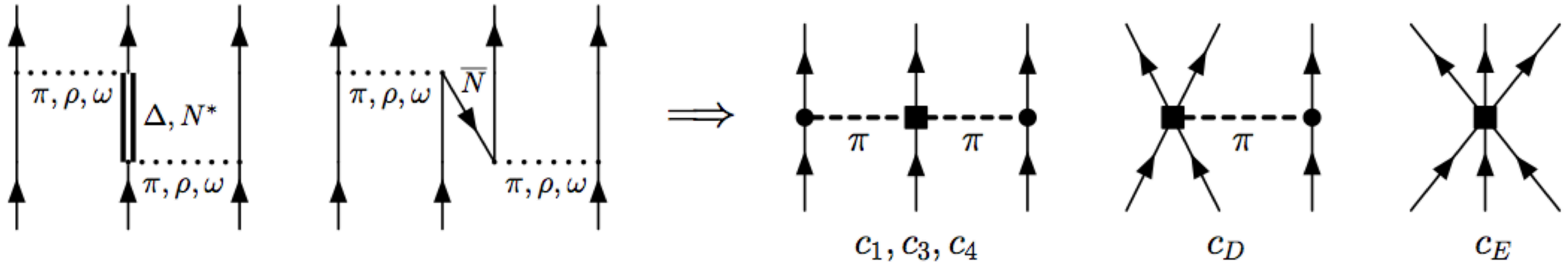
Chiral Effective Field Theory

- 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

Why three-nucleon forces?



Eliminating degrees of freedom leads to three-body forces.

Two-pion exchange with **virtual Δ excitation** – Fujita & Miyazawa (1957)

- Leading three-nucleon force terms
  - Long-range two-pion exchange
  - Medium-range one-pion exchange + two-nucleon contact
  - Short range three-nucleon contact

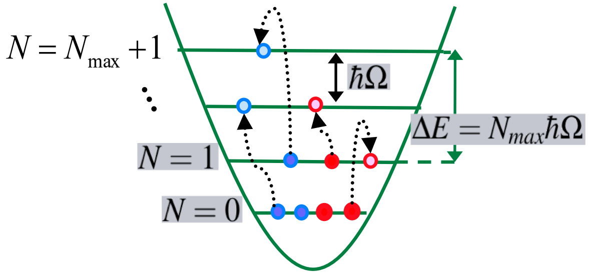
The question is not: Do three-body forces enter the description?

The only question is: How large are three-body forces?

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

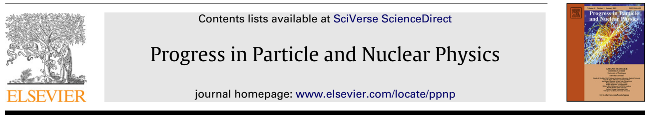
NCSM

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

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


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

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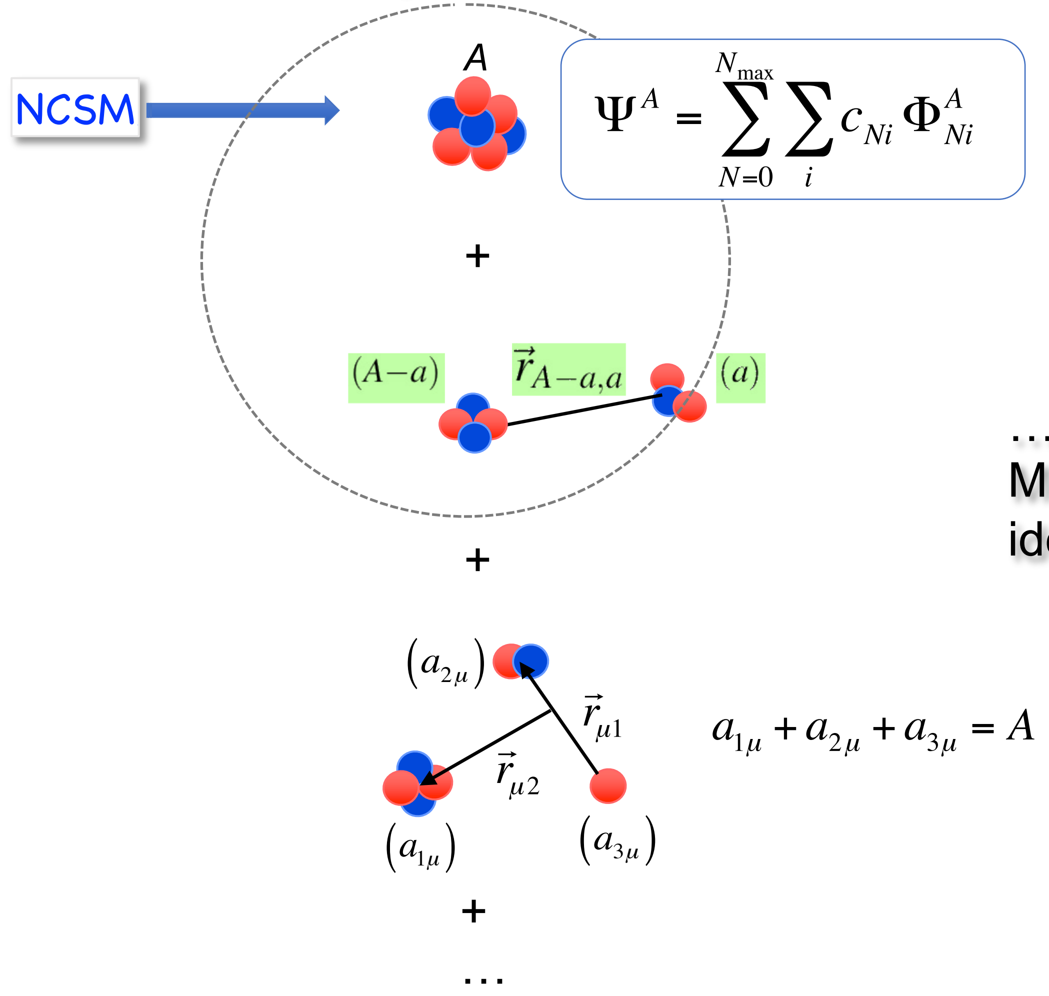
Review

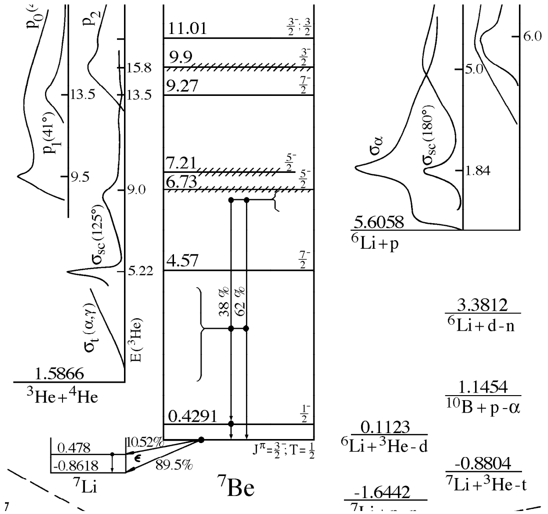
Ab initio no core shell model

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

Extending no-core shell model beyond bound states

Include more many nucleon correlations…





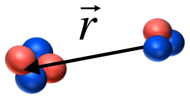
…using the Resonating Group Method (RGM) ideas

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)

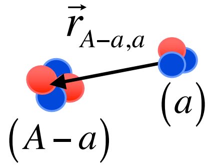
NCSMC

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

Unknowns

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

Binary cluster basis



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

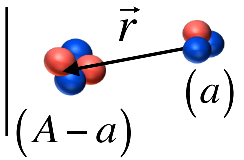
$$\left|\psi^{J^\pi T}\right\rangle = \sum_\nu \hat{A}_\nu \left[\left(\underbrace{\left|A-a\ \alpha_1 I_1^{\pi_1} T_1\right\rangle}_{\text{Target}} \underbrace{\left|a\ \alpha_2 I_2^{\pi_2} T_2\right\rangle}_{\text{Projectile}} \right)^{(sT)} Y_\ell(\hat{r}_{A-a,a}) \right]^{(J^\pi T)} \frac{g_\nu^{J^\pi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

- 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

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



Coupled NCSMC equations

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

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

$E_\lambda^{NCSM}\,\delta_{\lambda\lambda'}$ → H_{NCSM}

$\left\langle (A) \middle| H\,\hat{A}_\nu \middle| \underset{(a)}{\bullet} \xrightarrow{r} \underset{(A-a)}{\bullet} \right\rangle$ → h

$\delta_{\lambda\lambda'}$ → 1_{NCSM}

$\left\langle (A) \middle| \hat{A}_\nu \middle| \underset{(a)}{\bullet} \xrightarrow{r} \underset{(A-a)}{\bullet} \right\rangle$ → g

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

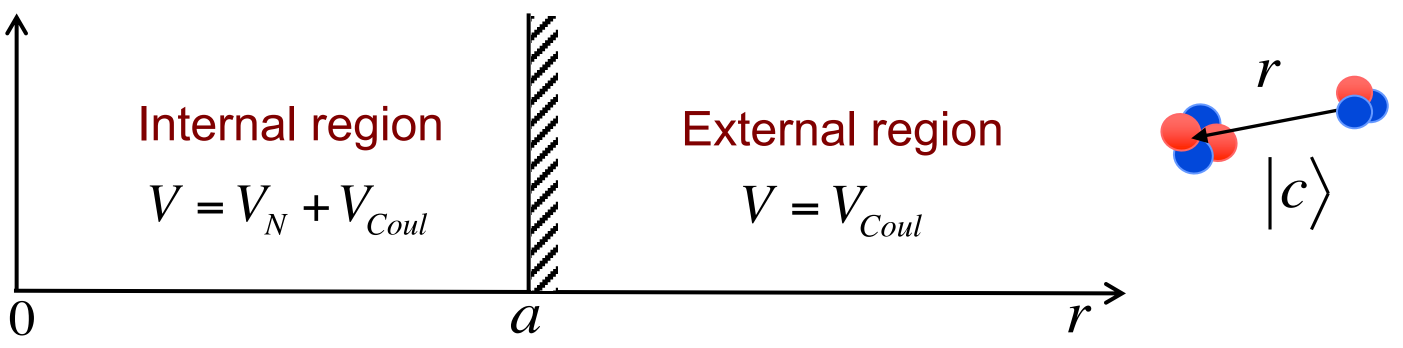
$\left\langle \underset{(A-a)}{\bullet} \xleftarrow{r'} \underset{(a)}{\bullet} \middle| \hat{A}_{\nu'}\, H\, \hat{A}_\nu \middle| \underset{(a)}{\bullet} \xrightarrow{r} \underset{(A-a)}{\bullet} \right\rangle$ → H_{RGM}

$\left\langle \underset{(A-a)}{\bullet} \xleftarrow{r'} \underset{(a)}{\bullet} \middle| \hat{A}_{\nu'}\, \hat{A}_\nu \middle| \underset{(a)}{\bullet} \xrightarrow{r} \underset{(A-a)}{\bullet} \right\rangle$ → N_{RGM}

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

Microscopic R-matrix theory on a Lagrange mesh – Coupled channels

- Separation into “internal” and “external” regions at the channel radius a



- Matching achieved through the Bloch operator: $L_c = \frac{\hbar^2}{2\mu_c}\delta(r-a)\left(\frac{d}{dr} - \frac{B_c}{r}\right)$
- System of Bloch-Schrödinger equations:

$$\left[\hat{T}_{rel}(r) + L_c + \overline{V}_{Coul}(r) - (E - E_c)\right]u_c(r) + \sum_{c'}\int dr' r' W_{cc'}(r,r')u_{c'}(r') = L_c u_c(r)$$

Microscopic R-matrix theory on a Lagrange mesh – Coupled channels

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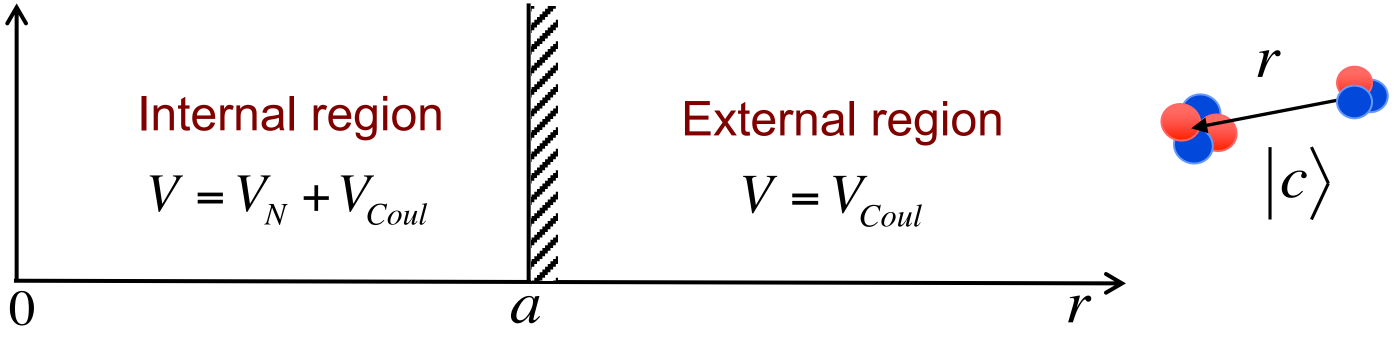

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- System of Bloch-Schrödinger equations:

$$\left[\hat{T}_{rel}(r) + L_c + \overline{V}_{Coul}(r) - (E - E_c)\right]u_c(r) + \sum_{c'}\int dr'\,r'\,W_{cc'}(r,r')\,u_{c'}(r') = L_c u_c(r)$$

- Internal region: expansion on square-integrable basis $u_c(r) = \sum_n A_{cn} f_n(r)$
- External region: asymptotic form for large r

Bound state $u_c(r) \sim C_c W(k_c r)$

Scattering state $u_c(r) \sim v_c^{-\frac{1}{2}}\left[\delta_{ci} I_c(k_c r) - U_{ci} O_c(k_c r)\right]$

Scattering matrix

To find the Scattering matrix – Coupled channels

- After projection on the basis $f_n(r)$:

$$\sum_{c'n'}\left[C_{cn,c'n'} - (E - E_c)\delta_{cn,c'n'}\right]A_{c'n'} = \frac{\hbar^2 k_c}{2\mu_c v_c^{1/2}}\left\langle f_n \middle| L_c \middle| I_c\delta_{ci} - U_{ci}O_c\right\rangle$$

$$\left\langle f_n \middle| \hat{T}_{rel}(r) + L_c + \bar{V}_{Coul}(r) \middle| f_{n'}\right\rangle\delta_{cc'} + \left\langle f_n \middle| W_{cc'}(r,r') \middle| f_{n'}\right\rangle$$

1. Solve for A_{cn}

2. Match internal and external solutions at channel radius, a

$$\sum_{c'} R_{cc'}\frac{k_{c'}a}{\sqrt{\mu_{c'}v_{c'}}}\left[I'_{c'}(k_{c'}a)\delta_{ci} - U_{c'i}O'_{c'}(k_{c'}a)\right] = \frac{1}{\sqrt{\mu_c v_c}}\left[I_c(k_c a)\delta_{ci} - U_{ci}O_c(k_c a)\right]$$

Lagrange basis associated with Lagrange mesh:

$$\{ax_n \in [0,a]\}$$

$$\int_0^1 g(x)dx \approx \sum_{n=1}^{N}\lambda_n g(x_n)$$

$$\int_0^a f_n(r)f_{n'}(r)dr \approx \delta_{nn'}$$

- In the process introduce *R*-matrix, projection of the Green's function operator on the channel-surface functions

$$R_{cc'} = \sum_{nn'}\frac{\hbar}{\sqrt{2\mu_c a}}f_n(a)\left[C - EI\right]^{-1}_{cn,c'n'}\frac{\hbar}{\sqrt{2\mu_{c'} a}}f_{n'}(a)$$

To find the Scattering matrix – Coupled channels

3. Solve equation with respect to the scattering matrix U

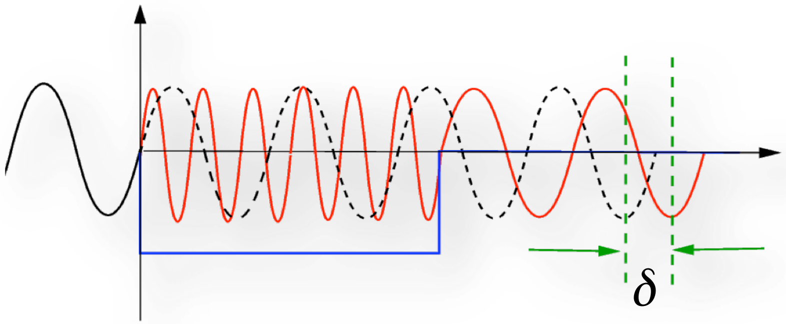
$$\sum_{c'} R_{cc'} \frac{k_{c'}a}{\sqrt{\mu_{c'}v_{c'}}}\left[I'_{c'}(k_{c'}a)\delta_{c'i} - U_{c'i}O'_{c'}(k_{c'}a)\right] = \frac{1}{\sqrt{\mu_c v_c}}\left[I_c(k_c a)\delta_{ci} - U_{ci}O_c(k_c a)\right]$$

4. You can demonstrate that the solution is given by:

$$U = Z^{-1}Z^*, \qquad Z_{cc'} = \left(k_{c'}a\right)^{-1}\left[O_c(k_c a)\delta_{cc'} - k_{c'}a\, R_{cc'}\, O'_{c'}(k_{c'}a)\right]$$

