The Galactic Aluminum Conundrum in the Light of New Data at Astrophysical Energies

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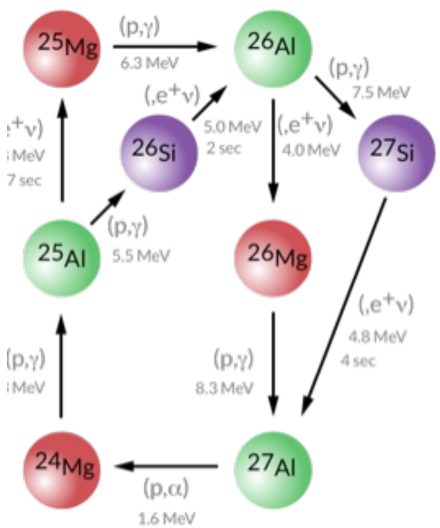
^{27}Al: an ingredient in multimessenger astronomy

MgAl cycle in massive stars

- It is ignited at temperatures > 0.03 GK and it is important to determine the abundances of medium mass nuclei

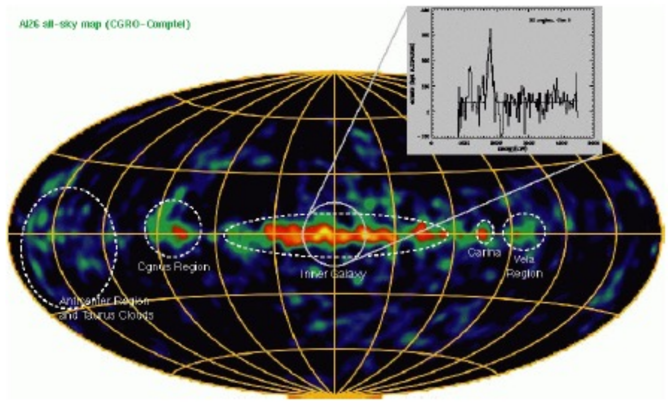


Mg-Al Cycles

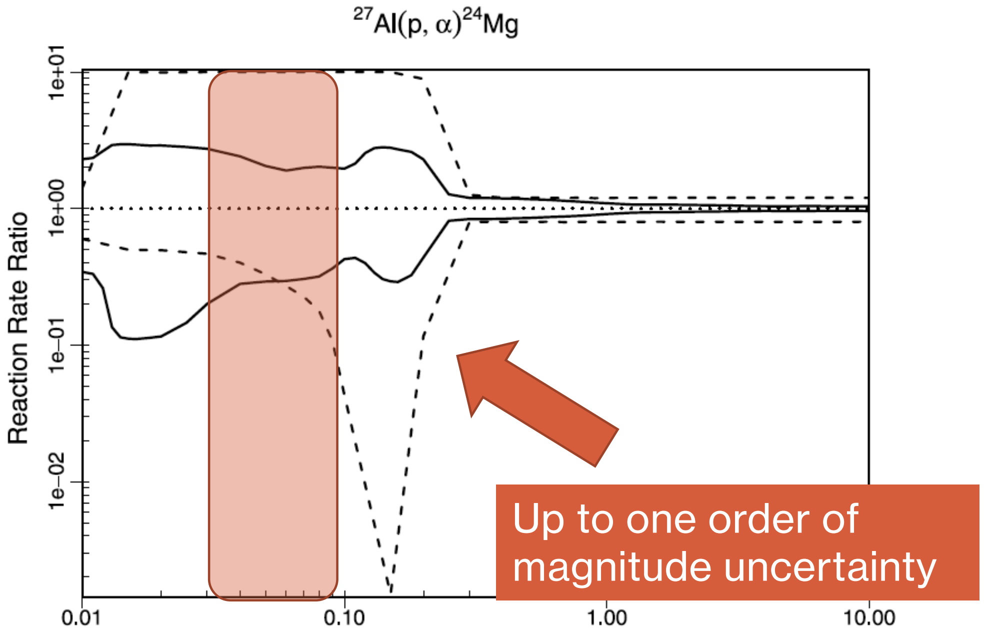
^{26}Al/^{27}Al abundance ratio

- ^{26}Al abundance is used to estimate the number of Galactic neutron stars and, therefore, of neutron star mergers (sources of GW)

The ^{26}Al/^{27}Al is generally estimated, so it is influenced by ^{27}Al abundance predictions



$^{27}Al(p,\alpha)^{24}Mg$ status of the art

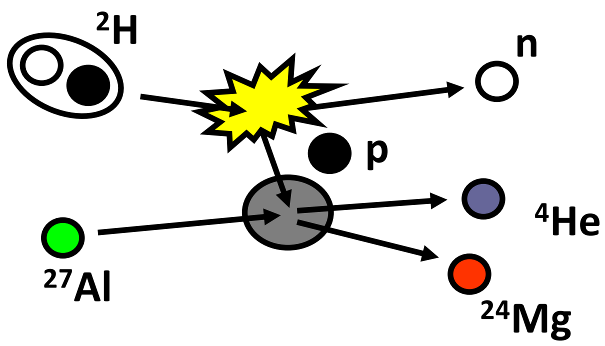


Upper Limits of Resonances
Note: enter partial width upper limit
Note: ...PT <B> for g-rays [enter: "u

Ecm	DEcm	Jr	G1	DG1
71.5	0.5	2	7.4e-14	0.0
84.3	0.4	1	2.6e-12	0.0
193.5	0.7	2	7.5e-4	0.0
214.7	0.4	3	9.7e-5	3.9e-5
282.1	0.4	4	6.4e-5	2.6e-5
437.2	0.4	5	3.4e-5	0.0

The most recent review [Iliadis et al. (2010)] shows that for most low-energy resonances only an upper limit is known
→ These resonances are the most influent for astrophysics

The method (see PRL 101, 152501 (2008))



<u>When narrow resonances dominate</u> the S-factor the reaction rate can be calculated by means of the resonance **<u>strengths and resonance energies only</u>**. Both can be deduced from the THM cross section.

