Indirect measurements of the -3 keV resonance in the $^{13}C(\alpha, n)^{16}O$ reaction: the THM approach

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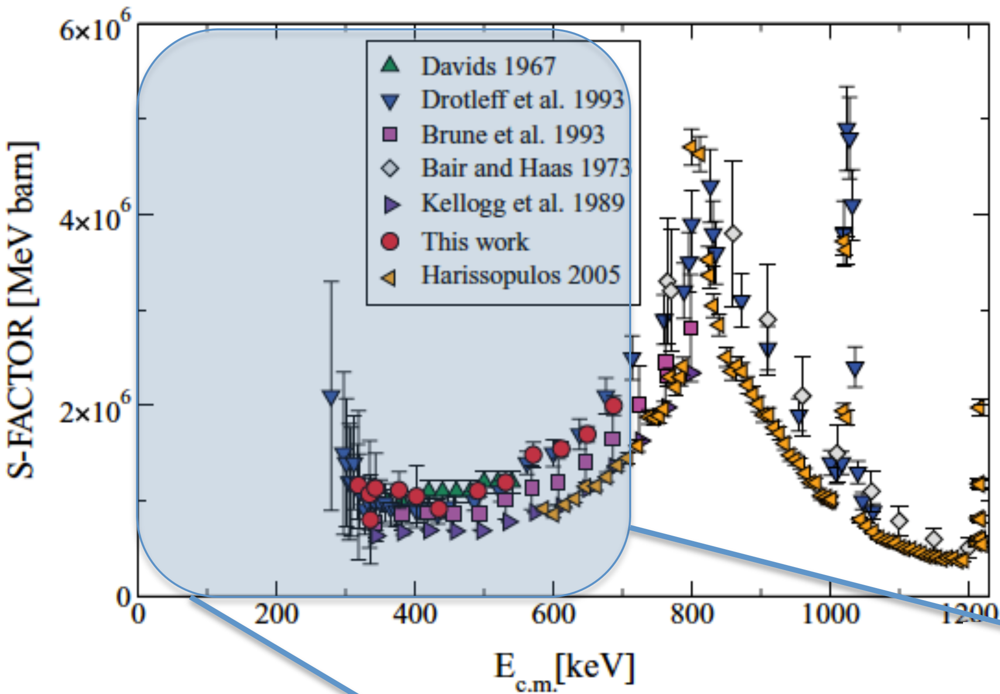
The $^{13}C(\alpha,n)^{16}O$ reaction

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

These neutrons are fundamental for the s-process: the slow neutron-capture reactions. Elements are produced through a series of subsequent neutron captures on stable nuclei followed by a beta-decay when an unstable nucleus is encountered. In fact, the typical time scale of neutron captures are longer than the half-life of unstable nuclei. The s-process needs a neutron density of about 10^6 - 10^{10} n/cm^3. This process is important for the production of about 50% of elements heavier than iron.

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



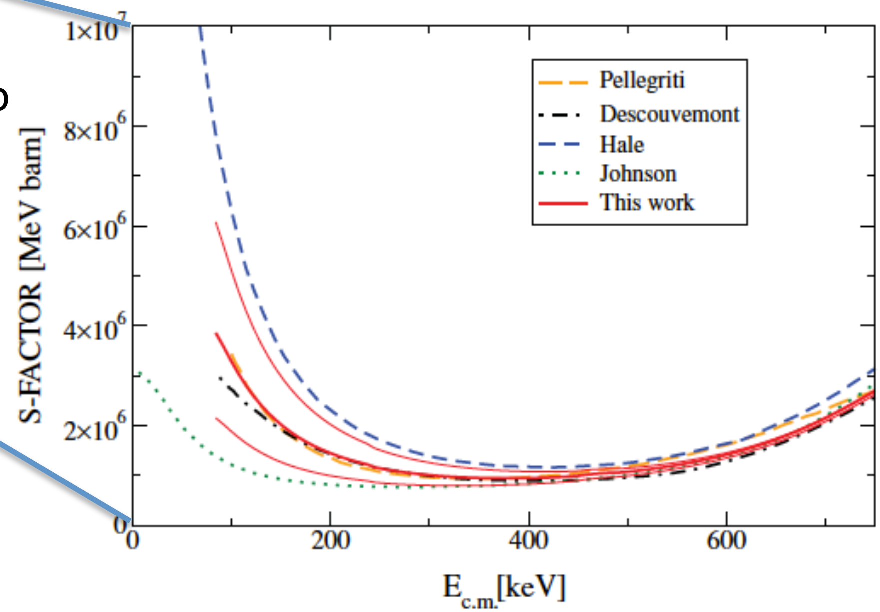
Direct data → several open issues

- 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



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.

