

Investigating threshold resonances using indirect methods

Going down to zero energy and even below!

Marco La Cognata



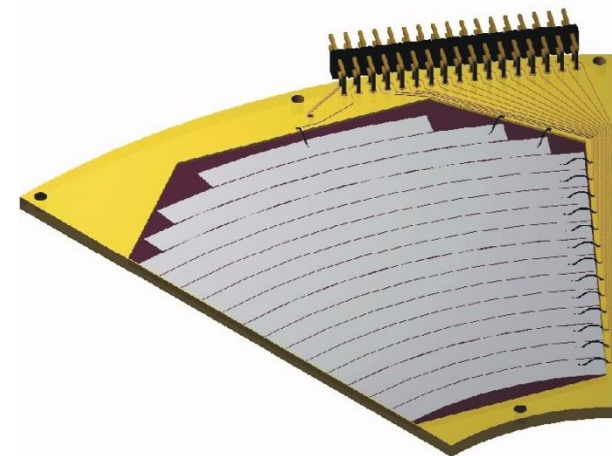
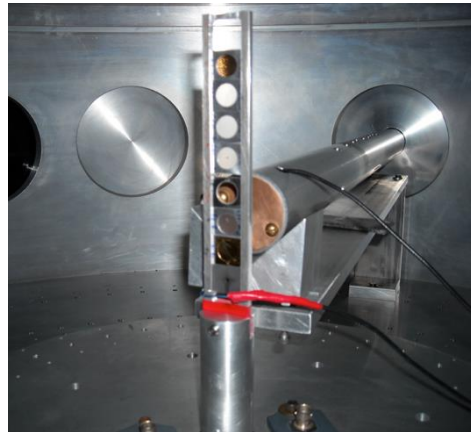
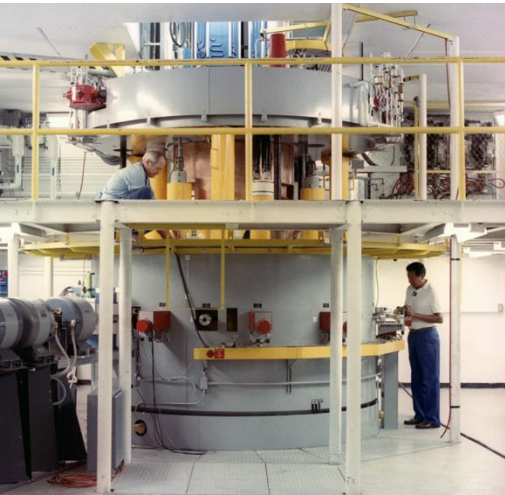
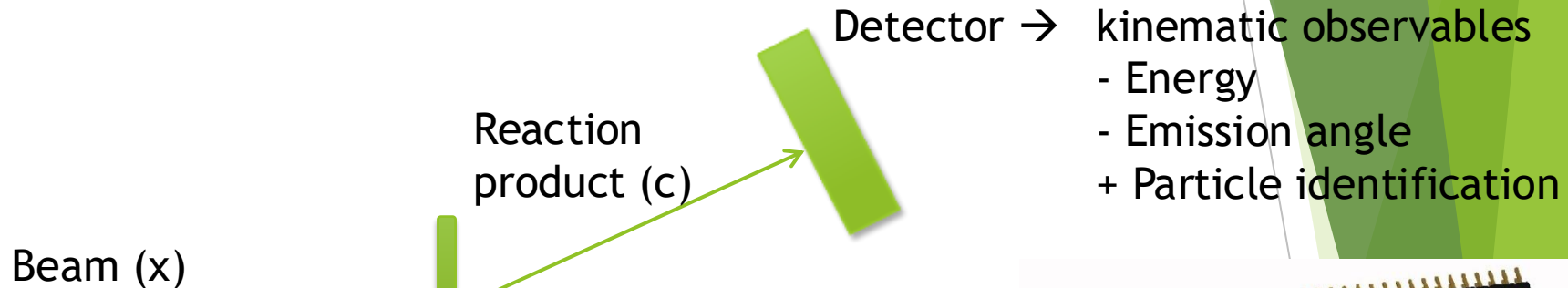
Istituto Nazionale di Fisica Nucleare

Outline

- What is nuclear astrophysics?
- How can we reach the energies of astrophysical interest?
- The indirect Trojan Horse Method
- The $^{27}\text{Al}(p,\alpha)^{24}\text{Mg}$ reaction and the (p,γ) channel
- The $^{19}\text{F}(p,\alpha)^{16}\text{O}$ reaction and the (p,γ) channel
- The $^{26}\text{Al}(n,\alpha)^{23}\text{Na}$ and the $^{26}\text{Al}(n,p)^{26}\text{Mg}$ reactions: preliminary results
- Outlook

Recipe for direct measurements

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



It looks **quite** simple!

RISK of EXTRAPOLATION (or the prejudice of consistency)

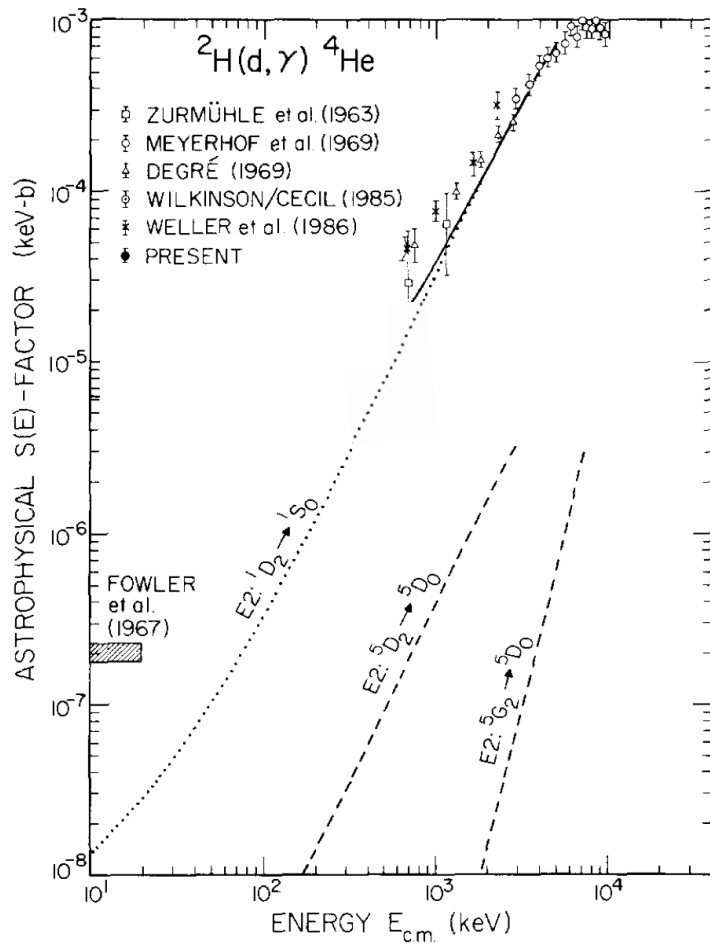


Fig. 1. Excitation function for ${}^2\text{H}(d, \gamma){}^4\text{He}$ from the present and previous work [3–8]. The data from 1–4 MeV are described well by an E2 direct capture process, ${}^1\text{D}_2 \rightarrow {}^1\text{S}_0$ (dotted curve). The high cross sections at low energies are attributed to E2 radiation from an initial S-state of relative motion of the deuterons. The calculated ${}^5\text{D}_2 \rightarrow {}^5\text{D}_0$ and ${}^5\text{G}_2 \rightarrow {}^5\text{D}_0$ yields are negligible. Also shown is the previously recommended astrophysical $S(0)$ value, $2 \times 10^{-7} \text{ keV b}$ [9].

How would you extrapolate if only data from Zurmuhle et al would have been available?

You would be probably happy with a E2 transition from the $L = 2$ scattering state in the $d + d$ system into the ($L = 0, S = 0$) component of the He ground state.

RISK of EXTRAPOLATION (or the prejudice of consistency)

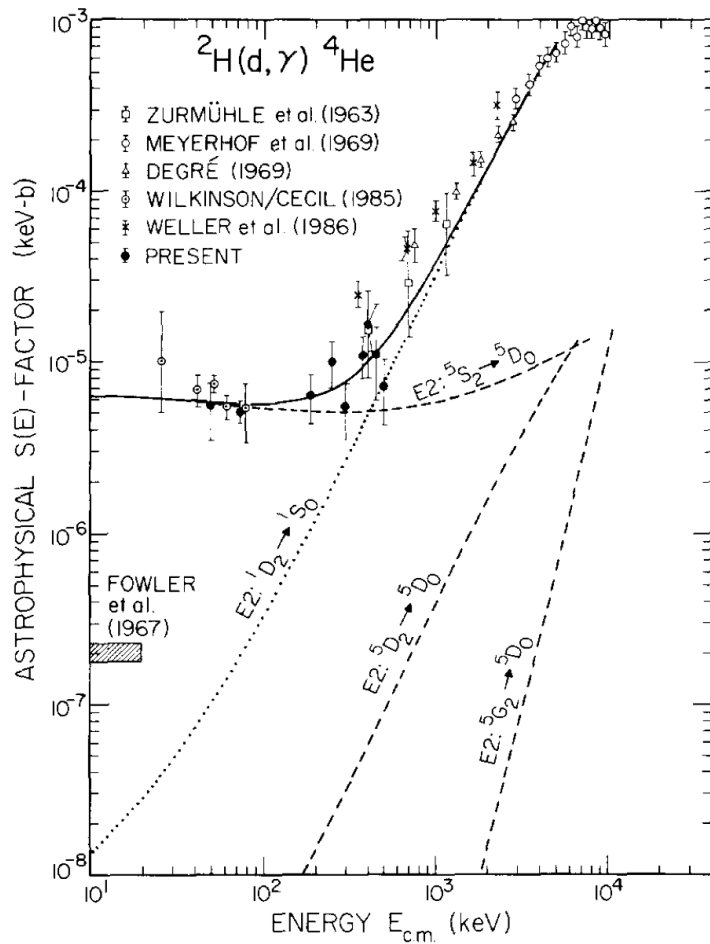


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You would be probably happy with a E2 transition from the $L = 2$ scattering state in the $d + d$ system into the $(L = 0, S = 0)$ component of the He ground state.

However, it was found [Barnes et al. PLB 197, 315 (1987)] that the cross section was strongly enhanced compared with what is expected for this case.

