Ab initio calculation of the ^{3}He$(\alpha,\gamma)^7$Be astrophysical S factor

Mack C. Atkinson

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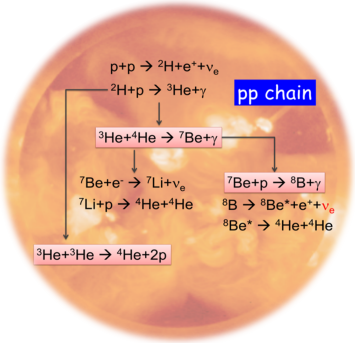
$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ important for solar-model predictions



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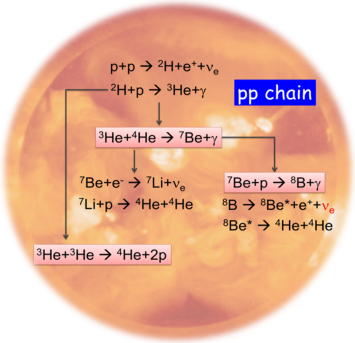

$$\sigma(E) = \frac{S_{34}(E)}{E}\exp\left\{-\frac{2\pi Z_1 Z_2 e^2}{\hbar\sqrt{2E/m}}\right\}$$

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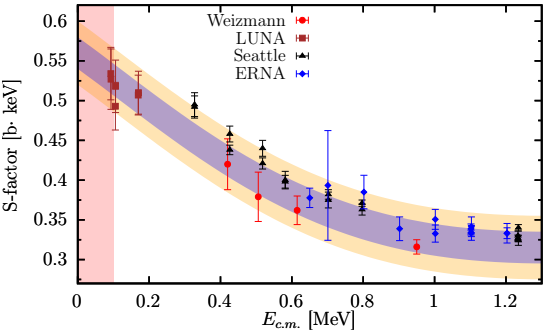

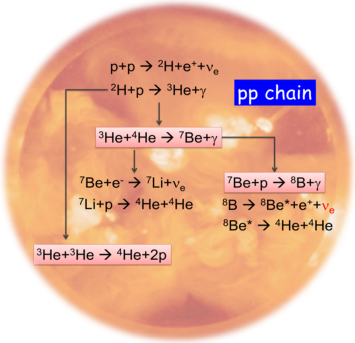

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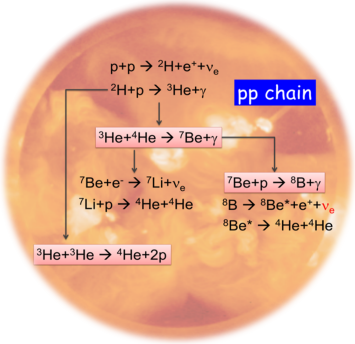
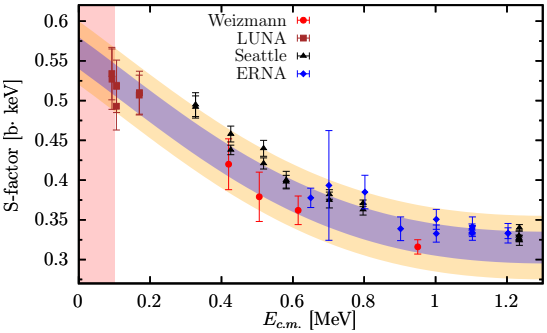
- Reaction rates too low at solar energies in the lab





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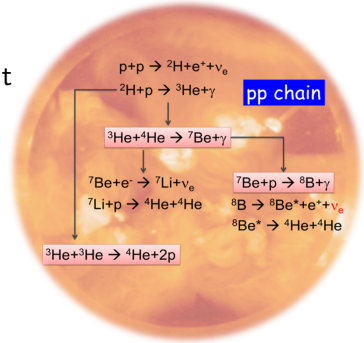
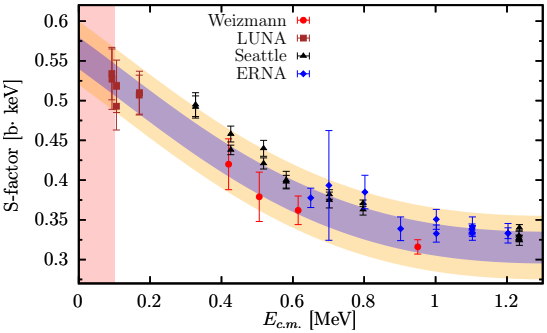
- Current evaluations depend on both theory and experiment





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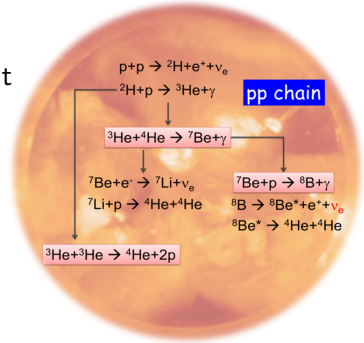
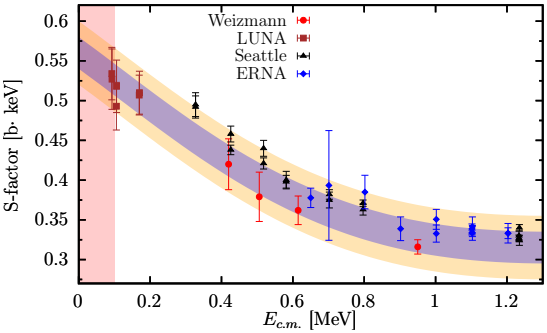
$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ important for solar-model predictions