Direct vs. indirect measurements

Indirect measurements:

Complicated but rewarding

✓ High energy experiments: up to several hundreds MeV

→ no Coulomb barrier suppression

→ negligible straggling

→ no electron screening

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

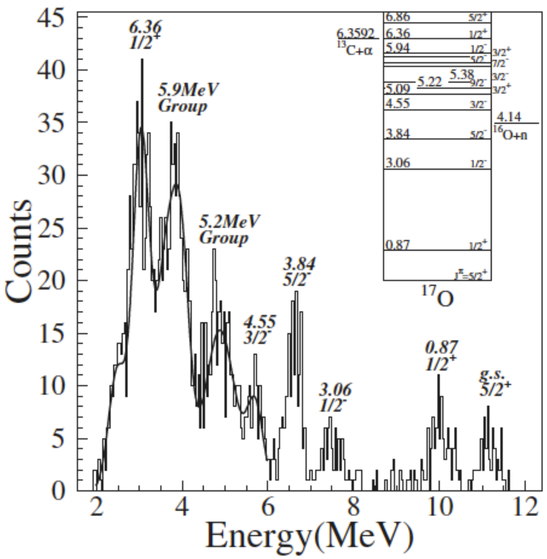
→ possible spurious contribution

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

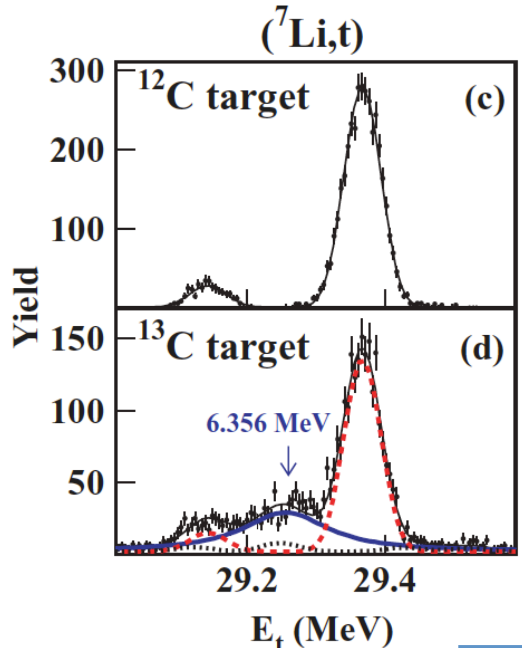
... Indirect techniques are complementary to direct measurements
Examples: Coulomb dissociation, ANC and Trojan horse method

Indirect measurements

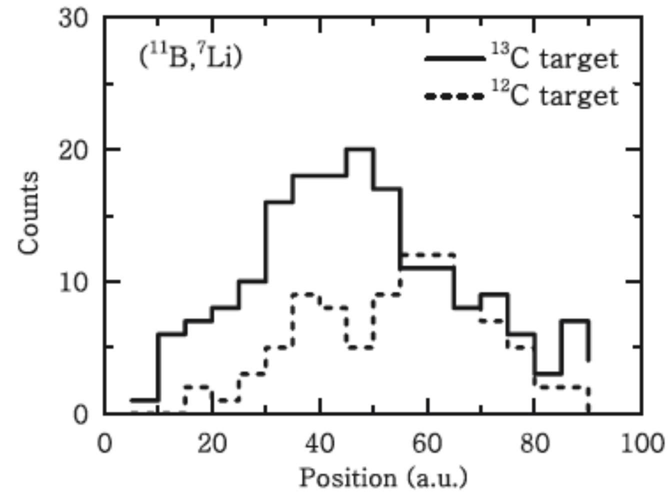
Johnson et al.



Pellegriti et al.



Guo et al.

