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Indirect Investigation for AGB Stellar Nucleosynthesis

Maria Letizia Sergi

for the AsFiN research group

DIPARTIMENTO DI FISICA E ASTRONOMIA "ETTORE MAJORANA"

INFN LNS

Istituto Nazionale di Fisica Nucleare

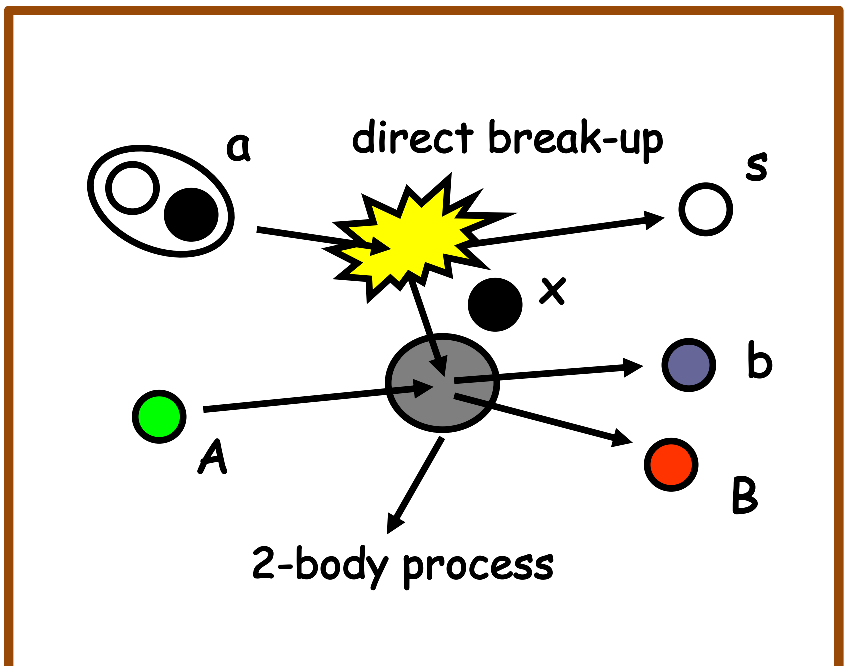
Laboratori Nazionali del Sud

Indirect Techniques: the Trojan Horse Method (THM)

- **Coulomb barrier → exponential damping of the cross section at astrophysical energies.**
- **Electron screening → enhancement of the cross section at the lowest energies due to atomic electrons.**

→ low-energy, bare-nucleus cross section is experimentally available only through <u>extrapolation OR indirect measurements.</u>

THM reaction



THM allows to deduce a charged-particle bare-nucleus two-body cross section

A+x → b+B

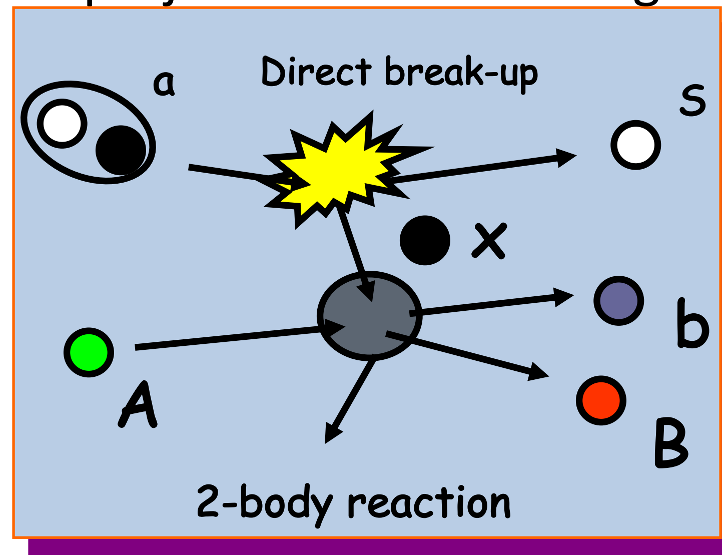
inside the Gamow window by selecting the Quasi-Free (QF) contribuiton to an appropriate three-body reaction

A+a→b+B+s

performed at energies well above the Coulomb barrier

The Trojan Horse Method I

- ✓ The QF $A + a \rightarrow b + B + s$ reaction between the projectile *A* and the target *a* can be described by the polar-diagram:



- ✓ Upper pole describes the break-up process of nucleus *a* in its "x" and "s" constituents. <u>The break-up is Quasi-Free if *s* maintains in the exit channel the same momentum distribution as in *a*;</u>

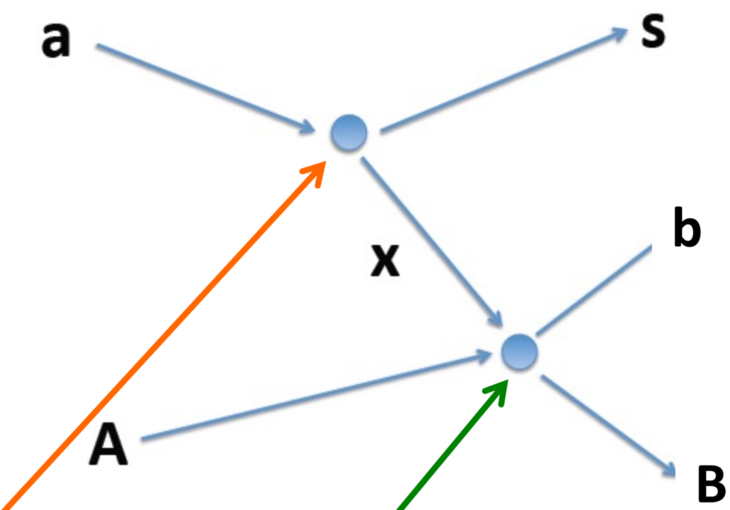
- ✓ Lower pole describes the astrophysically relevant two-body reaction A(x,b)B;

- ✓ The nucleus *a* (the so-called "TH-nucleus") is chosen because of:
  - its large amplitude in the $a = x \oplus s$ cluster configuration;
  - its relatively low-binding energy;
  - Its known *x-s* momentum distribution $|\Phi(\vec{p}_s)|^2$ in *a.*

- ✓ In this picture, "s" behaves as *spectator* while nucleus "*x*" is the *participant* of the astrophysical A(x,b)B reaction (Impulse Approximation approach).

The Trojan Horse Method II

The A(a,bB)s is induced at energies of the order of 20-50 MeV, higher than the Coulomb barrier in the entrance A-a channel.
The A-x interaction occurs directly in the nuclear field, thus **Coulomb suppression effects and the electron screening effect are naturally removed.**



The **cross section** for the A(a,bB)s process can be derived in the simple PWIA approach as

$$\frac{d^3\sigma}{dE_B d\Omega_B d\Omega_b} \propto KF \cdot |\Phi(\vec{p}_s)|^2 \cdot \left(\frac{d\sigma}{d\Omega}\right)\Bigg|_{A-x}^{N}$$

- $|\Phi(\vec{p}_S)|^2$ is a key quantity to be determined in each THM experiment!
- Using the kinematics of three body reactions:

$$E_{Ax} = \frac{m_x}{m_x + m_A} E_A - \frac{p_s^2}{2m_s} - \varepsilon_{s-x}$$

s-x binding energy

This allows to cover the energy region of interest for astrophysics by using only a mono-energetic beam!

The THM: a useful tool for studying AGB Nucleosinthesys

Universe 2022, 8, 128. https://doi.org/10.3390/universe8020128

universe

MDPI

Review

Trojan Horse Investigation for AGB Stellar Nucleosynthesis

Maria Letizia Sergi [1,2,*], Giuseppe D'Agata [3], Giovanni Luca Guardo [2], Giuseppe Gabriele Rapisarda [1,2], Vaclav Burjan [3], Silvio Cherubini [1,2], Marisa Gulino [2,4], Iolanda Indelicato [2], Marco La Cognata [2], Livio Lamia [1,2,5], Dario Lattuada [2,4], Jaromir Mrázek [3], Alessandro Alberto Oliva [1,2], Rosario Gianluca Pizzone [2], Stefano Romano [1,2,5], Roberta Spartá [2], Oscar Trippella [6] and Aurora Tumino [2,4]

- ✓ The $^{17,18}O(p,\alpha)^{14,15}N$ and $^{17,18}O(p,\gamma)^{18,19}F$ Reactions
- ✓ The $^{15}N(p,\alpha)^{12}C$ Reaction
- ✓ The Fluorine Problem: Study of the $^{19}F(p,\alpha_0)^{16}O$ and $^{19}F(\alpha,p)^{22}Ne$ Reactions
- ✓ Neutron Sources for s-Processes: the $^{13}C(\alpha,n)^{16}O$ Reaction
- ✓ Neutron Poison Reactions: the $^{17}O(n,\alpha)^{14}C$ and the $^{14}N(n,p)^{14}C$

SEE TALK. G. D'AGATA

A THM application: the case of the $^{17}O(p,\alpha)^{14}N$ reaction

$^{17}O(p,\alpha)^{14}N$ governs the destruction of ^{17}O and the formation of the short-lived radioisotope ^{18}F, which is of special interest for γ -ray astronomy.

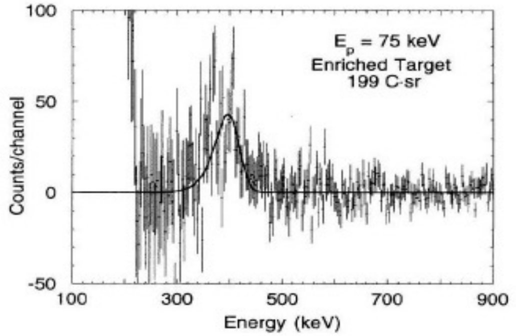
Stellar temperatures of primary importance for ^{17}O nucleosynthesis:
T=0.01-0.1 GK for red giant, AGB, and massive stars;
T=0.1- 0.4 GK for classical nova explosion

T=0.01-0.4 GK: $^{17}O(p,\alpha)^{14}N$ reaction cross section has to be precisely known in the center-of-mass energy range $E_{c.m.}$=0.017-0.37 MeV.

