Ab initio reactions: from continuum to bound states and back

Mack C. Atkinson

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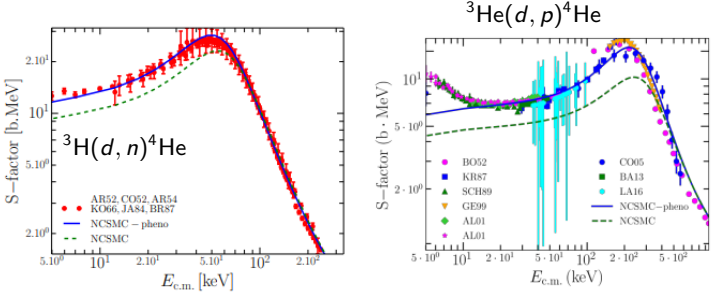
Introduction

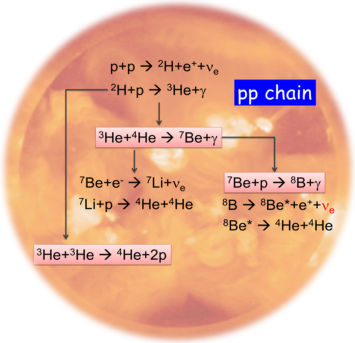
- Huge progress in *ab initio* calculations of bound properties
- *Ab initio* calculations of continuum properties are limited to much lighter nuclei
- While this is a limited region of the nuclear chart, there is an abundance of interesting reactions involving light nuclei that can be studied
- Simultaneous description of bound and scattering states leads to a better understanding of fusion rates, constraints on BSM physics, etc.



P. Navratil, S. Quaglioni arXiv:2204:01187

From continuum to bound: $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$

$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ important for solar-model predictions



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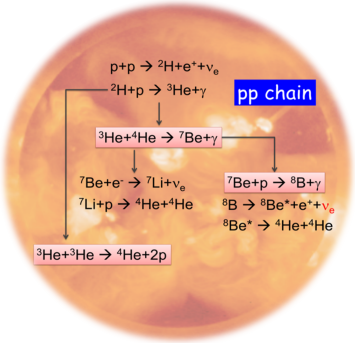

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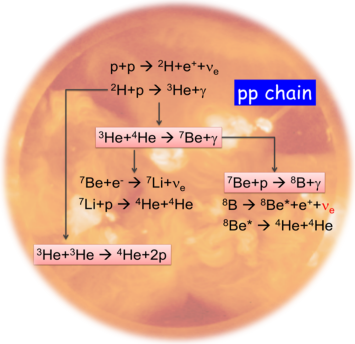

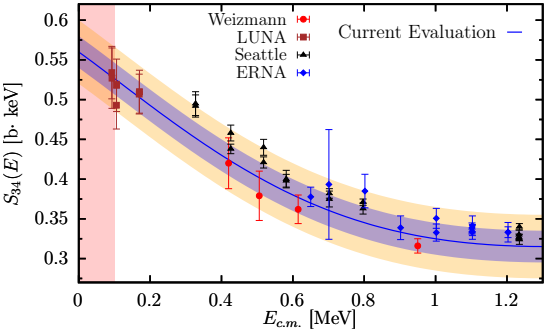

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Adelberger *et al.*, Rev Mod Phys **83** 195 (2011)

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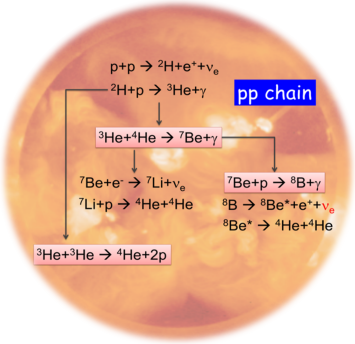

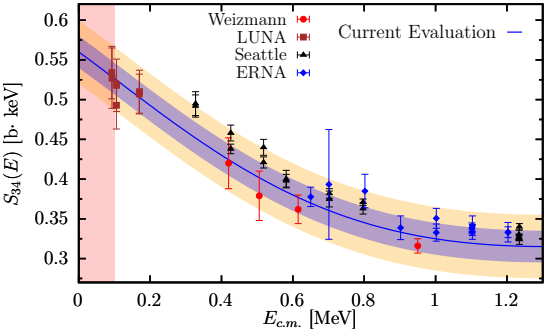

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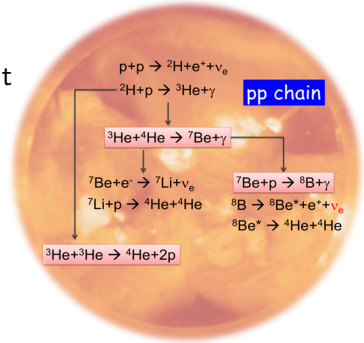