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





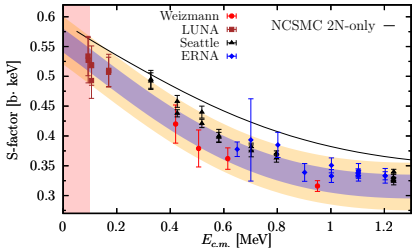
$$\sigma(E) = \frac{S_{34}(E)}{E}\exp\left\{-\frac{2\pi Z_1 Z_2 e^2}{\hbar\sqrt{2E/m}}\right\}$$

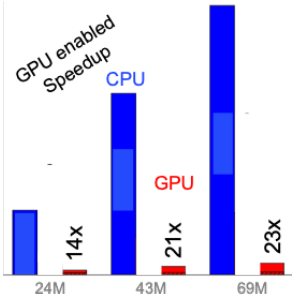
Goal: Reduce the theoretical uncertainty in the determination of $S_{34}(0)$

Current evaluation:

$$S_{34}(0) = 0.56 \pm 0.02(\text{expt.}) \pm \mathbf{0.02(theor.)}$$

- **How?**: Perform an *ab initio* calculation of the $^3\text{He}(\alpha,\gamma)^7\text{Be}$ reaction
  - Previously only possible using 2N forces





- I present the first *ab initio* calculation of $^3\text{He}(\alpha,\gamma)^7\text{Be}$ including 3N forces

No-Core shell model (NCSM)

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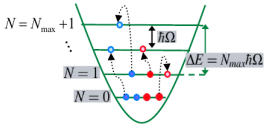
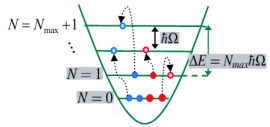


A

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

No-Core shell model (NCSM)



- Construct the Hamiltonian from χ_{EFT}

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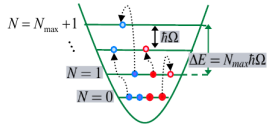

- Construct the Hamiltonian from χ_{EFT}

$$\hat{H} = \hat{T} + \hat{V}_{2N} + \hat{V}_{3N}$$

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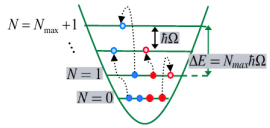

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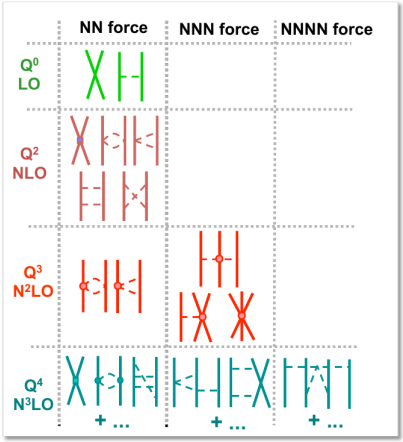

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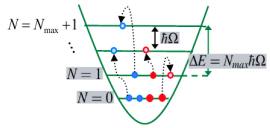

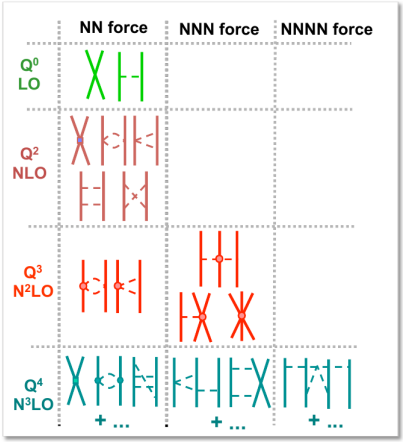

- Construct the Hamiltonian from χ_{EFT}

$$\hat{H} = \hat{T} + \hat{V}_{2N} + \hat{V}_{3N}$$

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

No-core shell model with continuum (NCSMC)

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

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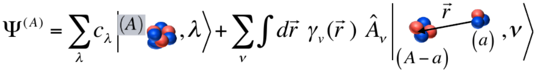
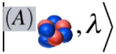
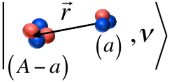
$$\left| {}^{(A)}\!\!\;, \lambda \right\rangle = |^7\mathrm{Be}\rangle$$





$= |{}^7\mathrm{Be}\rangle$



$\rightarrow |\alpha\rangle \otimes |{}^3\mathrm{He}\rangle$

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$$\left| {}_{(A-a)}\ \vec{r}\ {}_{(a)}, \nu \right\rangle \rightarrow |\alpha\rangle \otimes |{}^{3}\mathrm{He}\rangle$$

- $|{}^{7}\mathrm{Be}\rangle$, $|{}^{3}\mathrm{He}\rangle$, and $|\alpha\rangle$ from NCSM

