Progress on ^{19}F(alpha,n)

Global R-matrix analysis of the ^{19}F(alpha,n) reaction

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Why picking the 19F(α,n) reaction?

Helps to determine the neutron environment in applications such as:

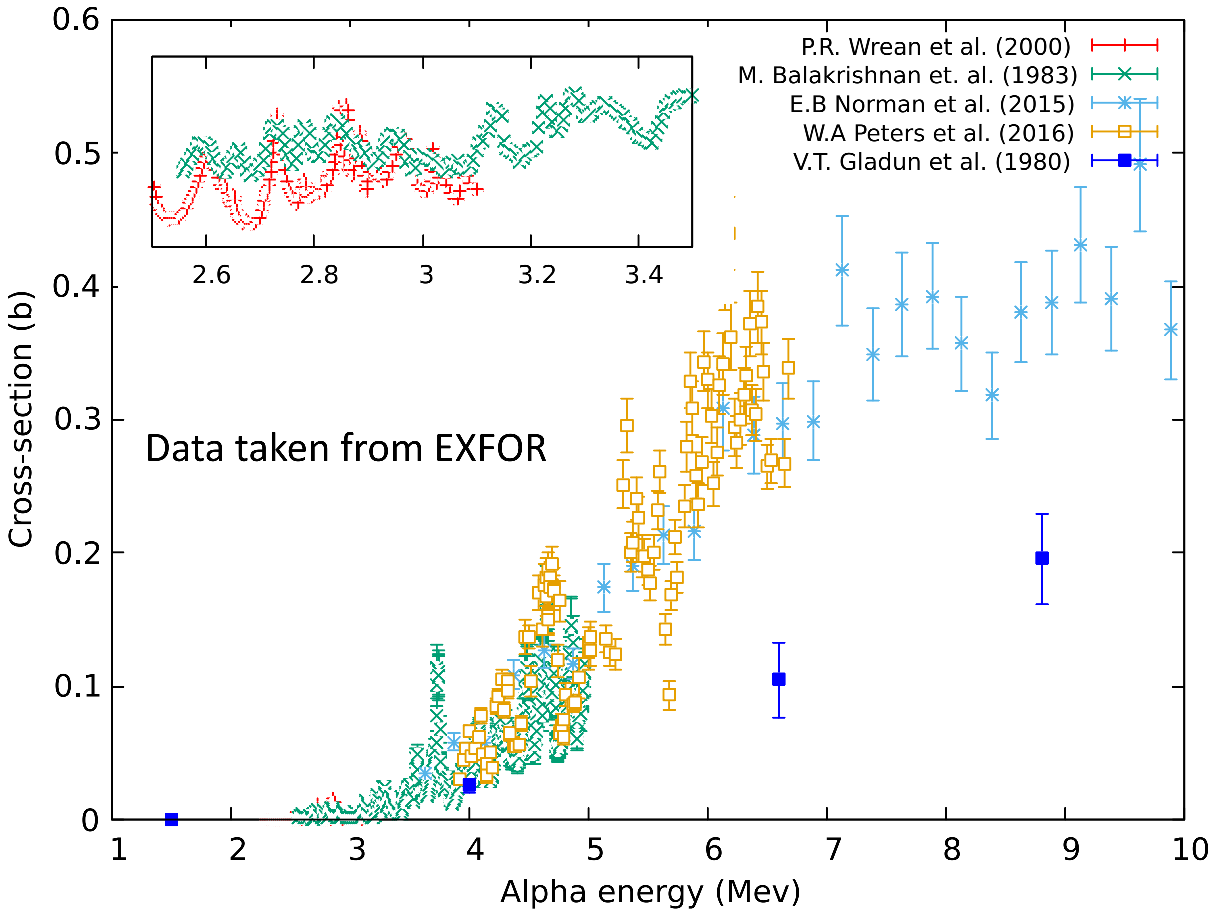
1. **Nuclear fuel cycle**
   - Fluorine compounds of U and Pu are everywhere in the nuclear fuel cycle thus F(α,n) neutrons are important to be understood to design non-destructive array measurements.

2. **Rare-events experiments**
   - Neutrons –coming from a-capture reactions- may dominate in background events in underground experiments looking for rare processes (such as dark matter WIMPs).

3. **Nucleosynthesis**
   - As the main source of ^{19}F in the universe has not been yet clearly identified –one of the answered questions in stellar modelling- the 19F(α,p) reaction that populates the 23Na system is the key ingredient and still hard to know in low energies. The 19F(α,n) reaction can be extremely useful in the interpretation of the data.