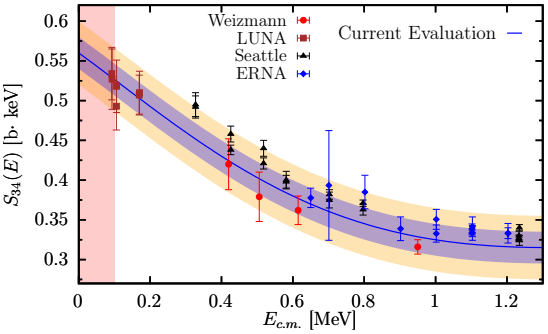

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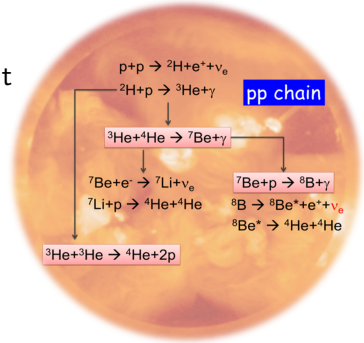
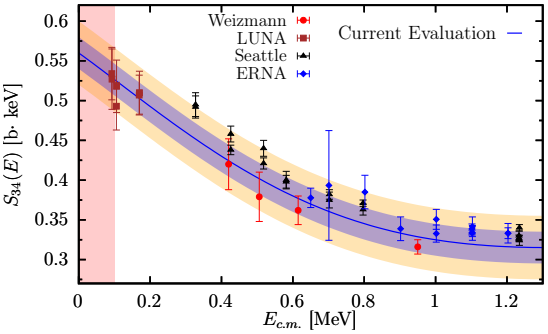
- Current evaluations depend on both theory and experiment
- Ideally, theory will accurately predict $S_{34}(0)$





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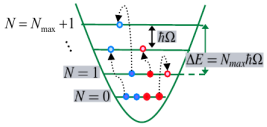

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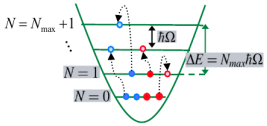

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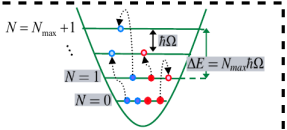

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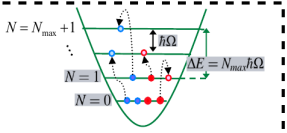

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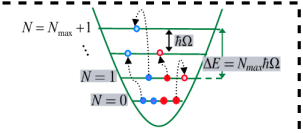

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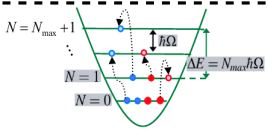

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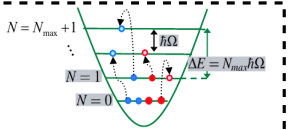

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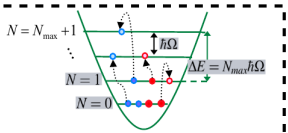

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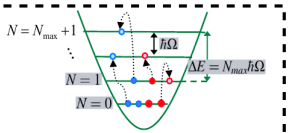

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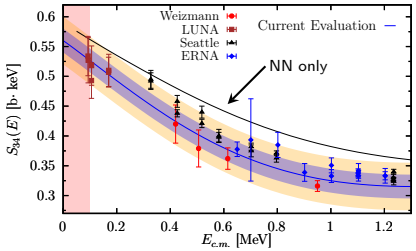

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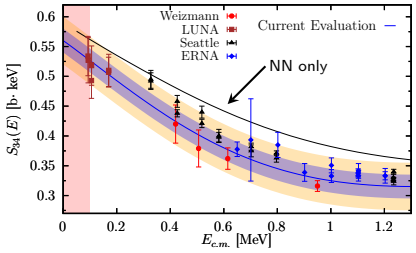

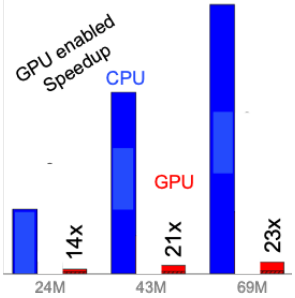

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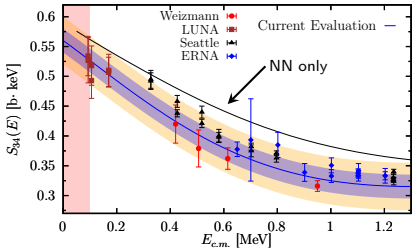
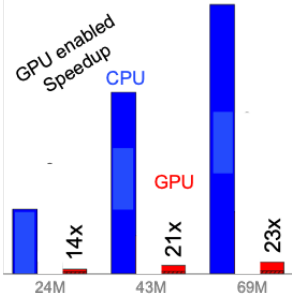
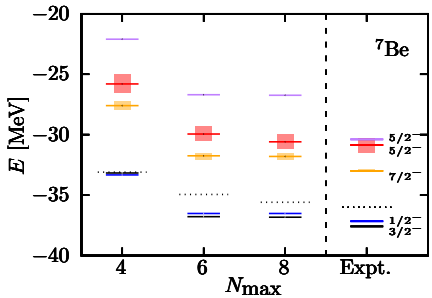




- GPU speedup $\Longrightarrow$ NNN forces are now included

NCSMC Calculation of ^{3}He+^{4}He shows reasonable agreement with data



NN-N3LO+3NInl

$\hbar\Omega = 20$ MeV

$\lambda_{\mathrm{SRG}} = 2.0$ fm^{-1}

D.R. Entem and R. Machleidt, PRC **68**, 041001 (2003)
P. Navratil, Few Body Systems **41**, 117 (2007)

