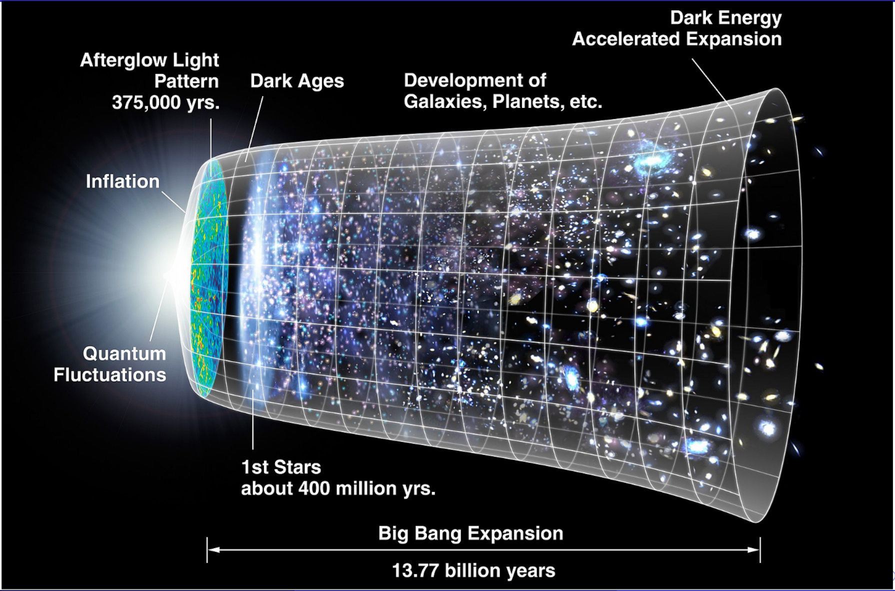
Ab initio prediction of $\alpha(d,\gamma)^6$Li and impact of the ^{6}Li properties onto α-induced reactions of astrophysical interest

Chloë Hebborn

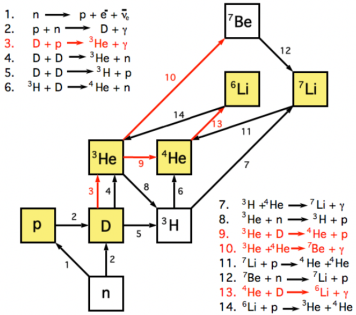
[PRL 129, 042503 (2022) & PRC 109, L061601 (2024)]

August, 21 2024

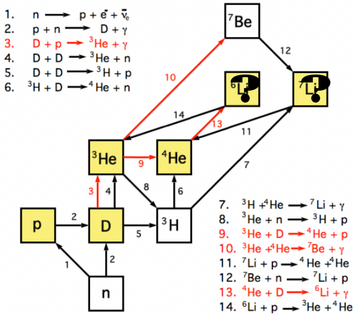
Light nuclei, such as Lithium, were already present ∼3 minutes after the Big Bang

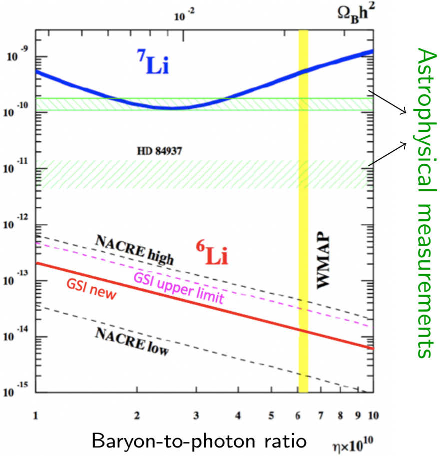


The Big-Bang nucleosynthesis accurately predicts abundances at early time...



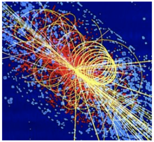
The Big-Bang nucleosynthesis accurately predicts abundances at early time... but for Lithium isotopes





[Fig. adapted from JPCS 665 012004 (2016)]

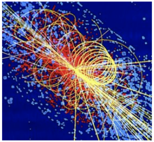
Different possible solutions to the Lithium problem exist



High-energy physics : inaccurate baryon-to-photon ratio

→ BSM physics ? unlikely as agreement for He and Be

Different possible solutions to the Lithium problem exist

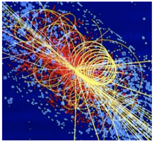


High-energy physics : inaccurate baryon-to-photon ratio

→ BSM physics ? unlikely as agreement for He and Be

Astrophysics : uncertainties in measuring the BBN abundances

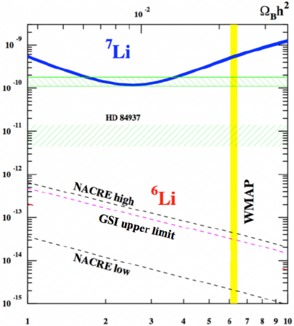
Different possible solutions to the Lithium problem exist



High-energy physics : inaccurate baryon-to-photon ratio

→ BSM physics ? unlikely as agreement for He and Be

Astrophysics : uncertainties in measuring the BBN abundances



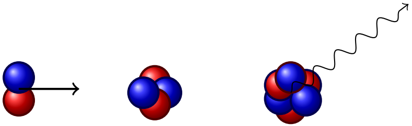
Nuclear physics :

→ Large uncertainties

→ $\alpha(d,\gamma)^6$Li dominates

Reactions at low energy are difficult to measure as the two charged nuclei repulse each other

$\alpha(d,\gamma)^6\mathrm{Li}$



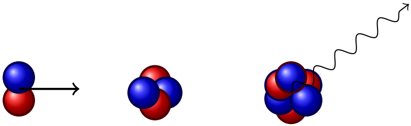
very low cross section

= low reaction probability

$$\sigma(E) = \frac{\exp[-2\pi\eta]}{E}\,\mathrm{S(E)}$$

Reactions at low energy are difficult to measure as the two charged nuclei repulse each other