This case is a nice example of cross-cutting nuclear data needs

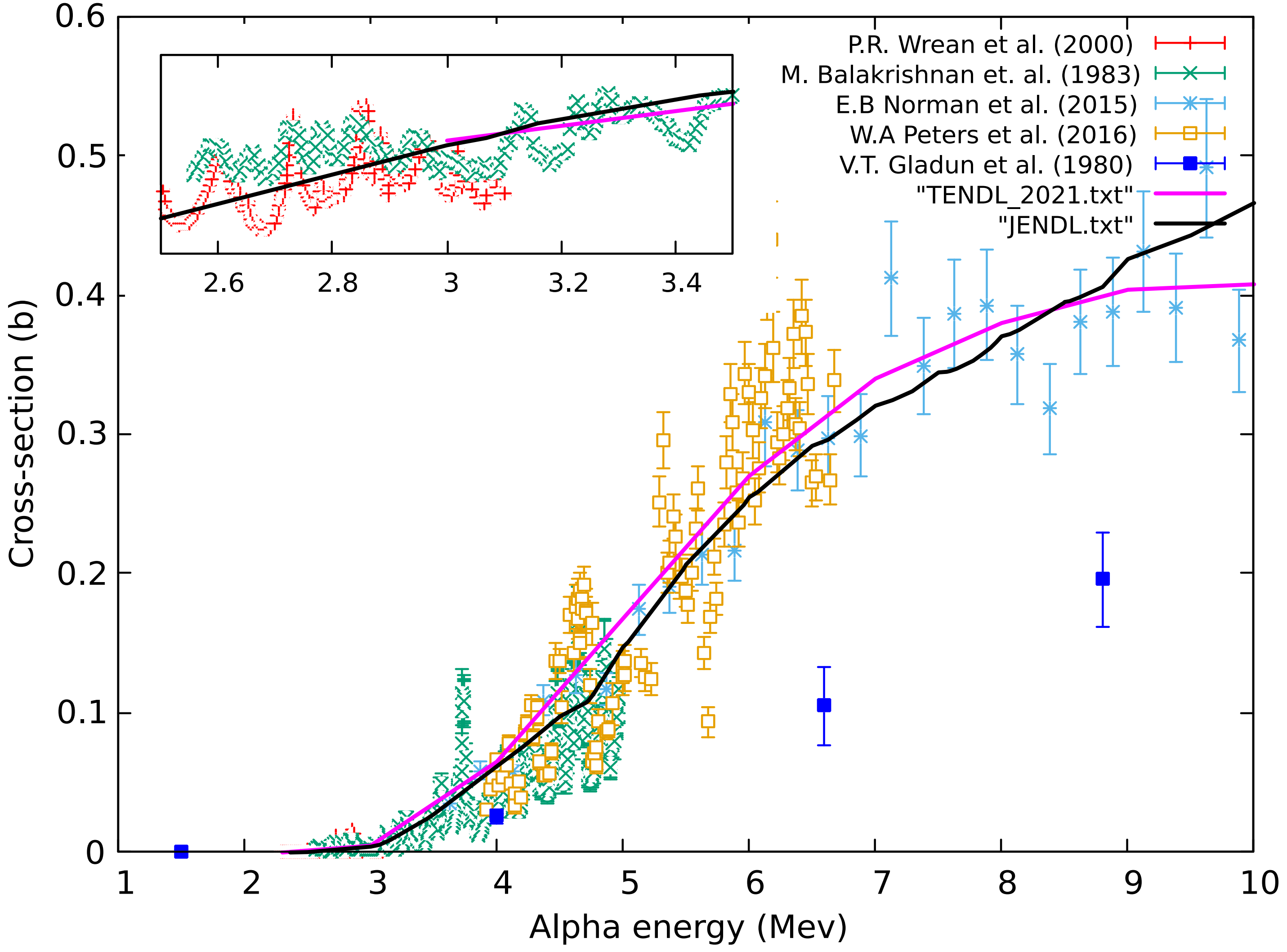
Total cross-sections of (α,n) reactions in fluorine (19F)



Data from:	Incident energy (MeV)	
Wrean et al.2000	Threshold-3.01	**Adopted dataset up to 3.1 MeV**
Balakrishnan, et al. 1983	2.6-5.1	Carbon contamination of the sample – significant contribution of the neutron yield especially below 3.4 MeV
Norman et al. 2015	3.63-9.88	From thick target yields
Peters et al. 2016	3.92-6.67	Idaho Lab. report
Gladun et al. 1980		Deviation from the other measurements
Van der Zwan and Geiger 1977	Threshold - 4.7 MeV	Excitation functions at 0 deg

Evaluated cross section data for the $^{19}F(\alpha,n)$

The evaluated cross sections were available in: **JENDL/AN-2005** and **TENDL-2021** while no data was found in JEFF-3.2 and ENDF/B-VII.1

