

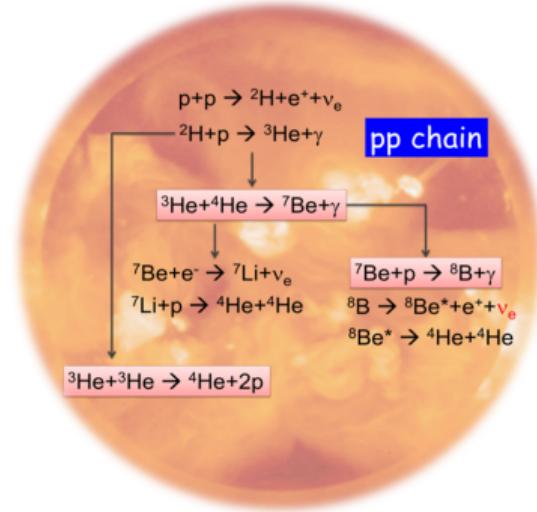
# *Ab initio* calculation of the $^3\text{He}(\alpha, \gamma)^7\text{Be}$ astrophysical $S$ factor...and beta-delayed proton emission from $^{11}\text{Be}$

UCSB, Santa Barbara

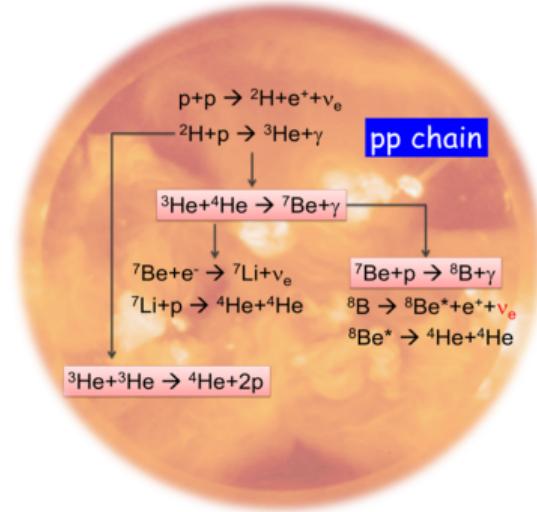
Mack C. Atkinson



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

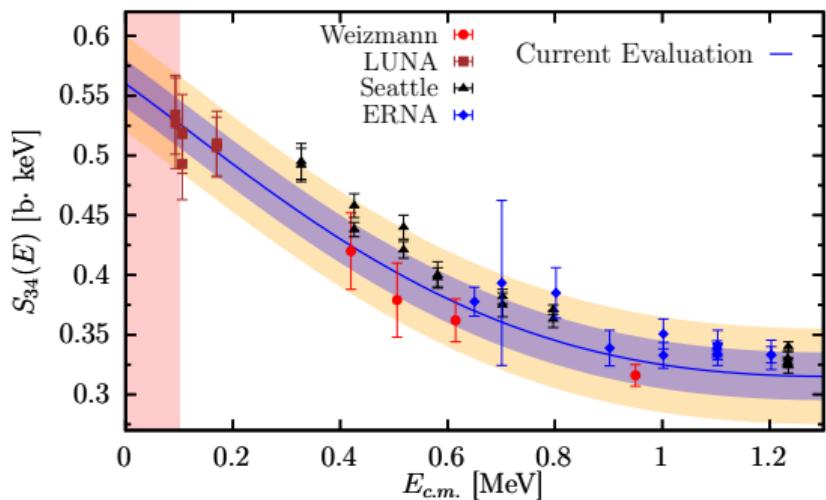


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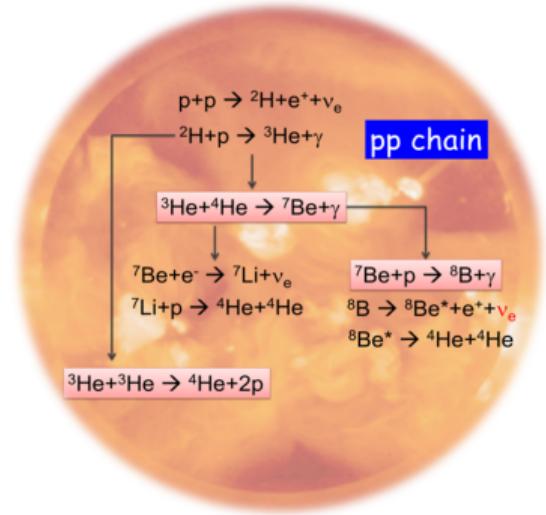
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Adelberger *et al.*, Rev Mod Phys 83 195 (2011)

atkinson27@llnl.gov

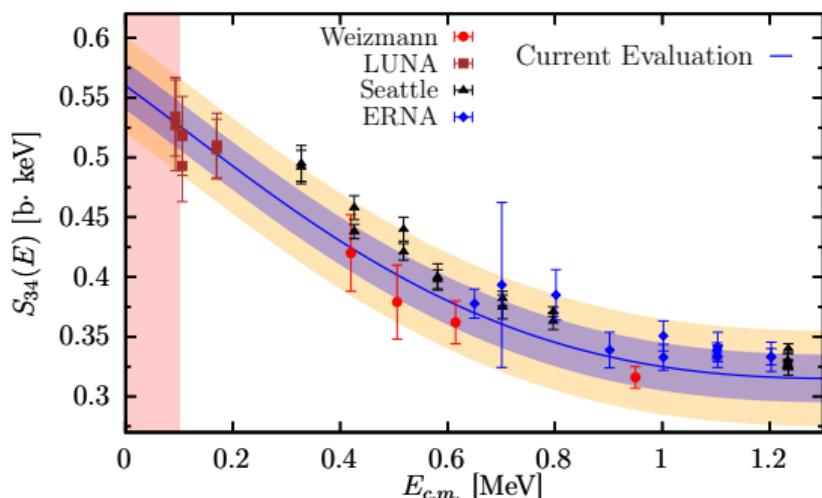
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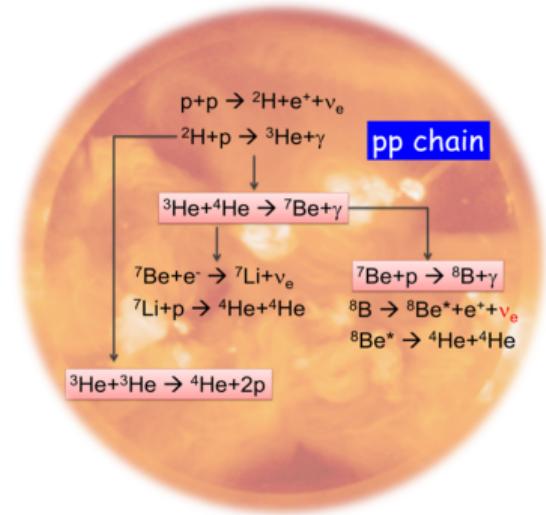
- Reaction rates too low at solar energies in the lab



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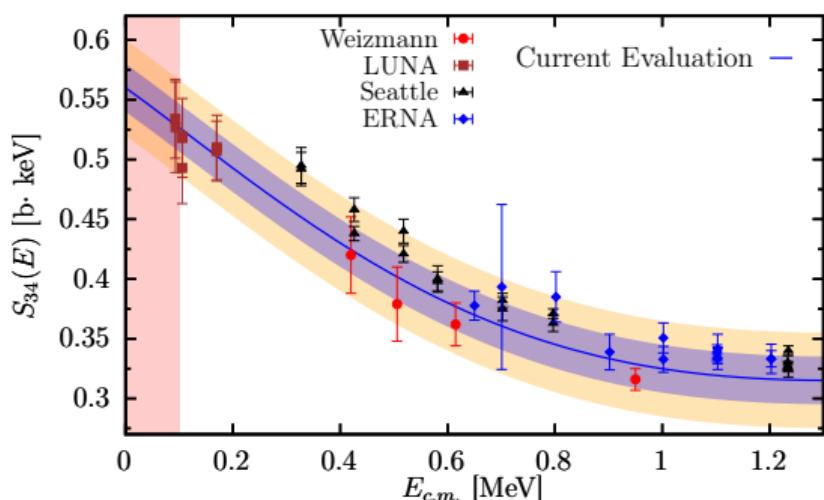
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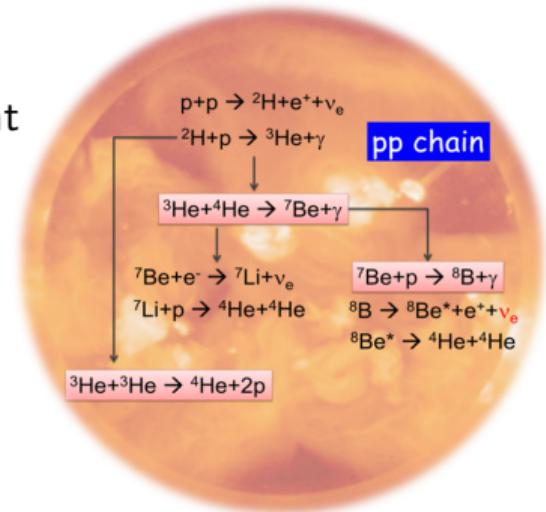
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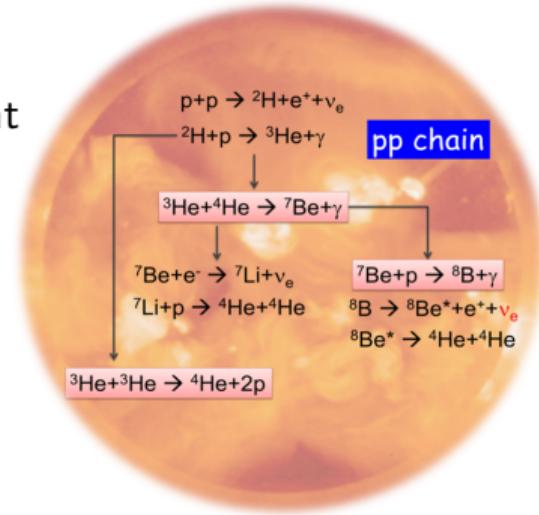
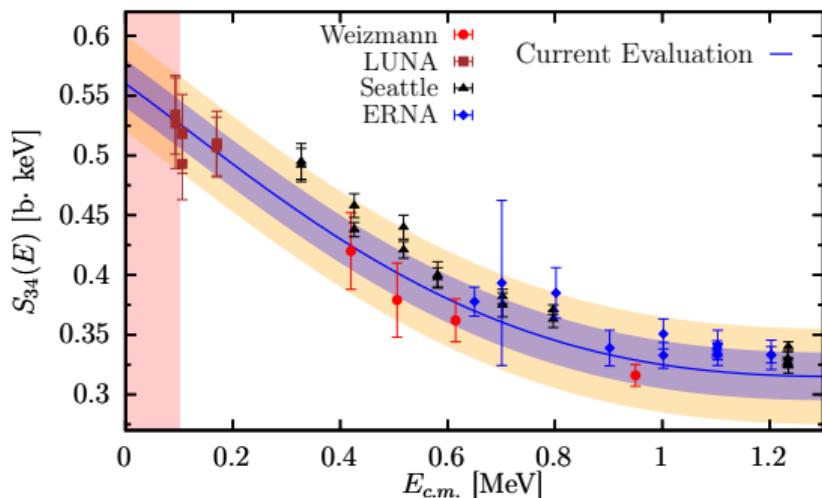
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- Reaction rates too low at solar energies in the lab
- Current evaluations depend on both theory and experiment
- Ideally, theory will accurately predict  $S_{34}(0)$