In this energetic region, two resonant levels of ^{18}F are important for $^{17}O(p,\alpha)^{14}N$ reaction:

- ✓ $E_{c.m.}$ = 65.0 keV $J^{\pi} = 1^-$
- ✓ $E_{c.m.}$ = 183.3 keV $J^{\pi} = 2^-$

corresponding to E_x = 5.673 MeV and E_x = 5.786 MeV respectively.



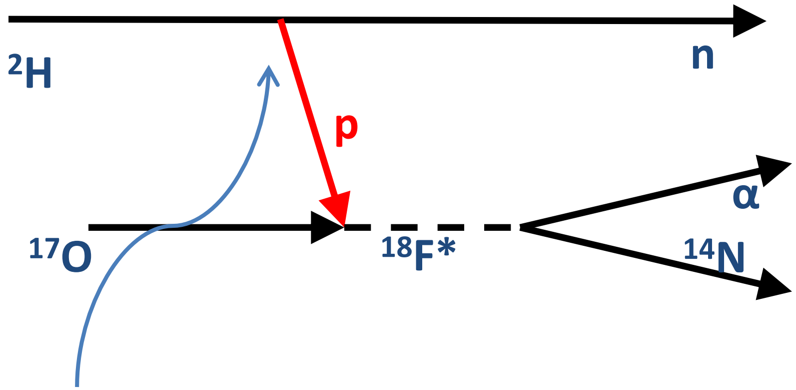
Works focussed on 183 keV resonance up to 2015:

A. Chafa et al., Phys. Rev. C 75 035810, (2007)
J. Newton et a., Phys. Rev. C 75, 055808, (2007)
B.H. Moazen et al., Phys. Rev. C 75, 065801, (2007)
D. Scott et al., Phys. Rev. Lett. 109, 202501, (2012)
A. Di Leva et al., Phys. Rev. C 89, 015803, (2014)

One work focussed on 65 keV resonance: J.C. Blackmon et al., Phys. Rev. Lett. 74 , 2642 (1995)

The experiment

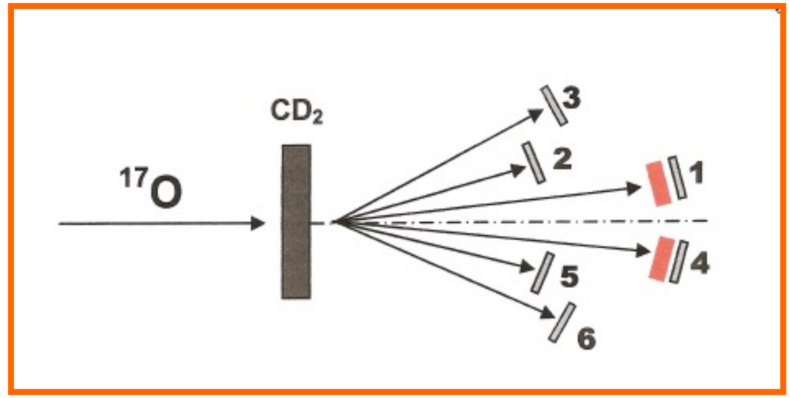
Trojan Horse Method



Upper vertex: direct deuteron breakup

$^{17}O + d \rightarrow {}^{14}N + \alpha + n$

$^{17}O + p \rightarrow {}^{14}N + \alpha$



Two different measurements:

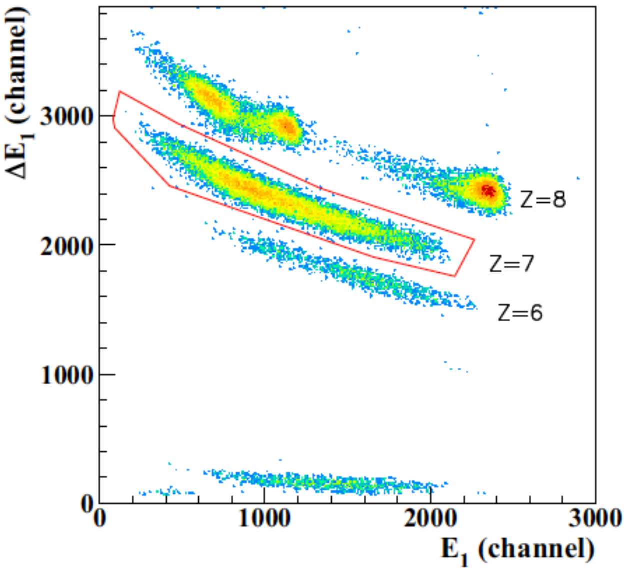
1) LNS – Catania (2006) (Sergi et. al., *Phys. Rev. C 82, 032801(R) (2010)*)
 E_{beam}= 41 MeV, Target thickness ~ 150 μg/cm²
2) NSL – Notre Dame, USA (2008) *(Sergi et al., Phys. Rev. C 91, 065803 (2015))*
 E_{beam}= 43.5 MeV, Target thickness ~ 150 μg/cm²

Two ionization chambers filled with 60 mbar of isobuthan gas as ΔE detector were in front of PSD1 and PSD4 detector

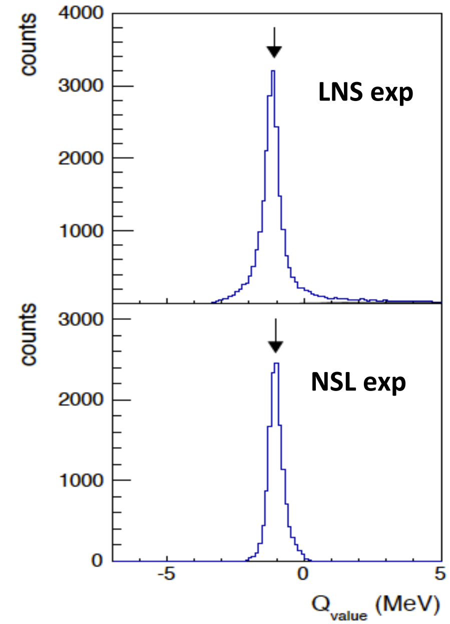
DETECTOR	LNS	NSL
1 (4)	5.1°-10.1°	5.0°-10.0°
2 (5)	13.8°-21.2°	13.1°-18.1°
3 (6)	24.4°-31.2°	23.8°-28.8°

$^{17}O(p,\alpha)^{14}N$ studied by $^{2}H(^{17}O,\alpha\,^{14}N)n$ via the THM

Reaction channel selection....

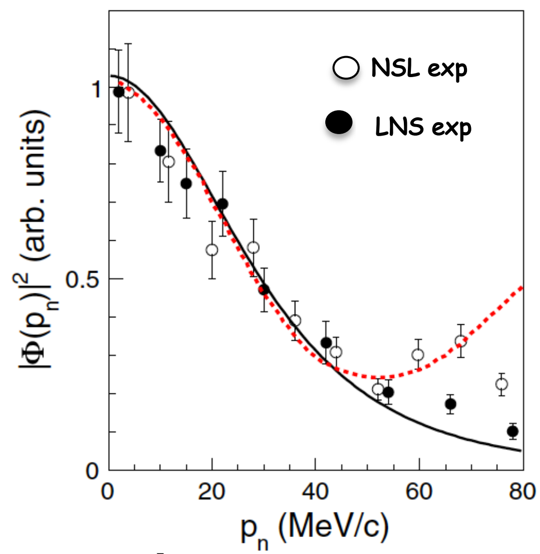


For the selected events (Z=7), the experimental Q_{value} spectrum was obtained



and QF mechanism selection....

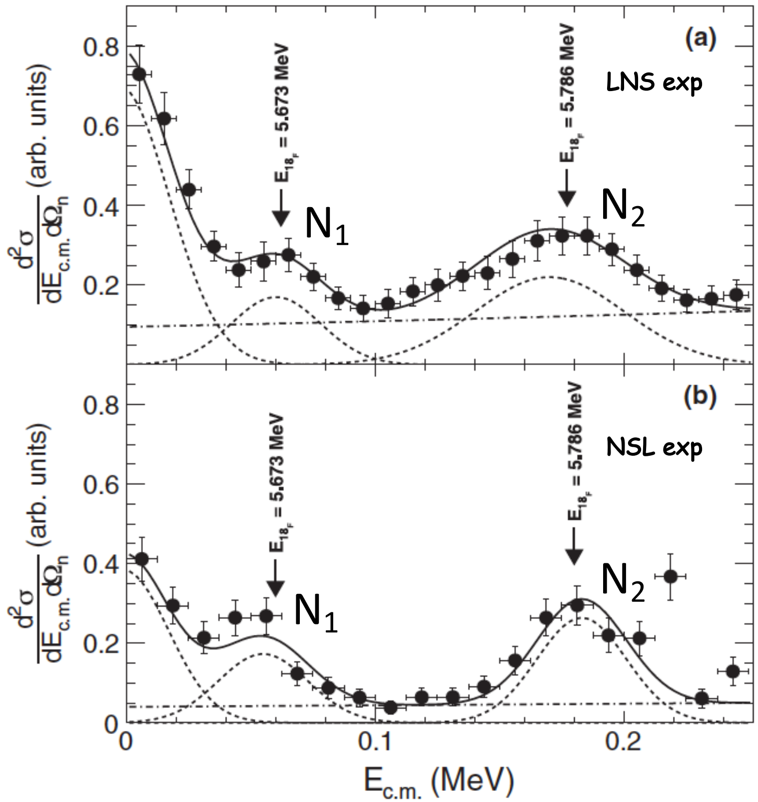
- Good agreement with the theoretical value Q_{th}=-1.033 MeV
- correct selection of the reaction channel;
- good calibration procedure
- no SD mechanism



---- DWBA → FRESCO CODE

—— Hulthén → FWHM=60 MeV/c

Trojan Horse Cross section



In order to separate the different contributions of the resonances on the extracted two body cross section, a fit of the nuclear cross section has been performed.