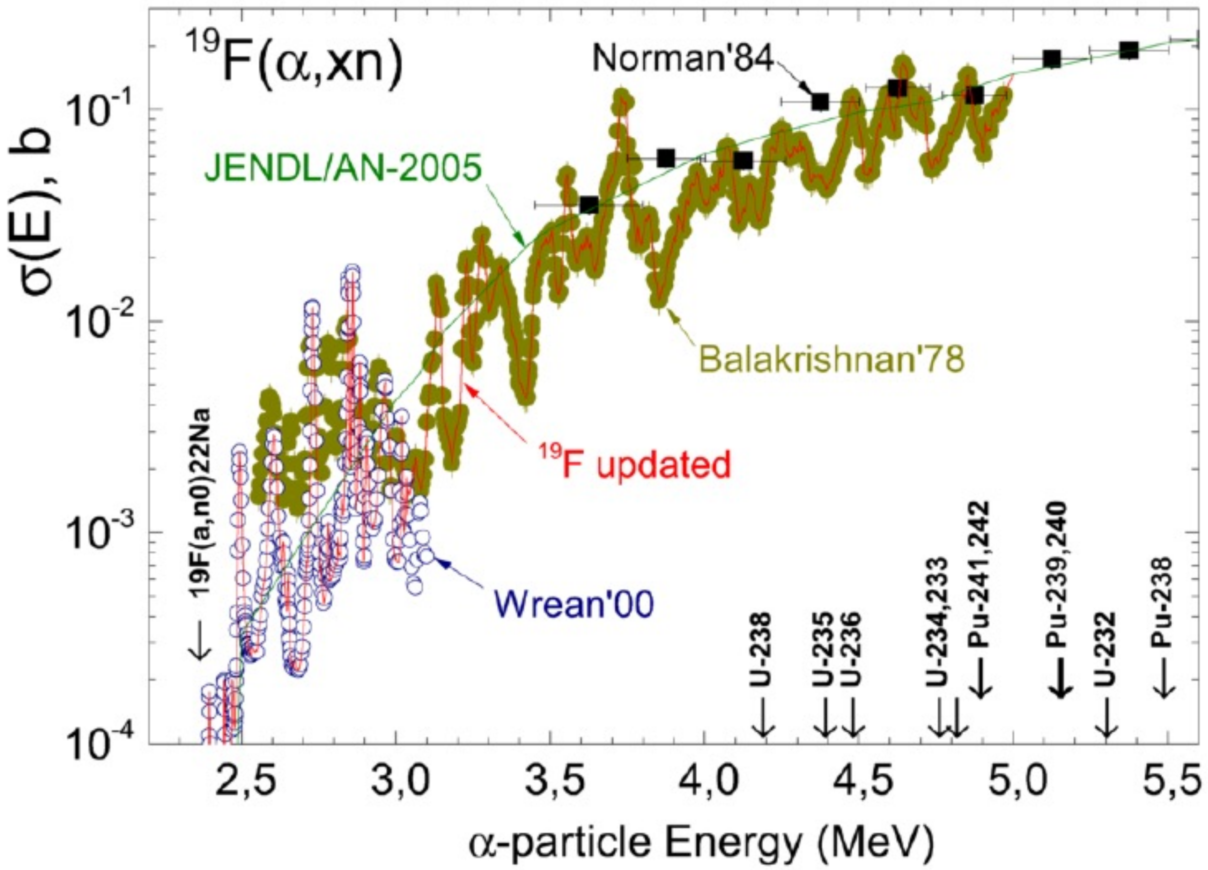


New evaluation

No-model evaluation – direct fit of cross sections

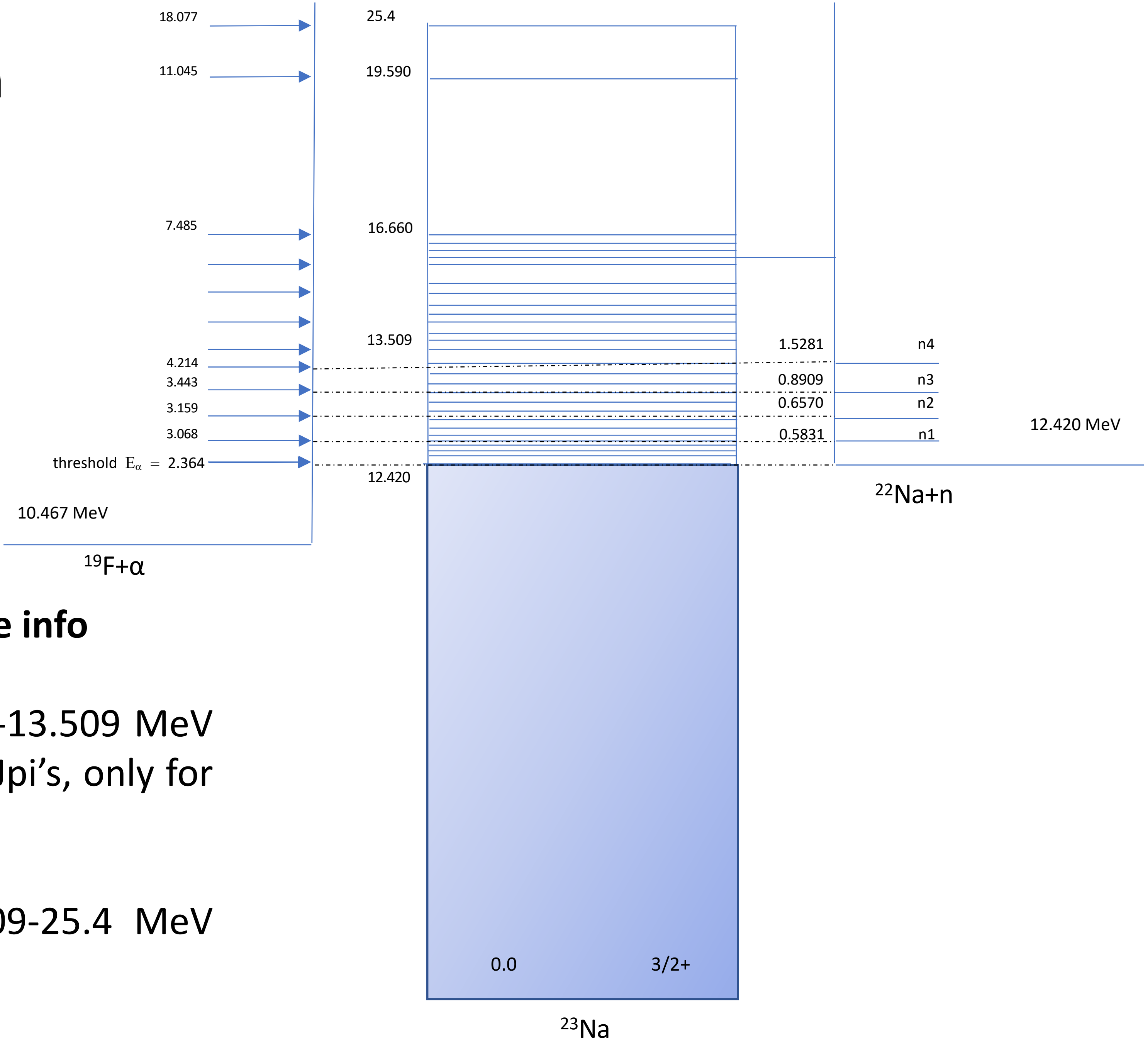
Adopted cross-section data up to 5 MeV:

- Up to 3 MeV adopt Wrean and Kavanagh 2001 data
- From 3 to 5 MeV adopt Balakrishnan et al 1978 data



Simakov et al., NDS 137 (2017) 190

Level diagram of the ^{23}Na compound system



ENSDF/TUNL databases: scarce info

In the energy region E_x=12.420-13.509 MeV there is no information for the Jpi's, only for energies E_R and widths Γ_R

In the energy region E_x=13.509-25.4 MeV only level energies are known

R-matrix analysis up to 3 MeV

- **AZURE2 R-matrix code**
  - Channels: alpha+^{19}F (incident)
    n+^{22}Na g.s.; p+^{22}Ne g.s.
    (outgoing)
  - Channel radius:$1.4\cdot(A_1^{1/3}+A_2^{1/3})$
  - L=4
  - No background poles