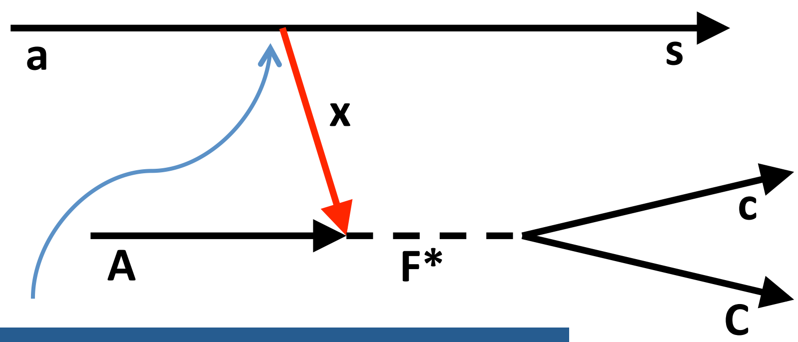


Transfer reactions are used to extract the ANC or the spectroscopic factor of the subthreshold resonance at -3 keV.

→ 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
Keeley et al.	2.4, 3.2
Guo et al.	4.0±1.1

The THM for resonance reactions



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

In the "Trojan Horse Method" (THM) the astrophysically relevant reaction, say
A(x,c)C,
is studied through the 2→3 direct process
A(a,cC)s:

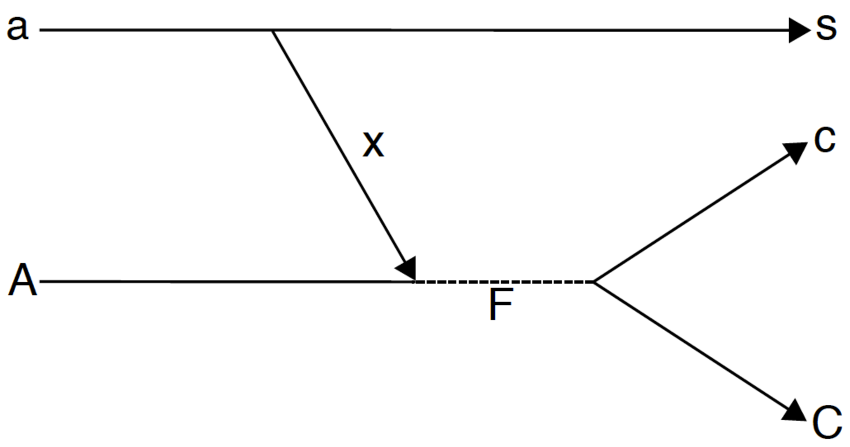
The process is a transfer to the continuum where x is participant, e.g. a proton or an alpha particle and s is the spectator

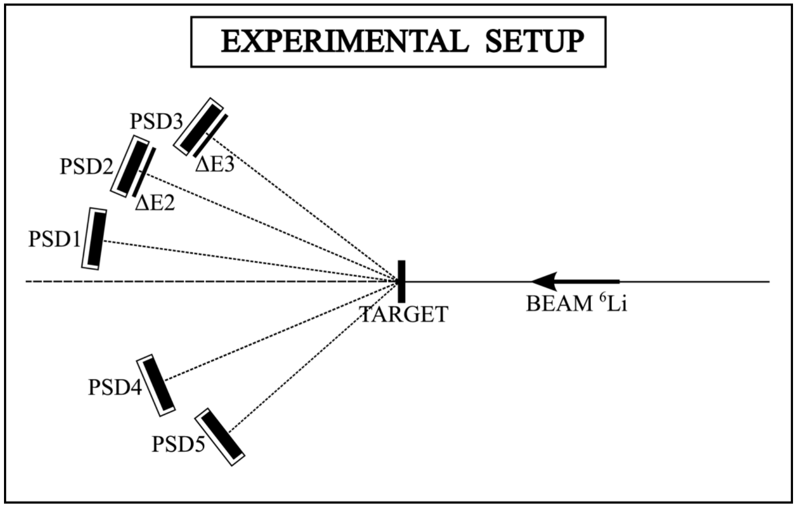
Standard R-Matrix approach cannot be applied to extract the resonance parameters of the A(x,c)C reaction because x is virtual → Modified R-Matrix is introduced instead (A. Mukhamedzhanov 2010)

