What's missing? An investigation of $^{3}\text{He}(\alpha, \gamma)^{7}\text{Be}$ radiative capture

Mack C. Atkinson

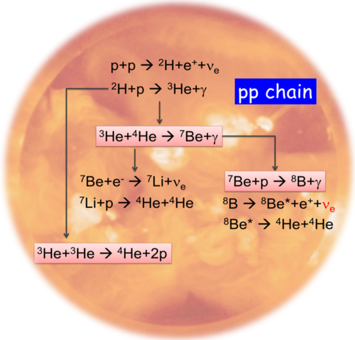
KITP, Santa Barbara

LLNL-PRES-845410

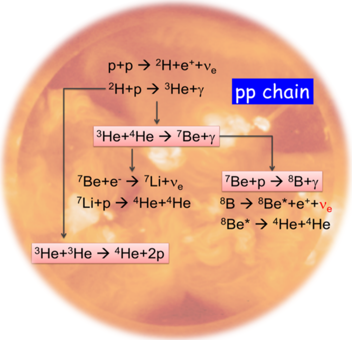
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

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

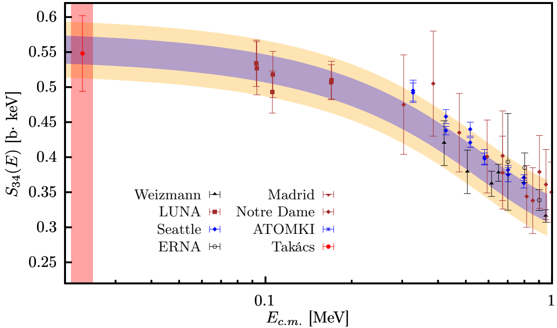


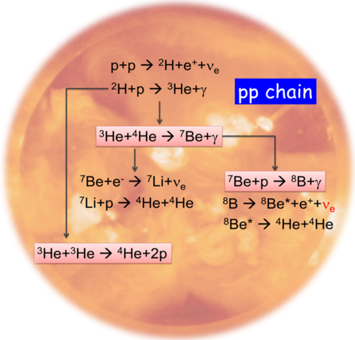
$^3He(\alpha,\gamma)^7Be$ important for solar-model predictions



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

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



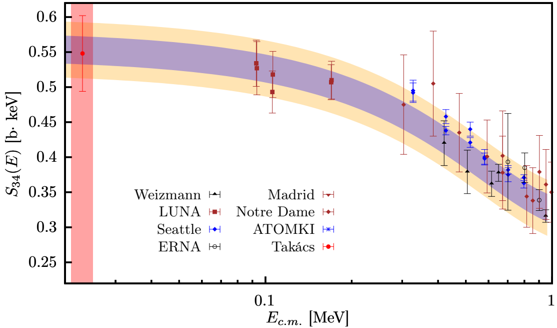


$$\sigma(E) = \frac{S_{34}(E)}{E}\exp\left\{-\frac{2\pi Z_1 Z_2 e^2}{\hbar\sqrt{2E/m}}\right\}$$

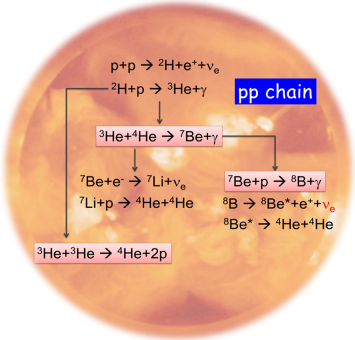
Adelberger *et al.*, Rev Mod Phys **83** 195 (2011)

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

- Reaction rates too low at solar energies in the lab



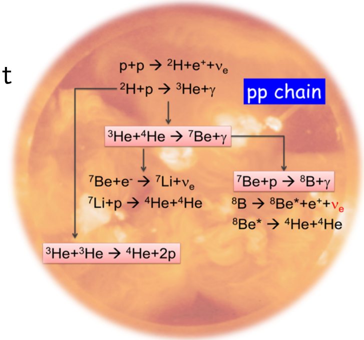
Adelberger *et al.*, Rev Mod Phys **83** 195 (2011)

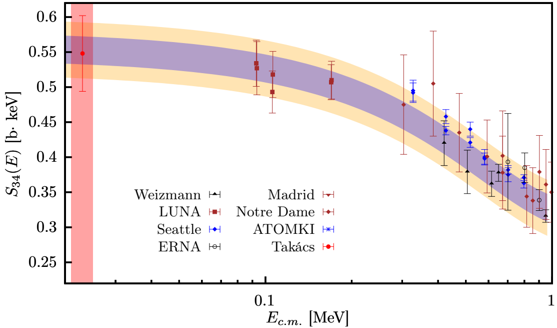


$$\sigma(E) = \frac{S_{34}(E)}{E}\exp\left\{-\frac{2\pi Z_1 Z_2 e^2}{\hbar\sqrt{2E/m}}\right\}$$

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

- Reaction rates too low at solar energies in the lab
- Current evaluations depend on both theory and experiment



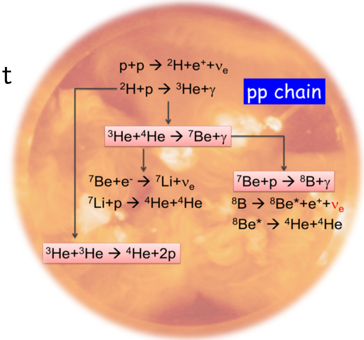


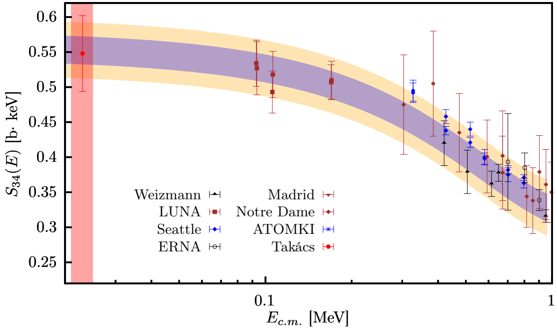
$$\sigma(E) = \frac{S_{34}(E)}{E} \exp\left\{-\frac{2\pi Z_1 Z_2 e^2}{\hbar\sqrt{2E/m}}\right\}$$

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

$^3He(\alpha,\gamma)^7Be$ 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 $S_{34}(E)$





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

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

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

Current evaluation:

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

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

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

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

Current evaluation:

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

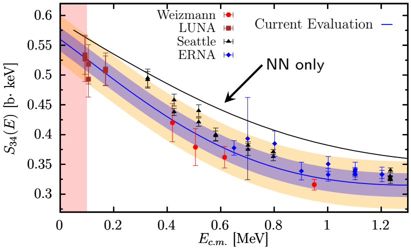
- **How?**: Perform an *ab initio* calculation of the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ reaction
  - Previously only possible using NN forces

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

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 NN forces

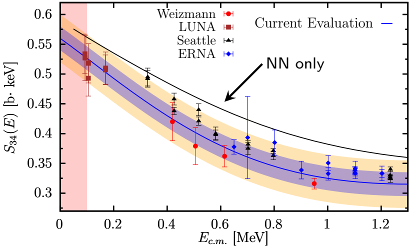


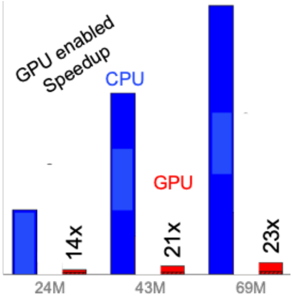
Goal: Improve the theoretical prediction of $S_{34}(E)$