Extraction of:

- ✓ **Resonance energies**
- ✓ **Peak value of the two resonances, N_1 and N_2,: used to derive the resonance strengths ωγ (case of narrow resonances)**
- ✓ **Vertical error bars (about 18%, only statistical)**

When narrow and isolated resonances dominate the cross section, the reaction rate can be calculated by means of the resonance strength *ωγ*

$$\begin{aligned} N_A < \sigma v >_R &= 1.5394 \times 10^{11} (AT_9)^{-3/2} (\omega\gamma) \exp(-11.605 E_R/T_9) \\ &+ 7.8318 \times 10^9 (Z_1 Z_2/A)^{1/3} S(E_0) T_9^{-2/3} \\ &\times \exp(-4.2486 (Z_1^2 Z_2^2 A/T_9)^{1/3}) \end{aligned}$$

The strength of the resonance at 65 keV is given from the ratio between the peak value N_1 and N_2 through the relation:

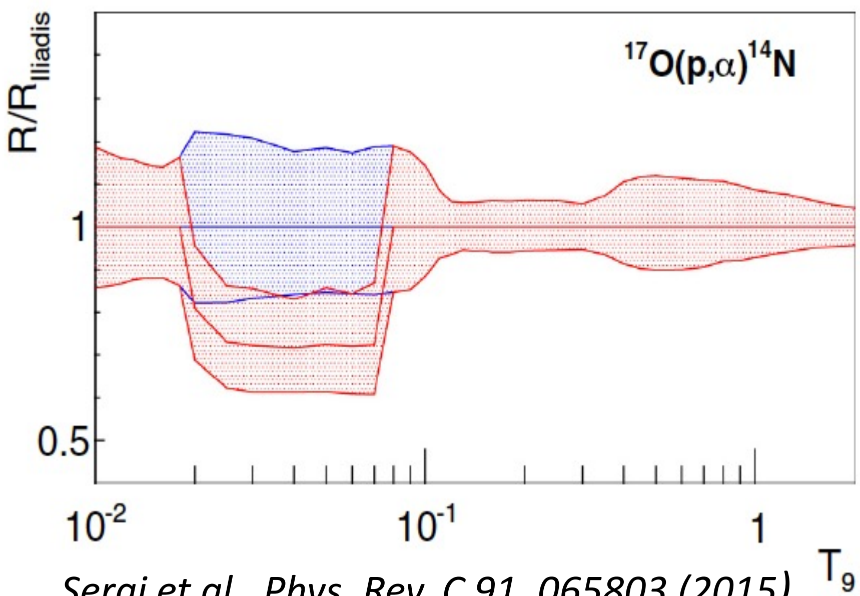
$$(\omega\gamma)_1 = \frac{\omega_1}{\omega_2} \frac{\Gamma_{(p^{17}O)_1}}{\sigma_{R_1}(\theta)} \frac{\sigma_{R_2}(\theta)}{\Gamma_{(p^{17}O)_2}} \frac{N_1}{N_2} (\omega\gamma)_2.$$

Sergi et al., Phys. Rev. C 91, 065803 (2015)
M. La Cognata et al., Astrophys. J. 708, 796 (2010)

Reaction rate determination

The THM reaction rate was calculated by considering the weighted average value of $\omega\gamma=(3.42\pm0.60)\times10^{-9}$ eV for the 65 keV resonance.

$$N_A\langle\sigma v\rangle_{tot}^{THM} = N_A\langle\sigma v\rangle_{tot}^{Iliadis} - N_A\langle\sigma v\rangle_{65keV}^{Iliadis} + N_A\langle\sigma v\rangle_{65keV}^{THM}$$



Sergi et al., Phys. Rev. C 91, 065803 (2015)

Ratio between the THM reaction rate and direct one

The red band marks the reaction-rate interval allowed by experimental uncertainties on the 65 keV resonance strength only. The blue band, instead, is used to display the range on uncertainty characterizing direct data (Iliadis et al. 2010).

T=0.02-0.07 GK: **the differences between the rate adopted in literature and the total rate calculated, if one considers the $N_A\langle\sigma v\rangle_{65}^{THM}$ extracted as explained before, is ∼ 30%.**

$^{17}O(p,\gamma)^{18}F$ Reaction rate determination

From the strength definition:

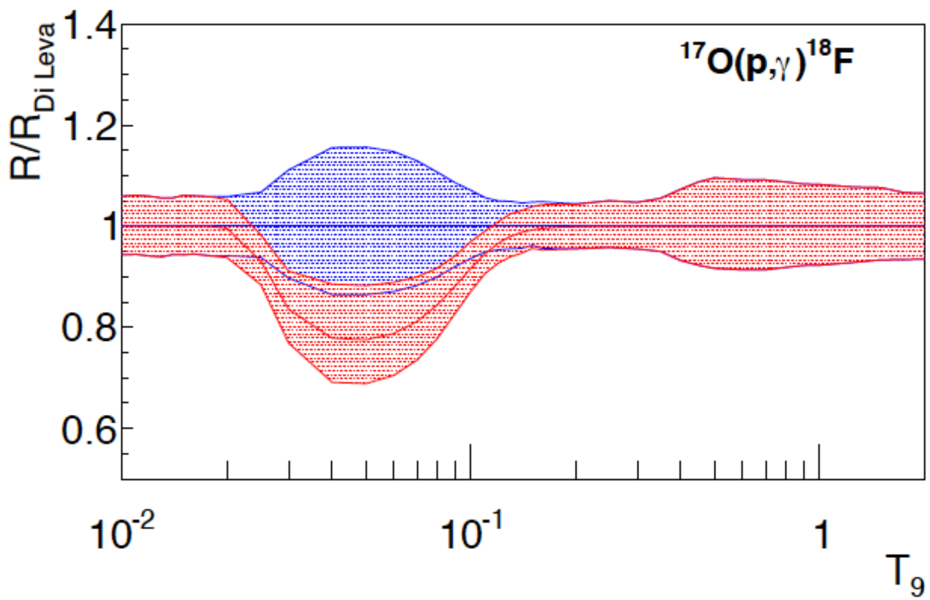
$$(\omega\gamma)_i = \frac{2J_{^{18}F_i}+1}{(2J_{^{17}O}+1)(2J_p+1)} \frac{\Gamma_{(p^{17}O)_i}(E_{R_i})\Gamma_{(\alpha^{14}N)_i}(E_{R_i})}{\Gamma_i(E_{R_i})}$$

$$(\omega\gamma)^{THM}_{p\gamma} = (\omega\gamma)^{THM}_{p\alpha}\frac{\Gamma_\gamma}{\Gamma_\alpha}$$

$$(\omega\gamma)^{THM}_{p\gamma} = (1.18 \pm 0.21)\times 10^{-11}\, eV$$

$$(\omega\gamma)_{p\gamma} = (1.64 \pm 0.28)\times 10^{-11}\, eV$$

Fox et al. Phys. Rev. C 71, 055801 (2005)



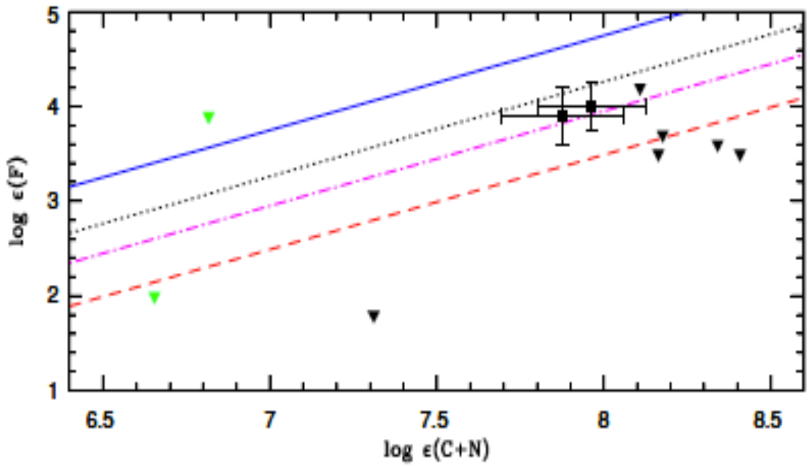
Ratio between the THM reaction rate and Di Leva et al. Phys. Rev. C 89, 015803 (2014) one

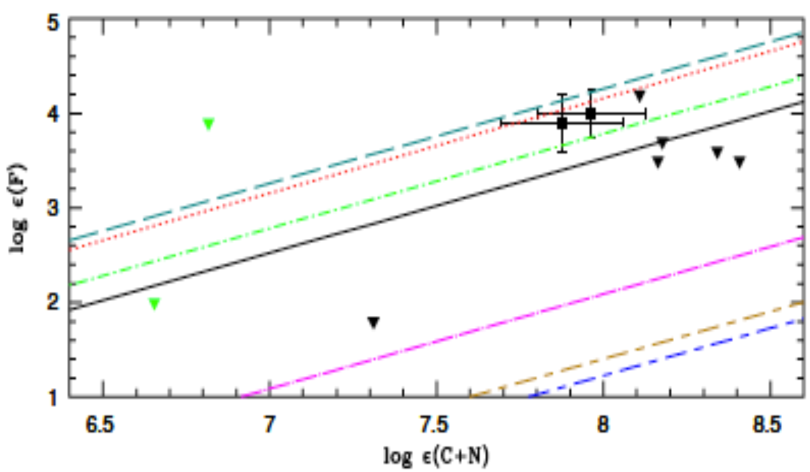
Sergi et al., Phys. Rev. C 91, 065803 (2015)

T=0.03-0.09 GK: **the differences between the rate adopted in literature and the total rate calculated, if one considers the $N_A\langle\sigma v\rangle_{65}^{THM}$ extracted as explained before, is ∼20%.**

The THM for the study of ^{19}F Nucleosynthesis

^{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!





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)

REVISION OF KEY NUCLEAR REACTION RATES????

^{12}C(p,γ)^{13}N(β^+)^{13}C [^{13}C-pocket?]