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

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

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





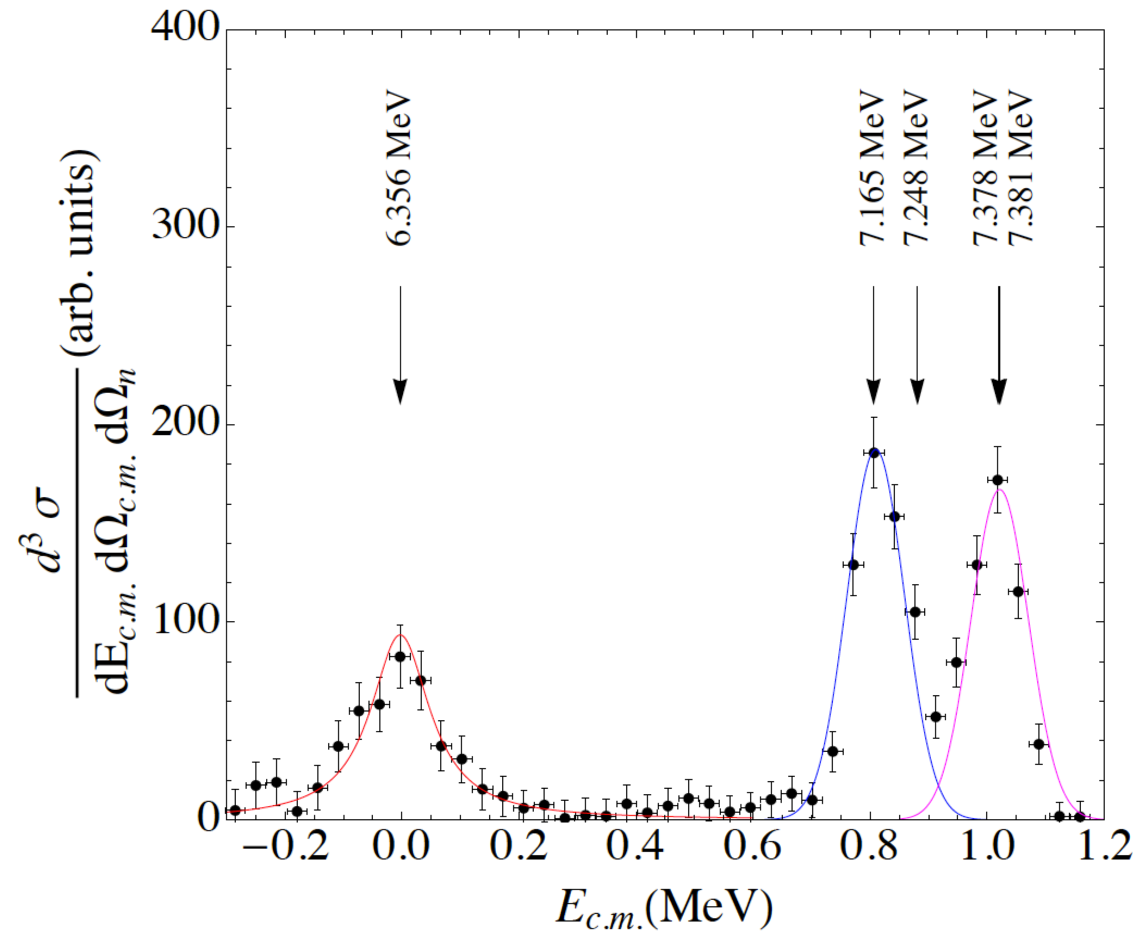
The experiment was performed at the Florida State University applying the indirect Trojan Horse Method. Our experiment was performed by measuring the sub-Coulomb $^{13}C(\alpha,n)^{16}O$ reaction through the $^{13}C(^{6}Li,n^{16}O)d$ reaction in the quasi-free kinematics regime.

We used a ^{6}Li beam of 7.82 MeV as Trojan Horse nucleus. ^{6}Li is considered to have a α+d structure, where deuteron is the spectator.

The experimental setup is made up of five silicon PSDs and two ΔE detectors. The PSD1, 2 and 3 detect deuteron with energy between 0 and 7.5 MeV while PSD 4 and 5 detect ^{16}O. There are also two ΔE-E telescopes (@ PSD2 and PSD3) to identify the deuteron.