$$\sigma(E) = \frac{S_{34}(E)}{E} \exp \left\{ -\frac{2\pi Z_1 Z_2 e^2}{\hbar \sqrt{2E/m}} \right\}$$

## Goal: Improve the theoretical prediction of $S_{34}(E)$

Current evaluation:

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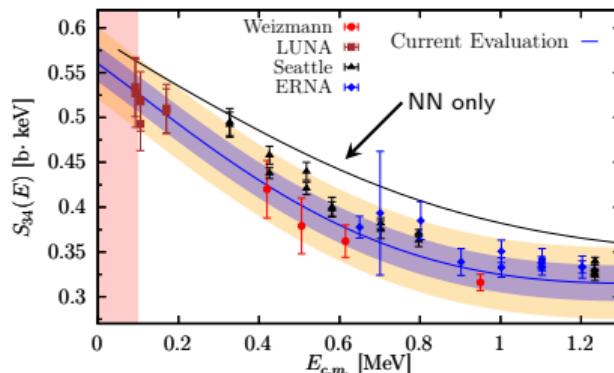
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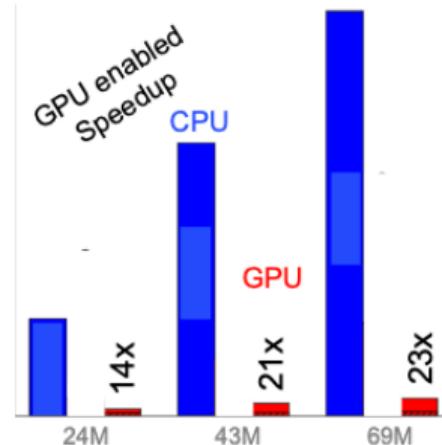
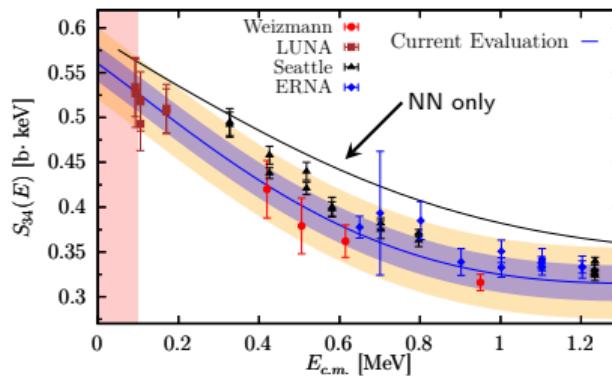


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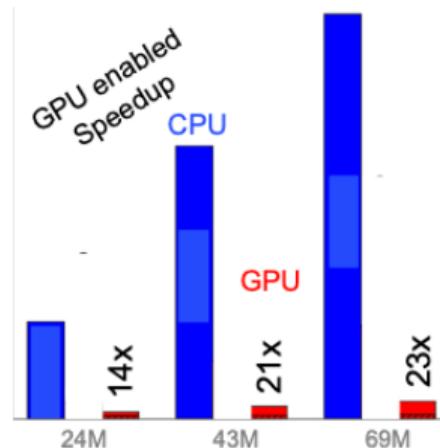
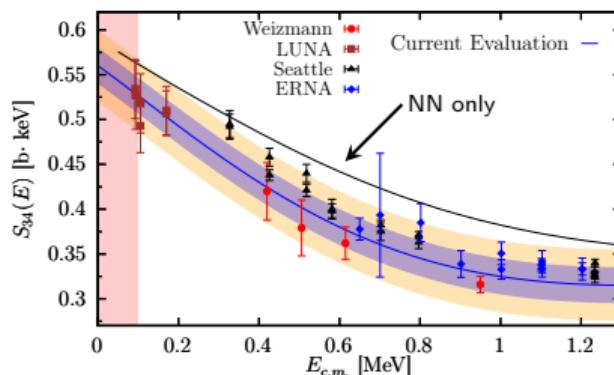


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- GPU speedup  $\implies$  NNN forces are now included

# The *ab initio* method: from NCSM to NCSMC

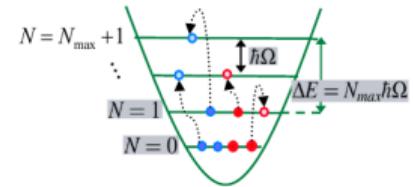
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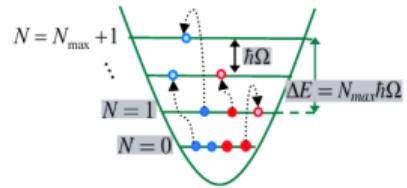


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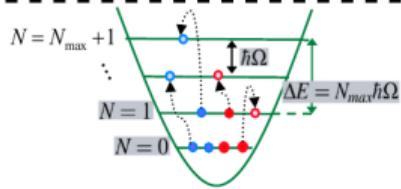
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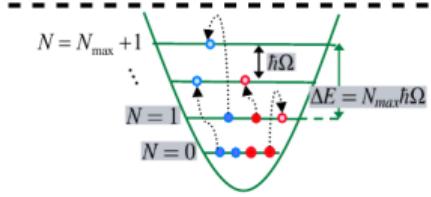
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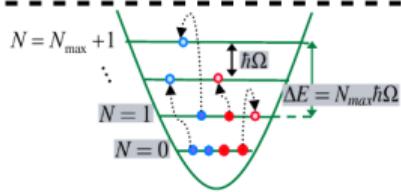
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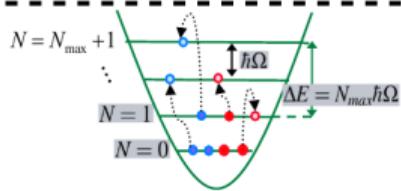
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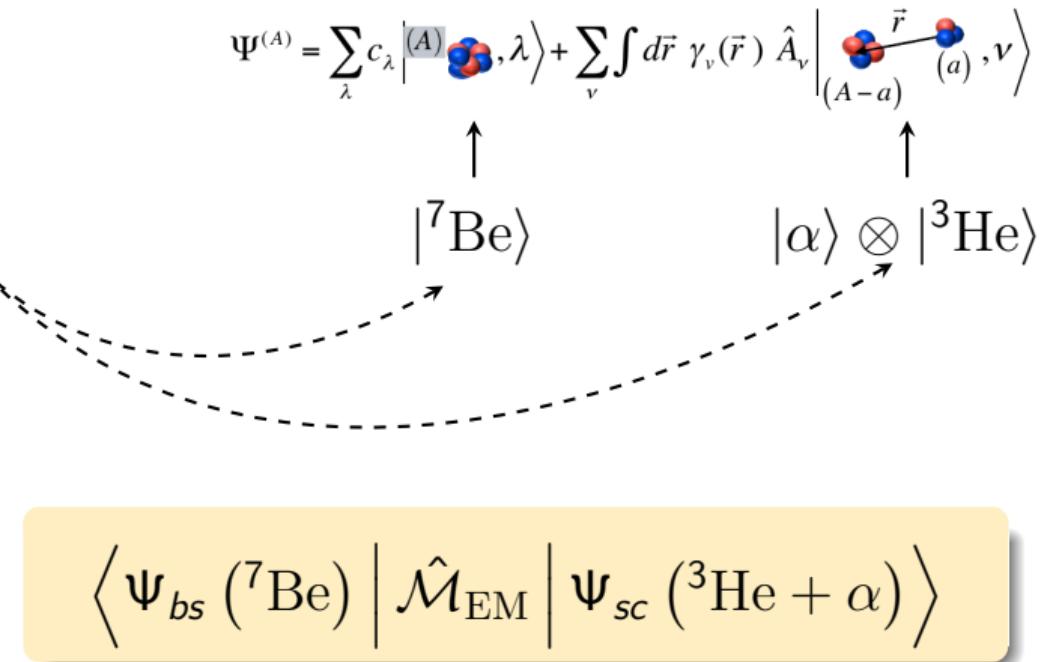
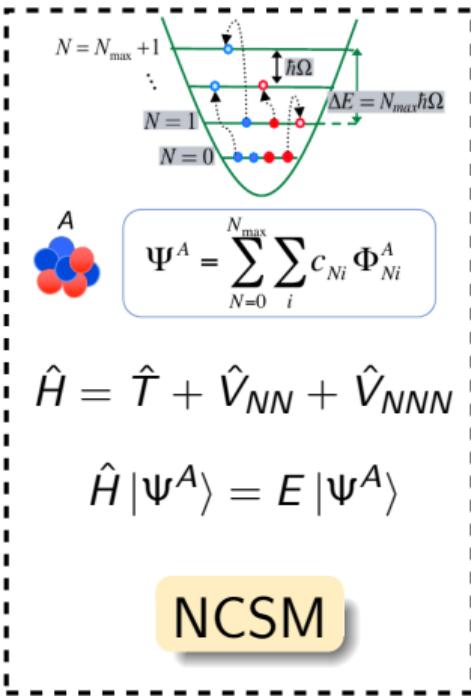
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↑    ↑  
 $|^7\text{Be}\rangle$                                      $|\alpha\rangle \otimes |^3\text{He}\rangle$

