Uni ct FISICA E ASTRONOMIA "ETTORE MAJORANA"
INFN LNS

Shedding light on $^{17}O(n,a)^{14}C$ reaction at astrophysical energies with Trojan Horse Method and Asymptotic Normalization Coefficient

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on behalf of the AsFiN group

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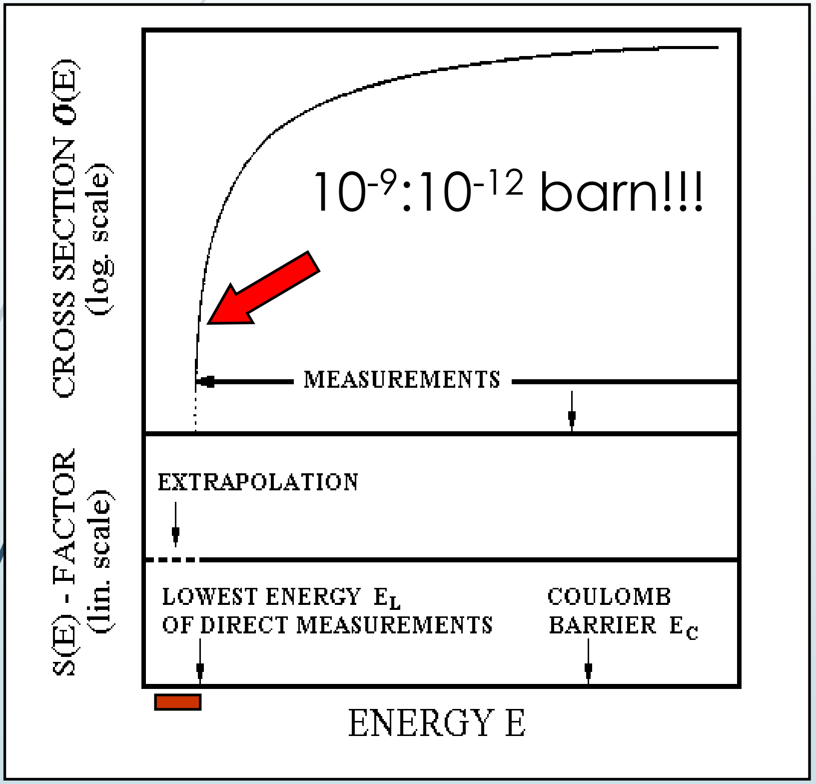
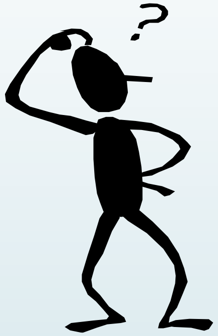
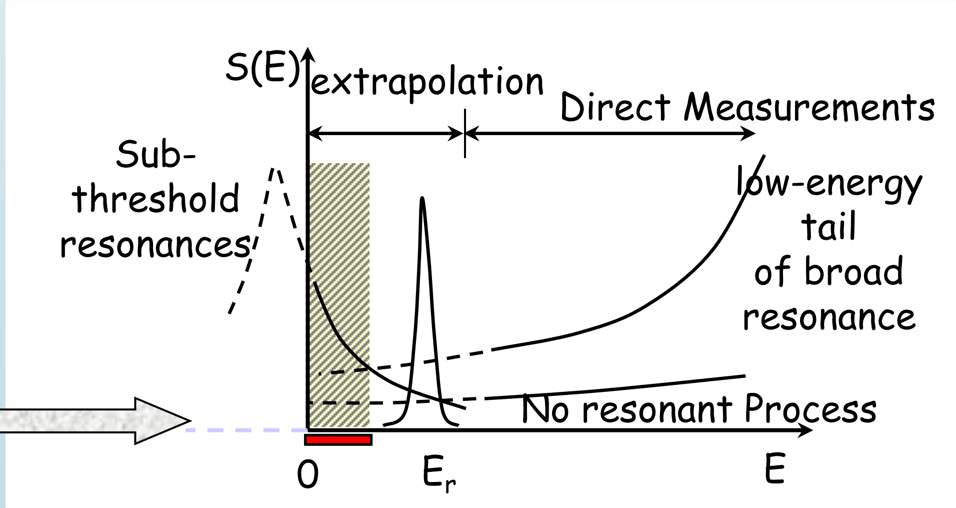
Direct measurement in nuclear astrophysics





