THE ORIGIN OF COSMIC ELEMENTS
Past and Present Achievements, Future Challenges
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Application of the Trojan Horse Method to resonance reactions and implications for stellar nucleosynthesis

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Direct vs. indirect measurements

Indirect measurements:

High energy experiments: up to several hundreds MeV

→ no Coulomb barrier suppression

→ negligible straggling

→ no electron screening

Indirect measurements are the only techniques allowing us to measure down to astrophysical energies with the present day facilities

Nuclear reaction theory required

→ cross checks of the methods needed

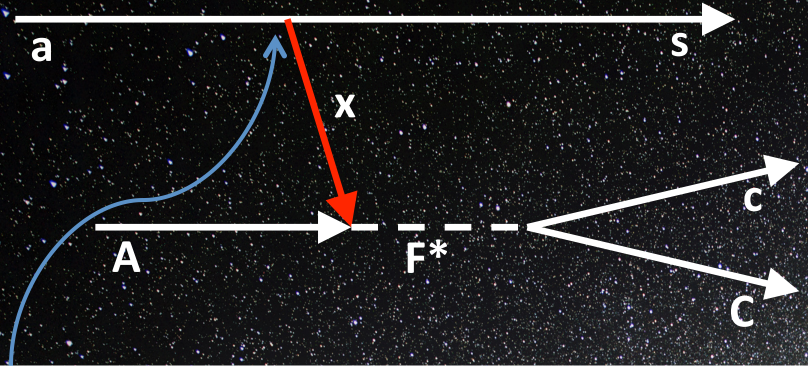
→ possible spurious contribution

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

... Indirect techniques are complementary to direct measurements
Examples: Coulomb dissociation, ANC and Trojan horse method

In particular, the THM aims to measure the cross section of the A(x,c)C reaction by means of a three-body process: A(a,cC)s where a=x+s is the Trojan horse nucleus

The THM for resonance reactions



Upper vertex: direct *a* breakup
$M_i(E)$ is the amplitude of the transfer

Using the kinematics of three body reactions:

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

It is possible to achieve negative energies in the A-x channel…
Out of reach for direct measurements

How to deal with negative energies?

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)

In the case of a resonant THM reaction the cross section takes the form:

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

M^2 is proportional to the ANC of the F state populated in the transfer reaction

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

Two examples discussed here:

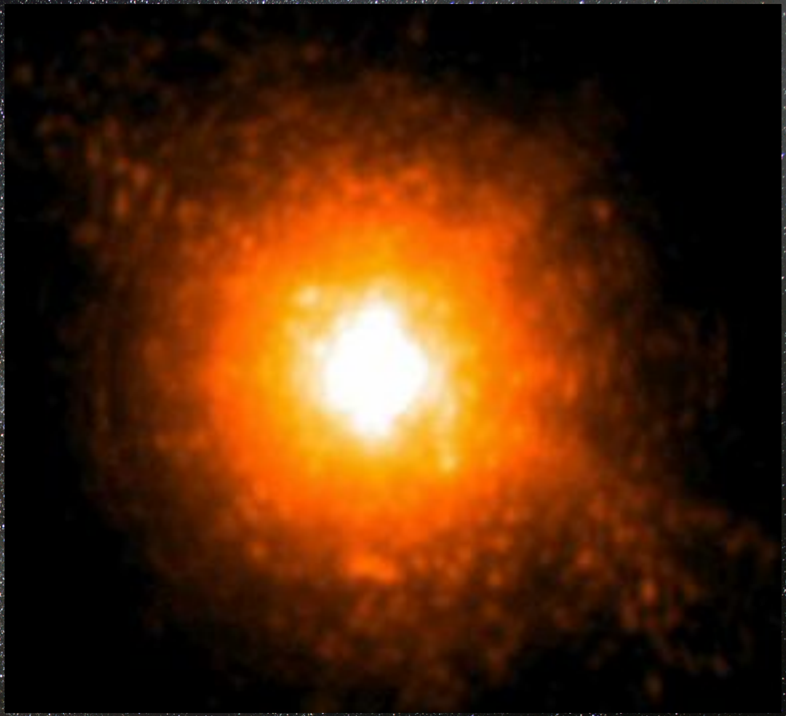
The $^{13}C(\alpha,n)^{16}O$ reaction studied through the $^{13}C(^{6}Li,n^{16}O)^{2}H$ reaction

The $^{19}F(p,\alpha)^{16}O$ reaction studied through the $^{2}H(^{19}F,\alpha^{16}O)n$ reaction

I'm late! I'm late! I'm late!

The $^{13}C(\alpha,n)^{16}O$ reaction

The $^{13}C(\alpha,n)^{16}O$ reaction is the main neutron source in low mass AGB stars at temperatures between 0.8 and 1 x 10^8 K in radiative conditions.



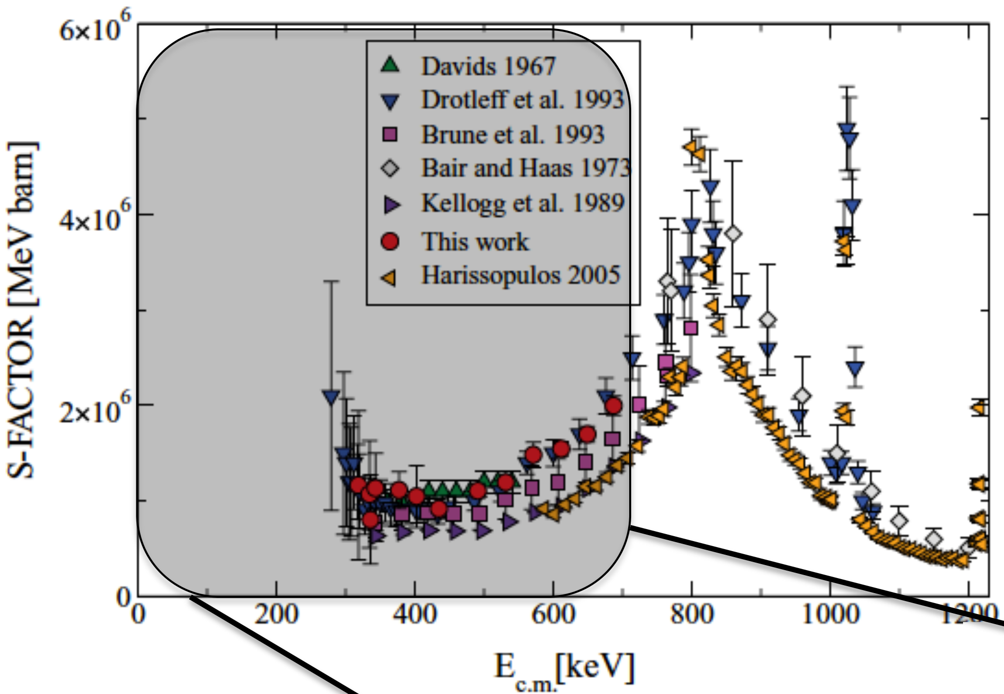
It provides a neutron density of about 10^6 - 10^8 n/cm^3. These neutrons are fundamental for the s-process.

^{13}C is produced starting from ^{12}C present in the instershell region when protons squeeze in during the third dredge-up.

In the typical stellar environment the energy region of astrophysical interest, the so-called Gamow window, corresponds to 150-230 keV at a temperature of about 10^8 K.

In this energy range the not well known influence of the broad (124 keV) subtreshold state J=1/2$^+$, corresponding to the excited level of ^{17}O at E_x = 6.356 MeV (E_r=-3keV), can be important.