Let's focus on resonance strengths

$$\omega\gamma_i = \frac{2J_i + 1}{(2J_p + 1)(2J_{^{27}Al} + 1)} \frac{\Gamma_p^i \Gamma_\alpha^i}{\Gamma_{tot}}$$

The strengths are calculated from resonance partial widths

What is its physical meaning?
Area of the Breit-Wigner describing the resonance

<u>Advantage:</u>
no need to know the resonance shape (moderate resolution necessary)

$$\omega\gamma_i^{\mathrm{THM}} \approx \omega_i N_i \frac{\Gamma^i_{p,\,\mathrm{s.p.}}}{\sigma_{(d,n)}(\theta_n^{c.m.})}$$

In the THM approach we determine the strength in arb.units. Normalization to a known resonance is necessary

How to get absolute units (from APJ 708 (2010) 796)

- For narrow resonances: $$\delta(x - E_{R_i}) = \lim_{\Gamma_i \to 0} \frac{1}{2\pi} \frac{\Gamma_i}{(x - E_{R_i})^2 + \left(\frac{\Gamma_i}{2}\right)^2}$$

- The THM cross section can be fitted using the equation: $$\frac{d^2\sigma}{dE_{c.m.}\, d\Omega_n} = \sum_{i=1}^{n} N_i \times \exp\left[-\frac{1}{2}\left(\frac{E_{c.m.} - E_{R_i}}{\sigma}\right)^2\right].$$

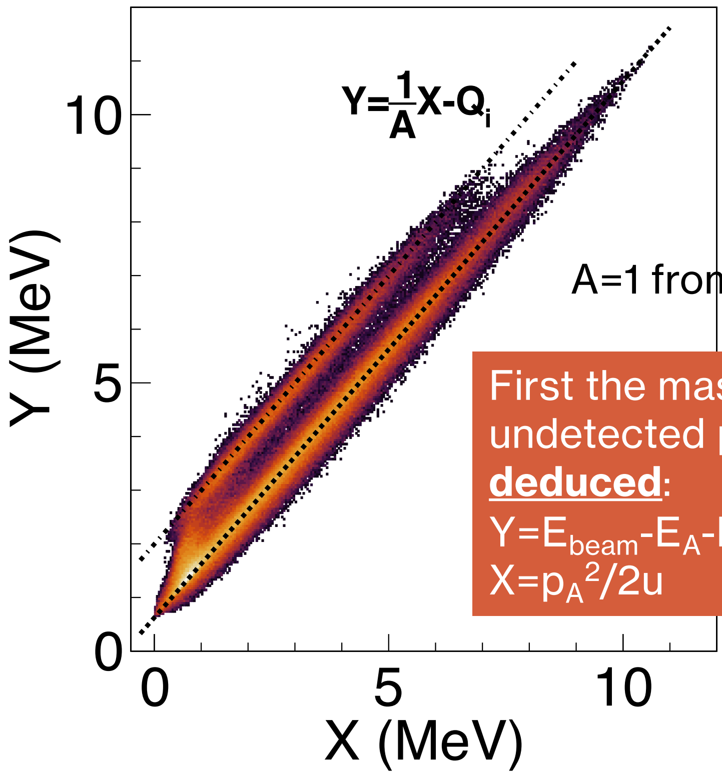
$$\boxed{\omega\gamma_i^{\mathrm{THM}} \approx \omega_i N_i \frac{\Gamma^i_{p,\,\mathrm{s.p.}}}{\sigma_{(d,n)}(\theta_n^{c.m.})}}$$

- $\Gamma_{\mathrm{s.p.}}$ is calculated using the potential model
- $\sigma(\theta)$ is calculated in PW using the same well & w.f.

$$\omega\gamma_i^{\mathrm{THM}} = \frac{\omega_i N_i}{\omega_{norm} N_{norm}} \frac{\dfrac{\Gamma^i_{p,\,\mathrm{s.p.}}}{\sigma^i_{(d,n)}(\theta_n^{c.m.})}}{\dfrac{\Gamma^{norm}_{p,\,\mathrm{s.p.}}}{\sigma^{norm}_{(d,n)}(\theta_n^{c.m.})}} \omega\gamma_i^{norm}$$

The double ratio ensures an extra small model dependence (6%)

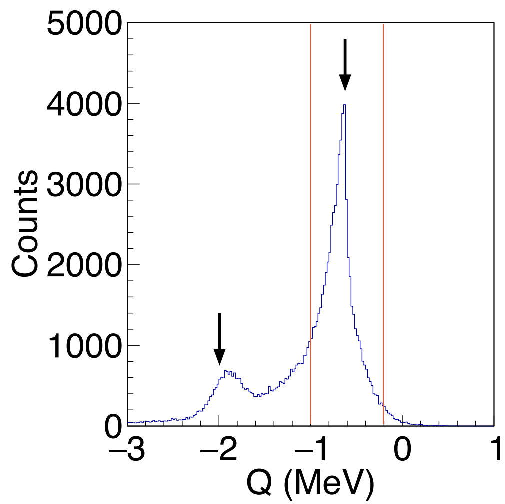
Channel selection

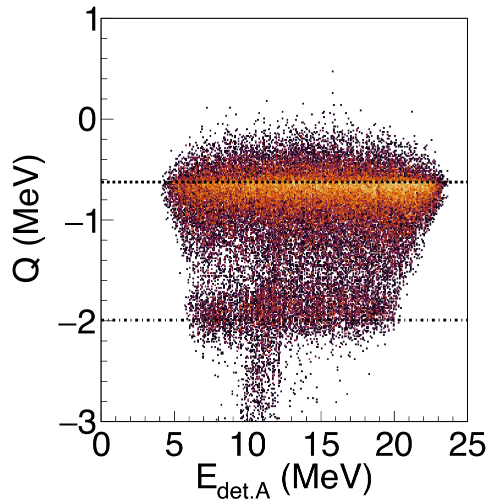


A=1 from the fit

First the mass of the undetected particle is **deduced**:
$Y=E_{beam}-E_A-E_C$
$X=p_A^2/2u$

Then the Qvalue spectrum is reconstructed

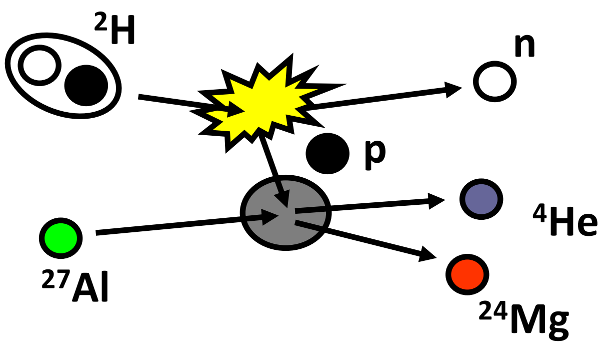




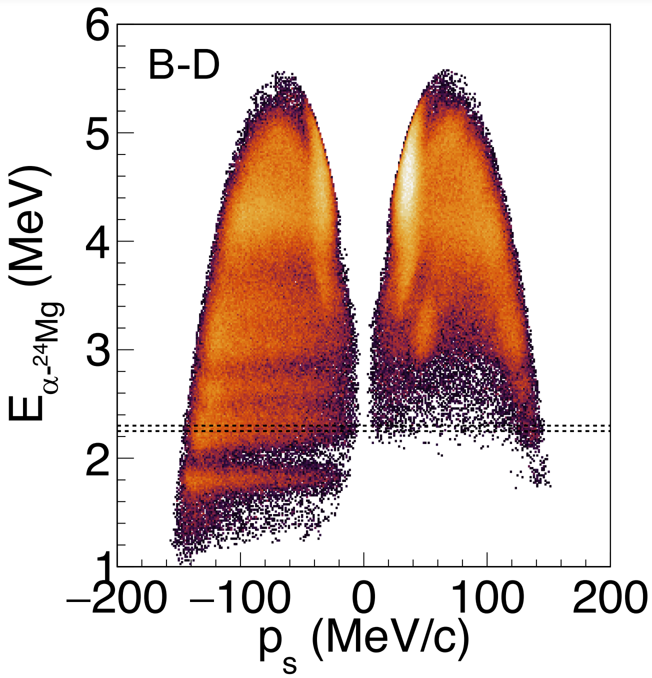
Two peaks for ^{24}Mg gs and 1^{st} excited