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 NN forces



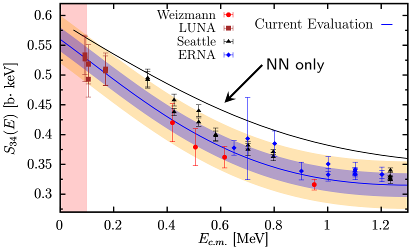


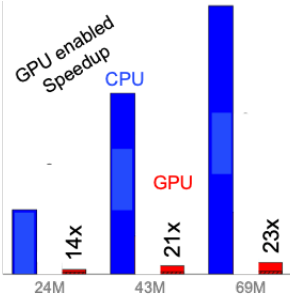
Goal: Improve the theoretical prediction of $S_{34}(E)$

Current evaluation:

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

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





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

Ab initio reaction theory needed for capture calculations

- Calculate EM transitions from ^{3}He$+\alpha$ scattering state to ^{7}Be bound state

Ab initio reaction theory needed for capture calculations

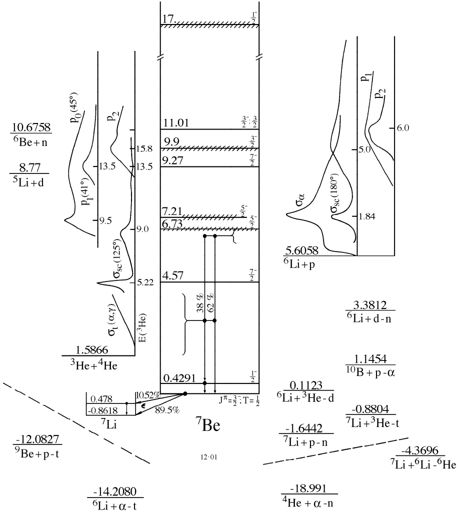
- Calculate EM transitions from ^{3}He+α scattering state to ^{7}Be bound state

$$\left\langle \Psi_{bs}\left({}^{7}\mathrm{Be}\right) \middle| \hat{\mathcal{M}}_{\mathrm{EM}} \middle| \Psi_{sc}\left({}^{3}\mathrm{He}+\alpha\right) \right\rangle$$

Ab initio reaction theory needed for capture calculations

- Calculate EM transitions from $^3\mathrm{He}+\alpha$ scattering state to $^7\mathrm{Be}$ bound state
  - Only $E1$, $E2$, and $M1$ transitions

$$\left\langle \Psi_{bs}\left(^7\mathrm{Be}\right) \middle| \hat{\mathcal{M}}_{\mathrm{EM}} \middle| \Psi_{sc}\left(^3\mathrm{He}+\alpha\right) \right\rangle$$

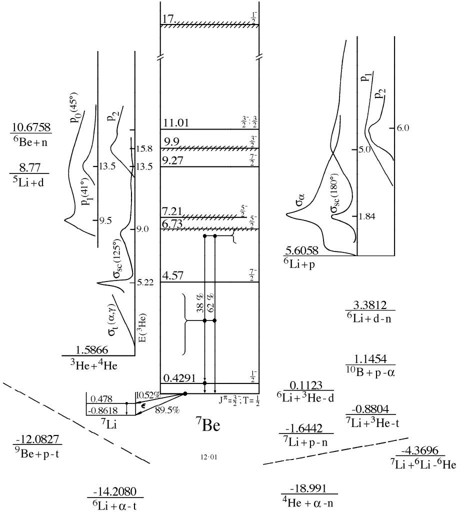


Ab initio reaction theory needed for capture calculations

- Calculate EM transitions from ^{3}He+α scattering state to ^{7}Be bound state
  - Only $E1$, $E2$, and $M1$ transitions

$$\left\langle \Psi_{bs}\left(^{7}\mathrm{Be}\right) \middle| \hat{\mathcal{M}}_{\mathrm{EM}} \middle| \Psi_{sc}\left(^{3}\mathrm{He}+\alpha\right) \right\rangle$$

- Need a method to calculate ψ_{sc} and ψ_{bs} simultaneously

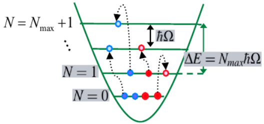


The *ab initio* method: from NCSM to NCSMC

$$\left\langle \Psi_{bs}\left({}^{7}\mathrm{Be}\right) \middle| \hat{\mathcal{M}}_{\mathrm{EM}} \middle| \Psi_{sc}\left({}^{3}\mathrm{He}+\alpha\right) \right\rangle$$

$$\left\langle \Psi_{bs}\left({}^{7}\mathrm{Be}\right) \middle| \hat{\mathcal{M}}_{\mathrm{EM}} \middle| \Psi_{sc}\left({}^{3}\mathrm{He}+\alpha\right) \right\rangle$$

?

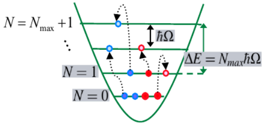


A

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

$$\left\langle \Psi_{bs}\left({}^7\mathrm{Be}\right) \middle| \hat{\mathcal{M}}_{\mathrm{EM}} \middle| \Psi_{sc}\left({}^3\mathrm{He} + \alpha\right) \right\rangle$$

?



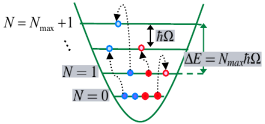
$$\Psi^A = \sum_{N=0}^{N_{\max}} \sum_i c_{Ni} \Phi_{Ni}^A$$

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

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

$$\left\langle \Psi_{bs}\left({}^7\mathrm{Be}\right) \middle| \hat{\mathcal{M}}_{\mathrm{EM}} \middle| \Psi_{sc}\left({}^3\mathrm{He} + \alpha\right) \right\rangle$$

?



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

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

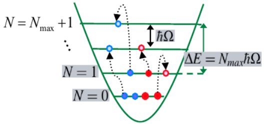
$$\hat{H} \left|\Psi^A\right\rangle = E \left|\Psi^A\right\rangle$$

NCSM

$$\left\langle \Psi_{bs}\left({}^7\mathrm{Be}\right) \middle| \hat{\mathcal{M}}_{\mathrm{EM}} \middle| \Psi_{sc}\left({}^3\mathrm{He} + \alpha\right) \right\rangle$$

?

The *ab initio* method: from NCSM to NCSMC



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

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

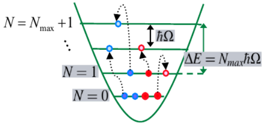
$$\hat{H} \left|\Psi^{A}\right\rangle = E \left|\Psi^{A}\right\rangle$$

NCSM

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

$$\left\langle \Psi_{bs}\left({}^{7}\mathrm{Be}\right) \middle| \hat{\mathcal{M}}_{\mathrm{EM}} \middle| \Psi_{sc}\left({}^{3}\mathrm{He} + \alpha\right) \right\rangle$$

?



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

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

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

NCSM

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

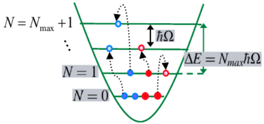
↑

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

$$\left\langle \Psi_{bs}\left(^7\mathrm{Be}\right) \middle| \hat{\mathcal{M}}_{\mathrm{EM}} \middle| \Psi_{sc}\left(^3\mathrm{He} + \alpha\right) \right\rangle$$

?