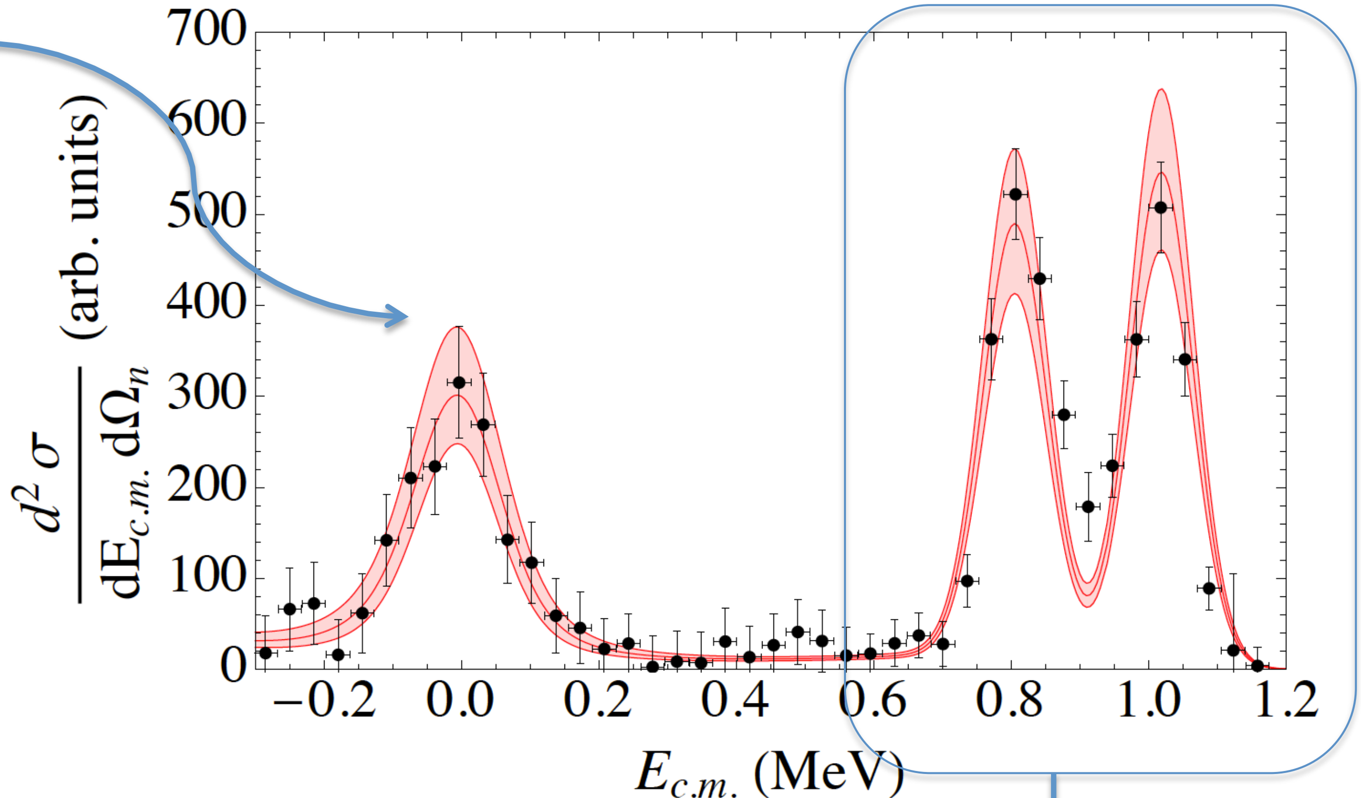
Raw THM data – background subtracted

No center-of-mass angular integral performed.
Large error bars due to flat background subtraction.
3 groups of resonances observed: 7.378 and 7.381 MeV not resolved, 7.248 MeV much smaller than the other resonances → not visible



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]

