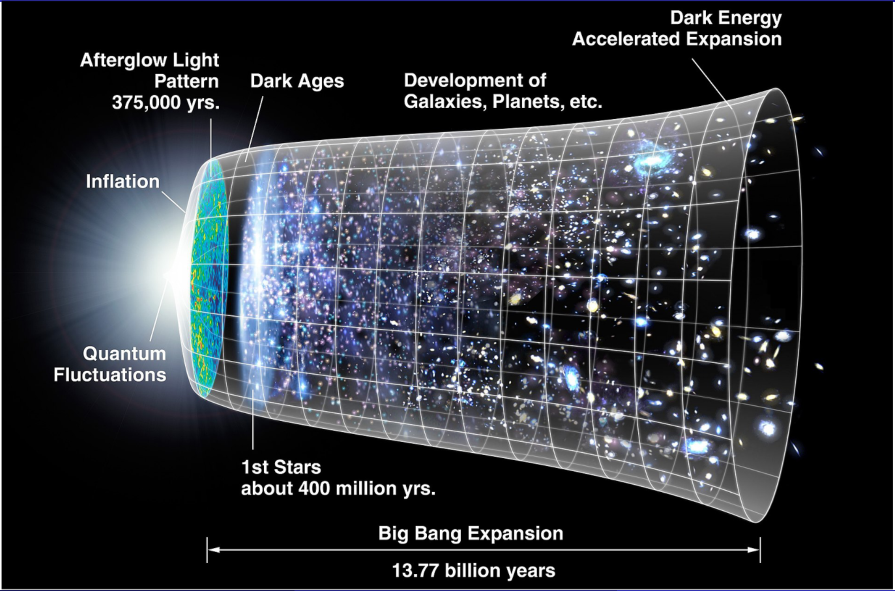
Ab initio prediction of $\alpha(d,\gamma)^6$Li and impact of the ^{6}Li properties onto α-induced reactions of astrophysical interest

Chloë Hebborn

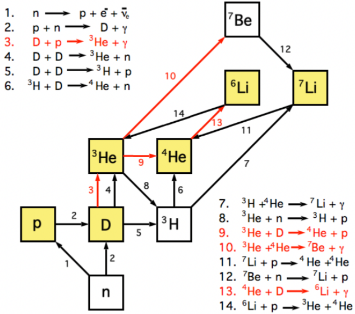
[PRL 129, 042503 (2022) & arXiv:2307.05636]

August, 2 2023

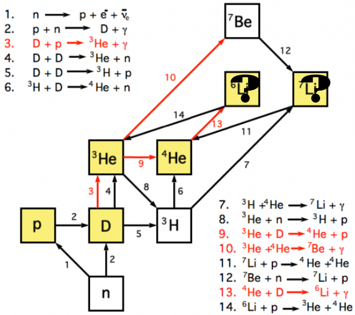
Light nuclei, such as Lithium, were already present ~3 minutes after the Big Bang



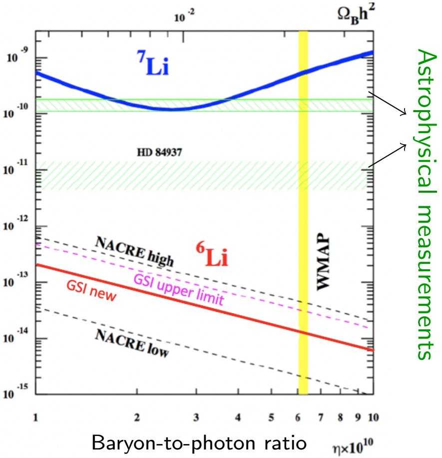
The Big-Bang nucleosynthesis accurately predicts abundances at early time...



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

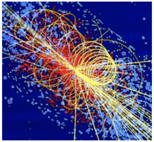


cf B. Acharya's talk



[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

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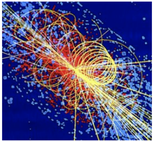

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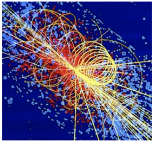

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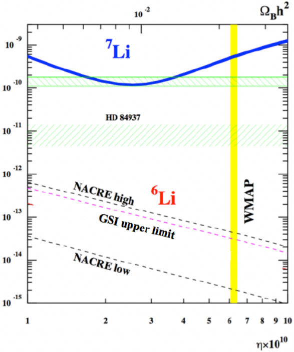


Nuclear physics :

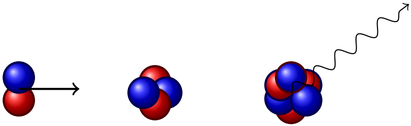
→ Large uncertainties

[cf B. Acharya's & C. Bruno's talks]

→ Uncertainties on $\alpha(d,\gamma)^6$Li dominates the uncertainties on ^{6}Li abundances

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

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

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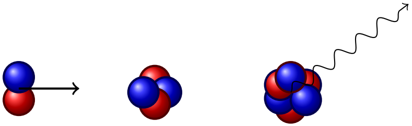

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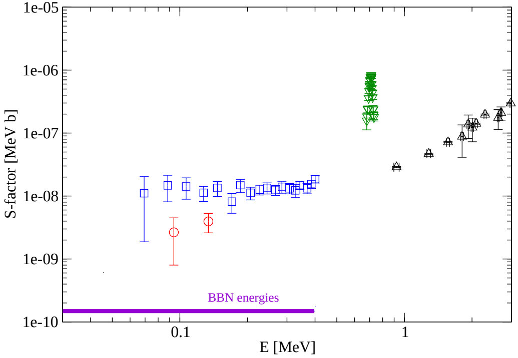
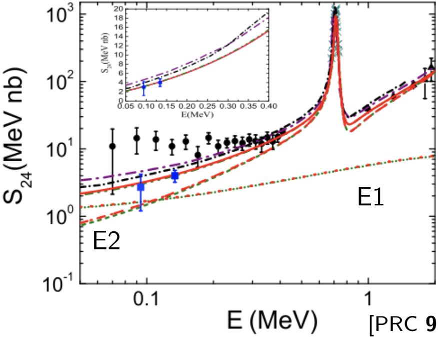