^{13}C(α,n)^{16}O [s-process]

^{14}N(n,p)^{14}C

^{14}C(α,γ)^{18}O or ^{14}N(α,γ)^{18}F(β^+)^{18}O

^{18}O(p,α)^{15}N → ^{15}N(p,α)^{12}C

^{18}O(α,γ)^{22}Ne

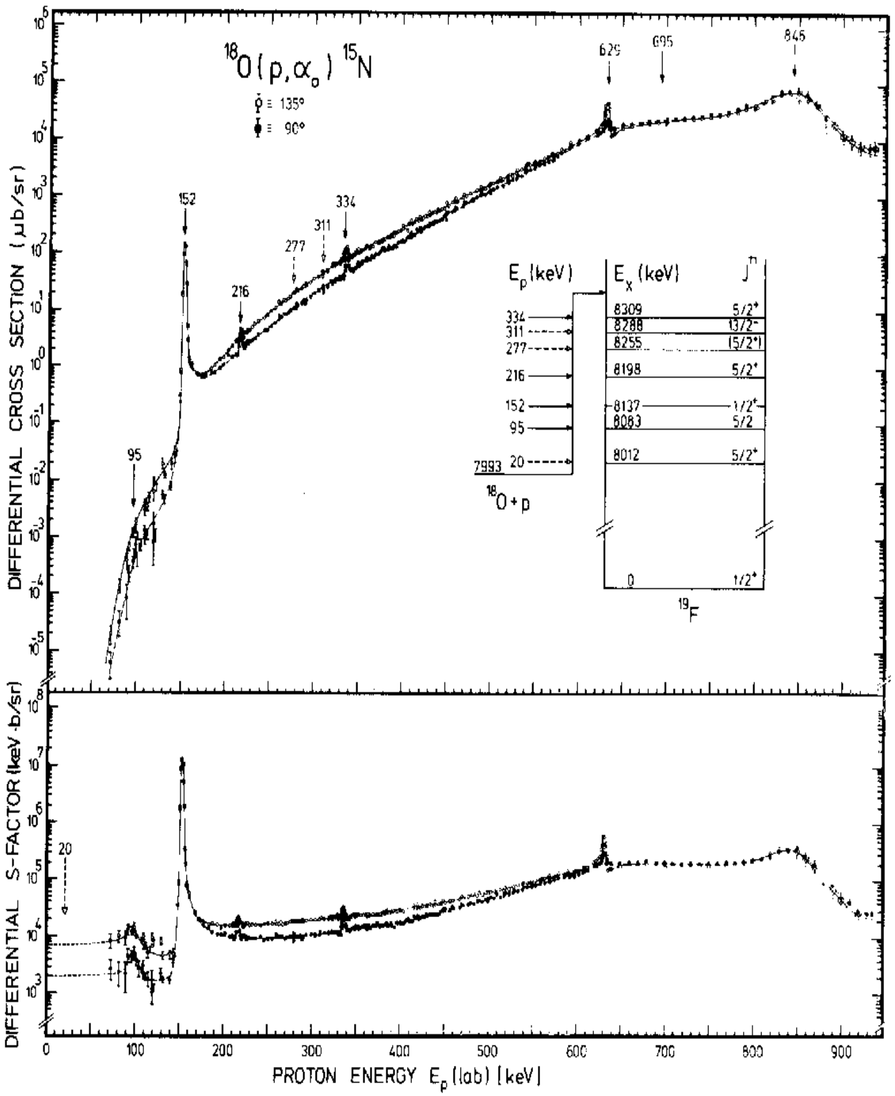
^{15}N(α,γ)^{19}F → ^{19}F(p,α)^{16}O

^{19}F(α,p)^{22}Ne

^{19}F depleting reactions

SEE TALK. G. D'AGATA

The $^{18}O(p,\alpha)^{15}N$ cross-section measurement before THM approach



~50 resonances in the 0-7 MeV region

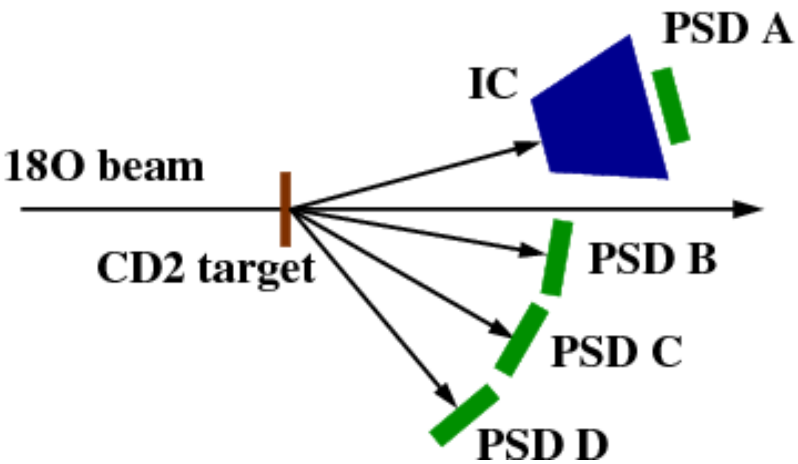
The main contribution to the reaction rate is given by the resonances:

@ 20 keV $J^\pi=5/2^+$
@ 144 keV $J^\pi=1/2^+$ (well established)
@ 656 keV $J^\pi=1/2^+$

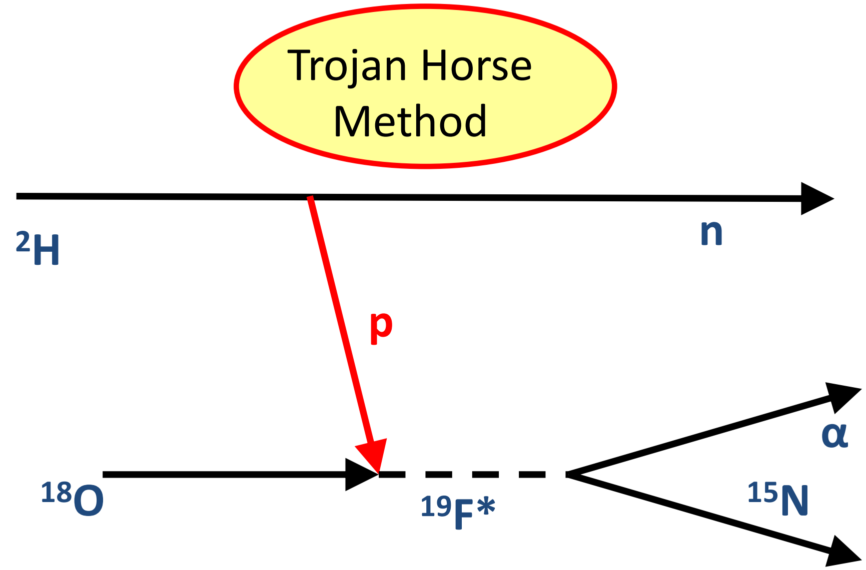
The resonance @ 90 keV provides a negligible contribution to the reaction rate (*A. E. Champagne et al., Nucl. Phys. A457, 367 (1986).*

The 656 keV resonance provides a significant contribution to the reaction rate both at low and high temperatures. The strength and FWHM of the 656 keV are very uncertain (~ 300%).

The THM experiment



Lab.: INFN-LNS Catania (Italy) - Tandem



PSD A + IC for nitrogen discrimination (ΔE- E)

PSD B C & D used to detect α's from the $^2H(^{18}O,\alpha^{15}N)n$ reaction

Detectors placed at the QF angles

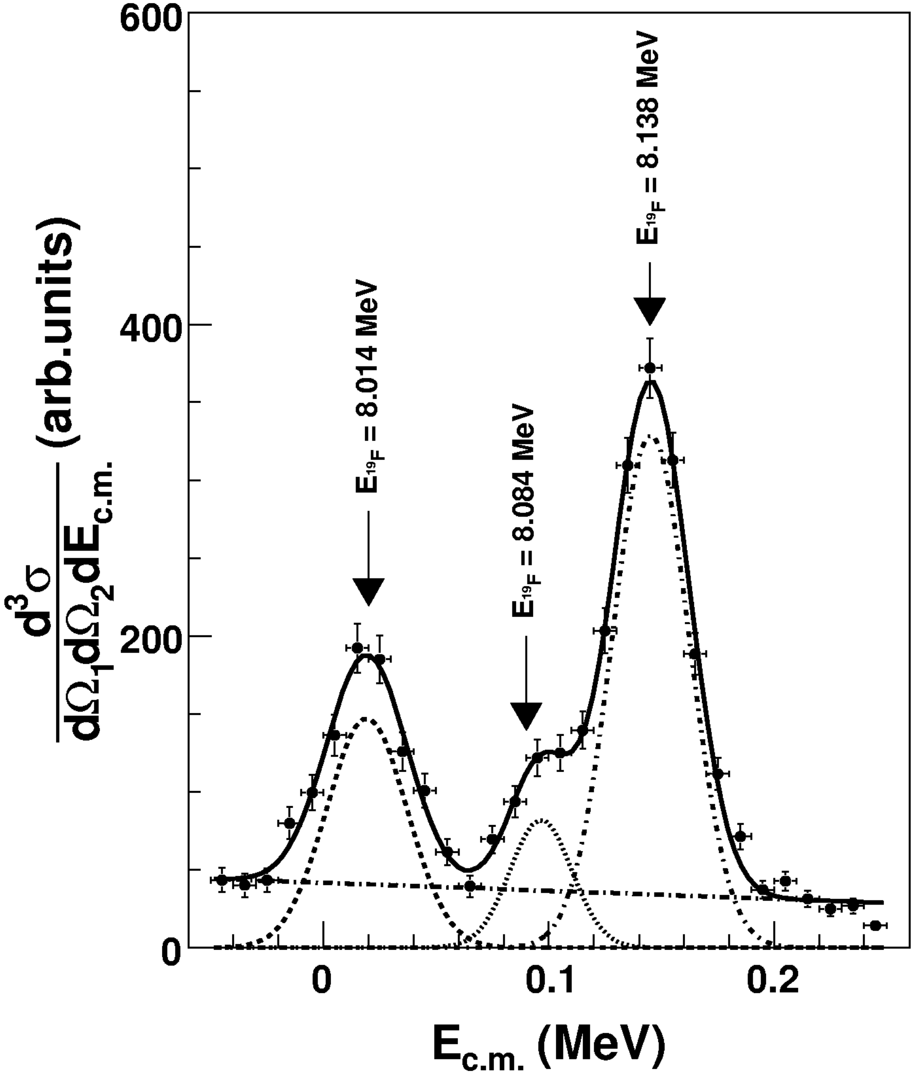
The three-body process (THM reaction) is:

$^2H(^{18}O,\alpha^{15}N)n$

@ E_{beam}= 54 MeV

A single beam energy → a full excitation function (covering the astrophysically relevant energy interval)

Trojan Horse cross section



M. La Cognata et al., Astrophys. J. 708, 796 (2010)

Present case: narrow resonances.
THM data are smoothed out because of 17 keV energy spread

The energies and the $\omega\gamma$ parameters are obtained from the fit of the experimental three-body cross section.

