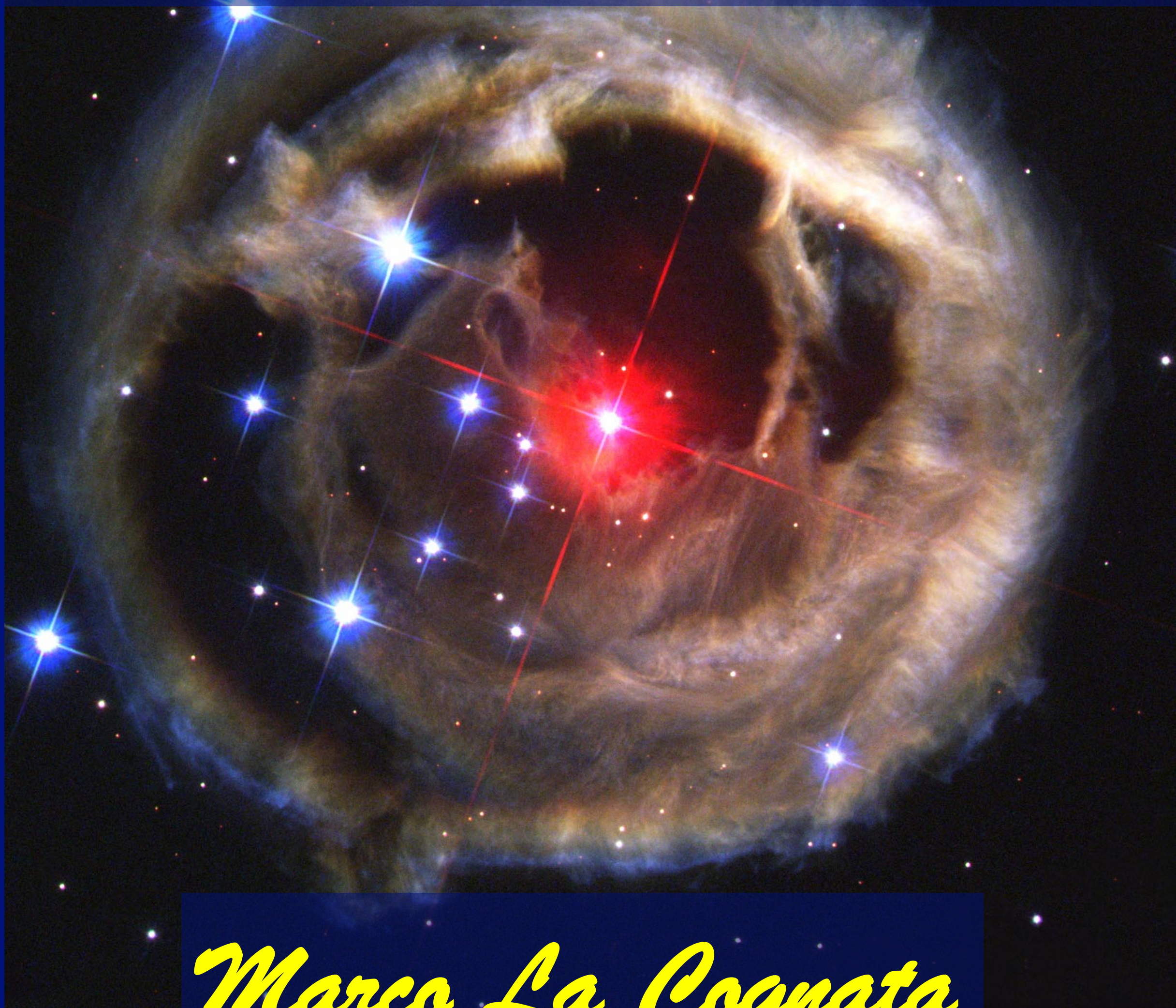
The Trojan Horse Method As A Tool To Investigate Low-energy Resonances: The $^{18}O(p,\alpha)^{15}N$ and $^{17}O(p,\alpha)^{14}N$ Cases