The *ab initio* method: from NCSM to NCSMC



A

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

$$\hat H = \hat T + \hat V_{NN} + \hat V_{NNN}$$

$$\hat H \left|\Psi^A\right\rangle = E \left|\Psi^A\right\rangle$$

NCSM

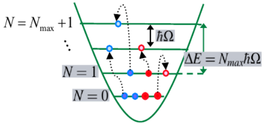
$$\Psi^{(A)} = \sum_\lambda c_\lambda \left| (A), \lambda \right\rangle + \sum_\nu \int d\vec r \; \gamma_\nu(\vec r) \; \hat A_\nu \left| (A-a) \; \vec r \; (a), \nu \right\rangle$$

$\uparrow$ $\left|{}^7\mathrm{Be}\right\rangle$

$\uparrow$ $\left|\alpha\right\rangle \otimes \left|{}^3\mathrm{He}\right\rangle$

$$\left\langle \Psi_{bs}\left({}^7\mathrm{Be}\right) \middle| \hat{\mathcal{M}}_{\mathrm{EM}} \middle| \Psi_{sc}\left({}^3\mathrm{He} + \alpha\right) \right\rangle$$

?



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

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

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

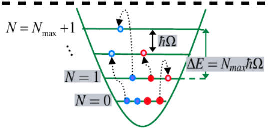
NCSM

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

$|^7\mathrm{Be}\rangle$ $\quad$ $|\alpha\rangle \otimes |^3\mathrm{He}\rangle$

$$\left\langle \Psi_{bs}\left(^7\mathrm{Be}\right) \middle| \hat{\mathcal{M}}_{\mathrm{EM}} \middle| \Psi_{sc}\left(^3\mathrm{He} + \alpha\right) \right\rangle$$

?



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

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

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

NCSM

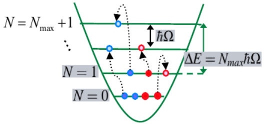
NCSMC

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

$$|{}^{7}\mathrm{Be}\rangle \qquad |\alpha\rangle \otimes |{}^{3}\mathrm{He}\rangle$$

$$\left\langle \Psi_{bs}\left({}^{7}\mathrm{Be}\right) \middle| \hat{\mathcal{M}}_{\mathrm{EM}} \middle| \Psi_{sc}\left({}^{3}\mathrm{He} + \alpha\right) \right\rangle$$

?



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

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

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

NCSM

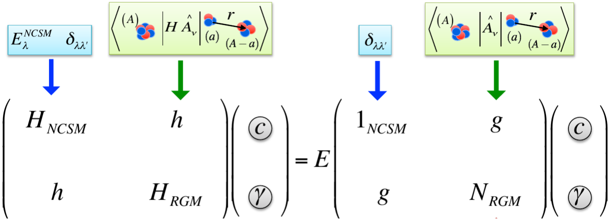
NCSMC

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

$\uparrow$ $\left|{}^{7}\mathrm{Be}\right\rangle$ $\qquad$ $\uparrow$ $\left|\alpha\right\rangle \otimes \left|{}^{3}\mathrm{He}\right\rangle$

$$\left\langle \Psi_{bs}\left({}^{7}\mathrm{Be}\right) \middle| \hat{\mathcal{M}}_{\mathrm{EM}} \middle| \Psi_{sc}\left({}^{3}\mathrm{He} + \alpha\right) \right\rangle$$

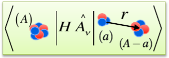
NCSMC Calculation of ^{3}He+^{4}He well-converged, levels need shifting



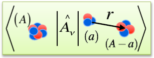
$$\begin{pmatrix} H_{NCSM} & h \\ h & H_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix} = E \begin{pmatrix} 1_{NCSM} & g \\ g & N_{RGM} \end{pmatrix} \begin{pmatrix} c \\ \gamma \end{pmatrix}$$

NCSMC Calculation of ^{3}He+^{4}He well-converged, levels need shifting

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



$\delta_{\lambda\lambda'}$

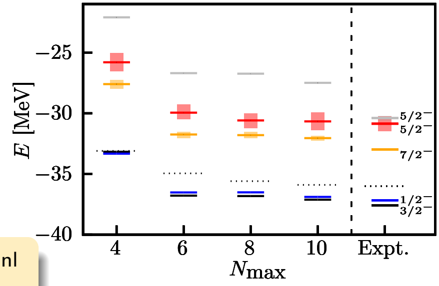


$$\begin{pmatrix} H_{NCSM} & h \\ h & H_{RGM} \end{pmatrix}\begin{pmatrix} c \\ \gamma \end{pmatrix} = E \begin{pmatrix} 1_{NCSM} & g \\ g & N_{RGM} \end{pmatrix}\begin{pmatrix} c \\ \gamma \end{pmatrix}$$

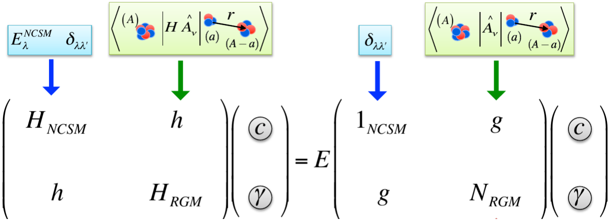
NN-N3LO+3NInl

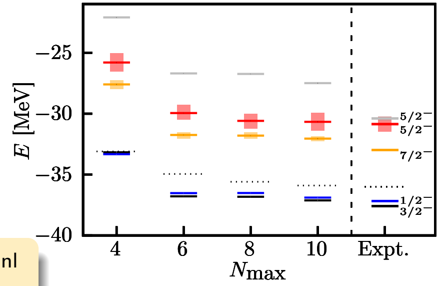
$\hbar\Omega = 20$ MeV

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



NCSMC Calculation of ^{3}He+^{4}He well-converged, levels need shifting





NN-N3LO+3NInl

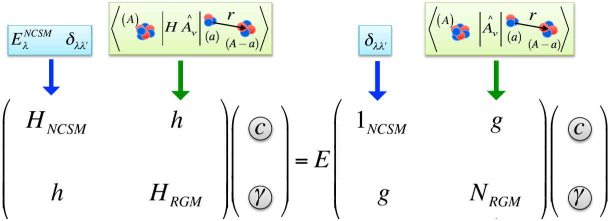
$\hbar\Omega = 20$ MeV

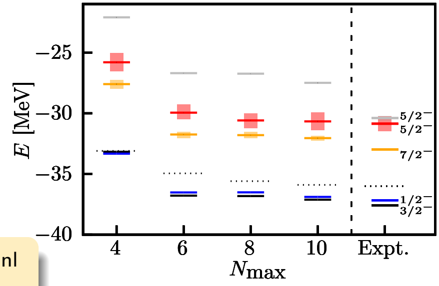
$\lambda_{\mathrm{SRG}} = 2.0$ fm^{-1}

- Capture rate accurate only if Expt. levels reproduced

$$E_{3/2^-} : -37.1\mathrm{MeV} \rightarrow -37.7\mathrm{MeV}$$
$$E_{1/2^-} : -36.9\mathrm{MeV} \rightarrow -37.2\mathrm{MeV}$$