Arrows: theoretical Qvalues

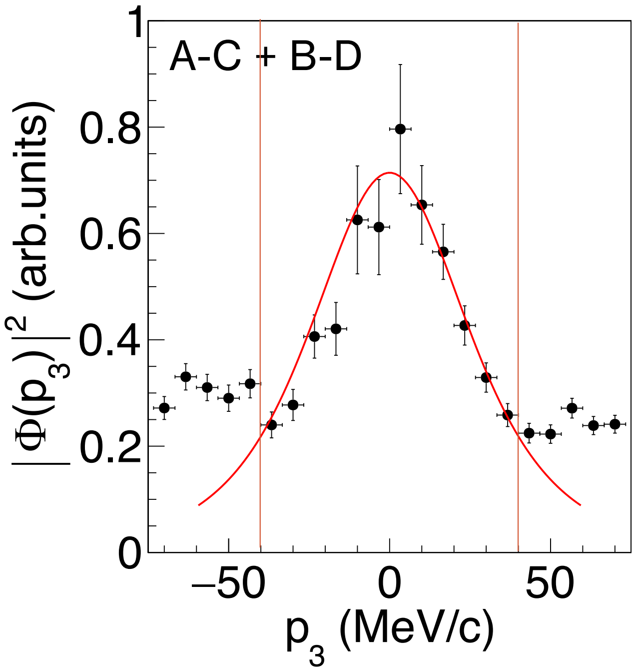
Selection of QF process



When the breakup is quasi-free, *n* retains the same momentum as inside *d* (adiabatic process). **So *n*-momentum distribution should be the same as in *d***



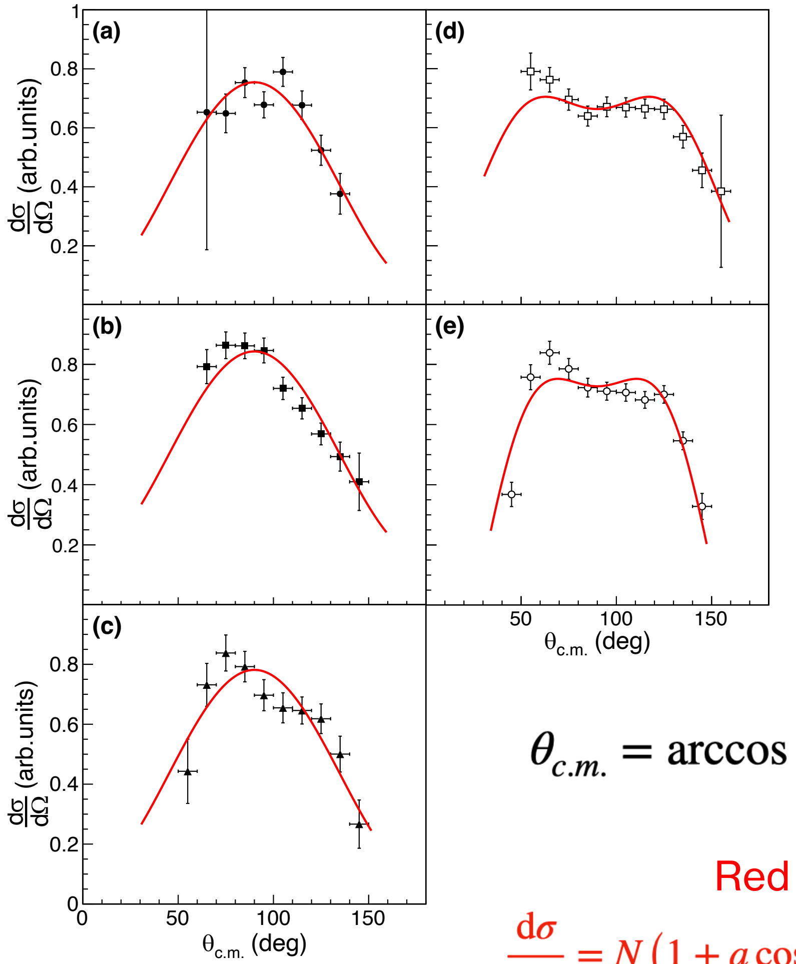
We gate on a 50 keV energy window to keep the cross section constant



The red curve is the theoretical one: normalization is the only fitting parameter

Angular distributions

- Angular distributions for each peak in the E_{cm} spectra [(a)-(e) in order of increasing energy] were deduced
- Each peak is the superposition of many resonances, so only the dominant wave can be deduced
- A-B & C-D show the same trend
- The region around **π**/2 is covered, which is the most influential for angular integration



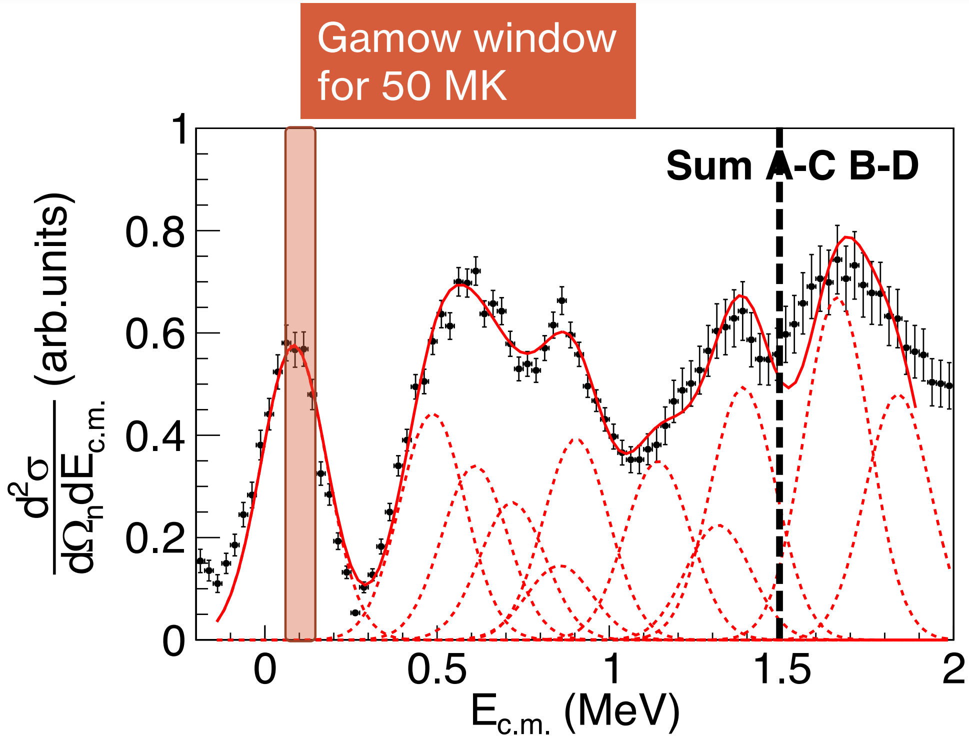
$$\theta_{c.m.} = \arccos\left(\hat{\mathbf{k}}_{p^{27}\mathrm{Al}} \cdot \hat{\mathbf{k}}_{\alpha^{24}\mathrm{Mg}}\right)$$