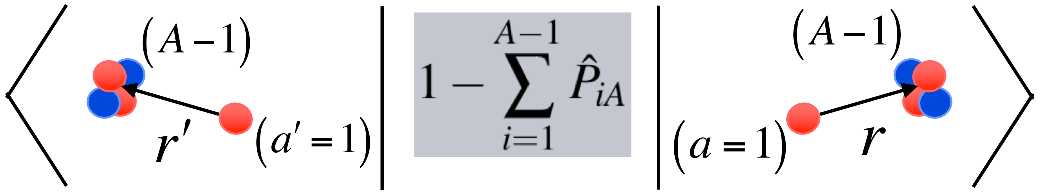
- Scattering phase shifts are extracted from the scattering matrix elements

$$U = \exp(2i\delta)$$



Norm kernel (Pauli principle): Single-nucleon projectile

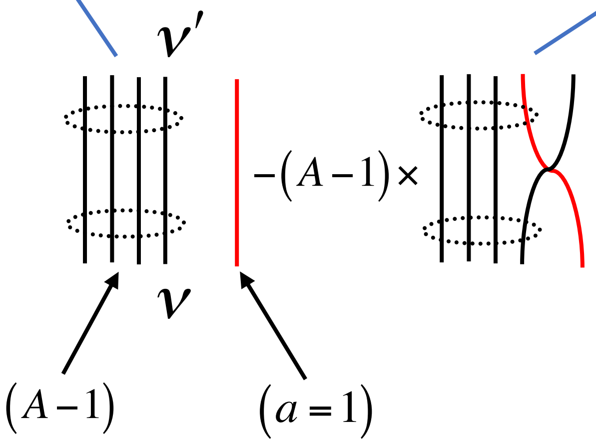
$$\left\langle \Phi^{J^\pi T}_{\nu' r'} \middle| \hat{A}_{\nu'} \hat{A}_{\nu} \middle| \Phi^{J^\pi T}_{\nu r} \right\rangle =$$



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

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

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)

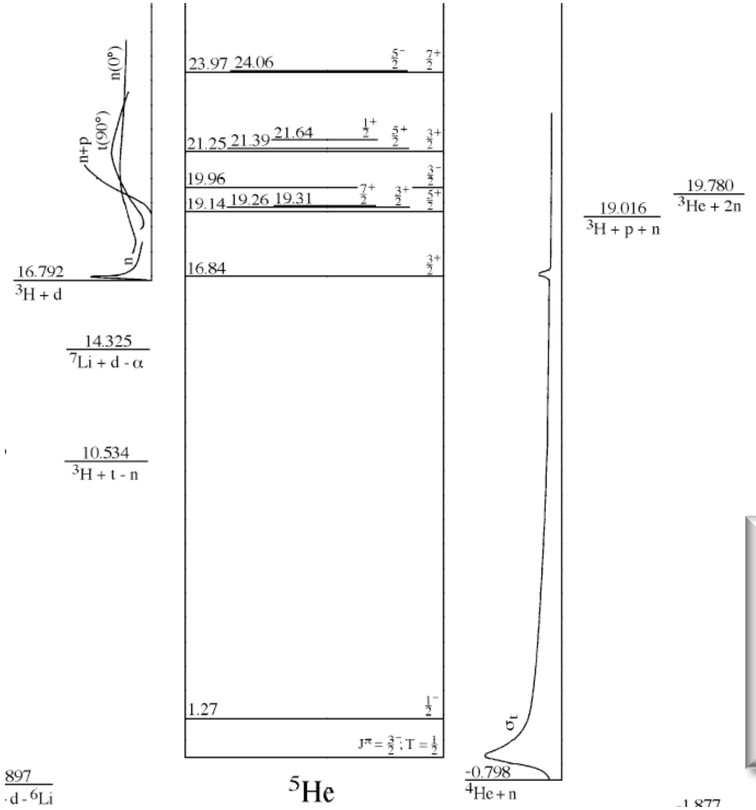
Trick #1

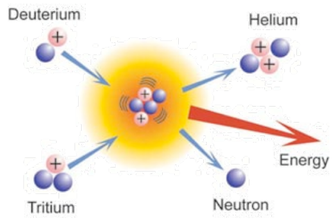
$$\frac{\delta(r - r_{A-a,a})}{r\, r_{A-a,a}} = \sum_n R_{n\ell}(r) R_{n\ell}(r_{A-a,a})$$

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

Deuterium-Tritium fusion

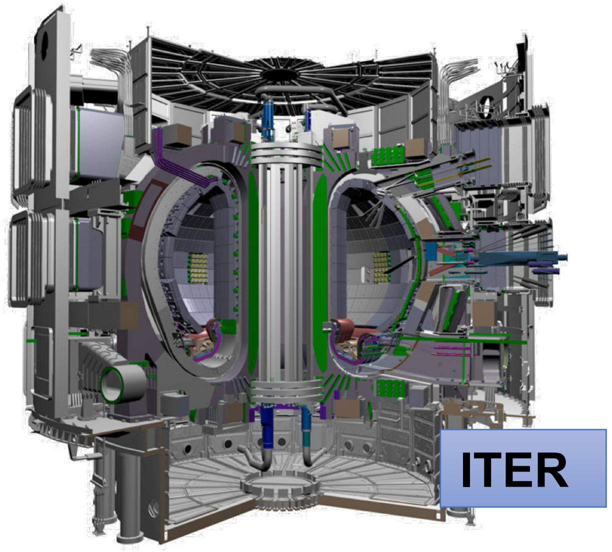
- The d+^{3}H$\rightarrow$$n$+^{4}He reaction
  - The most promising for the production of fusion energy in the near future
  - Used to achieve inertial-confinement (laser-induced) fusion at NIF, and magnetic-confinement fusion at ITER
  - With its mirror reaction, ^{3}He(d,p)^{4}He, important for Big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

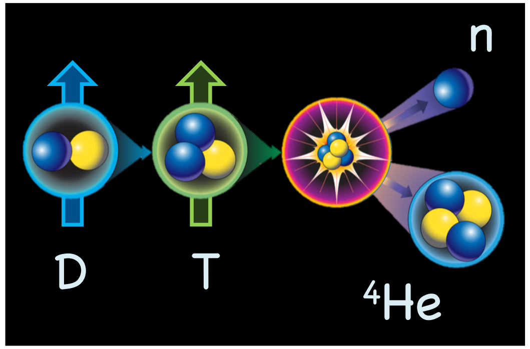


NCSMC calculation of the DT fusion

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

- 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

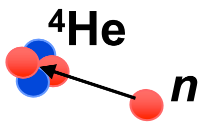
n-^{4}He scattering and ^{3}H+d fusion within NCSMC

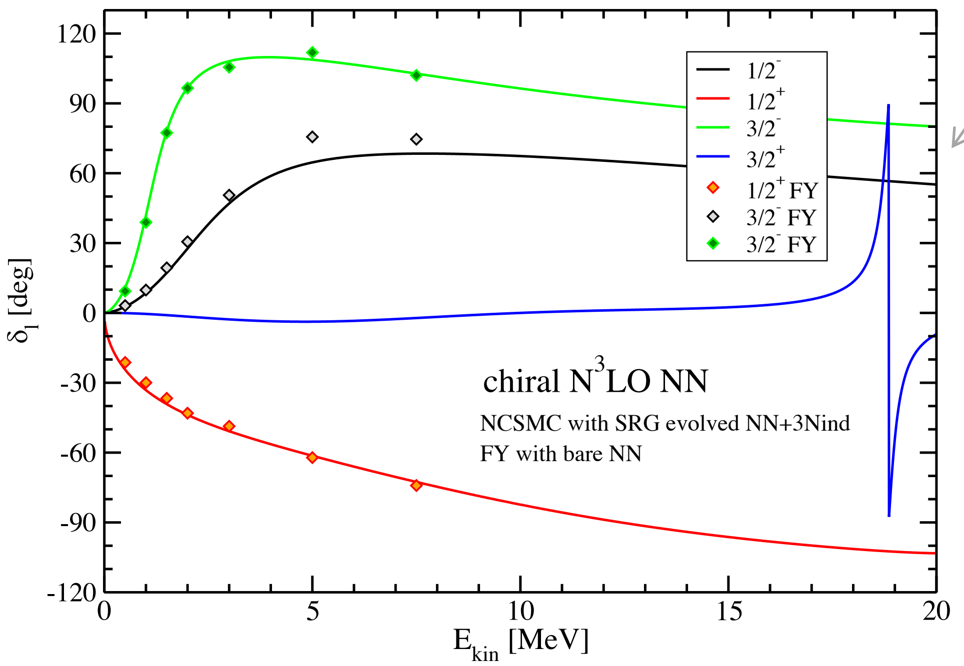


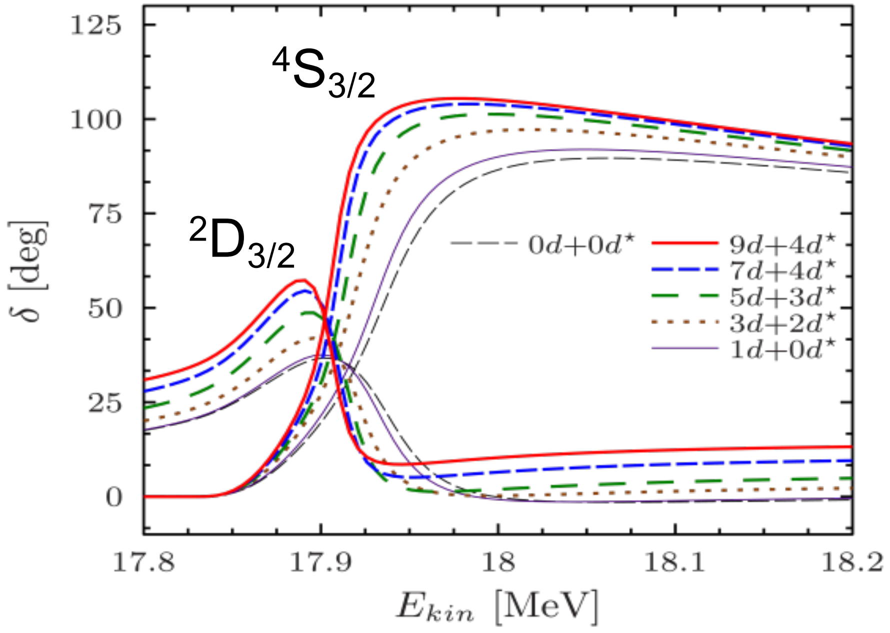
^{4}He+n -> ^{3}H+d

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

^{4}He+n



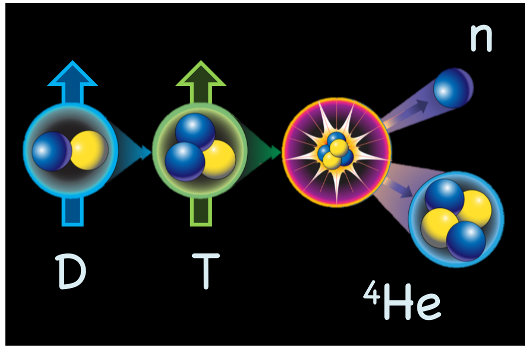




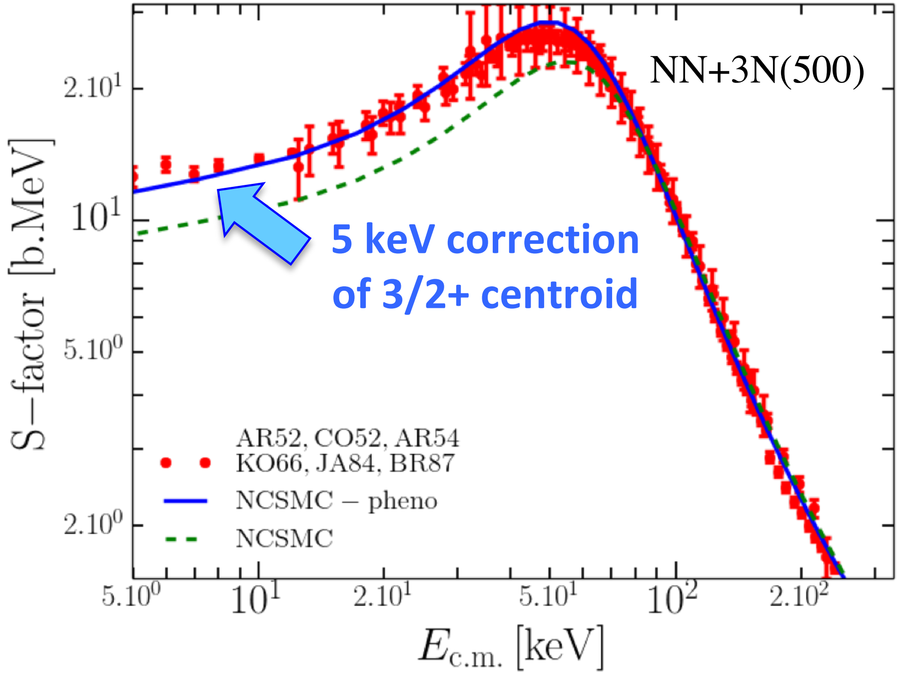
FY: Faddeev-Yakubovsky method - Rimantas Lazauskas

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

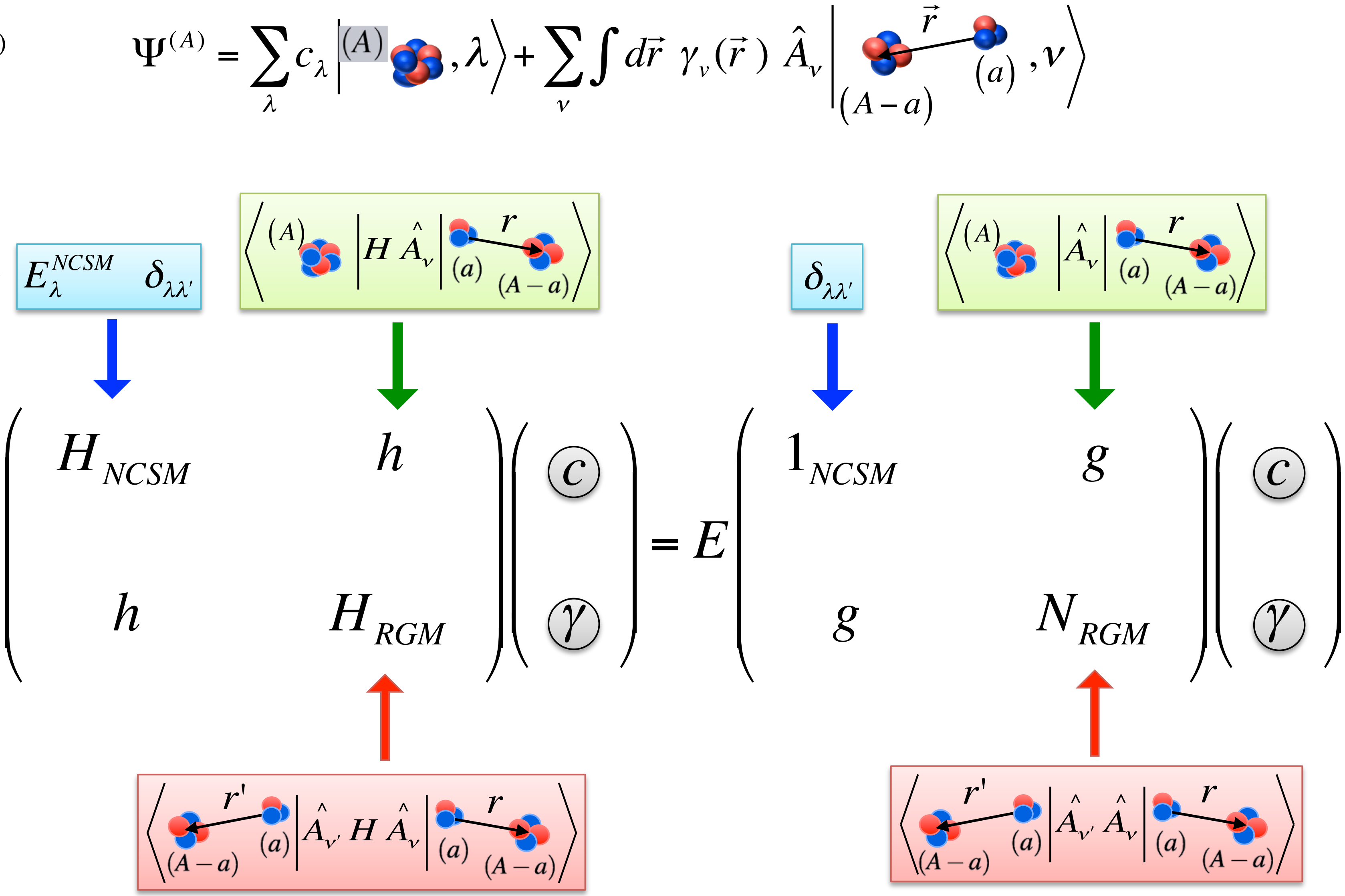
Fusion cross section

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

'Coulomb' Contribution (tunneling)