Data : [Anders *et al.* (LUNA) PRL **113** 042501 (2014)] [Kiener *et al.* PRC **44** 2196 (1991)] [Mohr *et al.* **50** 1543 (1994)] [Robertson *et al.* PRL **47** 1867 (1981)]

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

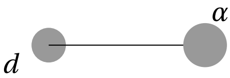


[PRC **93** 045805 (2016)]

Two-body models :

⊕ agree with direct data

⊖ use pheno. interaction



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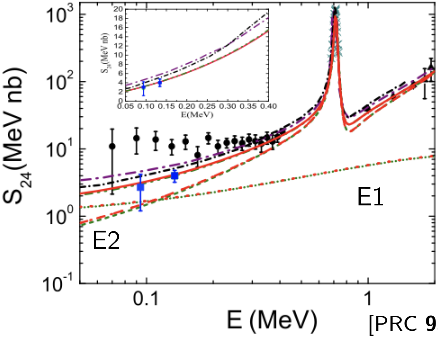

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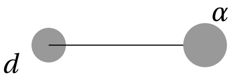

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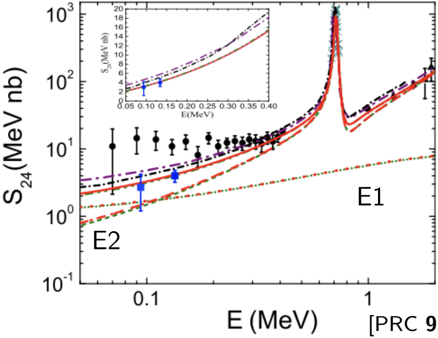

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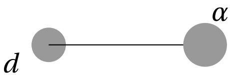
E1 dipole suppressed as $\boldsymbol{R}_{cm} = \boldsymbol{R}_{cm}^{ch}$



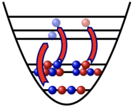
⊖ Use of pheno. prescription with exp. mass

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

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

No core shell-model

$$\Psi = \sum_{\lambda} c_{\lambda} \left| \quad \right\rangle$$



Discrete structure
information input

$\oplus$ **Bound states,**

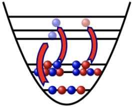
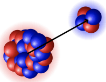
narrow resonances

$\rightarrow$ **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)]

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

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

$$\rangle$$

Discrete structure information input

Continuous dynamical input (clustering/reactions)

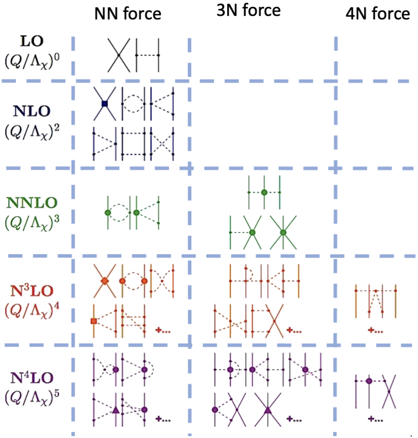
$\oplus$ **Bound states, narrow resonances**

→ short-range

$\oplus$ **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 15 ^{6}Li NCSM states,
d g.s. + 8 d pseudostates at $N_{max} = 11$

HPC at LLNL

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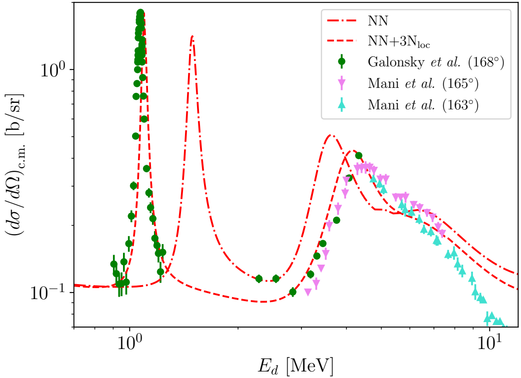
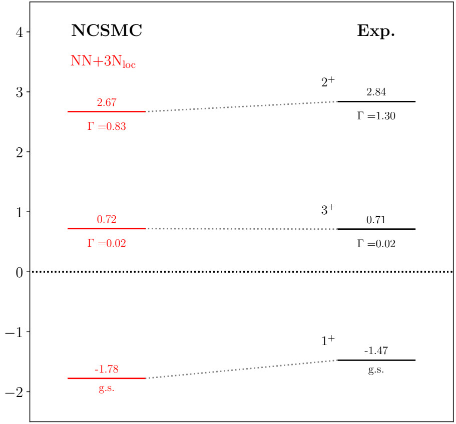


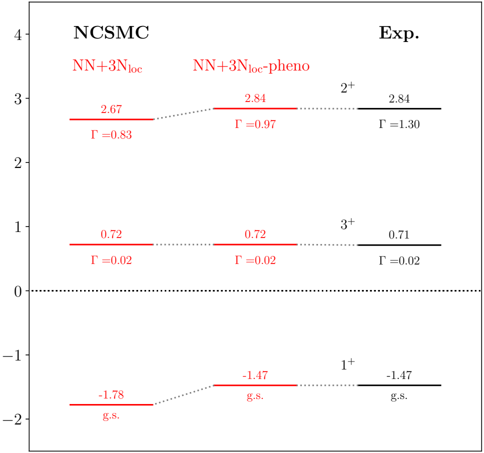
Importance of 3N (SRG-induced & chiral)

