Topical applications: R-matrix analysis of ^{14}N(p,γ)^{15}O

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Mini-school on Nuclear Reaction Theories for Nuclear Astrophysics

Outline

- AZURE R-matrix code
- Where to begin... Cross sections, levels, widths
- Analysis of ^{14}N+p
  $\longrightarrow$ Fitting method
  $\longrightarrow$ Results

AZURE R-matrix code

- General multichannel R/A-matrix and external capture
- Single entrance channel particle pair, many exit
- Elastic, inelastic, particle-particle, capture-γ
- Differential, angle-integrated cross sections
- MINUIT fitting of widths/energies
- Extrapolations to astrophysically interesting regions
- Input/output observed widths Γ

- FORTRAN 77,, Lapack, CERNLIB
- C/GTK graphical interface for easier setup
- Open source: www.nd.edu/ azure (BETA, azure@nd.edu)

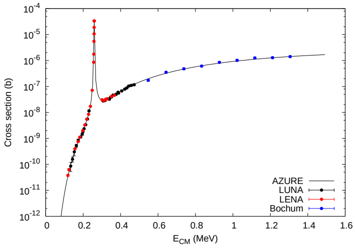
Astrophysical S-factor

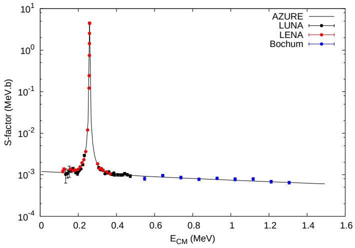
Express the cross section in terms of the astrophysical S-factor S(E):

$$\sigma(E) = \frac{1}{E}\exp(-2\pi\eta)S(E)$$

$$S(E) = E\exp(2\pi\eta)\sigma(E)$$

Allows us to factor out a large part of energy dependence, leaving the nuclear structure information in S(E):





Where to start

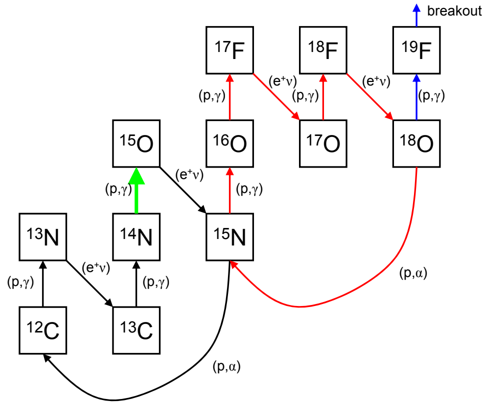
Data sources

- Ajzenberg-Selove Tables
- TUNL ND (www.tunl.duke.edu/nucldata) (A=3-20)
- EXFOR reactions database (www.nndc.bnl.gov/exfor/)
- NACRE (pntpm.ulb.ac.be/Nacre)
- Elastic scattering? Higher energy?
- ANC measurements from transfer reactions?

Fitting method

- Identify all available data (σ, levels, widths, ANCs)
- Identify and fit distinct (narrow) resonances
- Introduce non-resonant components
  $\longrightarrow$ Subthreshold, background, external capture
- Get the interferences right

The CNO cycle



^{14}N(p,γ)^{15}O: slowest step, determines rate

$^{14}N(p,\gamma)^{15}O$ - Published work

- Schröder et. al., NPA 467 (1987), 240
- Angulo and Descouvemont, NPA 690 (2001), 755
- Formicola et. al., PLB 591 (2004), 61
- Runkle et. al., PRL 94, 082503 (2005)
- Imbriani et. al., EPJ 25, (2005) 455
- Lemut et. al., PLB 634 (2006) 483
- Bochum data for 6.79 MeV transition
- Marta et. al., PRC 78 022802(R) (2008)

Previous results - Ground state transition

Energy [MeV]	$S_{0.00}(0)$ [keV b]	$S_{tot}(0)$ [keV b]
Formicola et. al. (2004)	0.25 ± 0.06	1.61 ± 0.08
Runkle et. al. (2005)	0.49 ± 0.08	1.68 ± 0.09
Marta et. al. (2008)	0.20 ± 0.05	-