State of the art



Direct data → several open issues

- Normalization especially at low energies
- Extrapolation to astrophysical energies
- Correction for the electron screening enhancement

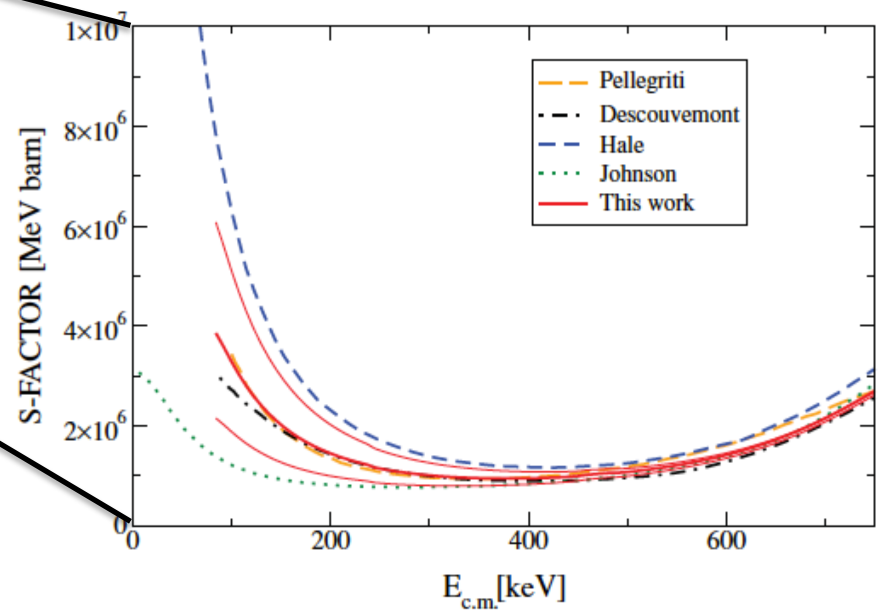
Why?

Low energies, neutron detection, theory

Extrapolation to astrophysical energies
Heil et al. 2008

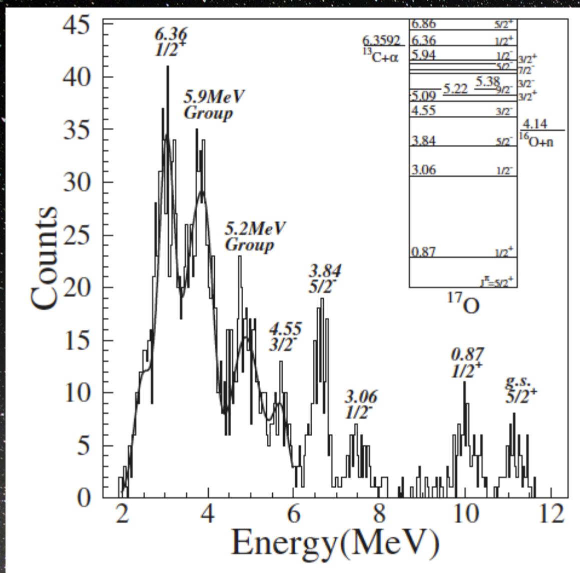
At astrophysical energies an error as large as a factor of 2 is obtained

Change on the cross section influences the neutron abundance and so the yield of some elements like Rb and Sr.

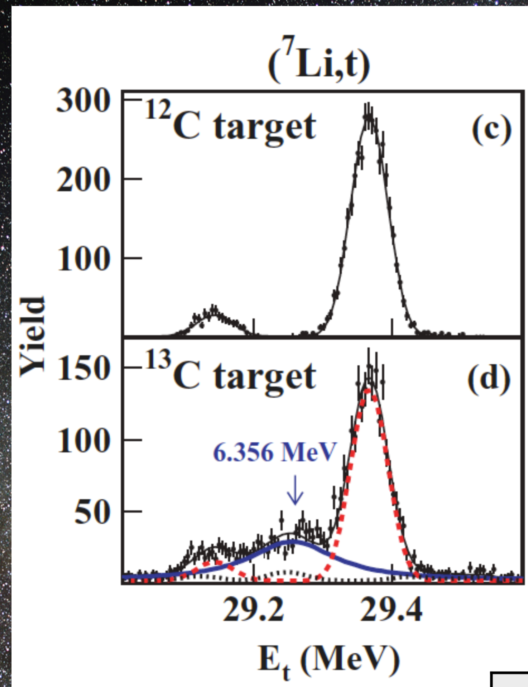


Indirect measurements

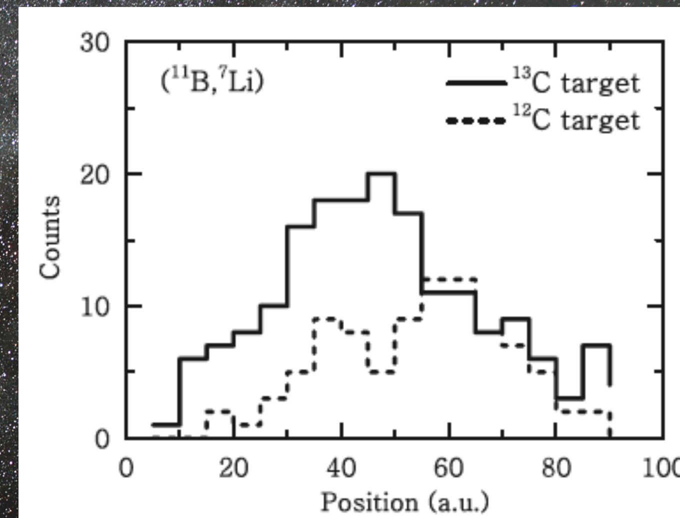
Johnson et al.



Pellegriti et al.



Guo et al.

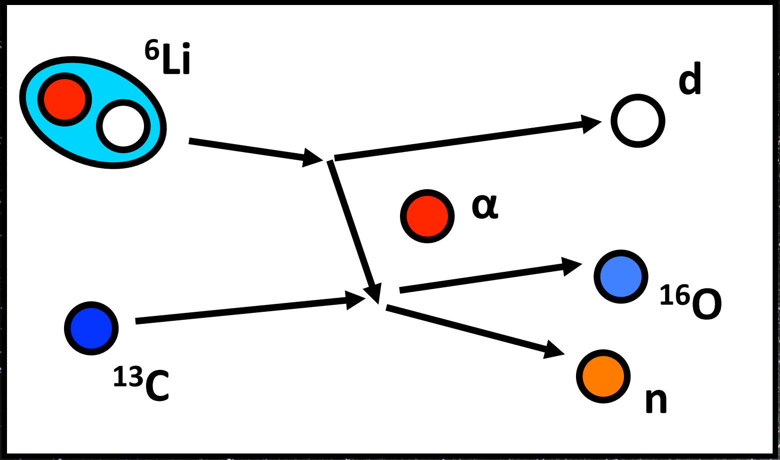


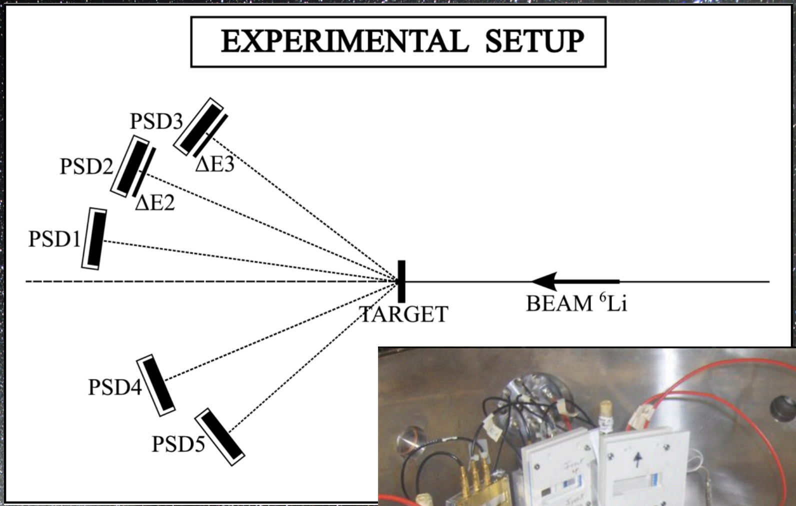
Transfer reactions are used to extract the ANC or the spectroscopic factor of the subthreshold resonance at -3 keV.