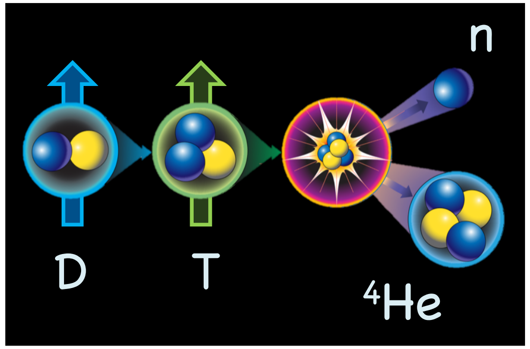
NCSMC phenomenology

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

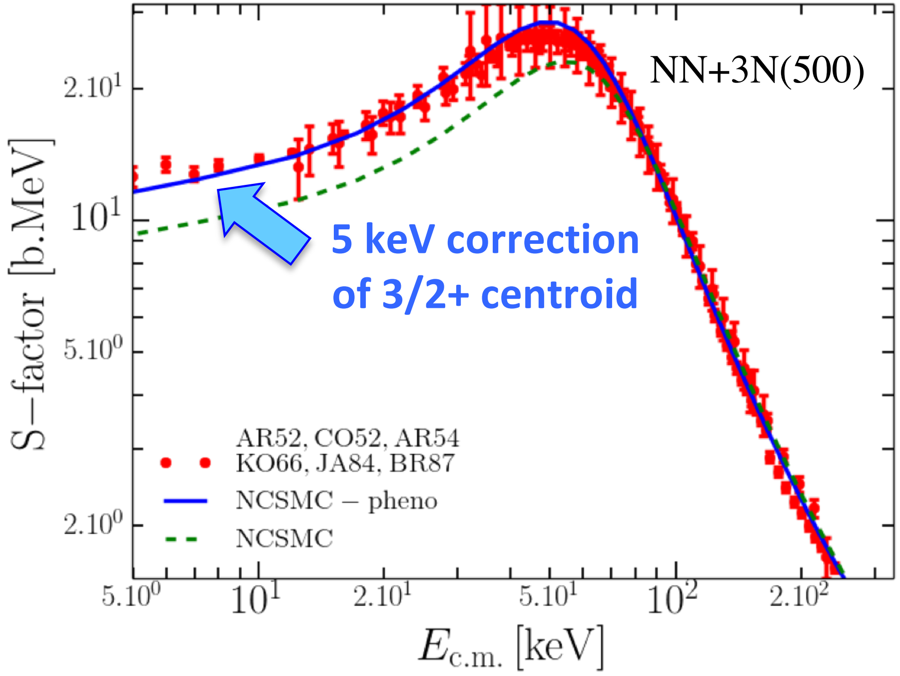


E_λ^{NCSM} energies treated as adjustable parameters

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



Astrophysical S-factor



Astrophysical S-factor: nuclear contribution

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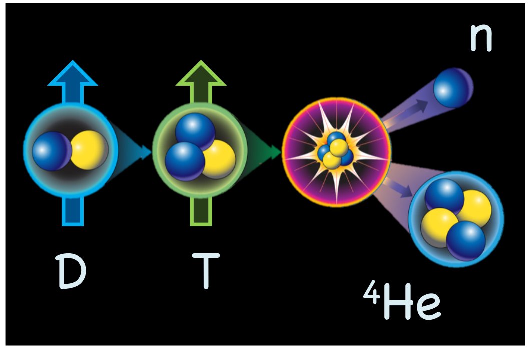
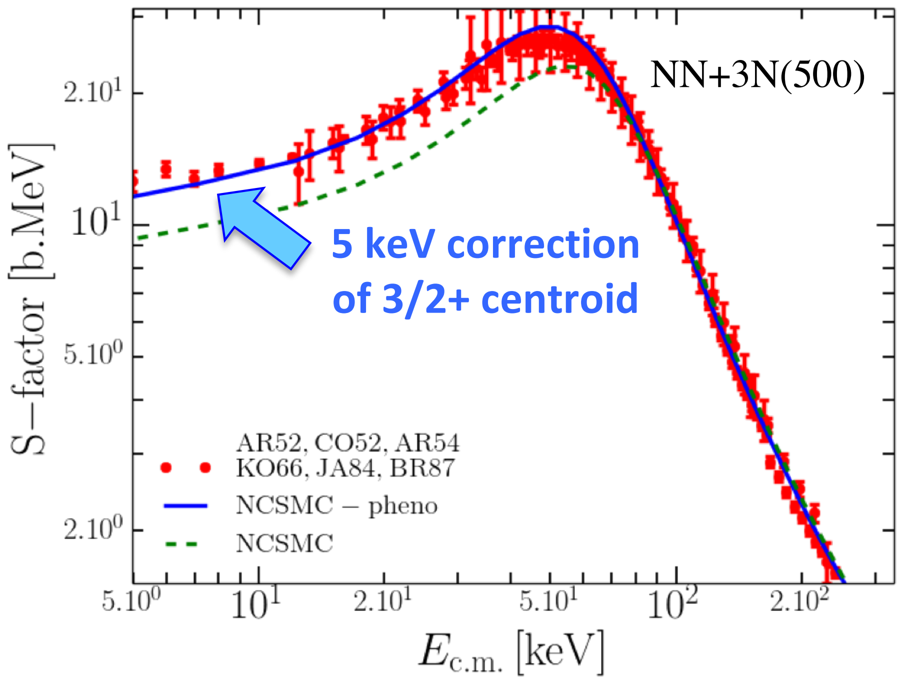
'Coulomb' Contribution (tunneling)

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



Astrophysical S-factor



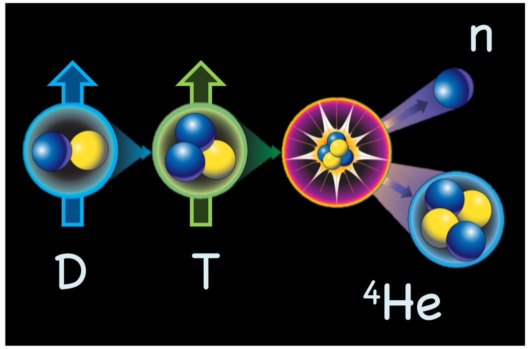
- While the DT fusion rate has been measured extensively, a fundamental understanding of the process is still missing
- Very little is known experimentally of how the polarization of the reactants' spins affects the reaction

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

$$\approx \frac{1}{3}\sigma_{\frac{1}{2}} + \frac{2}{3}\sigma_{\frac{3}{2}}$$

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

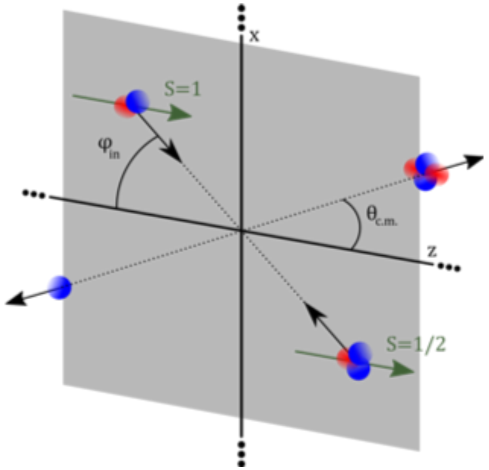
Assuming the fusion proceeds only in S-wave
with spins of D and T completely aligned:
Polarized cross section 50% higher than unpolarized

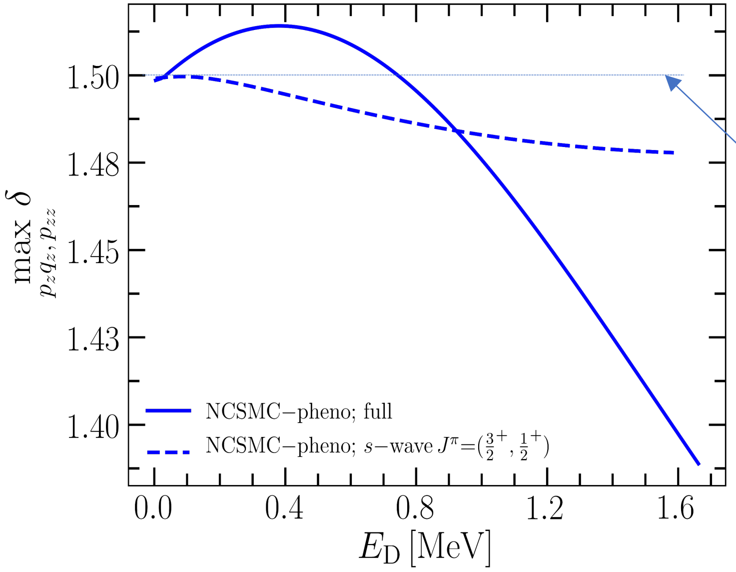


^{3}H(d,n)^{4}He with chiral NN+3N(500) interaction

Polarized fusion

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





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

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

nature COMMUNICATIONS

ARTICLE

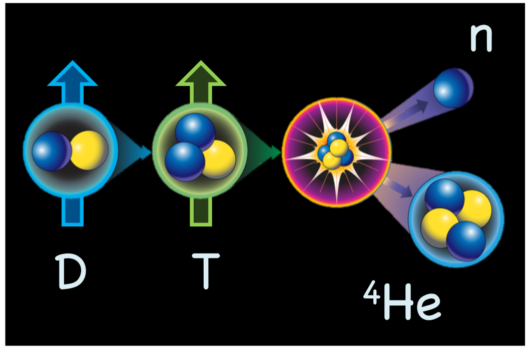
https://doi.org/10.1038/s41467-018-08052-6 OPEN

Ab initio predictions for polarized deuterium-tritium thermonuclear fusion

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

NCSMC calculation demonstrates impact of partial waves with $l > 0$ as well as the contribution of $l = 0$ $J^\pi = \frac{1}{2}^+$ channel

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



Polarized fusion

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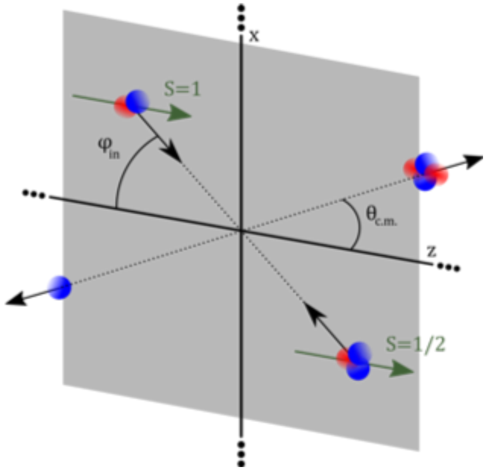

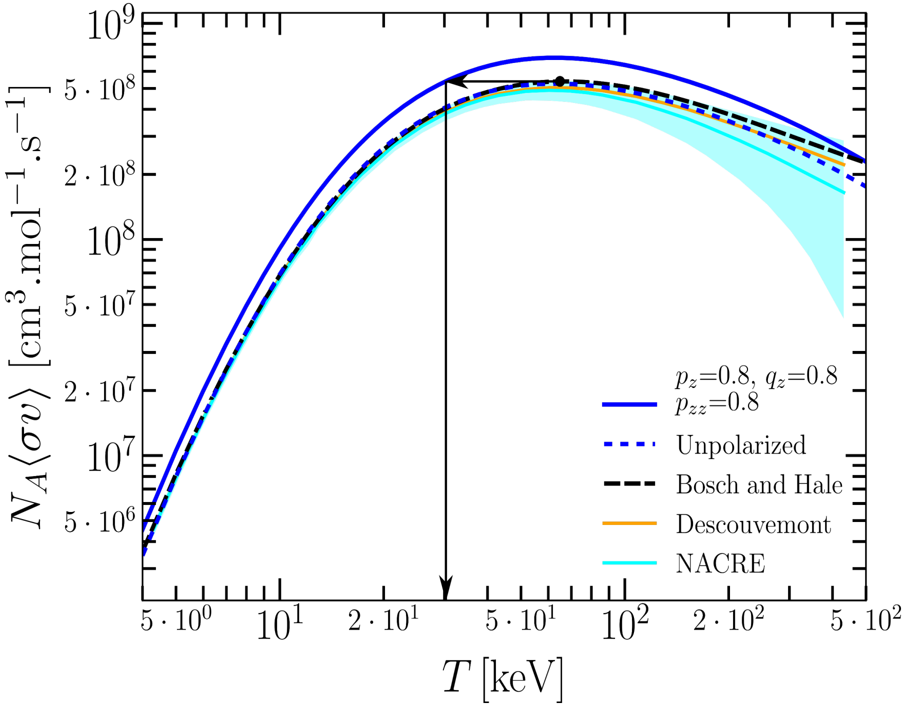

$$\langle\sigma v\rangle = \sqrt{\frac{8}{\pi\mu(k_bT)^3}}\int_0^\infty S(E)\, exp\left(-\frac{E}{k_bT}-\sqrt{\frac{E_g}{E}}\right)dE,$$

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

nature COMMUNICATIONS

ARTICLE

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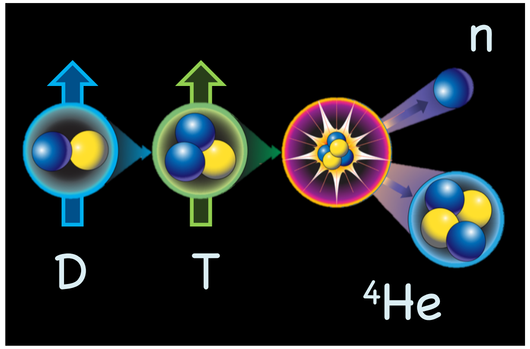
Ab initio predictions for polarized deuterium-tritium thermonuclear fusion

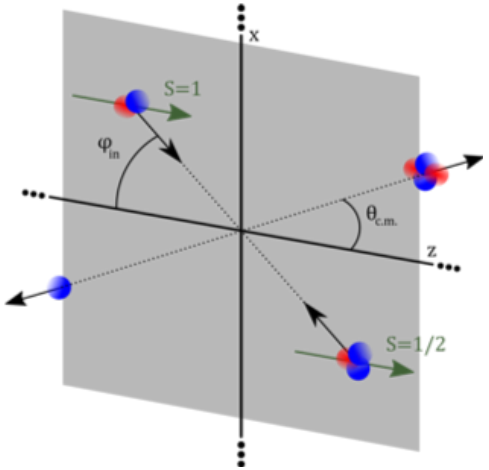
Guillaume Hupin[1,2,3], Sofia Quaglioni[3] & Petr Navrátil[4]

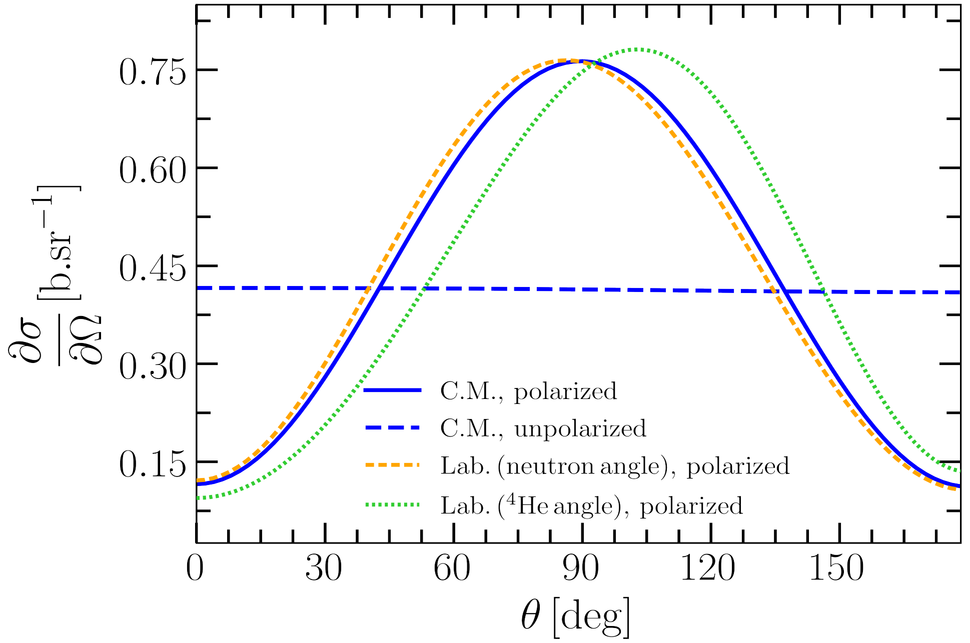


^{3}H(d,n)^{4}He with chiral NN+3N(500) interaction

Polarized fusion

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





For a realistic 80% polarization, outgoing neutrons and alphas emitted dominantly in the perpendicular direction to the magnetic field

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]

Solar *p-p* chain

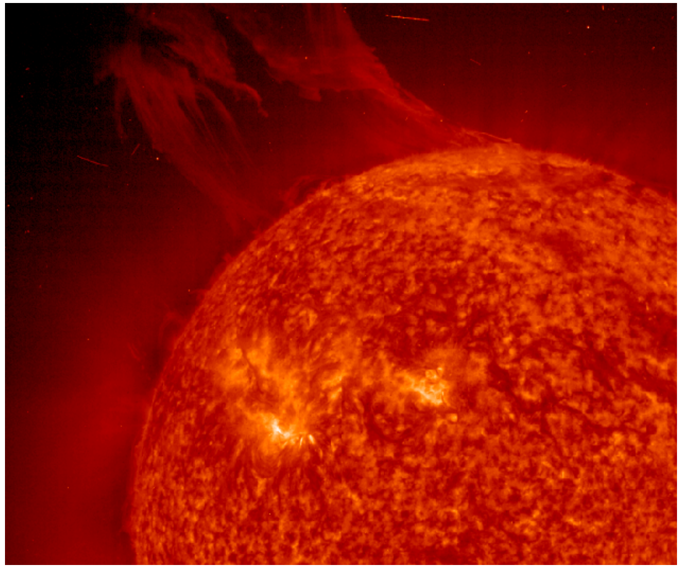
p-p chain

$p(p, e^+\nu)d$
$d(p,\gamma)^3He$

86%: $^3He(^3He, 2p)^4He$

14%: $^3He(\alpha,\gamma)^7Be$

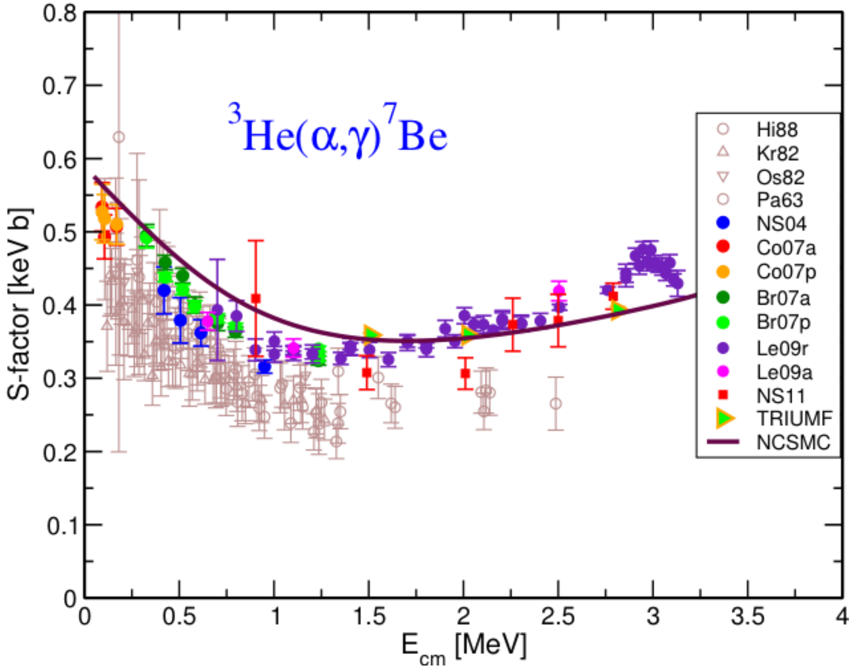
- 14%: $^7Be(e^-,\nu)^7Li$, $^7Li(p,\alpha)^4He$
- 0.02%: $^7Be(p,\gamma)^8B$, $^8B(e^+,\nu)^8Be$, $^8Be(\alpha)^4He$



Solar neutrinos

E_ν < 15 MeV

^{7}Be structure and capture reactions important for astrophysics



Physics Letters B 757 (2016) 430–436
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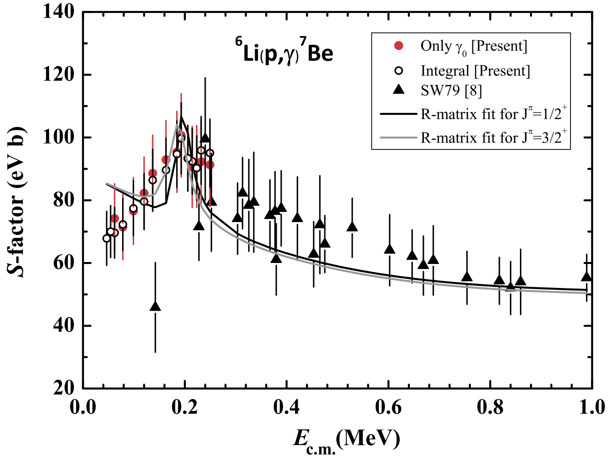
^{3}H$e(\alpha,\gamma)^7$Be and ^{3}H$(\alpha,\gamma)^7$Li astrophysical S factors from the no-core shell model with continuum

Jérémy Dohet-Eraly[a,*], Petr Navrátil[a], Sofia Quaglioni[b], Wataru Horiuchi[c], Guillaume Hupin[b,d,1], Francesco Raimondi[a,2]



Physics Letters B 725 (2013) 287–291
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Physics Letters B
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A drop in the ^{6}Li$(p,\gamma)^7$Be reaction at low energies

J.J. He[a,*], S.Z. Chen[a,b], C.E. Rolfs[c,a], S.W. Xu[a], J. Hu[a], X.W. Ma[a], M. Wiescher[d], R.J. deBoer[d], T. Kajino[e,f], M. Kusakabe[g], L.Y. Zhang[a,b], S.Q. Hou[a,b], X.Q. Yu[a], N.T. Zhang[a], G. Lian[h], Y.H. Zhang[a], X.H. Zhou[a], H.S. Xu[a], G.Q. Xiao[a], W.L. Zhan[a]

What resonances do we find in ^{7}Be within NCSMC?