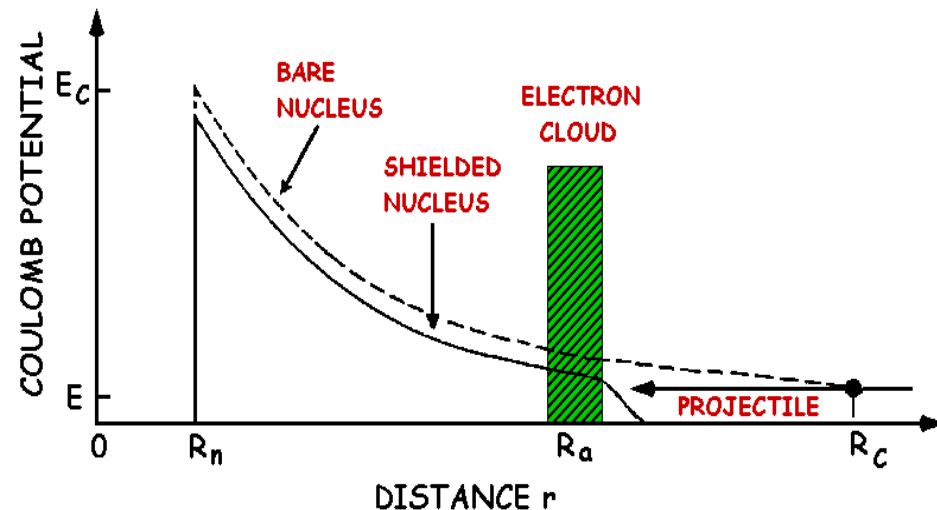
When the new experimental data became available they undoubtedly indicated the existence of a D-state component in the He ground state.

The electron screening effect

Thanks to recent experimental developments, measurements have been extended to the energies of interest for several reactions.

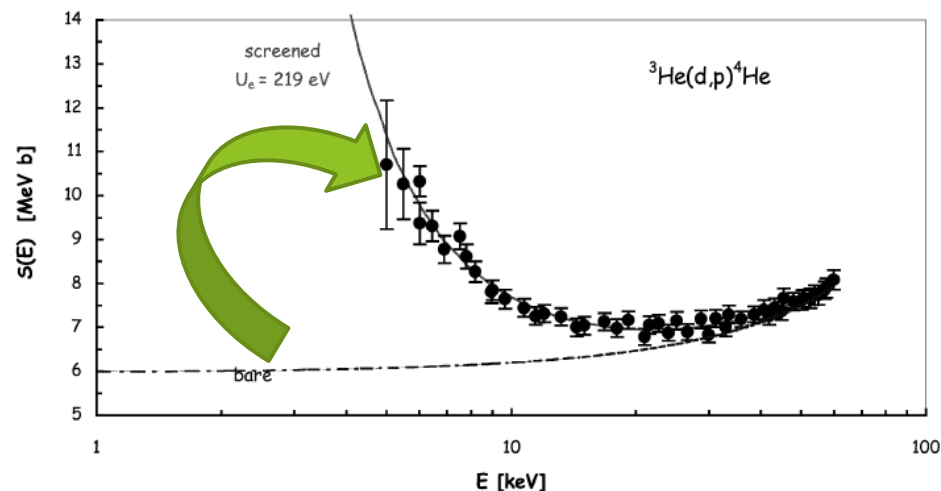
This leads to the discovery of electron screening: a such low energies atomic degrees of freedom cannot be neglected.

Pictorial view:



The electron cloud shields the nuclear charge thus the projectile meets a reduced Coulomb barrier → enhancement of the reaction probability as tunneling is more likely.

Experimentally:



Exponential enhancement!

$$\sigma_s(E)/\sigma_b(E) = \exp(\pi \eta U_e/E),$$

Bracci et al., NPA 513 (1990) 316

Rolfs & Rodney, Cauldrons in the Cosmos (Univ. Chicago Press) 1988

Strieder et al., Naturwissenschaften 88 (2001) 461

Direct vs. indirect measurements

Indirect measurements:

Complicated but rewarding

✓ High energy experiments: up to several hundreds MeV

→ no Coulomb barrier suppression → possibility to measure angular distributions

→ negligible straggling → no need to rely on stopping power models

→ no electron screening → no need to make assumptions for extrapolation

Indirect measurements are the only ones allowing you to measure down to astrophysical energies with the present-day facilities

Nuclear reaction theory required

→ cross checks of the methods needed

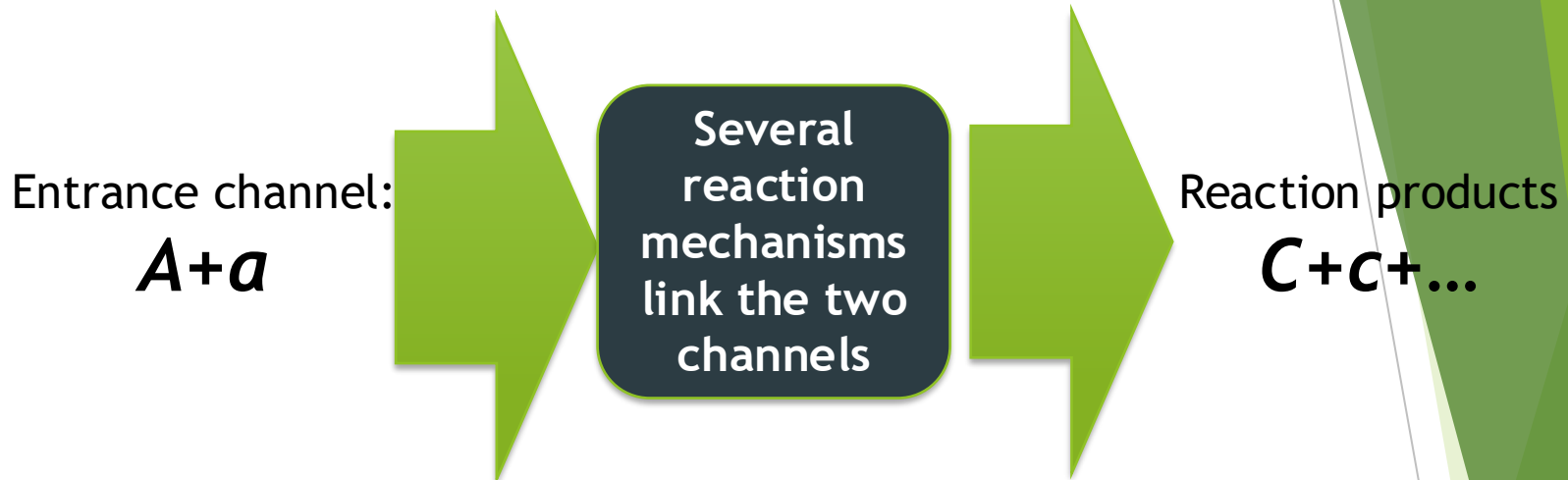
→ possible spurious contribution

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

... Indirect techniques are complementary to direct measurements

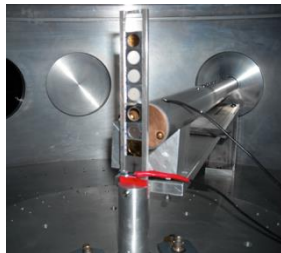
Examples: Coulomb dissociation, ANC and Trojan horse method, surrogate reactions...

Indirect Techniques: a cartoon



Only one reaction mechanism has to be selected, for which the reaction theory we have developed applies. A careful experimental & theoretical investigation is necessary

To recall the previous sketch:



Nuclear reaction theory

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

Indirect methods and RIBs

Reactions involving unstable nuclei → additional problems!

- ✓ lower beams intensities
 - reaction yield even smaller at astrophysical energies ($E < 1$ MeV in explosive scenarios where unstable nuclei take part to nuclear reactions)
- ✓ poorer energy resolution
- ✓ presence of contaminants in the beam, background...

Indirect studies would dramatically increase the yield thanks to

- the experimental setup (e.g. thicker targets)
- the suppression of Coulomb barrier

Moreover

Some reactions cannot be measured with present-day facilities such as:

- Neutron-induced reactions on exotic nuclei
- Reactions among unstable nuclei

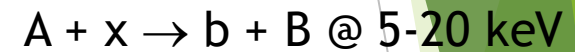
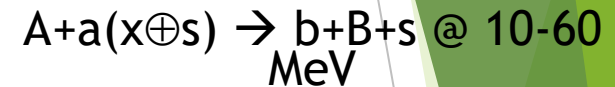
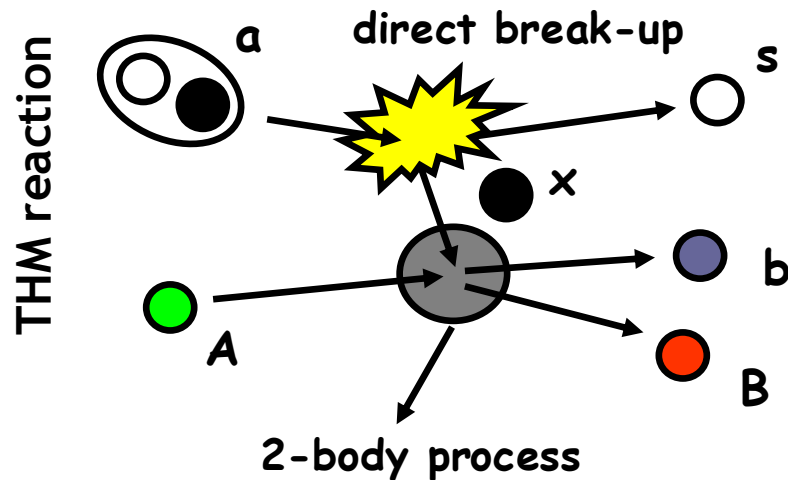
**As a first step, validation of the approach is needed to test how accurate is
This is accomplished by investigating reactions with stable beams**

The Trojan Horse Method

Coulomb barrier → exponential suppression of the cross section at astrophysical energies

+ electron screening

→ low-energy, bare-nucleus cross section is experimentally available only through extrapolation OR indirect measurements



By selecting the QF contribution

Though $E_A \gg V_{\text{Coul}}$ it is possible to measure at the Gamow peak since:

$$E_{\text{c.m.}} = E_{A-x} - Q_{x-s}$$

Additional advantages:

- reduced systematic errors due to straggling, background...

But...

- off-shell cross section deduced ($x \rightarrow$ virtual particle)
- no absolute units (also an advantage)

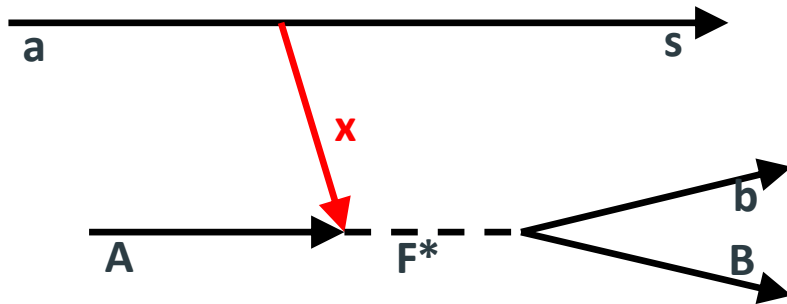
First work published in 1986

See Annu. Rev. Nucl. Part. Sci.