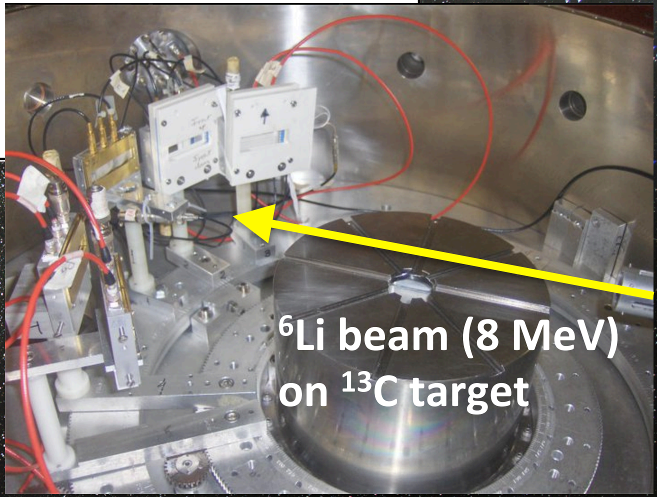
→ Anyway, contradictory results are obtained making extrapolation to low energies very uncertain.

Reference	ANC^2 (fm^{-1})
Johnson et al.	0.89±0.23
Pellegriti et al.	4.5±2.2
Kubono et al.	0.14 (SF)
Keeley et al.	2.4, 3.2 (SF)
Guo et al.	4.0±1.1

Measurement of the $^{13}C(\alpha,n)^{16}O$ reaction through the THM







The experiment was performed at the Florida State University applying the indirect THM. Our experiment was performed by measuring the sub-Coulomb $^{13}C(\alpha,n)^{16}O$ reaction through the $^{13}C(^{6}Li,n^{16}O)d$ reaction in the quasi-free kinematics regime.

FLORIDA STATE UNIVERSITY

Pros and cons of the experimental approach:

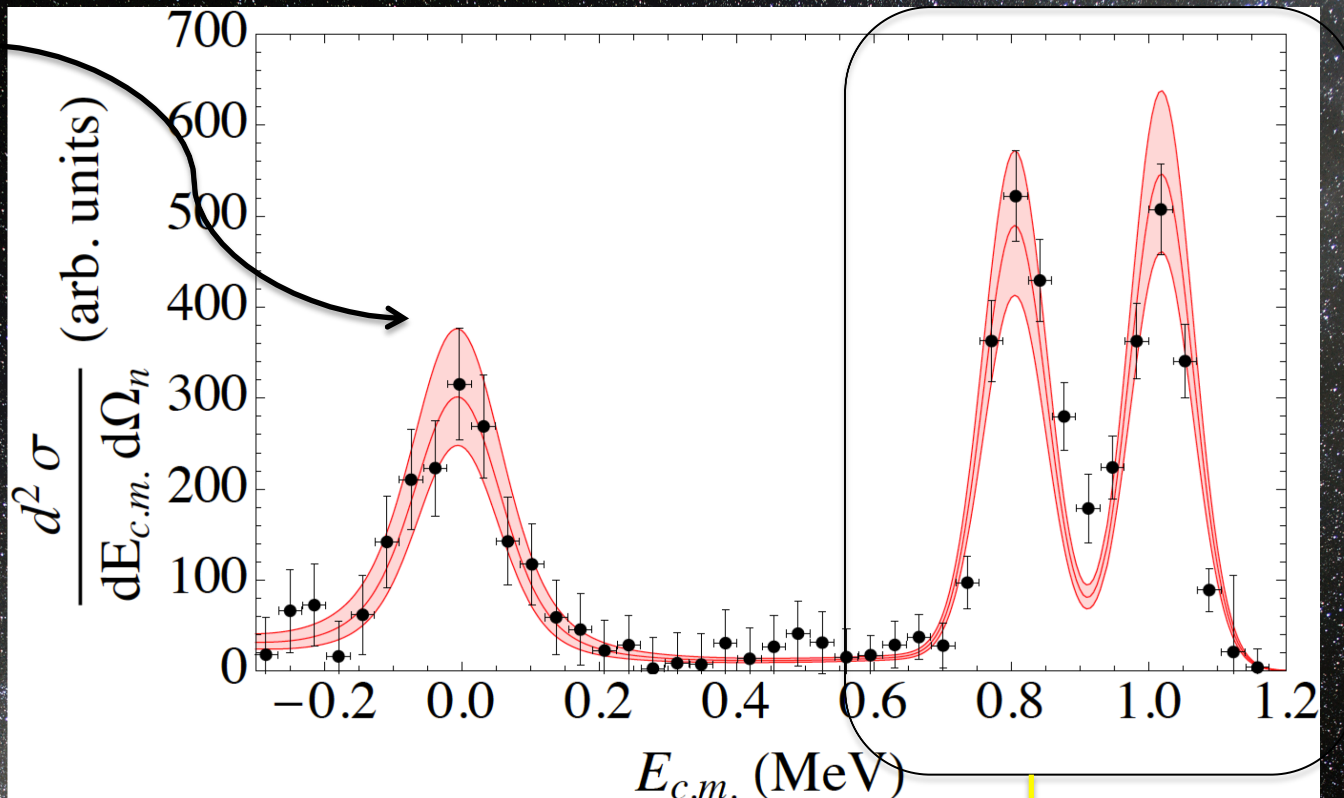
Deuteron detection in PSD 1-2-3 → No need for neutron detectors

Better detection efficiency and lower chances of systematic errors (see direct measurements!)

However d is emitter at zero degrees → the QF peak cannot be accessed in the experiment

Fitting THM data with the HOES R-matrix

Fitted HOES cross section: 2 parameters, the reduced n- and α-widths. Channel radii fixed at the Heil et al. ones [5.2 and 4 fm for the α- and n-channels]

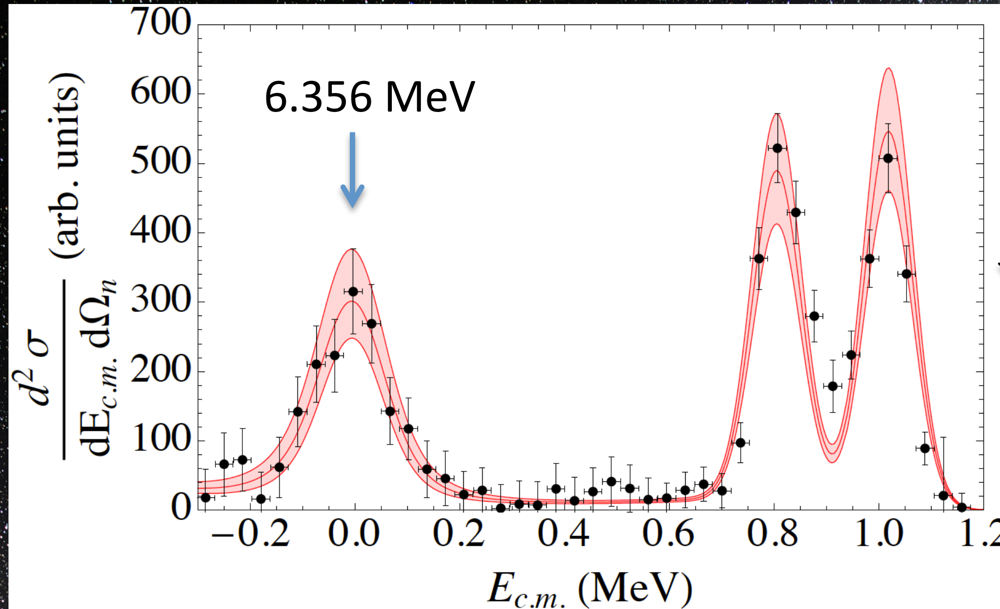


Coulomb corrected ANC² of the -3 keV resonance is: $6.7^{+0.9}_{-0.6}$ fm^{-1} (maximum error)

Γ_n of the -3 keV resonance is: $0.083^{+0.009}_{-0.012}$ MeV

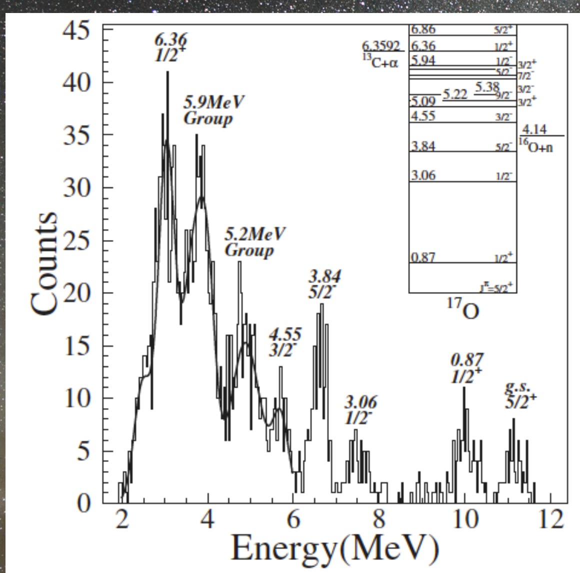
Normalization region: Scaling factor and energy resolution obtained (this one in agreement with the calculated one, 46 keV)