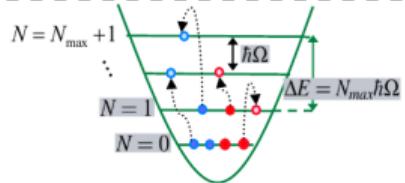
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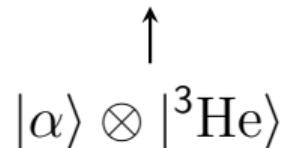
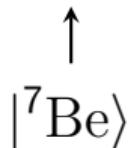
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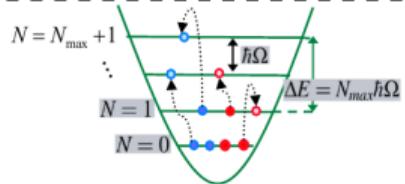
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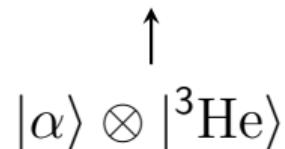
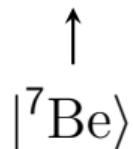
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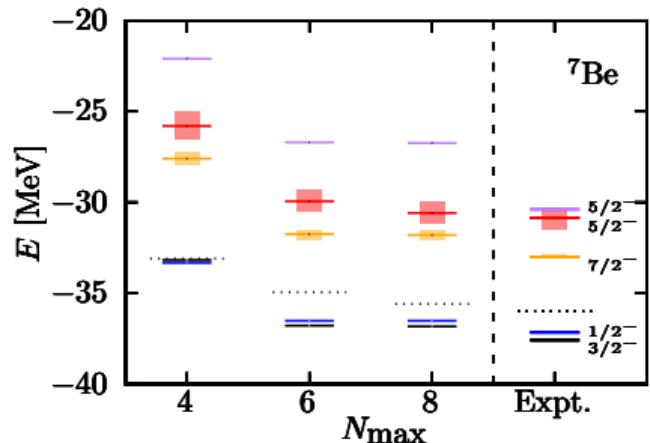
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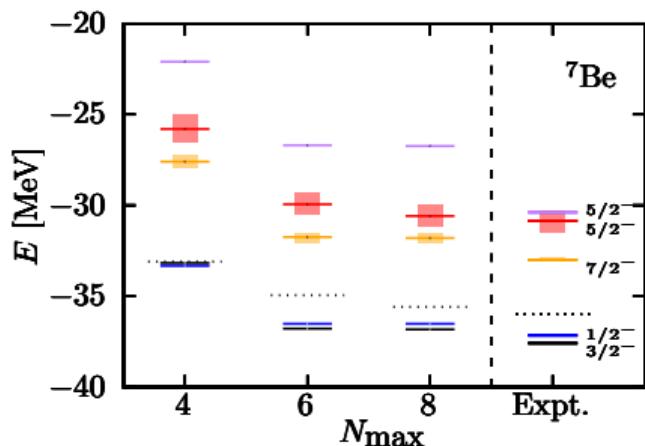
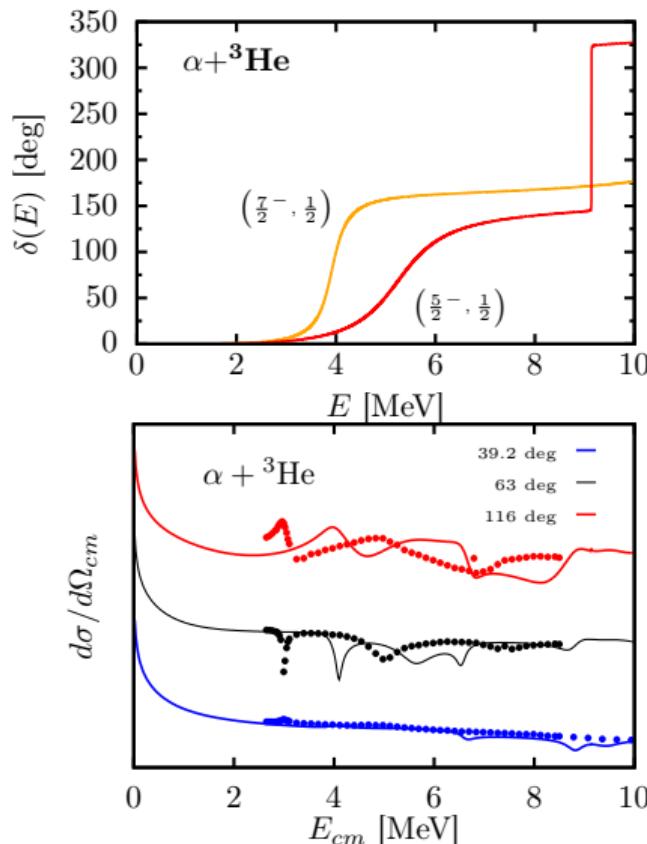
# NCSMC Calculation of $^3\text{He} + ^4\text{He}$ shows reasonable agreement with data



NN-N3LO+3Nlnl  
 $\hbar\Omega = 20$  MeV  
 $\lambda_{\text{SRG}} = 2.0$  fm $^{-1}$

D.R. Entem and R. Machleidt, PRC **68**, 041001 (2003)  
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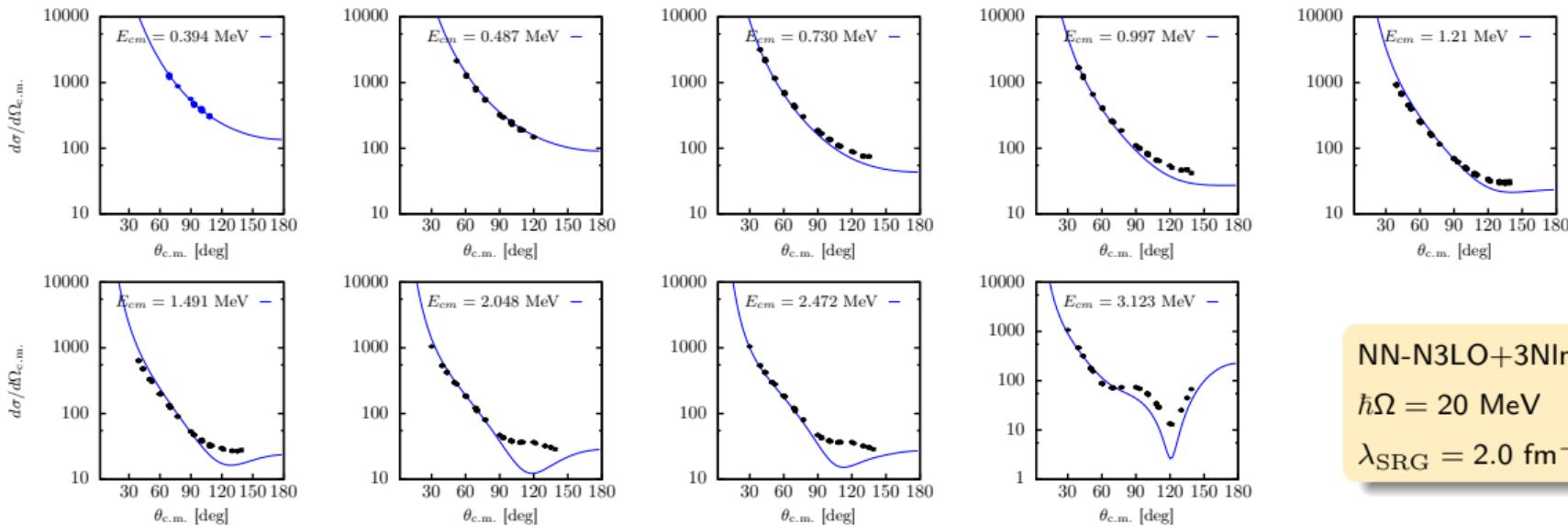


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# SONIK $^3\text{He} + ^4\text{He}$ elastic scattering cross sections