Ajzenberg-Selove Tables

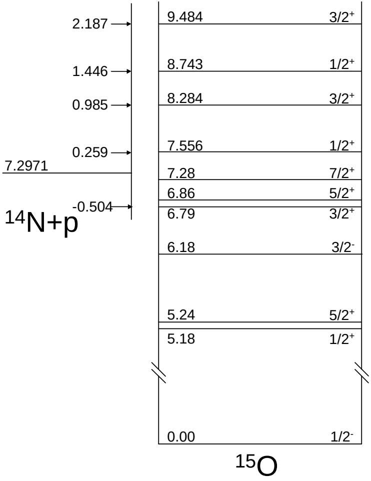
Resonaces in ^{14}N+p

TABLE 15.20

Resonances in $^{14}N+p$ [a])

E_p (keV)	Γ_{lab} (keV)	$\omega\Gamma_\gamma$ (eV)	Particles out	J^π	E_x (MeV)
278.1 ± 0.4	1.06 ± 0.11 [b])	$(14 \pm 1) \times 10^{-3}$ [a,b])	γ	$\frac{1}{2}^+$	7.5565
1058.0 ± 0.5	3.9 ± 0.7	0.31 ± 0.04 [a,b])	γ	$\frac{3}{2}^+$	8.2840
1550 ± 6	34	$(93 \pm 20) \times 10^{-3}$ [a,b])	γ	$\frac{1}{2}^+$	8.743
1742 ± 2 [c])	3.5 ± 0.3	0.16	γ, p_0	$\frac{5}{2}^+$	8.922
1742 ± 2 [c])	8	0.06	γ, p_0	$\frac{1}{2}^+$	8.922
1806.4 ± 1.5	4.2 ± 0.4	0.52	γ	$(\frac{3}{2})^-$	8.9821
2344 ± 8 [b])	205 [b])	6.1 ± 1.3 [b])	γ, p_0	$(\frac{3}{2}^+)$	9.484
2348 ± 3	10.8 ± 0.5	2.4	γ	$\frac{5}{2}^-$	9.488
2479 ± 1.7	9.4 ± 0.5	3.3	γ	$\frac{3}{2}^-$	9.609
2537 ± 4	2 ± 1		p_0	$(\frac{7}{2}, \frac{9}{2})^-$	9.664
3209	3 ± 1		p_0	$(\frac{5}{2}^-)$	10.291
3215	12 ± 2		p_0	$\frac{5}{2}^+$	10.296
3392 ± 5	<2	0.029 ± 0.010	γ_2, γ_6	$(\frac{9}{2}^+)$	10.461
3410	27 ± 5		γ_0, γ_2, p_0	$(\frac{3}{2})^-$	10.478
3440	150 ± 45		γ, p_0	$(\frac{3}{2})^+$	10.506
3880 ± 15	97		p_0	$\frac{7}{2}^+$	10.916
		Γ_{γ_0} (eV)			
3903 ± 3	106 ± 5	14 ± 3	γ, p_0, p_1	$\frac{1}{2}^+$	10.938
3996 ± 3	27 ± 2	1.4 ± 0.4	γ, p_0, p_1	$\frac{1}{2}^-$	11.025
4130 ± 15	<10		p_0		11.150