2021.71:345-76 for a recent review



The full THM: the complicate formula



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

In the latest years, large efforts were made to give a quantitative justification of THM, to estimate the uncertainties and improve the description of the $2 \rightarrow 3$ cross section

Amplitude of the TH reaction

$$\begin{aligned}
 M^{\text{PWA(prior)}}(P, k_{aA}) &= (2\pi)^2 \sqrt{\frac{1}{\mu_{bB} k_{bB}}} \varphi_a(p_{sx}) \\
 &\times \sum_{J_F M_F j' l' m' j' m_l m_{l'} M_n} i^{l+l'} \langle j m j l m_l | J_F M_F \rangle \langle j' m j' l' m_{l'} | J_F M_F \rangle \\
 &\times \langle J_x M_x J_A M_A | j' m j' \rangle \langle J_s M_s J_x M_x | J_a M_a \rangle e^{-i\delta_{bB}^{hs}} Y_{lm_l}(-\hat{k}_{bB}) \\
 &\times \sum_{\nu, \tau=1}^N [\Gamma_{\nu b B j l J_F}(E_{bB})]^{1/2} [A^{-1}]_{\nu \tau} Y_{l' m_{l'}}^*(\hat{p}_{xA}) \\
 &\times \sqrt{\frac{R_{xA}}{\mu_{xA}}} [\Gamma_{\nu x A l' j' J_F}(E_{xA})]^{1/2} P_{l'}^{-1/2}(k_{xA}, R_{xA}) (j_{l'}(p_{xA} R_{xA}) \\
 &\times [(B_{xA l'}(k_{xA}, R_{xA}) - 1) - D_{xA l'}(p_{xA}, R_{xA})] \\
 &+ 2Z_x Z_A e^2 \mu_{xA} \int_{R_{xA}}^{\infty} dr_{xA} \frac{O_{l'}(k_{xA}, r_{xA})}{O_{l'}(k_{xA}, R_{xA})} j_{l'}(p_{xA} r_{xA})).
 \end{aligned}$$

Same R-matrix term as in OES cross section but for the appearance of the inverse penetration factor making it possible to observe suppressed resonances at low energies

Fourier transform of the s-x relative motion wave function

Inverse penetration factor

THM: from the formal theory to the workable formula

Plane Wave Impulse Approximation:

- beam energy $\gg a = x \oplus b$ breakup Q-value
- projectile wavelength $k^{-1} \ll x - b$ intercluster distance
+ plane waves in the entrance and exit channel

→ the 3-body cross section factorizes:

$$\frac{d^3\sigma}{dE_C d\Omega_C d\Omega_c} \propto \text{KF} |\phi(-\vec{p}_b)|^2 \cdot \left(\frac{d\sigma}{d\Omega_{c.m.}} \right)^{\text{off}}$$

$$\frac{d^2\sigma}{dE_{C_c} d\Omega_s} \propto \frac{\Gamma_{(C_c)_i}(E) |M_i(E)|^2}{(E - E_{R_i})^2 + \Gamma_i^2(E)/4}$$

For resonant reactions

- KF kinematic factor
- $\phi(p_b)^2$ spectator momentum distribution
- M^2 is proportional to the transfer cross section
- $d\sigma^{\text{off}}/d\Omega$ (off-shell cross section
or “**nuclear**” (N) cross section

$d\sigma^{\text{off}}/d\Omega \rightarrow d\sigma/d\Omega$ (on shell)
The penetration factor P_l has to be introduced:

$$\frac{d\sigma}{d\Omega} = \sum_l P_l \frac{d\sigma_l^N}{d\Omega}$$

Moreover: exploring negative energies with the THM

Using the kinematics of three body reactions:

$$E_{Ax} = \frac{m_x}{m_x + m_A} E_A - \frac{p_s^2}{2\mu_{sF}} + \frac{\mathbf{p}_s \cdot \mathbf{p}_A}{m_x + m_A} - \varepsilon_{sx}$$

s-x Fermi motion s-x binding energy

It is possible to achieve negative energies in the A-x channel

How to deal with negative energies? what is their meaning?

Standard R-Matrix approach cannot be applied to extract the resonance parameters of the A(x,c)C reaction because x is virtual → Modified R-Matrix is introduced instead (A. Mukhamedzhanov 2010)

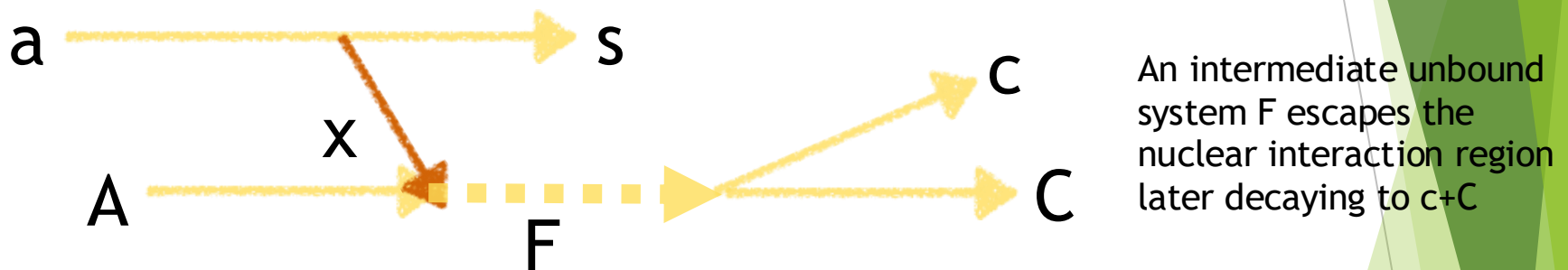
$$\frac{d^2\sigma}{dE_{Cc} d\Omega_s} \propto \frac{\Gamma_{(Cc)_i}(E) |M_i(E)|^2}{(E - E_{R_i})^2 + \Gamma_i^2(E)/4}$$

At negative energies M^2 is given by the product of the Whittaker function and the ANC of the F state populated in the transfer reaction

Merging together ANC and THM → deep connection of these two indirect methods

ANC vs. THM

THM: in the case of resonant reactions a metastable state is formed in the lower vertex:



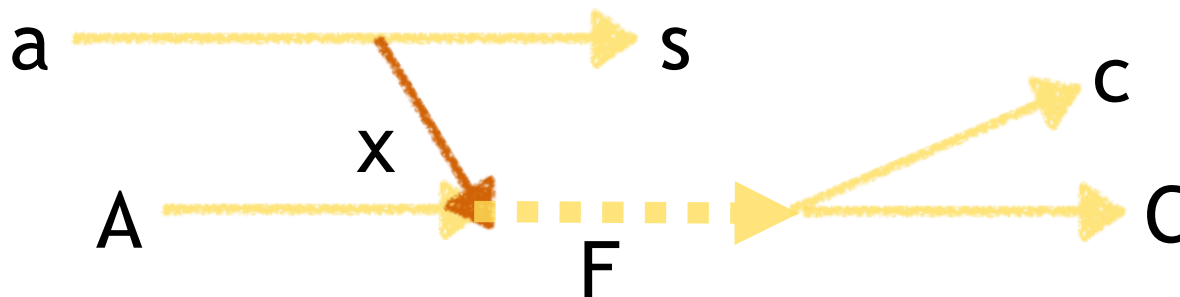
TRANSFER TO THE CONTINUUM

ANC => Transfer to a bound state

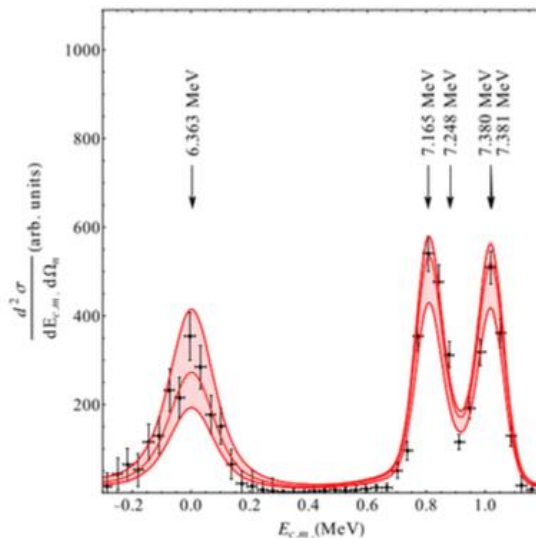
In both cases peripherality has to be enforced

ANC vs. THM

THM: in the case of resonant reactions a metastable state is formed in the lower vertex:

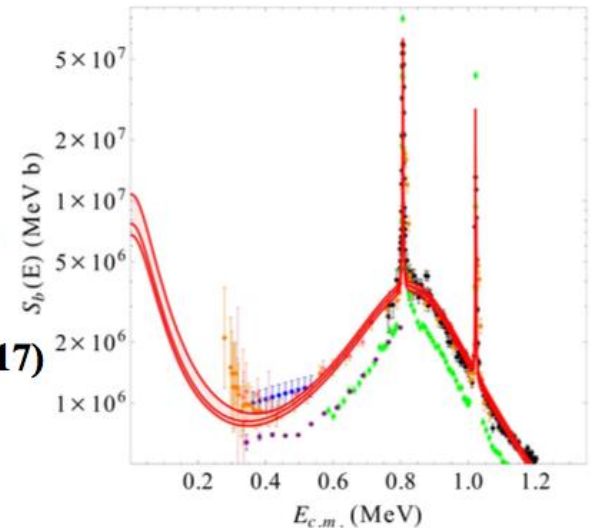


An intermediate unbound system F escapes the nuclear interaction region later decaying to $c+C$



same parameters

Trippella & La Cognata (2017)



And for narrow resonances?

When narrow resonances dominate the S-factor the reaction rate can be calculated by means of the resonance strength:

$$\omega\gamma_i = \frac{2J_i + 1}{(2J_p + 1)(2J_{^{27}\text{Al}} + 1)} \frac{\Gamma_p^i \Gamma_\alpha^i}{\Gamma_{\text{tot}}} \quad ({}^{27}\text{Al}(p,\alpha){}^{24}\text{Mg} \text{ case})$$

Where:

- $\hat{J}=2J+1$
- $\Gamma_{(AB)}$ is the partial width for the A+B channel
- Γ_i is the total width of the i-th resonance
- E_{Ri} is the resonance energy

What is its physical meaning?

→ Area of the Breit-Wigner describing the resonance

→ no need to know the resonance shape

In the THM approach: $\omega\gamma_i^{\text{THM}} \approx \omega_i N_i \frac{\Gamma_{p, \text{s.p.}}^i}{\sigma_{(d,n)}(\theta_n^{\text{c.m.}})}$

Advantages:

- possibility to measure down to zero energy
- No electron screening
- No spectroscopic factors in the $\Gamma_{(p180)} / |M_i|^2$ ratio

Where:

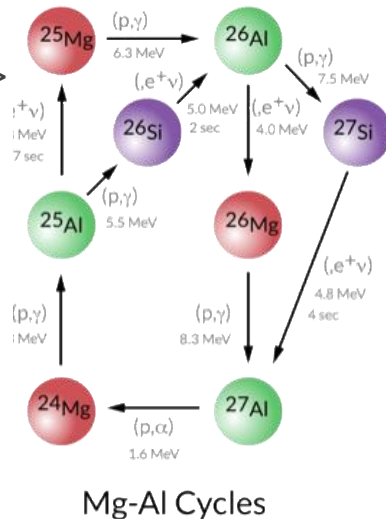
- $\omega_i = \hat{J}_i / \hat{J}_p \hat{J}_{180}$ statistical factor
- N_i = THM resonance strength
- $\sigma = M_i^2$ = transfer cross section

The Astrophysical Journal, Volume 708, Issue 1, pp. 796-811 (2010).