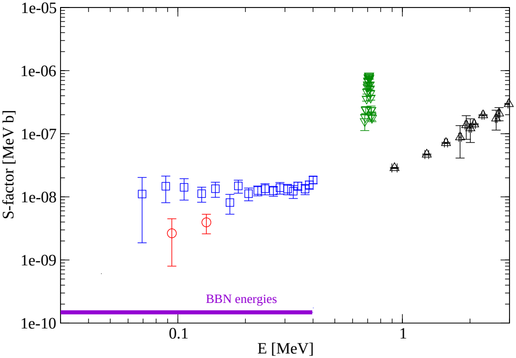
$\alpha(d,\gamma)^6\mathrm{Li}$



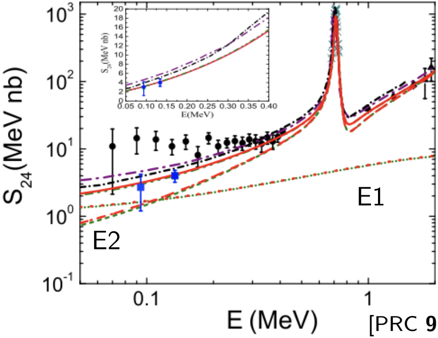
very low cross section

= low reaction probability

$$\sigma(E) = \frac{\exp[-2\pi\eta]}{E}\, \mathrm{S(E)}$$



Theories based on two-body models do not evaluate consistently all electromagnetic transitions

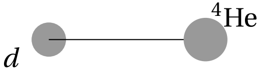


[PRC **93** 045805 (2016)]

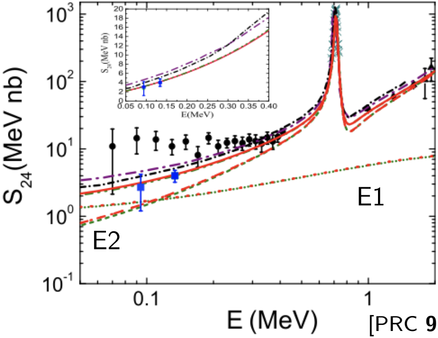
Two-body models :

⊕ agree with direct data

⊖ use pheno. interaction



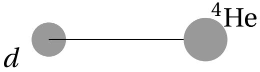
Theories based on two-body models do not evaluate consistently all electromagnetic transitions



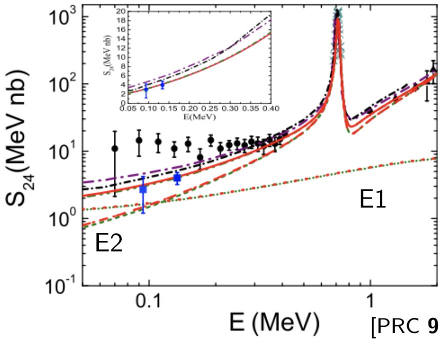
[PRC **93** 045805 (2016)]

Two-body models :

- ⊕ agree with direct data
- ⊖ use pheno. interaction
- ⊖ M1 not evaluated



Theories based on two-body models do not evaluate consistently all electromagnetic transitions



[PRC **93** 045805 (2016)]

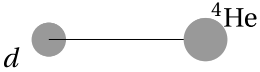
Two-body models :

⊕ agree with direct data

⊖ use pheno. interaction

⊖ M1 not evaluated

E1 dipole suppressed as $\boldsymbol{R}_{cm} = \boldsymbol{R}_{cm}^{ch}$



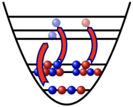
⊖ Use of pheno. prescription with exp. mass

⇒ Need for accurate **microscopic** prediction → *ab initio* methods

For a complete *ab initio* description, we need both structure...

No core shell-model

$$\Psi = \sum_{\lambda} c_{\lambda} \, |$$



$$\rangle$$

Discrete structure
information input

$\oplus$ **Bound states,**

narrow resonances

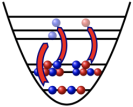
$\rightarrow$ **short-range**

For a complete *ab initio* description, we need both structure... and dynamical clustered description

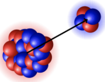
No core shell-model with continuum

[Navrátil, Quaglioni, Hupin, Romero-Redondo and Calci, Phys. Scr. **91**, 053002 (2016)]

$$\Psi = \sum_{\lambda} c_{\lambda} \,\Big|$$



$$\Big\rangle + \sum_{\nu} \int dr\, u_{\nu}(r) \,\Big|$$



$$\Big\rangle$$

Discrete structure information input

Continuous dynamical input (clustering/reactions)

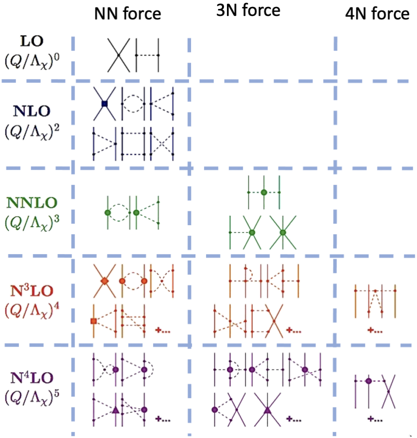
⊕ **Bound states, narrow resonances**

→ short-range

⊕ **Bound & scattering states, reactions**

→ long-range

Chiral-EFT links the nuclear force to QCD



Systematically improvable expansion !