- Very small cross section values reflect in a faint statistic;
- Very low signal-to-noise ratio makes hard the investigation at astrophysical energies;
- Instead of the cross section, the S(E)-factor is introduced

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



Neutron induced reactions in nuclear astrophysics

- No accelerator (no charge)
- No target available (half-life 885.7±0.8 sec)

NEUTRON BEAM FACILITY

- ^{9}Be photodissociation or a absorption
  - *Monoenergetic spectra*

- Nuclear reactors
- (γ,n) reactions (bremsstrahlung)
- (p,n) reactions
  - *Energy distributions → TAGGING (ToF, angles,…)*

INVERSE REACTIONS

- Low detection efficiency (<30%)

Indirect methods in nuclear astrophysics

Beyond the extrapolation procedure, indirect methods are highly demanded to address missing or incomplete aspects led by the complexity of nuclear reactions in stars

$^{17}O(n,\alpha)^{14}C$ reaction: a case study

Astrophysical Scenario

Weak component s-process

$^{17}O(n,\alpha)^{14}C$ and $^{17}O(\alpha,n)^{20}Ne$ since they act as a neutron poison and a recycle channel during s-process nucleosinthesys in massive stars ($M>8M_{SUN}$)

Astrophysical Scenario

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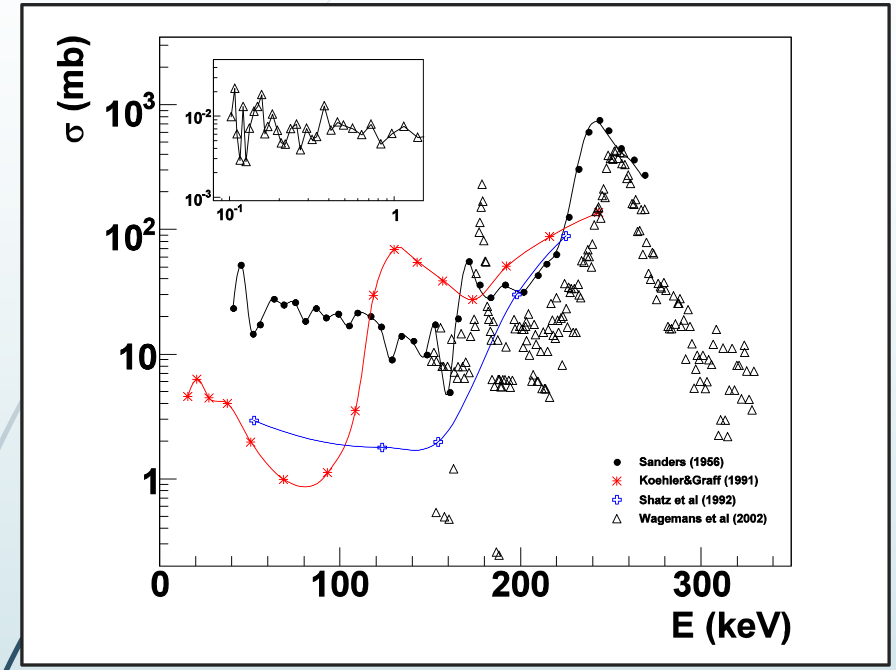
Temperature → $0.8<T_8<11$ K
Energy range→ ~0-100 keV

Status of the art



- R. M. Sanders, Phys. Rev., 104, 1434 (1956) INVERSE REACTION $^{14}C(a,n)^{17}O$

* P.E.Koehler & S.M.Graff, Phys. Rev., C44(6), 2788 (1991)

○ H. Schatz et al., Astroph. J., 413, 750 (1993)

Δ J. Wagemans et al., Phys. Rev., C65(3), 34614 (2002)

$E_{c.m.}$ (keV)	$^{18}O^*$ (MeV)	J^π
-7	8.039	1^-
75	8.125	5^-
166	8.213	2^+
236	8.282	3^-