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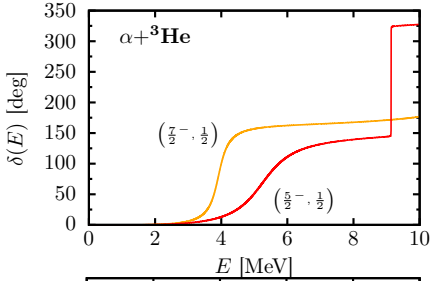

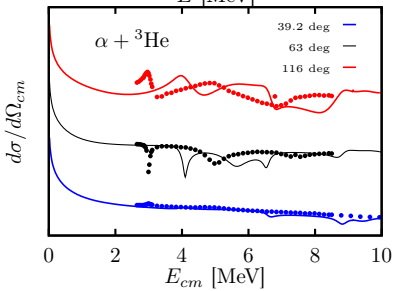

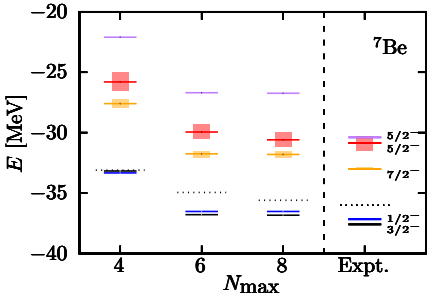

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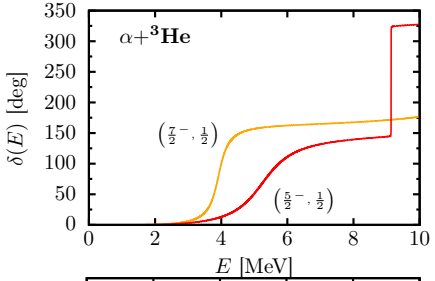
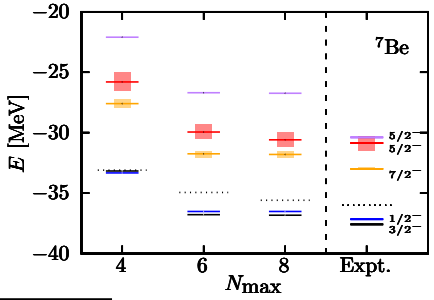
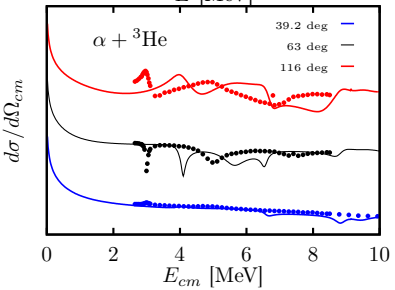
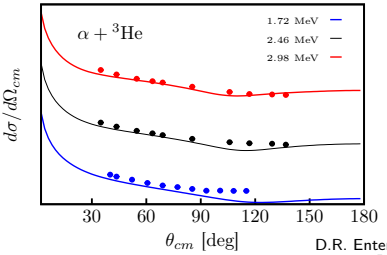








NN-N3LO+3Nlnl

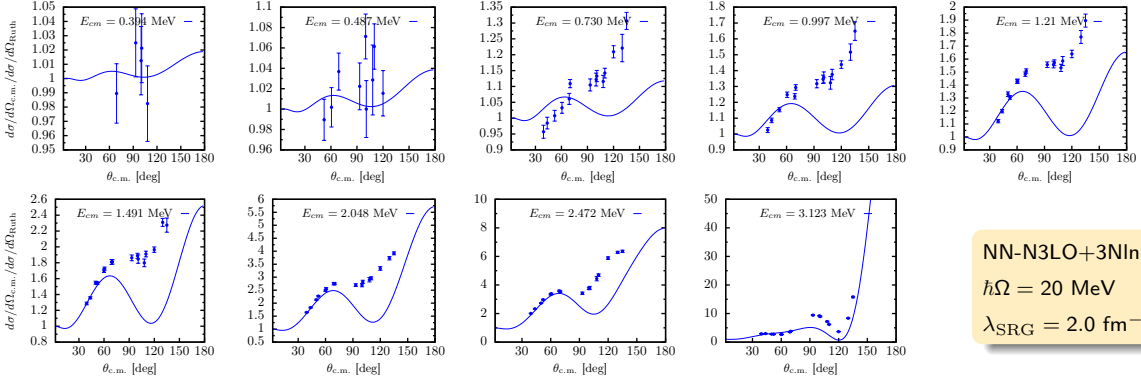
$\hbar\Omega = 20$ MeV

$\lambda_{\mathrm{SRG}} = 2.0$ fm^{-1}

D.R. Entem and R. Machleidt, PRC **68**, 041001 (2003)
P. Navratil, Few Body Systems **41**, 117 (2007)

SONIK ^{3}He+^{4}He elastic scattering ratio to Rutherford

- Experiment done at TRIUMF in 2022



NN-N3LO+3NInl

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$\lambda_{SRG} = 2.0$ fm^{-1}