$^{27}\text{Al}(p,\alpha)^{24}\text{Mg}$: Understanding ^{27}Al in massive stars

MgAl cycle in massive stars

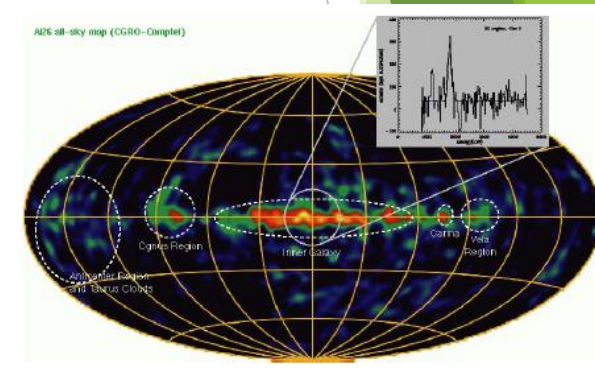
- It is ignited at temperatures > 0.03 GK and it is important to determine the abundances of medium mass nuclei



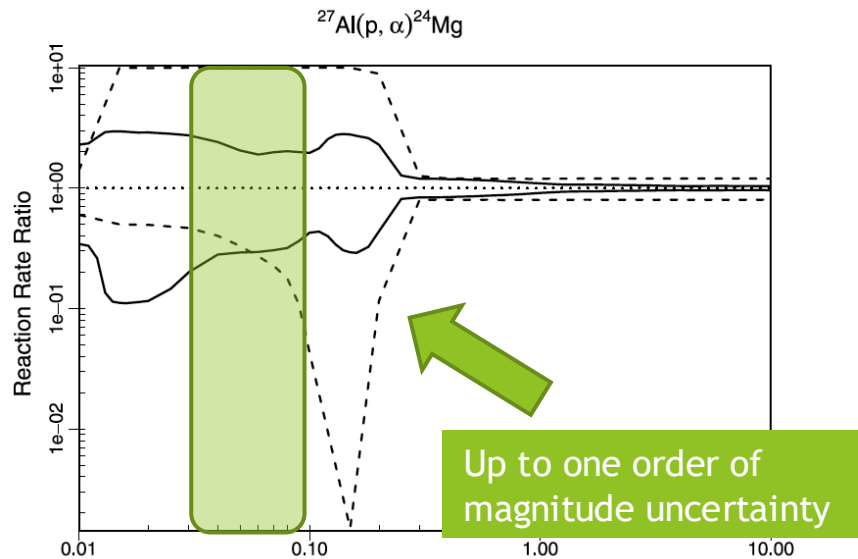
$^{26}\text{Al}/^{27}\text{Al}$ abundance ratio

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

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



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



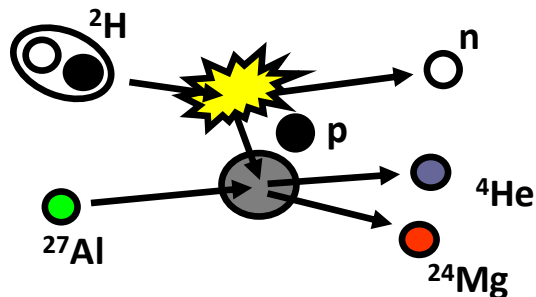
Upper Limits of Resonances

Note: enter partial width upper limit

Note: ...FT <E> 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

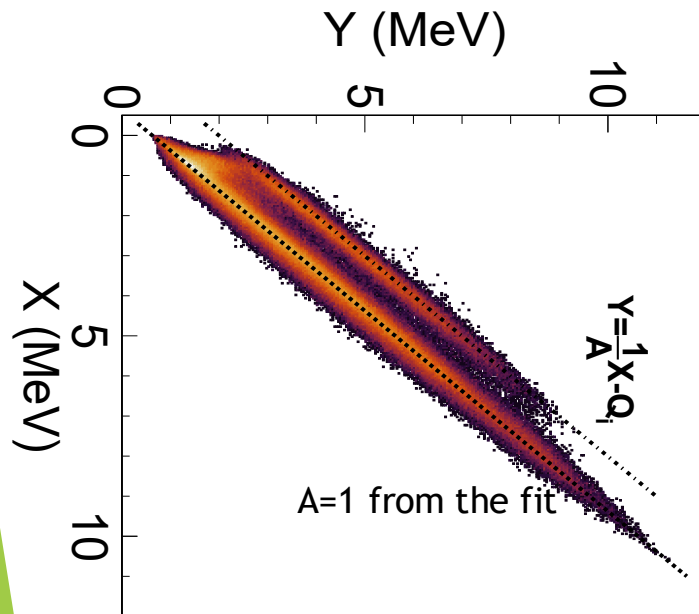


In the THM approach, we will use the DEUTERON as Trojan Horse nucleus

N → Spectator P → Participant

We populate narrow resonances in the ^{28}Si down to zero energy + a normalization region overlapping with existing data

Data analysis: channel selection

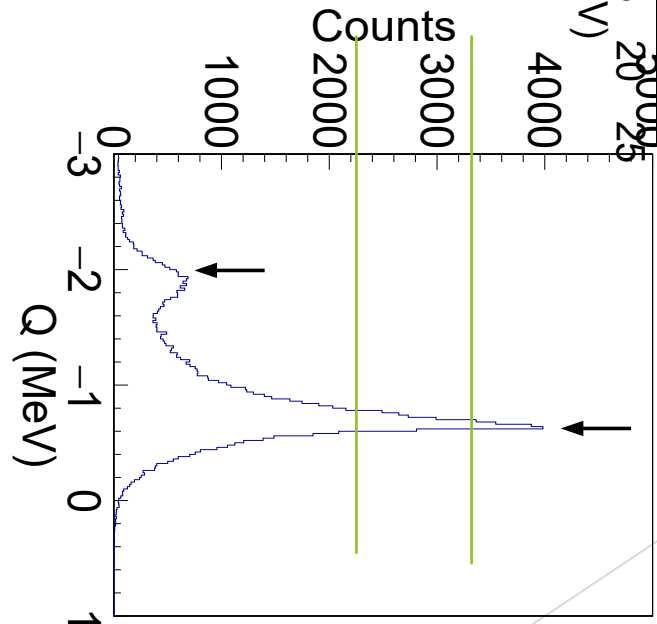


First the mass of the undetected particle is deduced:

$$Y = E_{\text{beam}} - E_A - E_C$$

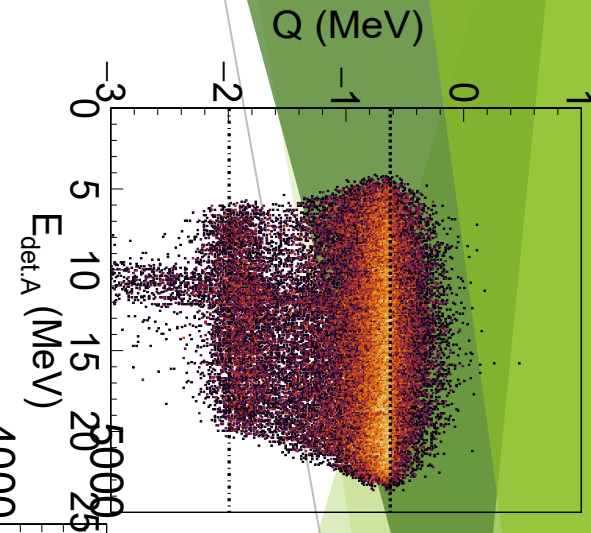
$$X = p_A^2 / 2u$$

Then the Qvalue spectrum is reconstructed



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

Arrows: theoretical Qvalues

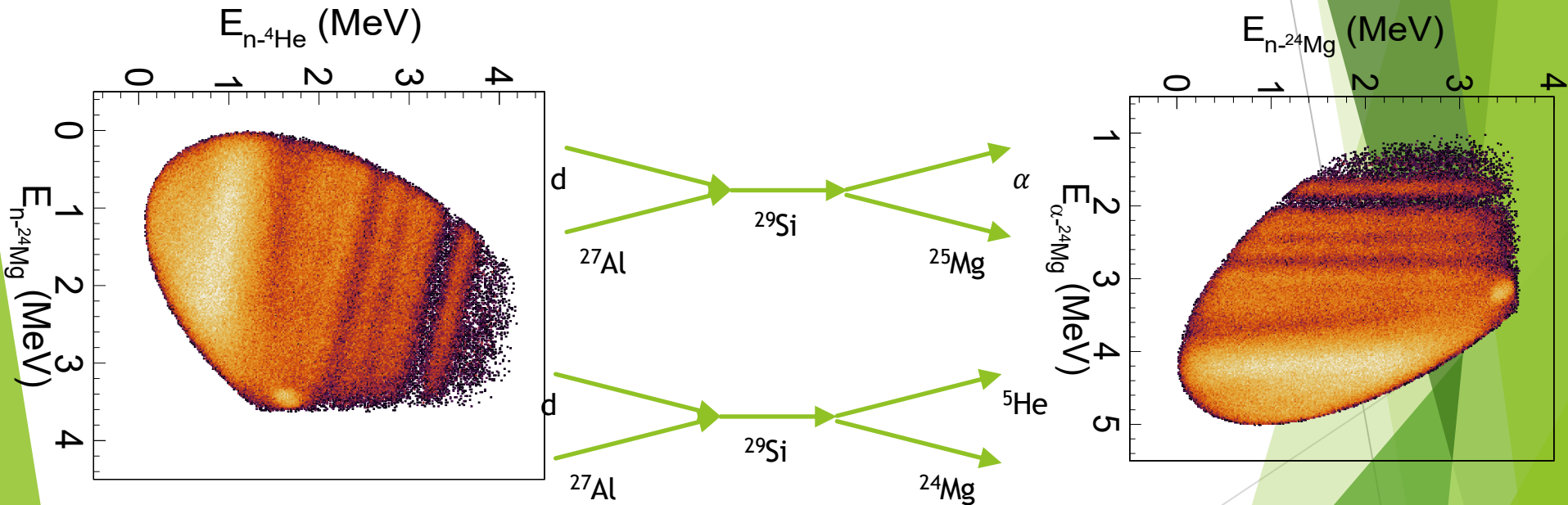


Data analysis: relative energy spectra

^{24}Mg - α relative energy $\rightarrow$ ^{28}Si excitation energies $\rightarrow$ This is the spectrum of astrophysical interest