PHYSICAL REVIEW C **100**, 024304 (2019)

^{7}Be and ^{7}Li nuclei within the no-core shell model with continuum

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

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Guillaume Hupin
Institut de Physique Nucléaire, CNRS/IN2P3, Université Paris-Sud, Université Paris-Saclay, F-91406, Orsay, France

^{7}Be structure and capture reactions important for astrophysics

NCSMC with SRG evolved chiral NN

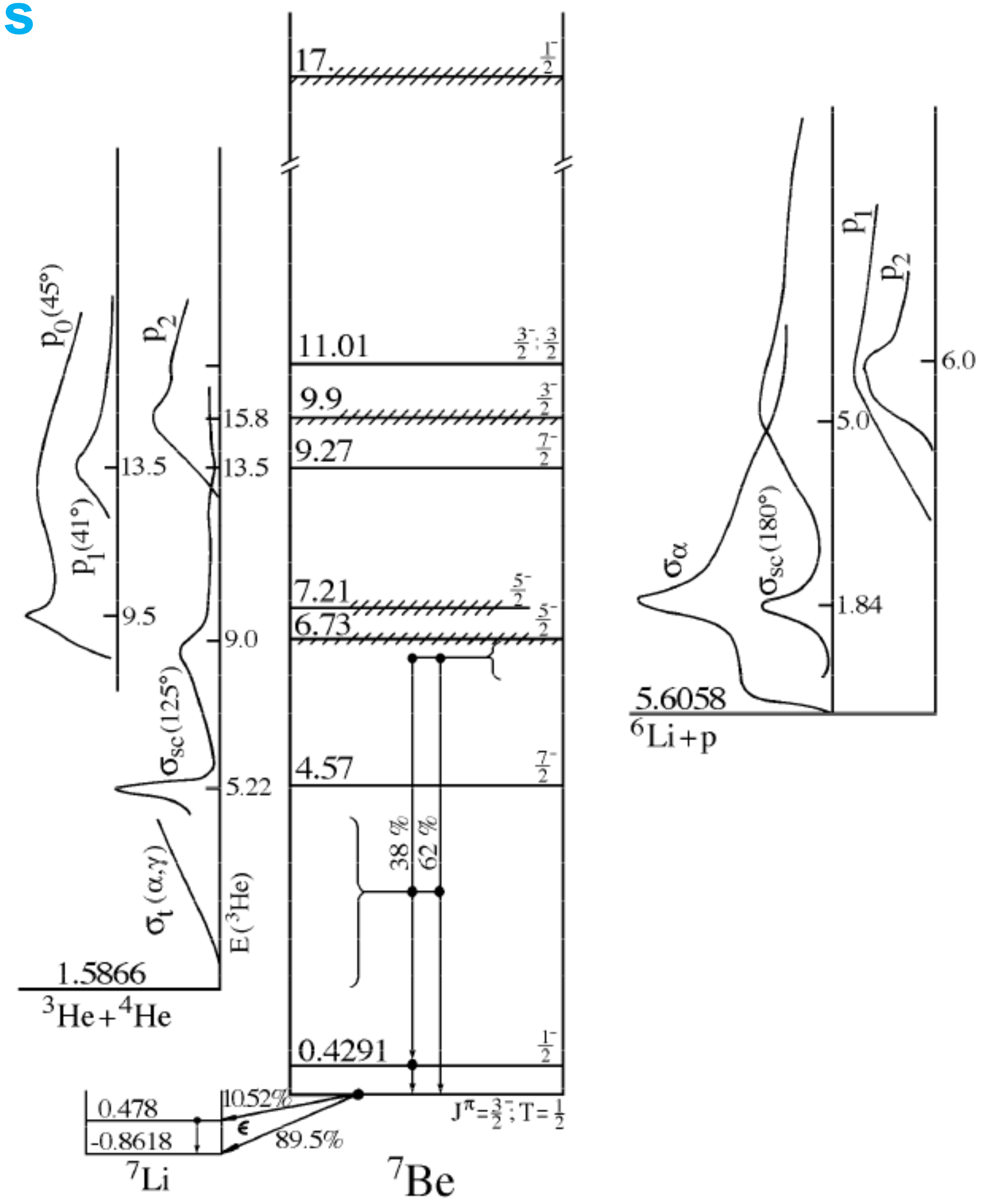
Analyzed mass partitions (no coupling yet)

- ^{3}He + ^{4}He
- p + ^{6}Li

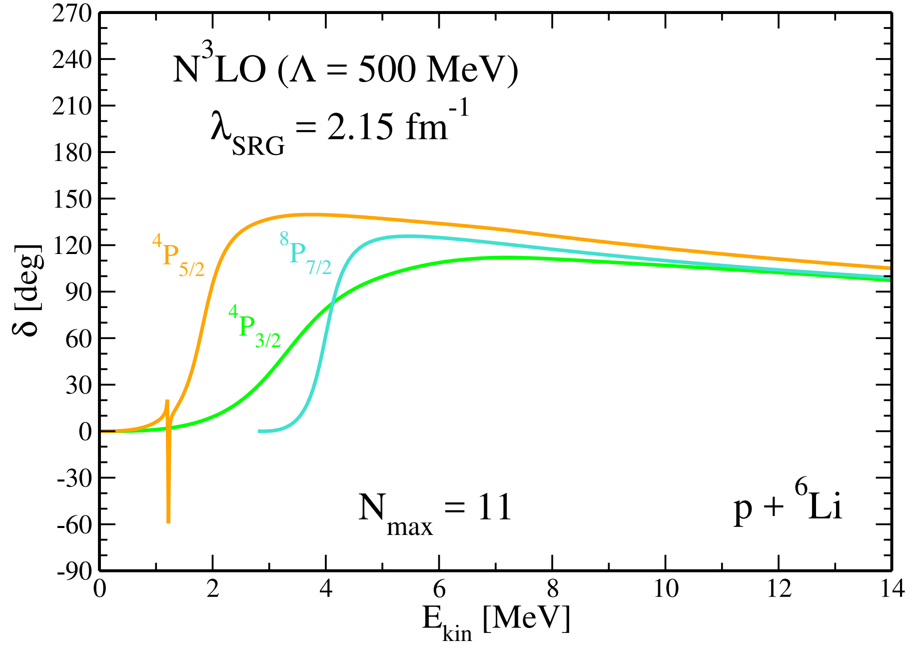
Exp.	$J^\pi = 3/2^-$
E [MeV]	-37.60

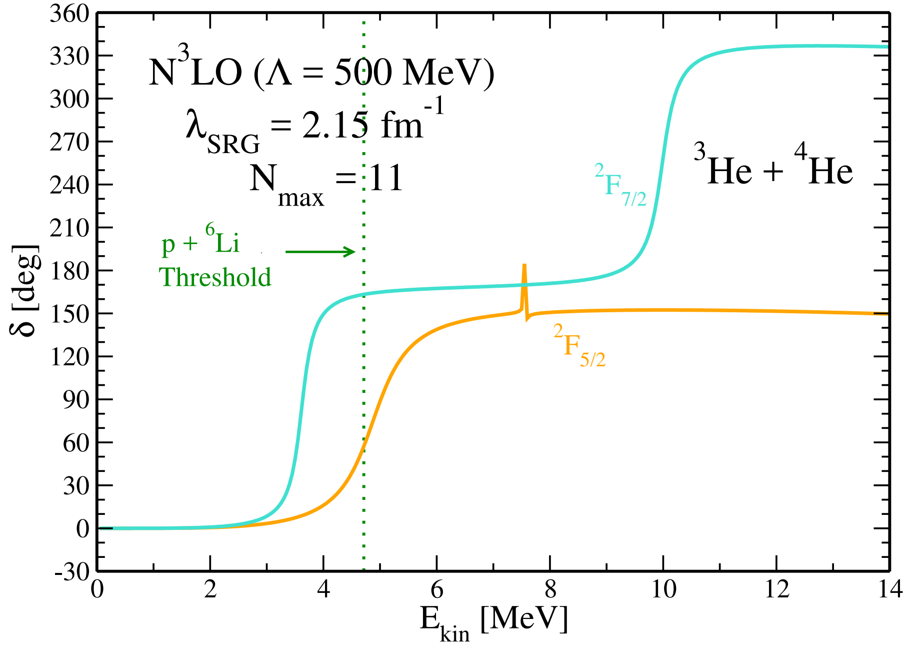
^{3}He + ^{4}He	$J^\pi = 3/2^-$	$J^\pi = 1/2^-$
E_{bound}	-1.519	-1.256
E [MeV]	-36.98	-36.71

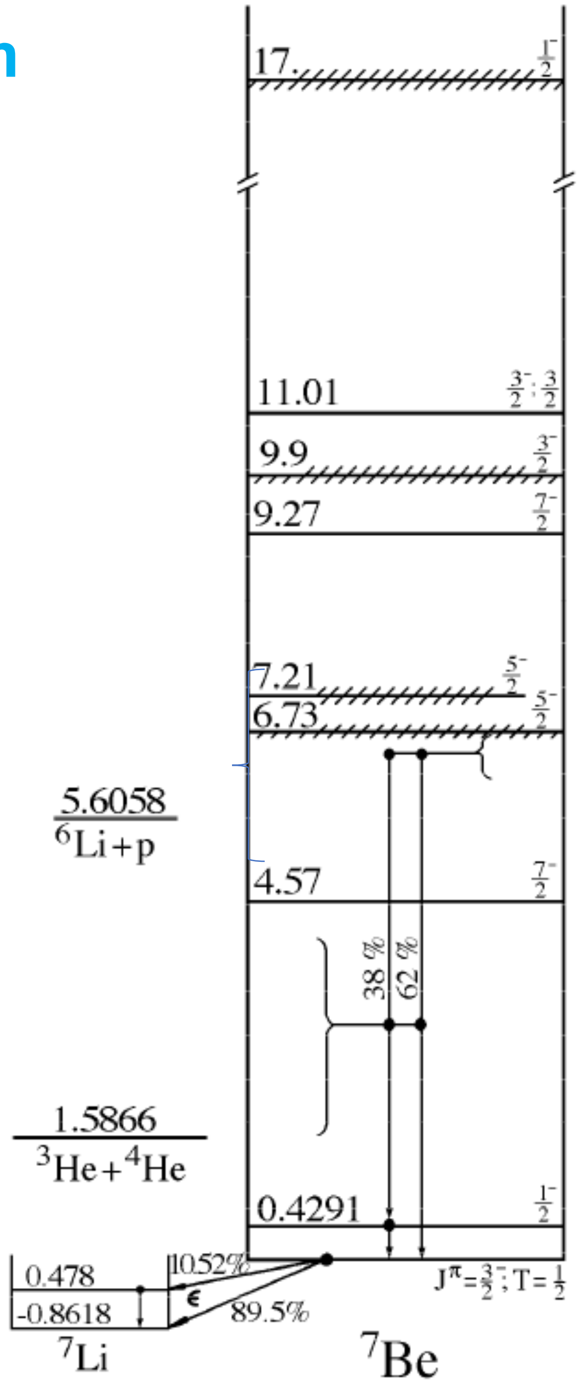
p + ^{6}Li	$J^\pi = 3/2^-$	$J^\pi = 1/2^-$
E_{bound}	-5.729	-5.389
E [MeV]	-36.47	-36.13



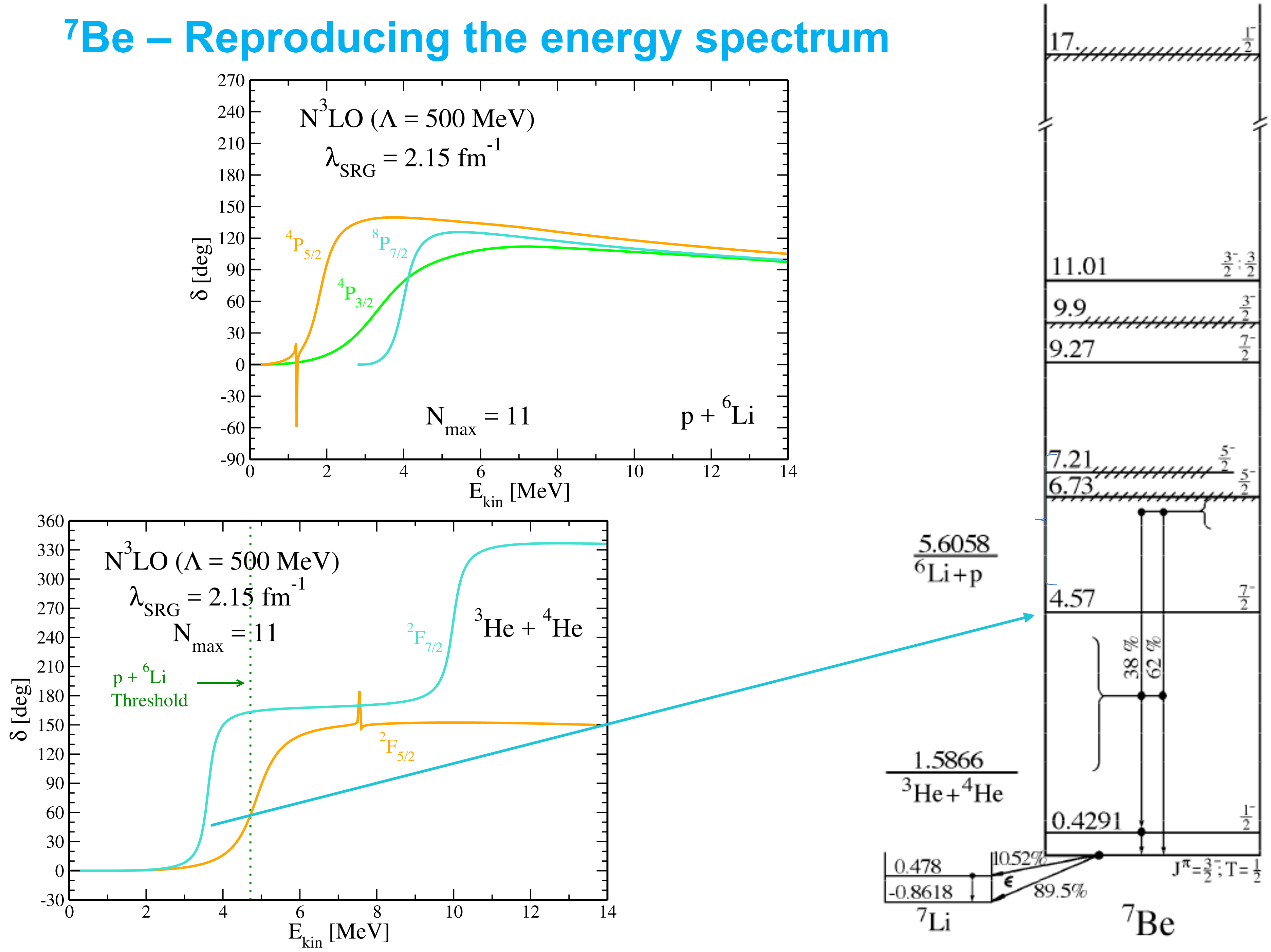
^{7}Be – Reproducing the energy spectrum