Red line:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = N\left(1 + a\cos^2\theta_{c.m.} + b\cos^4\theta_{c.m.}\right)$$

Extraction of the resonance strengths

- Black dots: sum over the two spectra for A-C and B-D
- Following discussion in APJ 708 (2010) 796 the red line is a fit with a sum of Gaussian functions, with fixed energies and fixed widths (from MC). Heights are proportional to strengths
- The most intense resonances in STARLIB were all included in the fit down to about 200 keV



Tails of higher energy resonances affects the region above 1.5 MeV

Tabulated strengths: THM vs. STARLIB

- In general, good agreement between THM and STARLIB
- Validation of the method and new results/better upper limits below about 200 keV

Energy in cm (keV) [from STARLIB]	Jpi	Strength (eV) [from STARLIB]	error (eV)	Strength (eV) [from THM]	error (eV)	
71.5	2+	2.47E-14	up lim	9.28E-15	up lim	
84.3	1-	2.60E-13	up lim	1.90E-14	4.7E-15	
193.5	2+	3.74E-07	up lim	2.82E-07	up lim	
214.7	3-	1.13E-07	up lim	4.92E-08	up lim	
486.74	2+	0.11	0.05	0.122	0.031	
609.49	3-	0.275	0.069	0.282	0.082	
705.08	1-	0.52	0.13	0.30	0.10	
855.85	3-	0.83	0.21	0.71	0.56	
903.54	3-	4.3	0.4	4.3	0.4	normalization value
1140.88	2+	79	27	83	21	
1316.7	2+	137	47	142	43	
1388.8	1-	54	15	70	18	

Since the two states around 200 keV cannot be resolved, a conservative limit is obtained attributing the whole THM strength to both resonances. This is because they have different l so the effect OES is different

Normalization test using a higher energy resonance

- In general, normalizing to 1.4 MeV resonance leads to a little smaller resonance strengths than before, still in agreement with STARLIB values

Energy in cm (keV) [from STARLIB]	Jpi	Strength (eV) [from STARLIB]	error (eV)	Strength (eV) [from THM]	error (eV)	
71.5	2+	2.47E-14	up lim	7.17E-15	up lim	
84.3	1-	2.60E-13	up lim	1.47E-14	4.3E-15	
193.5	2+	3.74E-07	up lim	2.18E-07	up lim	
214.7	3-	1.13E-07	up lim	3.80E-08	up lim	
486.74	2+	0.11	0.05	0.094	0.028	
609.49	3-	0.275	0.069	0.218	0.071	
705.08	1-	0.52	0.13	0.232	0.086	
855.85	3-	0.83	0.21	0.55	0.44	
903.54	3-	4.3	0.4	3.3	1.2	
1140.88	2+	79	27	64	19	
1316.7	2+	137	47	110	37	
1388.8	1-	54	15	54	15	normalization value

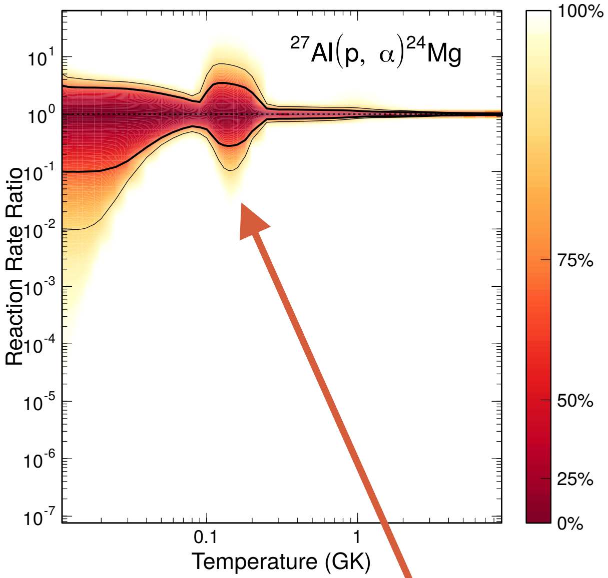
Average values

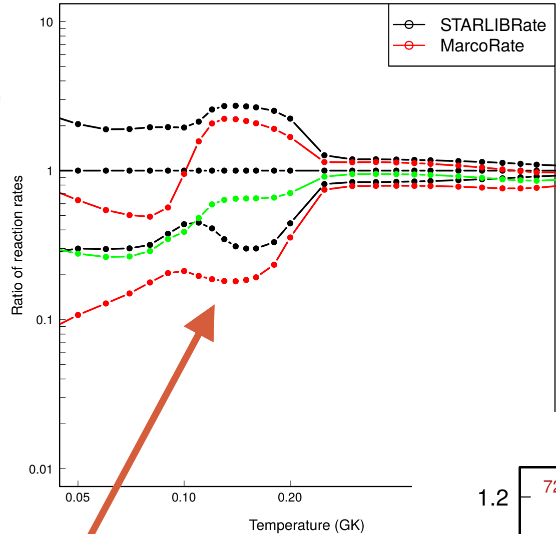
- We take the weighted average of the strengths obtained from the two normalizations procedure to reduce systematics errors

Energy in cm (keV) [from STARLIB]	Jpi	Strength (eV) [from STARLIB]	error (eV)	Strength (eV) [from THM]	error (eV)
71.5	2+	2.47E-14	up lim	8.23E-15	up lim
84.3	1-	2.60E-13	up lim	1.67E-14	3.2E-15
193.5	2+	3.74E-07	up lim	2.50E-07	up lim
214.7	3-	1.13E-07	up lim	4.36E-08	up lim
486.74	2+	0.11	0.05	0.107	0.021
609.49	3-	0.275	0.069	0.245	0.054
705.08	1-	0.52	0.13	0.261	0.065
855.85	3-	0.83	0.21	0.61	0.35
903.54	3-	4.3	0.4	4.20	0.38
1140.88	2+	79	27	73	14
1316.7	2+	137	47	124	28
1388.8	1-	54	15	61	12

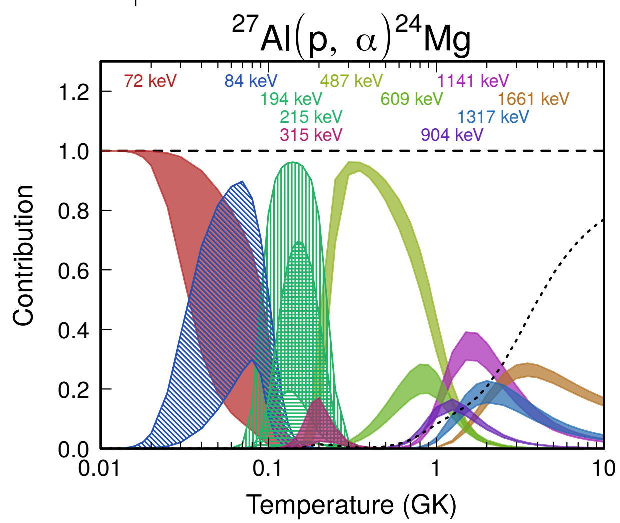
The full calculation using STARLIB (by Philip Adsley)