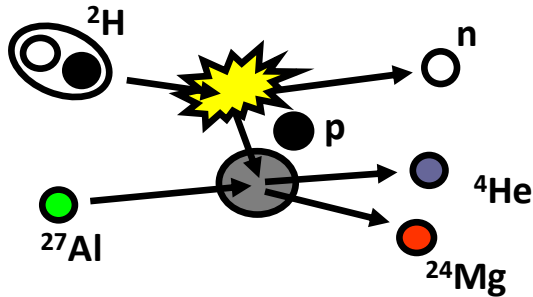
^{24}Mg -n relative energy $\rightarrow$ ^{25}Mg excitation energies $\rightarrow$ background (sequential decay)

^4He +n relative energy $\rightarrow$ ^5He excitation energies $\rightarrow$ background (sequential decay)



This is why it is called sequential decay, as you populate some compound nucleus that later decays (evaporation of fragments in sequence)

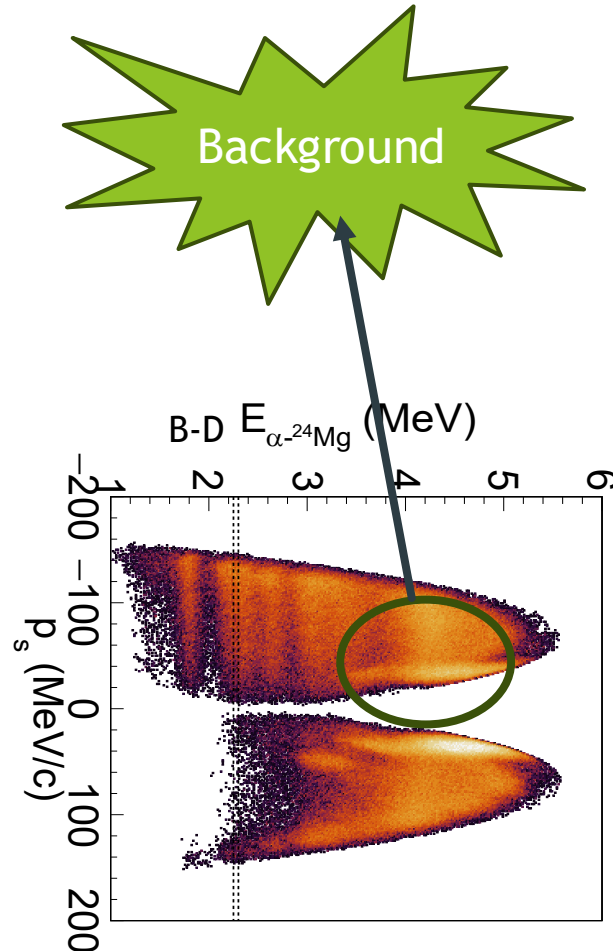
Data analysis: selection of QF process



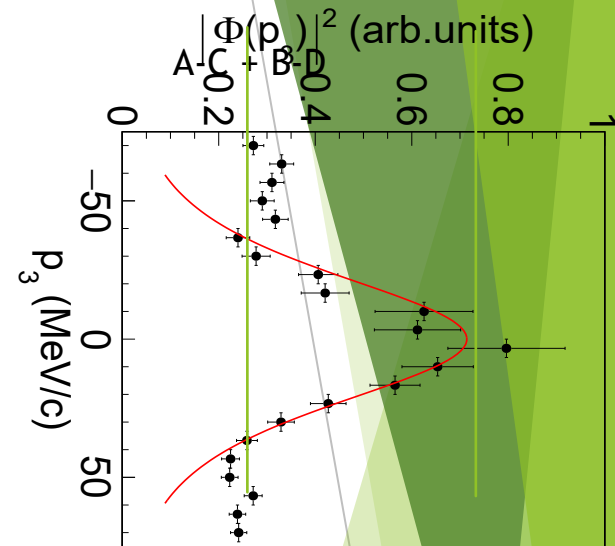
When the breakup is quasi-free, n retains the same momentum as inside d (adiabatic process). **So n -momentum distribution should be the same as in d**

We remove $p_s > 0$ in B-D and $p_s < 0$ in A-C to remove background

In any case that side show no resonances



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

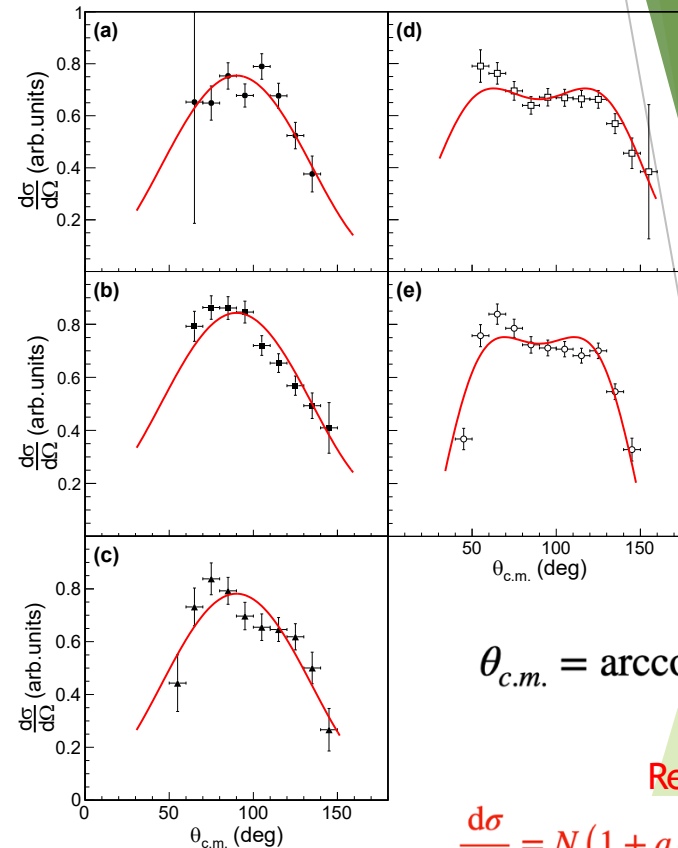


The red curve is the theoretical one: normalization is the only fitting parameter

Data analysis: angular distributions

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 $\pi/2$ is covered, which is the most influential for angular integration



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

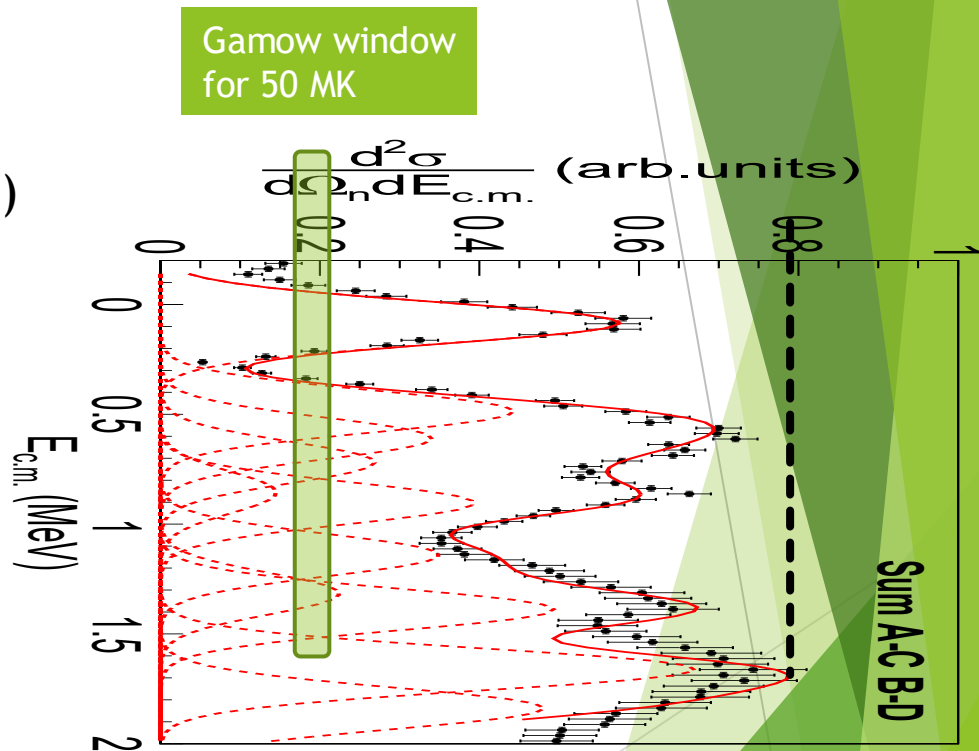
Red line:

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

Region (a) corresponds to about 100 keV: would you imagine extracting angular distributions at this energy, where you have 10 counts in direct experiments?

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

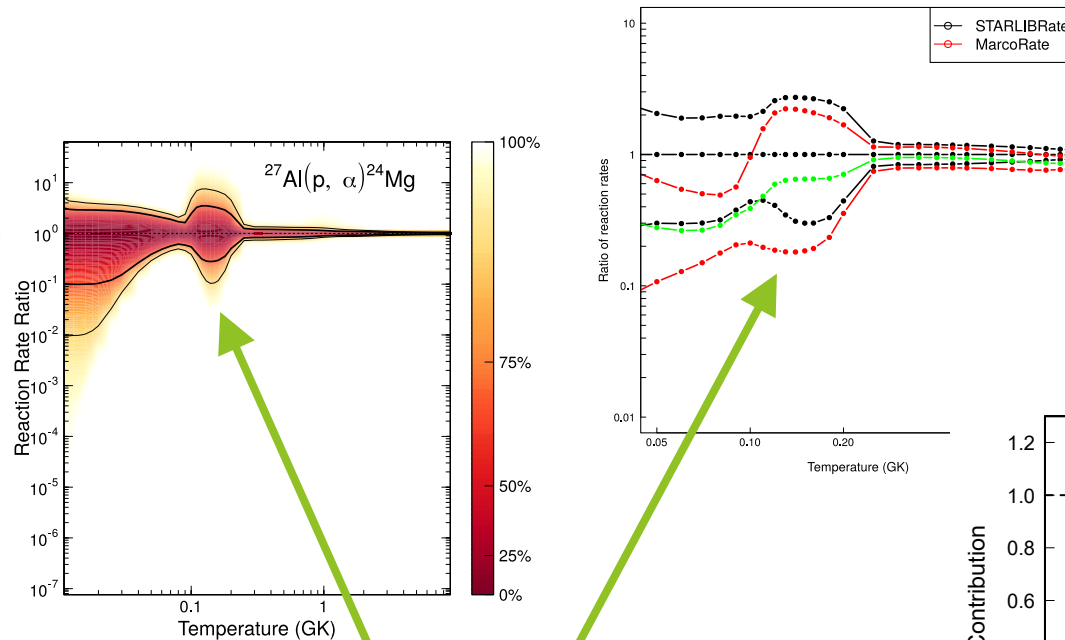
Average values

- 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

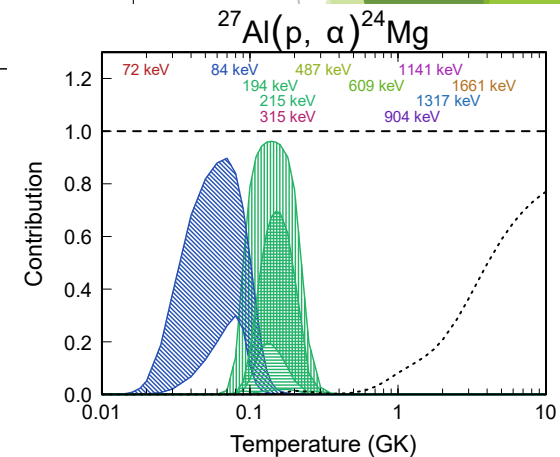
The full calculation using STARLIB (by Philip Adsley)

► 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?