- **Experimental data included in the analysis**
  - (alpha,n): Wrean-Kavanagh 2001, angle-integrated, E_α up to 3 MeV, norm. unc. ~8%
  - (alpha,n): L. Van Der Zwan et al. 1977. excit. func., 0 deg, E_α up to 4.7 MeV
  - (alpha,el/p_0/p_1): Cseh et al, 1984; excitation function at 5 angles, E_α up to 3.7 MeV, no info on syst. unc.
  - (alpha,p_0): Schier et al. 1976: angular distributions at ~20 angles, E_α up to 5 MeV

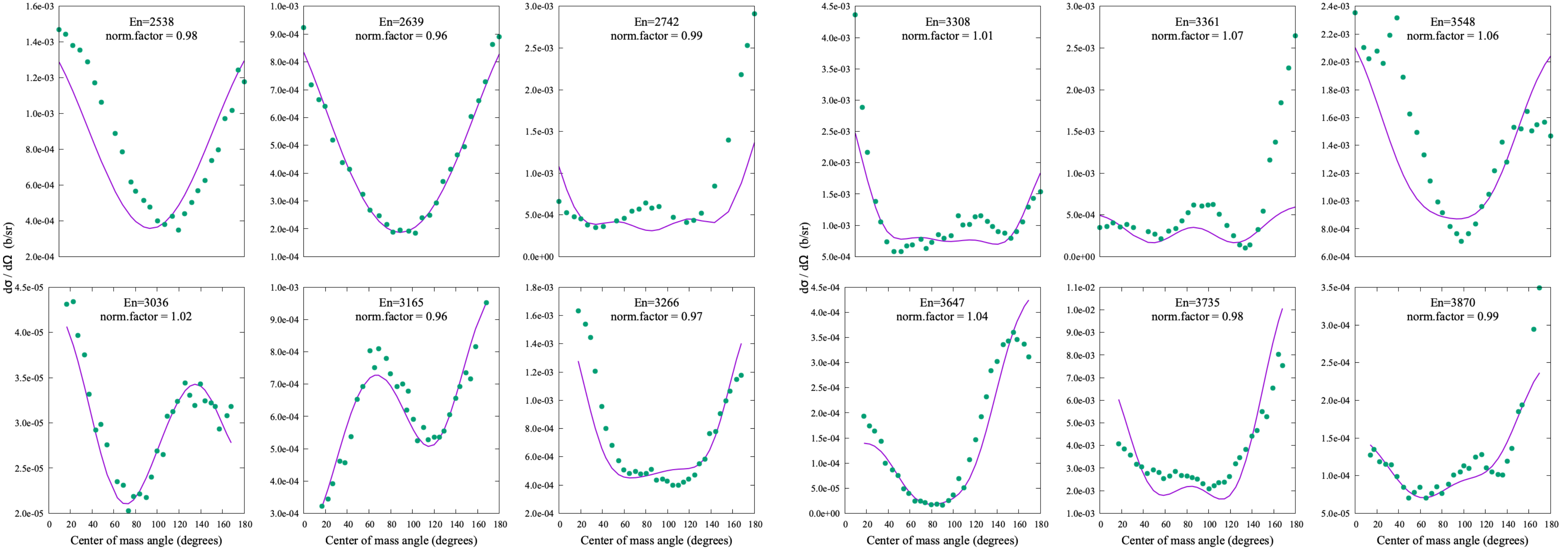
  Normalizations in R-matrix analysis: free

- *For energies above 2.4 MeV (E_x ~ 12.4 MeV) there is no J^π*

(alpha,p) channel

$^{19}F(\alpha,p_0)^{22}Ne$ differential cross section: we try to reproduce the data using Schier's extracted J^π values

Experimental data: Schier et al, 1976: angular distributions for excitation energies 12.563-14.453 MeV.
provides J^π values for all 21 resonances (single- and two-level R-matrix theory)