^{7}Be – Reproducing the energy spectrum



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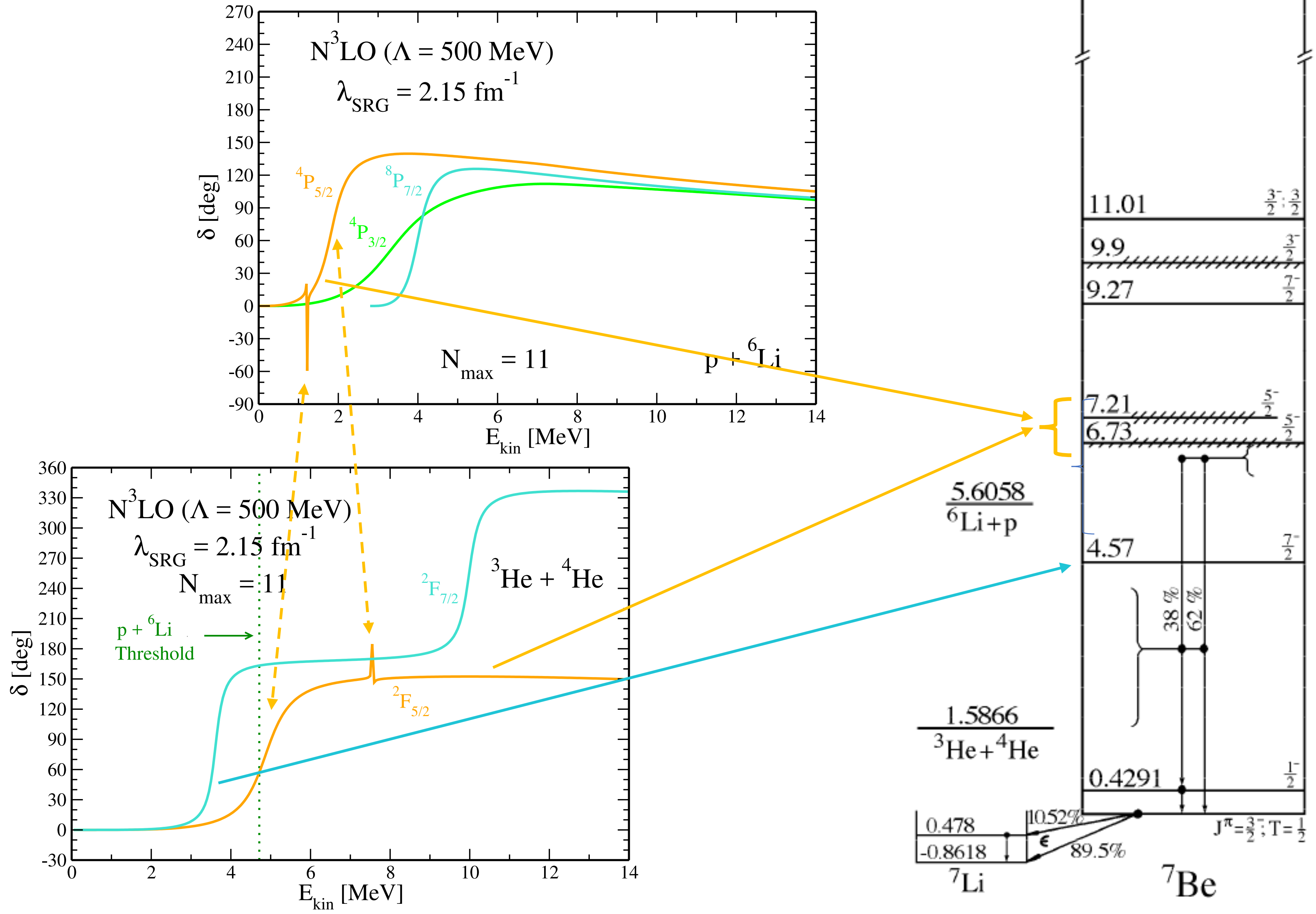

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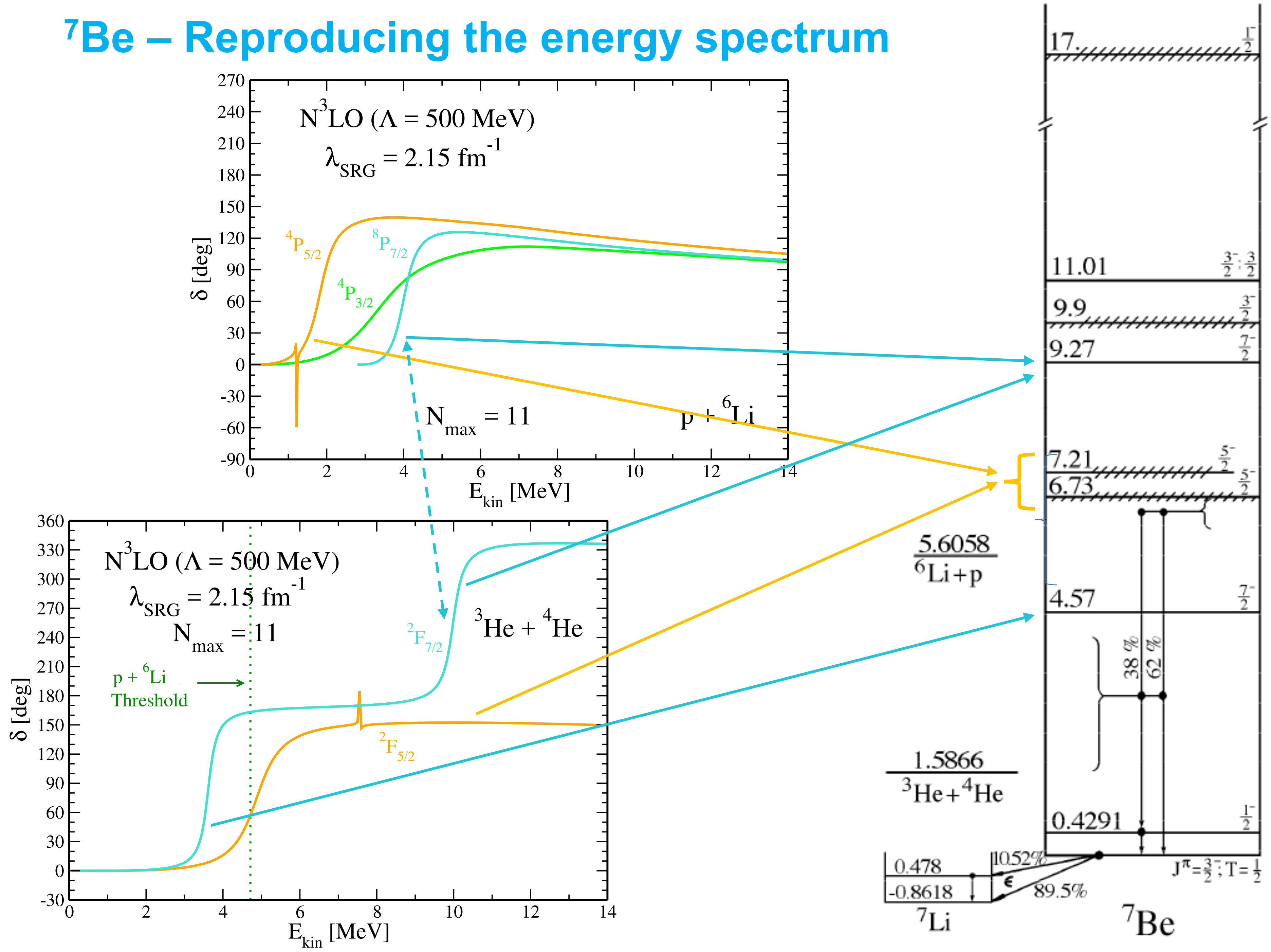
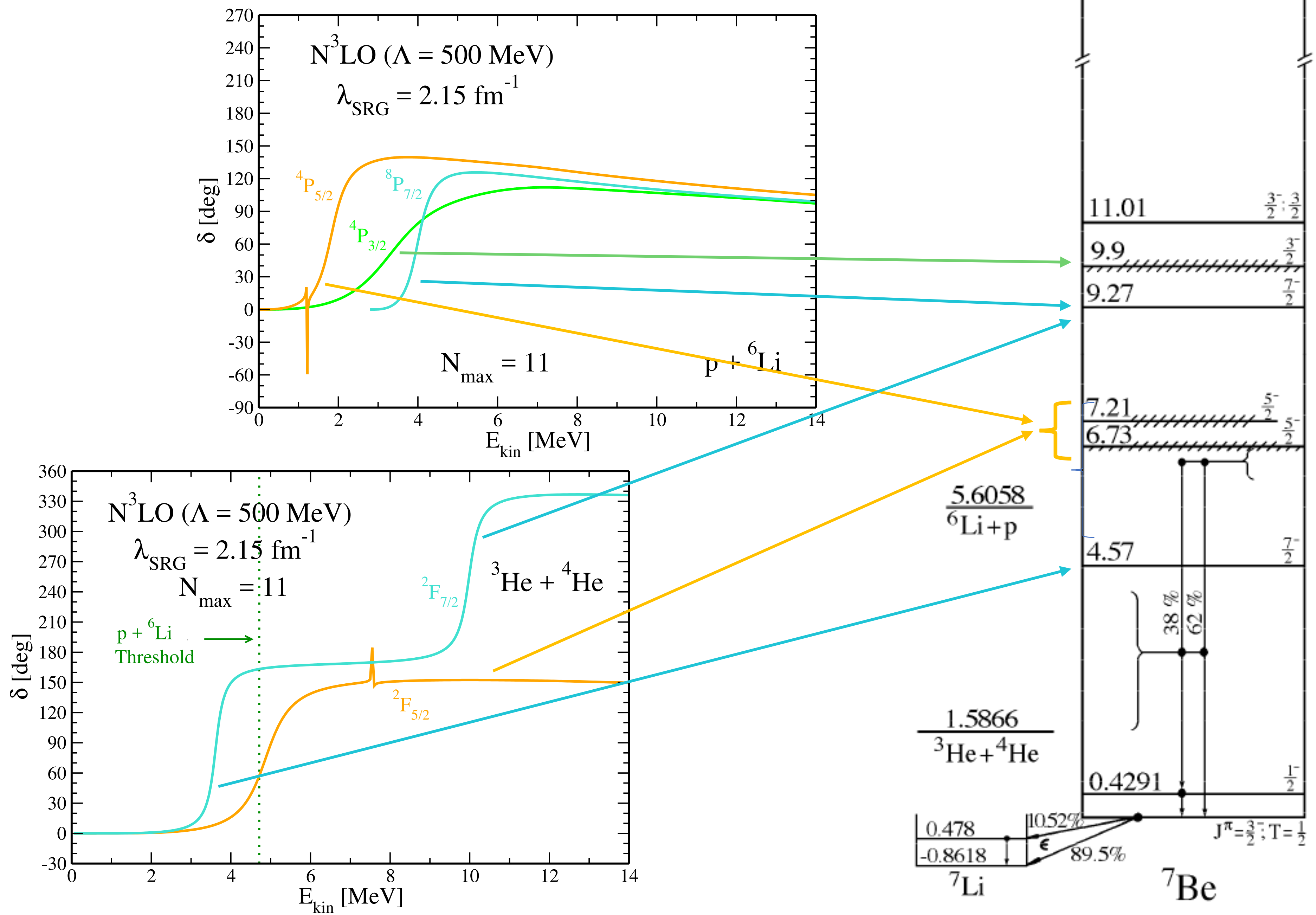
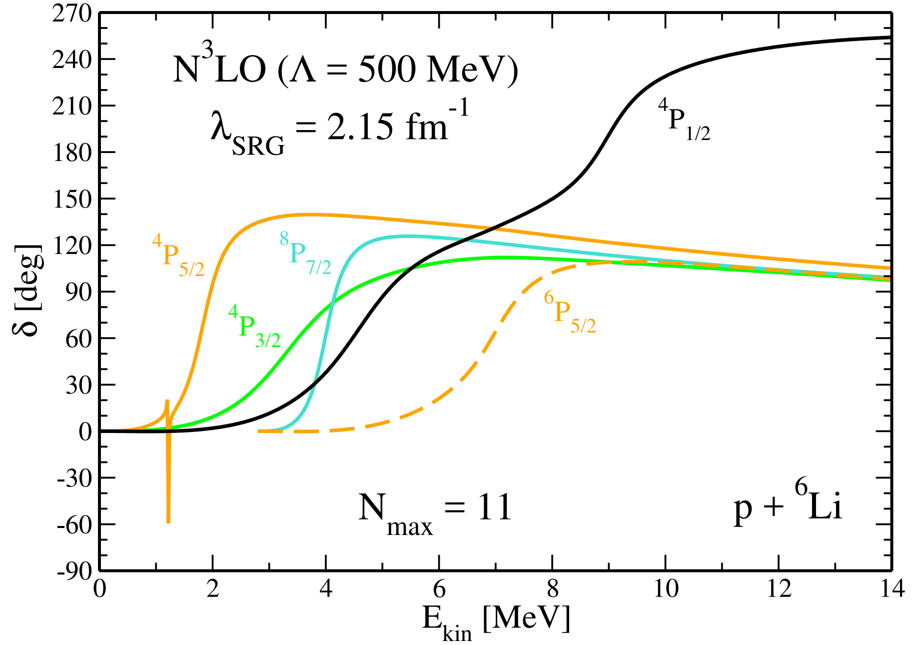
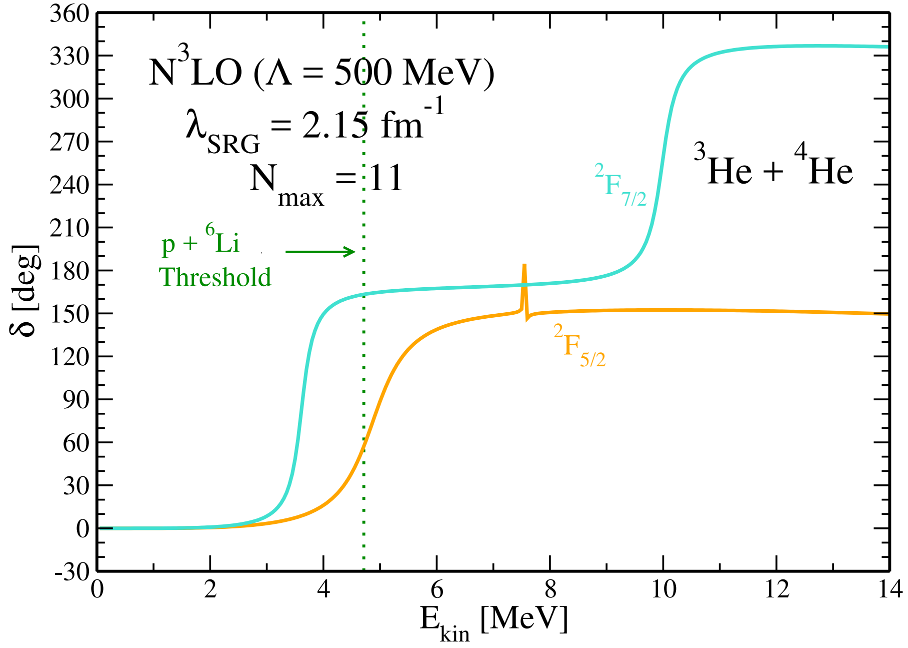


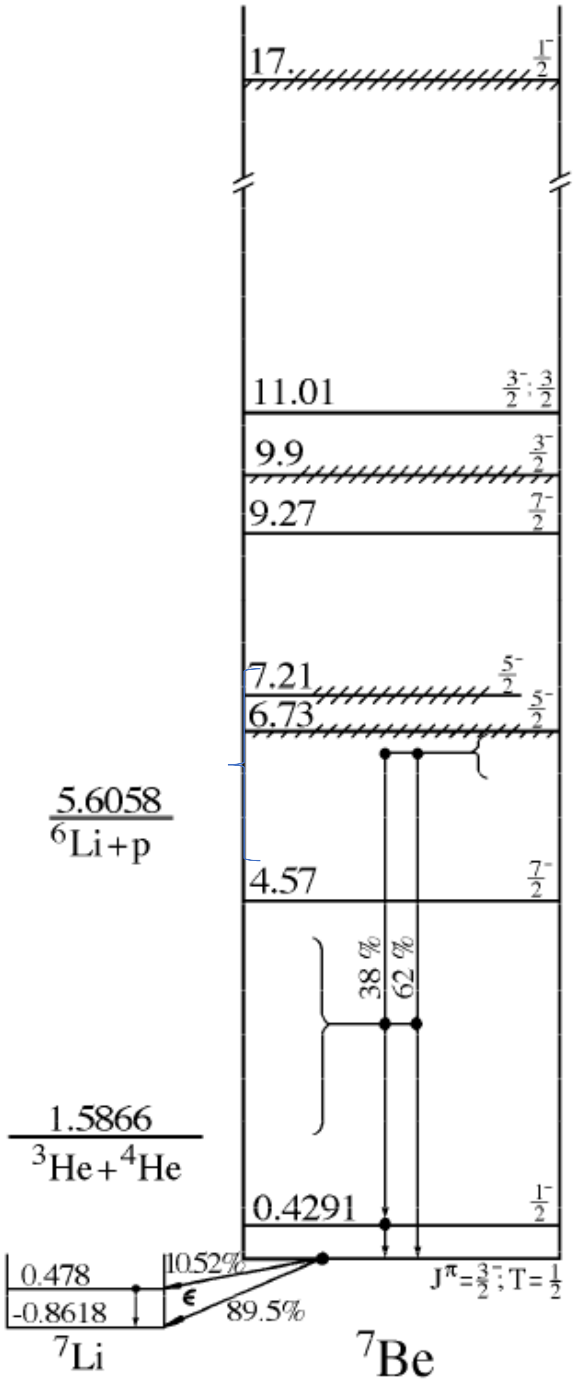
^{7}Be – Reproducing the energy spectrum