NCSMC Calculation of ^{3}He+^{4}He well-converged, levels need shifting





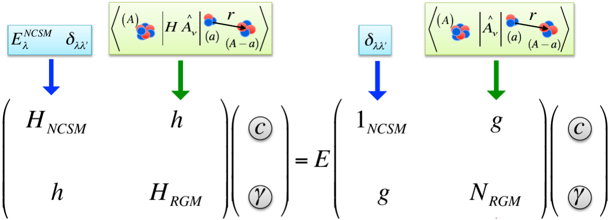
NN-N3LO+3NInl
$\hbar\Omega = 20$ MeV
$\lambda_{\rm SRG} = 2.0$ fm^{-1}

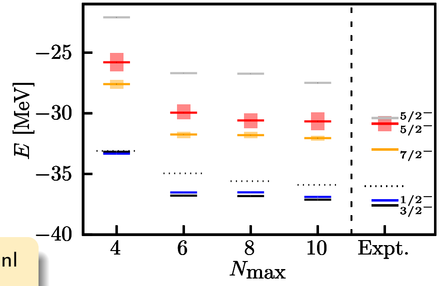
$E_\lambda^{NCSM} \rightarrow E_\lambda^{NCSM} + \epsilon$

- Capture rate accurate only if Expt. levels reproduced

$$E_{3/2^-} : -37.1\text{MeV} \rightarrow -37.7\text{MeV}$$
$$E_{1/2^-} : -36.9\text{MeV} \rightarrow -37.2\text{MeV}$$

NCSMC Calculation of ^{3}He+^{4}He well-converged, levels need shifting

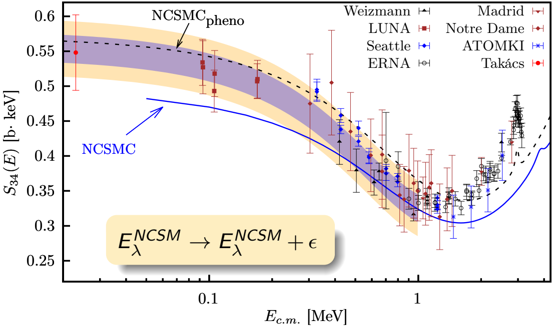




NN-N3LO+3NInl

$\hbar\Omega = 20$ MeV

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



$E_\lambda^{NCSM} \to E_\lambda^{NCSM} + \epsilon$

- Capture rate accurate only if Expt. levels reproduced

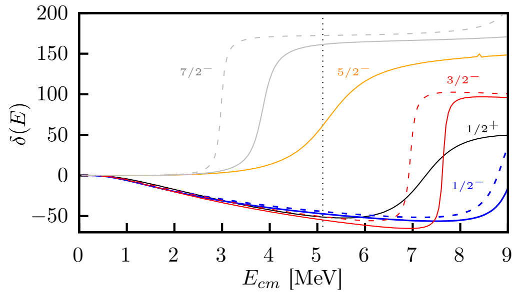
$$E_{3/2^-} : -37.1\text{MeV} \to -37.7\text{MeV}$$
$$E_{1/2^-} : -36.9\text{MeV} \to -37.2\text{MeV}$$

Minimal effect of phenomenological shift on scattering states

- Main impact of pheno is to alter ψ_{bs}

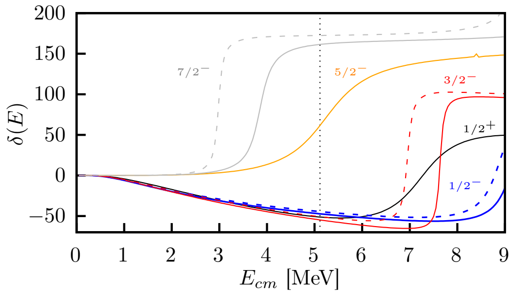
Minimal effect of phenomenological shift on scattering states

- Main impact of pheno is to alter ψ_{bs}
- Phase shifts at the relevant energies do not change



Minimal effect of phenomenological shift on scattering states

- Main impact of pheno is to alter ψ_{bs}
- Phase shifts at the relevant energies do not change
- The $3/2^-$ and $1/2^-$ scattering channels contribute minimally to $S_{34}(E)$
  - Dominated by the $E1$ transitions from $1/2^+$ scattering channel



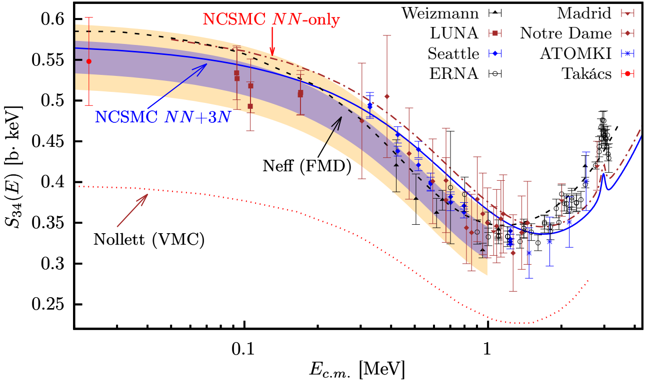
Comparing to other theoretical predictions of $S_{34}(E)$

- Inclusion of $3N$ force shows marked improvement over previous NN-only

NN-N3LO+3NInl

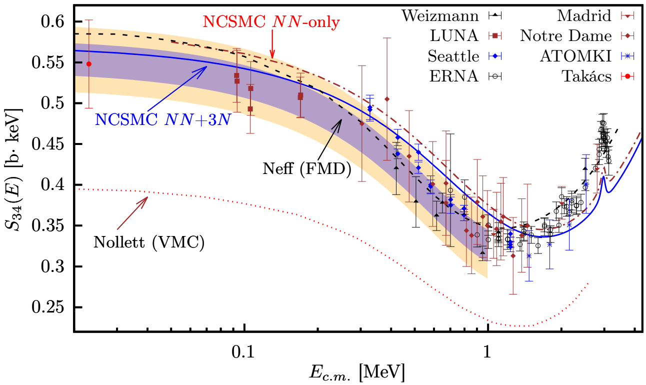
$\hbar\Omega = 20$ MeV

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



- Inclusion of $3N$ force shows marked improvement over previous NN-only
- NCSMC prediction similar to FMD (AV18-like interaction)

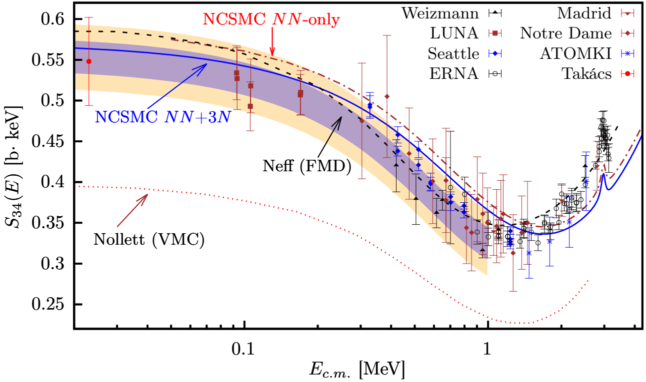
NN-N3LO+3NInl
$\hbar\Omega = 20$ MeV
$\lambda_{\text{SRG}} = 2.0\ \text{fm}^{-1}$



Comparing to other theoretical predictions of $S_{34}(E)$

- Inclusion of $3N$ force shows marked improvement over previous NN-only
- NCSMC prediction similar to FMD (AV18-like interaction)
- Consistent with current evaluation and capture data