Includes long-range π physics explicitly

→ empirically constrained parameters capture short-distance physics

Ab initio predictions are accurate for α-d scattering

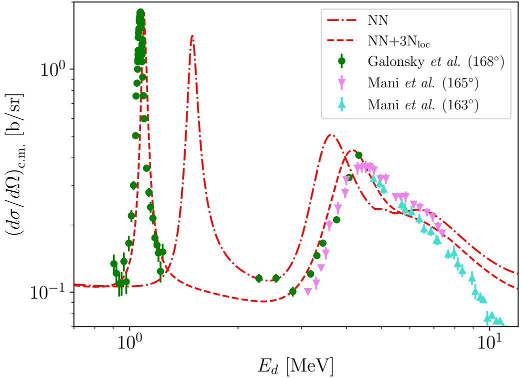
Convergence with 10 + & 5 − parity ^{6}Li states,
d g.s. + 8 d pseudostates
at $N_{max} = 11$

HPC at LLNL

Ab initio predictions are accurate for α-d scattering

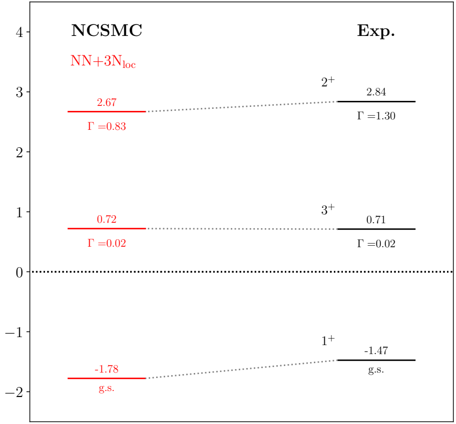
Convergence with 10 + & 5 − parity ^{6}Li states,
d g.s. + 8 d pseudostates
at $N_{max} = 11$

HPC at LLNL



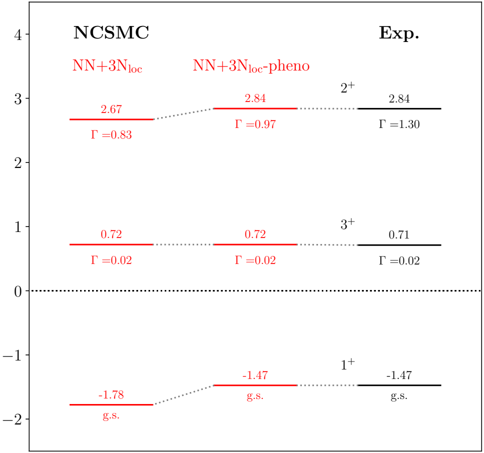
Importance of 3N (SRG-induced & chiral)

Ab initio predictions are accurate for ^{6}Li spectrum but... not perfect

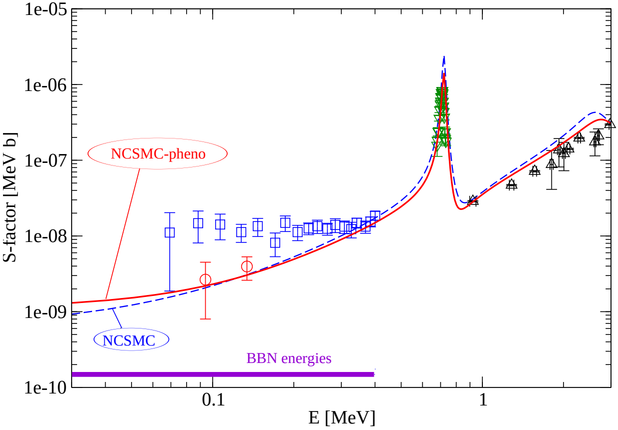


Accurate prediction of $\alpha(d,\gamma)^6$Li → need to have the right ^{6}Li g.s.

Use of a phenomenological correction for the overbinding and the position of the 2^+ resonance

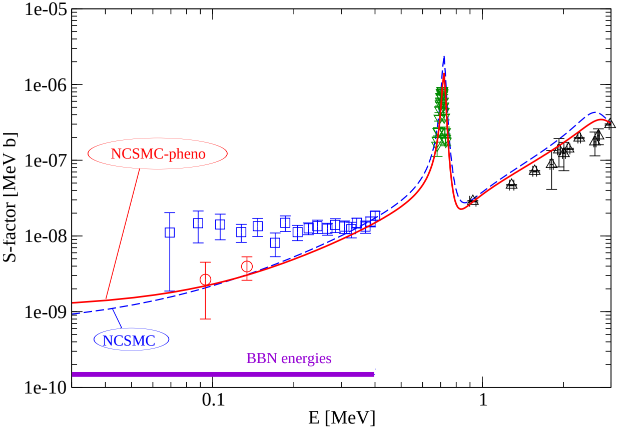


Ab initio prediction fills the experimental gap for $\alpha(d,\gamma)^6\mathrm{Li}$



Excellent agreement with data : importance of E_{1^+} at low energies and E_{2^+} at higher energies

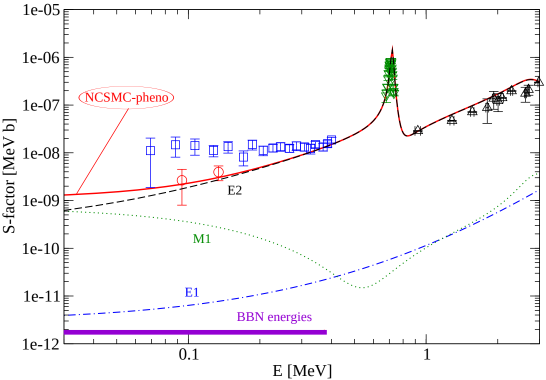
Ab initio prediction fills the experimental gap for $\alpha(d,\gamma)^6$Li



Excellent agreement with data : importance of E_{1^+} at low energies and E_{2^+} at higher energies

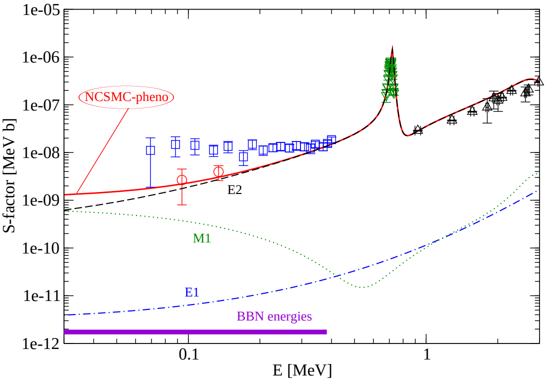
Which electromagnetic transitions drive this reaction ?