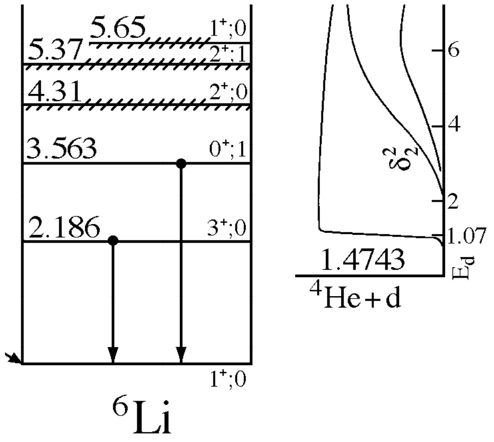
^{7}Be – New negative-parity states

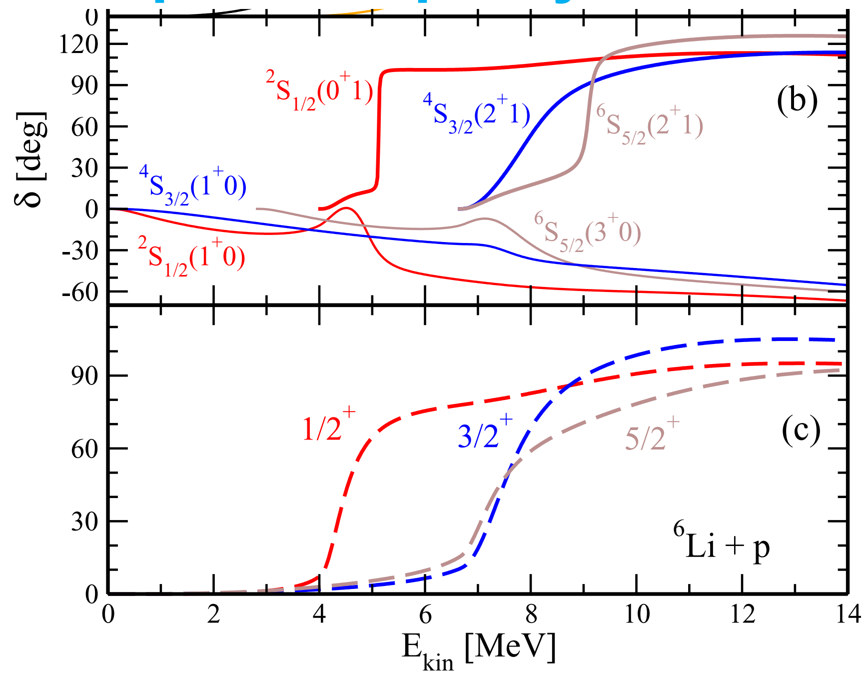


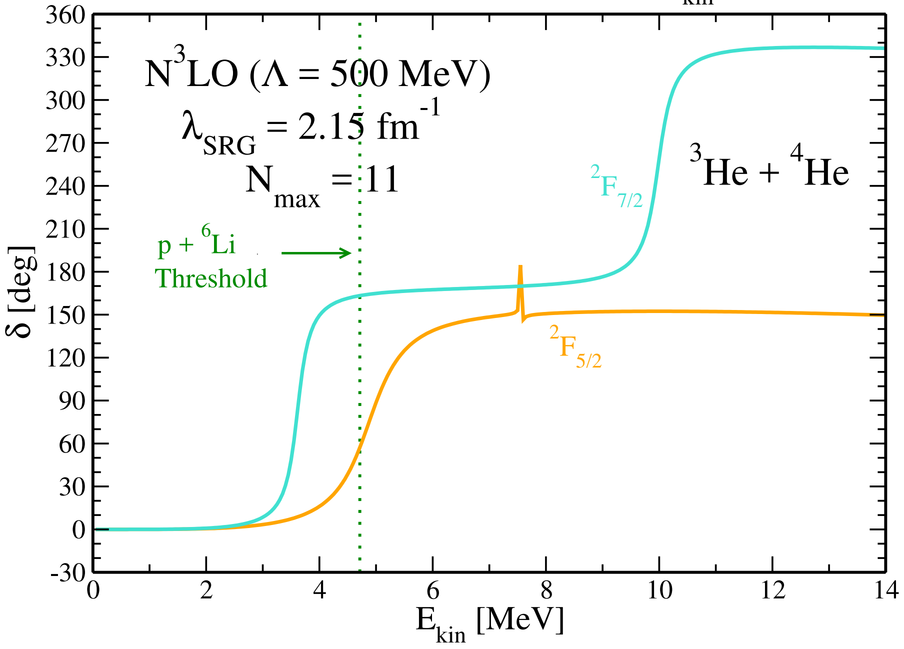


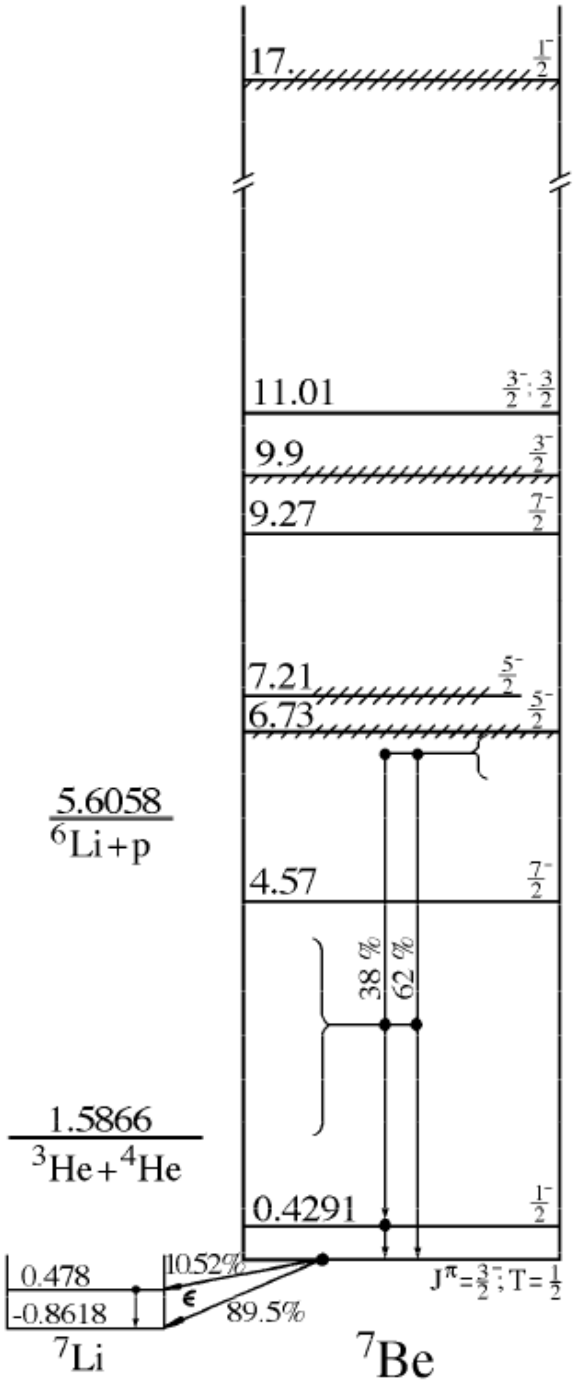


^{7}Be – New positive-parity states

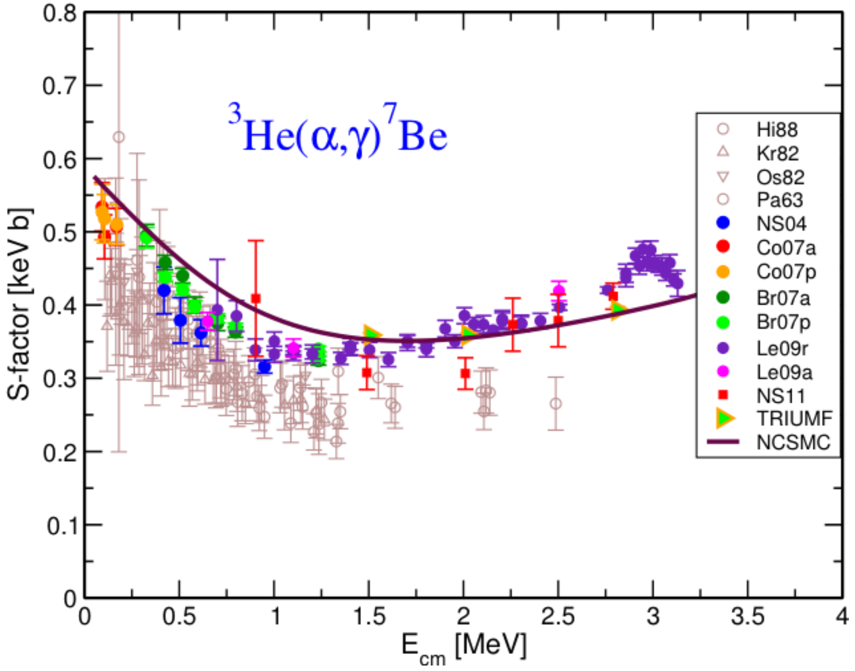








S-factor for $^3He(\alpha,\gamma)^7Be$ and $^6Li(p,\gamma)^7Be$ reaction



Physics Letters B 757 (2016) 430–436

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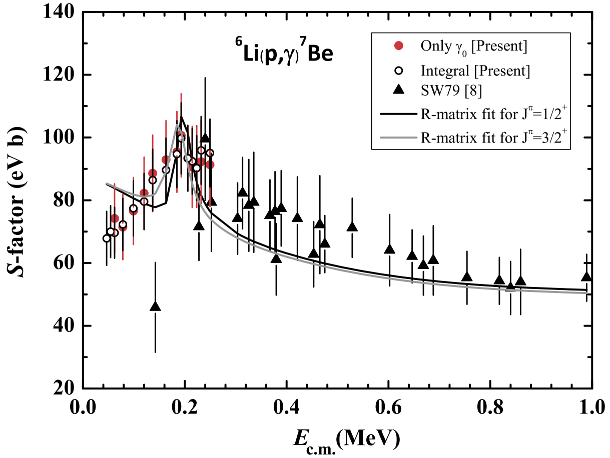

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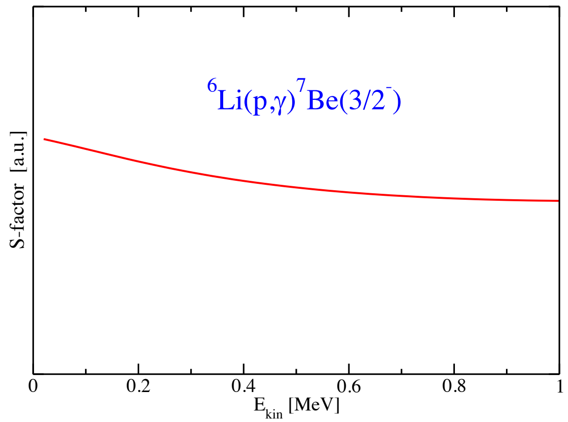

No resonance in ^{7}Be close to ^{6}Li+p threshold contrary to claim in Lanzhou experiment

PHYSICAL REVIEW C **100**, 024304 (2019)

^{7}Be and ^{7}Li nuclei within the no-core shell model with continuum

Matteo Vorabbi* and Petr Navrátil†
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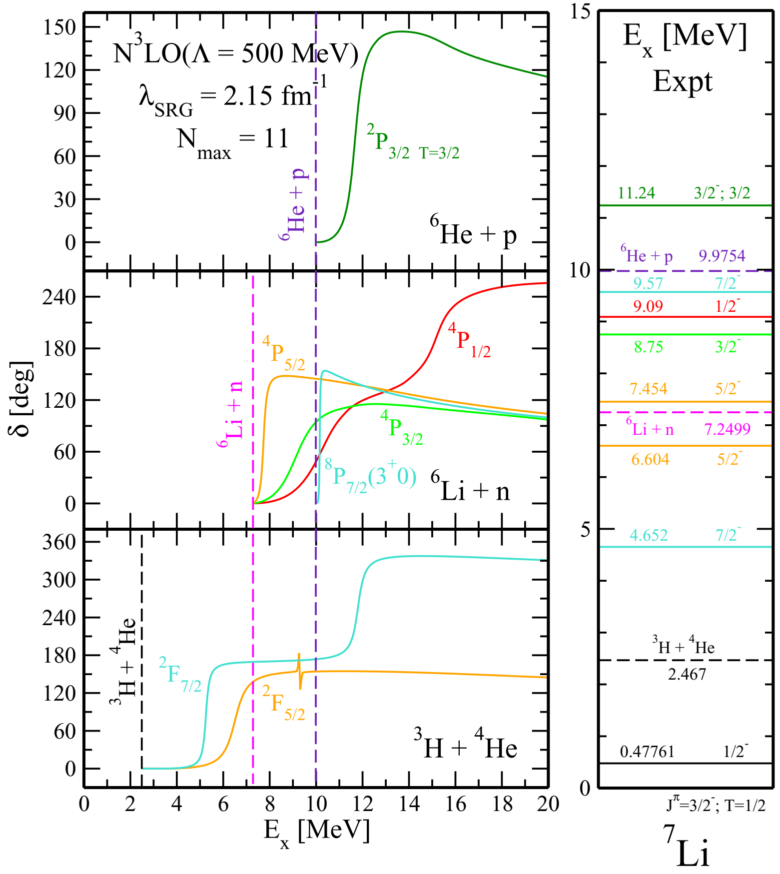
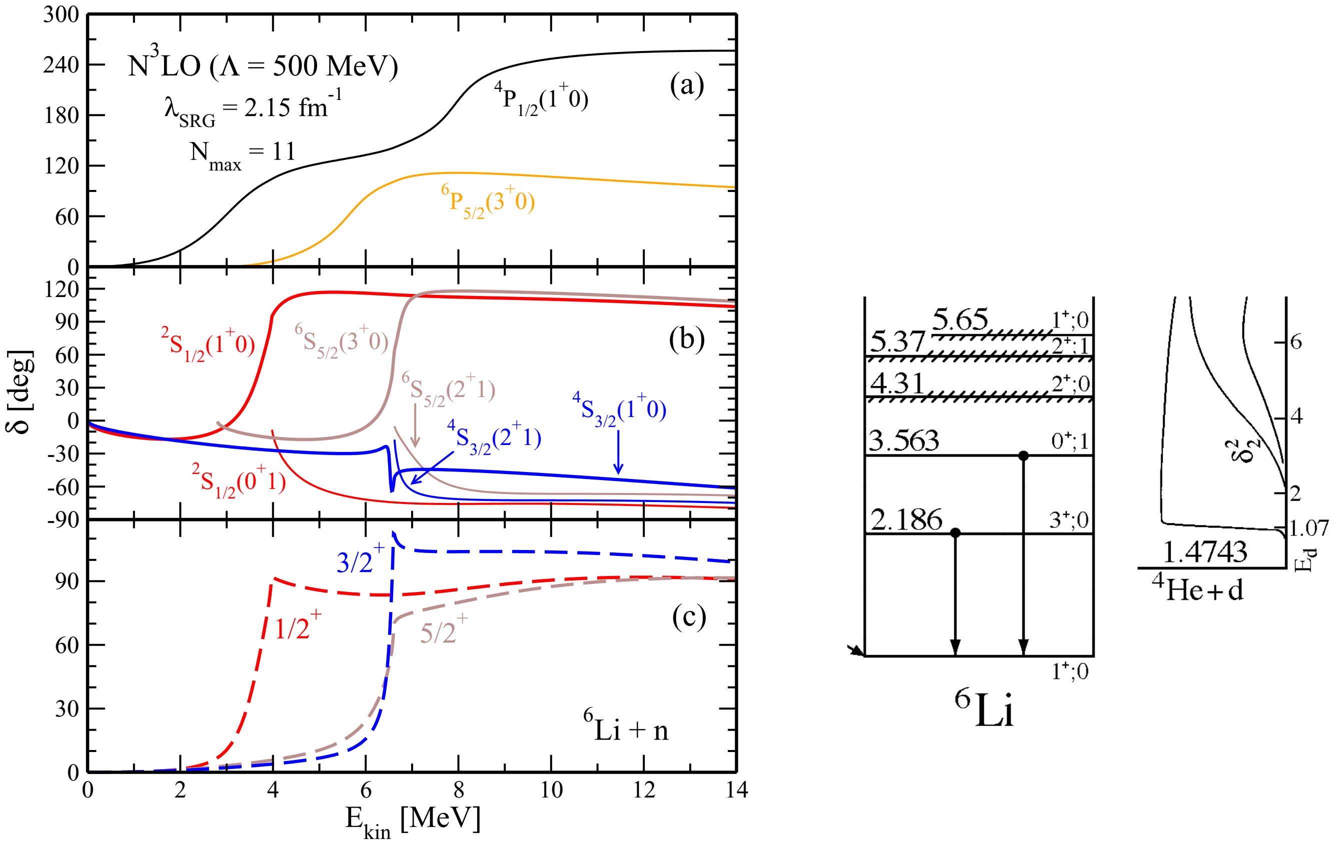
S-wave resonance just above the threshold of ^{6}He+p?

- NCSMC study of ^{7}Li and ^{7}Be nuclei using all binary mass partitions
  - Known resonances reproduced
  - Prediction of several new resonances of both parities





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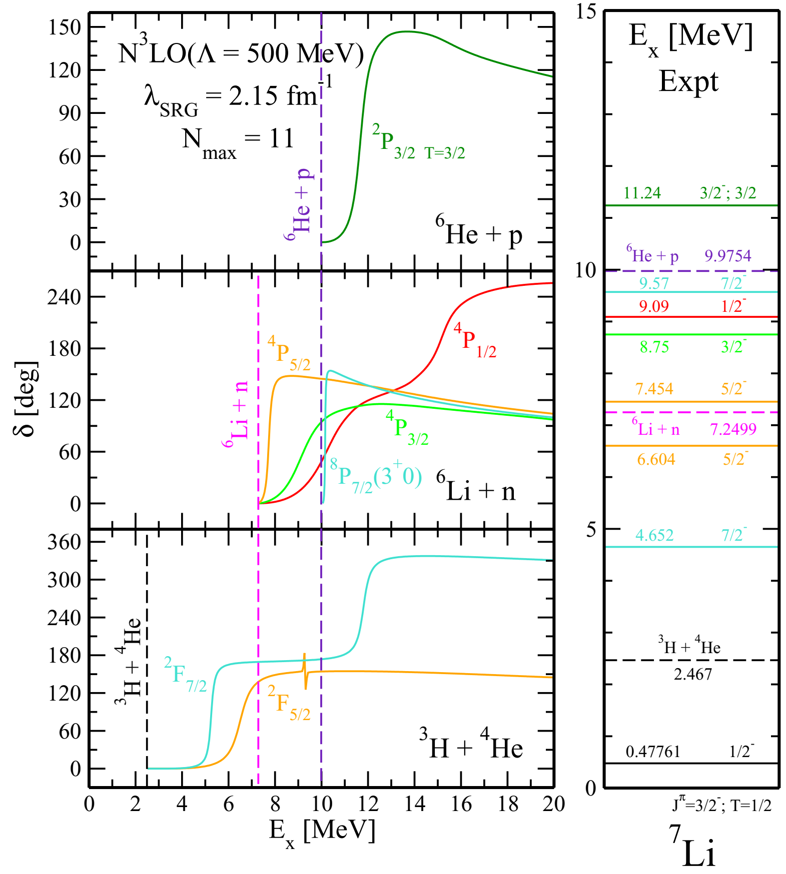
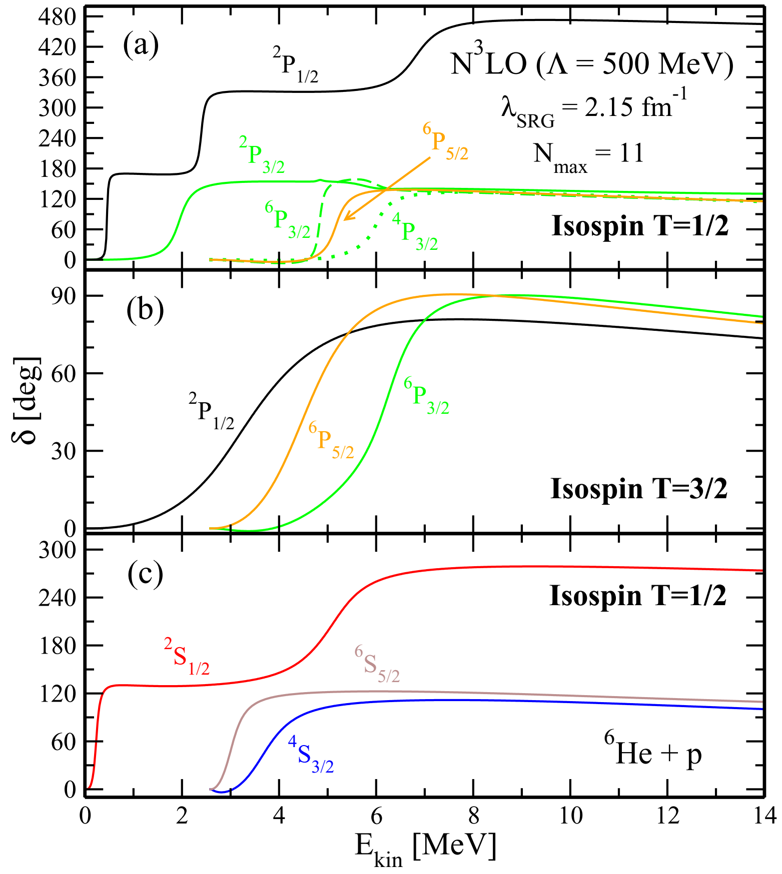




S-wave resonance predicted at low energy in ^{6}He+p scattering with possible astrophysics implications.
Can this be investigated at TRIUMF or elsewhere?