Marco La Cognata

INFN LNS

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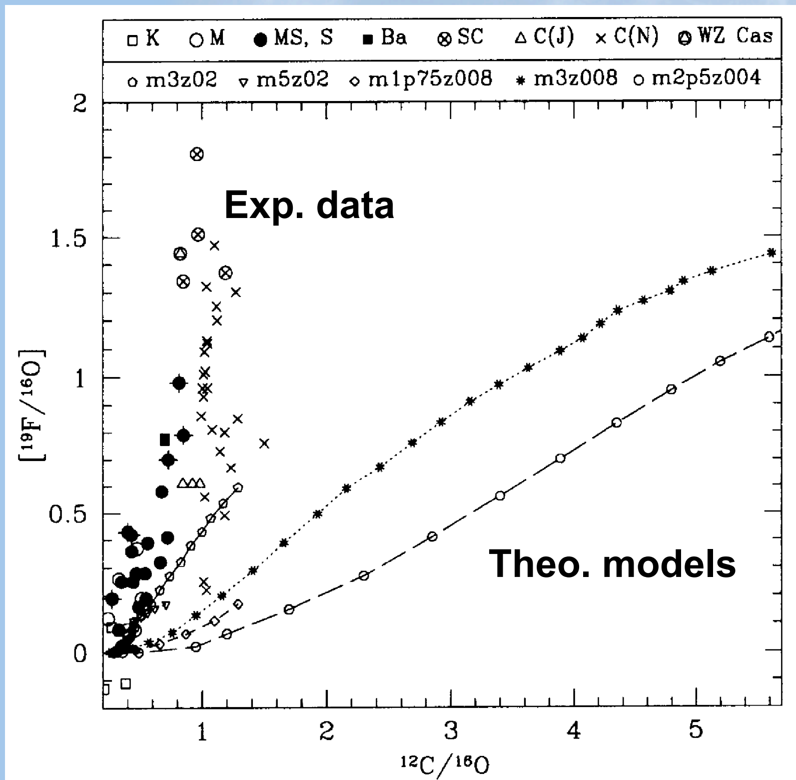
^{19}F Nucleosynthesis and Mixing

^{19}F is one of the few naturally occurring isotopes whose nucleosynthesis is still uncertain.

Possible sources: SNe, WF and AGB stars

Role: constraint in AGB models and s-process nucleosynthesis (TDU + TP)



Comparison of observed ^{19}F abundance and the predictions from AGB star models High ^{19}F abundances → high C/O

NOT supported by observations!

$^{12}C(p,\gamma)^{13}N(\beta^{+})^{13}C$ [^{13}C-pocket?]

$^{13}C(\alpha,n)^{16}O$ [s-process]

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

$^{14}C(\alpha,\gamma)^{18}O$ or $^{14}N(\alpha,\gamma)^{18}F(\beta^{+})^{18}O$

$^{18}O(p,\alpha)^{15}N$ → $^{15}N(p,\alpha)^{12}C$

$^{18}O(\alpha,\gamma)^{22}Ne$

$^{15}N(\alpha,\gamma)^{19}F$ → $^{19}F(\alpha,p)^{22}Ne$

} ^{19}F depleting reactions

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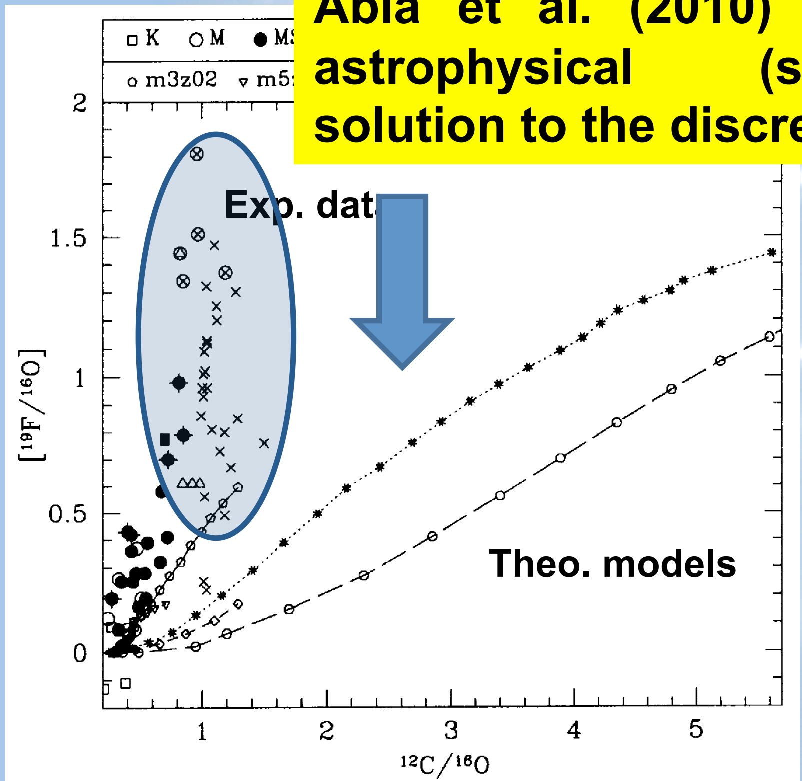