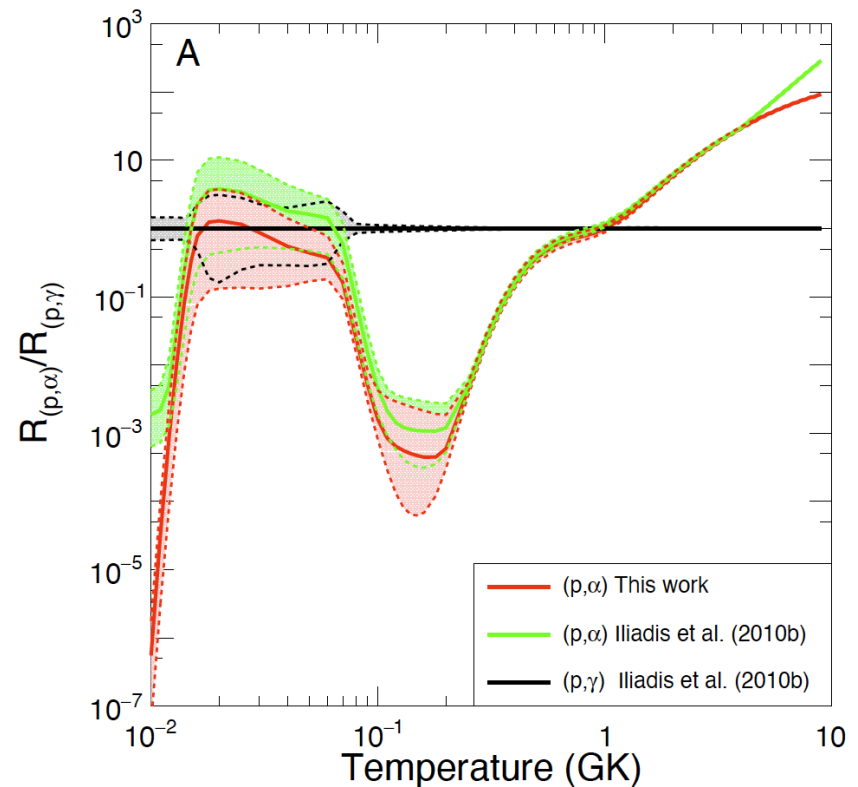


Some astrophysical consequences

- 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

- ▶ 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 Γ_p 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

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

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

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

The (p,γ) channel

- At astrophysical energies, in the case of some resonances it happens that: $\Gamma_p \ll \Gamma_\gamma \ll \Gamma_\alpha$
- This chain of inequations leads to a resonance strength $\omega\gamma$ of the (p, α) channel that is directly proportional to Γ_p 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

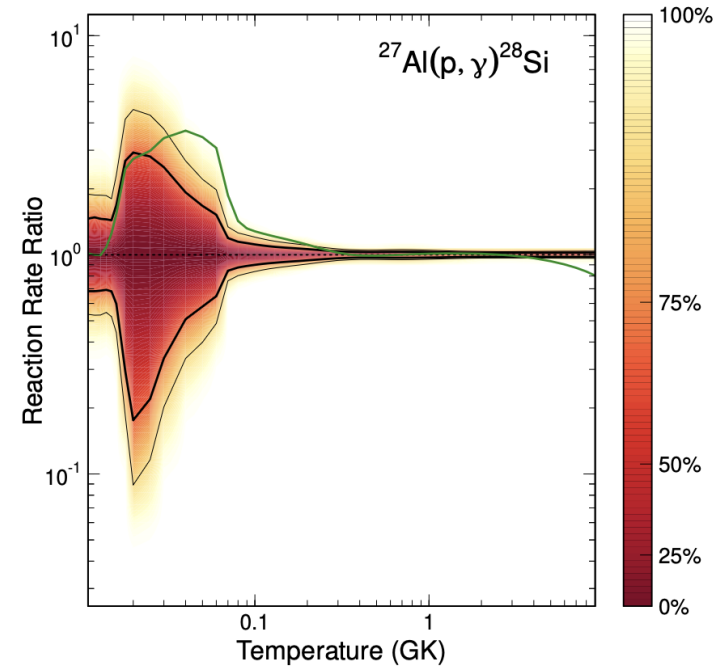
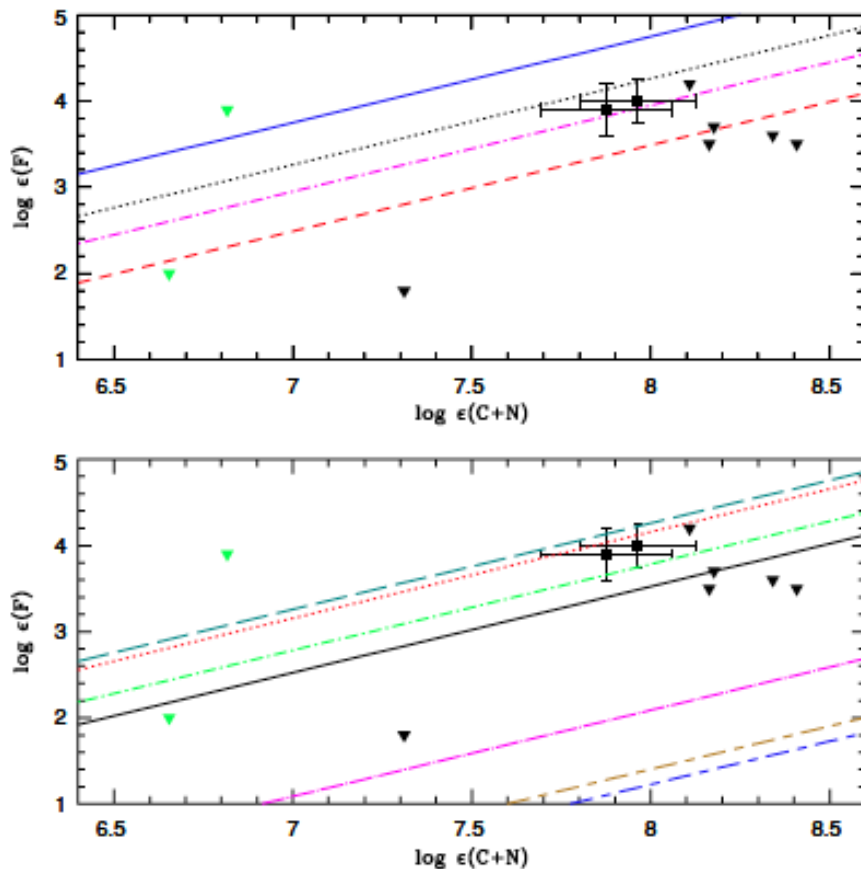


Figure 1. Green line: ratio of the STARLIB median reaction rate (Iliadis et al. 2010b) to the one calculated with the same statistical approach, using the THM updated resonance strengths in Tab.1. A significant reduction in the median rate is apparent. The contour plot shows the uncertainty of the THM 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.

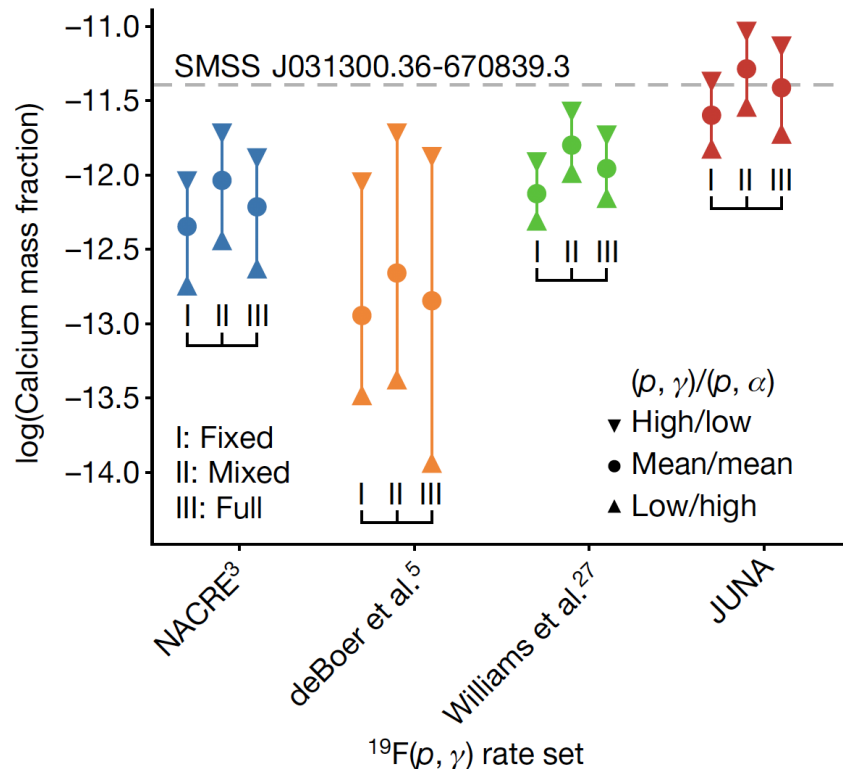
The ^{19}F p-induced destruction in stars



Lucatello, S., et al. 2011, ApJ, 729, 40

- ▶ s-nuclei are produced and brought to the surface thanks to mixing phenomena, together with fluorine that is produced in the same region from the same n-source.
- ▶ ^{19}F is a key isotope as it can be used to probe AGB star mixing phenomena and nucleosynthesis. But its production is still uncertain!
- ▶ Mostly, unphysical AGB models produce fluorine abundances compatible with observations

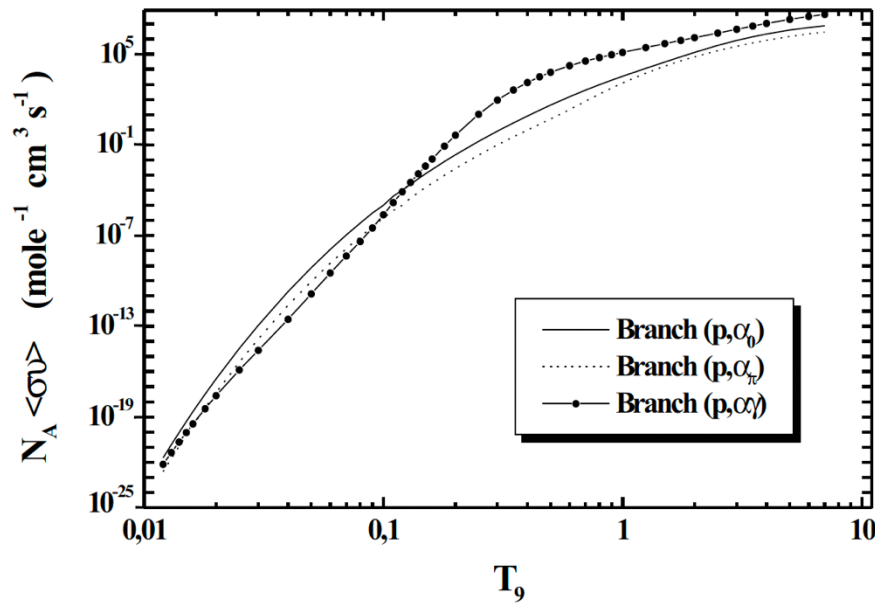
The ^{19}F p-induced destruction in stars