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

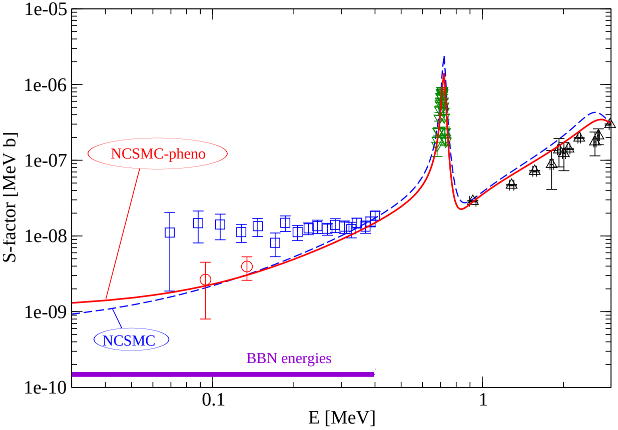


Accurate prediction of $\alpha(d,\gamma)^6$Li → need to have the right ^{6}Li g.s.

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

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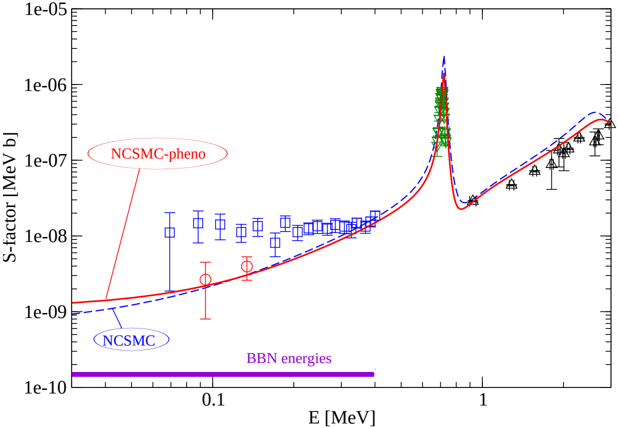

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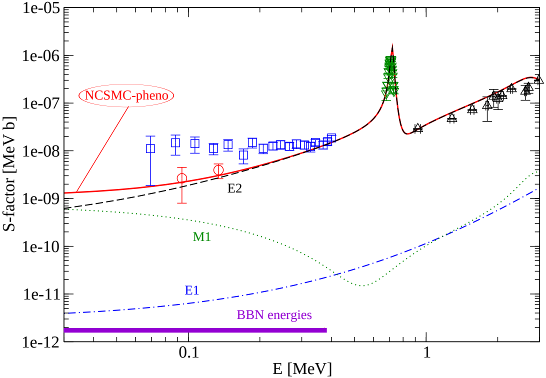
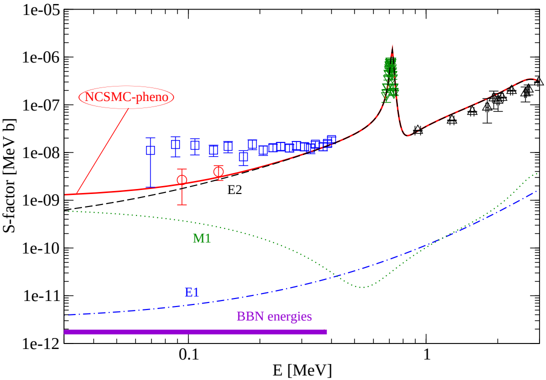
Which electromagnetic transitions drive this reaction ?

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 ?

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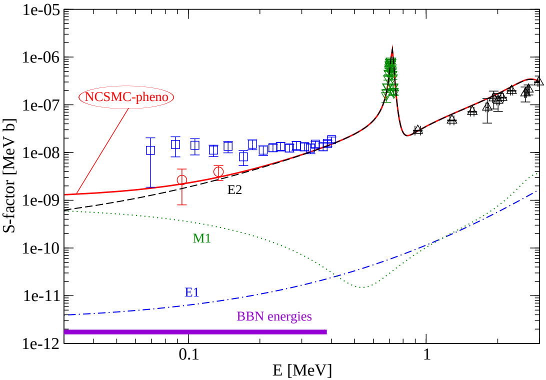

E1 evaluated with pheno. prescriptions predicted to be dominant
Isovector **E1 transitions negligible** due to small $T = 1$ mixing in ^{6}Li

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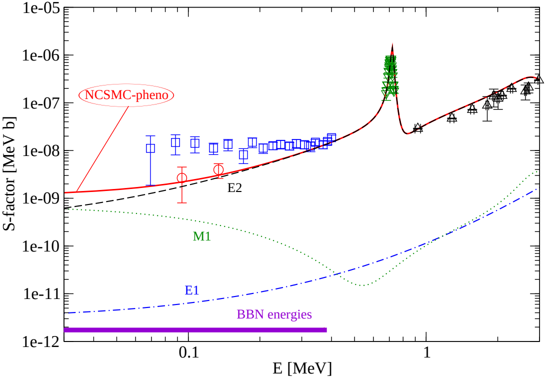

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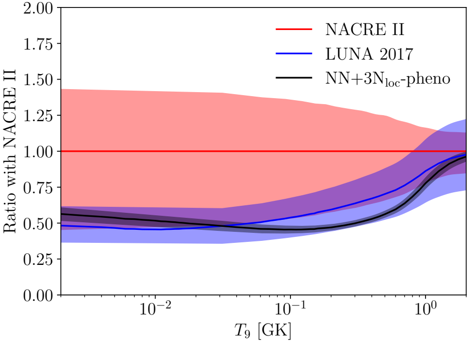
What is the uncertainty due to the choice of χ-EFT force & to the finite size of the basis ?