^{15}O compound nucleus



Final states

0.00 MeV $1/2^-$
5.18 MeV $1/2^+$
6.18 MeV $3/2^-$
6.79 MeV $3/2^+$
6.86 MeV $5/2^+$
7.28 MeV $7/2^+$

Ground state transition

Resonances

- 0.259 MeV $1/2^+$
- 0.985 MeV $3/2^+$
- 2.187 MeV $3/2^+$

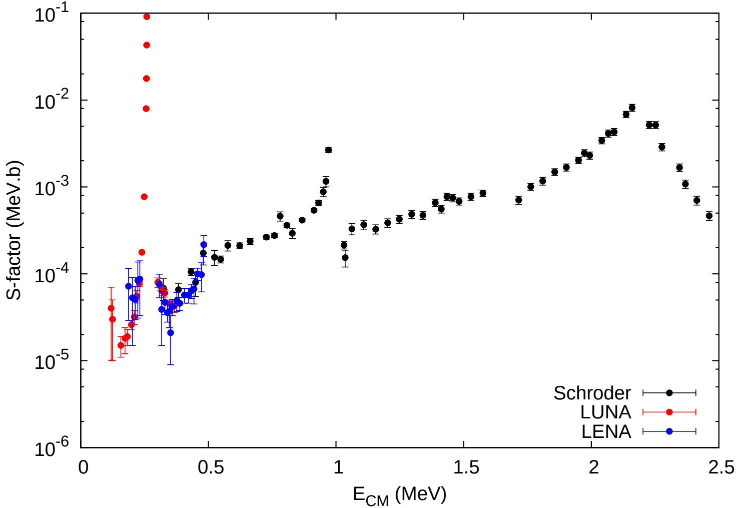
Non-resonant components

- Subthrehsold state
- External capture
- $3/2^+$ background pole

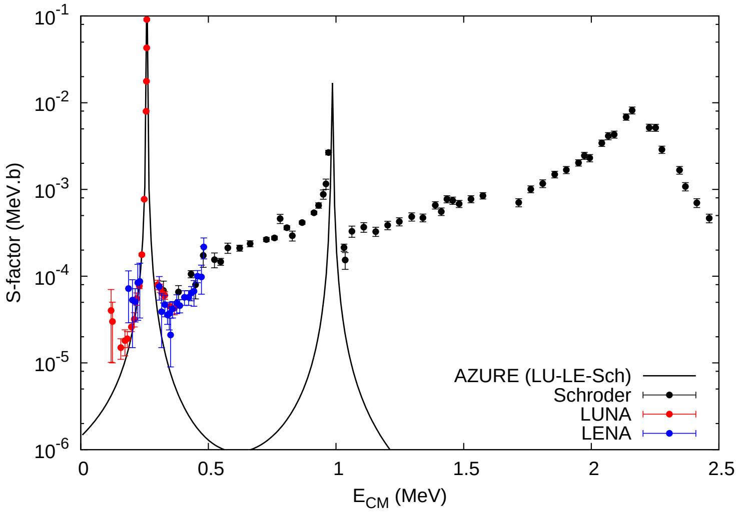
Constrain broad (non-resonant) components

- Fix subthreshold γ_p, background γ_p and ANC
- Fit only subthreshold and background γ_γ