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

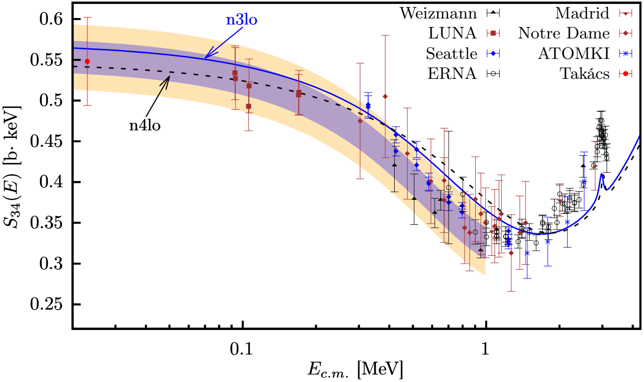


Checking dependence on NN and $3N$ interactions

- Only comparing two interactions, both at $N_{max} = 10$

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

NN-N4LO+3NlnlE7
$\hbar\Omega = 20$ MeV
$\lambda_{\text{SRG}} = 2.0$ fm^{-1}

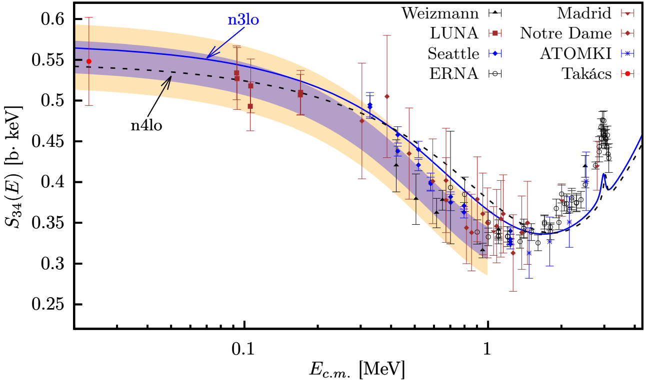


Checking dependence on NN and $3N$ interactions

- Only comparing two interactions, both at $N_{max} = 10$
- Roughly 8% difference in $S_{34}(E)$

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

NN-N4LO+3NInlE7
$\hbar\Omega = 20$ MeV
$\lambda_{\mathrm{SRG}} = 2.0$ fm^{-1}

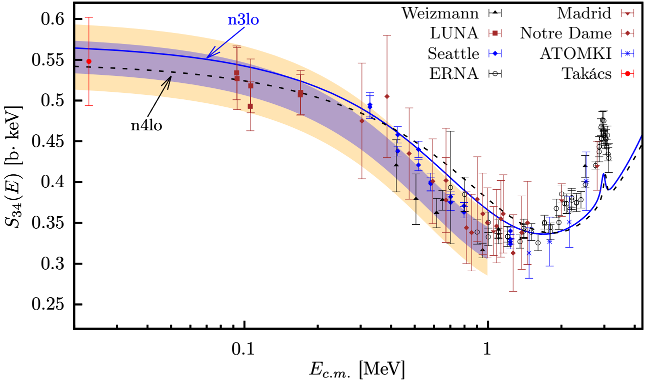


Checking dependence on NN and $3N$ interactions

- Only comparing two interactions, both at $N_{max} = 10$
- Roughly 8% difference in $S_{34}(E)$
- Will analyze more interactions in a future work

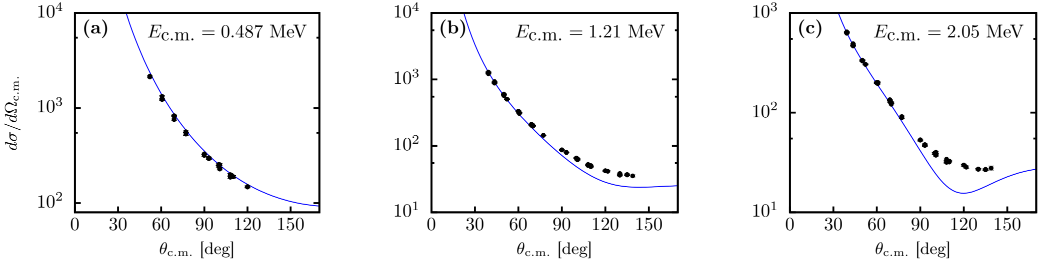
NN-N3LO+3NInl
$\hbar\Omega = 20$ MeV
$\lambda_{\text{SRG}} = 2.0$ fm^{-1}

NN-N4LO+3NInlE7
$\hbar\Omega = 20$ MeV
$\lambda_{\text{SRG}} = 2.0$ fm^{-1}



SONIK ^{3}He+^{4}He elastic scattering cross sections

- Compare to elastic scattering results to further probe ψ_{sc}

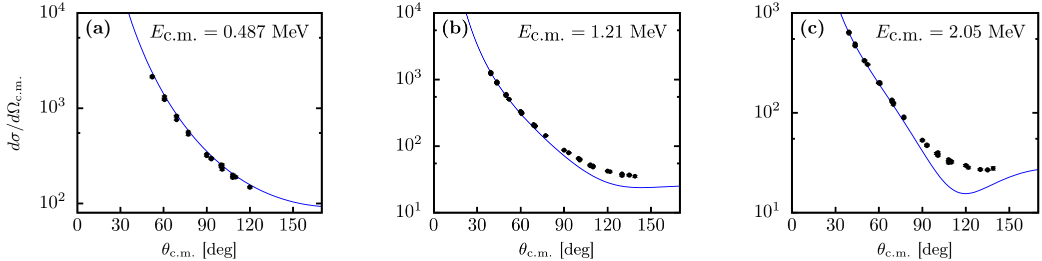


NN-N3LO+3NInl
$\hbar\Omega = 20$ MeV
$\lambda_{\text{SRG}} = 2.0$ fm^{-1}

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

SONIK ^{3}He+^{4}He elastic scattering cross sections

- Compare to elastic scattering results to further probe ψ_{sc}
- Experiment done at TRIUMF in 2022 $\rightarrow$ lowest E measured to date



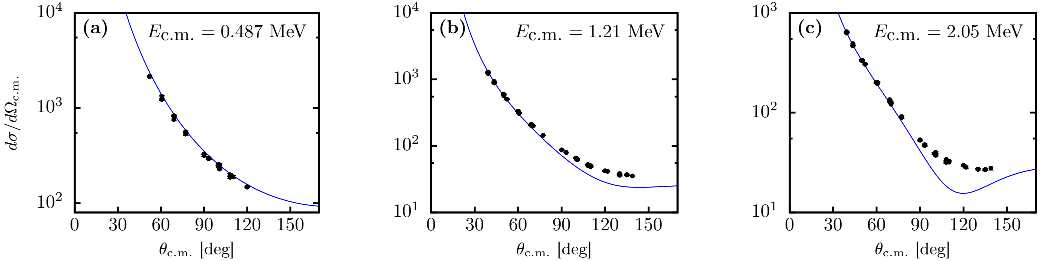
NN-N3LO+3Nlnl

$\hbar\Omega = 20$ MeV

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

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

- Compare to elastic scattering results to further probe ψ_{sc}
- Experiment done at TRIUMF in 2022 $\rightarrow$ lowest E measured to date