Effect of DW: 9.5%, included into the normalization error as it modifies the 2-peak relative height

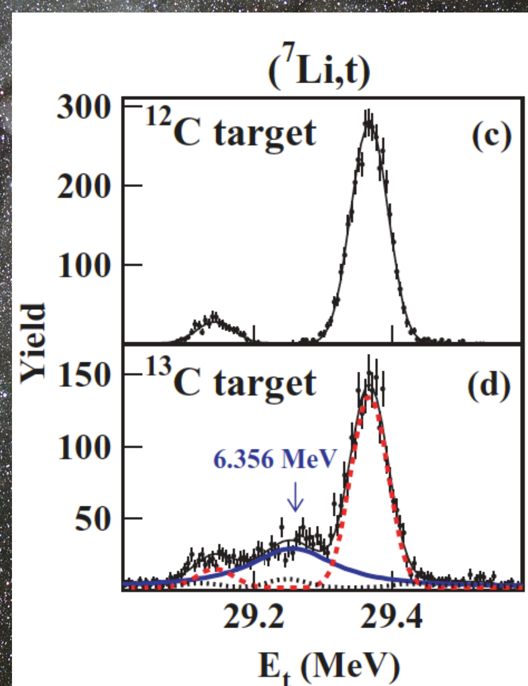


Only about 50% of the total statistics analyzed so far

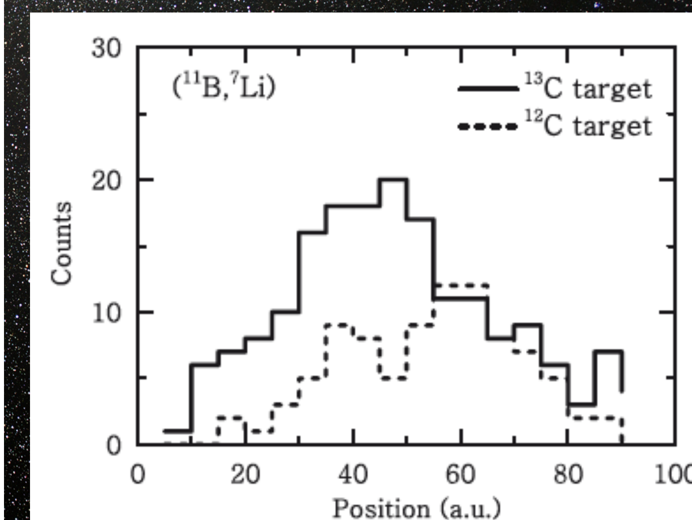
Johnson et al.

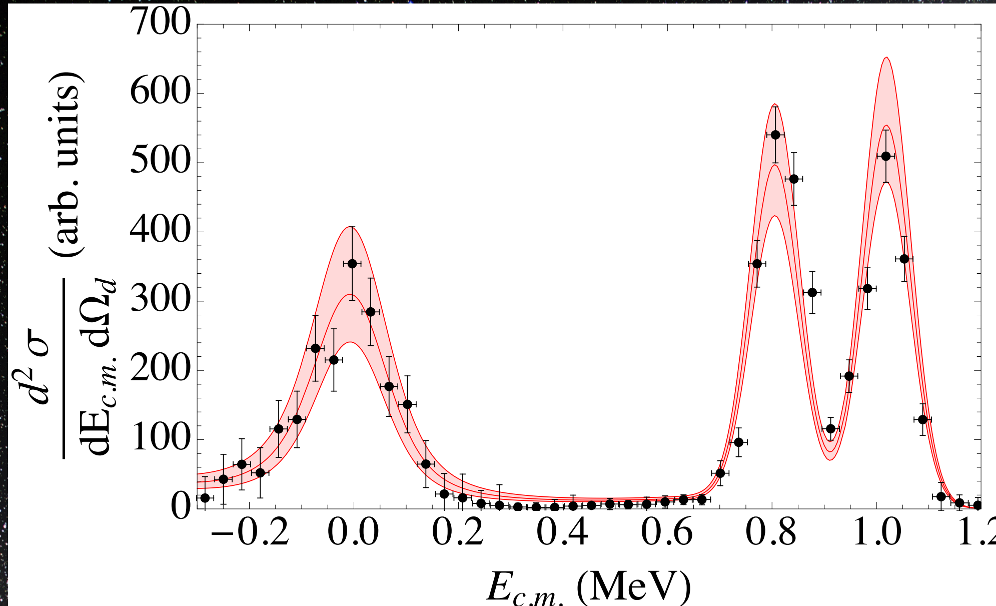


Pellegriti et al.



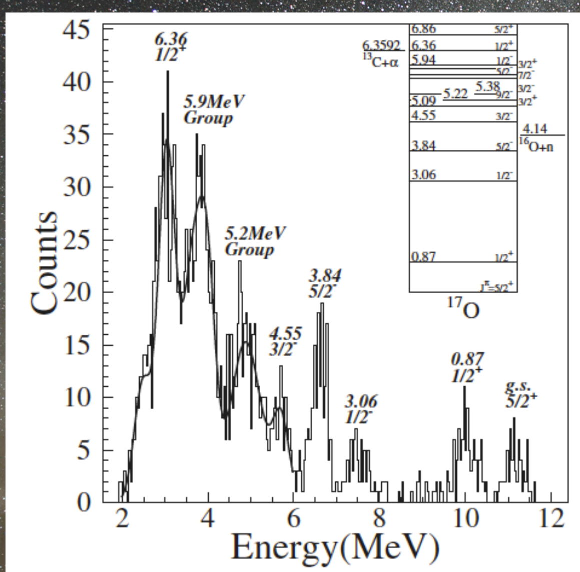
Guo et al.



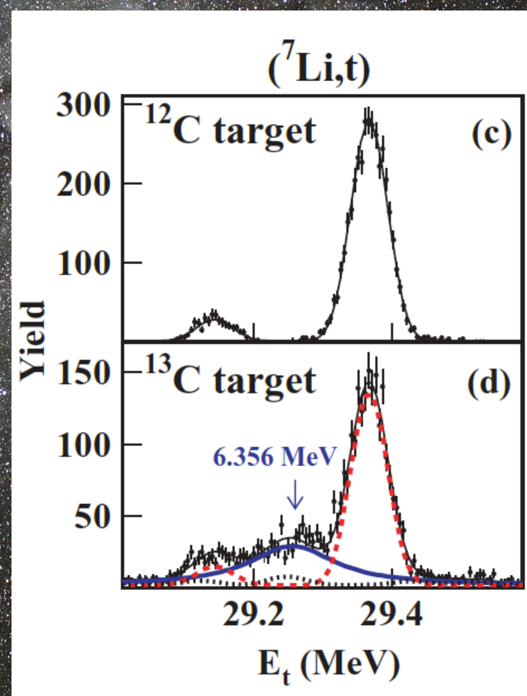


PRELIMINARY:
Full statistics plot
→ Perfect agreement with previous results (ANC a bit larger and Γ_α in better agreement with the value in the literature)

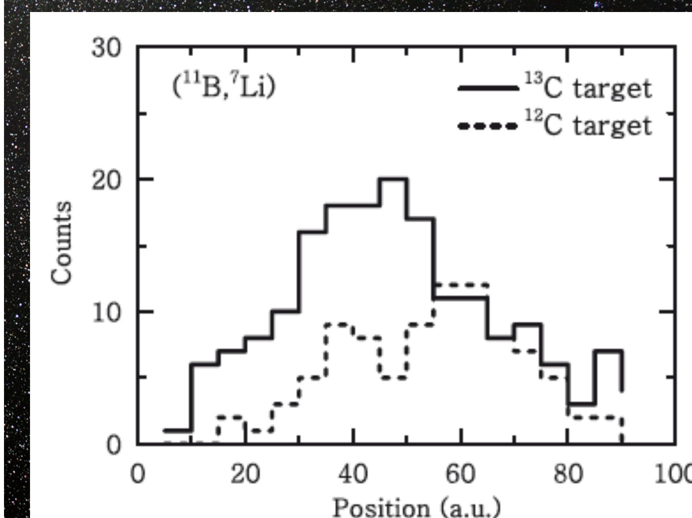
Johnson et al.