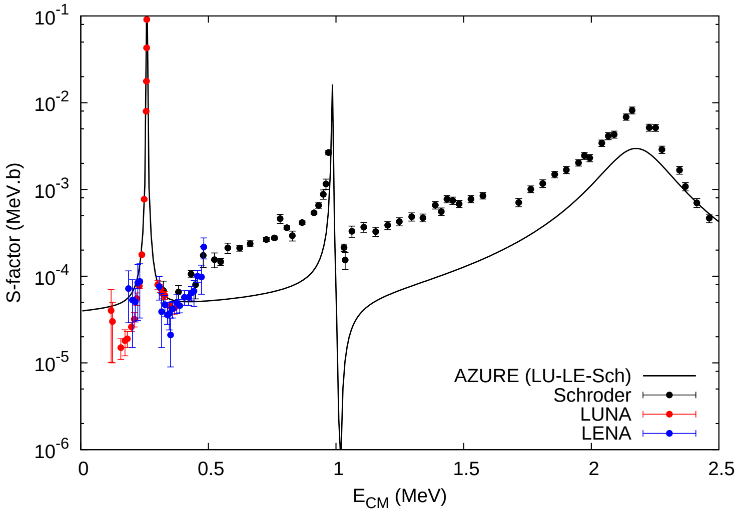
Begin with the data



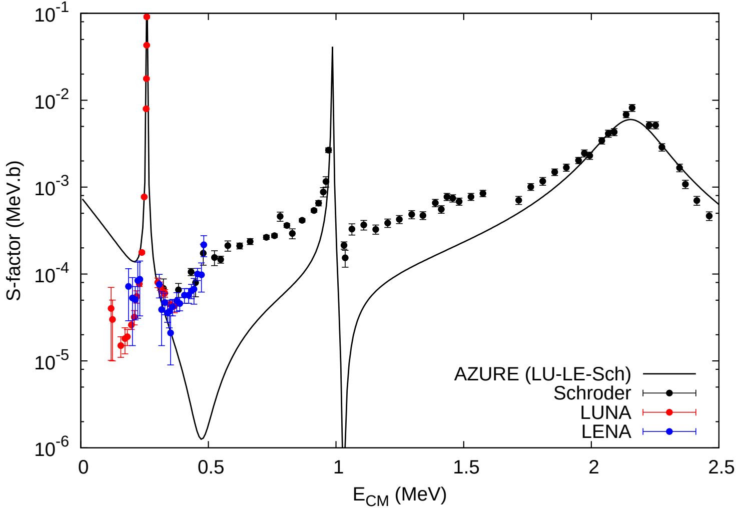
Add narrow resonances



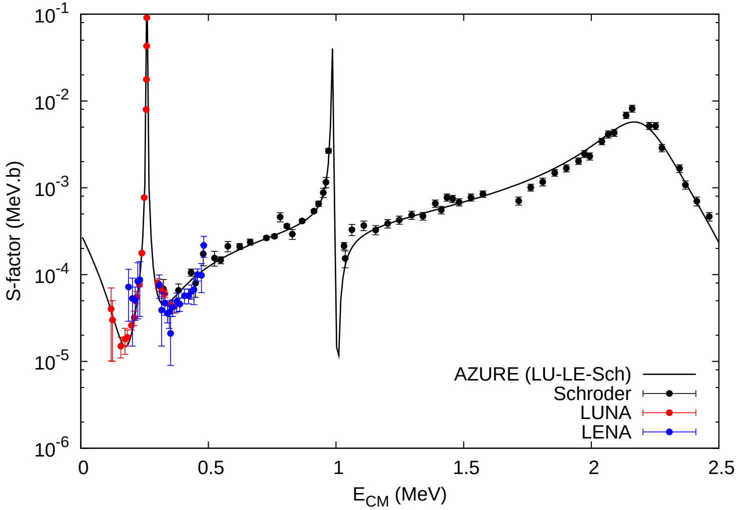
Add broad resonances



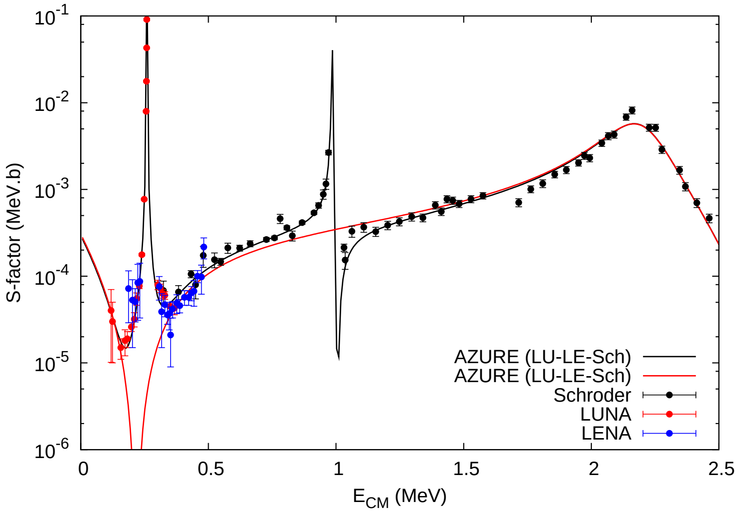