- The most metal-poor stars observed in the Milky Way's halo today display the diluted nucleosynthetic signatures resulting from pop III stars that preceded them
- Observers discovered one of the oldest known stars in the Universe, SMSS0313-6708, and suggested that a CNO breakout during hydrogen burning is the source of calcium production, reporting $[\text{Ca}/\text{H}] = -7.2$

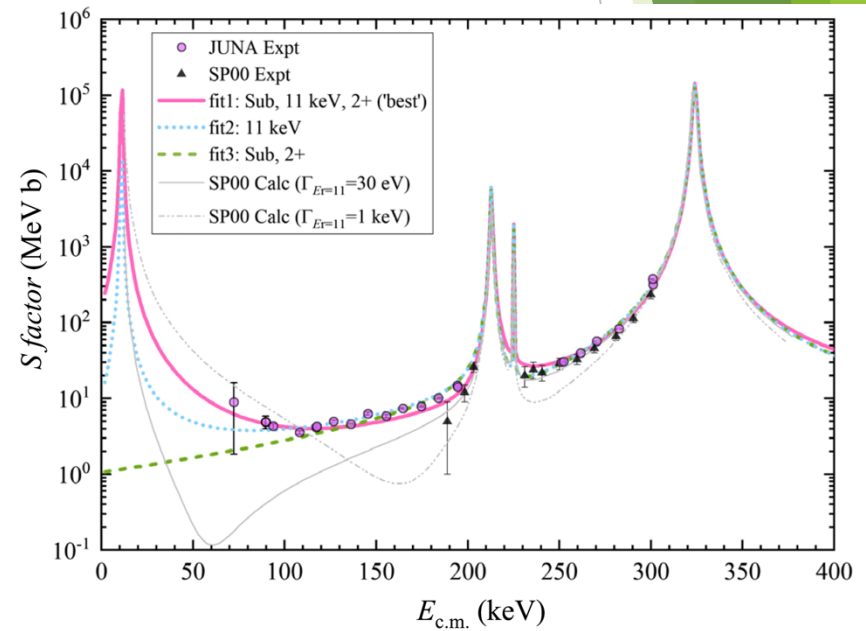
Recent underground measurements seem to have modified our present understanding...

► From the dominance of the α_0 channel



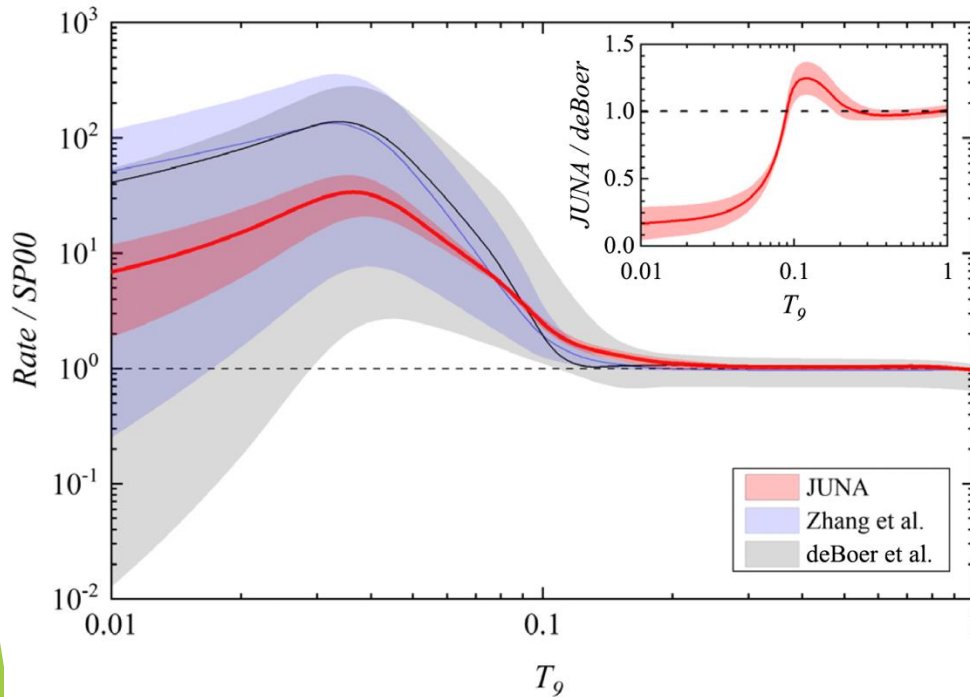
K. Spyrou et al., Eur. Phys. J. A 7, 79-85 (2000)

► To the appearance of the 11 keV peak



L. Y. Zhang et al., PHYSICAL REVIEW LETTERS 127, 152702 (2021)

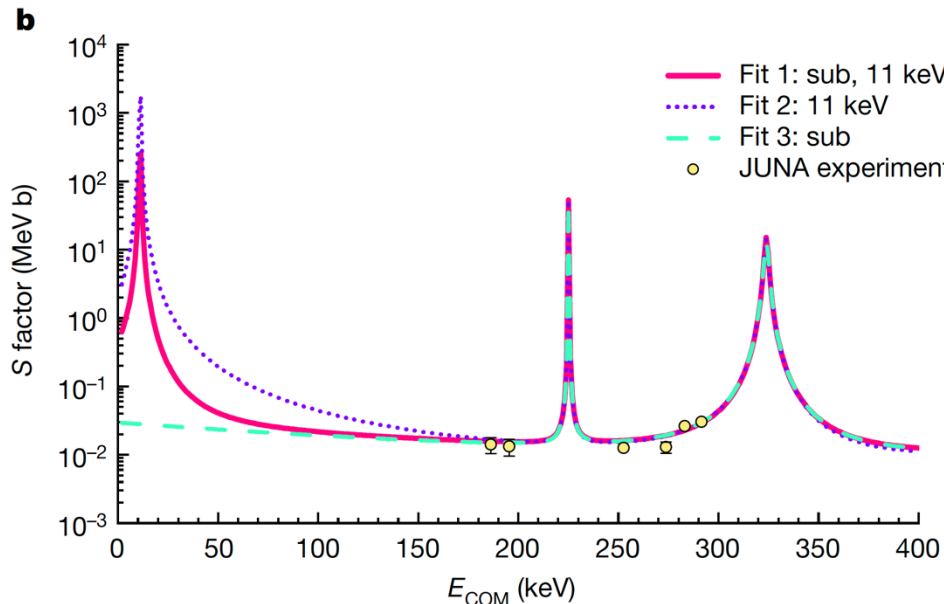
Why?



L. Y. Zhang et al., PHYSICAL REVIEW LETTERS 127, 152702 (2021)

- ▶ The JUNA collaboration corroborates the occurrence of a resonance at 11 keV based on their R-matrix analysis
- ▶ This resonance determines a huge increase in the rate of the $(p, \alpha \gamma)$ channel, even higher than a factor of 10 with respect to Spyrou et al. work at some temperatures.
- ▶ The resonance is so large that the effect extends up to 0.1 GK, with potential impact on several astrophysical scenarios

The radiative capture channel



Liyong Zhang et al., 656 | Nature | Vol 610 | 27 October 2022

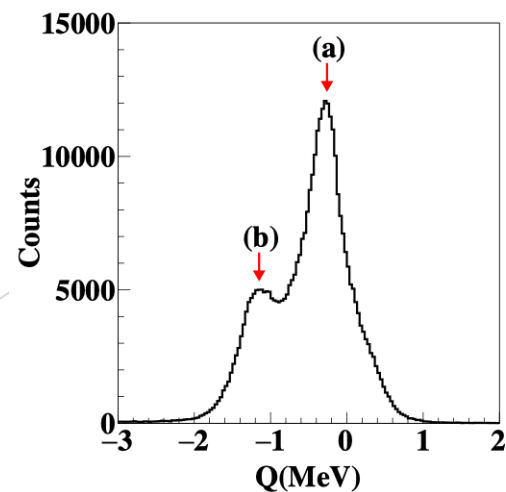
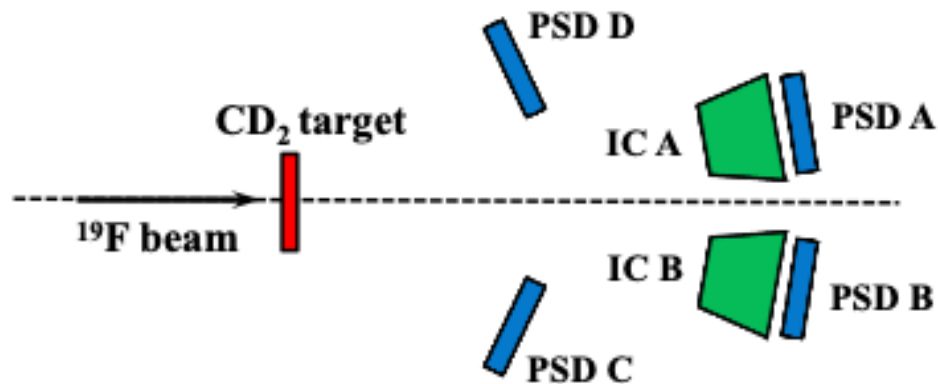
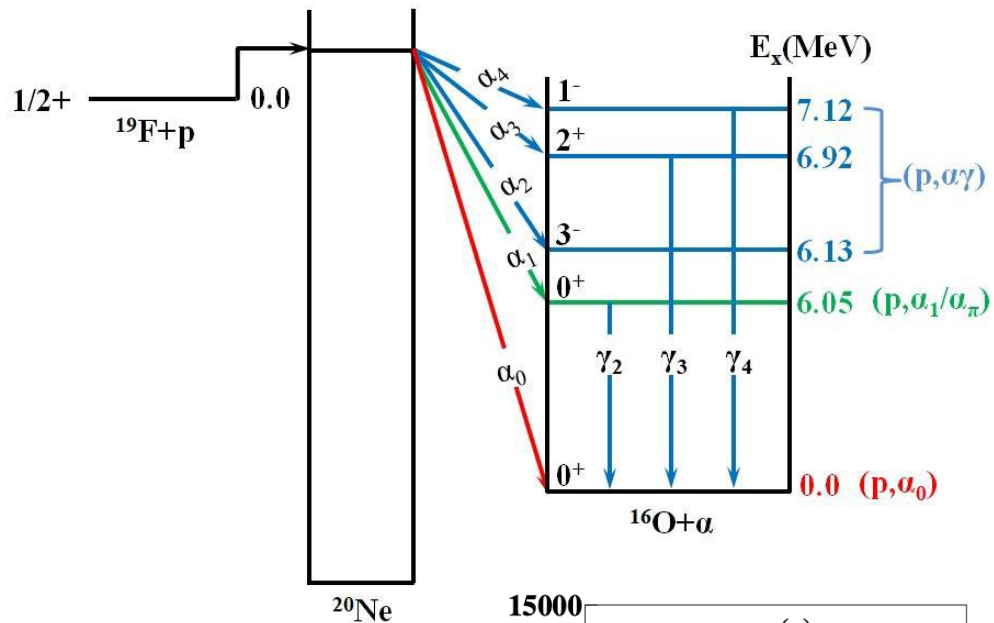
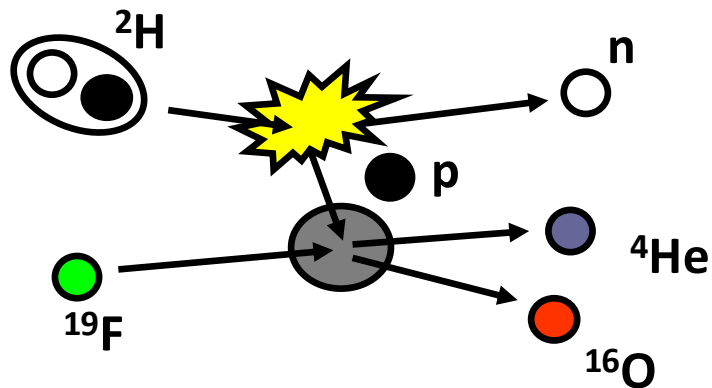
- ▶ This result has impacted also the investigation of the gamma-emission channel
- ▶ The ratio of the new rate to the NACRE one is as large as 200 at 0.01 GK, and the contribution of the 11 keV resonance is probably relevant event at 0.1 GK
- ▶ The new rate would justify the observations of Ca in old stars through the breakout from the CNOF cycles.