Pellegriti et al.



Guo et al.

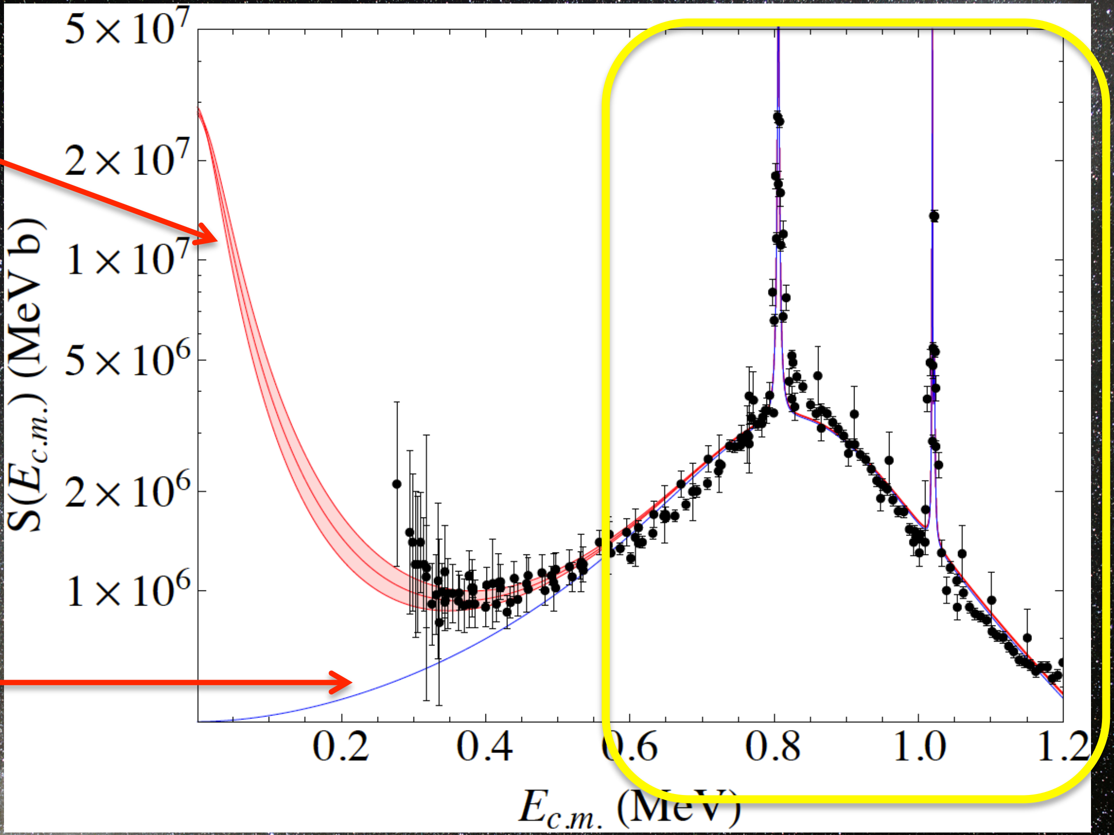


OES THM S(E) factor and available experimental data following the prescription of Heil et al.

OES R-matrix with the parameters from the THM data

Γ_n and ANC from THM data

No -3 keV resonance



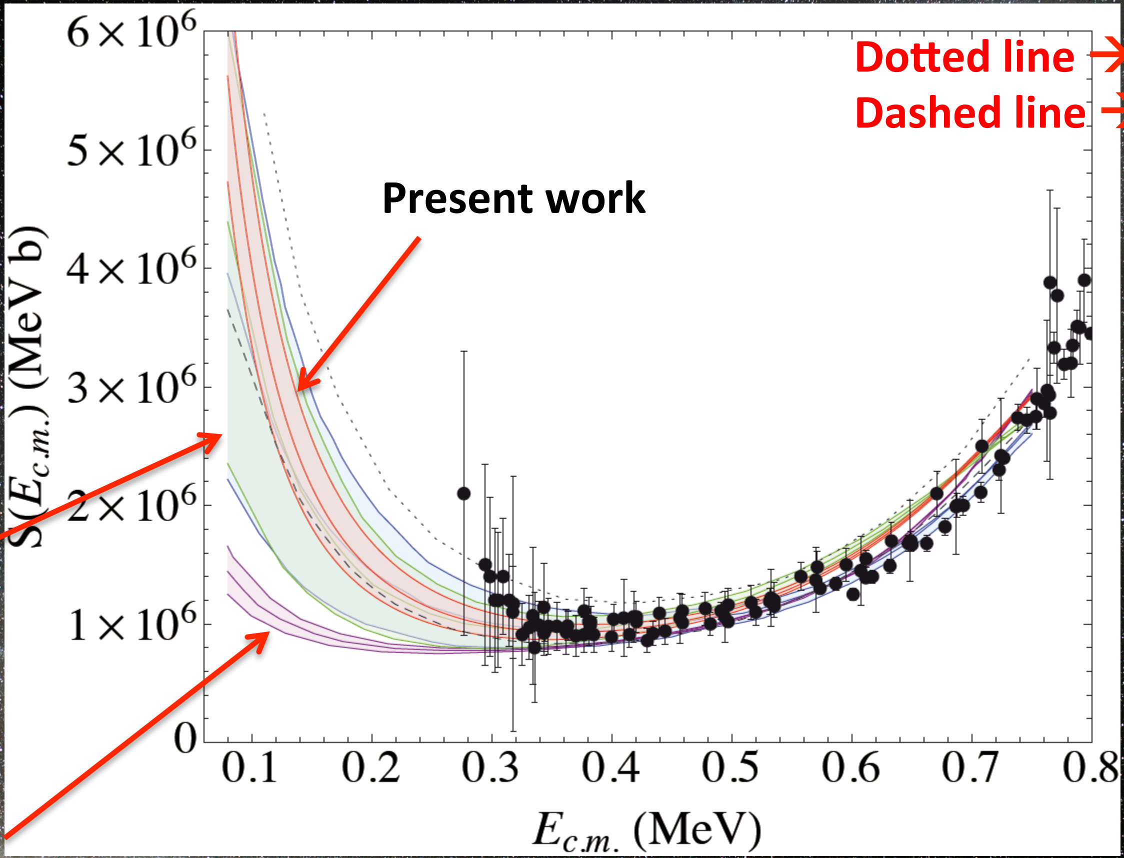
Normalization region → R-matrix function parameters from Heil et al.

The displayed uncertainty band includes statistical and normalization error → maximum error as the minimum and the maximum normalization constants are used

The interference with the -400 keV resonance is accounted for following Heil et al. approach

Comparison of our low-energy S-factor with some of the others present in the literature

Dotted line → Hale (Nacre)
Dashed line → Drotleff et al.



Green and blue bands (barely distinguishable) are Pellegriti et al. and Heil et al.

Johnson et al.

Several extrapolations are available, we show the most recent ones or those commonly in astrophysical modeling → Nacre (essentially the R-matrix by Hale) and Drotleff et al. (the type of calculation is not disclosed).

Electron screening? Included in Drotleff et al. calculation, not included by Heil et al.