The S-factor is dominated by E2 and M1 at low energies



E2 larger than previous eval. → larger **ANC**

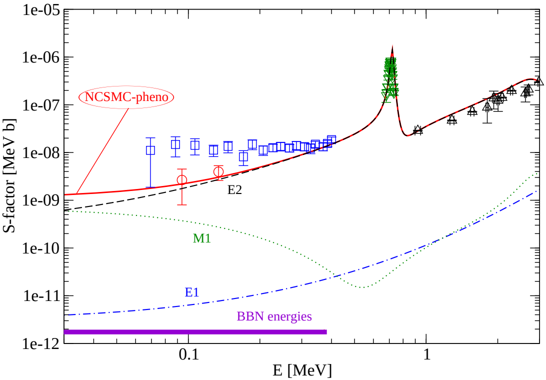
The S-factor is dominated by E2 and M1 at low energies



M1 are typically not evaluated in few-body models

M1 important at low E → which role in other capture reactions ?

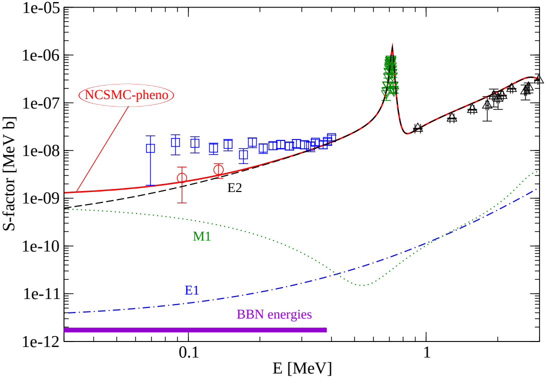
The S-factor is dominated by E2 and M1 at low energies



E1 evaluated with pheno. prescriptions predicted to be dominant

Isovector **E1 transitions negligible** due to small $T = 1$ mixing in ^{6}Li

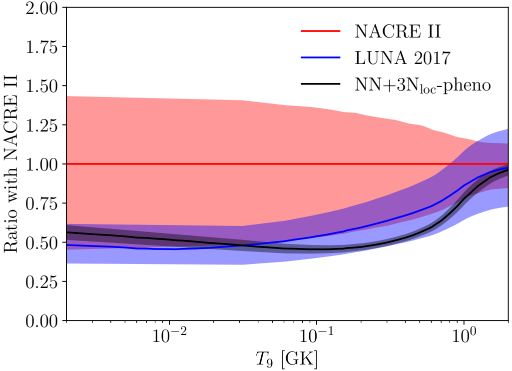
The S-factor is dominated by E2 and M1 at low energies



E1 evaluated with pheno. prescriptions predicted to be dominant
Isovector **E1 transitions negligible** due to small $T=1$ mixing in ^{6}Li

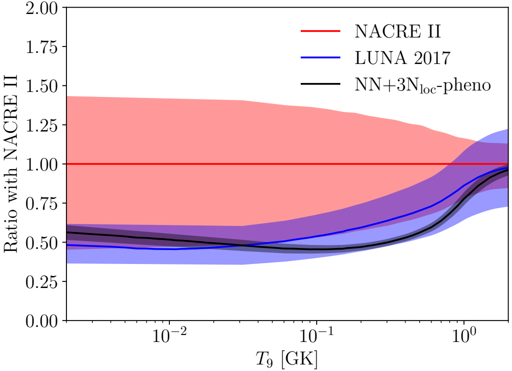
What is the uncertainty due to the choice of χ-EFT force & to the finite size of the basis ?

Ab initio-informed predictions reduce the uncertainties on the ^{4}He(d,γ)^{6}Li rate by an average factor 7



[Hebborn, Hupin, Kravvaris, Quaglioni, Navrátil, Gysbers, Phys. Rev. Lett. **129**, 042503 (2022)]

Ab initio-informed predictions reduce the uncertainties on the ^{4}He(d,γ)^{6}Li rate by an average factor 7

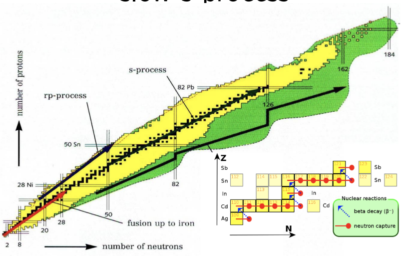


[Hebborn, Hupin, Kravvaris, Quaglioni, Navrátil, Gysbers, Phys. Rev. Lett. **129**, 042503 (2022)]

→ Discrepancy in ^{6}Li abundances cannot be explained by uncertainties on the reaction rates

Various α-induced reactions play a key role in astrophysics

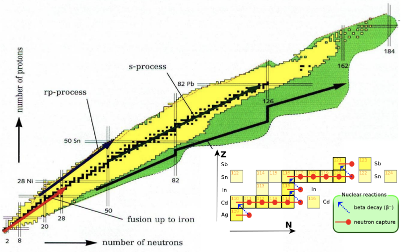
slow s-process



$^{13}\mathbf{C}(\alpha, n)^{16}\mathbf{O}$: major n source

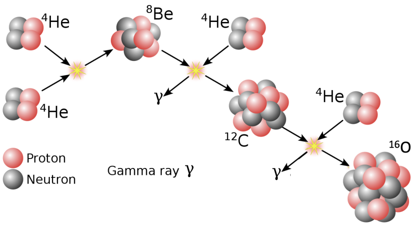
Various α-induced reactions play a key role in astrophysics

slow s-process

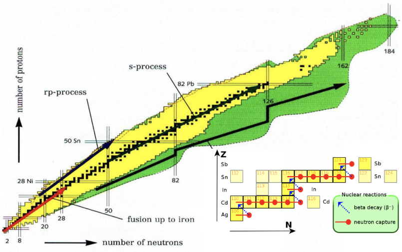


$^{13}\mathbf{C}(\alpha, n)^{16}\mathbf{O}$: major n source

Helium burning

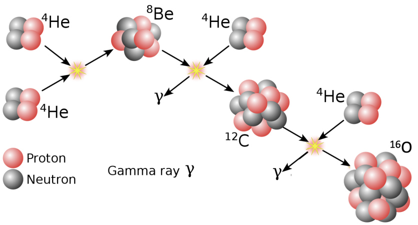


$^{12}\mathbf{C}(\alpha, \gamma)^{16}\mathbf{O}$:^{12}C$/^{16}$O abundances slow s-process