Subthreshold Level

Suppressed due to the centrifugal barrier

Available in literature

F. Ajzenberg-Selove, Nucl. Phys., A475, 1 (1987)

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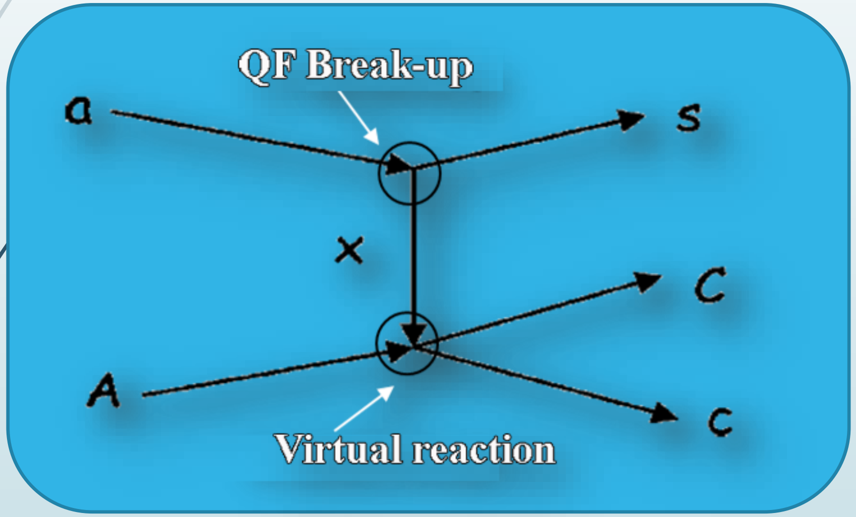
The Trojan Horse Method

*The idea of the **THM** is to extract the cross section of an astrophysically relevant two-body reaction **A+x→c+C** at low energies from a suitable three-body reaction **a+A→c+C+s***



Quasi free kinematics is selected

✓ **only x - A interaction**

✓ **s = spectator (p_s~0)**

$E_A > E_{Coul}$ →

- NO coulomb suppression
- NO electron screening
- NO centrifugal barrier

- *THM Review papers →* *Spitaleri C. et al., PAN, 2011*
  Tribble R. et al., Rep. Prog. Phys. 2014
  Spitaleri C. et al., EpJ A, 2019

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Theoretical approach

The TH-nucleus is chosen because of:

- its large amplitude in the *a*=x⊕s cluster configuration;
- its relatively low-binding energy;
- Its known x-s momentum distribution $|\Phi(p_s)|^2$ in *a*.

$$E_{Ax} = \frac{m_x}{m_x + m_A} E_A - B_{xs}$$

$B_{x\text{-}s}$ plays a key role in compensating for the beam energy thanks to the x-s *intercluster motion* inside a, it is possible to span an energy range of several hundreds of keV with only one beam energy

In the Plane Wave Impulse Approximation (PWIA) the cross section of the three body reaction can be factrorized as:

$$\frac{d^3\sigma}{d\Omega_c d\Omega_C dE_c} \propto KF \cdot |\Phi(p_s)|^2 \cdot \frac{d\sigma_{Ax}}{d\Omega}$$

Three body measured cross section

Calculated kinematical factor

Fourier trasform for the x-s intercluster motion

Astrophysically relevant two body cross section

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THM resonant cross section

Virtual nature of x particle → A+x interaction is off–energy shell

Cross section of the bare nucleus but NO absolute value → normalization to direct data available at higher energies

Standard R-Matrix approach cannot be applied to extract the resonance parameters → Modified R-Matrix is introduced instead