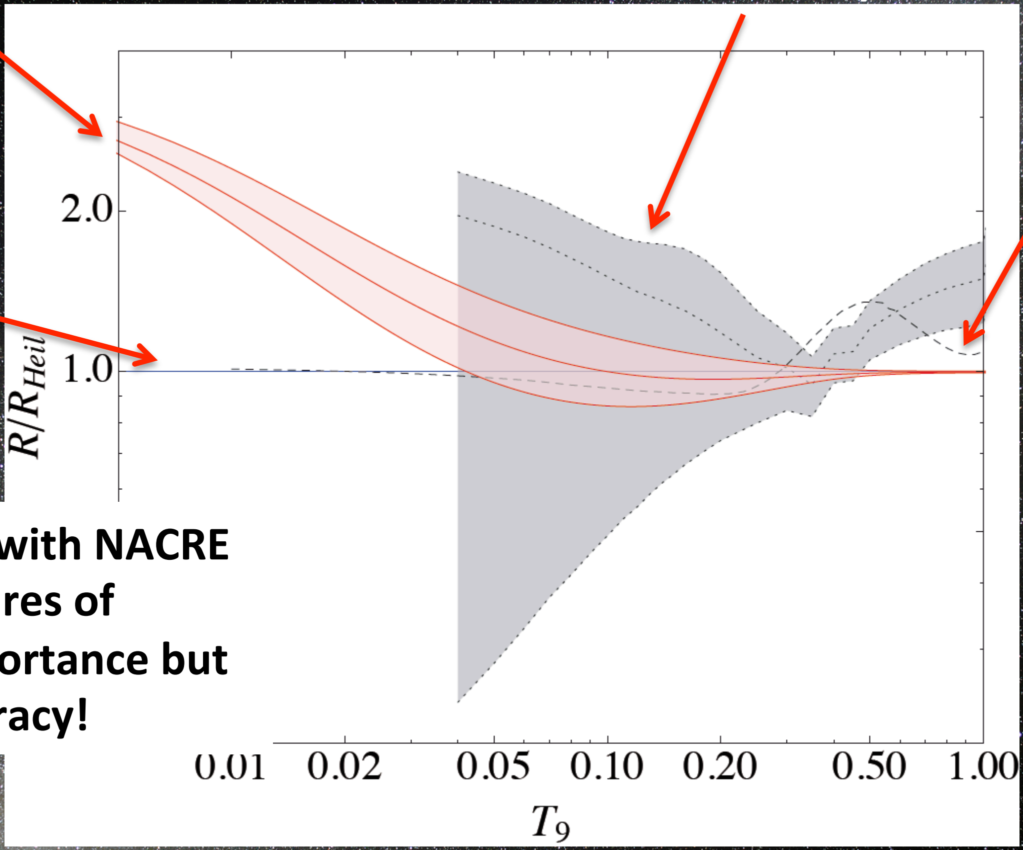
Comparison of the reaction rate with the one Heil et al. one

Present work / Heil et al. reaction rate

Nacre rate / Heil et al.

Drotleff et al. / Heil et al.

Heil et al. rate = 1 in this scale

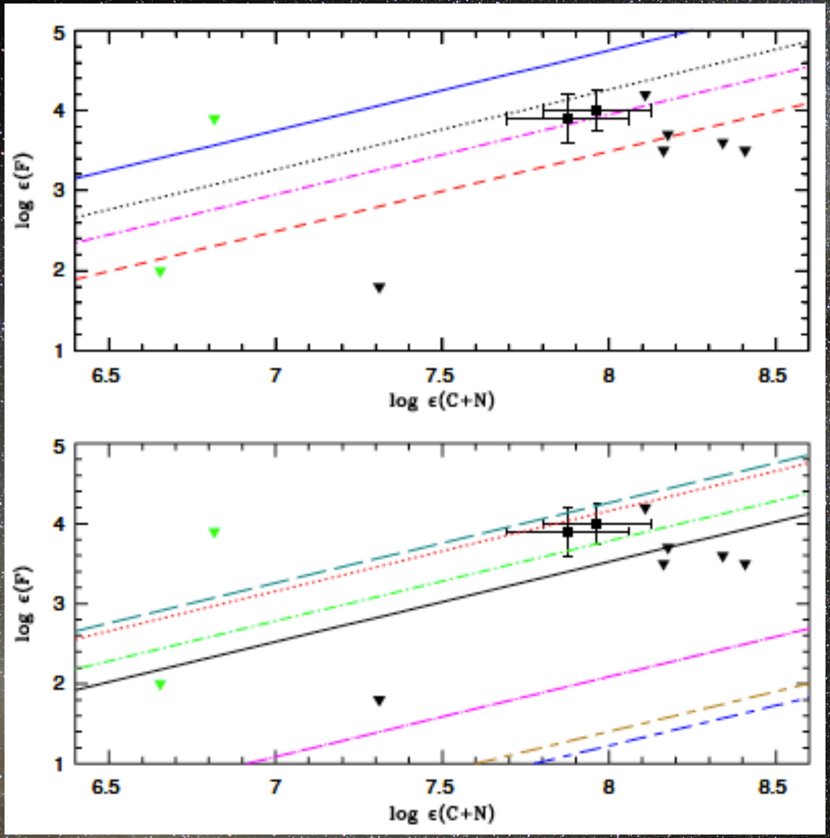


Good agreement with NACRE rate at temperatures of astrophysical importance but much better accuracy!

The rates that are usually used in astrophysics are the one by Drotleff et al., which is in agreement with the Heil et al. one in the range of interest of astrophysics, and the Nacre one.
For the Drotleff et al. rate no uncertainty is given.
Nacre have about 100% indetermination.

Fluorine in astrophysics

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 in astrophysics as it can be used to probe AGB star mixing phenomena and nucleosynthesis. But its production is still uncertain!

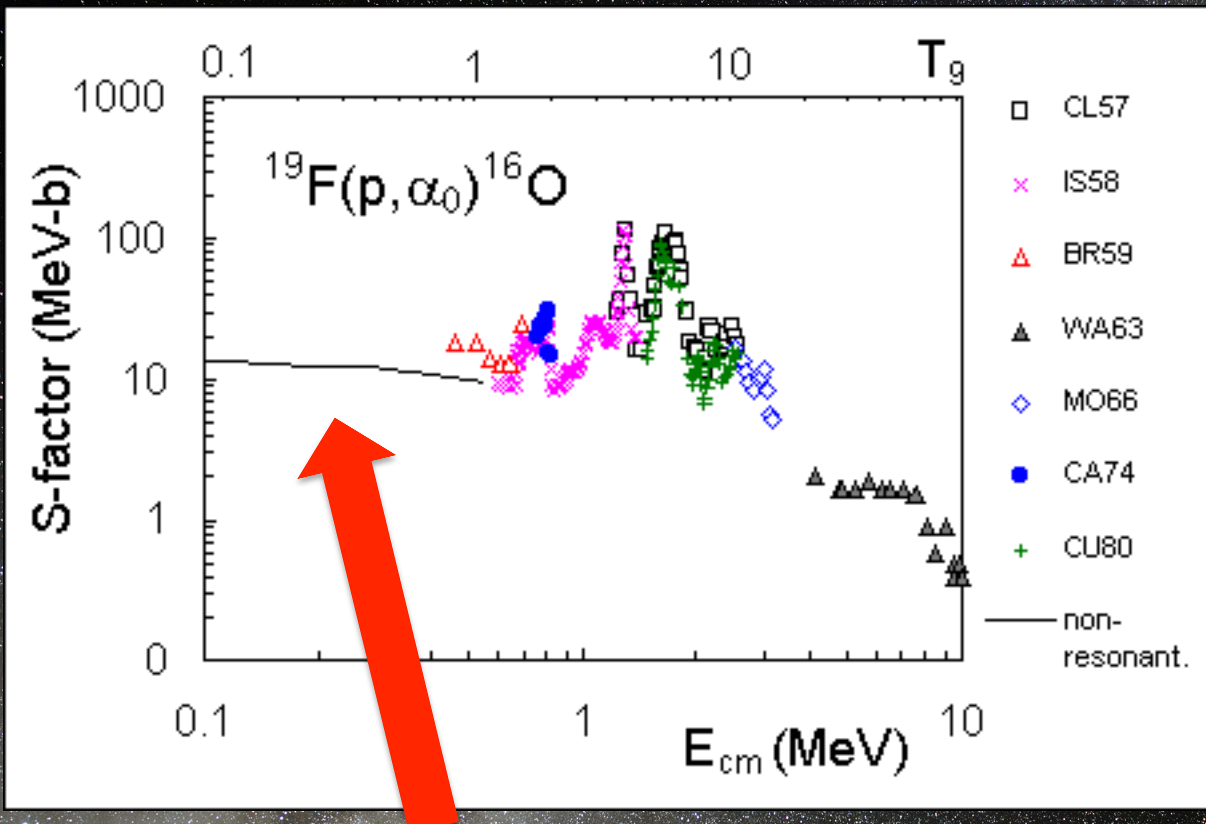


Observations have improved very much in the last years (Abia et al 2010, 2011)

In the case of metal poor AGB stars our understanding is far from satisfactory (Lucatello et al. 2011, Abia et al 2011).