$^{13}\mathbf{C}(\alpha, n)^{16}\mathbf{O}$: major n source

Helium burning



$^{12}\mathbf{C}(\alpha, \gamma)^{16}\mathbf{O}$:^{12}C/^{16}O abundances

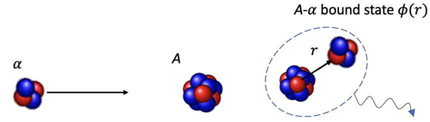
^{13}C$(\alpha, n)^{16}$O & ^{12}C$(\alpha, \gamma)^{16}$O influence abundances of heavier isotopes !

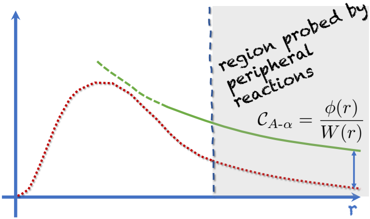
Too many nucleons for ab initio predictions of reaction...

How can we predict accurately (<10% error) α-induced rates ?

Below the Coulomb barrier, radiative capture reactions are peripheral, they scale with the ANC^2

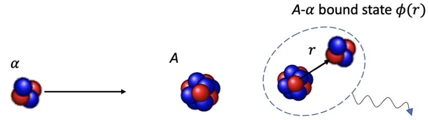
At low energies :

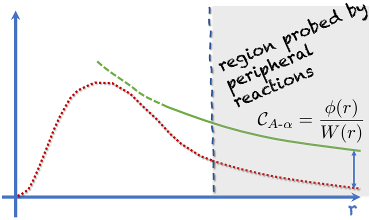




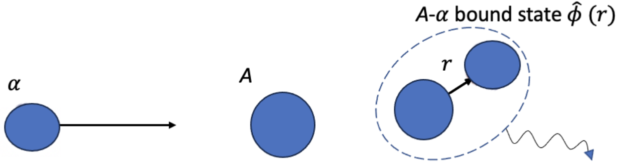
Below the Coulomb barrier, radiative capture reactions are peripheral, they scale with the ANC^2

At low energies :





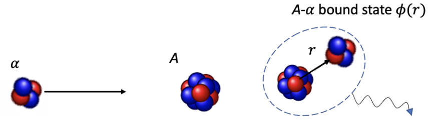
The cross section can be obtained in a two-body model

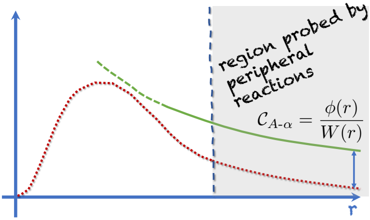


$$\sigma_{\alpha,\gamma} \approx C^2_{A-\alpha} \frac{\hat{\sigma}_{\alpha,\gamma}}{\hat{C}^2_{A-\alpha}}$$

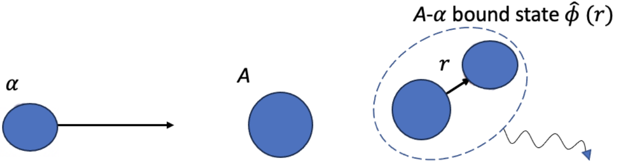
Below the Coulomb barrier, radiative capture reactions are peripheral, they scale with the ANC^2

At low energies :





The cross section can be obtained in a two-body model

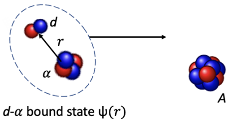


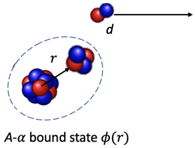
$$\sigma_{\alpha,\gamma} \approx C^2_{A-\alpha} \frac{\hat{\sigma}_{\alpha,\gamma}}{\hat{C}^2_{A-\alpha}}$$

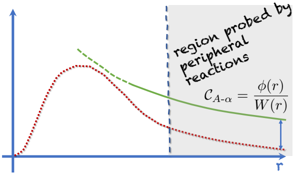
How can we determine accurately $C^2_{A-\alpha}$?

α-transfer (^{6}Li, d) around the Coulomb barrier are also peripheral and can be used to extract ANCs

At low energies :

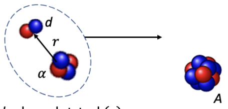




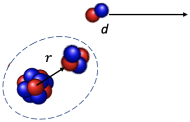


α-transfer (^{6}Li, d) around the Coulomb barrier are also peripheral and can be used to extract ANCs

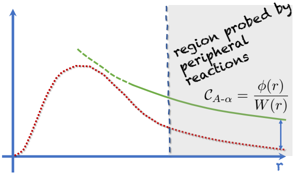
At low energies :