- Experiment done at TRIUMF in 2022



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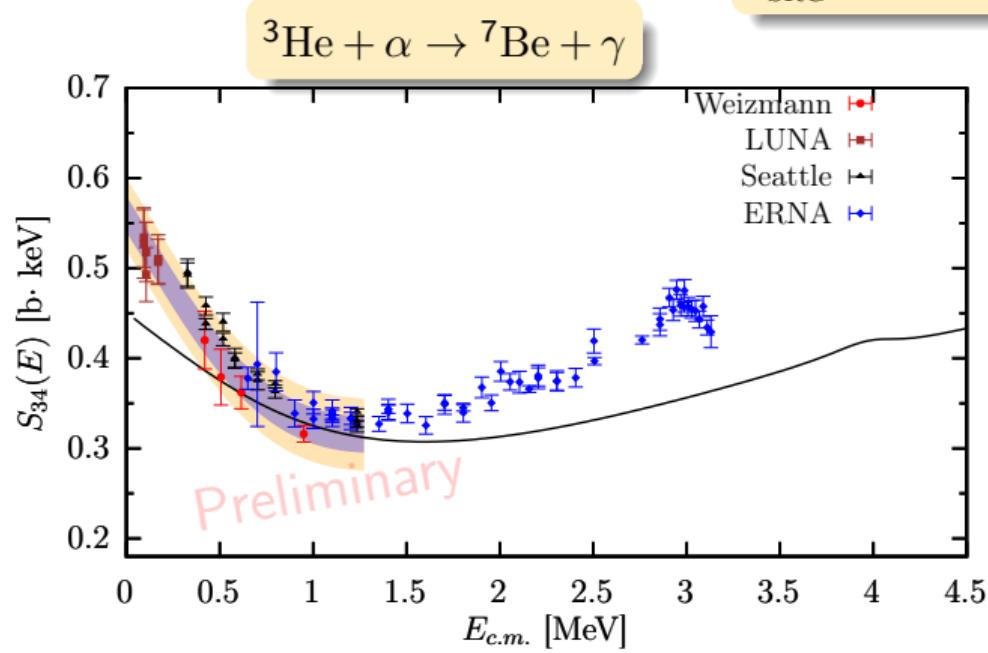
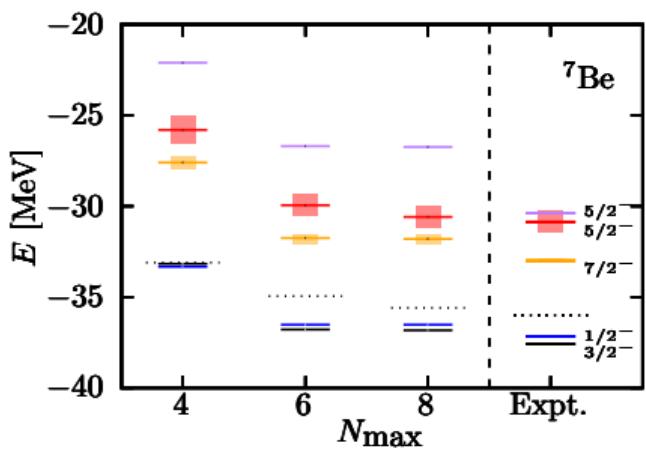
# Results are promising but convergence needs to be explored

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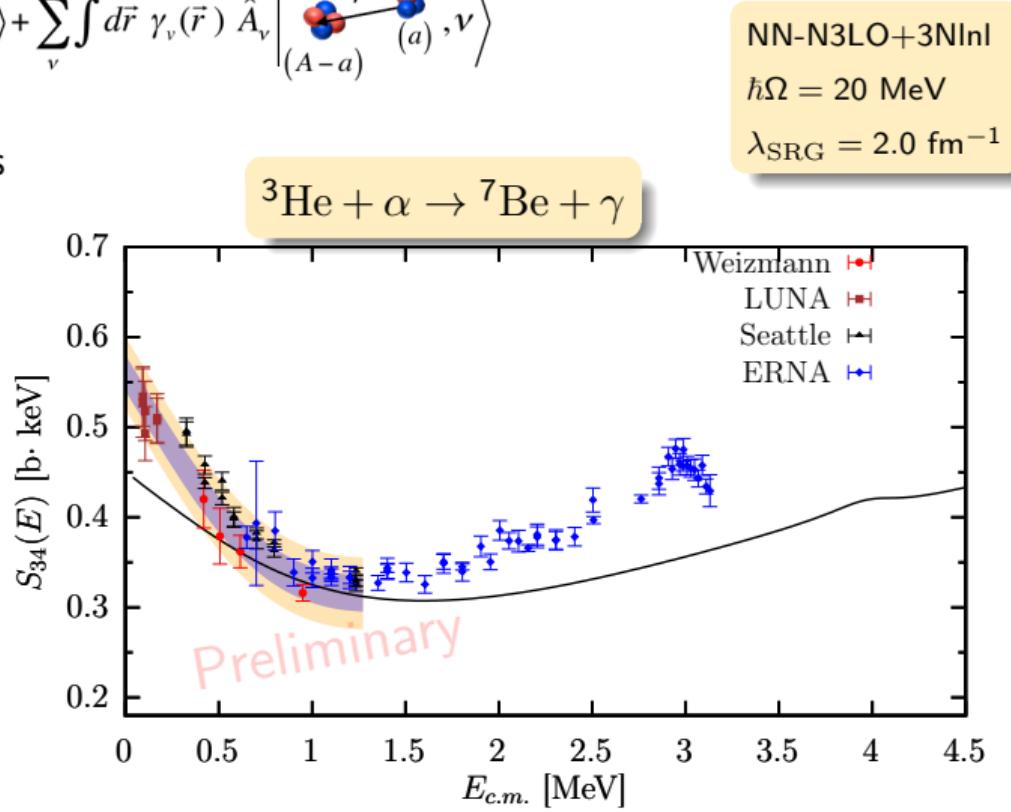
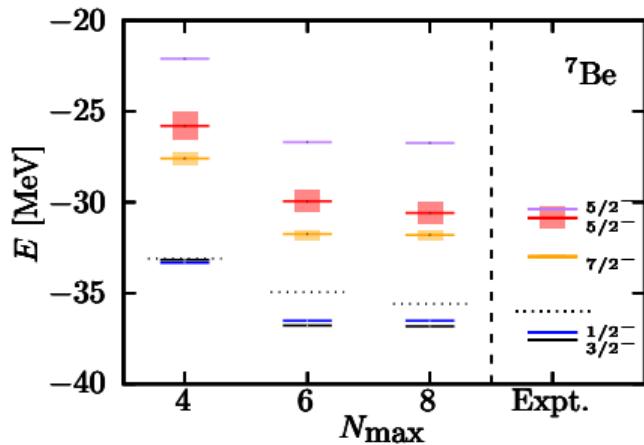
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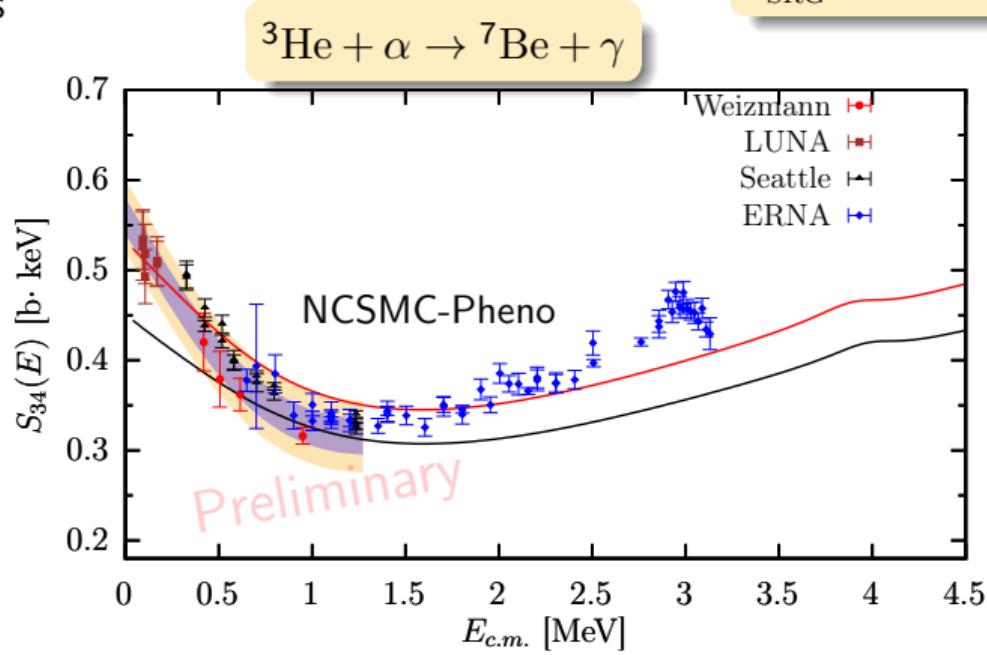