Ab initio-informed predictions reduce the uncertainties on the $\alpha(d,\gamma)^6$Li rate by an average factor 7

Comparison of two chiral forces and different N_{max}

→ Small uncertainties thanks to the adjustment of the ^{6}Li g.s. energy



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

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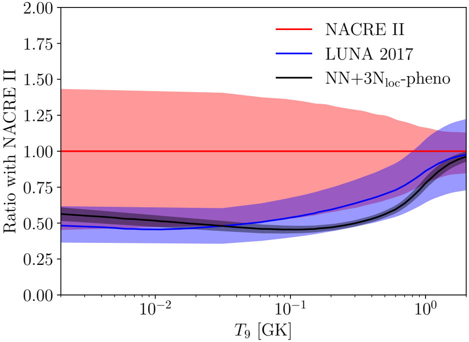
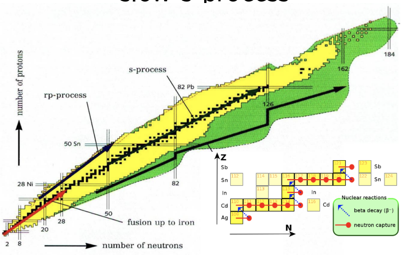


[Hebborn, Hupin, Kravvaris, Quaglioni, Navrátil, Gysbers, Phys. Rev. Lett. **129**, 042503 (2022)]

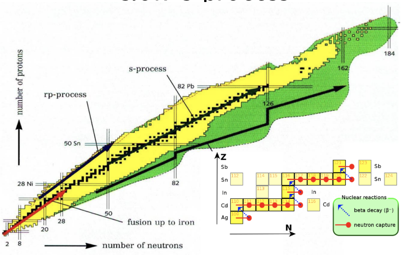
→ **Discrepancy in ^{6}Li abundances cannot be explained by uncertainties on the $\alpha(d,\gamma)^6$Li reaction rate** slow s-process



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

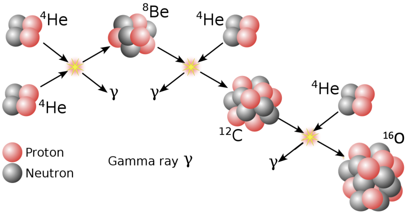
Various α-induced reactions play a key role in astrophysics

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

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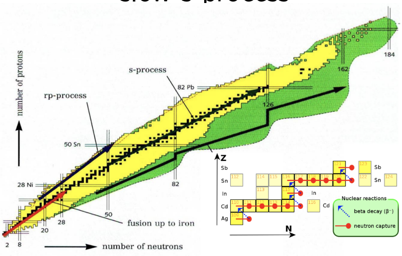

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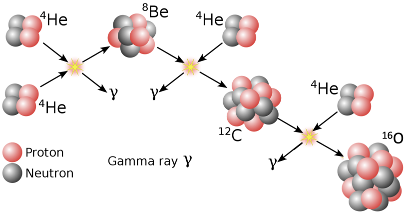


^{13}**C**$(\alpha,n)^{16}$**O** : major n source

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

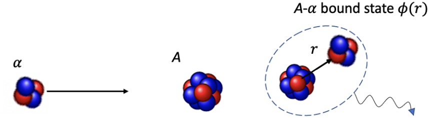
^{13}C$(\alpha,n)^{16}$O & ^{12}C$(\alpha,\gamma)^{16}$O influence abundances of heavier isotopes !

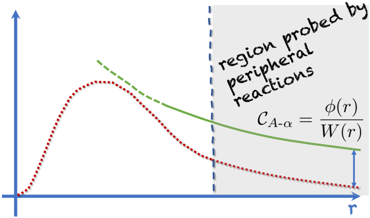
Too many nucleons for ab initio predictions of reaction...

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

At $E \to 0$ MeV, non-resonant reactions are peripheral, they scale with the ANC^2 of subthreshold states

At low energies :





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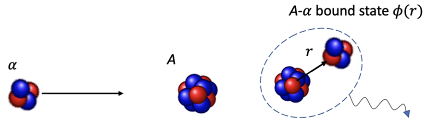
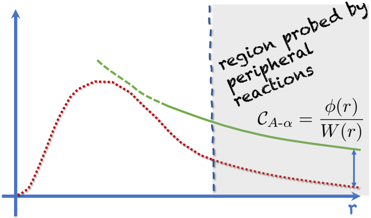
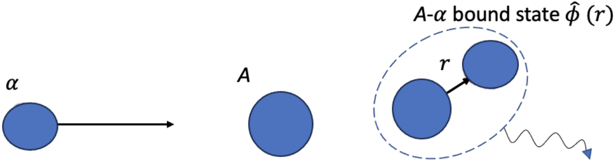




The cross section can be obtained in a two-body model

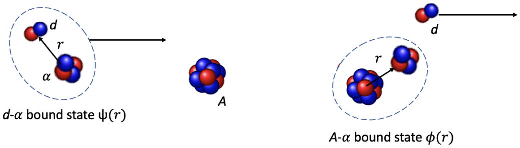


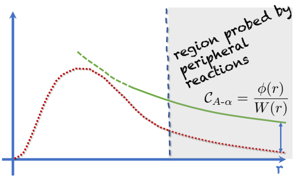
$$\sigma_{\alpha,\gamma} \approx C^2_{A-\alpha} \hat{\sigma}_{\alpha,\gamma}$$

If one knows $C^2_{A-\alpha}$, one can determine accurately the rate at low E !