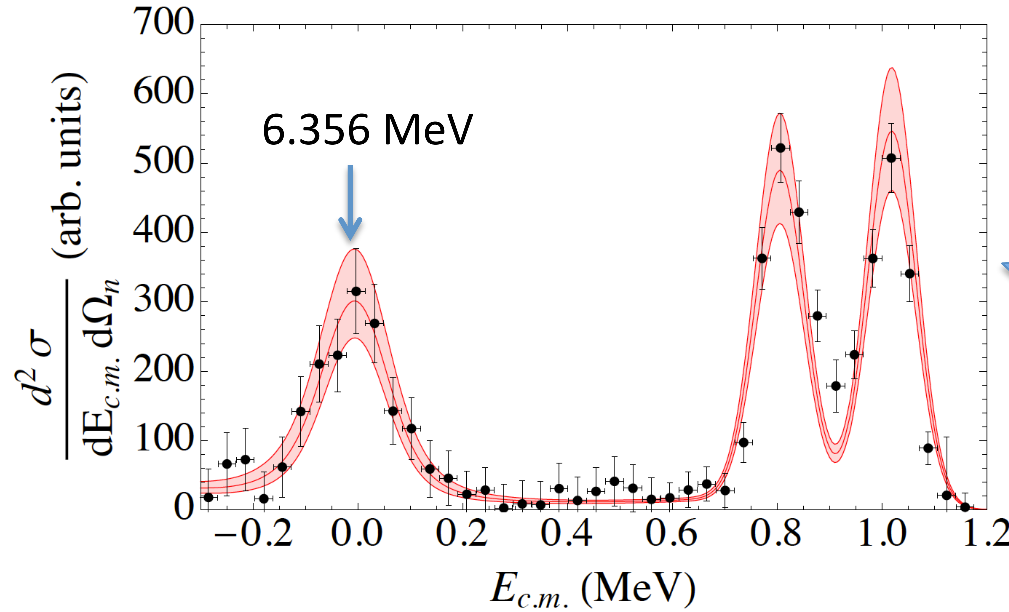


Normalization region:
Scaling factor and energy resolution obtained (this one in agreement with the calculated one, 46 keV)

Coulomb corrected ANC[2] of the -3 keV resonance is:
$6.7^{+0.9}_{-0.6}$ fm^{-1} (maximum error)

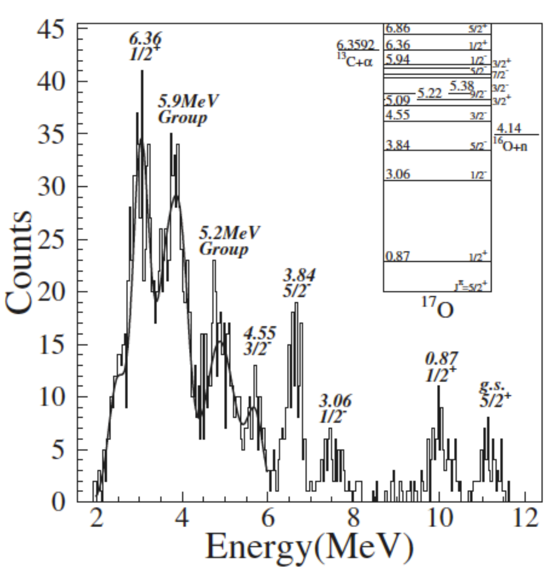
Γ_n of the -3 keV resonance is:
$0.083^{+0.009}_{-0.012}$ MeV