Add definite non-resonant components



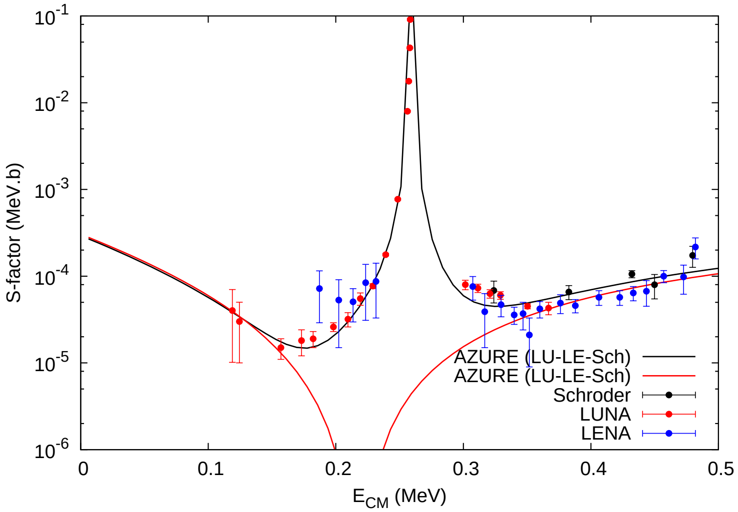
AZURE fit - Ground state transition



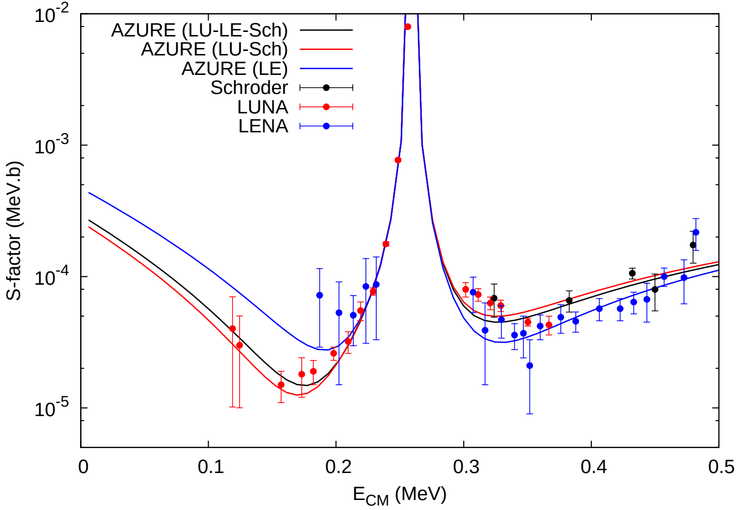
Remove narrow resonances...



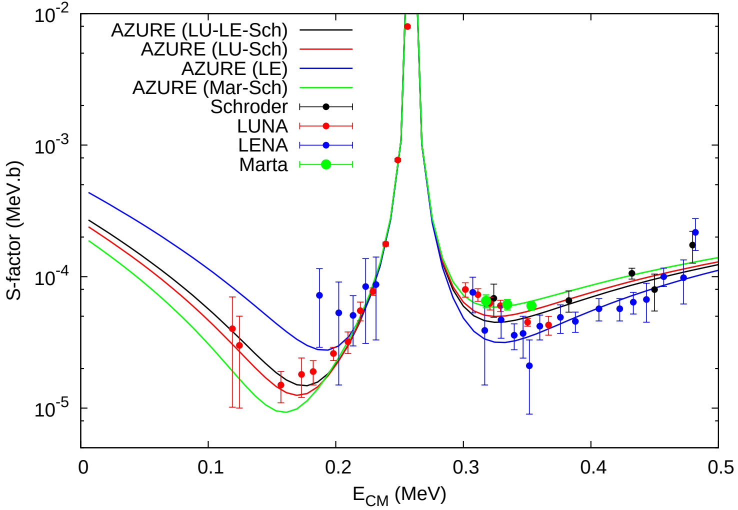
Remove narrow resonances...