We note that a significant fraction of the upper limits are located under the predicted lines (Lucatello et al. 2011)

The $^{19}F(p,\alpha_0)^{16}O$ reaction



The S(E) factor shows several resonances around 1 MeV.

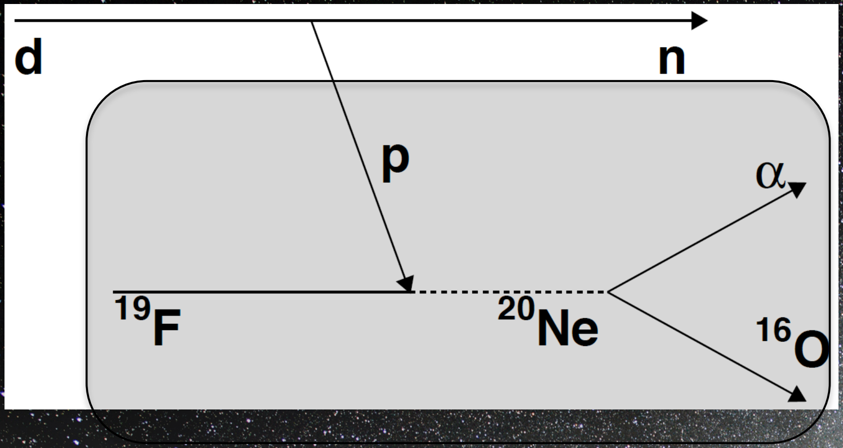
Breuer (1959) claimed the occurrence of two resonances at around 400 keV

Unpublished data (Lorentz-Wirzba 1978) suggests that no resonance occurs

α_0 is the dominant channel in the energy region of astrophysical interest

Below E_{cm} = 460 keV, where data do not exist, a non resonant contribution is calculated for *s*-capture. The S-factor was adjusted as to the lower experimental points between 460 and 600 keV

The experiment



d: Trojan horse nucleus p+n

B=2.2 MeV $|p_s|$=0 MeV/c

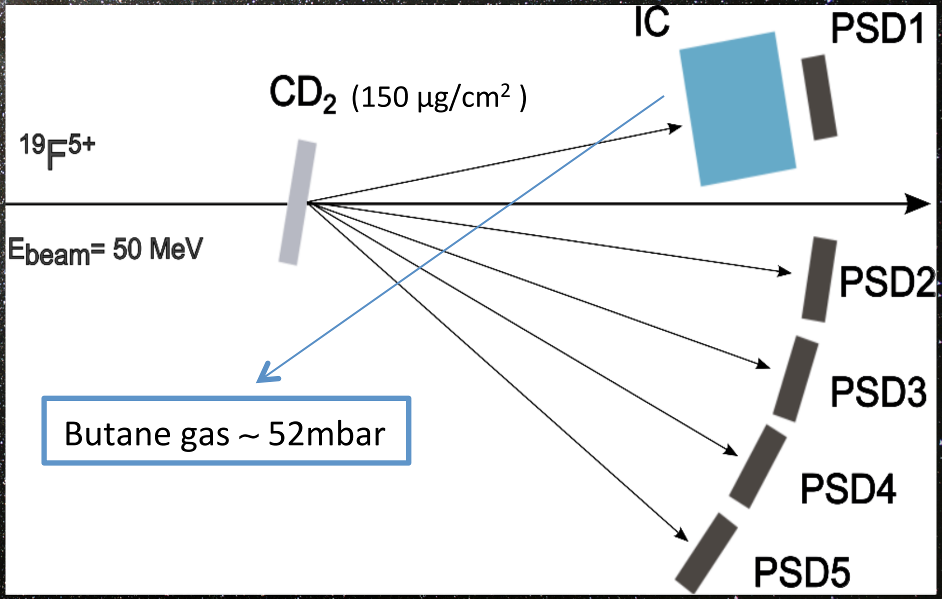
n: spectator

p: participant

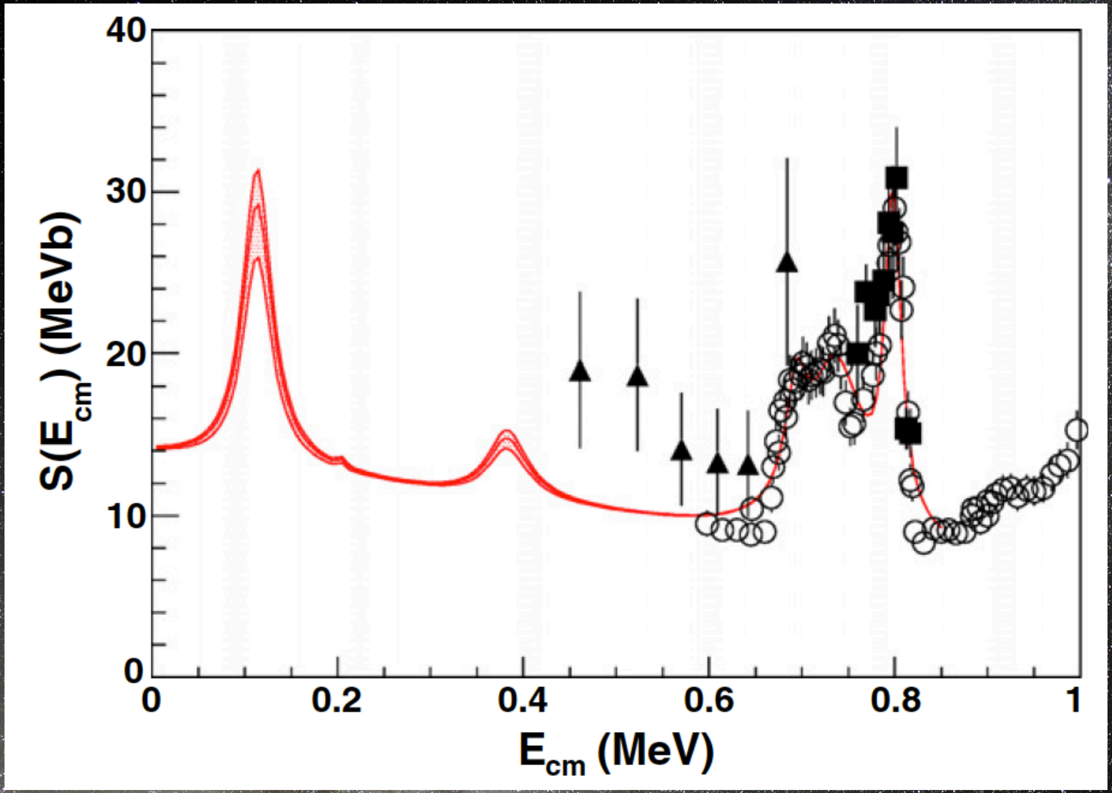
$d(^{19}F,\alpha^{16}O)n$ Q_{3b}=5.889 MeV

$^{19}F(p,\alpha)\ ^{16}O$ Q_{2b}=8.113 MeV

INFN-LNS 15 MV tandem



The $^{19}F(p,\alpha)^{16}O$ cross section



R-matrix parameterization of the $^{19}F(p,\alpha_0)^{16}O$ astrophysical factor.