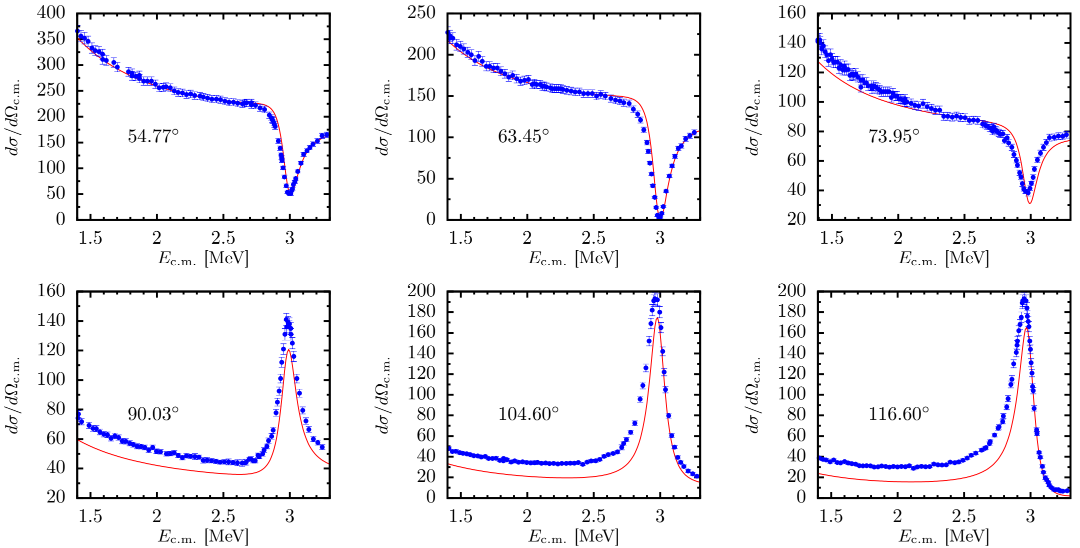


- What is the source of discrepancy at large angles?

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

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

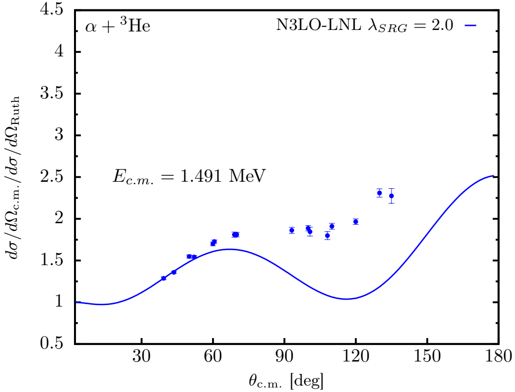
Same large-angle discrepancy when comparing to 1964 Barnard *et al.*



Diagnosing the discrepancy

- Rutherford obscures the fact that a constant shift accounts for the discrepancy

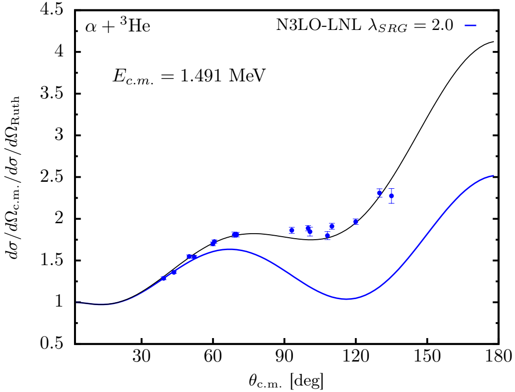
$$\frac{d\sigma}{d\Omega}_{\rm Ruth} = \left(\frac{Z_1 Z_2 e^2}{8\pi\epsilon_0 m v^2 \sin^2\left(\frac{\theta}{2}\right)} \right)^2$$



Diagnosing the discrepancy

- Rutherford obscures the fact that a constant shift accounts for the discrepancy

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

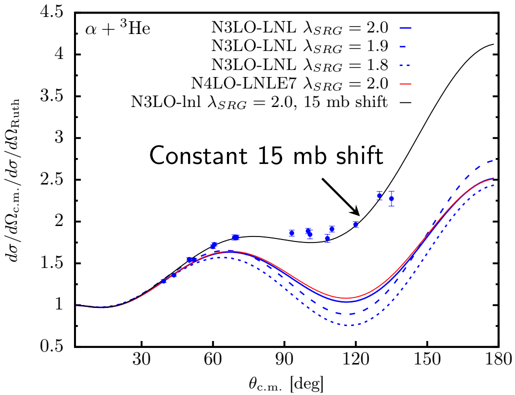


Diagnosing the discrepancy

- 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



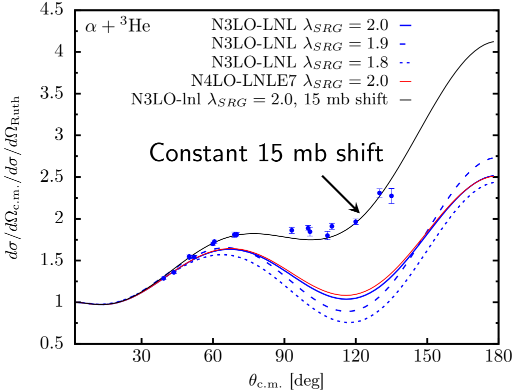
Diagnosing the discrepancy

- Rutherford obscures the fact that a constant shift accounts for the discrepancy

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

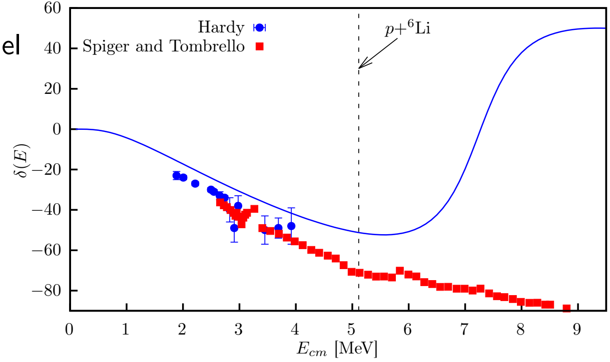
- Varied properties of the interaction
- Nothing in the NCMSC appears to reproduce the 15 mb shift

How can we emulate a constant shift?



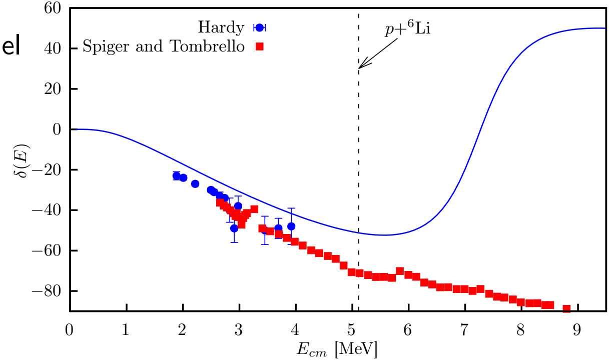
The $1/2^+$ channel can produce this constant shift

- More repulsion is needed in the $1/2^+$ channel



The $1/2^+$ channel can produce this constant shift

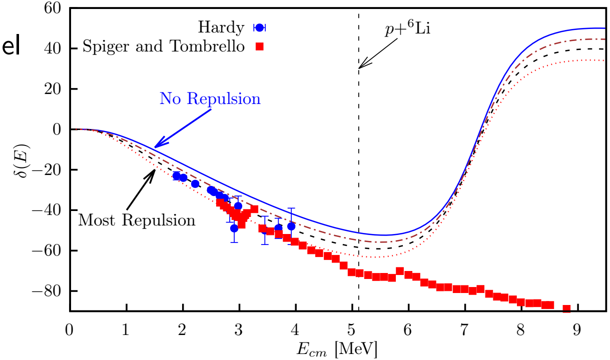
- More repulsion is needed in the $1/2^+$ channel
- Already shown that changing *NN* and 3*N* interactions does not fix