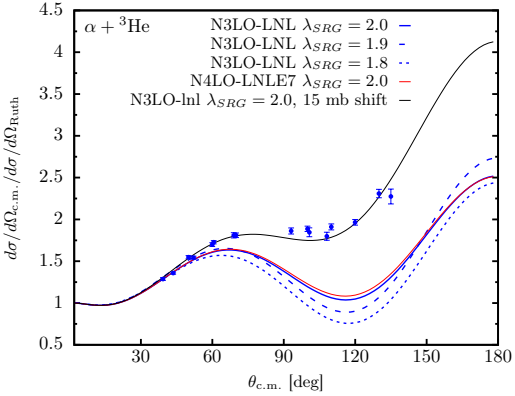
Paneru *et al.*, arXiv:2211.14641 (2022)

Discrepancy in NCSMC results

- Lack of strength in cross section ratio to Rutherford appears at high angles
- Rutherford obscures the fact that a constant shift accounts for the discrepancy

$$\frac{d\sigma}{d\Omega_{\mathrm{Ruth}}} = \left(\frac{Z_1 Z_2 e^2}{8\pi\epsilon_0 m v^2 \sin^2\left(\frac{\theta}{2}\right)} \right)^2$$

- Varied properties of the interaction
- Nothing in the NCMSC appears to reproduce the 15 mb shift



Results are promising but convergence needs to be explored

$$^{3}\mathrm{He} + \alpha \rightarrow {}^{7}\mathrm{Be} + \gamma$$

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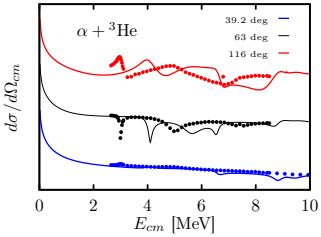

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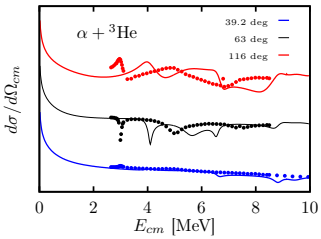

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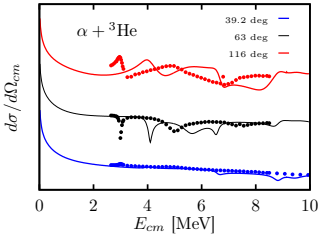

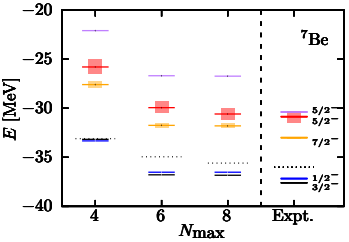

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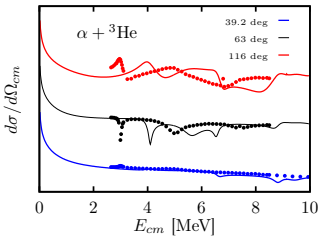

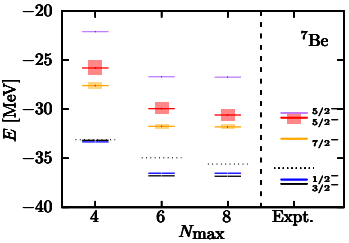

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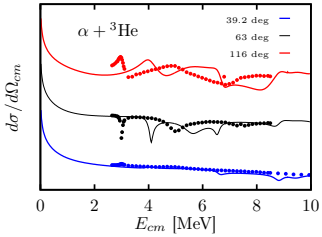

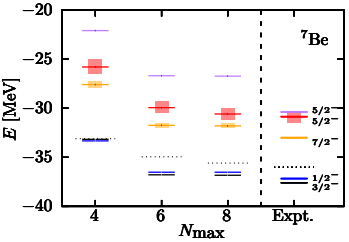

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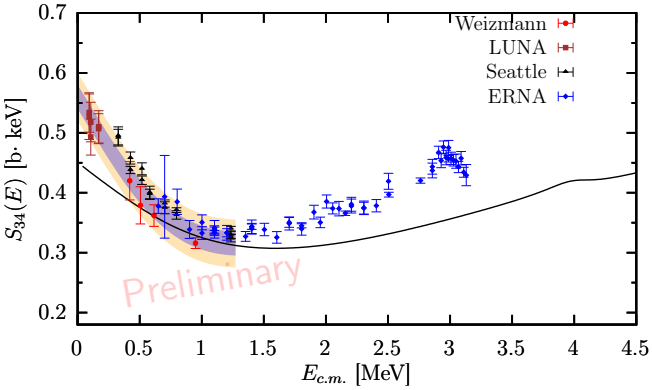

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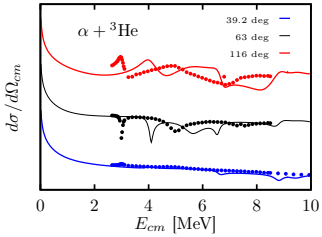