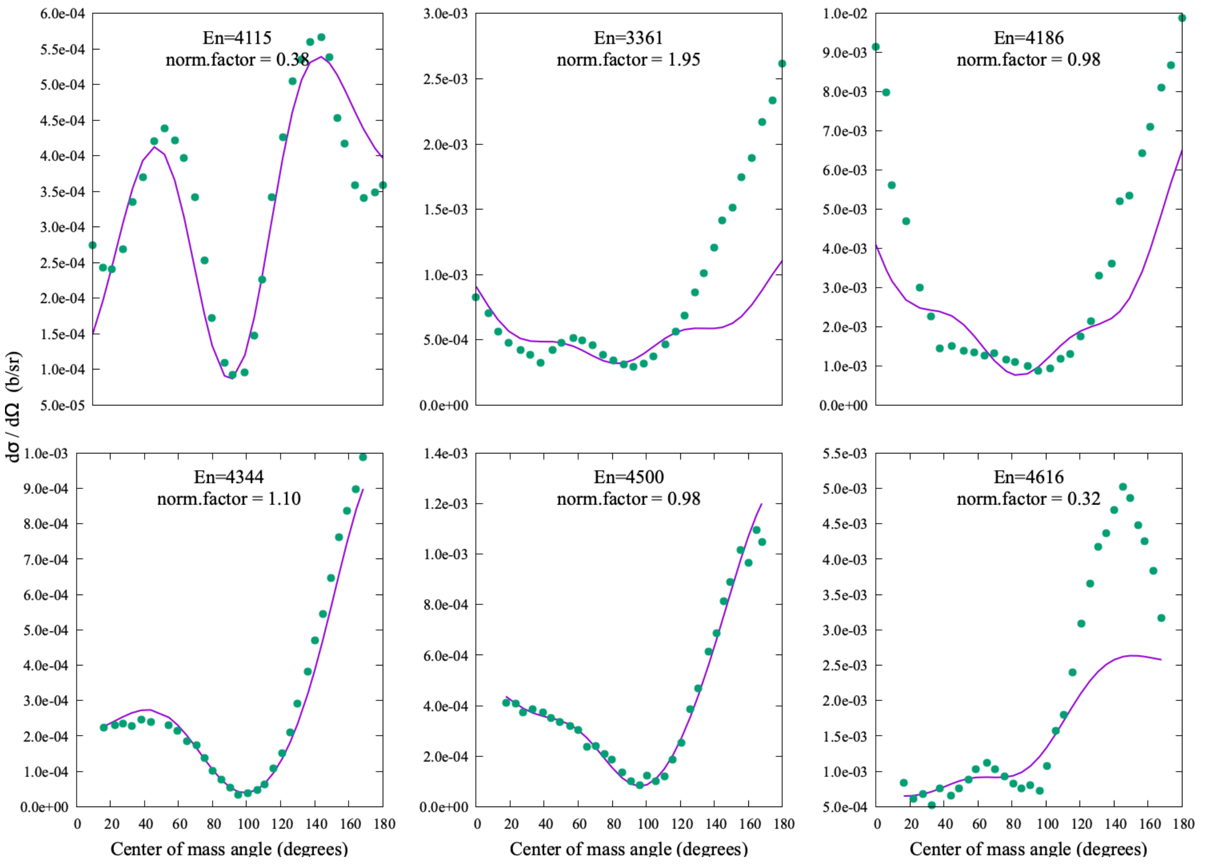


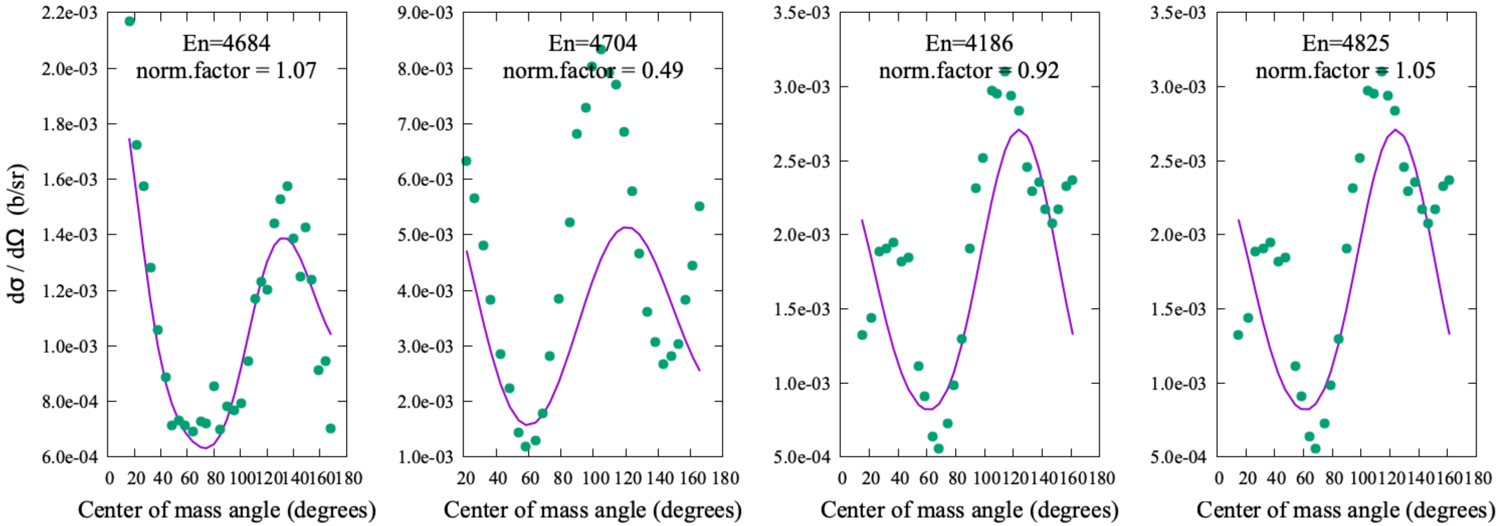
(alpha,p) channel,cont

- AZURE2 analysis for the (alpha, p) channel does a rather good job of describing most of the Schier et al. data
- In all data, J^{π} values suggested by Schier et al. were used (highlighted data).

(α,p_0) measurements Schier et al, 1976

E_a	E_x	Jpi
2.538	12.564	3/2+,3/2-
2.639	12.647	3/2-
2.742	12.732	5/2+,7/2-
3.036	12.975	1/2+,7/2-
3.165	13.082	1/2+,7/2-
3.266	13.165	5/2+,7/2-
3.308	13.200	7/2-,9/2+
3.361	13.243	5/2+,5/2-
3.548	13.398	3/2-,7/2-
3.735	13.552	1/2-,5/2+
3.87	13.664	5/2+,7/2-
4.115	13.866	1/2-,7/2-
4.186	13.925	3/2-,5/2+
4.344	14.056	3/2-,7/2-
4.5	14.184	3/2-,3/2+
4.616	14.280	3/2-,3/2+
4.704	14.353	1/2+,7/2-
4.825	14.453	1/2+,7/2-
4.895	14.511	1/2-,9/2+





All channels (alpha, alpha/p/n) included:

different resonances seen in different channels

(α,p_0) measurements Schier et al, 1976

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Cseh et al, 1984: no definitive J^π is given