Similarity to ^{10}Be+p system?

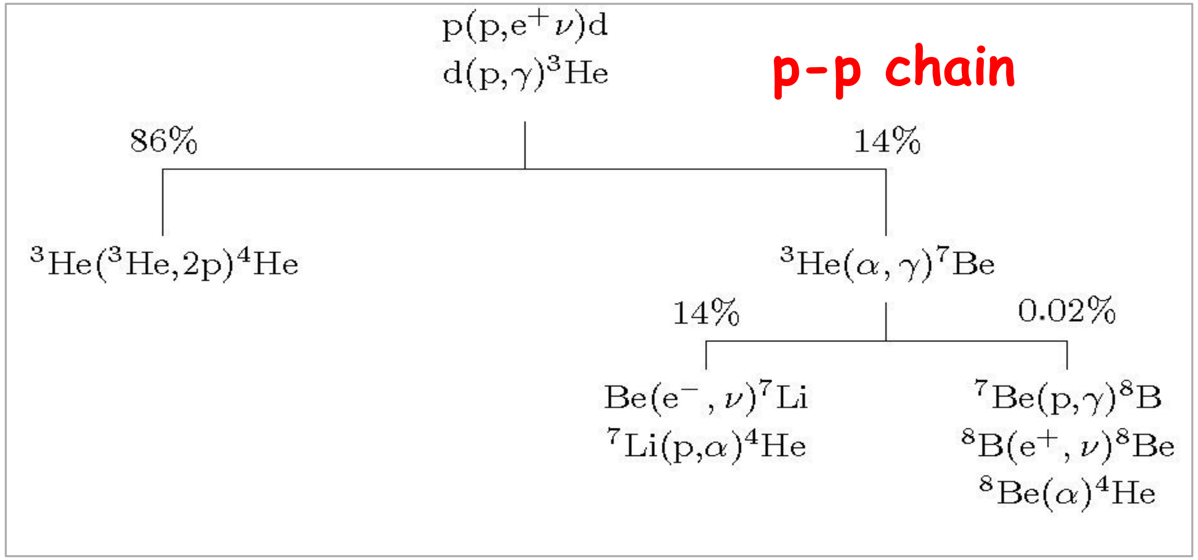
PHYSICAL REVIEW LETTERS 123, 082501 (2019)
Editors' Suggestion

Direct Observation of Proton Emission in ^{11}Be

Y. Ayyad,[1,2,*] B. Olaizola,[3] W. Mittig,[2,4] G. Potel,[1] V. Zelevinsky,[1,2,4] M. Horoi,[5] S. Beceiro-Novo,[4] M. Alcorta,[3] C. Andreoiu,[6] T. Ahn,[7] M. Anholm,[3,8] L. Atar,[9] A. Babu,[3] D. Bazin,[2,4] N. Bernier,[3,10] S. S. Bhattacharjee,[3] M. Bowry,[3] R. Caballero-Folch,[3] M. Cortesi,[2] C. Dalitz,[11] E. Dunling,[3,12] A. B. Garnsworthy,[3] M. Holl,[3,13] B. Kootte,[3,8] K. G. Leach,[14] J. S. Randhawa,[2] Y. Saito,[3,10] C. Santamaria,[15] P. Šiurytė,[3,16] C. E. Svensson,[9] R. Umashankar,[3] N. Watwood,[2] and D. Yates[3,10]

p+^{11}C scattering and $^{11}C(p,\gamma)^{12}N$ capture

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



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

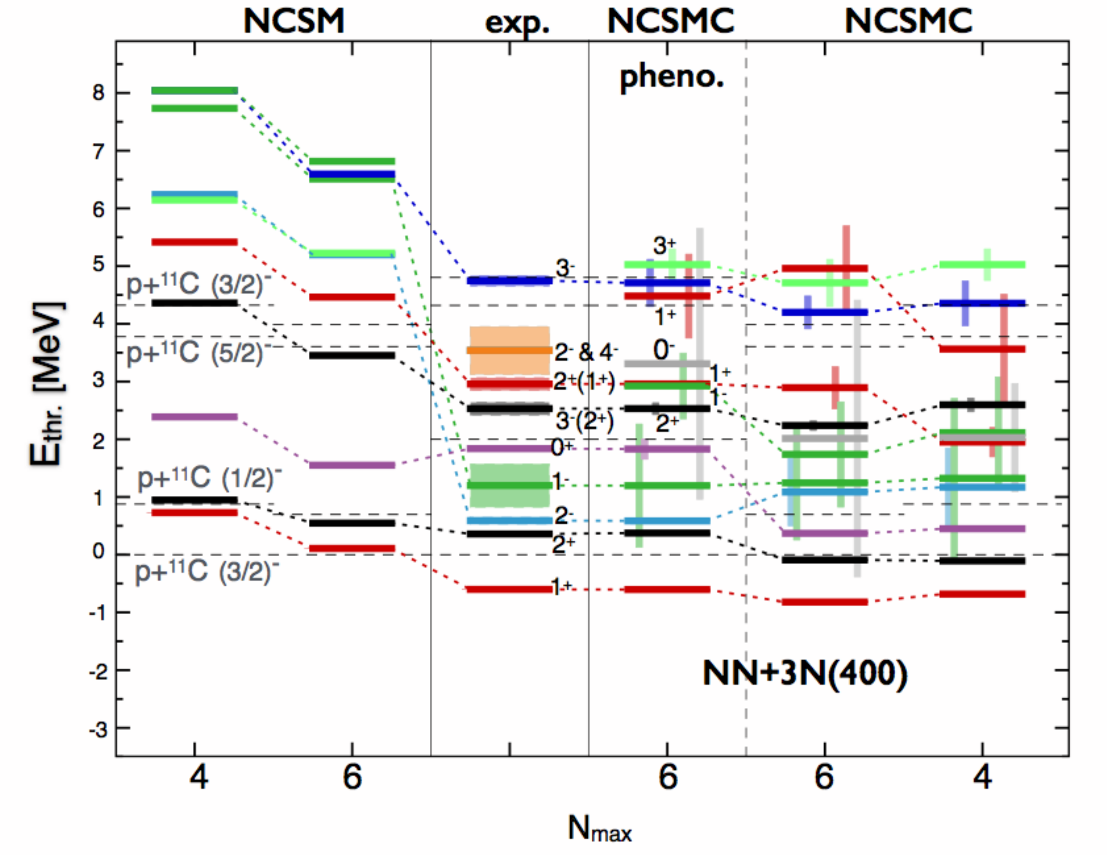
$$^{3}He(\alpha,\gamma)^{7}Be(\alpha,\gamma)^{11}C(p,\gamma)^{12}N(\beta^{+},\nu)^{12}C(p,\gamma)^{13}N(p,\gamma)^{14}O$$

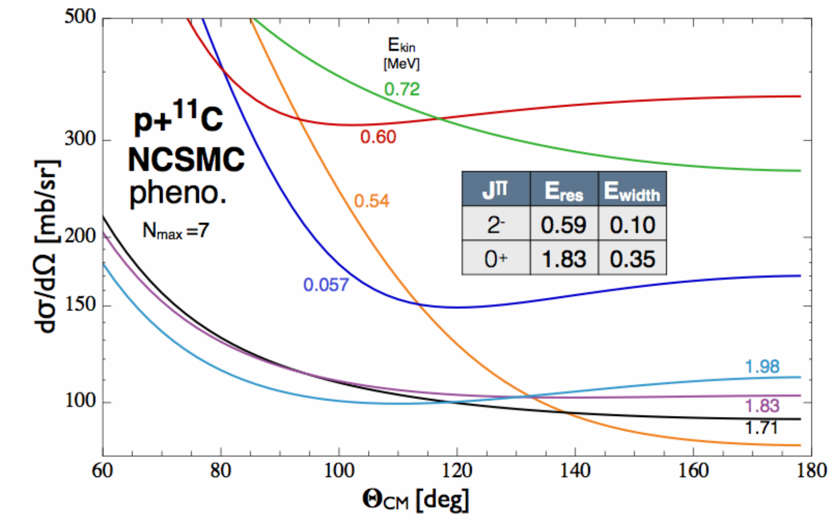
$$^{11}\mathrm{C}(\beta^{+}\ \nu)^{11}\mathrm{B}(p,\alpha)^{8}\mathrm{Be}(^{4}\mathrm{He},^{4}\mathrm{He})$$

Measurement of $^{11}C(p,p)$ resonance scattering planned at TRIUMF TUDA facility

p+^{11}C scattering and $^{11}C(p,\gamma)^{12}N$ 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



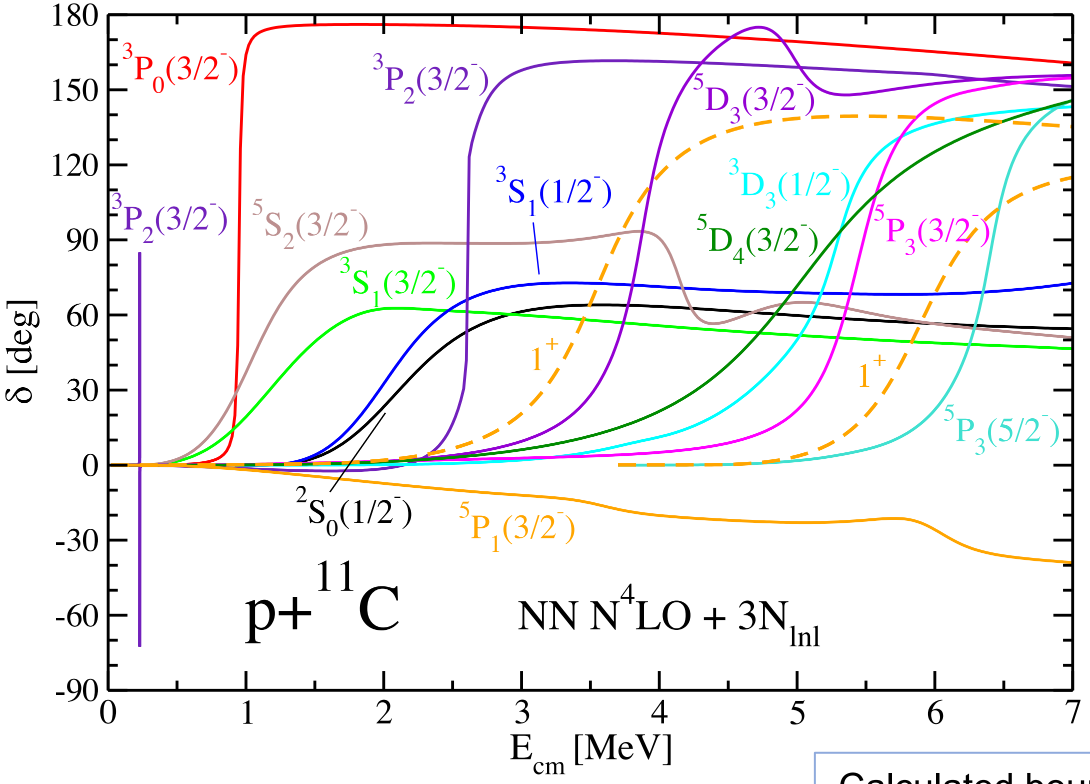


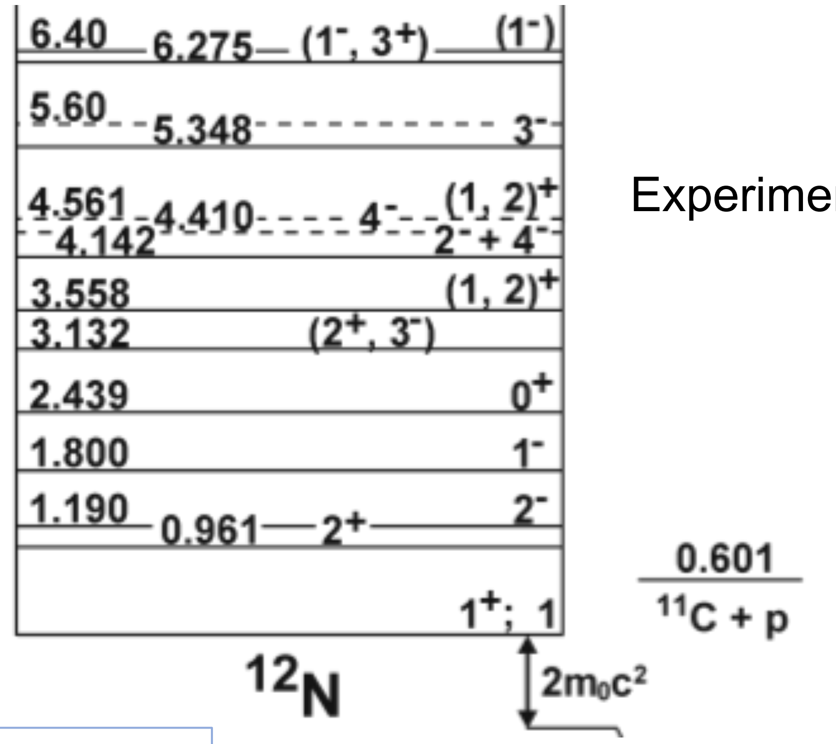
NCSMC calculations to be validated by measured cross sections and applied to calculate the $^{11}C(p,\gamma)^{12}N$ capture

Measurement of $^{11}C(p,p)$ resonance scattering planned at TRIUMF TUDA facility

p+^{11}C scattering and $^{11}C(p,\gamma)^{12}N$ capture

- NCSM with continuum calculations of $^{11}C(p,p)$ with higher-precision chiral NN+3N under way
  - ^{11}C and ^{12}N NCSM eigenstates calculated with NCSD code on Summit using GPU acceleration
  - 1024 nodes, 6144 MPI tasks with 1 GPU/task and 7 OpenMP threads/task
  - Largest matrix dimensions: 131 million for ^{11}C and 167 million for ^{12}N (~7 hours to get 9 eigenstates)





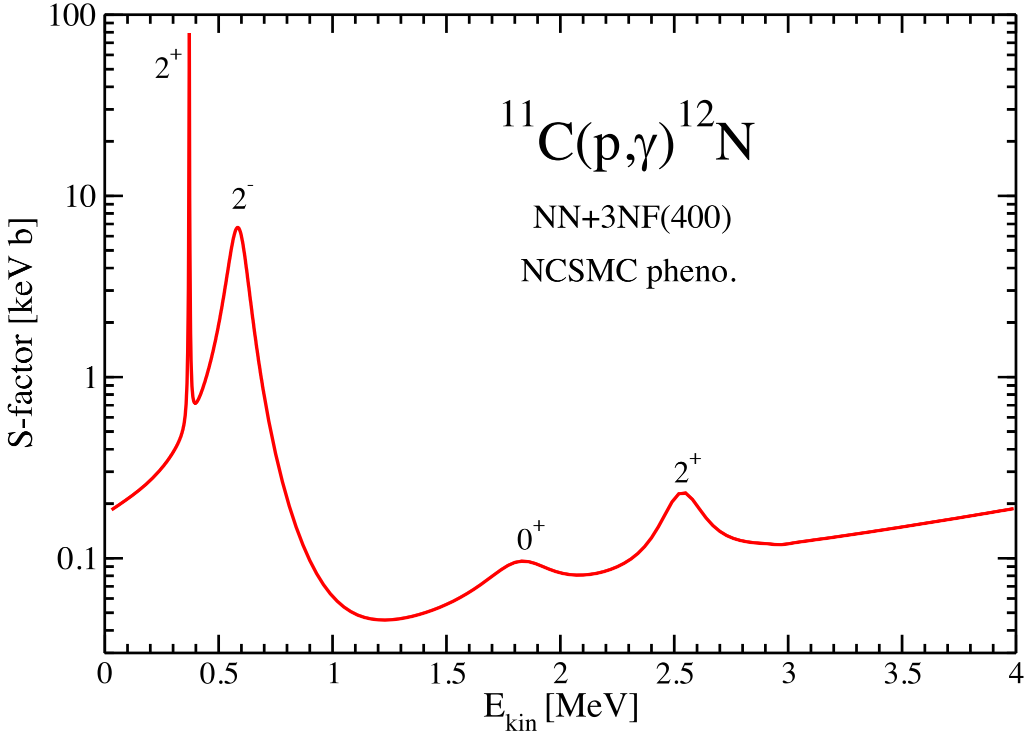
Experiment

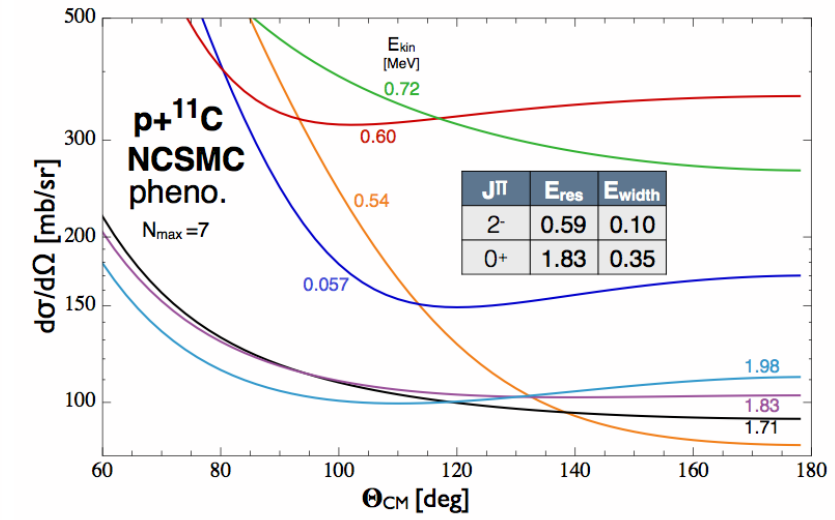
Calculated bound-state energy E(1⁺ 1) = -0.52 MeV