The $1/2^+$ channel can produce this constant shift

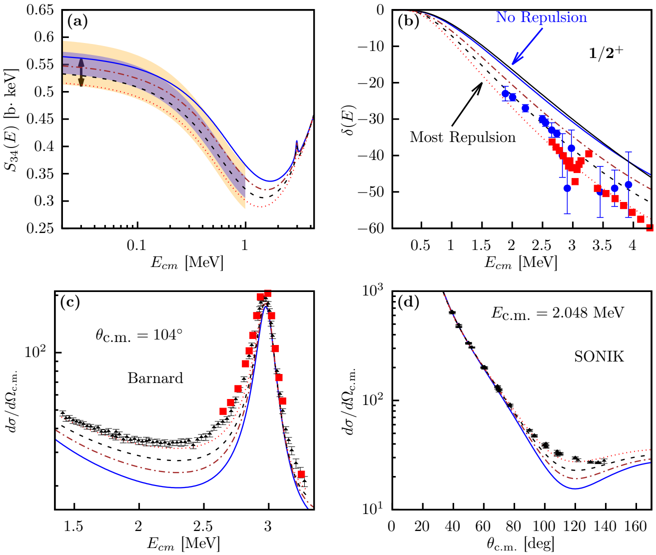
- More repulsion is needed in the $1/2^+$ channel
- Already shown that changing NN and $3N$ interactions does not fix
- We explicitly add repulsion to the $1/2^+$ Hamiltonian kernel

$$V(r,r') = \frac{V_0}{1+e^{(R-r_0)/a_0}} \times e^{(r-r')^2/a_0^2}$$



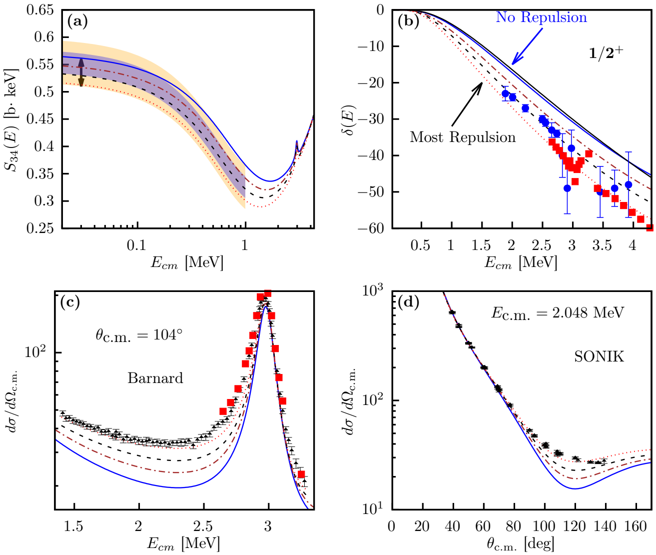
$$\mathcal{H}_{RGM}(r,r') \rightarrow \left\langle \alpha + {}^3He \middle| \mathcal{A}^\dagger H \mathcal{A} \middle| \alpha + {}^3He \right\rangle + V(r,r')$$

Tension Among Data Sets



Tension Among Data Sets

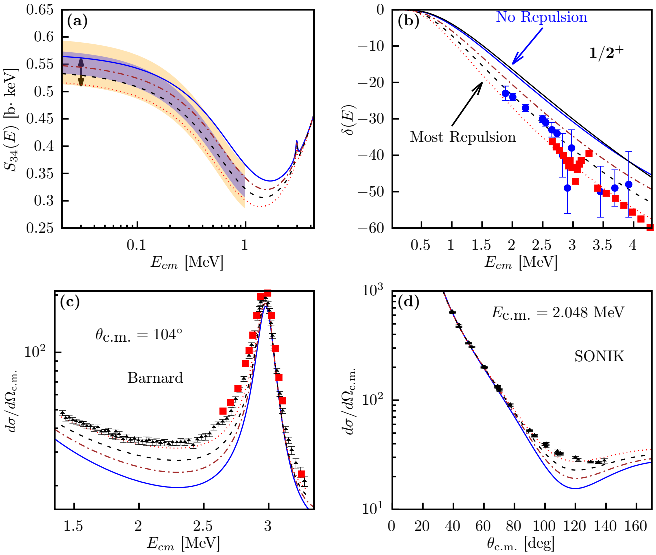
- Elastic and capture data inconsistent
- Cannot describe both simultaneously



Tension Among Data Sets

- Elastic and capture data inconsistent
- Cannot describe both simultaneously

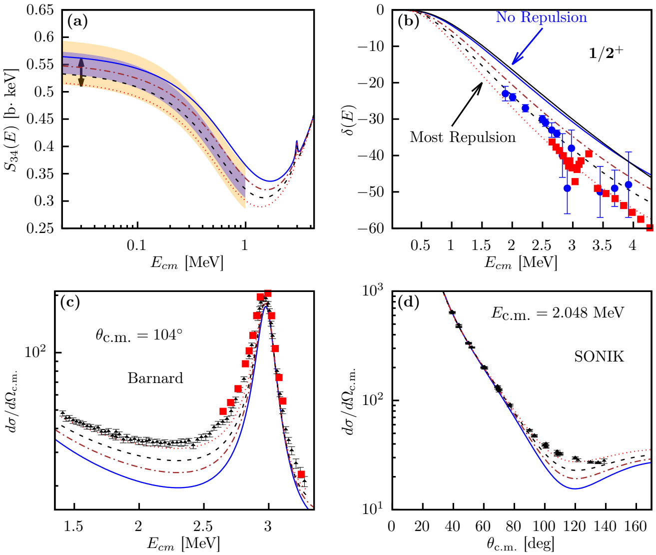
$1/2^+$	a_0
NCSMC	9.07
NCSMC + $V(13\text{MeV})$	14.3
NCSMC + $V(22\text{MeV})$	24.2
NCSMC + $V(34\text{MeV})$	33.2
SONIK R-matrix	36.7



Tension Among Data Sets

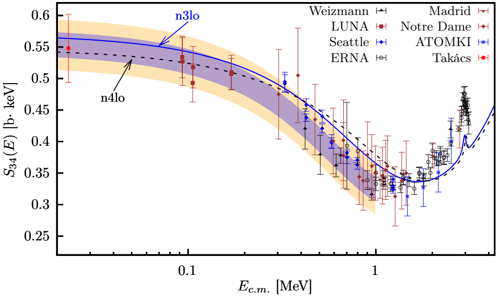
- Elastic and capture data inconsistent
- Cannot describe both simultaneously
- Considering all data provides new band

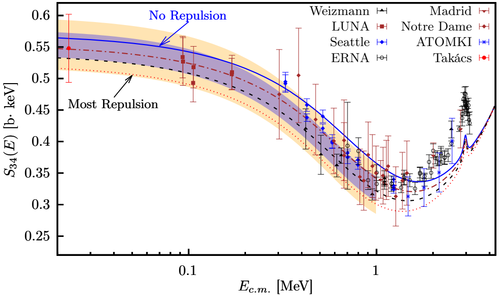
$1/2^+$	a_0
NCSMC	9.07
NCSMC + $V(13\text{MeV})$	14.3
NCSMC + $V(22\text{MeV})$	24.2
NCSMC + $V(34\text{MeV})$	33.2
SONIK R-matrix	36.7