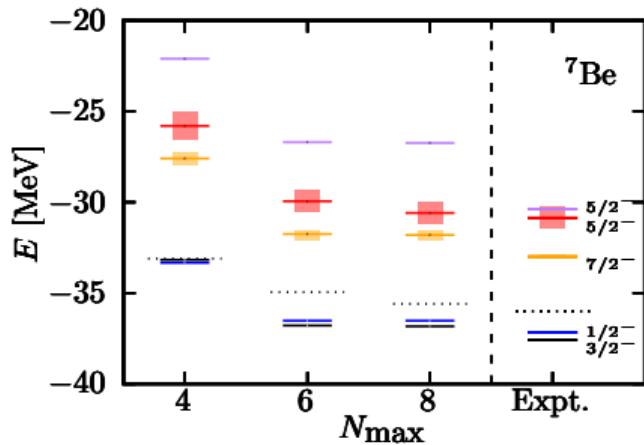
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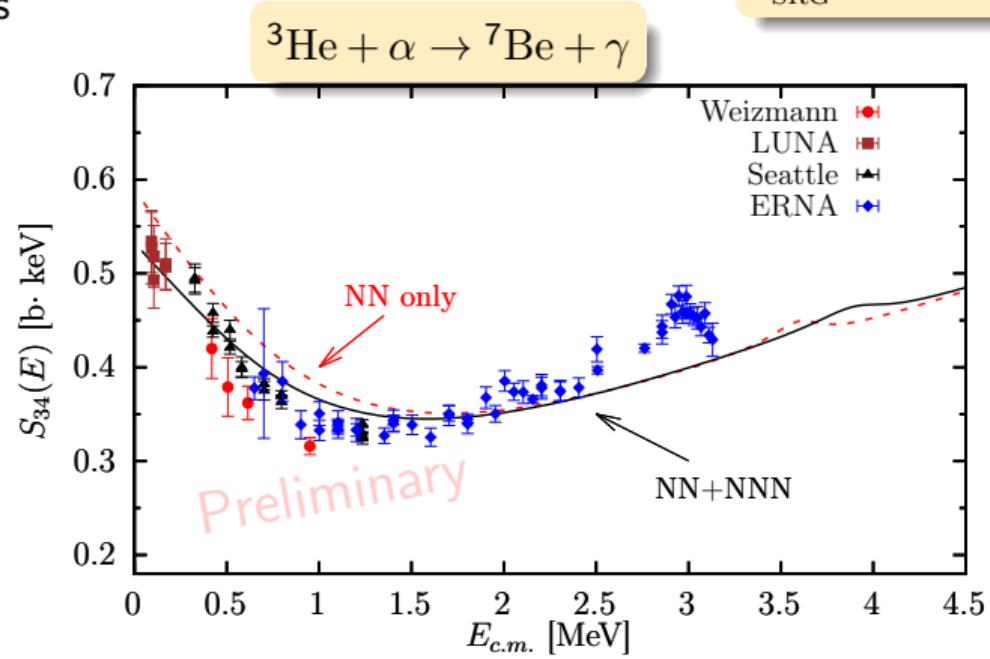
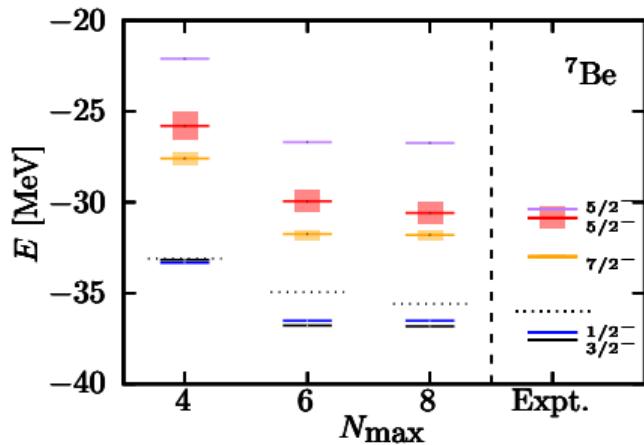
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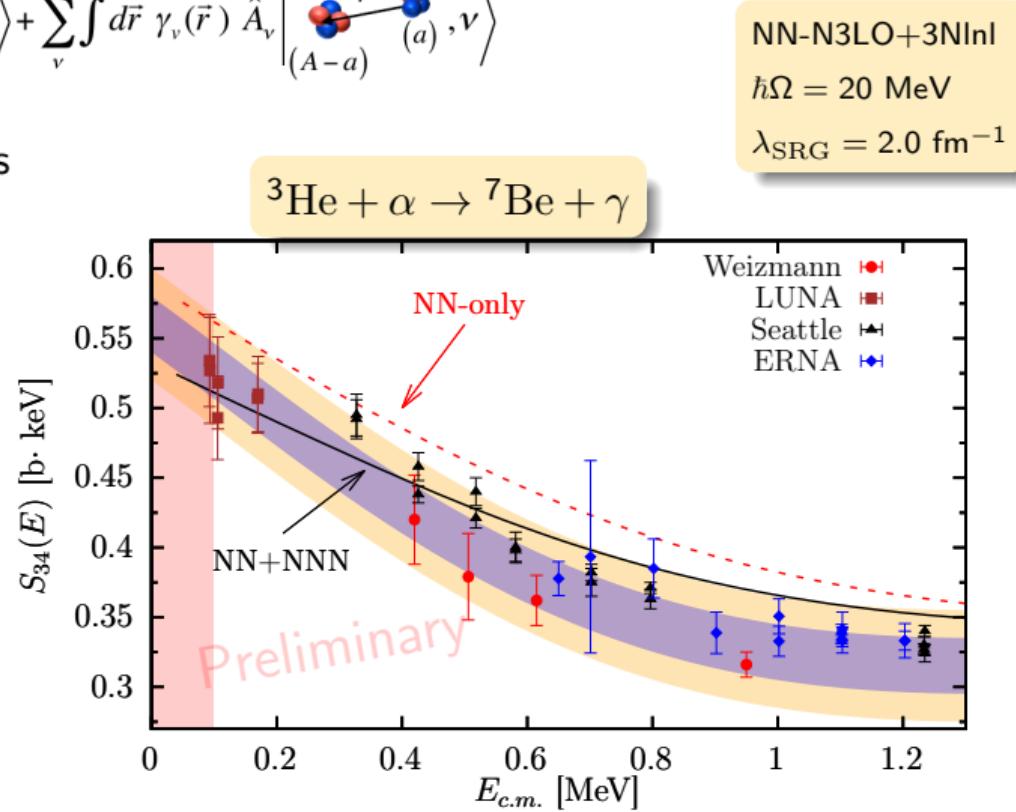
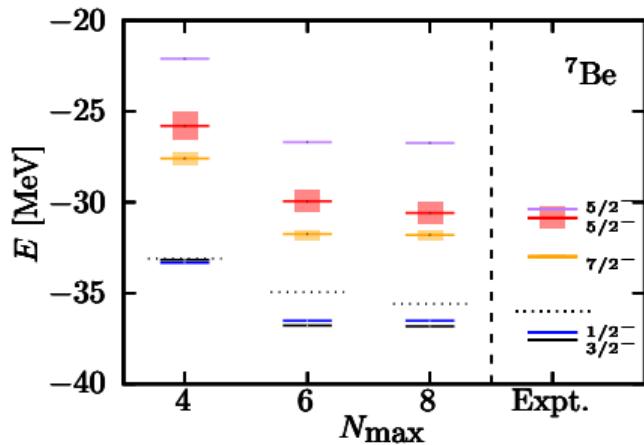
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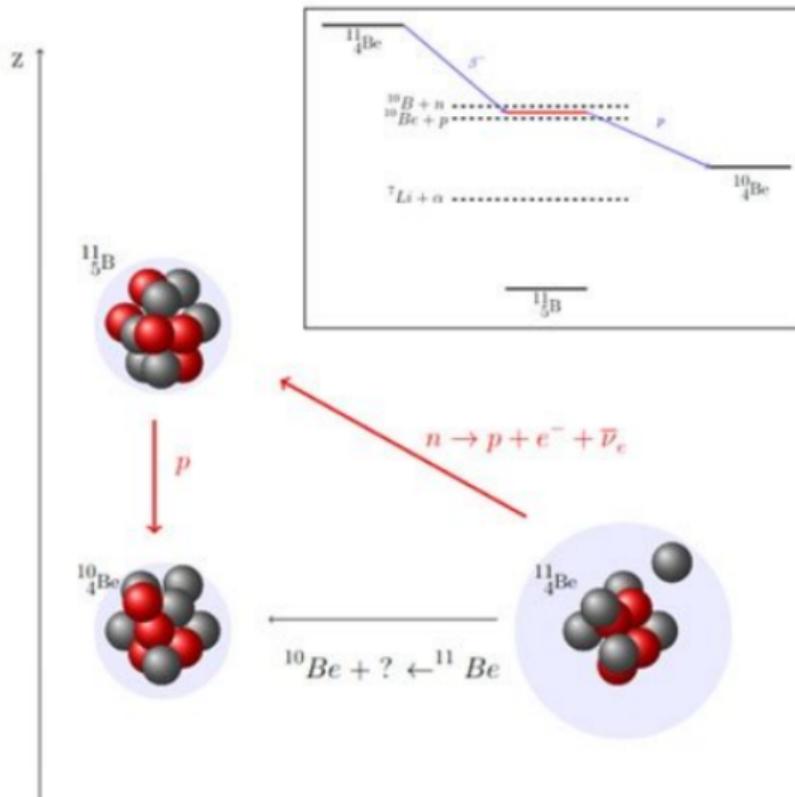
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Now for  $^{11}\text{Be}$