Absolute values are obtained by normalizing to the well known resonance at 144 keV

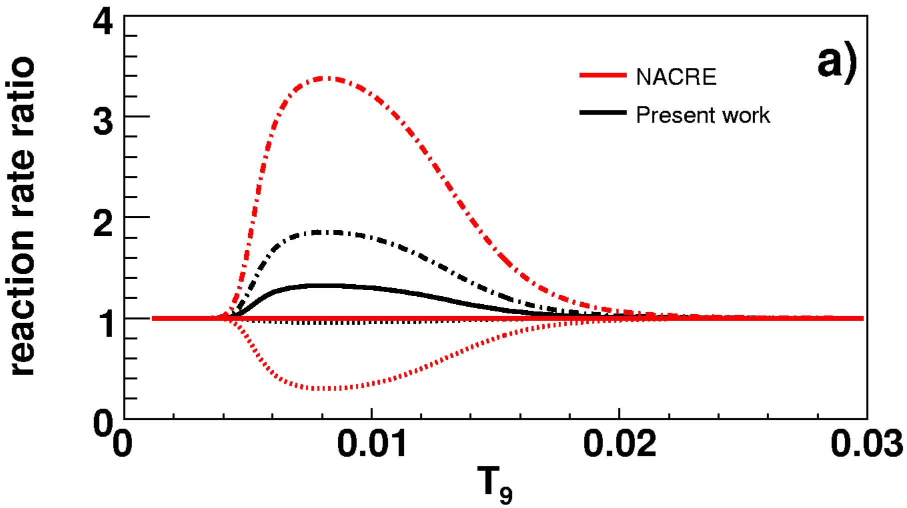
$$(\omega\gamma)_i = \frac{\omega_i}{\omega_3} \frac{\Gamma_{p_i}(E_{R_i})}{|M_i(E_{R_i})|^2} \frac{|M_3(E_{R_3})|^2}{\Gamma_{p_3}(E_{R_3})} \frac{N_i}{N_3} (\omega\gamma)_3$$

$\omega\gamma$ (eV)	Present work	NACRE
20 keV	$8.3^{+3.8}_{-2.6}\ 10^{-19}$	$6^{+17}_{-5}\ 10^{-19}$
90 keV	$1.8 \pm 0.3\ 10^{-7}$	$1.6 \pm 0.5\ 10^{-7}$

Reaction rate determination

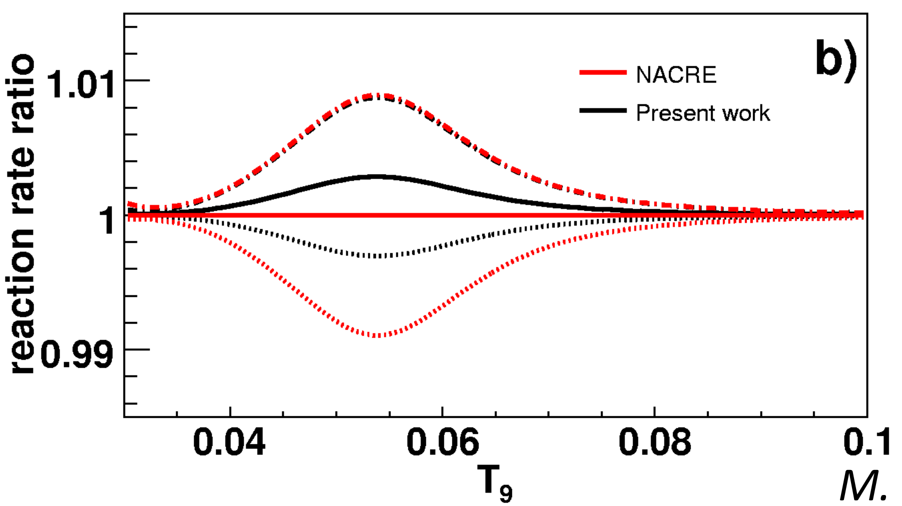
By using the obtained THM $\omega\gamma$ parameters, the contribution to the reaction rate of each resonance is determained by:

$$N_A \langle \sigma v \rangle_R = 1.5394 \times 10^{11} A^{-3/2} (\omega\gamma) T_9^{-3/2} \exp(-11.605 E_r / T_9)$$



Comparison of the THM reaction rate of the $^{18}O(p,\alpha)^{15}N$ reaction with the NACRE one.

By assuming equal to 1 NACRE recommended value we can evaluate how much the rate changes because of the THM estimate of $\omega\gamma$



If $T_9 < 0.03$ (fig a) the reaction rate can be about **35% larger** than the one given by NACRE, while the indetermination is greatly reduced (**a factor 8.5**)

M. La Cognata et al., Astrophys. J. 708, 796 (2010)

The Astrophysical Journal, 764:128 (16pp), 2013 February 20

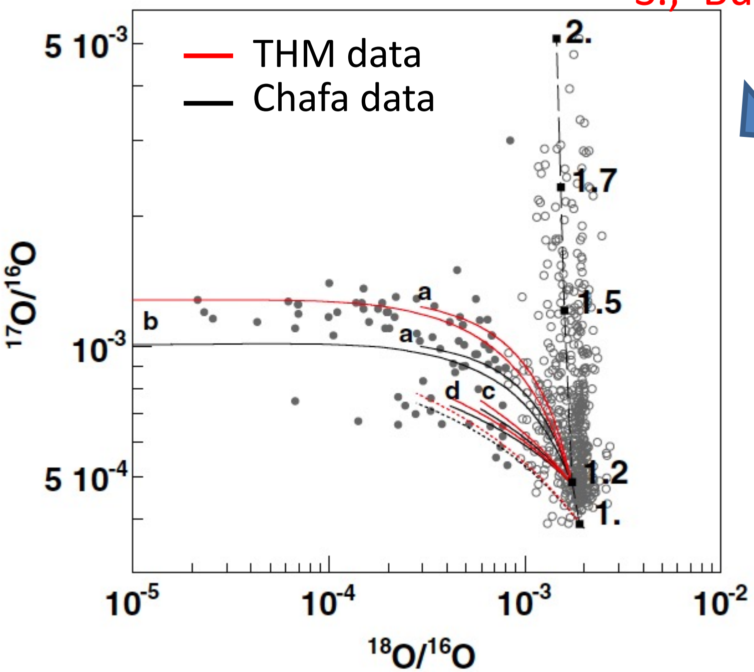
ASTROPHYSICAL IMPLICATIONS

THE RGB AND AGB STAR NUCLEOSYNTHESIS IN LIGHT OF THE RECENT $^{17}O(p,\alpha)^{14}N$ AND $^{18}O(p,\alpha)^{15}N$ REACTION-RATE DETERMINATIONS

S. Palmerini[1,2,4], M. L. Sergi[1,3], M. La Cognata[1], L. Lamia[3], R. G. Pizzone[1], and C. Spitaleri[1,3]
[1] INFN-Laboratori Nazionali del Sud, Catania, Italy
[2] CSFNSM-Centro Siciliano di Fisica Nucleare e Struttura della Materia, Catania, Italy
[3] Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy
Received 2012 July 31; accepted 2012 December 19; published 2013 January 31

The deduced rates for the $^{18}O(p,\alpha)^{15}N$, $^{17}O(p,\alpha)^{14}N$, and $^{17}O(p,\gamma)^{18}F$ processes have been introduced into the state-of-the-art of the AGB models for proton-capture nucleosynthesis coupled with extra-mixing episodes.

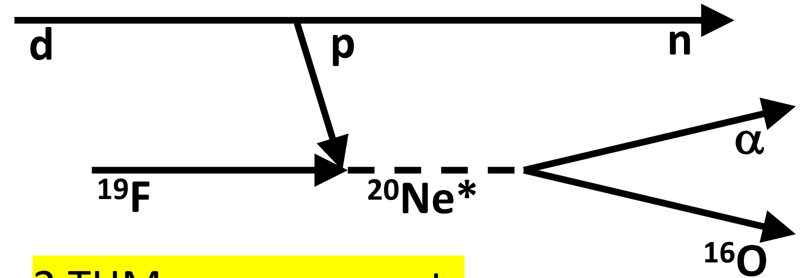
Comparison of the oxygen isotopic mix measured in a sample of oxide grains and extra-mixing calculations performed using the model in the work by Palmerini, S., Cristallo, S., Busso, M., et al. 2011a, ApJ, 741, 26



(a) $\Delta = 0.1$, $\dot{M} = 1\times10^{-6}\ M_\odot\ yr^{-1}$
(b) $\Delta = 0.1$, $\dot{M} = 3\times10^{-6}\ M_\odot\ yr^{-1}$
(c) $\Delta = 0.22$, $\dot{M} = 1\times10^{-6}\ M_\odot\ yr^{-1}$
(d) $\Delta = 0.22$, $\dot{M} = 3\times10^{-6}\ M_\odot\ yr^{-1}$
where Δ is the mixing depth

Improved agreement is found between the models and the isotopic mix of oxide grains of AGB origins, whose composition is the signature of low temperature proton-capture nucleosynthesis.