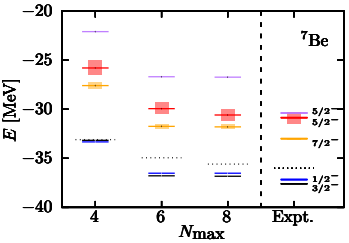

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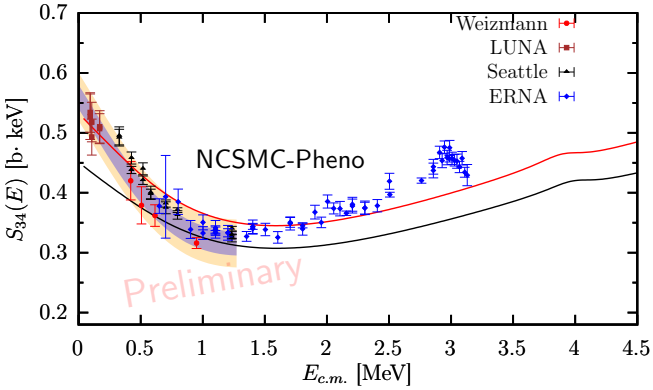

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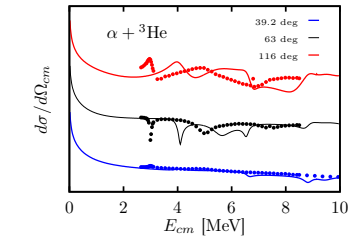

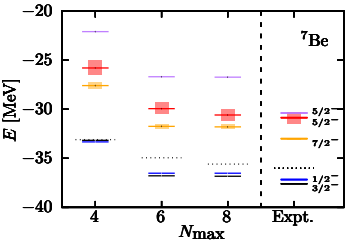

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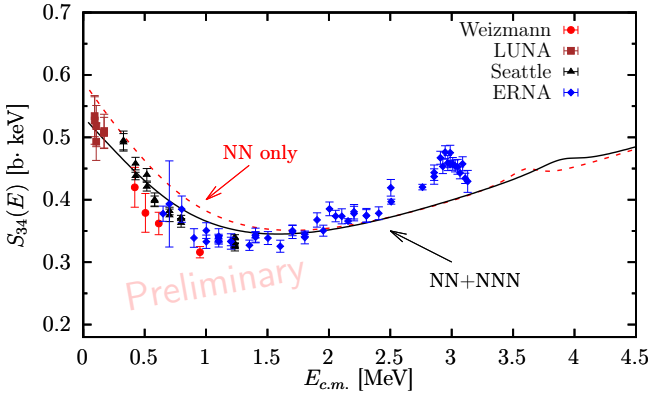

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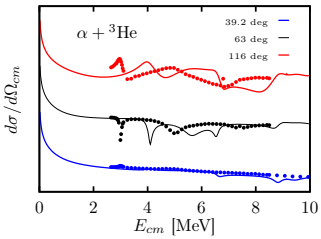

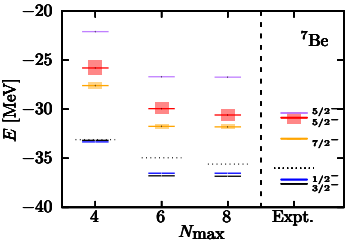

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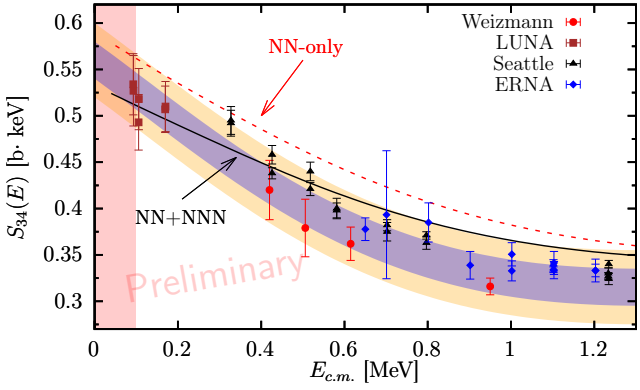

From bound to continuum: $^{11}\mathrm{Be} \rightarrow (p + {}^{10}\mathrm{Be}) + \beta + \nu$

Physics Letters B 732 (2014) 305–308

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D. Baye and E.M. Tursunov, PLB **696**, 4, 464-467 (2011)

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PHYSICAL REVIEW LETTERS **123,** 082501 (2019)

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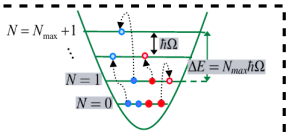
- Measured consistent branching ratio $b_p = 1.3(3) \times 10^{-5}$
  - Still orders of magnitude larger than theoretical predictions
- Predict the $(\frac{1}{2}^+, \frac{1}{2})$ proton resonance at 197 keV from the proton energy distribution

NCSMC calculation of ^{11}Be and ^{11}B



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

$$\hat{H} = \hat{T} + \hat{V}_{NN} + \hat{V}_{NNN}$$

$$\hat{H}\,|\Psi^A\rangle = E\,|\Psi^A\rangle$$

NCSM

NCSMC

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

$|^{11}\mathrm{B}\rangle$ $\qquad$ $|p\rangle \otimes |^{10}\mathrm{Be}\rangle$

$$\left\langle \Psi_{sc}\left(p + {}^{10}\mathrm{Be}\right) \middle| \hat{\mathcal{M}}_{\mathrm{GT}} \middle| \Psi_{bs}\left({}^{11}\mathrm{Be}\right) \right\rangle$$