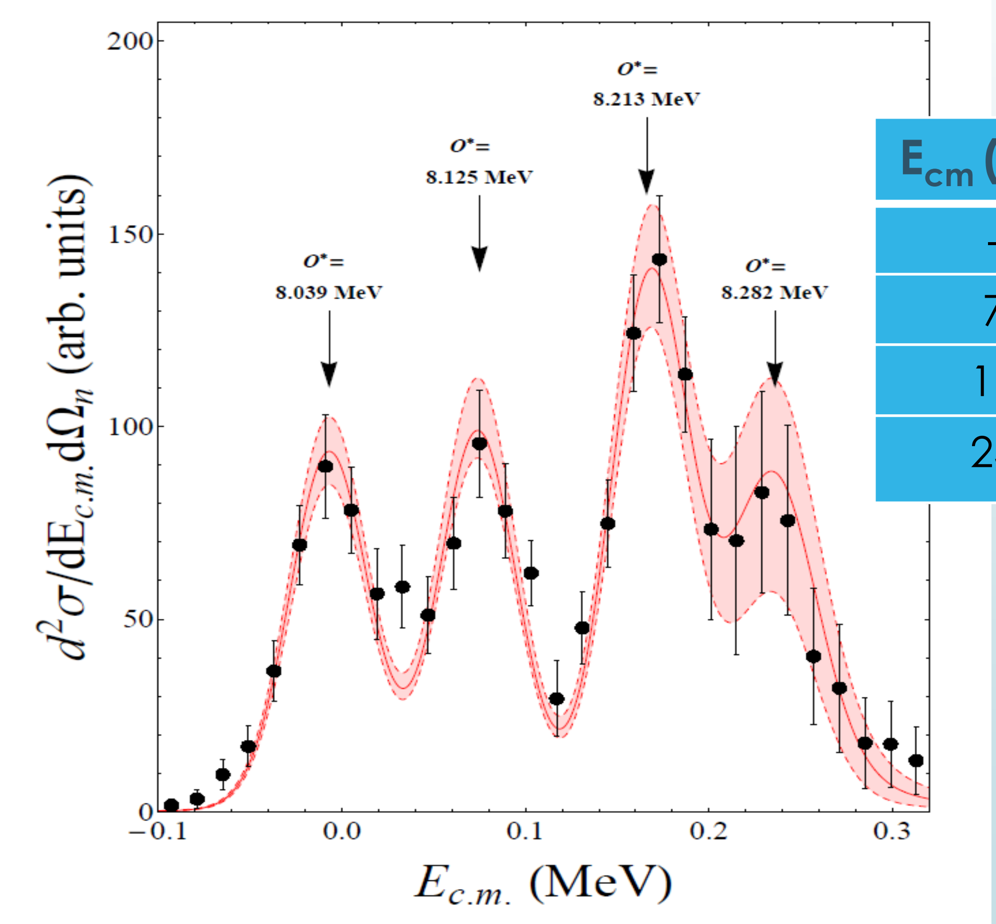
$$\frac{d^2\sigma}{dE_{xA}d\Omega_s} = \mathrm{NF}\sum_i (2\mathrm{J}_i+1) \times \left| \sqrt{\frac{\mathrm{k_f}(E_{xA})}{\mu_{cC}}} \frac{\sqrt{2P_{l_i}(k_{cC}R_{cC})}M_i(p_{xA}R_{xA})\gamma^i_{cC}\gamma^i_{xA}}{D_i(E_{xA})} \right|^2$$

where:

- $M_i\ (p_{xa}R_{xa})$ describes the transfer amplitude for the QF-process;
- γ_{xa} and γ_{Cc} represents the reduced partial widths for the resonant excited states that are the same of the direct measurements

La Cognata et al., ApJ, 777, 143, 2013

Modified R-Matrix approach to the $^{17}O(n,a)^{14}C$ reaction



E_{cm} (keV)	Γ_n (eV)	Γ_a (eV)	Γ_{TOT} (eV)	$\Gamma_{wag.}$ (eV)
-7	0,01±0,001	2362±307	2362±307	2400
75	0,05±0,006	36±5	36±5	-
166	86±11	2171±282	2257±293	2258±135
236	1714±446	13021±3386	14735±3832	14739±590

Guardo et al., Phys. Rev. C, 95, 025807, 2017

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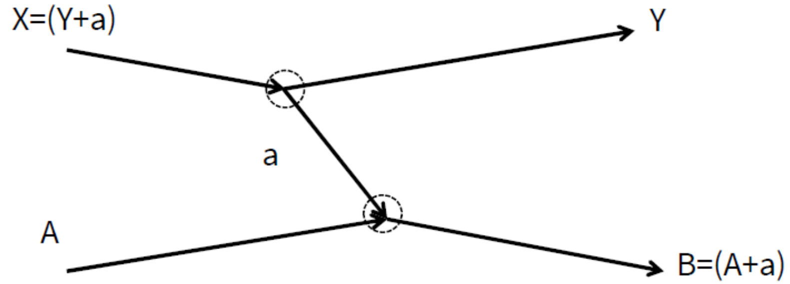
The Asymptotic Normalization Coefficient Method