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

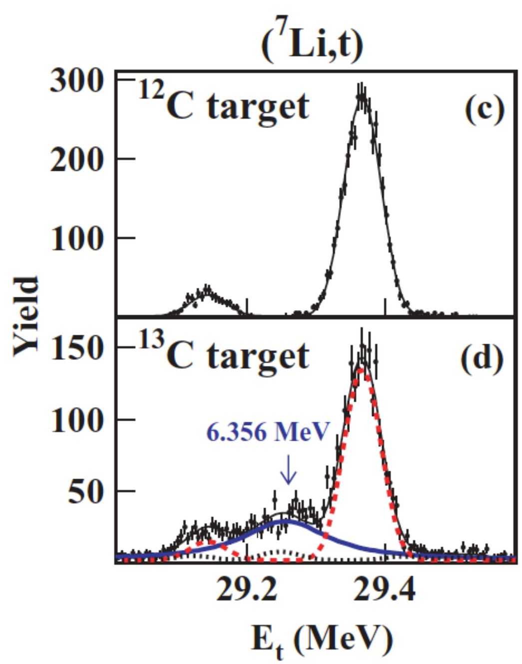


Only about 50% of the total statistics analyzed so far

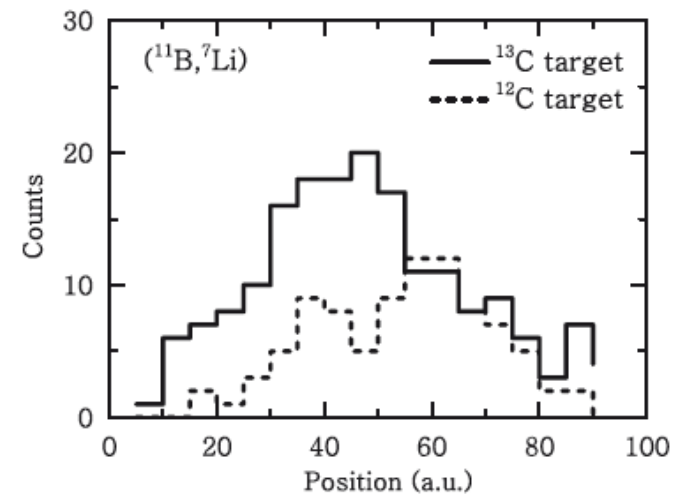
Johnson et al.



Pellegriti et al.



Guo et al.



Comparison with the parameters in the literature

Reference	CC-ANC^2 (fm^{-1})	Γ_n (MeV)
Present work	$6.7^{+0.9}_{-0.6}$	$0.083^{+0.009}_{-0.012}$
Heil et al.	-	0.1581
Johnson et al.	0.89±0.23	-
Tilley et al.	-	0.124±0.12
Pellegriti et al.	4.5±2.2	-
Kubono et al.	0.14	-
Keeley et al.	2.4, 3.2	-
Guo et al.	4.0±1.1	-

Tilley et al. is a summary of the older data. Γ_n was obtained through the R-matrix analysis of n-induced reactions, with n-channel radius 3.86 fm and fit obtained "visually". No mention on how broad subthreshold resonances were accounted for.

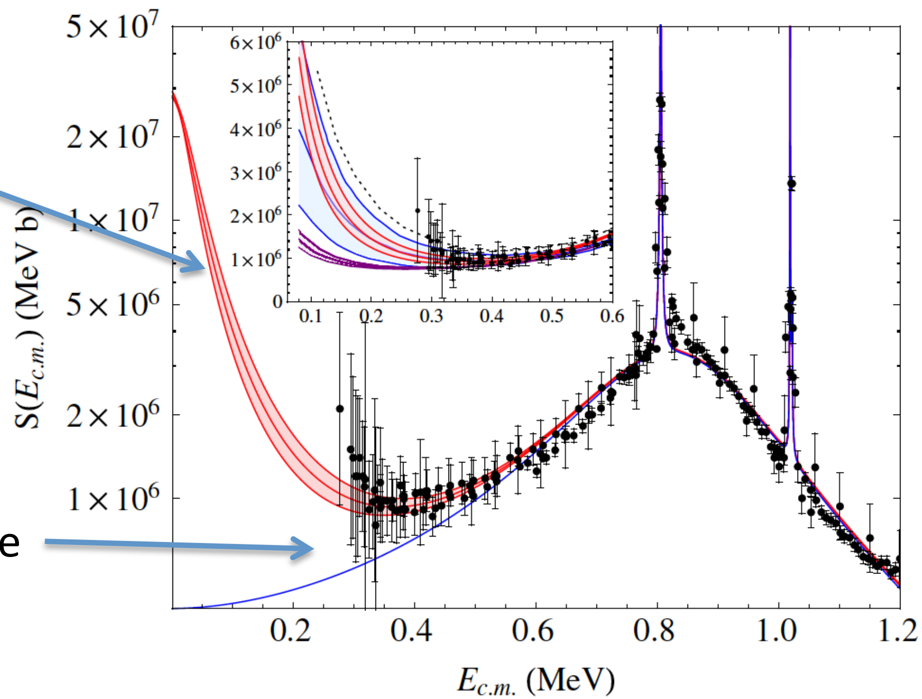
Only in our measurement we are sensitive to both Γ_n and n-^{16}O ANC of the subthreshold state. In other cases Γ_n from Tilley et al. was used to extrapolate the astrophysical S-factor. Apart from Drotleff et al., no mention of electron screening enhancement is made

OES THM S(E) factor from THM and comparison with previous measurements and extrapolations

OES R-matrix with the parameters from the THM data

Γ_n and ANC from THM data

No -3 keV resonance



Red band → THM S-factor
Dotted line → Hale (Nacre)
Purple band → Johnson
Blue band → Heil