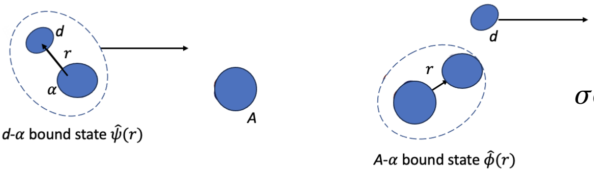
α-transfer (^{6}Li, d) around the Coulomb barrier are also peripheral and can be used to extract ANCs

At low energies :





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



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

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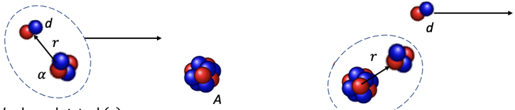
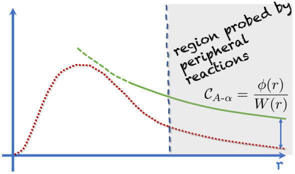


d-α bound state $\psi(r)$

A-α bound state $\phi(r)$



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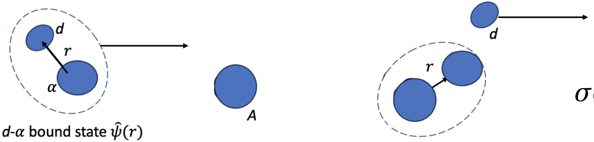


d-α bound state $\hat{\psi}(r)$

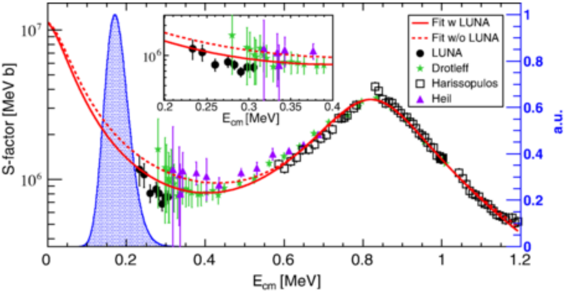
A-α bound state $\hat{\phi}(r)$

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

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

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

The $^{13}C(\alpha, n)^{16}O$ S-factor has been measured underground and extrapolated to zero energies...



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

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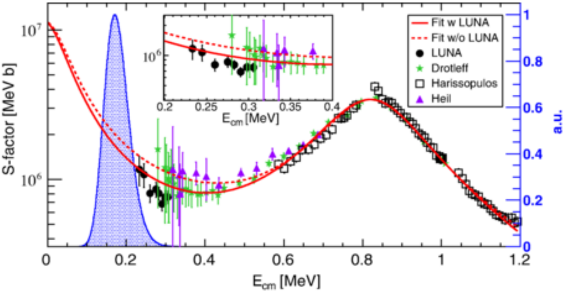

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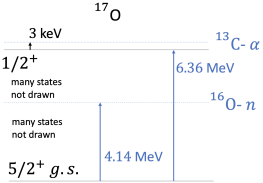
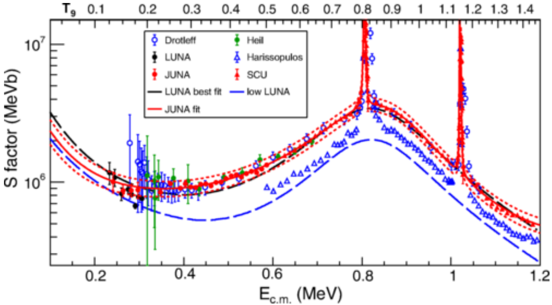


$(C^{1/2+}_{^{13}C-\alpha})^2$ constrains the extrapolation

Deduced from $(^6\text{Li}, d)$ data at $\sim 0.6A$ MeV

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

but new underground measurements predict a S(0) 21% smaller than LUNA...



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

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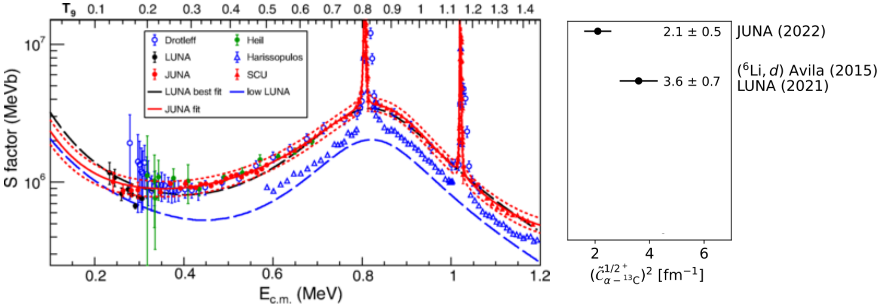

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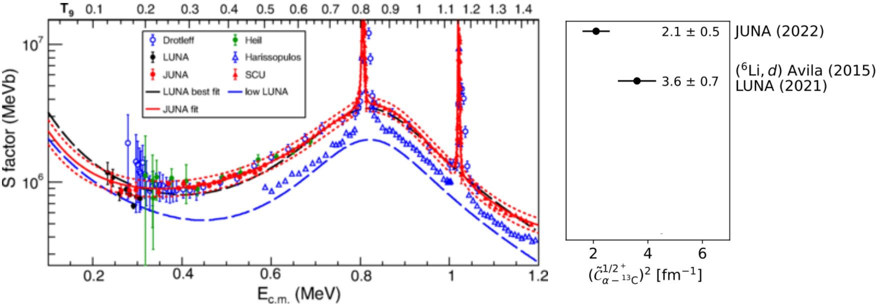
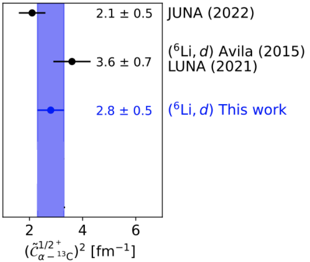


[Gao *et al.* (JUNA collaboration) PRL **129**, 132701 (2022)]

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

Using the ab initio $C_{\alpha-d}$ to reanalyze (^{6}Li, d) data, we reconcile both LUNA and JUNA analyses !



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

→ unaccounted syst. uncertainties !