Abia et al. (2010) proposed an astrophysical (spectroscopic) solution to the discrepancy

… of observed ^{19}F abundance … redictions from AGB star … h ^{19}F abundances → high C/O

NOT supported by observations!

$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C$ [^{13}C-pocket?]
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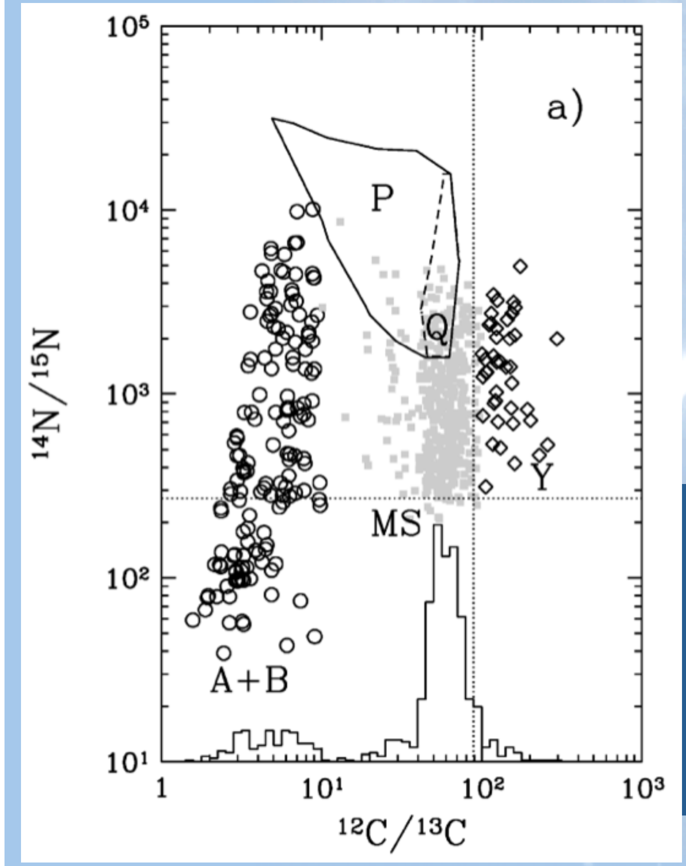
} ^{19}F depleting reactions

Isotopic Ratios in Meteorite Grains

Meteorite grains are dust grains found inside meteorites.

A part was formed in the atmosphere of AGB stars (in particular SiC grains)

→ they bear information about nucleosynthesis and convective mixing in these stars