Reproduction of previous fits

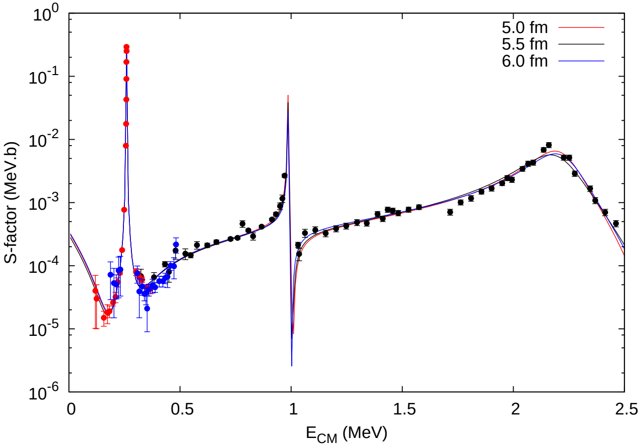


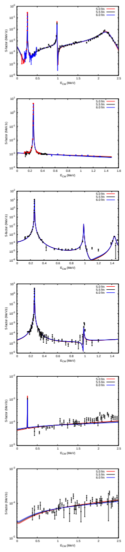
Fits using Marta et al. data



All transitions

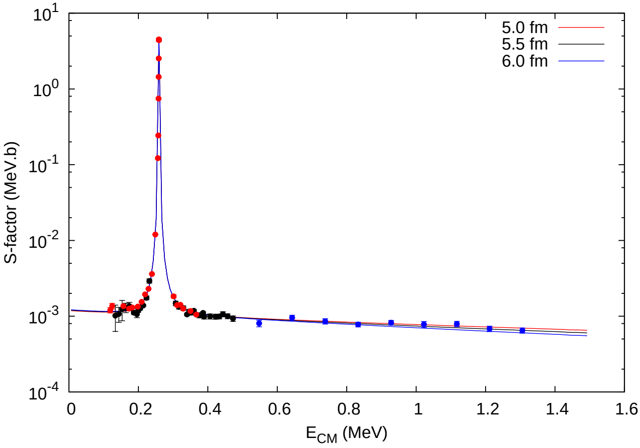
Ground state

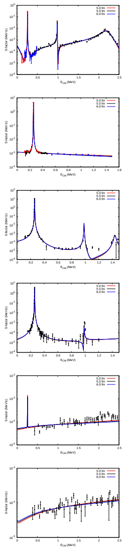




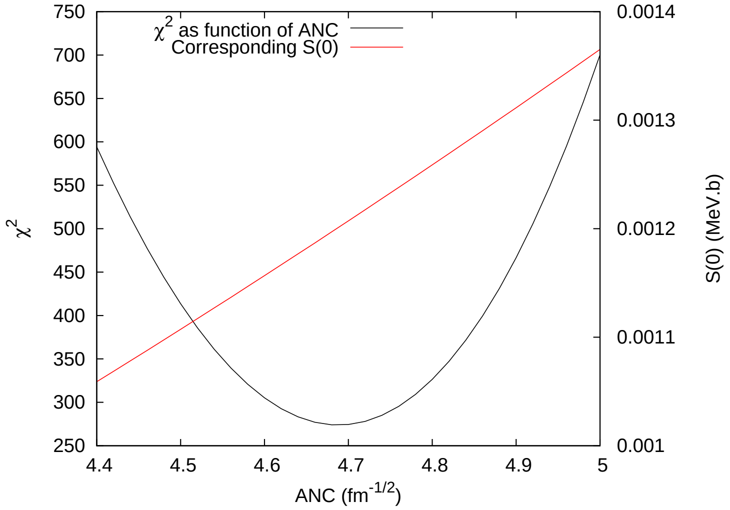
All transitions

6.79 MeV Final state



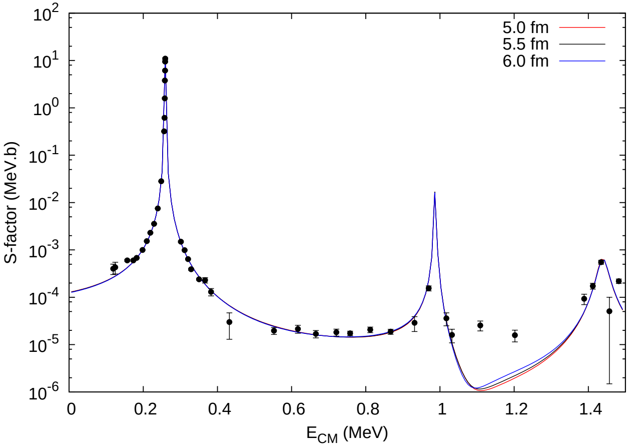


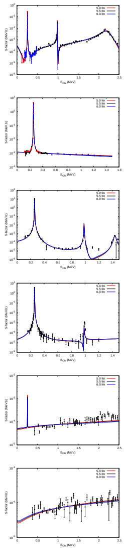
6.79 MeV transition - ANC



All transitions

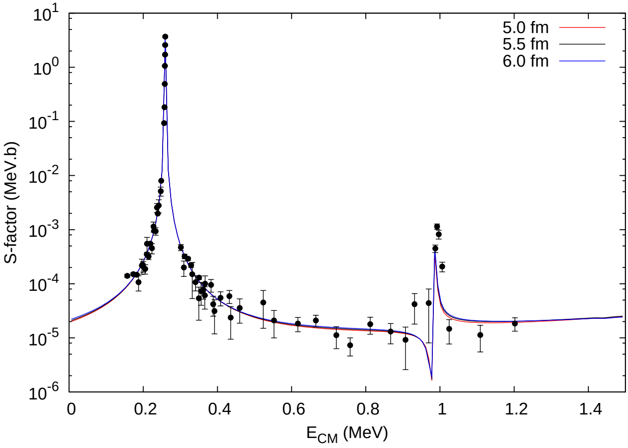
6.18 MeV Final state

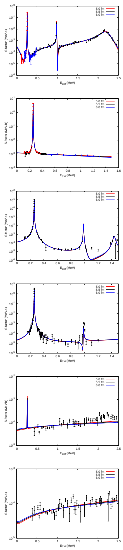




All transitions

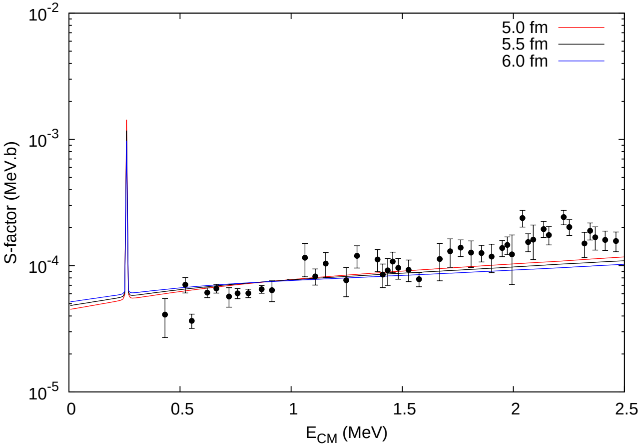