Data-Informed S-factor

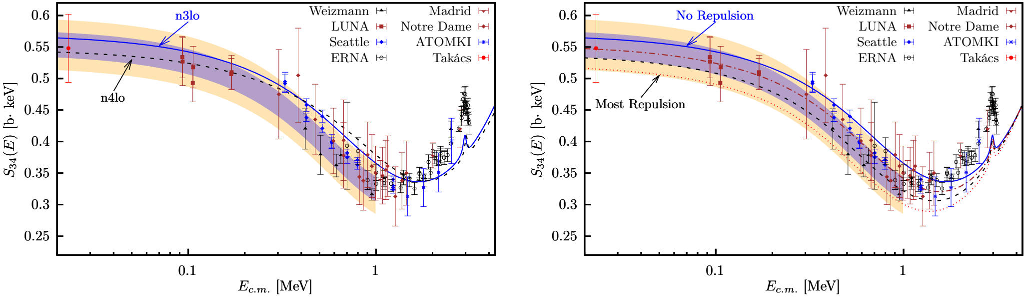
- Consider spread of $S_{34}(E)$ from different interactions as well as considering elastic data





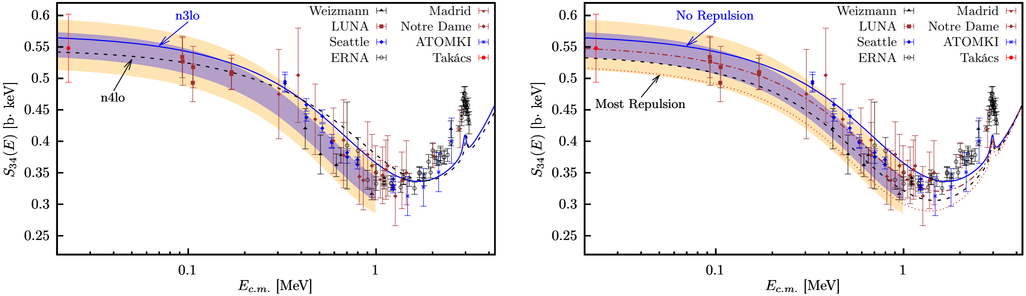
Data-Informed S-factor

- Consider spread of $S_{34}(E)$ from different interactions as well as considering elastic data
- Discrepancy between elastic and capture data dominates the uncertainty



Data-Informed S-factor

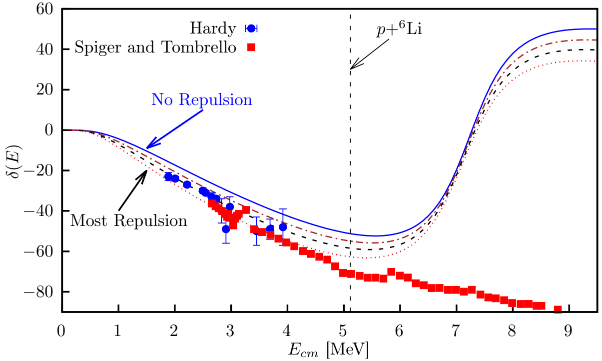
- Consider spread of $S_{34}(E)$ from different interactions as well as considering elastic data
- Discrepancy between elastic and capture data dominates the uncertainty



- For Solar Model calculations, I would provide the spread due to elastic vs. capture data inconsistency (right figure)

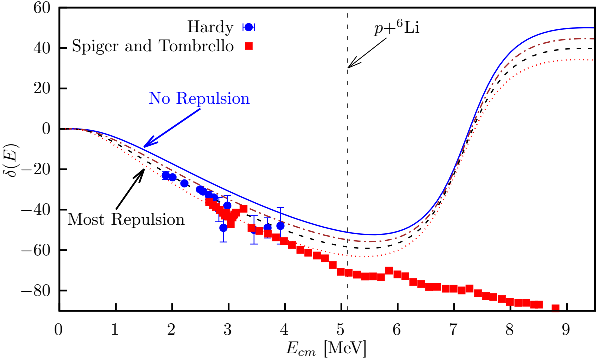
Future: Including $p+^6$Li channel to improve $1/2^+$ phase shift

- We predict a $1/2^+$ resonance roughly 2 MeV above $p+^6$Li threshold



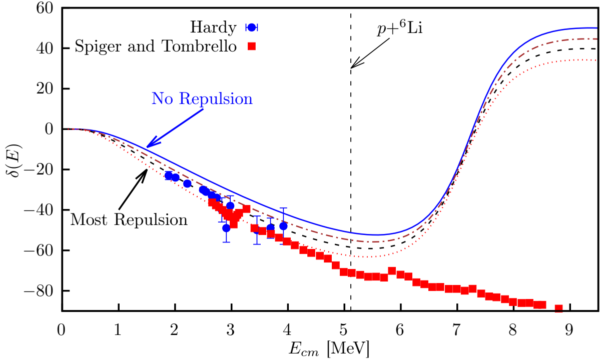
Future: Including p+^{6}Li channel to improve $1/2^+$ phase shift

- We predict a $1/2^+$ resonance roughly 2 MeV above p+^{6}Li threshold
  - Proton resonance due to close proximity to threshold



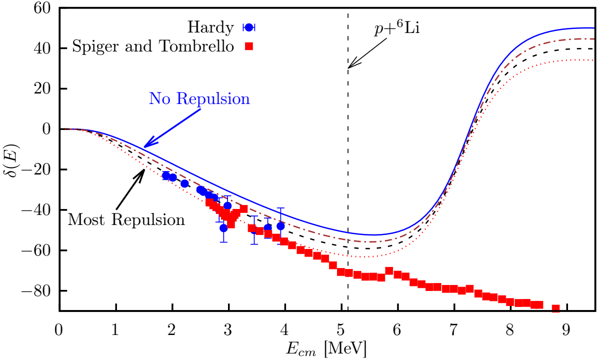
Future: Including $p+^6$Li channel to improve $1/2^+$ phase shift

- We predict a $1/2^+$ resonance roughly 2 MeV above $p+^6$Li threshold
  - Proton resonance due to close proximity to threshold
- Inclusion of $p+^6$Li channel will improve description resonance



Future: Including $p+^6$Li channel to improve $1/2^+$ phase shift

- We predict a $1/2^+$ resonance roughly 2 MeV above $p+^6$Li threshold
  - Proton resonance due to close proximity to threshold
- Inclusion of $p+^6$Li channel will improve description resonance
- Could address discrepancy between data sets



Conclusions

- *Ab initio* calculation of $^3\text{He}(\alpha,\gamma)^7\text{Be}$ capture reaction using the NCSMC
- Can provide both an *ab initio* prediction as well as a data-informed prediction
- The NCSMC allows the simultaneous analysis of elastic and capture data, revealing a discrepancy
- Future: Include $p+{}^6\text{Li}$ channel
- Future: More robust uncertainty quantification

Thanks!

Sofia Quaglioni

Kostas Kravvaris

(LLNL)

Guillame Hupin

(IN2P3)

Petr Navratil

(TRIUMF)