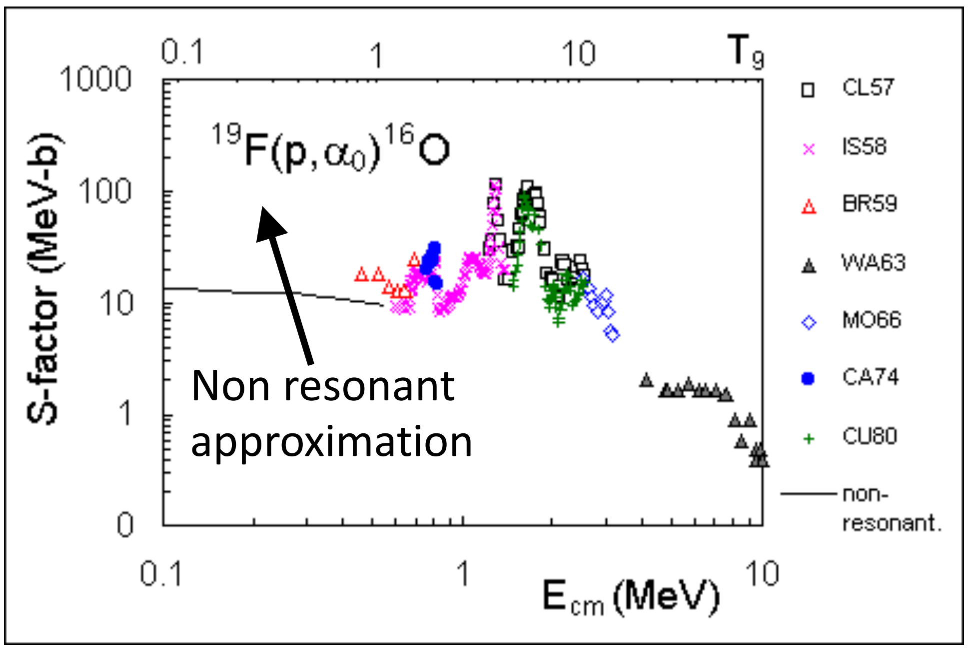
Measurement of the $^{19}F(p,\alpha_0)^{16}O$ reaction using the Trojan Horse Method (THM)

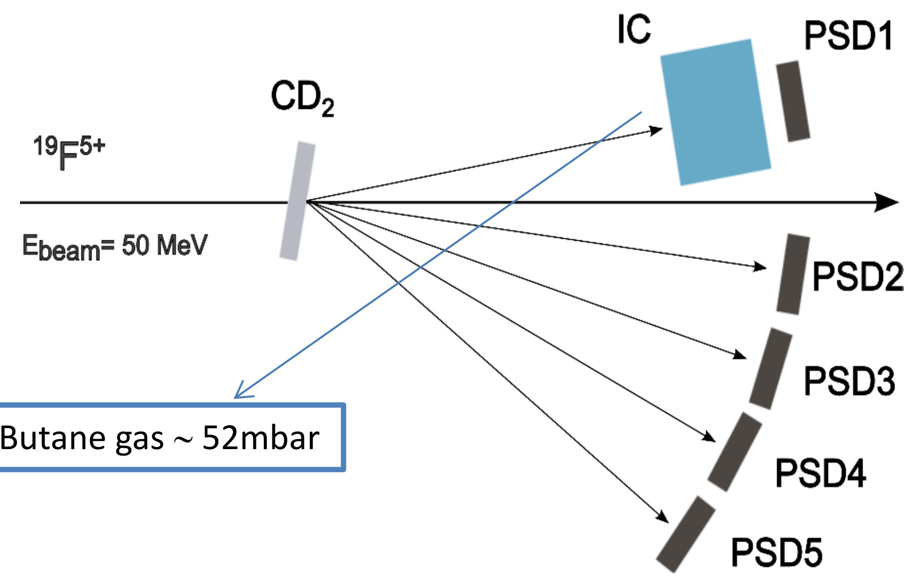


The $^{19}F(p,\alpha_0)^{16}O$ reaction is the main fluorine destruction channel at the bottom of the convective envelope in AGB stars (H-rich environment) but no data were available around ~100 keV (energy of astrophysical interest)

2 THM measurements
at LNS-INFN (CATANIA)
and at LNL-INFN (LEGNARO)

$d(^{19}F,\alpha^{16}O)n$	Q_{3b}=5.889 MeV
$^{19}F(p,\alpha)\ ^{16}O$	Q_{2b}=8.113 MeV

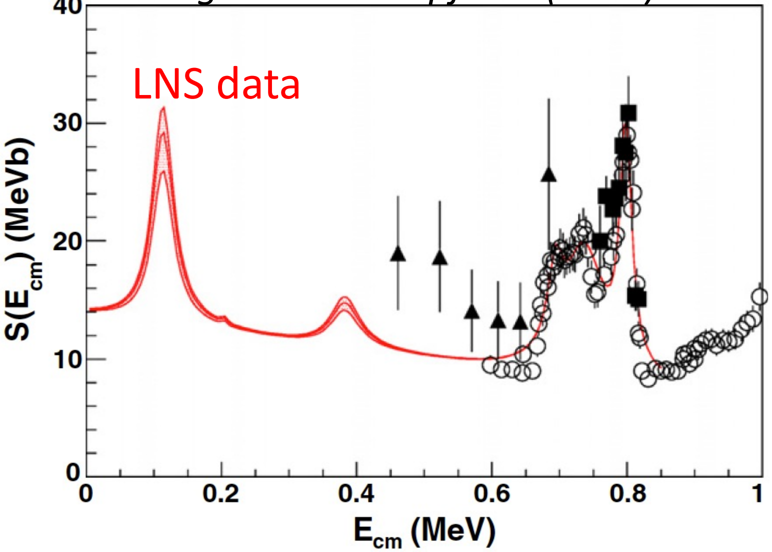


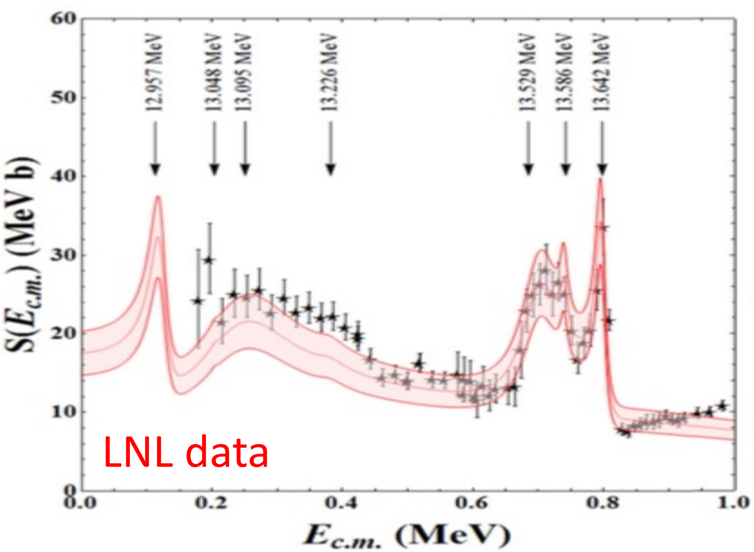


Below E_{cm} = 460 keV, where data do not exist, a non resonant contribution is calculated for *s*-capture.

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

La Cognata et al. Apj 739 (2011) L54





I. Indelicato et al., ApJ 845 (2017) 19

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

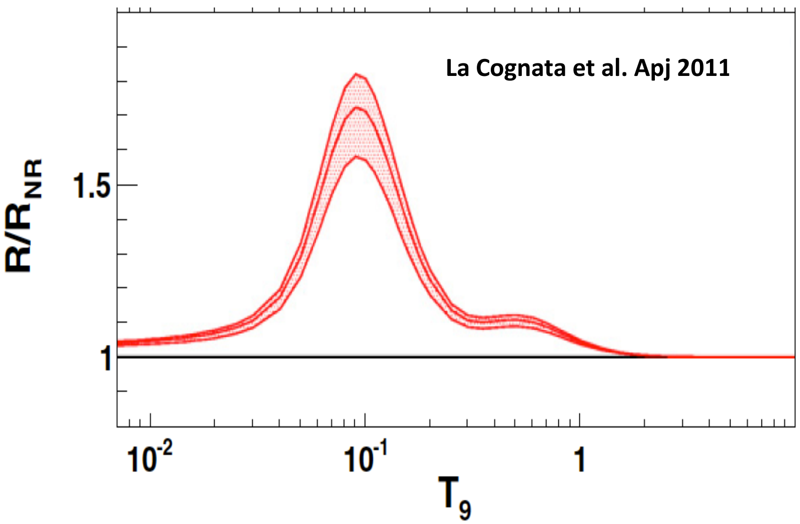
The non-resonant contribution is taken from NACRE (1999).

New direct data down to about 200 keV: «I. Lombardo et al., J. Phys. G: Nucl. Part. Phys. **40** (2013) 125102» and «I. Lombardo et al., Phys. Lett. B 748 (2015) 178»

New THM measurement: improved energy resolution allowed for

- better level separation
- angular distribution analysis

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



Ratio of the THM reaction rate 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 AGB stars, i.e. about T_9~0.04.

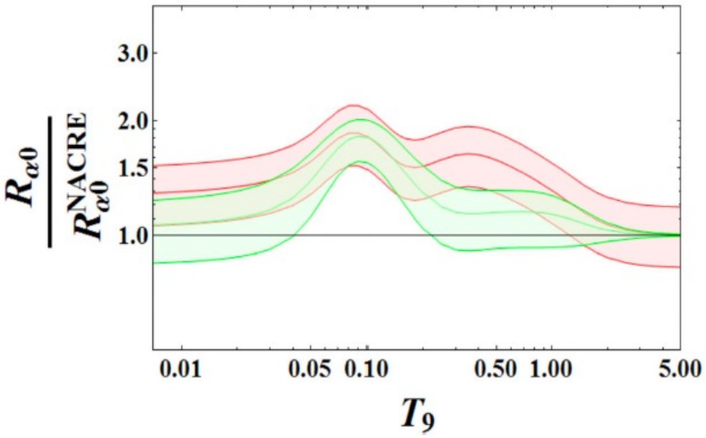
Astrophysical implication:

- Impact of the new $^{19}F(p,a)^{16}O$ reaction rate in M = 2$M_\odot$ and Z = 10^{-4} AGB star**;**
- Extra-mixing calculations according to Busso et al. (2010) & Palmerini et al. (2011);
- Depletion of about 40% (T_9=0.06) and about 27% (T_9=0.05) with respect astrophysical calculations adopting the NACRE reaction rate;
- These depletion factors are of the same order of magnitude as those necessary for explaining the observational evidences of Lucatello et al. 2011. See La Cognata et al. 2011 for details;
- Further experimental runs are still under evalutions, as for instance the (p,α_1) channel for a more comprehensive study.