NCSMC Calculation of ^{11}B and ^{11}Be

NN-N4LO(500)+3Nlnl
$\hbar\Omega = 18$ MeV, $N_{\max} = 7$
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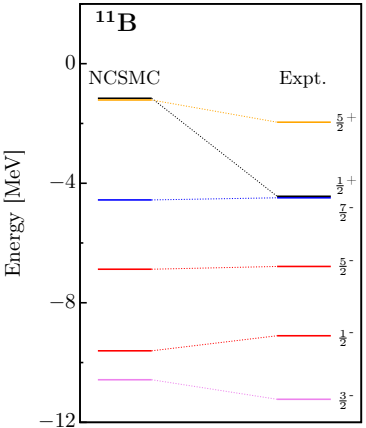

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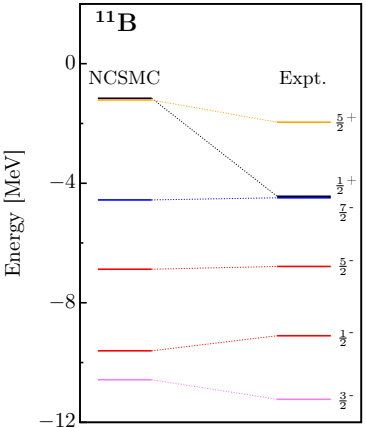

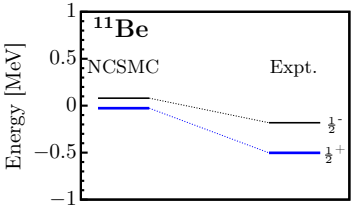

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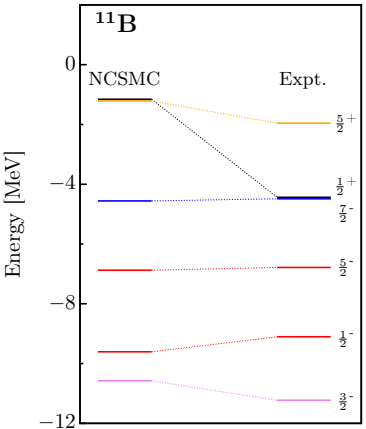

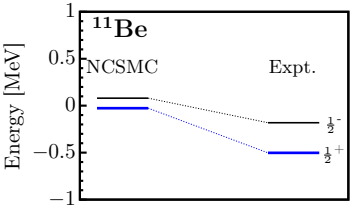

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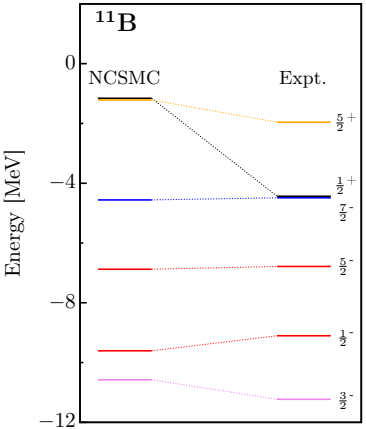

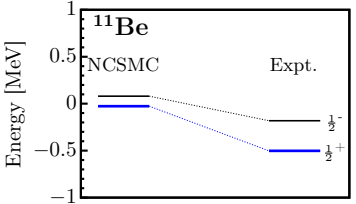

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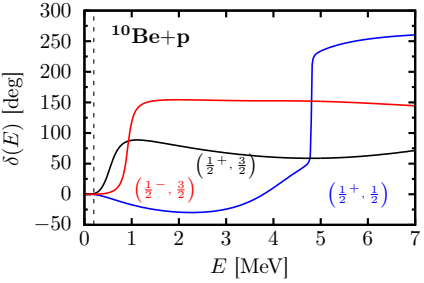

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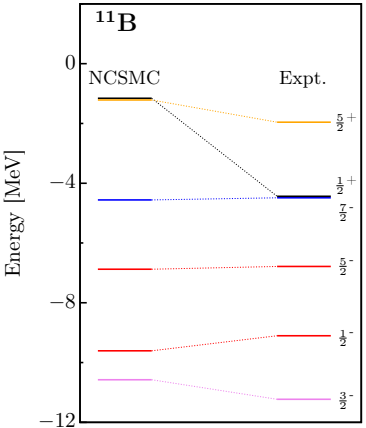

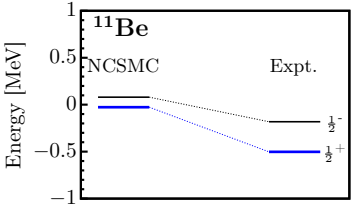

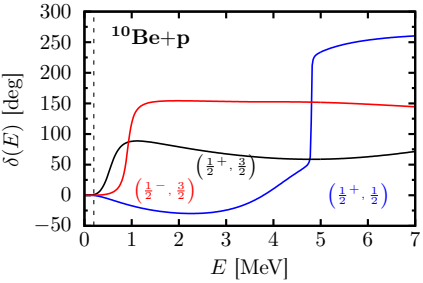

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NCSMC Calculation of ^{11}B and ^{11}Be