# Beta-delayed proton emission in $^{11}\text{Be}$





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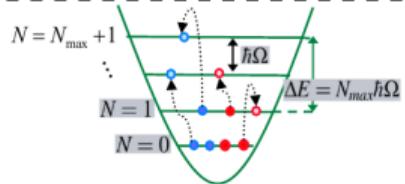
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  - Still orders of magnitude larger than theoretical predictions
- Predict the  $(\frac{1}{2}^+, \frac{1}{2})$  proton resonance at 197 keV from the proton energy distribution

# NCSMC calculation of $^{11}\text{Be}$ and $^{11}\text{B}$



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

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

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

NCSM

NCSMC

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} |(A) \text{ nuclei}, \lambda\rangle + \sum_v \int d\vec{r} \gamma_v(\vec{r}) \hat{A}_v |(A-a), \vec{r}, (a), v\rangle$$

$$|^{11}\text{B}\rangle$$

$$|p\rangle \otimes |^{10}\text{Be}\rangle$$

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

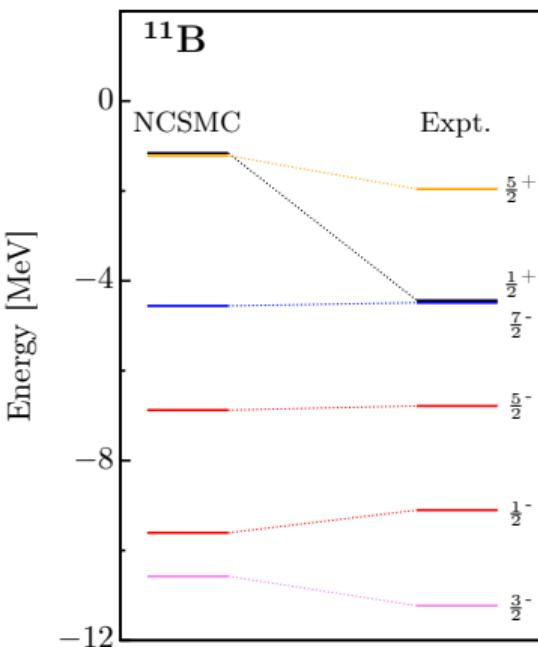


# NCSMC Calculation of $^{11}\text{B}$ and $^{11}\text{Be}$

NN-N4LO(500)+3Nlnl

$\hbar\Omega = 18 \text{ MeV}$ ,  $N_{\max} = 7$

$\lambda_{\text{SRG}} = 1.8 \text{ fm}^{-1}$



P. Navratil, *Few-Body Systems* **41**, 117 (2007)

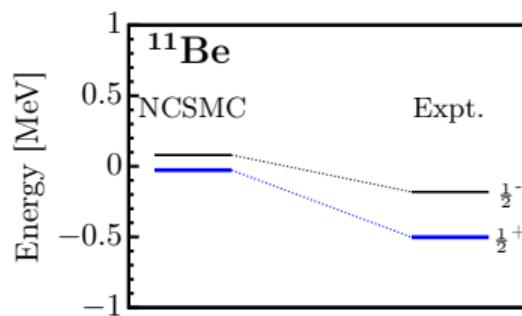
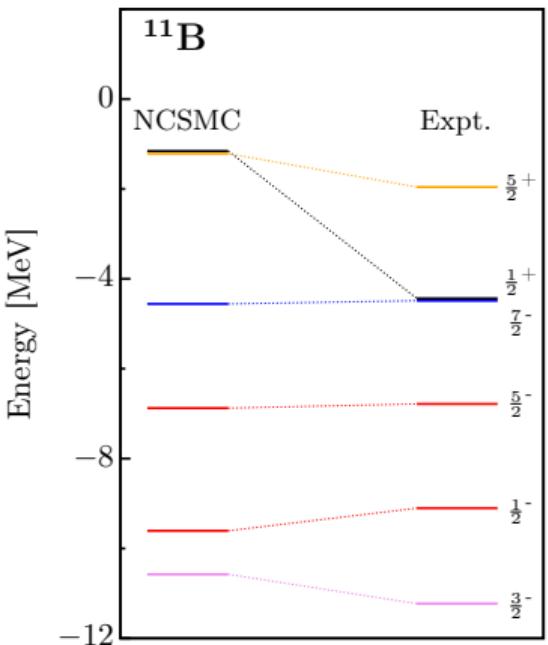
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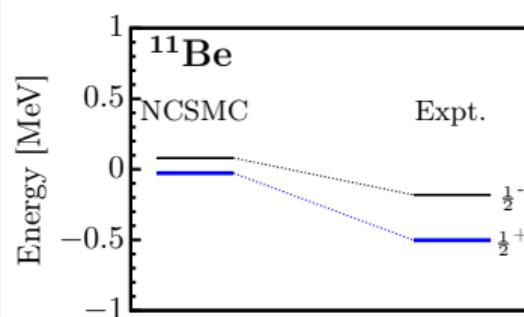
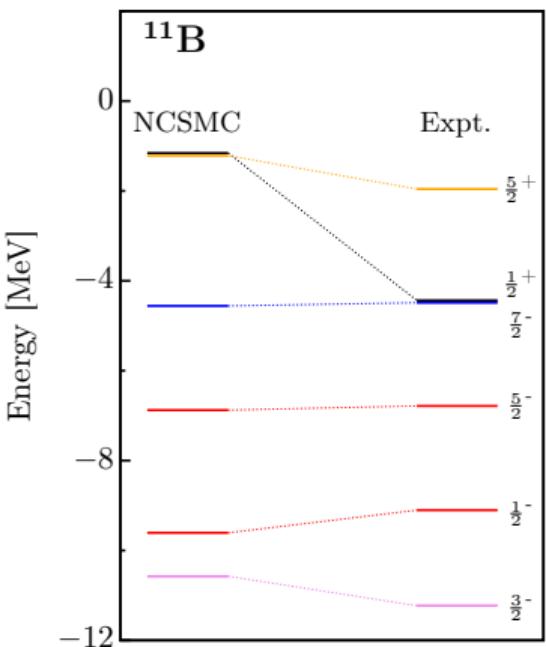
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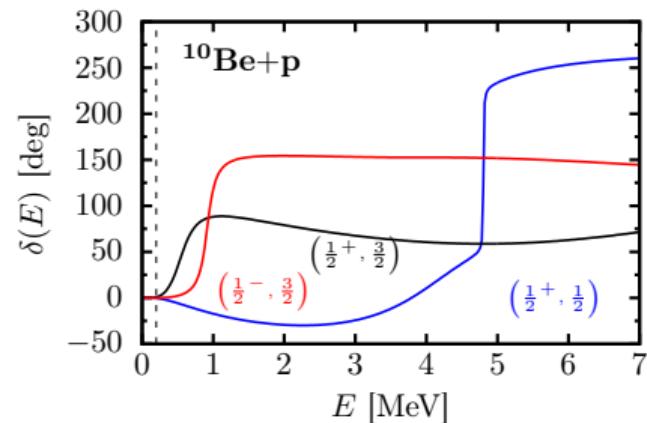
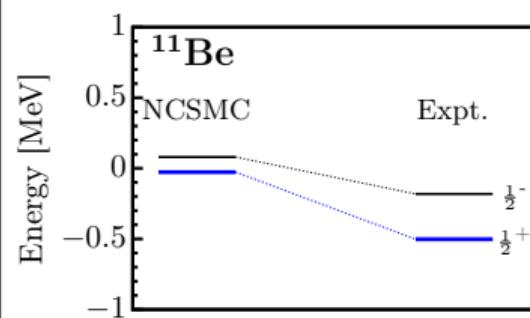
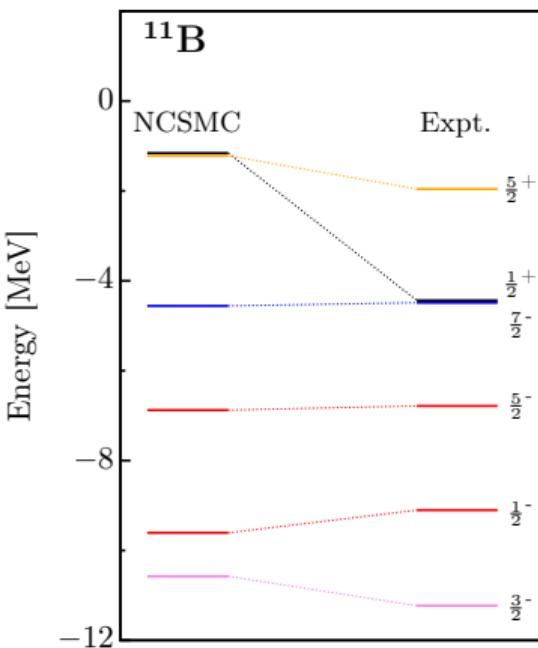
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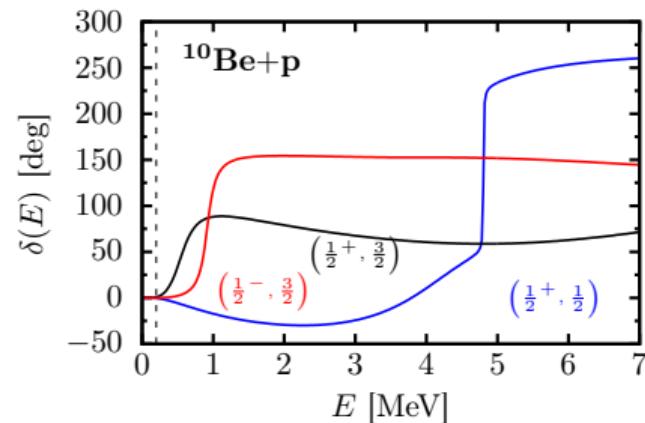
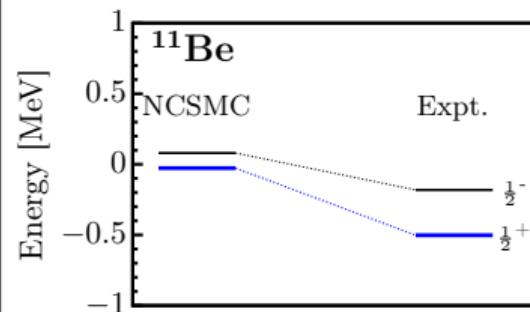
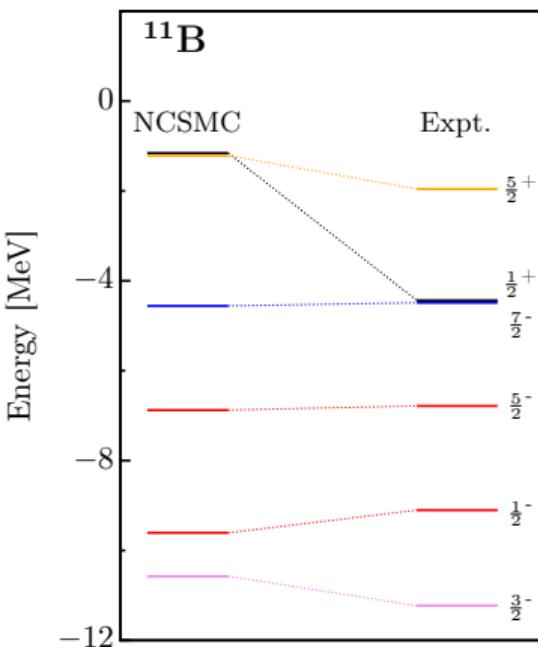
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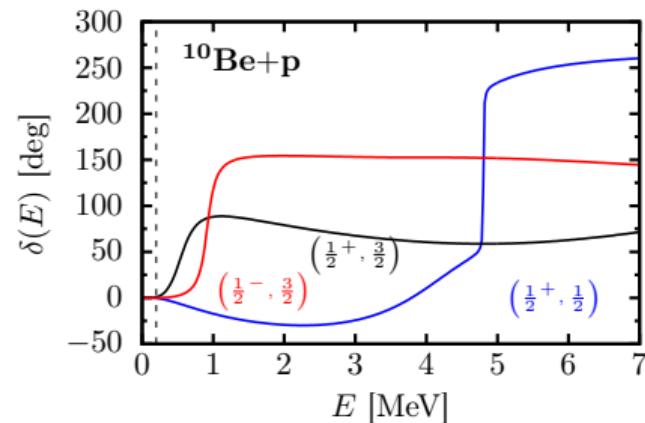
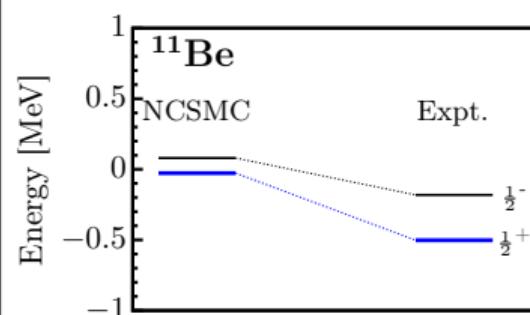
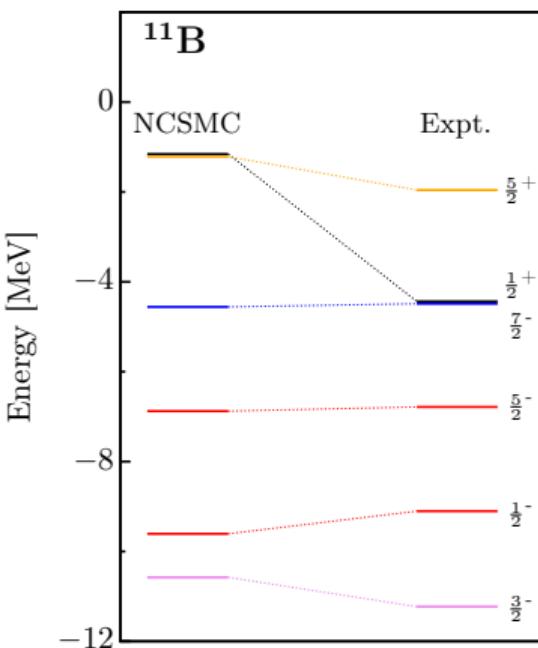
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- Phenomenologically shift levels to calculate  $\beta$ -decay