THANKS FOR YOUR ATTENTION!

SPARE SLIDES

Astrophysical consequences...

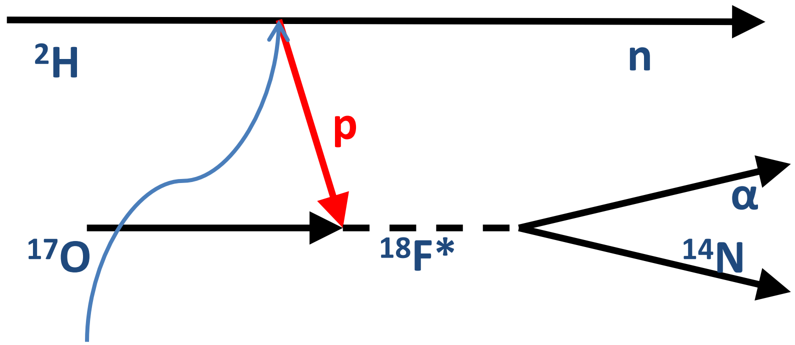


...Work in progress!!!

A quantitative estimate of the impact of this measurement has been attempted. Following the suggestion in Lucatello et al. (2011) and Abia et al. (2011), we run parametric extra-mixing calculations according to the model in Busso et al. (2010); Palmerini et al. (2011) to evaluate to what extent the fluorine destructions varies if the NACRE reaction rate is replaced by the one obtained here. We found that the fluorine surface abundance can be depleted 40% more with respect to the NACRE rate in an M = 2 M and Z = 10−4 AGB star. Since a significant fraction of fluorine upper limits for a sample of metal-poor AGB stars are located under the predicted values by a factor of the same order (Lucatello et al. 2011), this updated reaction rate can help to solve the fluorine puzzle in these stars in the framework of extra-mixing. In the M = 2 M and Z = 10−4 AGB stellar model9 used for preliminary calculations, the mixed material experiences temperatures up to T9 ∼ 0.05, where the reaction rate is 27% higher than in NACRE. An even larger destruction is expected in those environments where the reaction rate enhancement approaches a factor of 1.7 (T9 ∼ 0.1). Therefore, extensive calculations are undergoing to understand the consequences of the present results on astrophysics.

The Trojan horse method for resonant reactions

In the "Trojan Horse Method" (THM) the astrophysically relevant reaction, in particular $^{17}O(p,\alpha)^{14}N$, is studied through an appropriate three-body process → $^{2}H(^{17}O,\alpha^{14}N)n$:



The process is a transfer to the continuum where proton (p) is the transferred particle

Upper vertex: direct deuteron breakup

Standard R-Matrix approach cannot be applied to extract the resonance parameters of the $^{17}O(p,\alpha)^{14}N$ → Modified R-Matrix is introduced instead

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

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

$M_i(E)$ is the amplitude of the transfer reaction (upper vertex) that can be easily calculated → The resonance parameters can be extracted and in particular the strenght

How to extract the resonant strength?

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

$$(\omega\gamma)_i = \frac{2J_{^{18}\mathrm{F}_i}+1}{(2J_{^{17}\mathrm{O}}+1)(2J_p+1)} \frac{\Gamma_{(p^{17}\mathrm{O})_i}(E_{R_i})\Gamma_{(\alpha^{14}\mathrm{N})_i}(E_{R_i})}{\Gamma_i(E_{R_i})}$$

($^{17}O(p,\alpha)^{14}N$ case)

Where:

- $\Gamma_{(AB)}$ is the partial width for the A+B channel
- Γ_i is the total with 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:

$$(\omega\gamma)_i = \frac{1}{2\pi}\omega_i N_i \frac{\Gamma_{(p^{17}\mathrm{O})_i}(E_{R_i})}{\sigma_{R_i}(\theta)},$$

Where:

- $\omega_I = \hat{J}_i \,/\, \hat{J}_p \hat{J}_{18O}$ statistical factor
- N_i = THM resonance strength
- $\sigma_{Ri}(\theta)$ = direct transfer reaction cross section for the binary reaction $^{17}O+d \rightarrow {}^{18}F_i+n$ populating the i-*th* resonant state in ^{18}F

Advantages:

- possibility to measure down to zero energy
- No electron screening
- No spectroscopic factors in the $\Gamma_{(p17O)} \,/\, |M_i|^2$ ratio

The ωγ parameter for the 65 keV resonant level and reaction rate

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

The strength of the resonance at 65 keV is given from the ratio between the peak value N_1 and N_2 through the relation:

$$(\omega\gamma)_1 = \frac{\omega_1}{\omega_2} \frac{\Gamma_{(p^{17}O)_1}}{\sigma_{R_1}(\theta)} \frac{\sigma_{R_2}(\theta)}{\Gamma_{(p^{17}O)_2}} \frac{N_1}{N_2} (\omega\gamma)_2.$$

Experiment	$(\omega\gamma)_1^{\mathrm{THM}}$ (eV)
LNS	$(3.72 \pm 0.78) \times 10^{-9}$
NSL	$(3.16 \pm 0.68) \times 10^{-9}$
Adopted	$(3.42 \pm 0.60) \times 10^{-9}$

These values are, within the experimental errors, in agreement:

✓ **with the value $5.5^{+1.8}_{-1.0} \cdot 10^{-9}$ eV adopted in NACRE, (Γ_α=130 eV measured by Mak'80 and Γ_p=22 neV found by Blackmon'95)**

✓ **with the $(4.7 \pm 0.8) \cdot 10^{-9}$ eV calculated by using the value of Γ_α and Γ_p reported in Chafa'07**

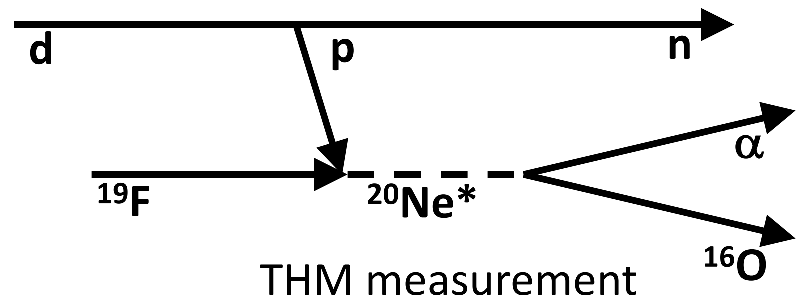
Sergi et al., Phys. Rev. C 91, 065803 (2015)
M. La Cognata et al., Astrophys. J. 708, 796 (2010)

For an isolated and narrow resonance:

$$\begin{aligned} N_A < \sigma v >_R &= 1.5394 \times 10^{11} (AT_9)^{-3/2} (\omega\gamma) \exp(-11.605 E_R / T_9) \\ &+ 7.8318 \times 10^9 (Z_1 Z_2 / A)^{1/3} S(E_0) T_9^{-2/3} \\ &\times \exp(-4.2486 (Z_1^2 Z_2^2 A / T_9)^{1/3}) \end{aligned}$$

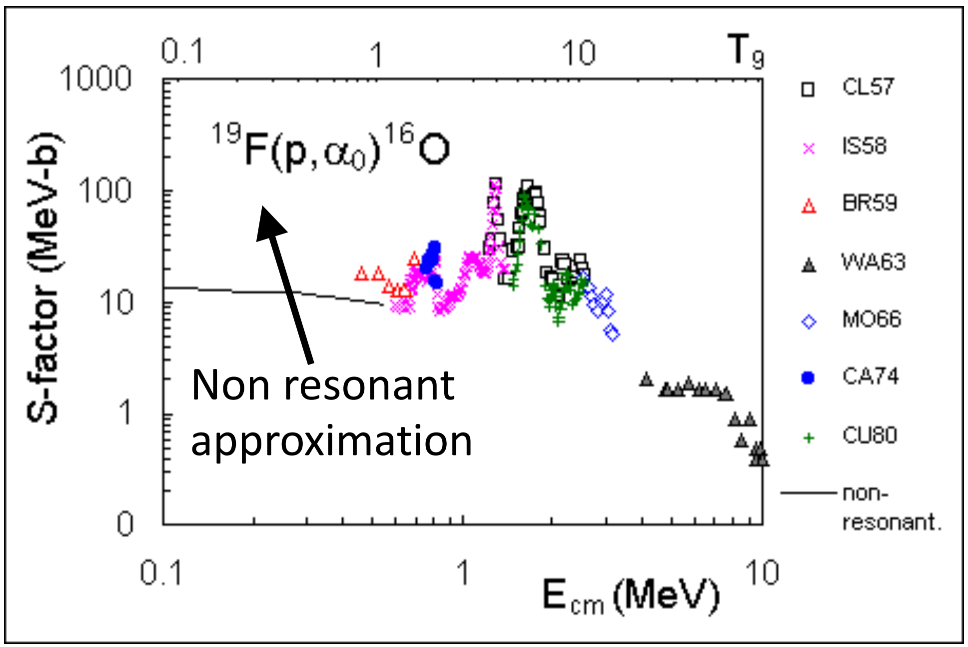
where $N_A<\sigma v>_R$ is expressed in *cm^3 mol^{-1} sec^{-1}*, E_R and $\omega\gamma$ in *MeV* and $S(E_0)$ in *MeV b*.
Z_1 and Z_2 are the projectile and the target atomic number respectively.