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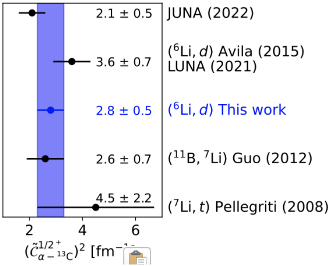

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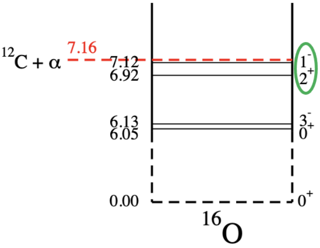
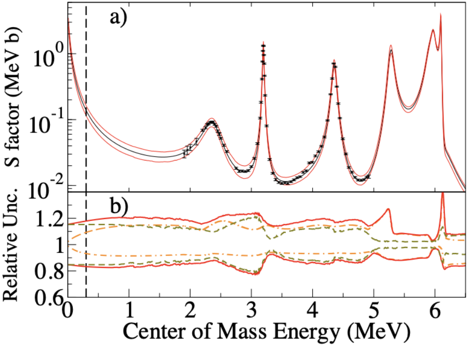
Our $(C_{\alpha-d})^2$ explains the discrepancy between JUNA and LUNA S(0),

is more precise, & favors the JUNA evaluation of S(0) !

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

$C_{\alpha-^{12}C}$ extracted from $(^6Li, d)$ data used in R-matrix fits
(large set of data : ANCs, S-factor, el. scattering, β-delayed α emission)



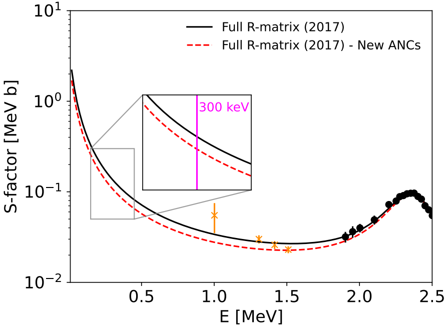


[deBoer *et al.* Rev. Mod. Phys. **89**, 035007 (2017)]

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	$(^6\mathrm{Li}, d)$	2.43(30)	1.88(16)	$\times 10^6$
3^-	6.13	$(^6\mathrm{Li}, d)$	1.93(25)	1.49(14)	$\times 10^4$
2^+	6.92	$(^6\mathrm{Li}, d)$	1.24(24)	0.96(16)	$\times 10^{10}$
		$(^6\mathrm{Li}, d)$	1.48(16)	1.14(7)	
1^-	7.12	$(^6\mathrm{Li}, d)$	4.33(84)	3.34(58)	$\times 10^{28}$
		$(^6\mathrm{Li}, d)$	4.39(59)	3.39(34)	

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



Data : [Schürmann *et al.* EPJA **26**, 301 (2005)]
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Data sets cannot constrained ANCs → renormalization factors

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		$(^7\mathrm{Li}, t)$	2.07(80)		
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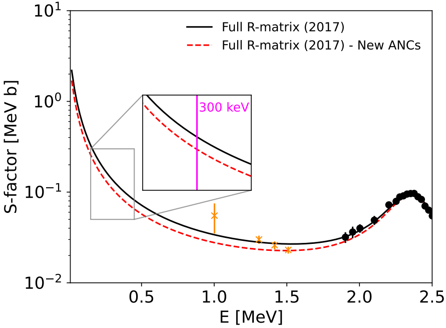
		$(^6\mathrm{Li}, d)$	4.39(59)	3.39(34)	
		$(^7\mathrm{Li}, t)$	4.00(138)		

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



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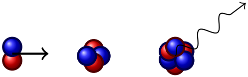
Data sets cannot constrained ANCs → renormalization factors

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

Summary and prospects

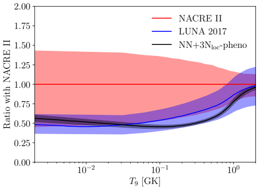


Ab initio methods are accurate for light systems

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

& no pheno. approximation of the E1 and M1 !

Ab initio prediction reduces the uncertainties on the $\alpha(d,\gamma)^6$Li rate by ∼7 !



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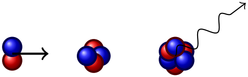

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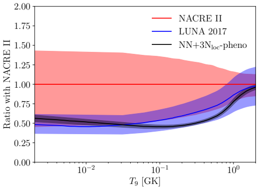

Use of ab initio input in the analysis of indirect measurements :

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

→ $^{12}C(\alpha,\gamma)^{16}O$ S-factor at stellar energies reduced by 21% !

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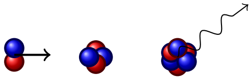

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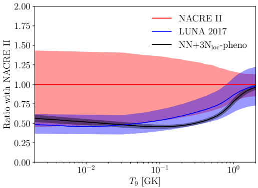

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- propagate these rates into nucleosynthesis network

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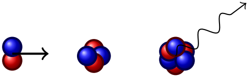

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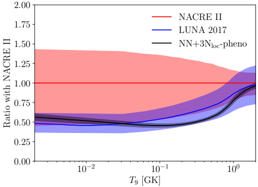

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Prospects : - comprehensive R-matrix fit of ^{12}C$(\alpha,\gamma)^{16}$O at all E
- propagate these rates into nucleosynthesis network
- improvements of theoretical description of transfer reaction

And because there are so many nice physics to do, opening postdoctoral position in few-body physics at FRIB ☺ !