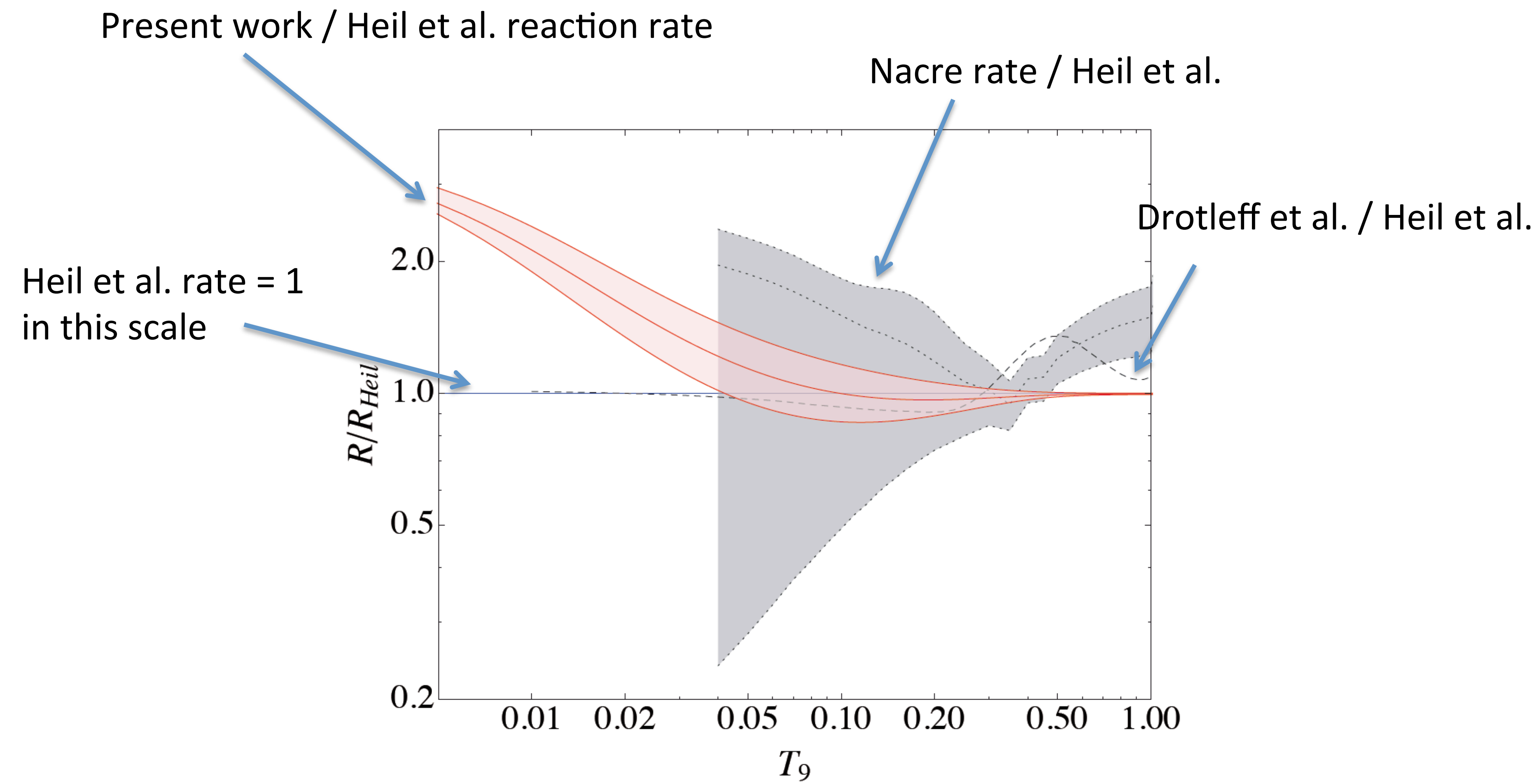
The displayed uncertainty band includes statistical and normalization error → maximum error as the minimum and the maximum normalization constants are used

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

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



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.

Stay tuned… more accurate data to be published

Thanks for your attention

Measurement of the −3 keV Resonance in the Reaction $^{13}C(\alpha, n)^{16}O$ of Importance in the *s*-Process

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