Measurement of the $^{19}F(p,a_0)^{16}O$ reaction using the Trojan Horse Method (THM)

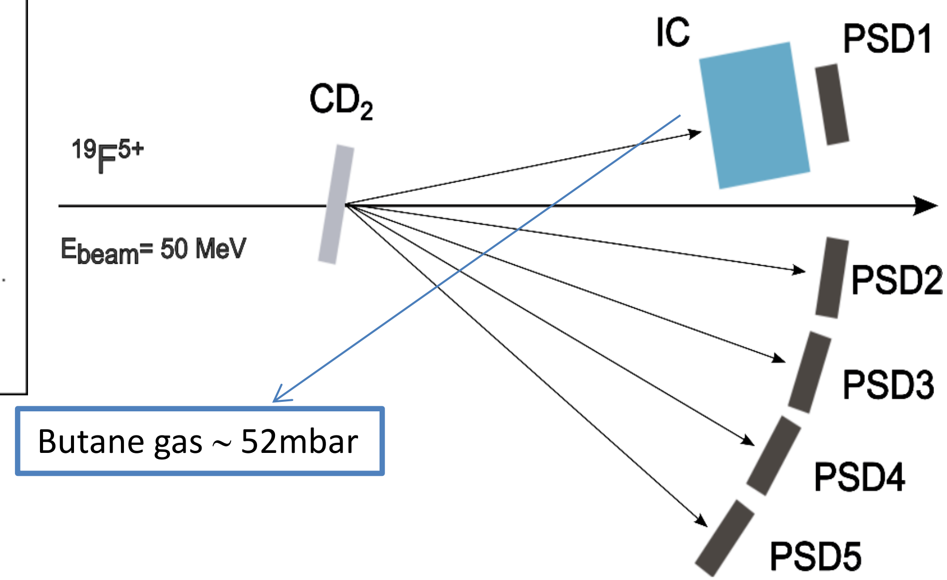


The $^{19}F(p,\alpha_0)^{16}O$ reaction is the main fluorine destruction channel at the bottom of the convective envelope in AGB stars (H-rich environment) but no data are available around ~100 keV (energy of astrophysical interest)

THM measurement at LNS-INFN (CATANIA)



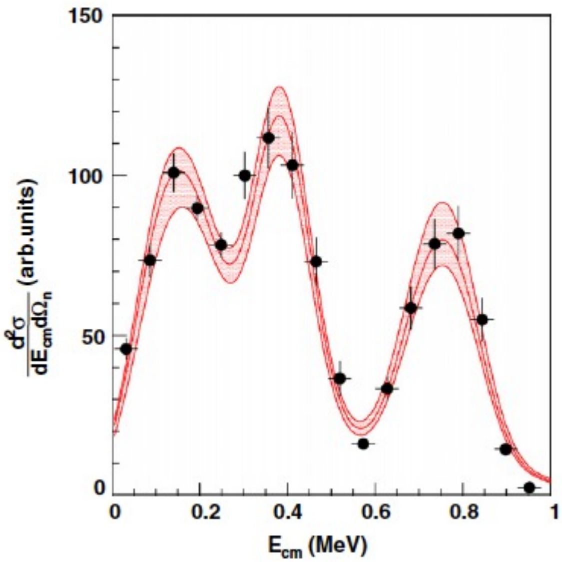
$d(^{19}F,\alpha^{16}O)n$	Q_{3b}=5.889 MeV
$^{19}F(p,\alpha)\ ^{16}O$	Q_{2b}=8.113 MeV



Below E_{cm} = 460 keV, where data do not exist, a non resonant contribution is calculated for *s*-capture.

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

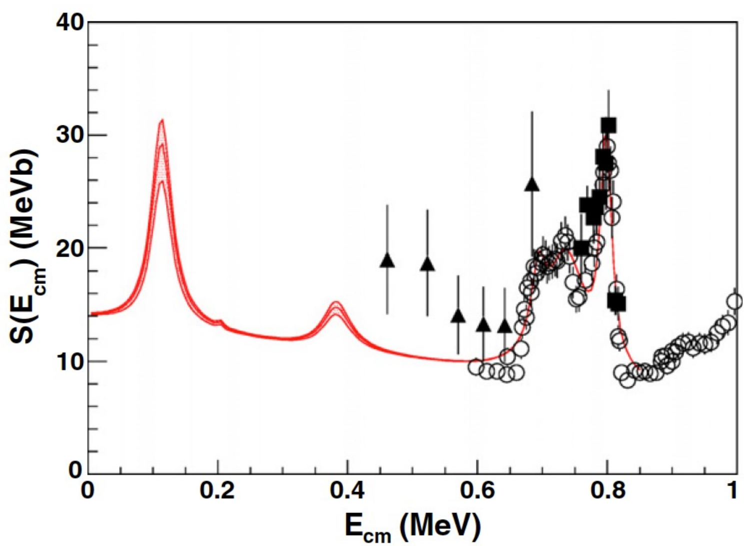
THM x-section shows a rich resonant pattern!



horizontal error bars → p–^{19}F-relative-energy binning.

The vertical error bars → statistical and angular-distribution integration uncertainties.

Red band → the cross section calculated in the modified *R*-matrix approach, normalized to the peak at about 750 keV and convoluted with the experimental resolution.



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

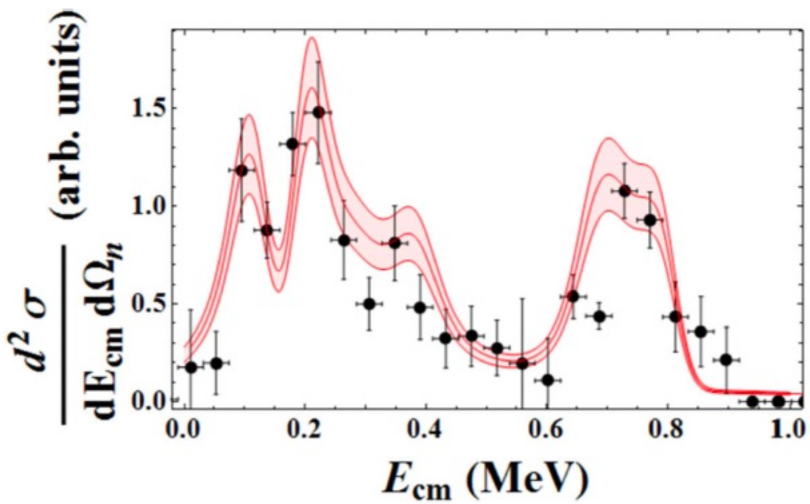
Above 0.6 MeV, the reduced partial widths were obtained through an *R*-matrix fit of direct data

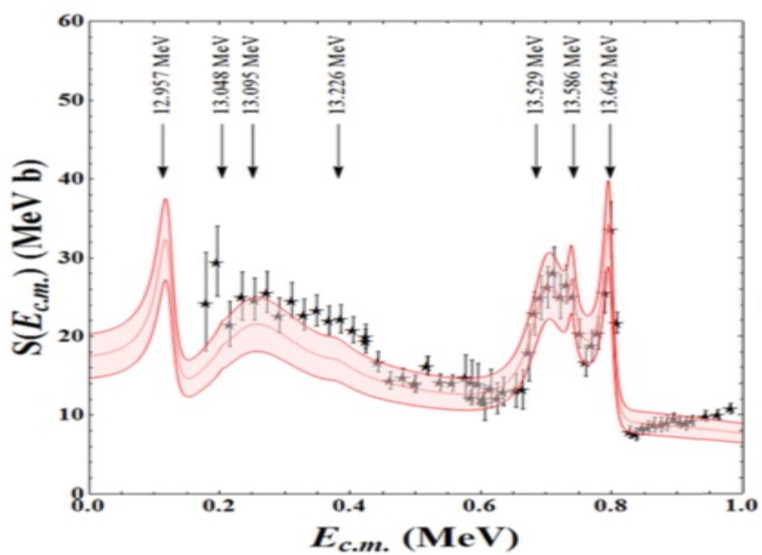
Below 0.6 MeV, the resonance parameters were obtained from the modified *R*-matrix fit

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

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

New direct data down to about 200 keV: «I. Lombardo et al., J. Phys. G: Nucl. Part. Phys. **40** (2013) 125102» and «I. Lombardo et al., Phys. Lett. B 748 (2015) 178»





A new THM measurement was performed at the Laboratori Nazionali di Legnaro (Italy).

Improved energy resolution allowed for

- better level separation
- angular distribution analysis

The basic feature → 113 keV resonance is confirmed

Interference is also confirmed → New THM S-factor

I. Indelicato et al., ApJ 845 (2017) 19

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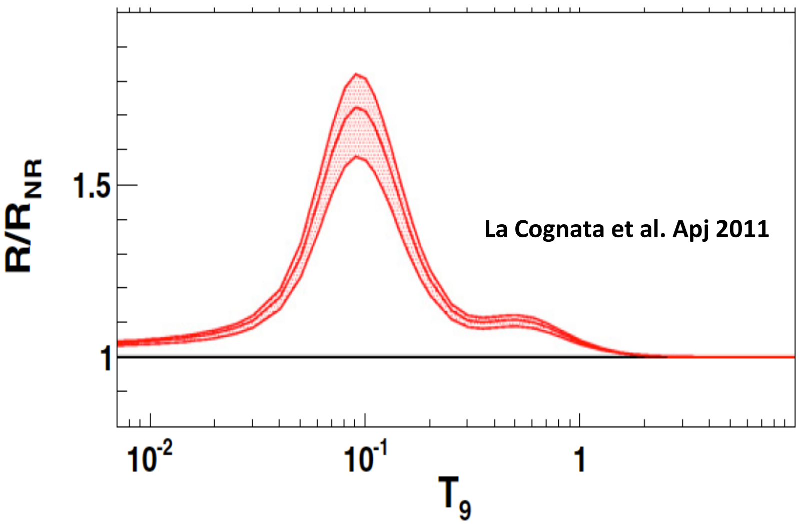

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