Classification → $^{12}C/^{13}C$ and $^{14}N/^{15}N$ ratios

Main Stream (MS) grains = 94%

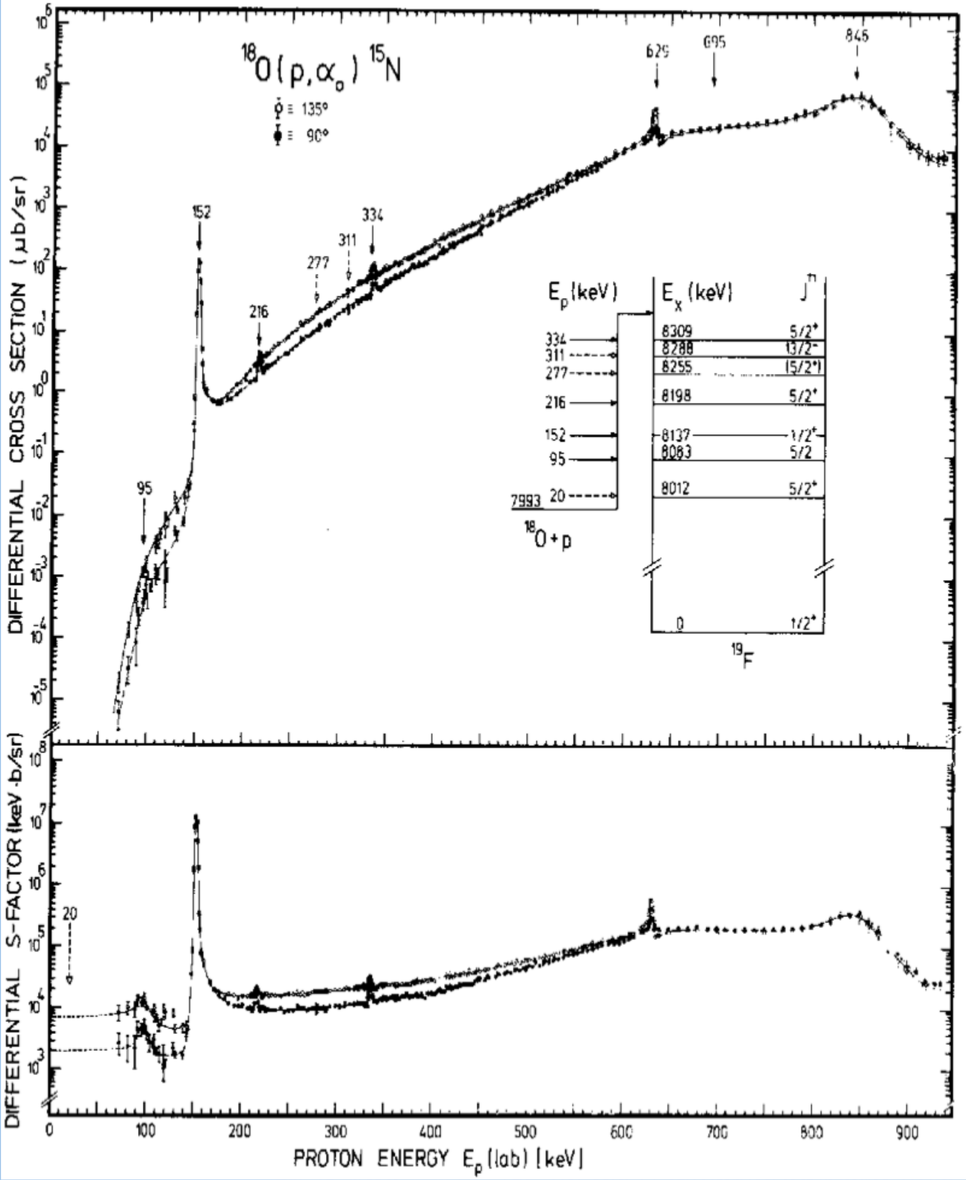
A+B grains = 4%

$^{12}C/^{13}C$: justified according to present AGB models (including HBB for A+B)

$^{14}N/^{15}N$: only the largest ratios can be reproduced

If a sub-solar initial abundance is assumed, the MS full range of the $^{14}N/^{15}N$ ratio can be retrieved though the extremely low values displayed by A+B grains are not reproduced. Is the cause related to nuclear physics?