https://careers.msu.edu/cw/en-us/job/515301/research-associatefixed-term

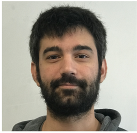
Deadline on August 21 (start date negotiable)

ask me any questions ☺

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

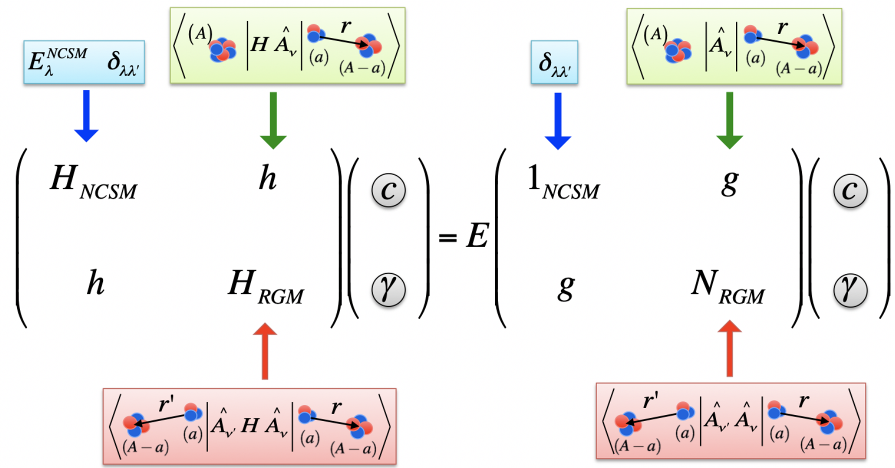
Argonne NATIONAL LABORATORY

Melina Avila

and thank you for your attention !

Appendices

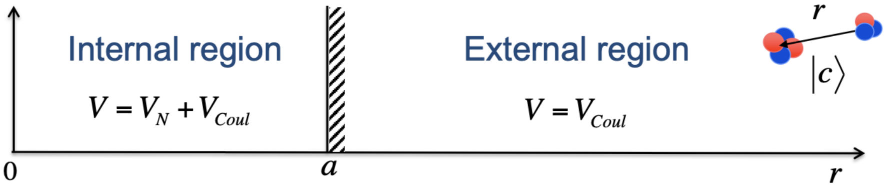
No core shell model with continuum Hamiltonian



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

Using microscopic R-matrix theory to obtain both bound and scattering states

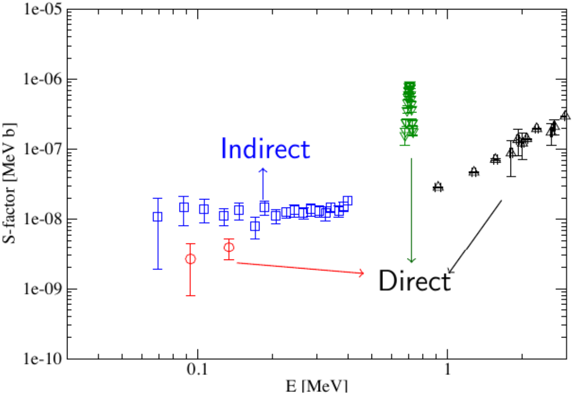
Microscopic R-matrix theory : [Descouvement and Baye, Rep. Prog. Phys. **73**, 036301 (2010)]



Internal part :
need to compute the potential

External :
only free components

Direct measurements are scarce and have large uncertainties

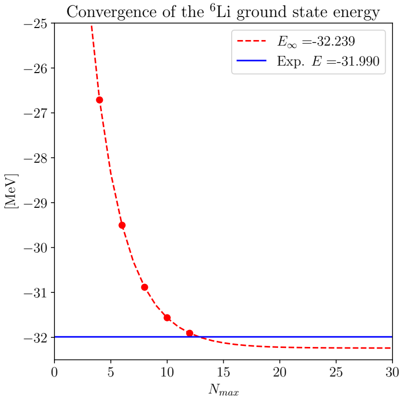


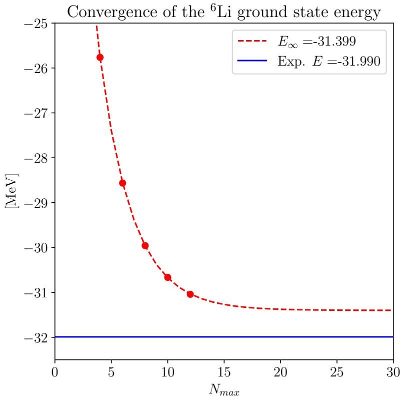
Direct measurements : $\alpha + d \rightarrow {}^{6}\mathrm{Li} + \gamma$

Indirect measurements : time-inversed reaction ${}^{6}\mathrm{Li} + {}^{208}\mathrm{Pb} \rightarrow \alpha + d$

→ Errors due to nuclear interferences [Hammache *et al.* PRC **82** 065803 (2010)]]

Can the χ-EFT force reproduce the exp. binding energy ?





NCSM extrapolation in N_{max} :

NN(N3LO) + 3N locally regulated : ^{6}Li E_{1^+} overestimated by 250 keV

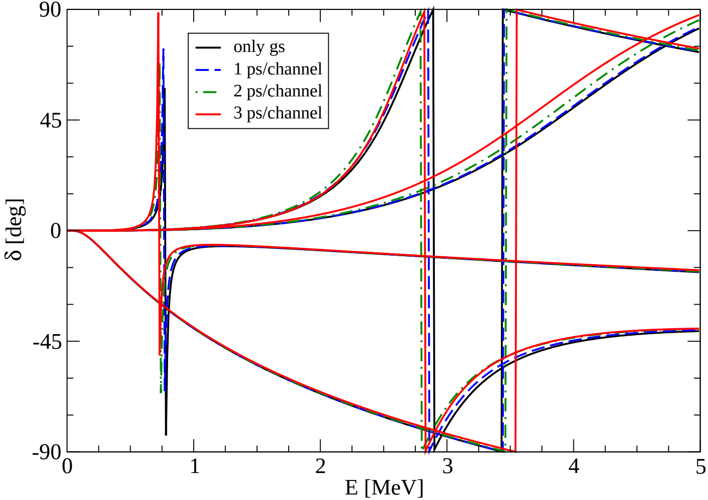
[Gazit, Quaglioni, Navrátil, PRL **122**, 029901 (2019)]