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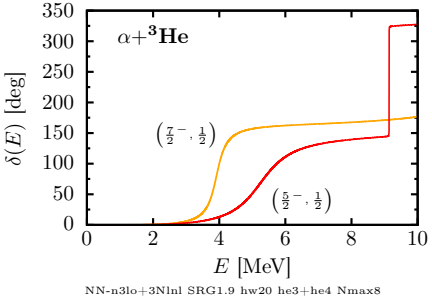
- $|{}^{7}\mathrm{Be}\rangle$, $|{}^{3}\mathrm{He}\rangle$, and $|\alpha\rangle$ from NCSM

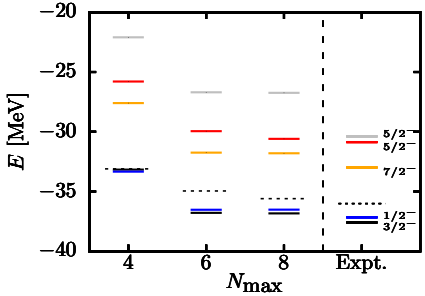
$$\begin{pmatrix} H_{NCSM} & h \\ h & H_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix} = E \begin{pmatrix} 1_{NCSM} & g \\ g & N_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix}$$

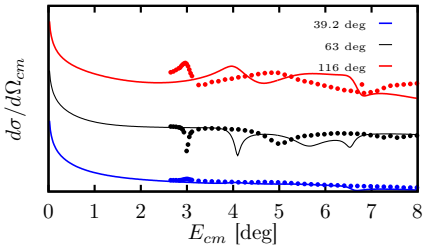
$E_{\lambda}^{NCSM}\ \delta_{\lambda\lambda'}$ — $\left\langle {}^{(A)} \left| H \hat{A}_{\nu} \right| {}_{(a)}\ r\ {}_{(A-a)} \right\rangle$ — $\delta_{\lambda\lambda'}$ — $\left\langle {}^{(A)} \left| \hat{A}_{\nu} \right| {}_{(a)}\ r\ {}_{(A-a)} \right\rangle$

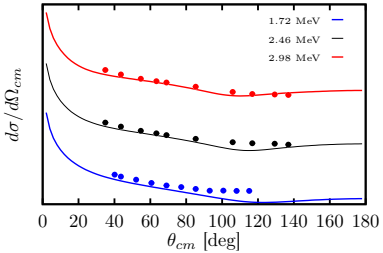
$\left\langle {}_{(A-a)}\ r'\ {}_{(a)} \left| \hat{A}_{\nu'} H \hat{A}_{\nu} \right| {}_{(a)}\ r\ {}_{(A-a)} \right\rangle$ — $\left\langle {}_{(A-a)}\ r'\ {}_{(a)} \left| \hat{A}_{\nu'} \hat{A}_{\nu} \right| {}_{(a)}\ r\ {}_{(A-a)} \right\rangle$

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







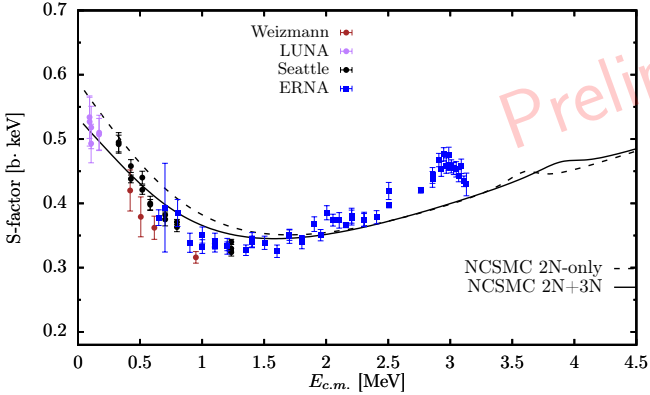


NN-N3LO+3Nlnl

$\hbar\Omega = 20$ MeV

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

Results are promising but convergence needs to be explored



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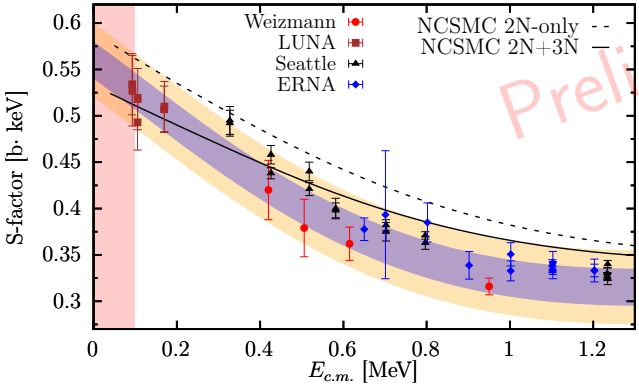

Summary and Outlook

- Included 3N forces in the calculation of 4He+3He using the boost formalism
- Results are promising but convergence needs to be explored

Thanks

- Sofia Quaglioni
- Kostas Kravvaris
- Petr Navratil
- Guillame Hupin