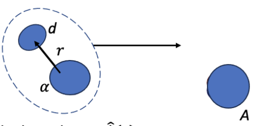
d-α bound state $\psi(r)$



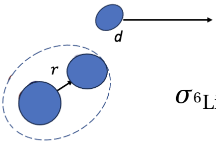
A-α bound state $\phi(r)$



The cross section can be obtained in a three-body model



d-α bound state $\hat{\psi}(r)$

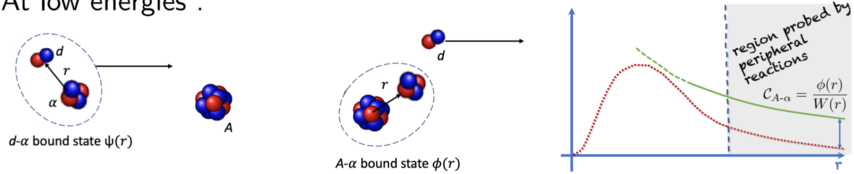


A-α bound state $\hat{\phi}(r)$

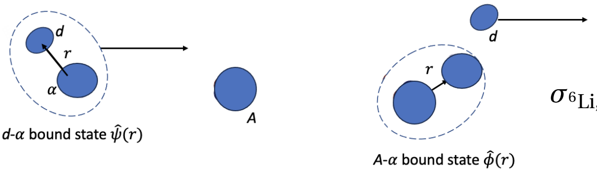
$$\sigma_{^6\text{Li},d} \approx C^2_{\alpha-d} C^2_{A-\alpha} \frac{\hat{\sigma}^{DWBA}_{^6\text{Li},d}}{\hat{C}^2_{A-\alpha} \hat{C}^2_{\alpha-d}}$$

α-transfer (^{6}Li, d) around the Coulomb barrier are also peripheral and can be used to extract ANCs

At low energies :



The cross section can be obtained in a three-body model



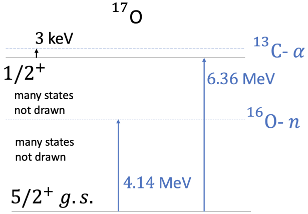
$$\sigma_{^6\mathrm{Li},d} \approx C^2_{\alpha-d} C^2_{A-\alpha} \frac{\hat{\sigma}^{DWBA}_{^6\mathrm{Li},d}}{\hat{C}^2_{A-\alpha} \hat{C}^2_{\alpha-d}}$$

If one knows $C^2_{\alpha-d}$, one can determine $C^2_{A-\alpha}$ from (^{6}Li, d) data !

ANC method : [Tribble *et al.* Rep. Prog. Phys. **77**, 106901 (2014)]

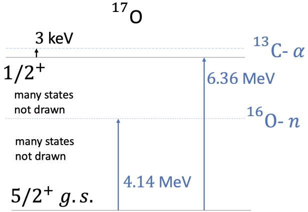
S-factors for ^{13}C$(\alpha, n)^{16}$O have been constrained using ANCs extracted from $(^{6}$Li$, d)$...

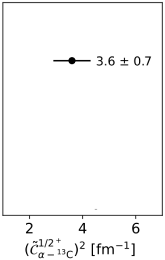
Normalization of the ^{13}C$(\alpha, n)^{16}$O S-factor dominated by the $(C^{1/2+}_{^{13}\mathrm{C}-\alpha})^2$ of ^{17}O



S-factors for ^{13}C$(\alpha, n)^{16}$O have been constrained using ANCs extracted from $(^6$Li$, d)$...

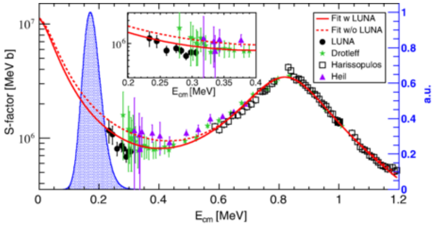
Normalization of the ^{13}C$(\alpha, n)^{16}$O S-factor dominated by the $(C^{1/2+}_{^{13}\text{C}-\alpha})^2$ of ^{17}O





$(^6$Li, $d)$ Avila (2015)
LUNA (2021)

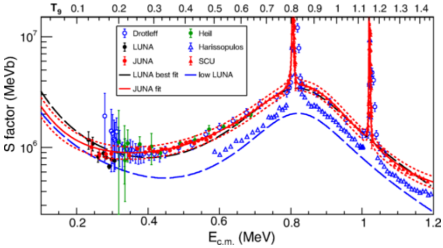
[Avila *et al.* PRC **91**, 048801 (2015)]



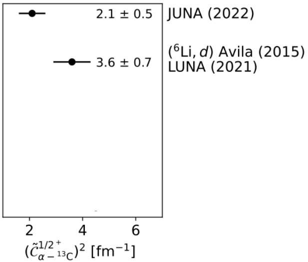
[Ciani *et al.* PRL **127**, 152701 (2021)]

but are inconsistent with recent measurements... and the differences can be traced back to the $C_{\alpha-^{13}\mathrm{O}}^{1/2^+}$

JUNA just fits new S-factor data and found larger S-factor and $C_{\alpha-^{13}\mathrm{O}}^{1/2^+}$!

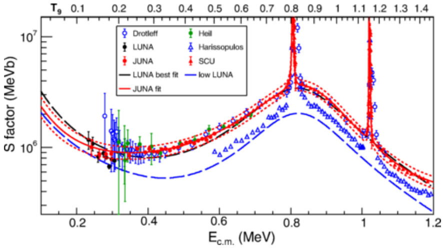


[Gao *et al.* PRL **129**, 132701 (2022)]

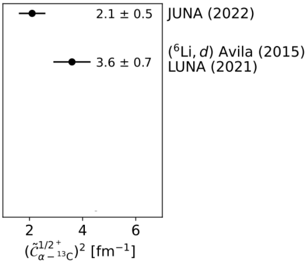


but are inconsistent with recent measurements... and the differences can be traced back to the $C^{1/2^+}_{\alpha-{}^{13}\mathrm{O}}$

JUNA just fits new S-factor data and found larger S-factor and $C^{1/2^+}_{\alpha-{}^{13}\mathrm{O}}$!