- We run the full code (for STARLIB and STARLIB+THM replacing our results in the standard input)





The green line is the THM recommended rate



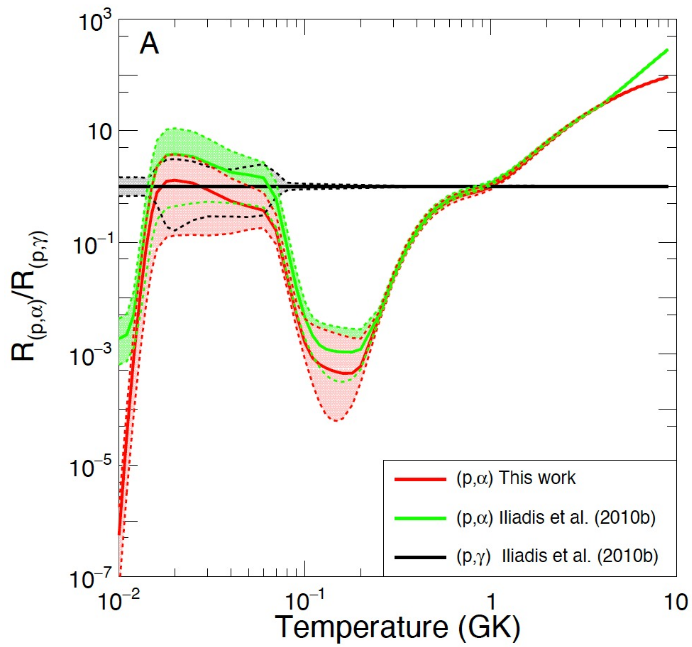
Is the upper limit for the resonance at about 200 keV overestimated?

Some astrophysical consequences

- Closure of the MgAl cycle

→ THM data seem to strengthen the fact that no closure of the cycle is to be expected, but uncertainties are large

- More work necessary
- Need of more accurate p,γ S-factor



The (p,γ) channel

When narrow resonances dominate the S-factor the reaction rate can be calculated by means of the resonance strengths and resonance energies only. **This applies only in the cases direct capture is negligible**

Let's focus on resonance strengths

- At astrophysical energies, in the case of some resonances it happens that: $\Gamma p \ll \Gamma\gamma \ll \Gamma\alpha$
- This chain of inequations leads to a resonance strength $\omega\gamma$ of the (p, α) channel that is directly proportional to Γp through the statistical factor ω.

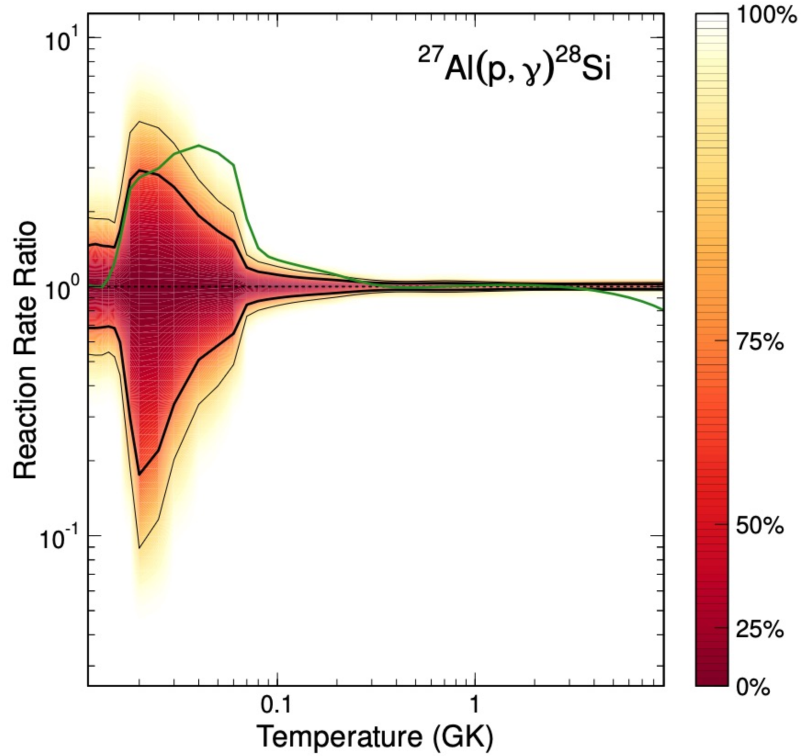
E_i^R (keV)	$\omega\gamma$ (eV) (Iliadis et al. 2010a)	$\omega\gamma$ (eV) (present work)
71.5	$\leq 6. \times 10^{-15}$	$\leq 2 \times 10^{-15}$
84.3	$\leq 4. \times 10^{-13}$	$2.5 \pm 1.3 \times 10^{-14}$
705.08	0.129 ± 0.007	0.077 ± 0.004

$$\omega\gamma_i = \frac{2J_i + 1}{(2J_p + 1)(2J_{^{27}Al} + 1)} \frac{\Gamma_p^i \Gamma_\alpha^i}{\Gamma_{tot}}$$

$$\omega\gamma_i = \frac{2J_i + 1}{(2J_p + 1)(2J_{^{27}Al} + 1)} \frac{\Gamma_p^i \Gamma_\gamma^i}{\Gamma_{tot}}$$

The (p,γ) channel

- At astrophysical energies, in the case of some resonances it happens that: $\Gamma p << \Gamma\gamma << \Gamma\alpha$
- This chain of inequations leads to a resonance strength $\omega\gamma$ of the (p, α) channel that is directly proportional to Γp through the statistical factor ω.



E_i^R (keV)	$\omega\gamma$ (eV) (Iliadis et al. 2010a)	$\omega\gamma$ (eV) (present work)
71.5	$\leq 6. \times 10^{-15}$	$\leq 2 \times 10^{-15}$
84.3	$\leq 4. \times 10^{-13}$	$2.5 \pm 1.3 \times 10^{-14}$
705.08	0.129 ± 0.007	0.077 ± 0.004

Figure 1. Green line: ratio of the STARLIB median reaction rate (Iliadis et al. 2010b) to the one calculated with the same statistical approach, using the THM updated resonance strengths in Tab.1. A significant reduction in the median rate is apparent. The contour plot shows the uncertainty of the THM reaction rate, taken equal to one over the whole examined temperature range. The thick lines are used to encompass the 68% confidence interval, while the thin lines are used for the 95% one.