Studies performed by means of «simple» transfer reactions



In Distorted Wave Born Approximation, the transition amplitude between the states before and after the reactions can be written as:

$$M(E_i, \vartheta_{c.m.}) = \sum_{M_a} \left\langle \chi_f^{(-)} \, \boldsymbol{I}_{Aa}^{B} \left| \Delta V \right| \boldsymbol{I}_{Ya}^{X} \, \chi_i^{(+)} \right\rangle$$

Using DWBA we were able to find the ANC's coefficients from the spettroscopic factors. This gives us some advantages:

- For perihperal reactions, ANCs have small dependance from the potential
- R_{l_B, j_B, l_x, j_x} is nearly indipendent from b^2
- ANCs are defined in the nuclear «exterior», so are «observable»

$$\frac{d\sigma}{d\Omega} = \sum_{j_B, j_x} \left(C_{Aa, l_B, j_B}^{B}\right)^2 \left(C_{Ya, l_x, j_x}^{X}\right)^2 \frac{\sigma_{l_B, j_B, l_x, j_x}^{DWBA}}{b_{Aa, l_B, j_b}^{2} \, b_{Ya, j_x, j_x}^{2}} = $$

$$= \sum_{j_B, j_x} \left(C_{Aa, l_B, j_B}^{B}\right)^2 \left(C_{Ya, l_x, j_x}^{X}\right)^2 R_{l_B, j_B, l_x, j_x}$$