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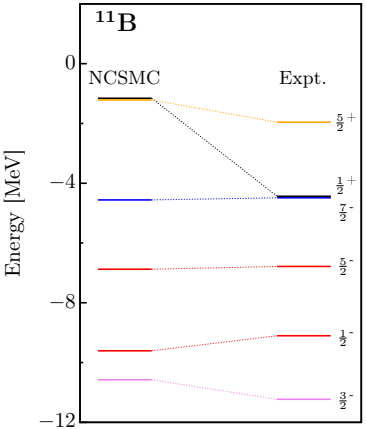

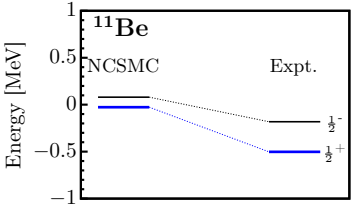

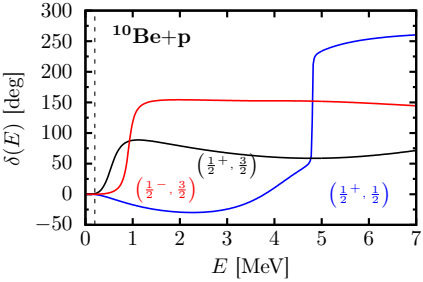

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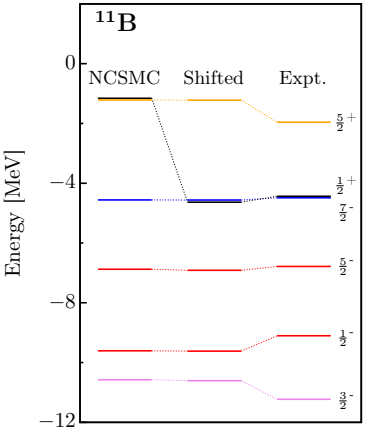

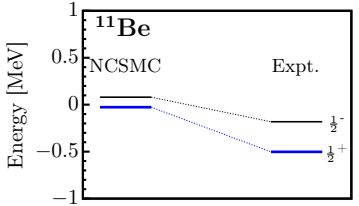

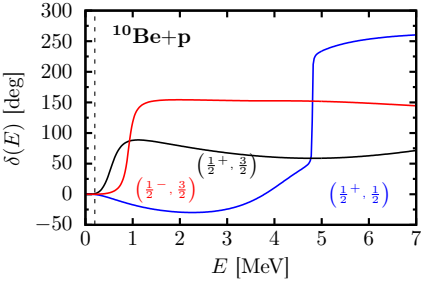

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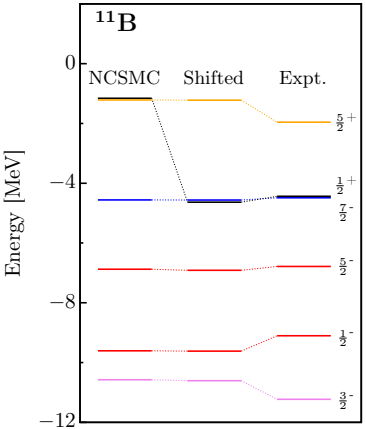

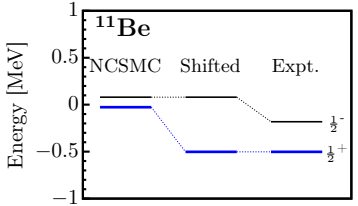

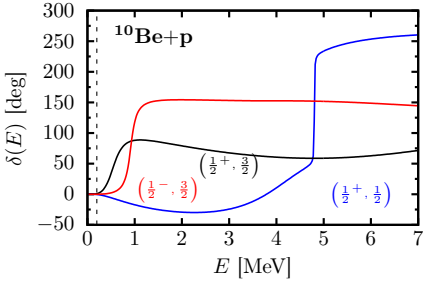

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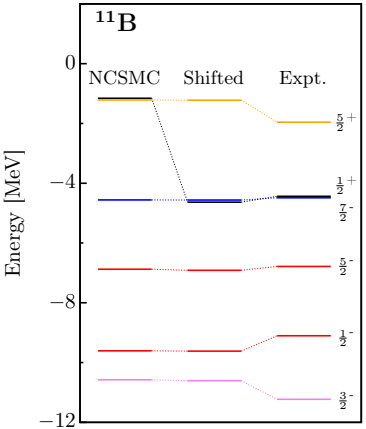

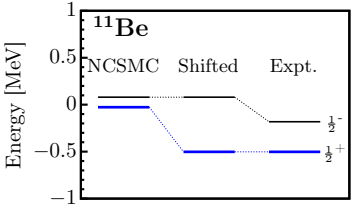

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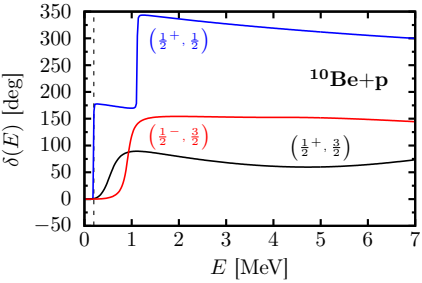