Concluding remarks

- We could explore the whole energy region of astrophysical interest for the alpha 0 channel.
- We could extract the strength of the 84 keV resonance and set more stringent upper limits
- The calculated rate is about 3 times lower at astrophysically relevant temperatures than presently assumed.
- The same results were found for the radiative capture channel
- Astrophysical calculations show a moderate impact on astrophysics (no closure expected)

Thanks to:

- The director for authorizing the experiment
- The technical staff of LNS
- Philip Adsley for running STARLIB
- Flavia Dell'Agli for the astrophysical models

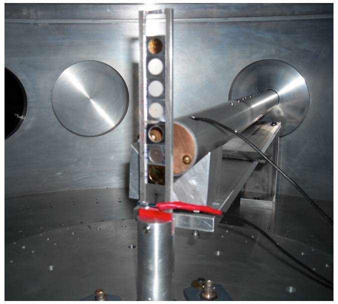
The team:

M. La Cognata,[1] S. Palmerini,[2,3,4] P. Adsley,[5,6] F. Hammache,[7] A. Di Pietro,[1] P. Figuera,[1] F. Dell'Agli,[4] R. Alba,[1] S. Cherubini,[8,1] G.L. Guardo,[1,8] M. Gulino,[9,1] L. Lamia,[8,1] D. Lattuada,[9,1] C. Maiolino,[1] A. Oliva,[8,1] R.G. Pizzone,[1] P.M. Prajapati,[1,*] G.G. Rapisarda,[8,1] S. Romano,[8,1] D. Santonocito,[1] R. Spartá,[1,8] M.L. Sergi,[8,1] A. Tumino,[9,1] and P. Ventura[4]

S. Palmerini et al. Eur. Phys. J. Plus (2021) 136: 898
M. La Cognata et al. Phys. Lett. B (2022) 826: 136917

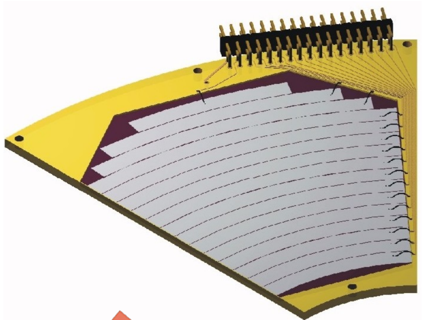
The need of indirect methods: direct vs. indirect methods

How to measure the A+x→c+C reaction in a *direct* way?

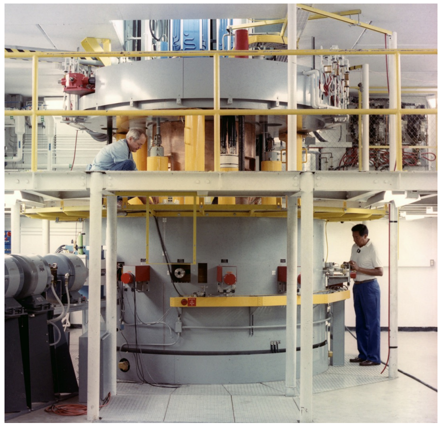


Target (A)

Detector → kinematic observables
- Energy
- Emission angle
& Particle identification



Beam (x)



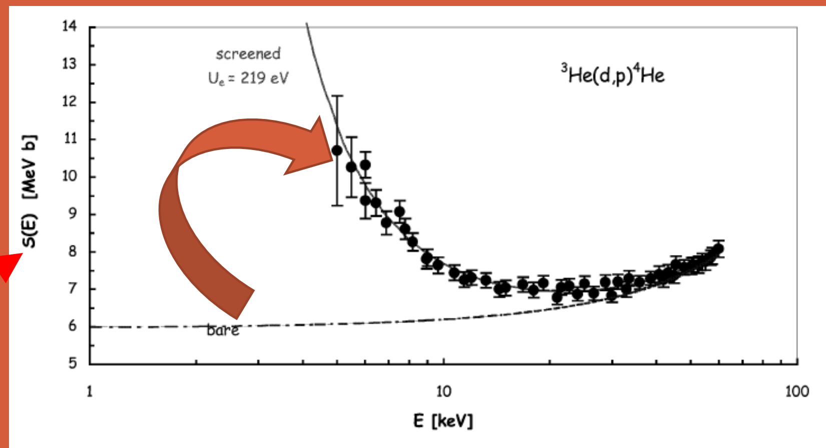
Reaction product (c)

It looks *quite* simple!

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

However, several reasons make the low-energy region of astrophysical interest difficult to access

- Coulomb barrier suppression of the cross section
- Cosmic background and systematic errors due to, e.g., straggling in the target
- ***Electron screening hiding the nuclear cross section***



The need of indirect methods: direct vs. indirect methods

Entrance channel:
A+a

Several reaction mechanisms link the two channels

Reaction products
C+c+…

Nuclear reaction theory required

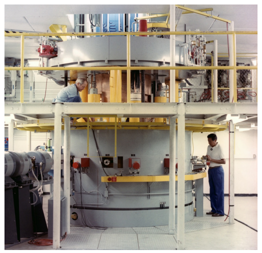
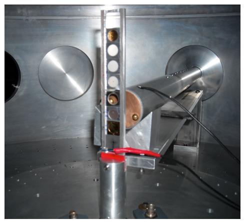
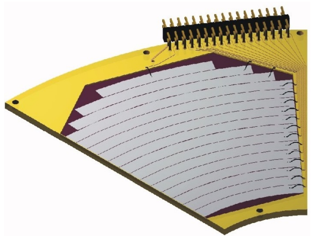
→ cross checks of the methods needed

→ possible spurious contribution

→ additional systematic errors (is the result model independent?)

Advantages include no need of low energies → no straggling, no Coulomb suppression, no electron screening
Possibility to access astrophysical energies with high accuracy

To recall the previous sketch:

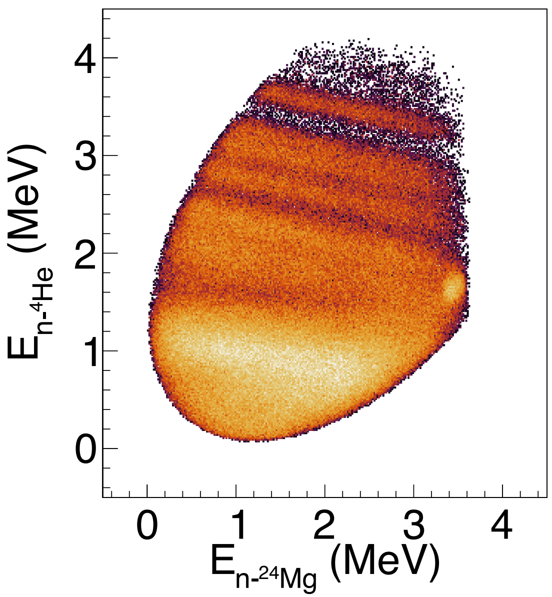
Nuclear reaction theory

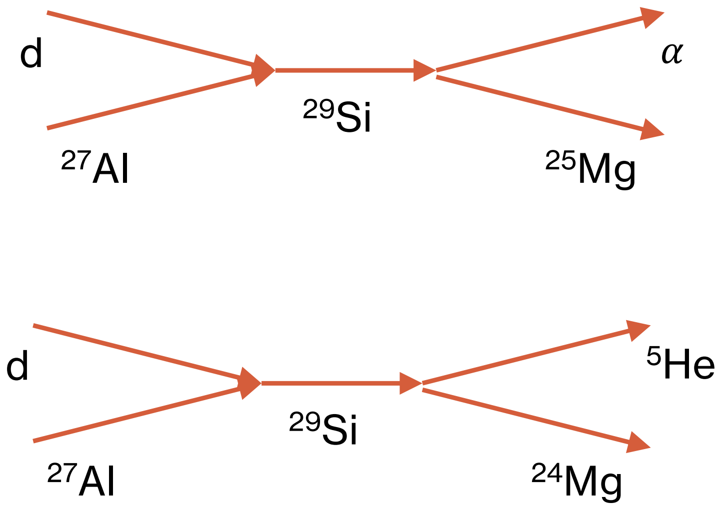
R. Tribble et al., Rep. Prog. Phys. **77** (2014) 106901

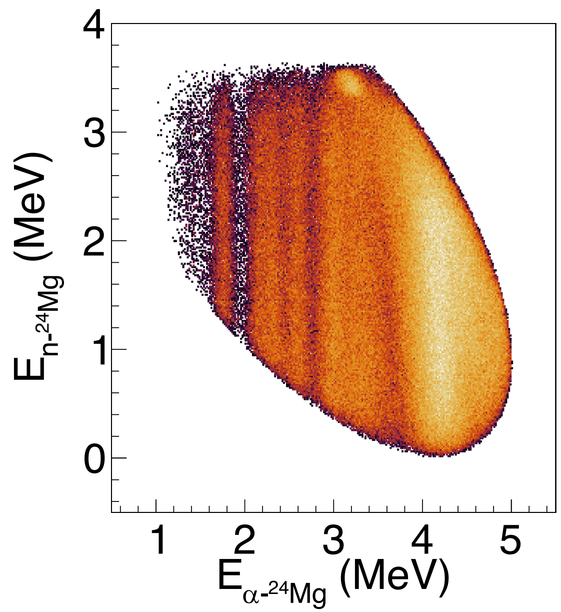
Indirect methods are especially useful in the case of reactions involving **radioactive nuclei**
- Higher cross sections
- Possibility to study reactions induced by neutrons on radioactive nuclei
- Reactions among unstable nuclei
- Easier experimental procedures

Data analysis: relative energy spectra

^{24}Mg-α relative energy → ^{28}Si excitation energies **→ This is the spectrum of astrophysical interest**
^{24}Mg-n relative energy → ^{25}Mg excitation energies → background (sequential decay)
^{4}He+n relative energy → ^{5}He excitation energies → background (sequential decay)



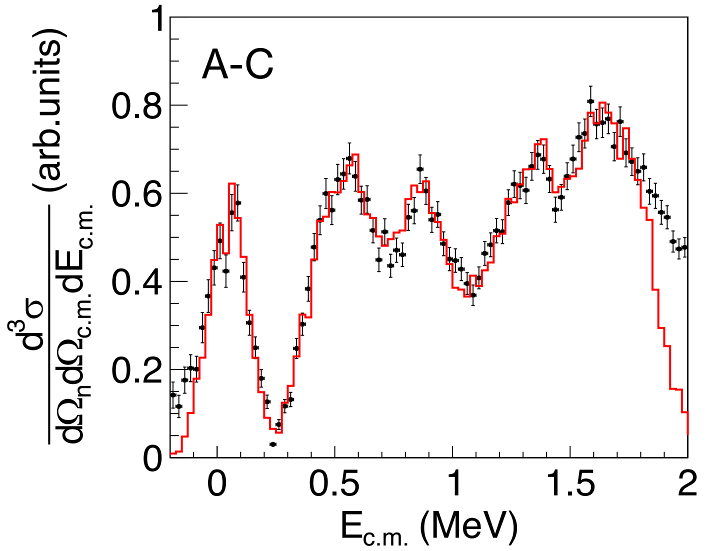




Center-of-mass energy spectra

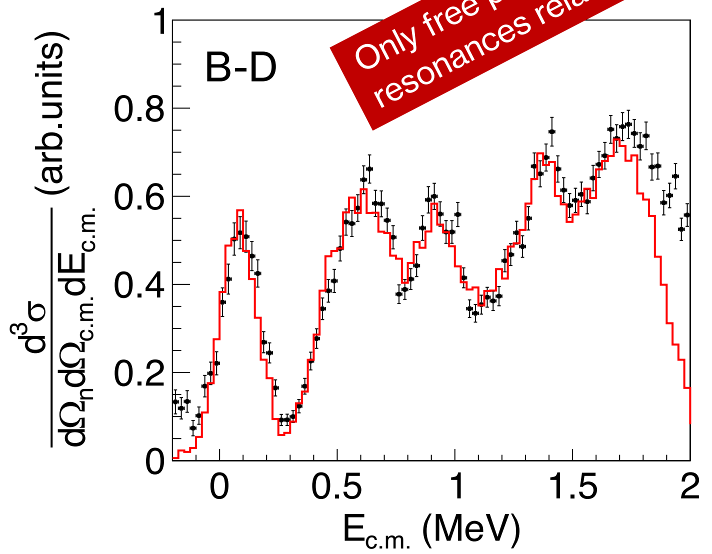
- For the analysis cuts we deduce the E_{cm} spectra from the standard formula: $E_{c.m.} = E_{\alpha-^{24}\mathrm{Mg}} - Q_{^{27}\mathrm{Al}(p,\alpha)^{24}\mathrm{Mg}}$

Only free parameters: resonances relative heights



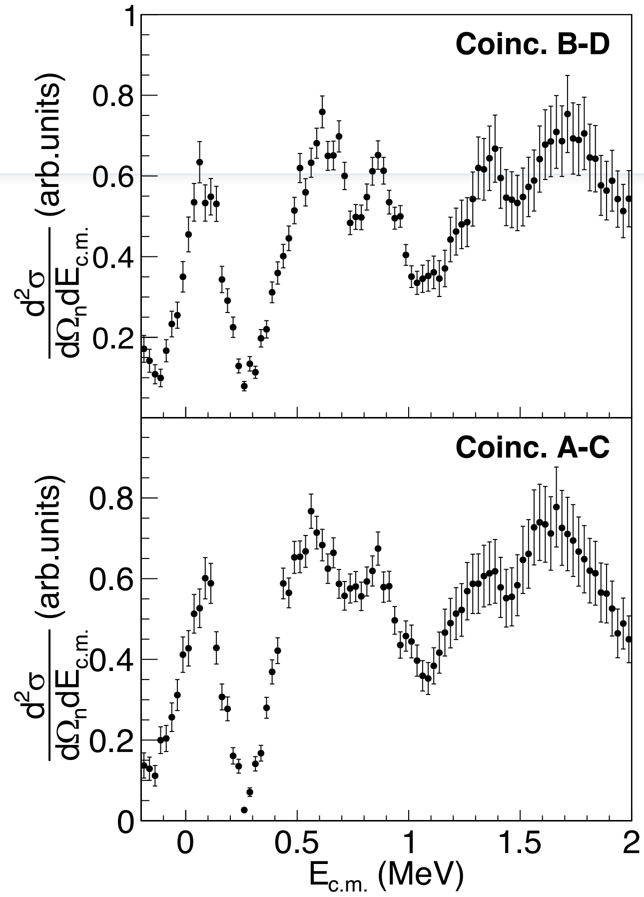
Black points: QF reaction yield corrected for phase space effects for THM data

Red line: **simulated** QF reaction yield corrected for space effects:
- All experimental effect accounted for (pixel size, energy resolution beam, ...)