$^{19}F(\alpha, \alpha_0)^{19}F$ resonance parameters

E_α [a] (MeV)	E_x [b] (MeV)	l_α	J^π	Γ_α/Γ [c]	Γ [c] (keV)	γ_α^2 (keV)
2.513	12.544	2	$\frac{3}{2}^+, \frac{5}{2}^+$	0.23, 0.16	6.6	76, 52
2.632	12.642	0	$\frac{1}{2}^+$	0.17	11	15
		1	$\frac{1}{2}^-, \frac{3}{2}^-$	0.21, 0.11	13	34, 18
2.737	12.729	2	$\frac{3}{2}^+, \frac{5}{2}^+$	0.17, 0.12	12	44, 31
2.813	12.791	2	$\frac{3}{2}^+, \frac{5}{2}^+$	0.065, 0.045	11	12, 9
2.846	12.819	1	$\frac{1}{2}^-, \frac{3}{2}^-$	0.37, 0.20	3.4	8.4, 4.5
2.873	12.841	2	$\frac{3}{2}^+, \frac{5}{2}^+$	0.11, 0.074	17	27, 19
2.887	12.852	0	$\frac{1}{2}^+$	0.11	5.5	2.3
		1	$\frac{1}{2}^-, \frac{3}{2}^-$	0.12, 0.064	12	8.4, 4.5
3.126	13.050	2	$\frac{3}{2}^+, \frac{5}{2}^+$	0.14, 0.097	9	9, 6.2
3.151	13.071	1	$\frac{1}{2}^-, \frac{3}{2}^-$	0.39, 0.21	6.8	8.5, 4.6
3.156	13.075	2	$\frac{3}{2}^+, \frac{5}{2}^+$	0.21, 0.15	12	18, 12
3.250	13.153	2	$\frac{3}{2}^+, \frac{5}{2}^+$	0.18, 0.12	11	11, 7.5
3.302	13.195	0	$\frac{1}{2}^+$	0.90	6.3	9
3.359	13.243	3	$\frac{5}{2}^-, \frac{7}{2}^-$	0.15, 0.11	12	24, 18
3.467	13.332	2	$\frac{3}{2}^+, \frac{5}{2}^+$	0.24, 0.17	23	18, 12
3.567	13.422	3	$\frac{5}{2}^-, \frac{7}{2}^-$	0.07, 0.053	15	8.3, 6.3
3.621	13.459	1	$\frac{3}{2}^-$	0.69	22	20

Cseh resonances were added with due care to avoid double counting

Van Der Zwan et al, 1977 (α,n) data: no J^π given

E_a	E_x	Jpi
2.606	12.62	1/2-
2.731	12.724	3/2+
2.861	12.831	3/2+
2.881	12.848	3/2-
2.904	12.866	3/2+
3.246	13.149	5/2+
3.286	13.182	1/2+
3.298	13.192	1/2-
3.310	13.2	9/2+
3.350	13.235	1/2-
3.521	13.376	1/2-
3.950	13.73	3/2+
3.996	13.768	1/2-
4.037	13.802	1/2+
4.170	13.912	1/2-
4.330	14.044	3/2-
4.350	14.061	3/2-
4.456	14.148	3/2-
4.597	14.246	3/2-

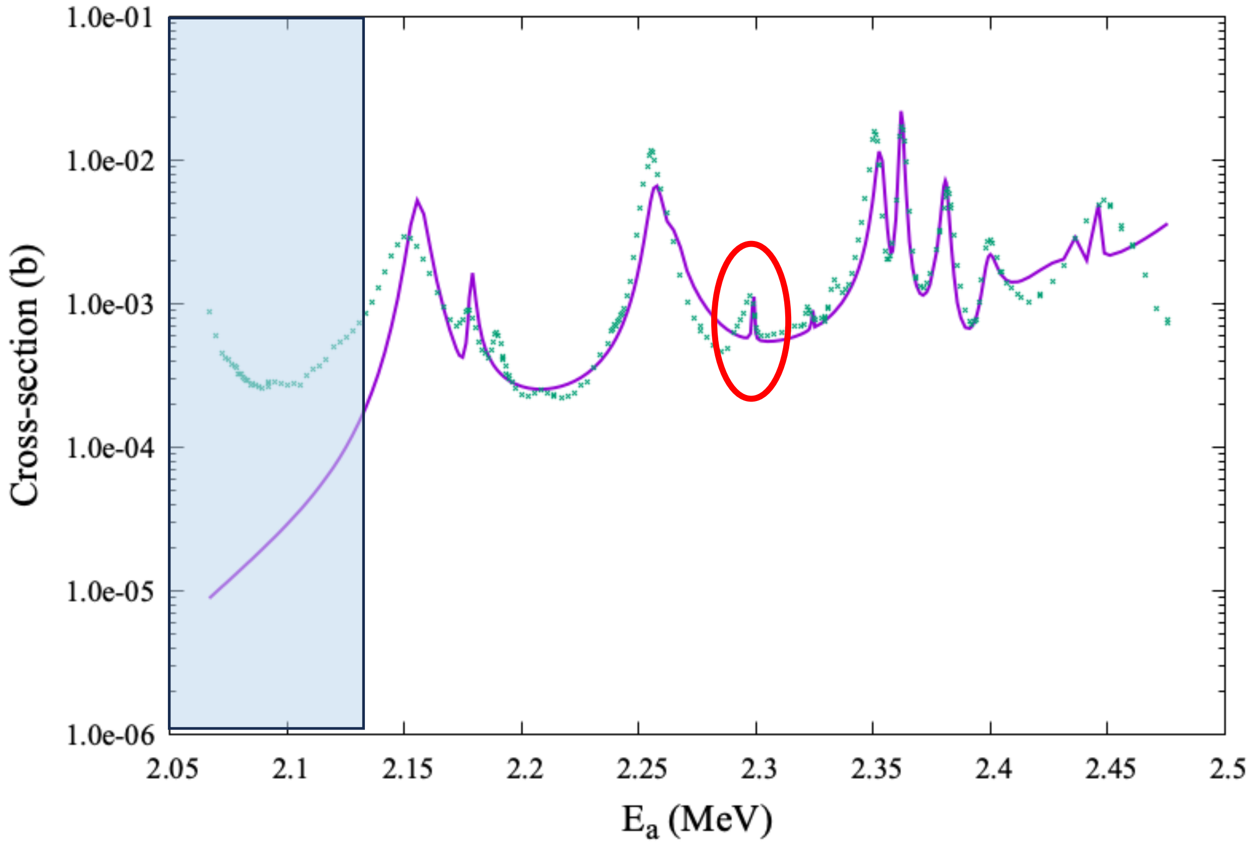
In some cases, J^π had to be changed to keep good fit (magenta)