Above 0.6 MeV, the reduced partial widths were obtained through an *R*-matrix fit of direct data

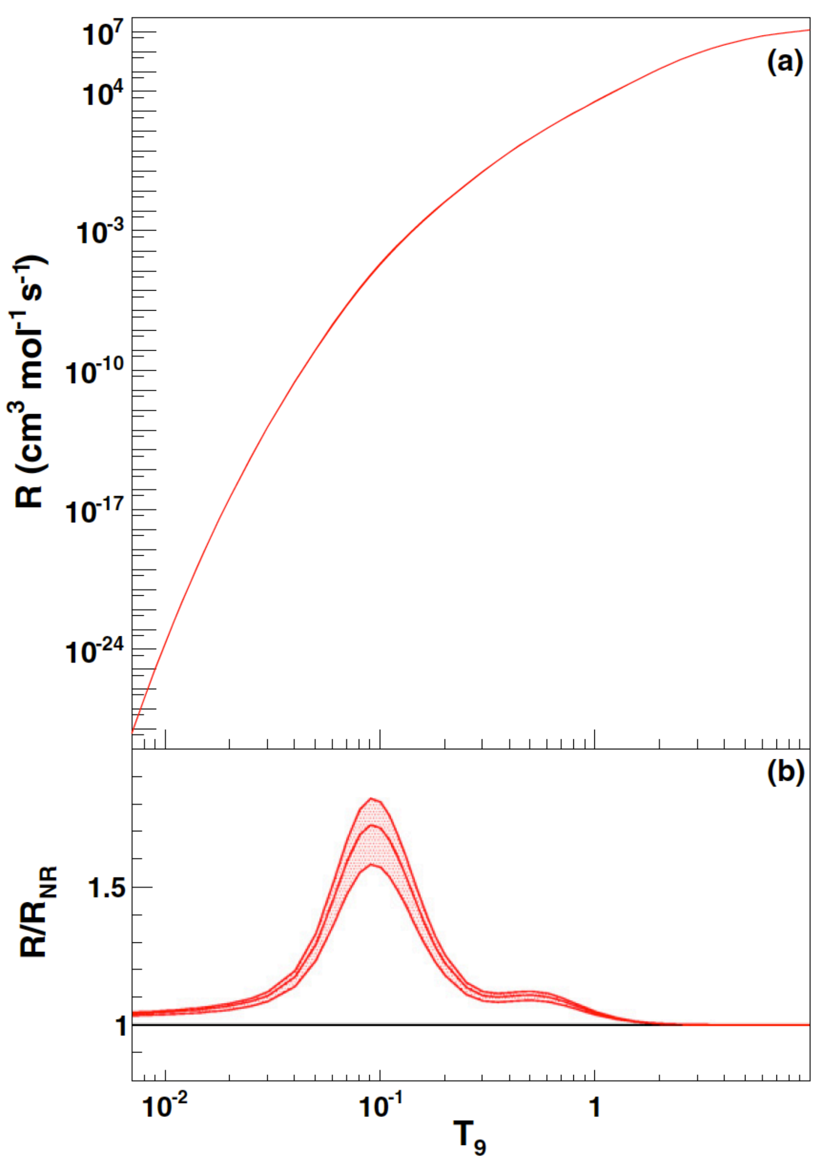
Below 0.6 MeV, the resonance parameters were obtained from the modified *R*-matrix fit

The non-resonant contribution is taken from NACRE (1999).

Because of spin-parity, only the resonance at 12.957 MeV provide a significant contribution

Gamow window: 27-94 keV → this level lies right at edge of the Gamow window for extramixing in AGB stars

$^{19}F(p,\alpha)^{16}O$ reaction reaction rate

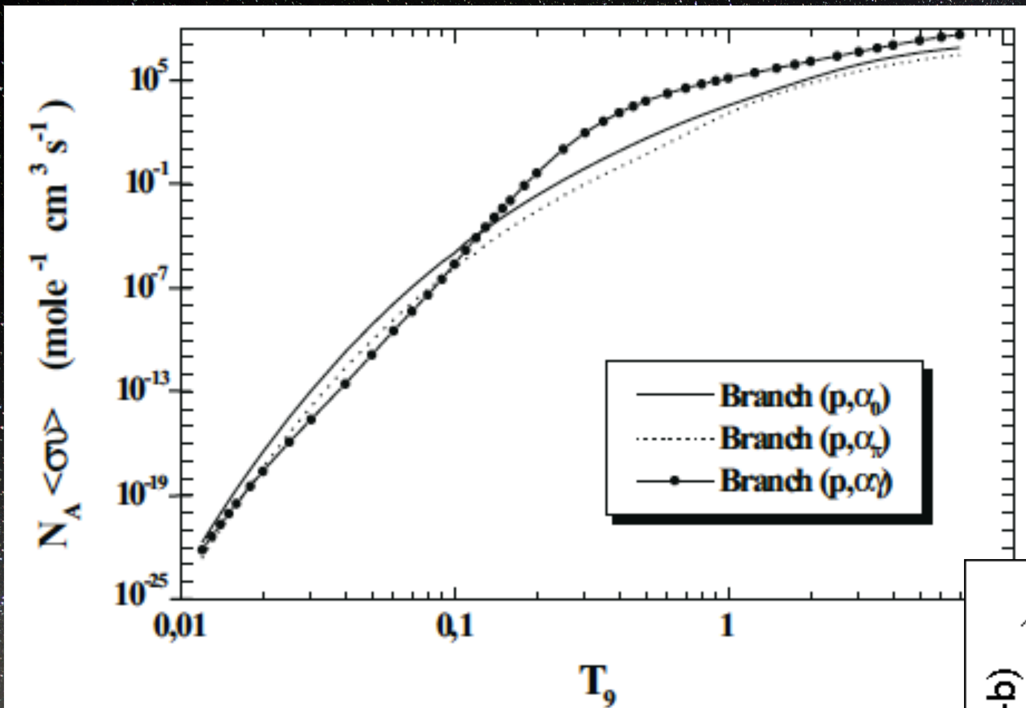


(a) Reaction rate for the $^{19}F(p,\alpha_0)^{16}O$. Upper and lower limits are also given, though they are barely visible because of the large rate range.

(b) Ratio of the reaction rate in panel (a) to the rate of the $^{19}F(p,\alpha_0)^{16}O$ reaction evaluated following the prescriptions in NACRE (1999). The red band arises from statistical and normalization errors.

→ A reaction rate enhancement up to a factor of 1.8 is obtained close to temperatures of interest for astrophysics (for instance, T_9~0.04 in AGB stars)

Perspectives

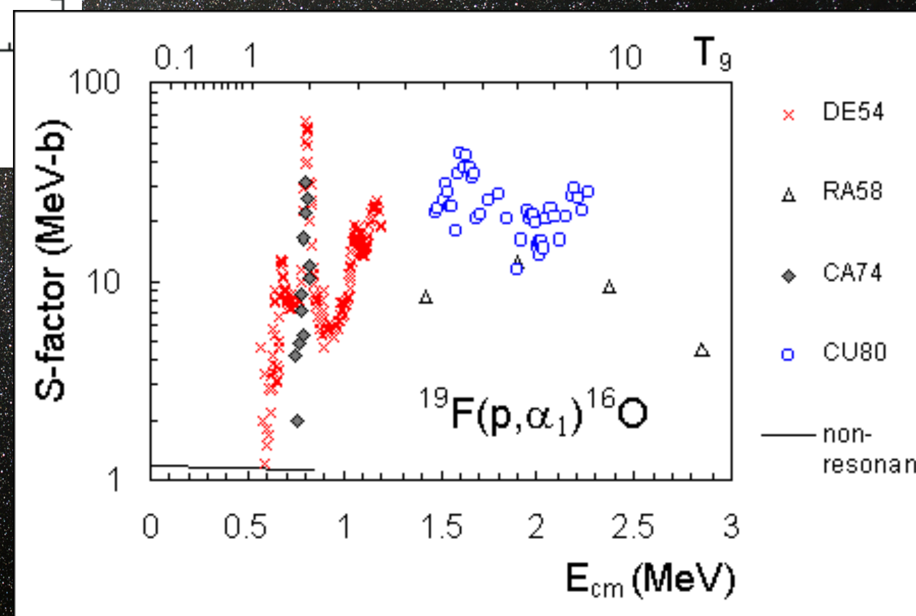


The contribution of the α_0 channel only has been addressed since this is currently regarded as the dominant one at temperatures relevant for AGB stars

← Spyrou et al. (2000)

α_1 channel is even more uncertain!

An experimental campaign is scheduled to extract the cross section for the α_1 channel and to improve the spectroscopy of the resonances discussed here.



Summary

- Resonance reactions are key processes in astrophysics as they can significant alter the nucleosynthesis flow (among others!)
- THM is very suited to investigate resonance reactions as the same reduced widths show up in the THM and OES cross section
- THM and ANC are strictly related and this may lead to future developments of the method
- The $^{13}C(\alpha,n)^{16}O$ and $^{19}F(p,\alpha_0)^{16}O$ reactions have been successfully investigated with this new THM approach

Thanks for your attention