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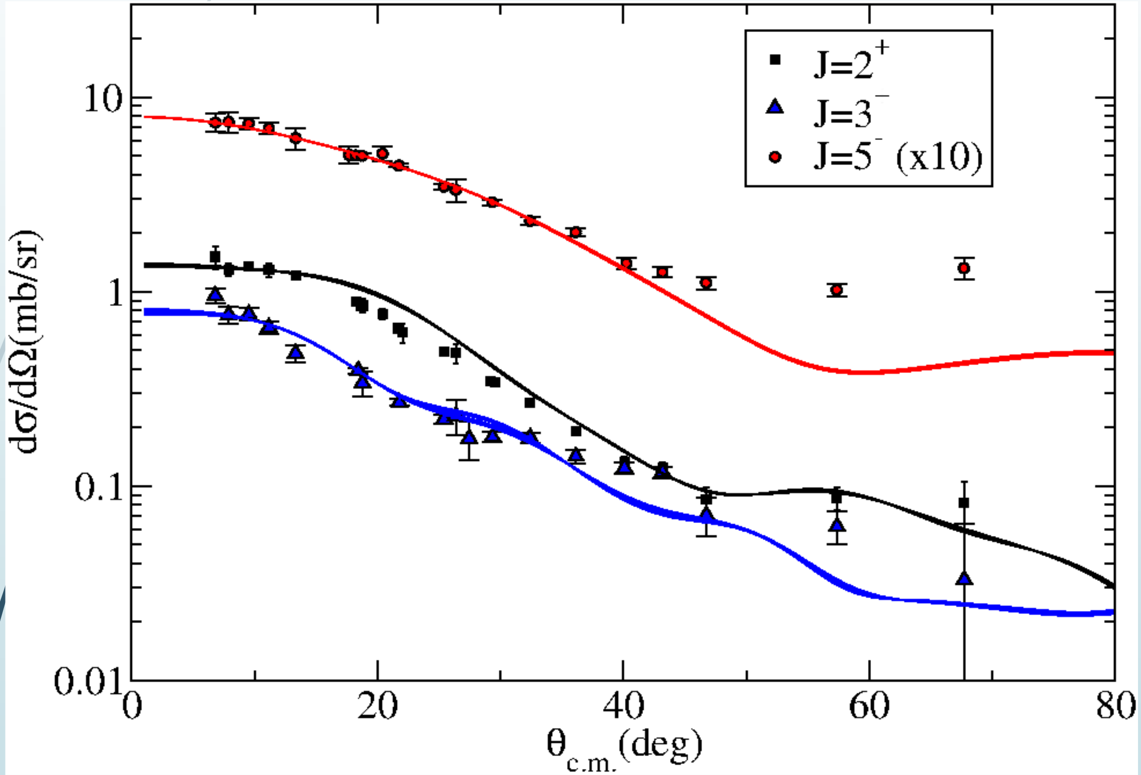
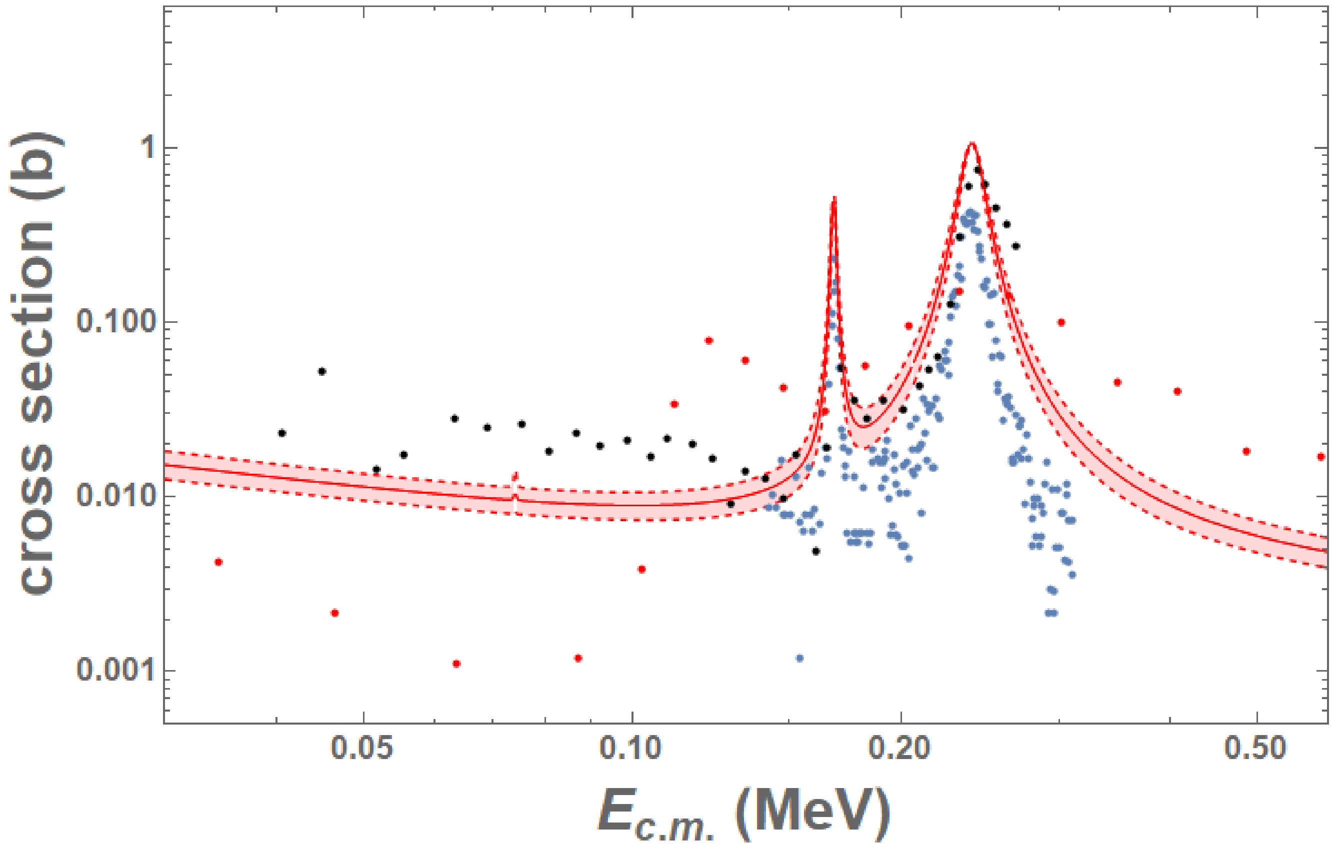
ANC extrapolation from $^{17}O(d,p)^{18}O$ transfer reaction



$E_{^{18}O}$ (MeV)	J^π	l	$\|C\|^2$ (fm^{-1})	Orbital
8.125	5^-	3	$3.06 \pm 0.46 \cdot 10^{-8}$	1f5/2
			$2.53 \pm 0.38 \cdot 10^{-8}$	1f7/2
8.213	2^+	2	$2.85 \pm 0.43 \cdot 10^{-5}$	2d3/2
			$2.87 \pm 0.43 \cdot 10^{-5}$	2d5/2
8.282	3^-	1	$3.20 \pm 0.48 \cdot 10^{-4}$	2p3/2
			$3.17 \pm 0.47 \cdot 10^{-4}$	2p1/2