Measurement of $^{11}C(p,p)$ resonance scattering planned at TRIUMF TUDA facility

p+^{11}C scattering and $^{11}C(p,\gamma)^{12}N$ 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



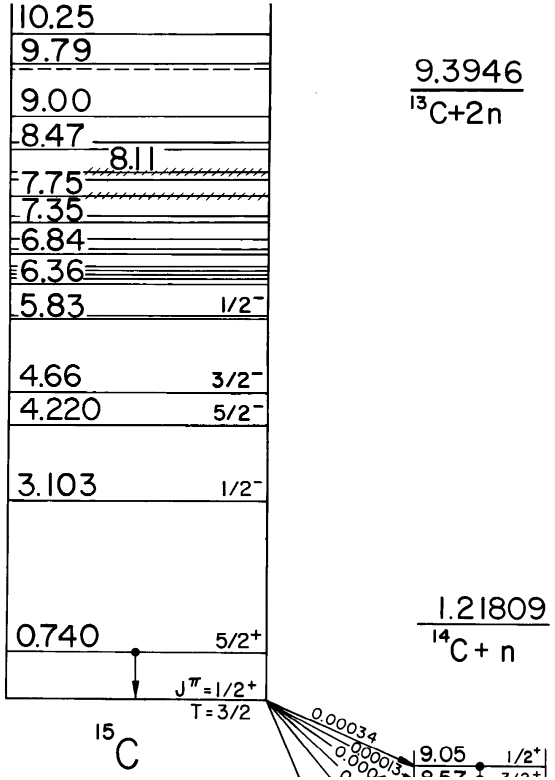


NCSMC calculations to be validated by measured cross sections and applied to calculate the $^{11}C(p,\gamma)^{12}N$ capture

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

- Motivation:
  - Halo ½+ *S*-wave and $5/2^+$ *D*-wave bound states
  - $^{14}C(n,\gamma)^{15}C$ capture relevant for astrophysics

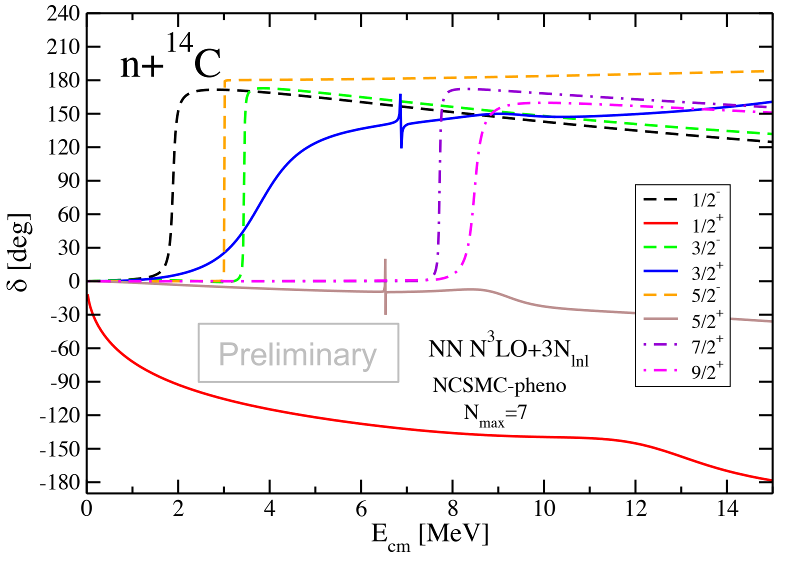
- Calculations in progress – all results preliminary
- NN chiral interaction – N^3LO Entem & Machleidt 2003, SRG evolved with λ = 2.0 fm^{-1}
- 3N chiral interaction – N^2LO with local/non-local regulator, SRG evolved with λ = 2.0 fm^{-1}

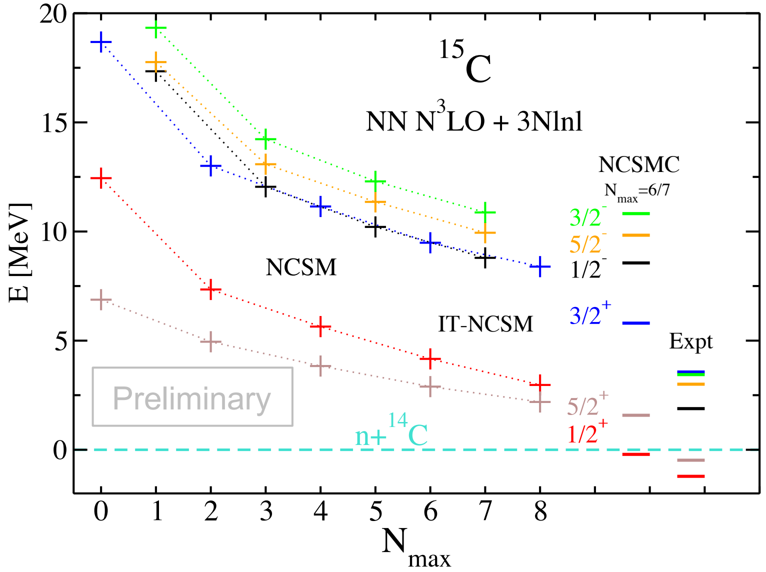


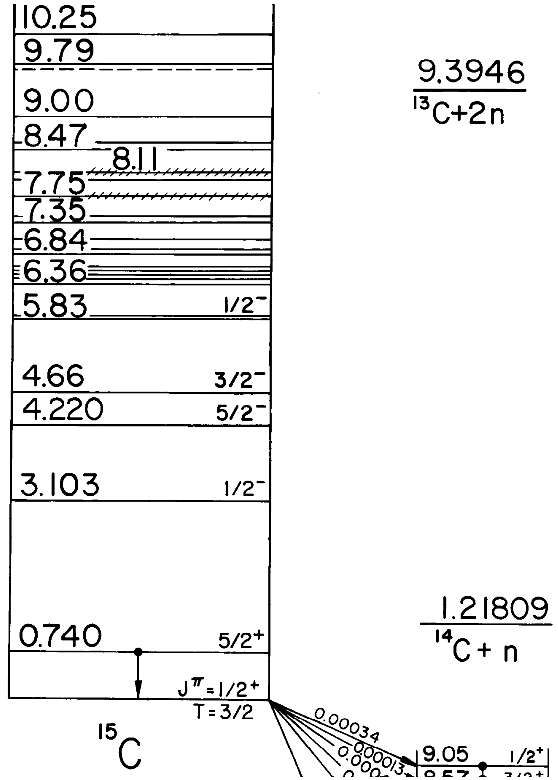
Halo *sd*-shell nucleus ^{15}C

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

NCSMC-pheno

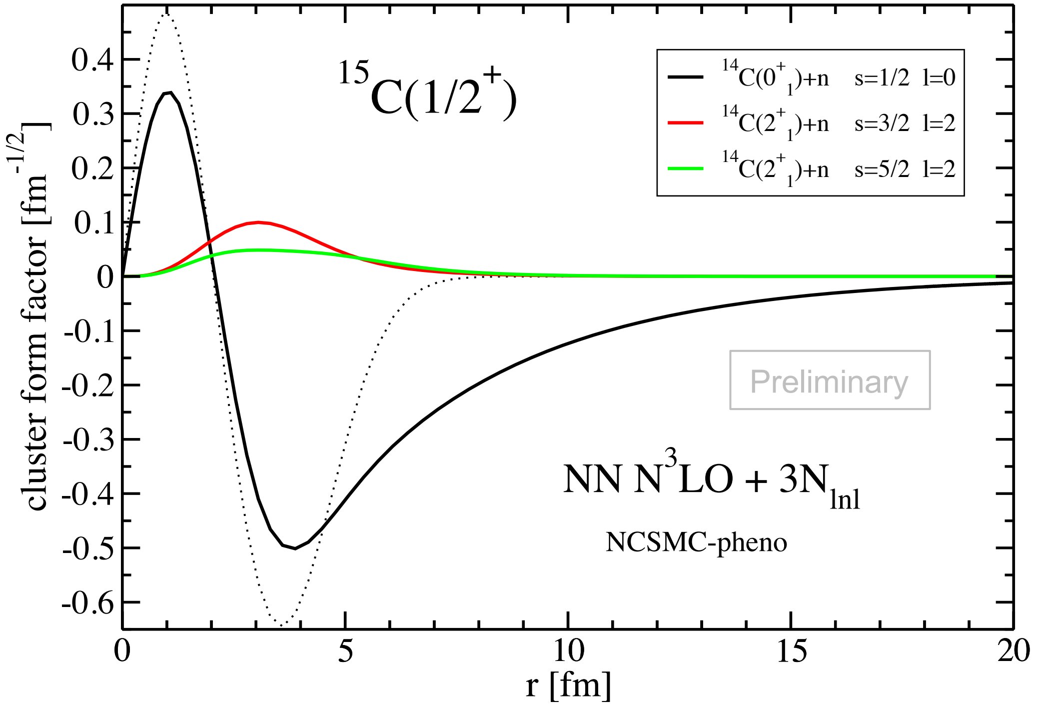


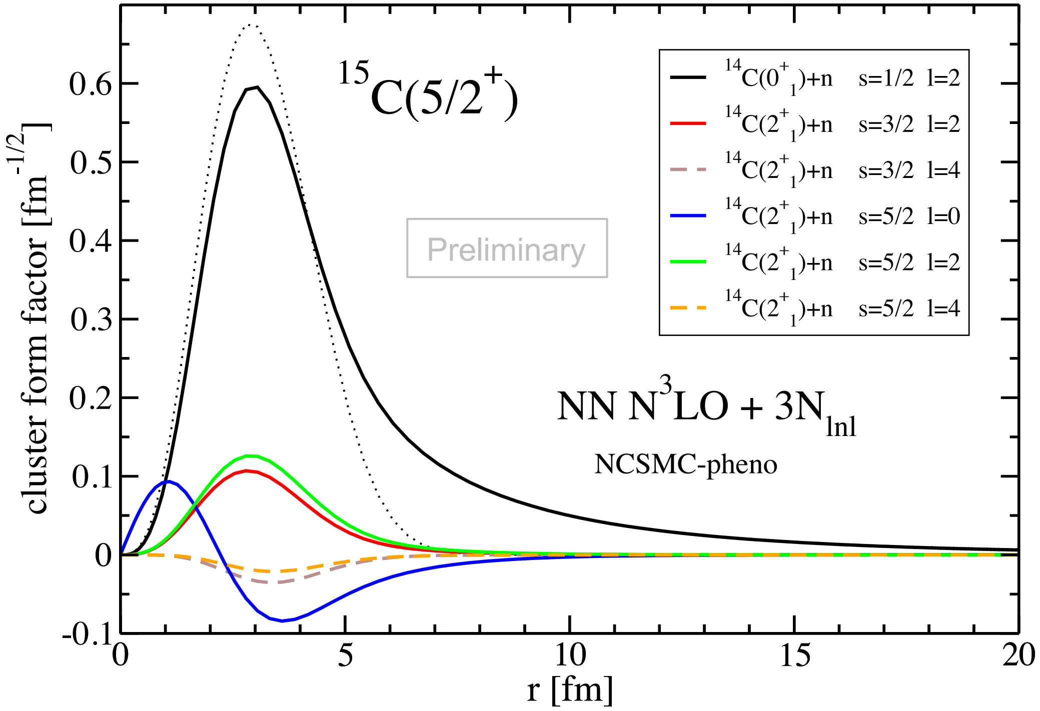




^{15}C cluster form factors

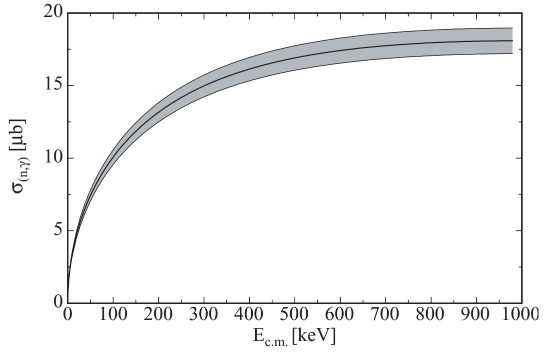
- 1/2$^+$ *S*-wave and 5/2$^+$ *D*-wave ANCs
  - $C_{1/2+}$ = 1.282 fm$^{-1/2}$ - compare to Moschini & Capel inferred from transfer data: 1.26(2) fm$^{-1/2}$
  - $C_{5/2+}$ = 0.048 fm$^{-1/2}$ 0.056(1) fm$^{-1/2}$
  - Spectroscopic factors: 0.96 for 1/2$^+$ and 0.90 for 5/2$^+$ - experiments 0.95(5)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

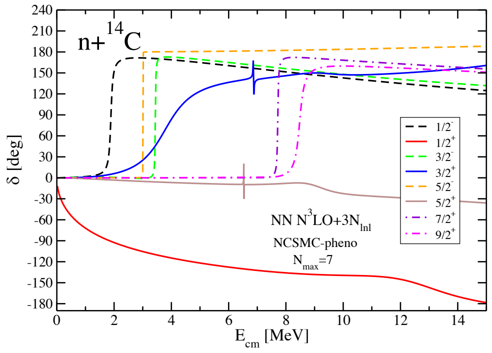


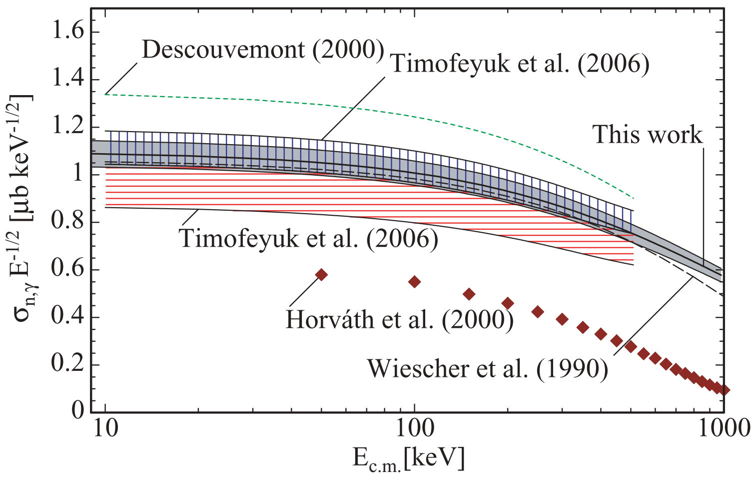


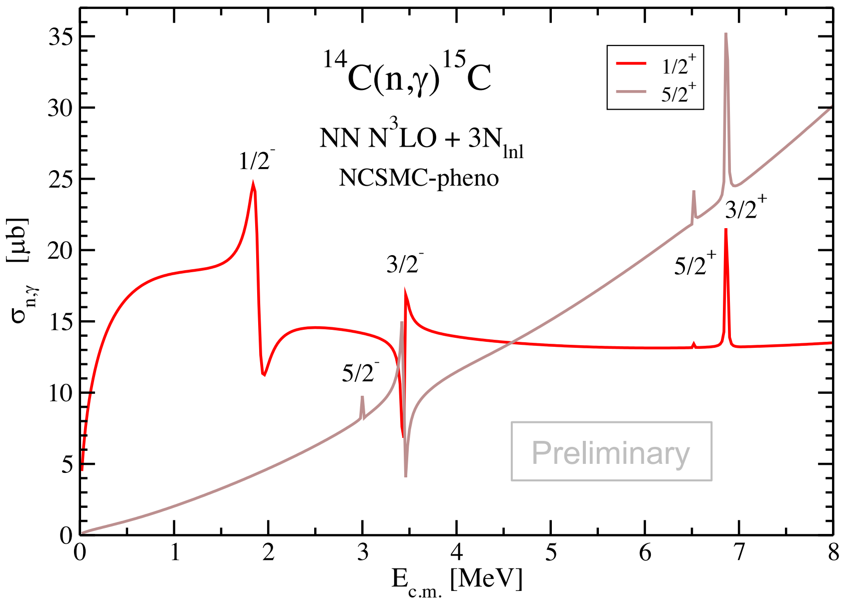
$^{14}C(n,\gamma)^{15}C$ capture cross section

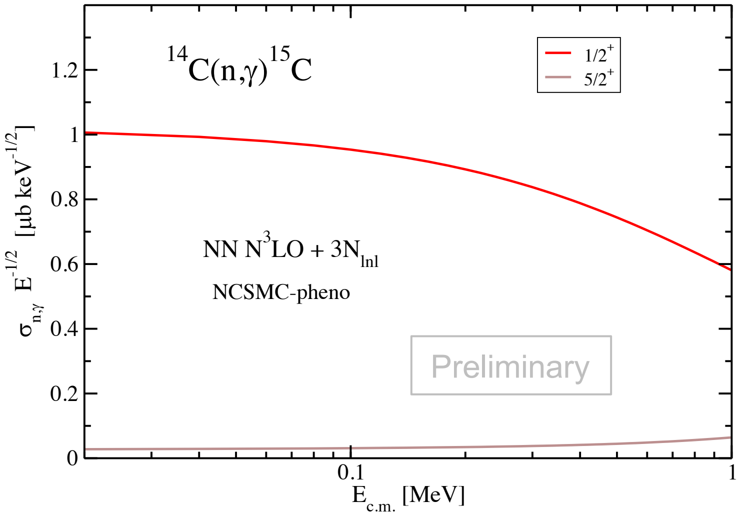
- Comparison to Karlsruhe experiment – Phys. Rev. C 77, 015804 (2008)











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 with predictive power becoming feasible beyond the lightest nuclei
- These calculations 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
- Structure of ^{7}Be and ^{7}Li from different binary mass partitions
  - Investigation of capture reactions relevant for astrophysics
  - Observation of a narrow S-wave resonance above 6He+p threshold – similarity to ^{10}Be+p system?
- ^{11}C(p,γ)^{12}N NCSMC calculations with validation of the 11C+p scattering by TRIUMF experiment
- ^{15}C NCSMC calculations in progress
  - Capture cross section, cluster form factor, ANCs

TRIUMF

Thank you!
Merci!

Discovery, accelerated