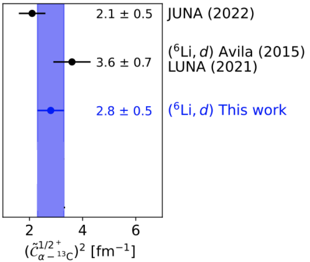


[Gao *et al.* PRL **129**, 132701 (2022)]



What can explain this discrepancy ? $\sigma_{^6\mathrm{Li},d} \approx C^2_{\alpha-d} C^2_{A-\alpha} \frac{\hat{\sigma}^{DWBA}_{^6\mathrm{Li},d}}{\hat{C}^2_{A-\alpha}\hat{C}^2_{\alpha-d}}$

Using the ab initio prediction of $C_{\alpha-d}$ onto of $C^{1/2^+}_{\alpha-{}^{13}\mathrm{C}}$, we reconcile both LUNA and JUNA analyses !



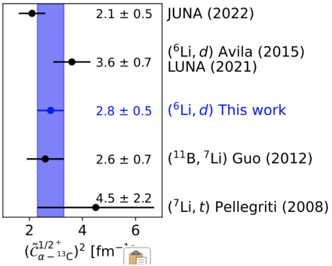
Previous $(C_{\alpha-d})^2$: Blokhintsev *et al.* PRC **48**, 2390 (1993)

- evaluated using simple models

  → unaccounted syst. uncertainties !

- 22% smaller than ab initio $(C_{\alpha-d})^2$

Using the ab initio prediction of $C_{\alpha-d}$ onto of $C^{1/2^+}_{\alpha-^{13}\text{C}}$, we reconcile both LUNA and JUNA analyses !



Previous $(C_{\alpha-d})^2$: Blokhintsev *et al.* PRC **48**, 2390 (1993)

- evaluated using simple models

  → unaccounted syst. uncertainties !

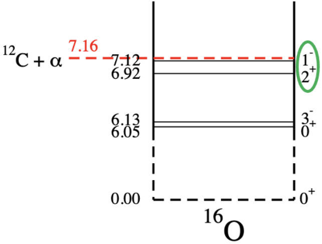
- 22% smaller than ab initio $(C_{\alpha-d})^2$

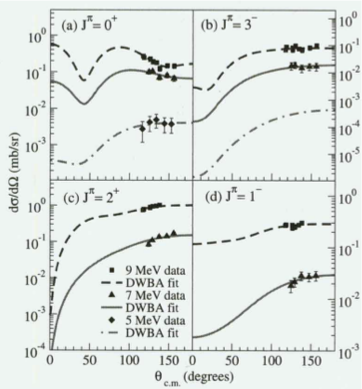
Our $(C_{\alpha-d})^2$ explains the discrepancy between JUNA and LUNA analyses,

& is more precise

Another key astrophysical reaction $^{12}C(\alpha,\gamma)^{16}O$ have been constrained using (^{6}Li, d) data and previous ANC !

$C_{\alpha-^{12}C}$ extracted from (^{6}Li, d) data



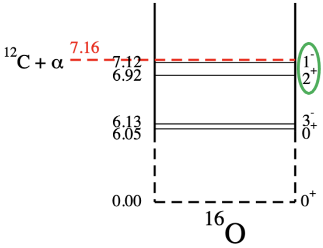


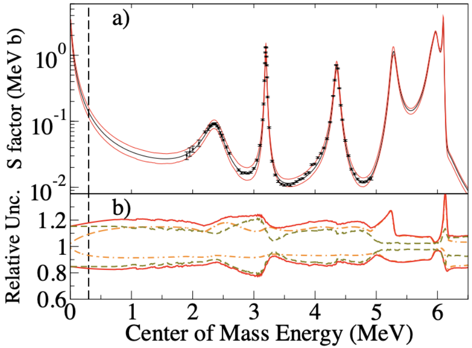
[Avila *et al.* PRL **114**, 071101 (2015)]
[Brune *et al.* PRL **83**, 4025 (1999)]

Another key astrophysical reaction $^{12}C(\alpha,\gamma)^{16}O$ have been constrained using (^{6}Li, d) data and previous ANC !

$C_{\alpha-^{12}C}$ extracted from (^{6}Li, d) data used in R-matrix fits

(large set of data : ANCs, S-factor, el. scattering, β-delayed α emission)



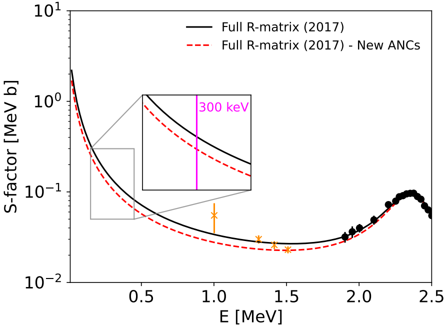


[deBoer *et al.* Rev. Mod. Phys. **89**, 035007 (2017)]

The ab initio $(C_{\alpha-d})^2$ leads to a reduction of 21% of the $(C_{\alpha-{}^{12}C})^2$ & S-factor at stellar energies !

J^π	E_{ex}	Probe	$(\mathcal{C}^{J^\pi}_{\alpha\text{-}^{12}C})^2$ Past Work		
0^+	6.05	$(^6Li, d)$	2.43(30)	1.88(16)	$\times 10^6$
3^-	6.13	$(^6Li, d)$	1.93(25)	1.49(14)	$\times 10^4$
2^+	6.92	$(^6Li, d)$	1.24(24)	0.96(16)	$\times 10^{10}$
		$(^6Li, d)$	1.48(16)	1.14(7)	
1^-	7.12	$(^6Li, d)$	4.33(84)	3.34(58)	$\times 10^{28}$
		$(^6Li, d)$	4.39(59)	3.39(34)	

[Brune *et al.* PRL **83**, 4025 (1999)]
[Avila *et al.* PRL **114**, 071101 (2015)]



[Schürmann *et al.* EPJA **26**, 301 (2005)]
[Plag *et al.* PRC **86**, 015805 (2012)]

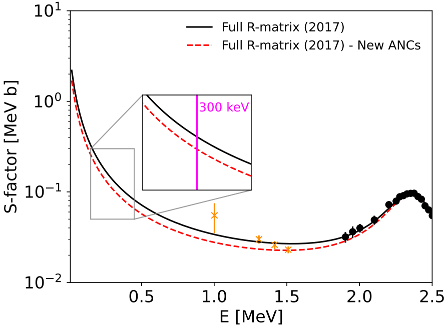
Data sets cannot constrained ANCs → renormalization factors

S-factor at low E scale with $(C_{\alpha-{}^{12}C})^2$ of 1^- and 2^+ !