Direct data comparison



- J. Wagemans et al., Phys. Rev., C65(3), 34614 (2002)
- R. M. Sanders, Phys. Rev., 104, 1434 (1956)
  INVERSE REACTION $^{14}C(a,n)^{17}O$

* P.E.Koehler & S.M.Graff, Phys. Rev., C44(6), 2788 (1991)

Figure 8. Comparison of the cross section of the neutron capture $^{17}O(n,\alpha)^{14}C$ reaction determined by ANC method (red line) with experimental data taken from Wagemans et al. (2002) (blue points), Koehler & Graff (1991) (red points) and Sanders (1956) (black points). The red band takes into account the error on the ANC calculation.

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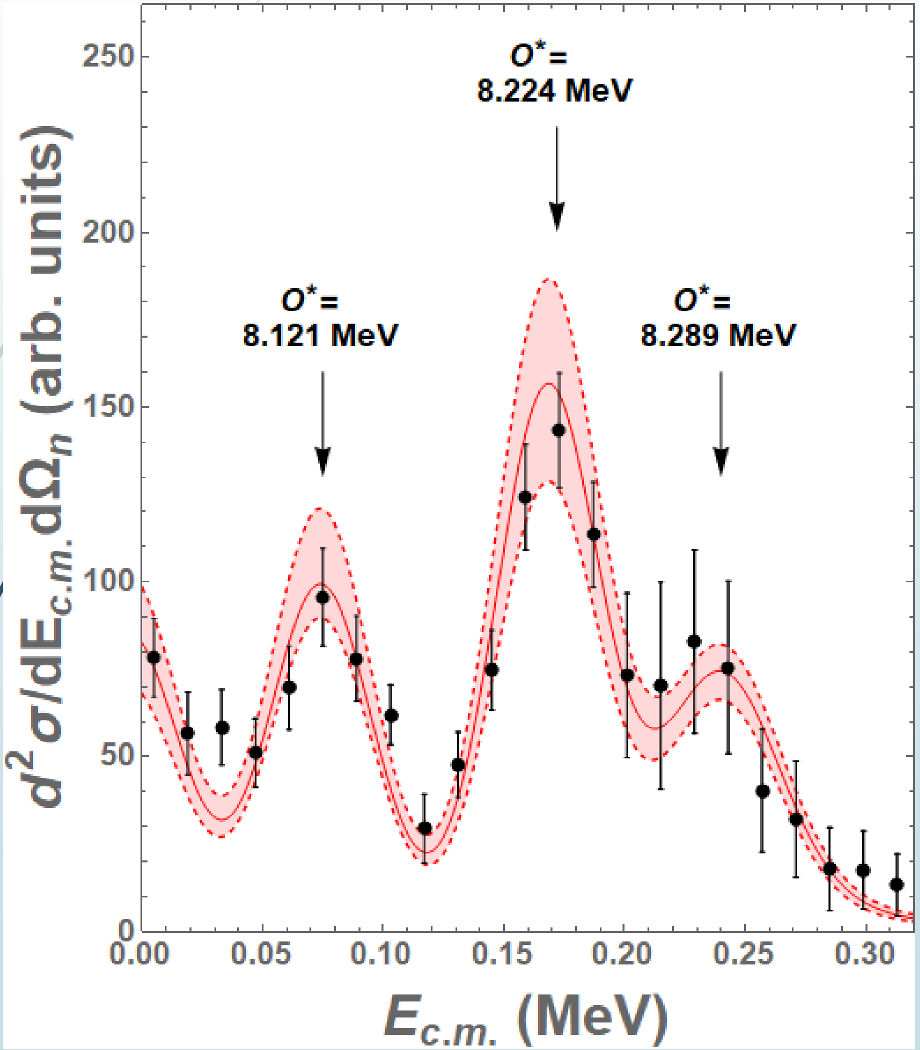
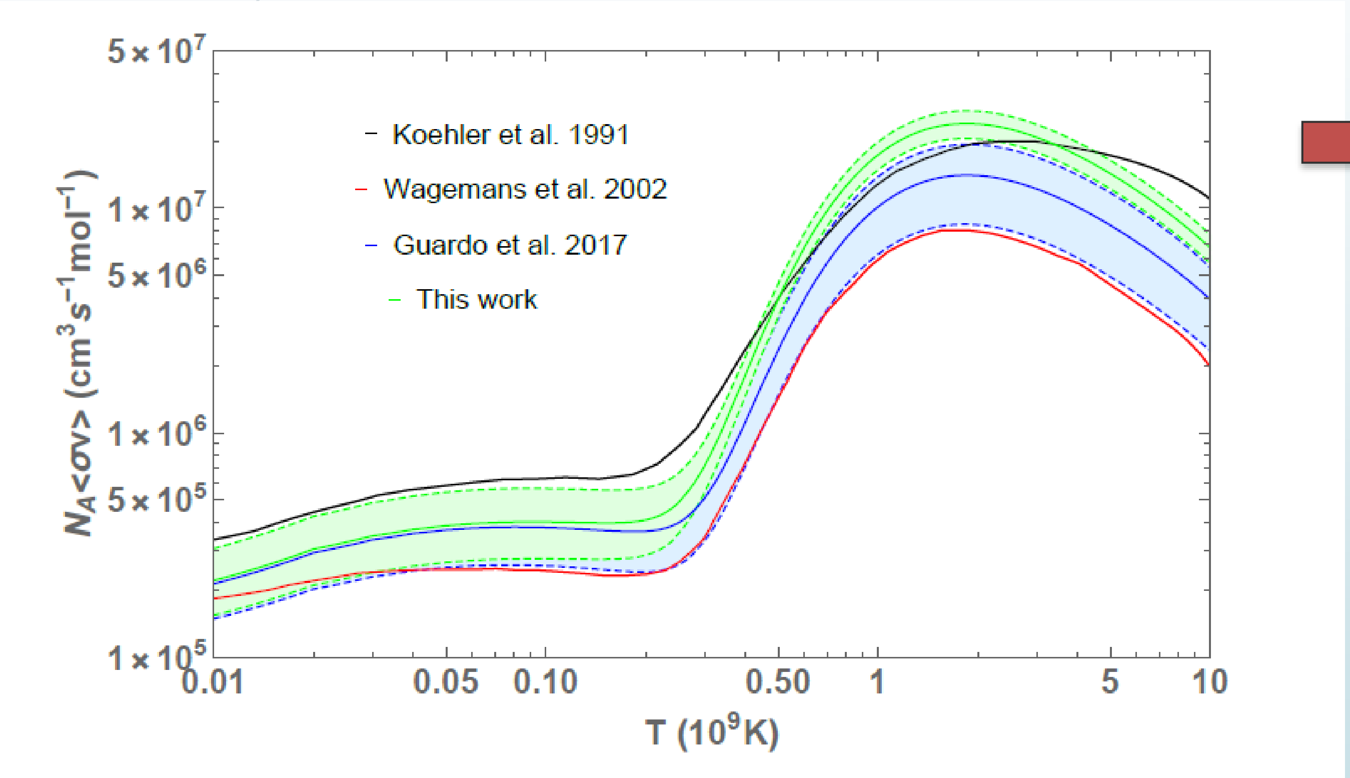
THM data comparison



E_{cm} (keV)	Koehler & Graff (1991)	Wagemans et al. (2002)
75	–	–
178	1280±1000 eV	2258±235 eV
244	8000±1000 eV	14739±590 eV

E_{cm} (keV)	Guardo et al. (2017)	This Work
75	36±5 eV	33±5 eV
178	2260±300 eV	2150±323 eV
244	14700±3800 eV	16670±2500 eV

Astrophysical rate



Possible impact on stellar nucleosynthesis?

Conclusions

A - It is possible measure the bare nucleus cross section s_b (or the bare nucleus Astrophysical Factor $S_b(E)$) at Gamow energy for reactions involving charged particles and neutron.

B - One of the few ways to measure the electron screening effect; comparison with direct data;

C - Measurements of radiative capture reaction cross section at Gamow energy;

D - Application to the radioactive beam measurements;

Method complementary to direct measurements (Multi Diagnostic Experiments)

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The ASFIN collaboration

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Thank you for your attention

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