5.18 MeV Final state

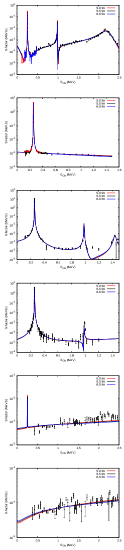




All transitions

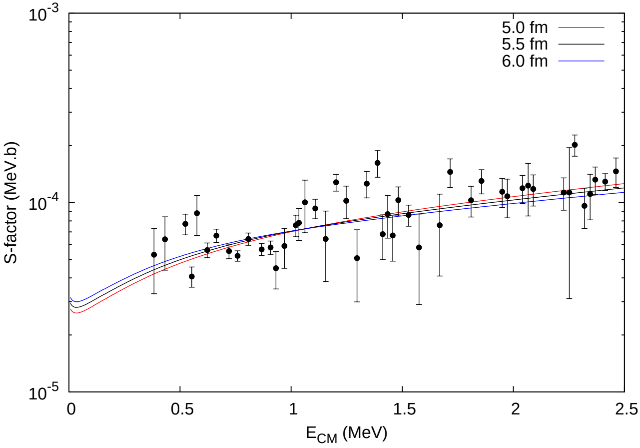
6.86 MeV Final state

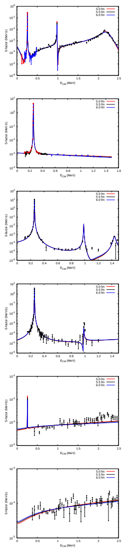




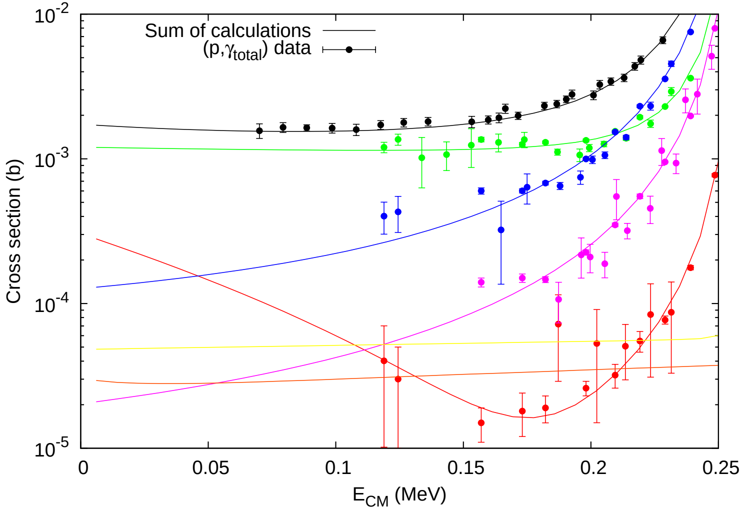
All transitions

7.28 MeV Final state





Sum of all transitions



Conclusions

- Find all previous data (cross section, resonace energies, widths etc.)
- Investigate sensitivities (radius parameter, widths, ANC)
- Consider all open channels

AZURE R-matrix code

- Adaptable, multi-channel R-matrix
- Open source and available
- E-mail: azure@nd.edu

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