The J^π values for the Zwan et al. resonances were selected by the trial & error technique

Multichannel overview

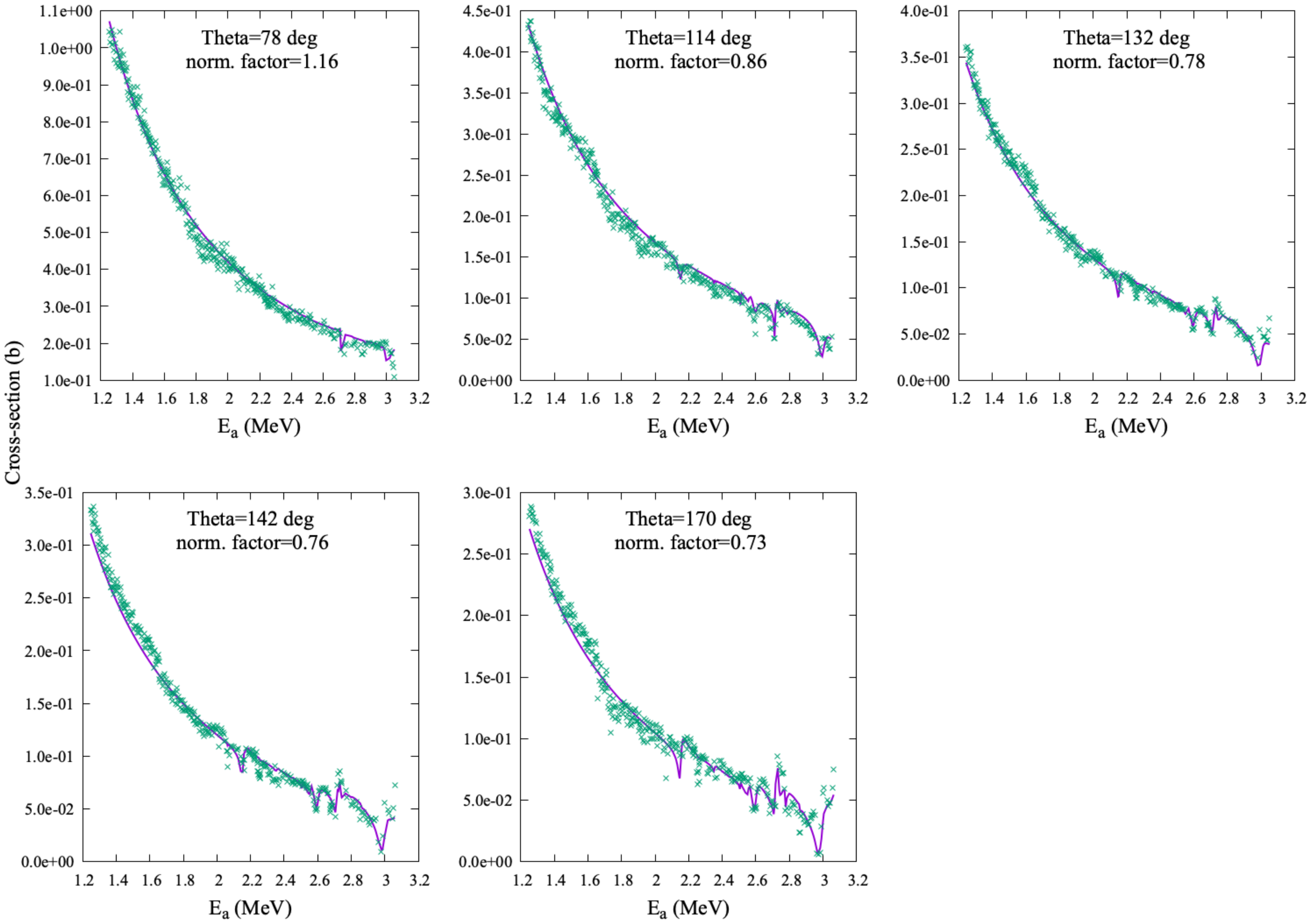
$^{19}F(a,n)^{22}Ne$ cross section

- Limited energy range:
  - For lower part need to add the resonances from ENSDF/TUNL (Kuperus et. al, 1965)
  - High-energy threshold not included yet (**currently focus on this energy region**)



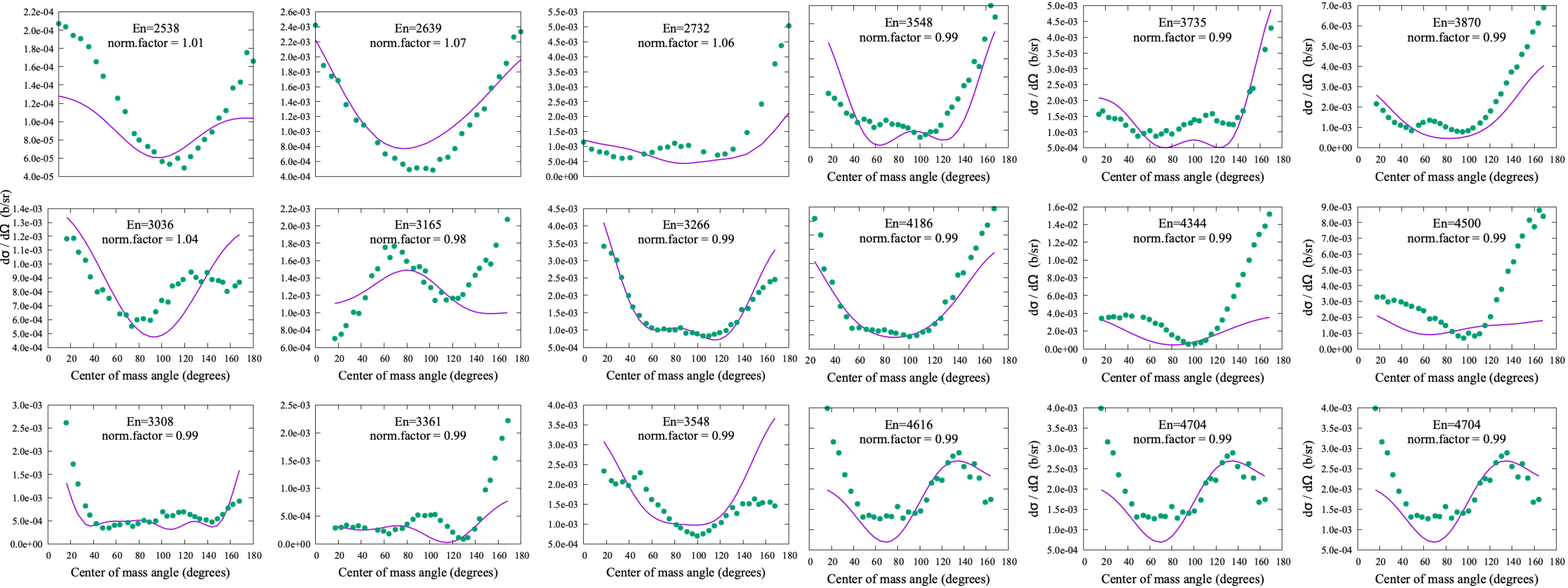
Multichannel overview, cont.