Integrated THM cross sections

- Integration over $\theta_{c.m.}$ was carried out for the two couples of detectors separately, using the fitting curve in the previous slide
- Uncertainties on the shape of the angular distributions beyond the fitting regions were taken into account, through the uncertainties affecting fitting parameter *a* and *b*
- Uncertainties are larger for higher energies
- For the two couples, independent analyses were carried out, compatible results → low systematic erros



Extraction of the upper limits/1

- Below 200 keV, our data are compatible with a single resonance centered at about 80 keV, with l=1
- For the other resonances we can provide upper limits

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***********************************
Upper Limits of Resonances
Note: enter partial width upper limit
Note: ...PT=<B> for g-rays [enter: "u
Ecm      DEcm     Jr     G1       DG1
  71.5   0.5      2      7.4e-14  0.0
  84.3   0.4      1      2.6e-12  0.0
 193.5   0.7      2      7.5e-4   0.0
 214.7   0.4      3      9.7e-5   3.9e-5
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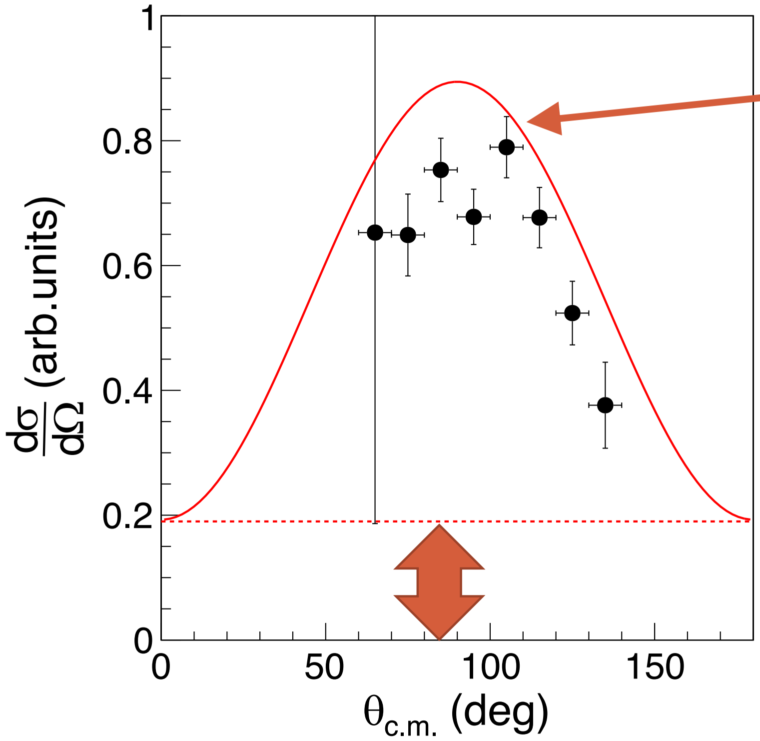


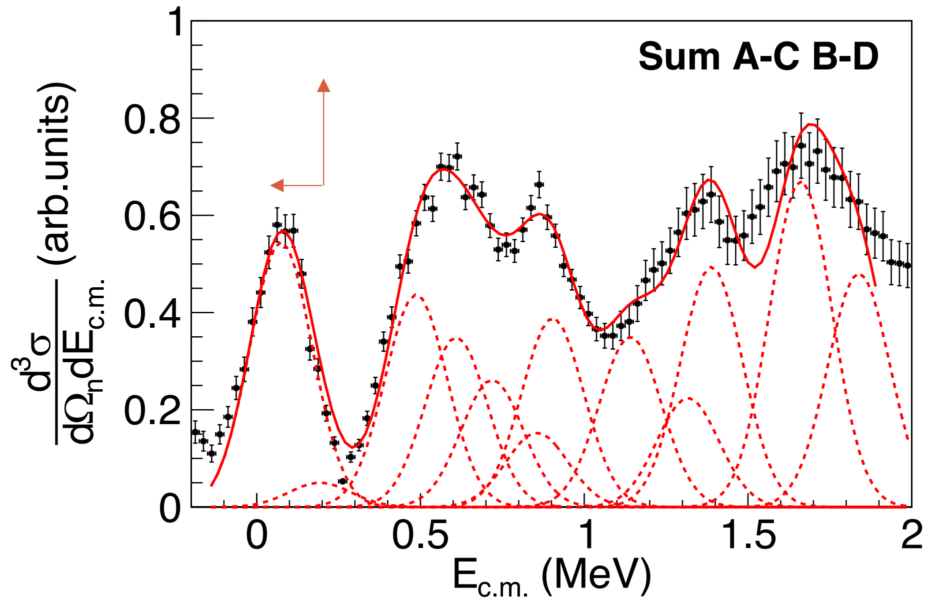
Conservative upper limit: 36% fo the 84 keV resonance strength

Upper limit for the l=0 71.5 keV resonance is deduced from angular distributions

Extraction of the upper limits/2

- Below 200 keV, our data are compatible with a single resonance centered at about 80 keV, with l=1
- For the other resonances we can provide upper limits

```
************************************
Upper Limits of Resonances
Note: enter partial width upper limit
Note: ...PT=<B> for g-rays [enter: "u
Ecm      DEcm     Jr     G1       DG1
  71.5   0.5      2      7.4e-14  0.0
  84.3   0.4      1      2.6e-12  0.0
 193.5   0.7      2      7.5e-4   0.0
 214.7   0.4      3      9.7e-5   3.9e-5
```



For the states around 200 keV statistics is too low so the upper limits is deduced by shifting the peak by 1 energy bin and adding a Gaussian as large as possible

Some astrophysical consequences 2

- We inspect the AGB evolution of intermediate mass stars at solar metallicity (Z=0.014) computed with the stellar evolution code ATON. We select the 4.5 M_{sun} (mild HBB) and 6 M_{sun} (strong HBB)
- Negligible differences are found for 6M_{sun}: the temperatures at the base of the envelope are so hot (>80 MK) that the $^{27}Al(p,\gamma)^{28}Si$ channel is dominant
- For 4.5M_{sun} we find a 5% increase in the surface 27Al when the new rates for $^{27}Al(p,\alpha)^{24}Mg$ are adopted, a difference that rises to 25% when the lower limits are used.