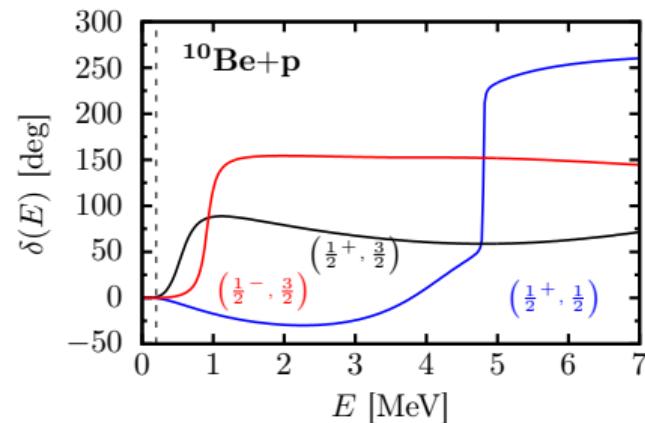
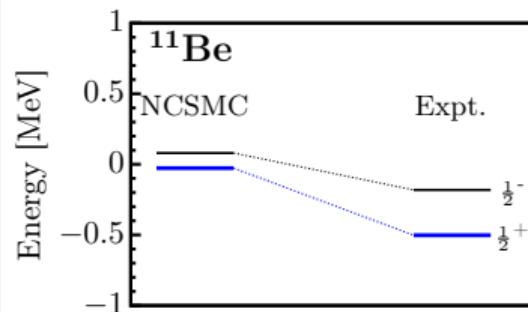
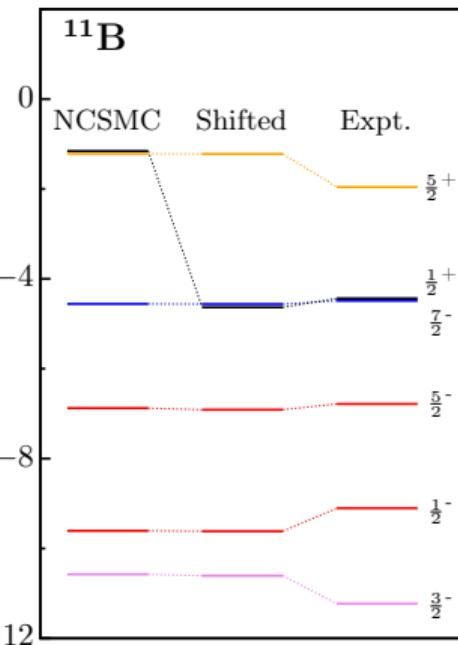
# NCSMC Calculation of $^{11}\text{B}$ and $^{11}\text{Be}$

NN-N4LO(500)+3Nlnl

$\hbar\Omega = 18 \text{ MeV}$ ,  $N_{\max} = 7$

$\lambda_{\text{SRG}} = 1.8 \text{ fm}^{-1}$

- Parity inversion reproduced
- Resonance found, but not at expt. energy
- Phenomenologically shift levels to calculate  $\beta$ -decay



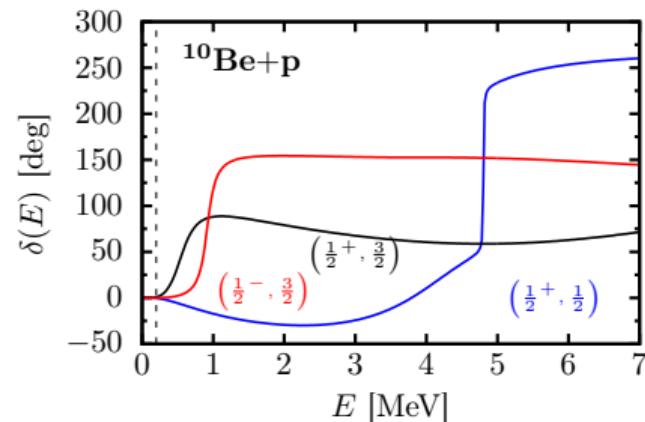
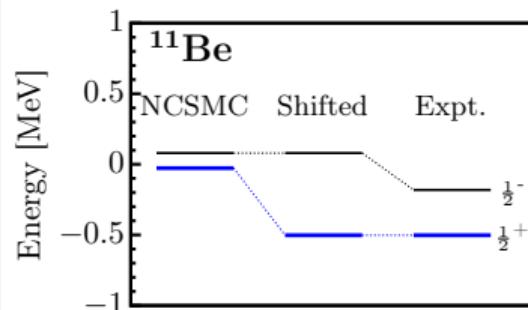
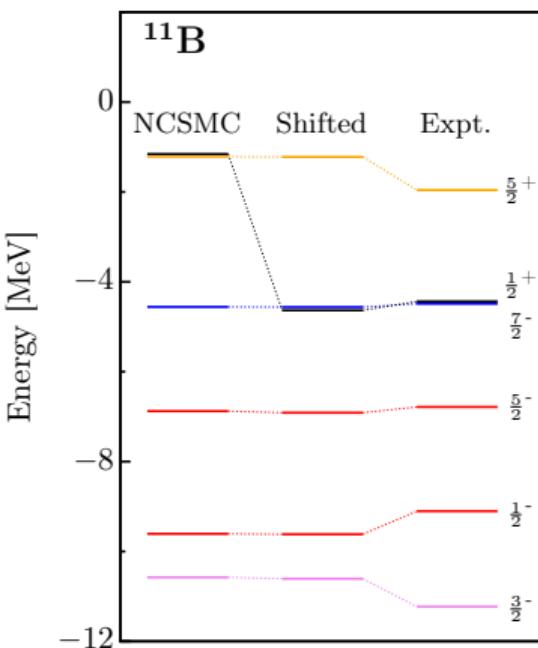
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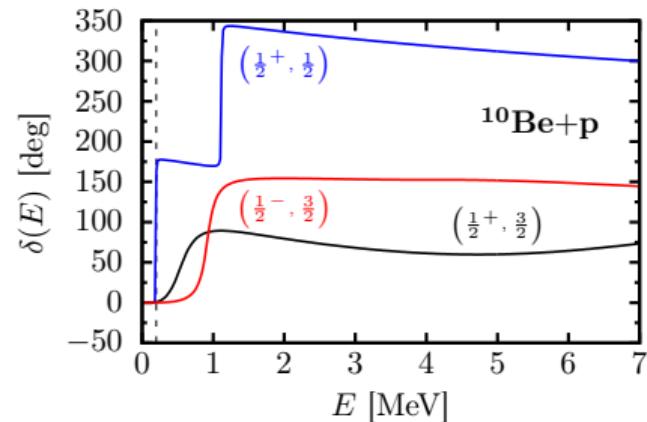
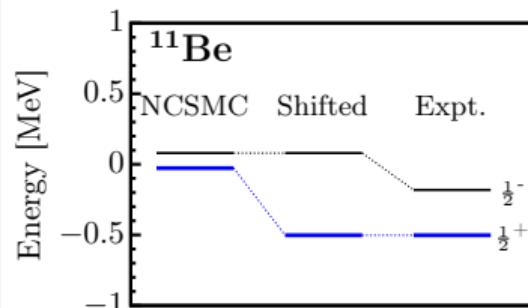
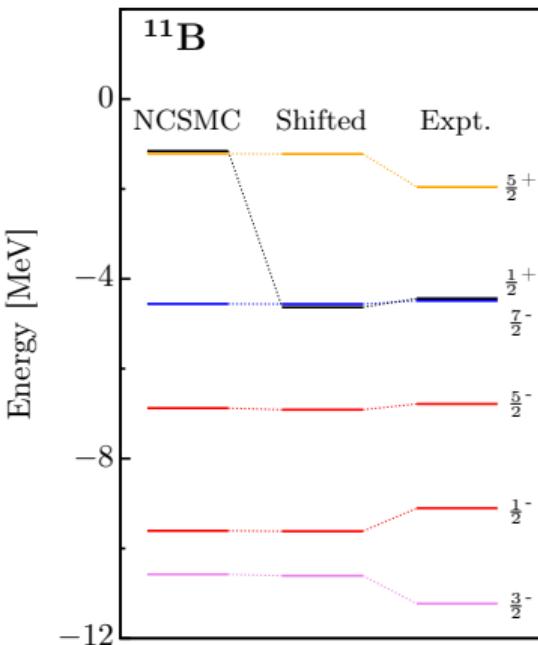
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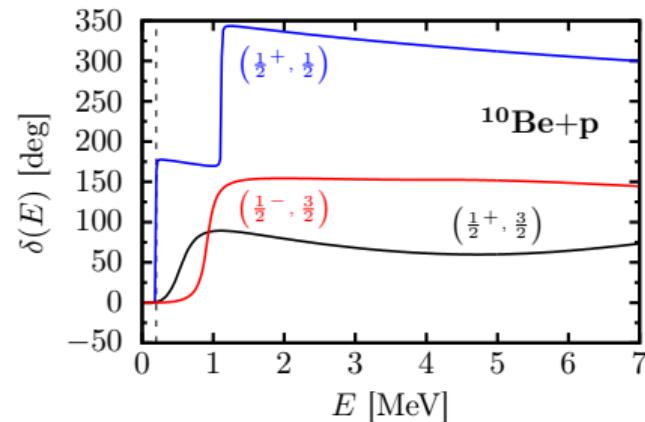
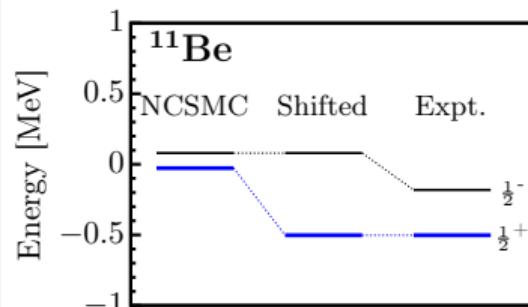
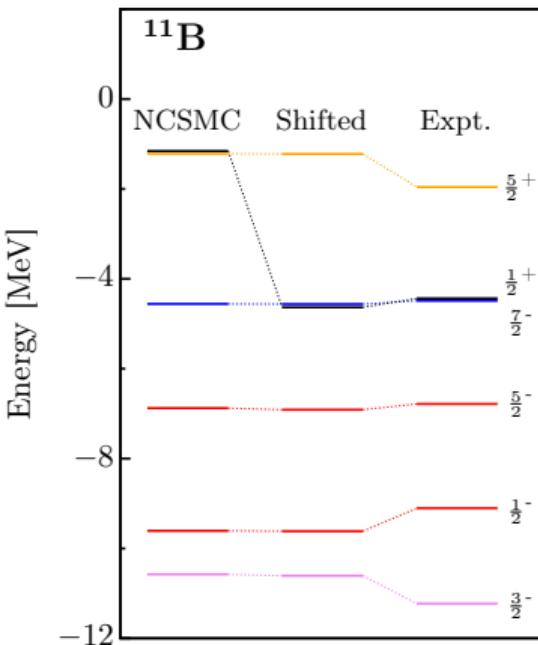
# NCSMC Calculation of $^{11}\text{B}$ and $^{11}\text{Be}$