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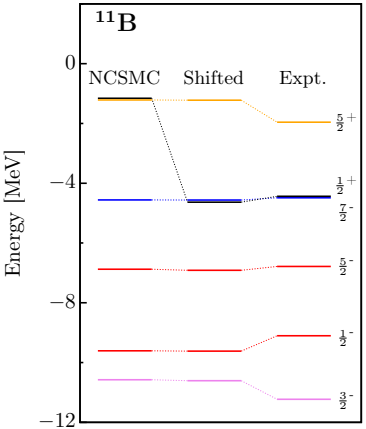

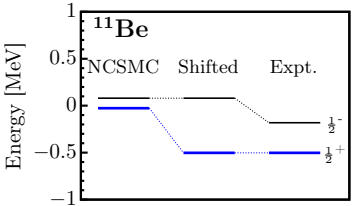

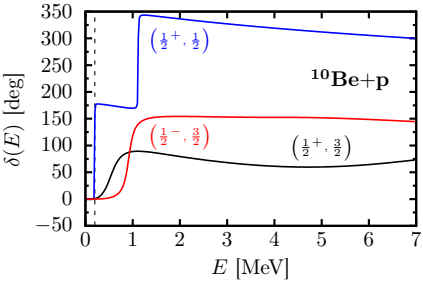

	NCSMC-shifted	Expt.
E [keV]	197	197(20)
Γ [keV]	10	12(5)

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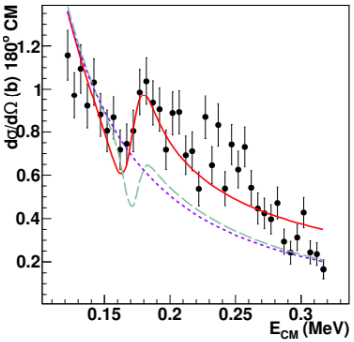
β-Decay to Resonant State

Ayyad *et al.*, PRL **129** 012501 (2022)



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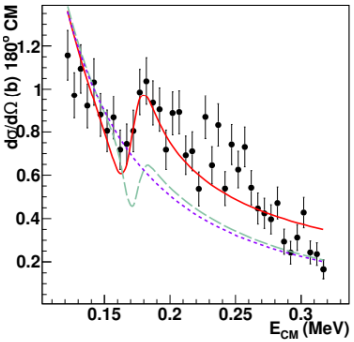

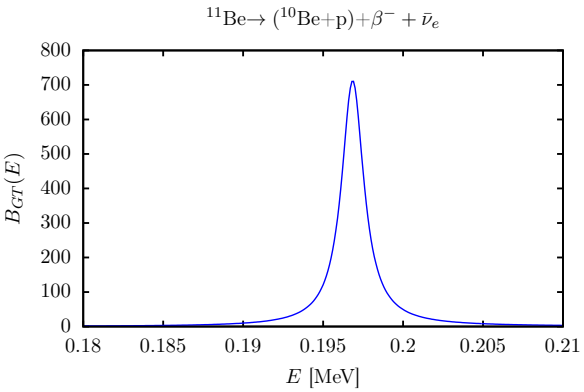

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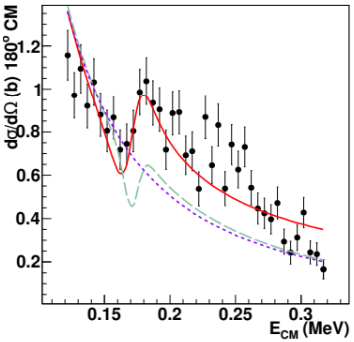

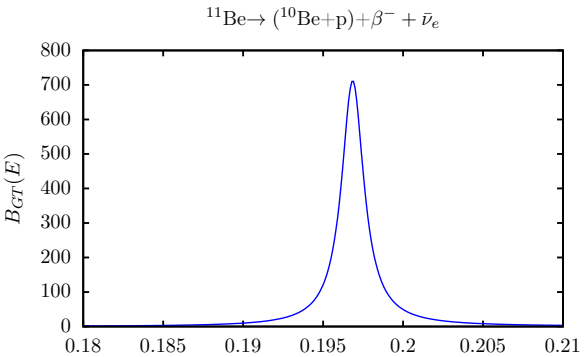

$(1/2^+, 1/2)$	$N_{\max}=5$ NCSM	$N_{\max}=5$ $\mathrm{NCSMC_{pheno}}$	$N_{\max}=7$ NCSM	$N_{\max}=7$ $\mathrm{NCSMC_{pheno}}$	Expt.
$B(\mathrm{GT})$	1.95	0.325	1.39	0.565	$5.5^{8.3}_{3.3}$
b_p	-	7.4×10^{-7}	-	1.3×10^{-6}	$1.3(3) \times 10^{-5}$

Conclusions and Outlook

- The NCSMC provides a simultaneous description of bound and scattering states
- We can now include the *NNN* force in ^{3}He(α,γ)^{7}Be
- Our calculation of ^{11}B confirms the existence of the $1/2^{+}$ resonacne
- The corresponding $B(GT)$ explains the large branching ratio observed in experiment
- Future: include the $\alpha + {}^{7}$Li channel in ^{11}B calculation
- Future: include the p+^{6}Li channel in $S_{34}(E)$ calculation

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(LLNL)

Guillame Hupin

(IN2P3)

Petr Navratil

(TRIUMF)