$^{19}F(a,a)^{19}F$ cross section



Multichannel overview, cont.

^{19}F(a,p)^{19}F cross section

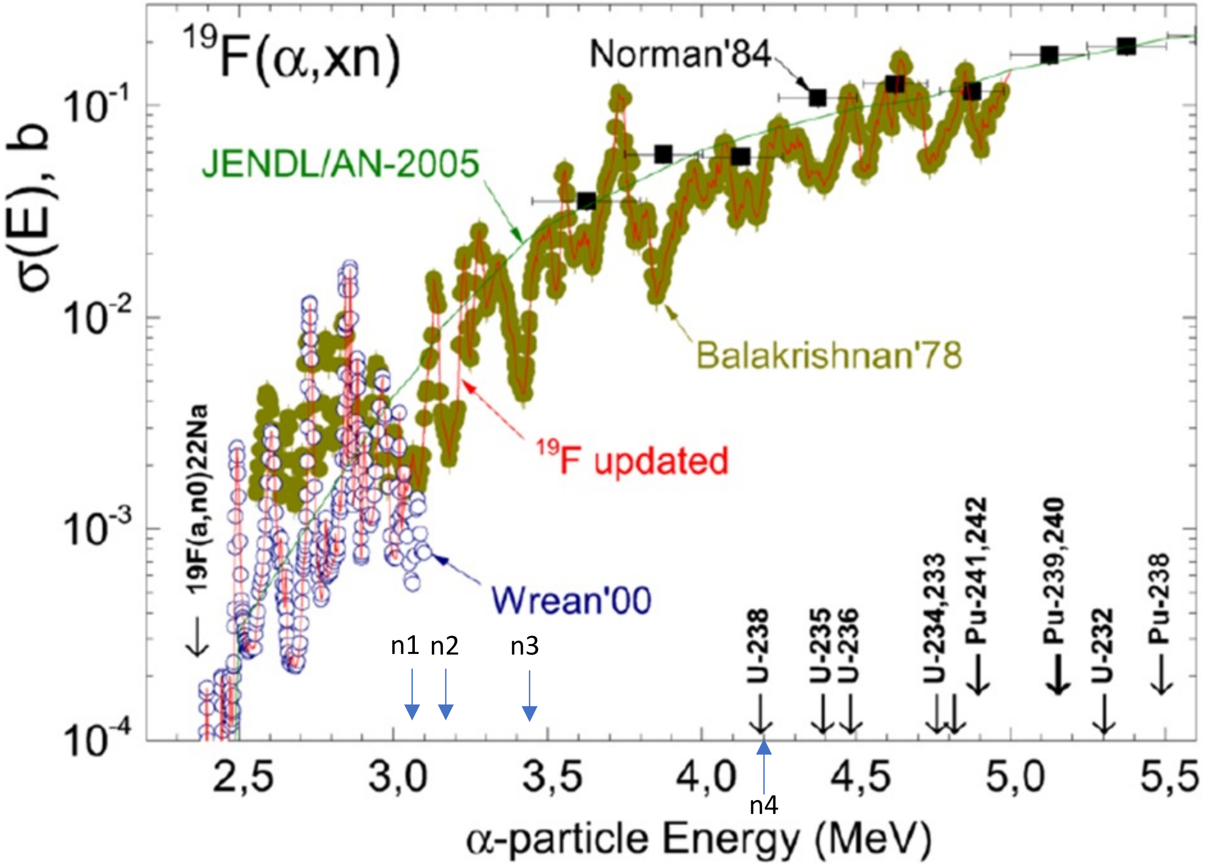


Conclusions so far

- R-matrix analysis of the alpha+^{19}F (^{23}Na compound) system up to 3 MeV is almost complete.
- The simultaneous fits for all open channels is a rather difficult task mainly due to the scarce nuclear structure information
- Can we trust Schier's and/or our spin-parity assignments (based on trial and error)?
- Alternative approach: apply machine-learning algorithms to get the spin-parities
- More experimental data are needed

Next steps

- Extend the R-matrix analysis to 5 MeV
- Include inelastic channels
- Include Balakrishnan et al. angle-integrated (alpha,n) data and other (alpha, p1) differential cross-section data
- Potential problem: quality of data



Goal

- Perform an evaluation up to 9 MeV incident alpha energies – for applications
- Produce ENDF files
- Challenges:
  - Quality of data
  - Growing number of channels
  - Breakup channel: $^{15}N+2\alpha$; threshold 4830 keV
- Solution to dealing with growing number of channels, break-up, etc.: Reduced R-matrix calculations – currently not implemented in AZURE2

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