The ab initio $(C_{\alpha-d})^2$ leads to a reduction of 21% of the $(C_{\alpha-^{12}C})^2$ & S-factor at stellar energies !

J^π	E_{ex}	Probe	$(\mathcal{C}^{J^\pi}_{\alpha\text{-}^{12}C})^2$ Past Work		
0^+	6.05	$(^6Li, d)$	2.43(30)	1.88(16)	$\times 10^6$
3^-	6.13	$(^6Li, d)$	1.93(25)	1.49(14)	$\times 10^4$
2^+	6.92	$(^6Li, d)$	1.24(24)	0.96(16)	$\times 10^{10}$
		$(^6Li, d)$	1.48(16)	1.14(7)	
		$(^7Li, t)$	1.33(29)		
		$(^7Li, t)$	2.07(80)		
1^-	7.12	$(^6Li, d)$	4.33(84)	3.34(58)	$\times 10^{28}$
		$(^6Li, d)$	4.39(59)	3.39(34)	
		$(^7Li, t)$	4.00(138)		

[Brune *et al.* PRL **83**, 4025 (1999)]
[Avila *et al.* PRL **114**, 071101 (2015)]
[Oulebsir *et al.* PRC **85**, 035804 (2012)]



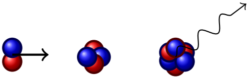
[Schürmann *et al.* EPJA **26**, 301 (2005)]
[Plag *et al.* PRC **86**, 015805 (2012)]

Data sets cannot constrained ANCs → renormalization factors

S-factor at low E scale with $(C_{\alpha-^{12}C})^2$ of 1^- and 2^+ !

Tension with $(^7Li, t)$ results → unaccounted uncertainties in $C_{\alpha-t}$?

Summary and prospects

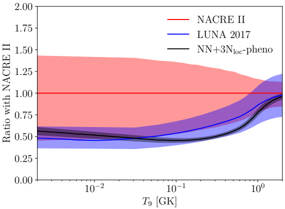


Ab initio methods are accurate for light systems

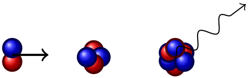
→ Start from a χ-EFT NN+3N Hamiltonian

& no pheno. approximation of the E1 and M1 !

Ab initio reduces uncertainties for the ^{4}He(d,γ)^{6}Li rate by ~7 !



Summary and prospects



Ab initio methods are accurate for light systems

→ Start from a χ-EFT NN+3N Hamiltonian

& no pheno. approximation of the E1 and M1 !

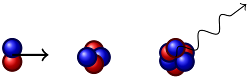
Ab initio reduces uncertainties for the ^{4}He(d,γ)^{6}Li rate by ~7 !

Impacts ANCs extracted from (^{6}Li, d) data :

→ Reconciliation of LUNA & JUNA S-factors for ^{13}C(α, n)^{16}O

→ ^{12}C(α, γ)^{16}O S-factor at stellar energies reduced by 21% !

Summary and prospects



Ab initio methods are accurate for light systems

→ Start from a χ-EFT NN+3N Hamiltonian

& no pheno. approximation of the E1 and M1 !

Ab initio reduces uncertainties for the ^{4}He(d,γ)^{6}Li rate by ~7 !

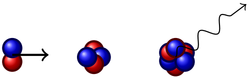
Impacts ANCs extracted from (^{6}Li, d) data :

→ Reconciliation of LUNA & JUNA S-factors for ^{13}C(α, n)^{16}O

→ ^{12}C(α, γ)^{16}O S-factor at stellar energies reduced by 21% !

Prospects : ^{12}C(α, γ)^{16}O R-matrix & use it into nucleosynthesis network

Summary and prospects



Ab initio methods are accurate for light systems

→ Start from a χ-EFT NN+3N Hamiltonian

& no pheno. approximation of the E1 and M1 !

Ab initio reduces uncertainties for the ^{4}He(d,γ)^{6}Li rate by ~7 !

Impacts ANCs extracted from (^{6}Li, d) data :

→ Reconciliation of LUNA & JUNA S-factors for ^{13}C(α, n)^{16}O

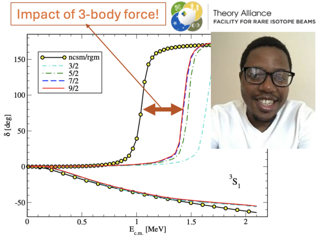
→ ^{12}C(α, γ)^{16}O S-factor at stellar energies reduced by 21% !

Prospects : ^{12}C(α, γ)^{16}O R-matrix & use it into nucleosynthesis network

Improvements of few-body models,

e.g. importance of 3-body force

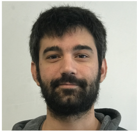
[Hlophe, Kravvaris, Quaglioni, PRC **107** 014315 (2023)]



Thanks to my collaborators...

Lawrence Livermore National Laboratory

Sofia Quaglioni



Kostas Kravvaris

Gregory Potel

TRIUMF

Petr Navratil

Peter Gysbers

IJCLab Irène Joliot-Curie

Guillaume Hupin

Argonne NATIONAL LABORATORY

Melina Avila

to the few-body reaction group at MSU, ...


Filomena Nunes


Chloë Hebborn


Kyle Beyer


Patrick McGlynn


Cate Beckman


Manuel Catacora Rios


Andy Smith


Daniel Shiu


Pablo Giuliani


Grigor Sargsyan

& you for your attention !