NN(N3LO) + 3N local/non-local regulated : ^{6}Li E_{1^+} underestimated by 600 keV

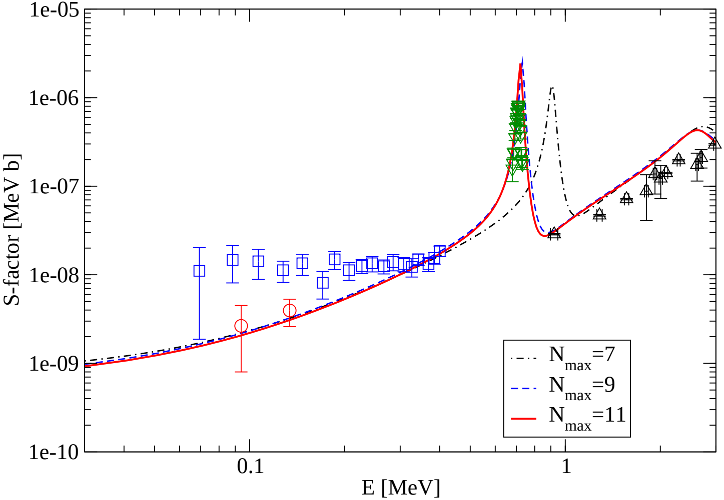
[Entem, Machleidt, Nosyk, PRC **96**, 024004 (2017)]

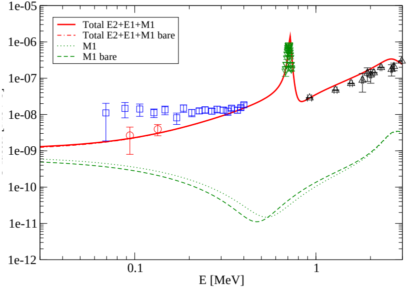
Convergence in pseudostates

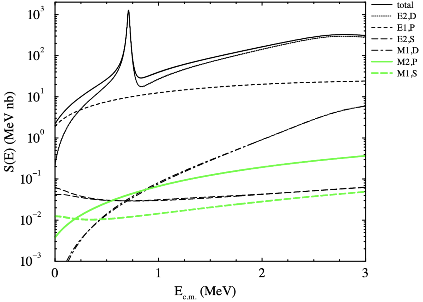
d pseudostates in ${}^3S_1$-${}^3D_1$, ${}^3D_2$ and ${}^3D_3$-${}^3G_3$



Convergence in $N_{\max}$







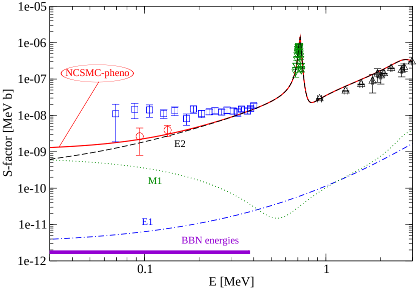
[Nollett *et al.* PRC **63**, 024003 (2001)]

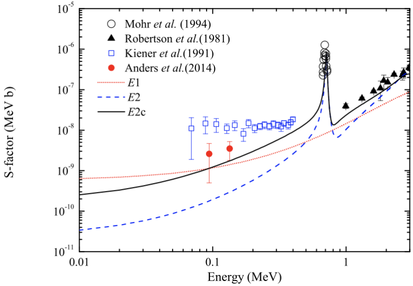
Independence of the SRG evolution

Arise from internal structure of d of ^{6}Li

→ visible in other models including microscopic d and ^{6}Li

Comparison with a three-body model of ^{6}Li





Three-body model of $^6\text{Li} \equiv \alpha + n + p$ **:** [Baye and Tursunov, JPG **45**, 085102 (2018)]

→ **smaller E2** : explained by smaller ANCs

→ no M1 in their model

→ non-negligible E1 : due to transition $\langle ^6\text{Li}(1^+; T=1) | M^{E1} | \alpha - d(T=0) \rangle$
with ^{6}Li 1^+ T=0.005 **vs** T=0.0003 in NCSMC

DWBA analysis of $^{13}C(^6Li,d)^{17}O$ data

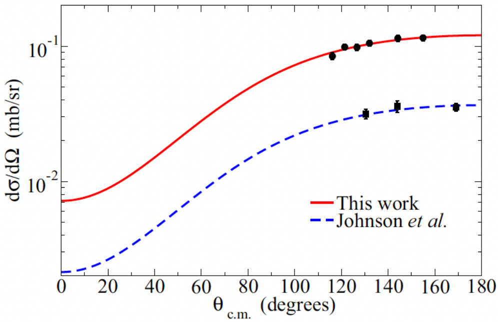
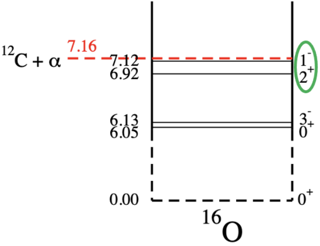
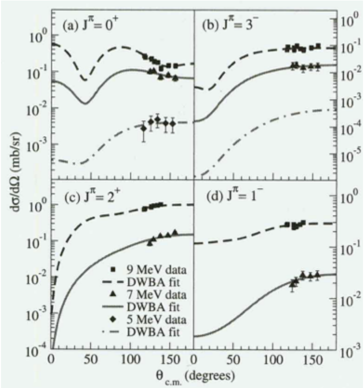


FIG. 3. (Color online) Cross section and DWBA fit as a function of center-of-mass angle of the $1/2^+$ subthreshold resonance state of excitation energy 6.356 MeV in ^{17}O measured in the present work (solid line) and in Ref. [5] (dashed line) by using a ^{13}C beam energy of 7.72 and 7.81 MeV, respectively.

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

DWBA analysis of $^{12}C(^6Li, d)^{16}O$ data





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