NN-N4LO(500)+3Nlnl

$\hbar\Omega = 18 \text{ MeV}$ ,  $N_{\max} = 7$

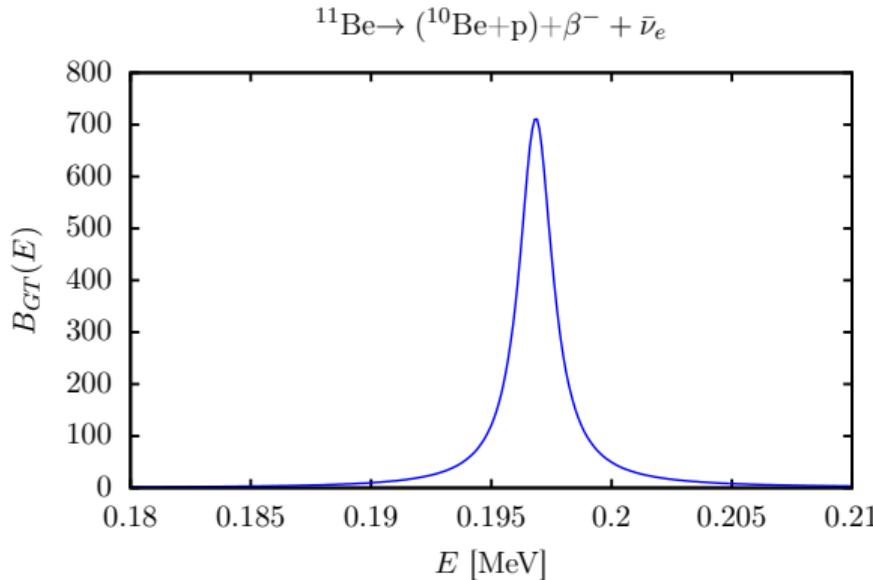
$\lambda_{\text{SRG}} = 1.8 \text{ fm}^{-1}$

- Parity inversion reproduced
- Resonance found, but not at expt. energy
- Phenomenologically shift levels to calculate  $\beta$ -decay

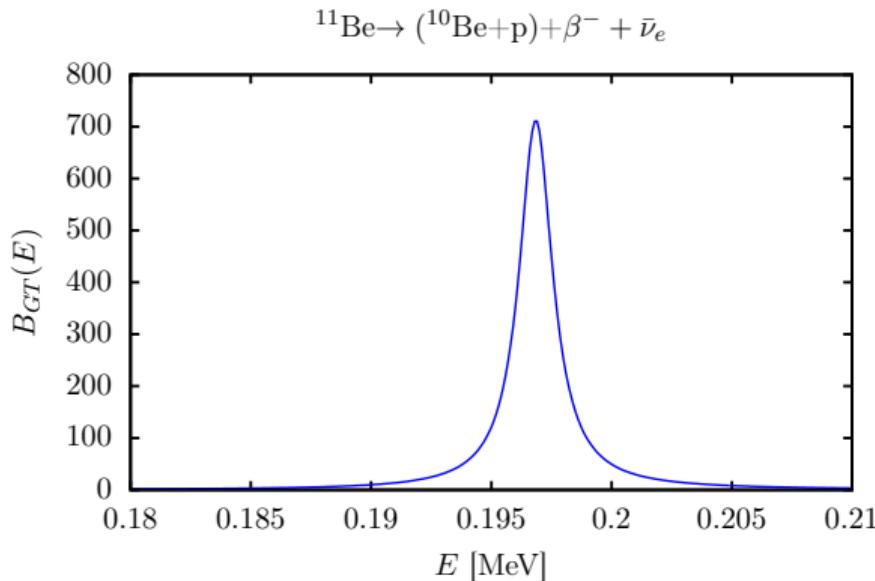


	NCSMC-shifted	Expt.
$E$ [keV]	197	197(20)
$\Gamma$ [keV]	10	12(5)

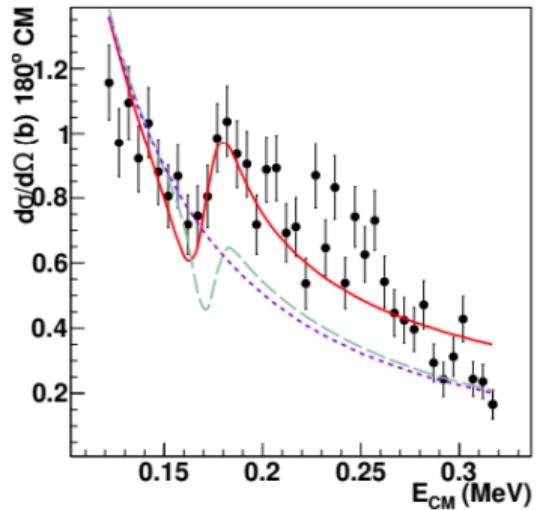
# $\beta$ -Decay to Resonant State



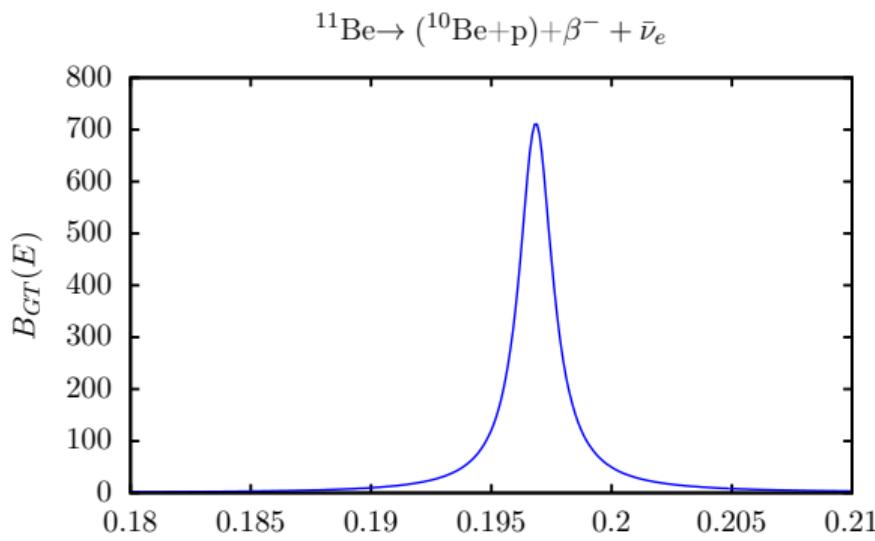
# $\beta$ -Decay to Resonant State



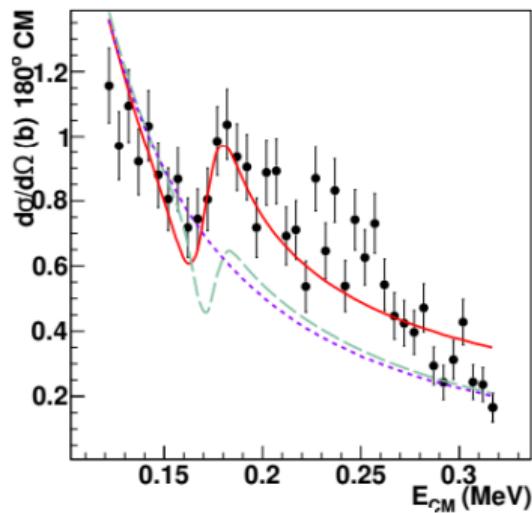
Ayyad *et al.*, PRL **129** 012501 (2022)



# $\beta$ -Decay to Resonant State



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



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

## Conclusions and Outlook

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

# Thanks!



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