However

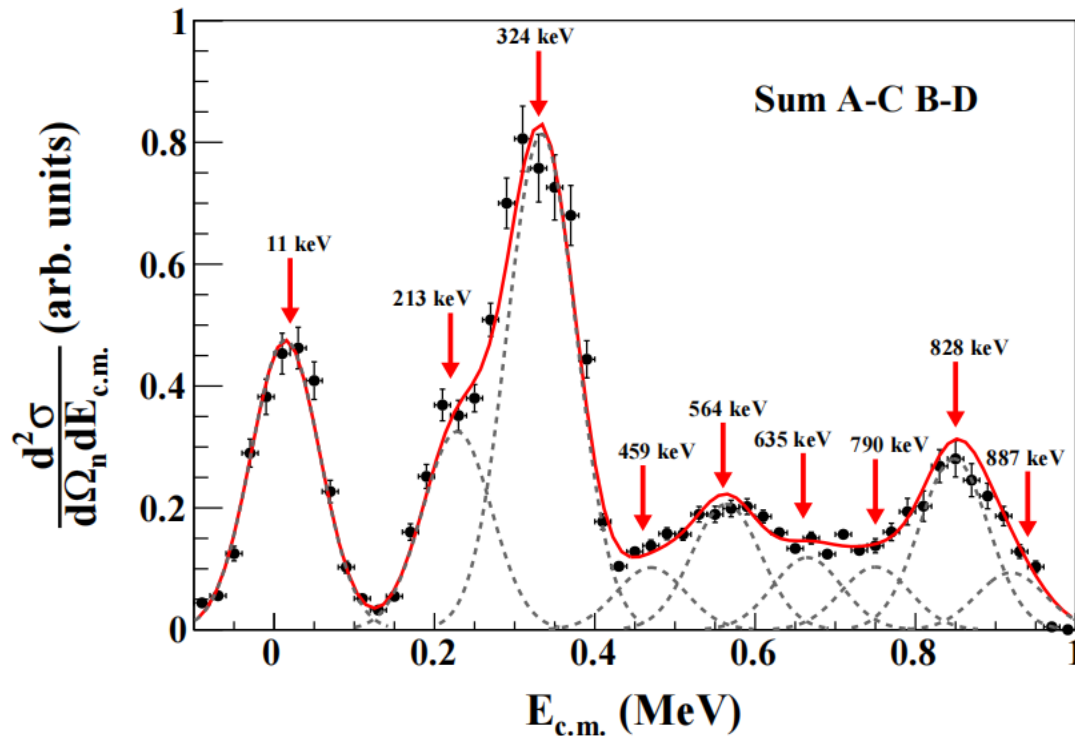
- ▶ Even if the JUNA collaboration could reach record low energies by measuring deep underground, the lowest energy points were measured at 70 keV for the $(p, \alpha\gamma)$ channel and 185 keV for the (p, γ) channel.
- ▶ 70 keV Gamow energy corresponds to 50 MK and 185 keV to 220 MK, above the typical temperatures for fluorine burning in AGB stars (<40 MK), and also for hot CNO breakout in early stars (~ 100 MK).
- ▶ **Extrapolation was carried out using R-matrix analysis**, including a -448 keV subthreshold resonance. The existence of the 11 keV state and of the latter, their spin-parities and strengths of such states, would be crucial to verify the conclusions based on extrapolations

The THM experiment

- We run at LNS Tandem using a 55 MeV ^{19}F beam and CD_2 target



From the THM cross section...



From the fitting of the THM cross section we deduce the resonance strengths in arbitrary units (only fitting parameters: strengths)

Normalization to the most prominent peaks at 324 keV and 828 keV (each has a strength known with 4% accuracy)

A-C and B-D detector couples are consistent, so data are summed up to improve precision

Normalization error is about 3%
Model dependence at most 13%

...to the resonance strengths...

	E_i^R (keV)	J^π	$\omega\gamma$ (eV) ^a	$\delta\omega\gamma$ (eV) ^a	$\omega\gamma$ (eV) ^b	$\delta\omega\gamma$ (eV) ^b
(1)	11	1^+	7.5×10^{-29}	3×10^{-29}	1.3×10^{-29}	1.6×10^{-30}
(2)	212.71	2^-	2.2×10^{-2}	4×10^{-3}	2.3×10^{-2}	2.7×10^{-3}
(3)	323.31	1^+	23.1	0.9	24.5	1.8
(4)	459.53	1^+	9.5	0.7	11.4	1.3
(5)	564.42	2^-	50	6	43.7	4.1
(6)	635.31	1^+	88	10	103.4	11.4
(7)	790.53	2^+ ^c	27	6	23.7	2.7
(8)	828.17	2^-	785	32	664.2	59.0
(9)	887.14	1^+	452	31	567.1	63.2

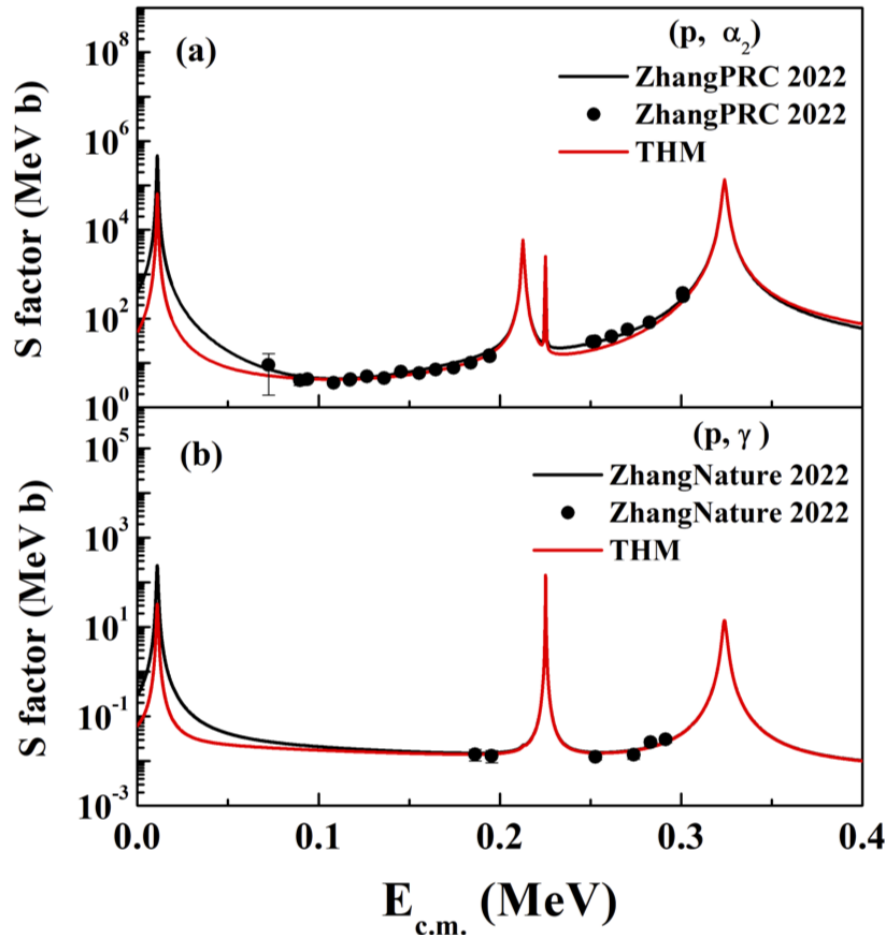
^a Strengths as reported in NACRE.

^b Present-work strengths.

^c Our analysis suggests this state is 2^+ .

- The main result of our work is the first time observation of the 11 keV resonance
- we confirm the 1^+ spin parity attribution based on our experimental angular distributions analysis
- Our measured strength is 5.8 times smaller than the extrapolated values
- The analysis was extended to all resonances below 1 MeV to conduct a validity test of our method (with a maximum deviation of 1.8σ)
- We do not observe the 225 keV resonance due to energy resolution effects

... to the THM S-factors



- To evaluate the compatibility of the present $^{19}\text{F}(p, \alpha\gamma)^{16}\text{O}$ and $^{19}\text{F}(p, \gamma)^{20}\text{Ne}$ S-factors with Zhang et al 2022 results, we have used the THM strength of the 11 keV resonance, alongside the strengths available in the literature for the other resonances, to calculate the astrophysical factor $S(E)$ in the R-matrix framework using AZURE2
- The corresponding astrophysical factors are in good agreement with available experimental data where available, denoting a poor constraint set by direct experimental data taken at energies far from the region of interest

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Summary

- What are indirect methods? Why are they needed?
- Some theory about the THM for resonant reactions
- Near threshold astrophysical factors for $^{27}\text{Al}+p$ and $^{19}\text{F}+p$
- $^{26}\text{Al}+n$ reactions: work in progress

Thanks for
your
attention



" What did you take away from the meeting ? "