The $^{18}O(p,\alpha)^{15}N$ Reaction: Current Status



~50 resonances in the 0-7 MeV region

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

1- 20 keV $J^\pi=5/2^+$
2- 144 keV $J^\pi=1/2^+$ (well established)
3- 656 keV $J^\pi=1/2^+$

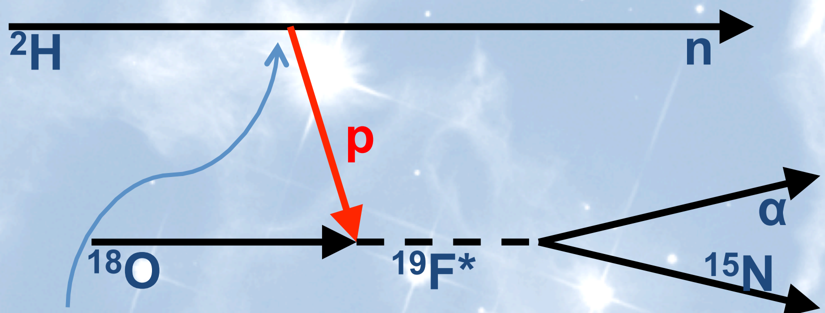
20 keV resonance parameters are deduced from an indirect measurement

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%).

Subthreshold resonance at 7.9 MeV

The Trojan horse method for resonant reactions

In the "Trojan Horse Method" (THM) the astrophysically relevant reaction, in particular $^{18}O(p,\alpha)^{15}N$, is studied through an appropriate three-body process → $^{2}H(^{18}O,\alpha^{15}N)n$:



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 $^{18}O(p,\alpha)^{15}N$ → 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 strength

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:

$$(\omega\gamma)_i = \frac{\hat{J}_i}{\hat{J}_p \hat{J}_{^{18}\mathrm{O}}} \frac{\Gamma_{(p^{18}\mathrm{O})_i}(E_{R_i})\,\Gamma_{(\alpha^{15}\mathrm{N})_i}(E_{R_i})}{\Gamma_i(E_{R_i})}$$

(^{18}O(p,α)^{15}N case)

Where:
- $\hat{J}=2J+1$
- $\Gamma_{(AB)}$ 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

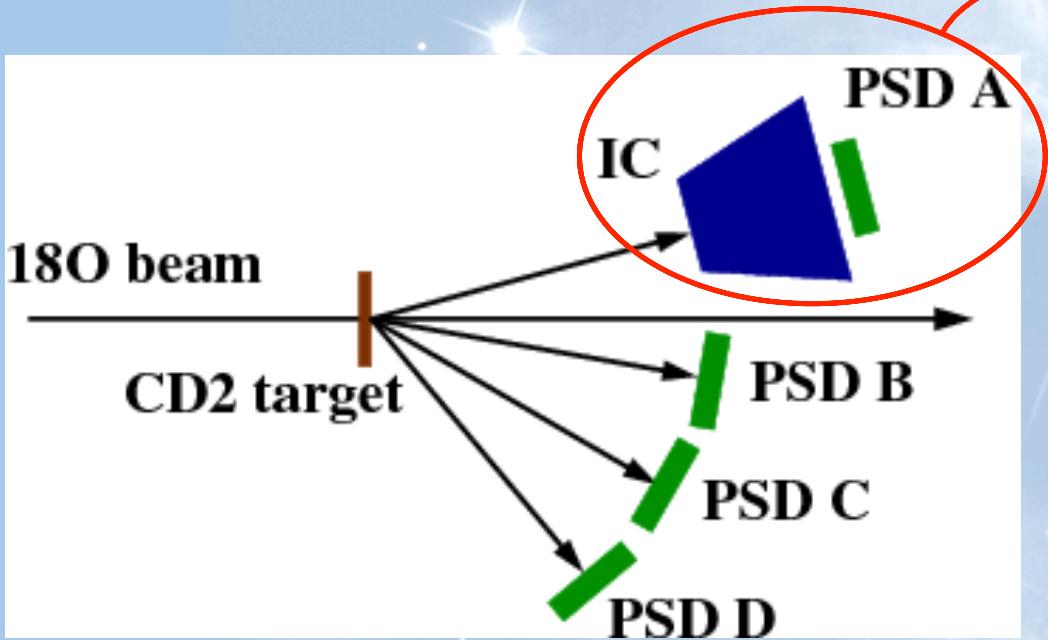
In the THM approach:

$$(\omega\gamma)_i = \frac{1}{2\pi}\omega_i N_i \frac{\Gamma_{(p^{18}\mathrm{O})_i}}{|M_i|^2}$$

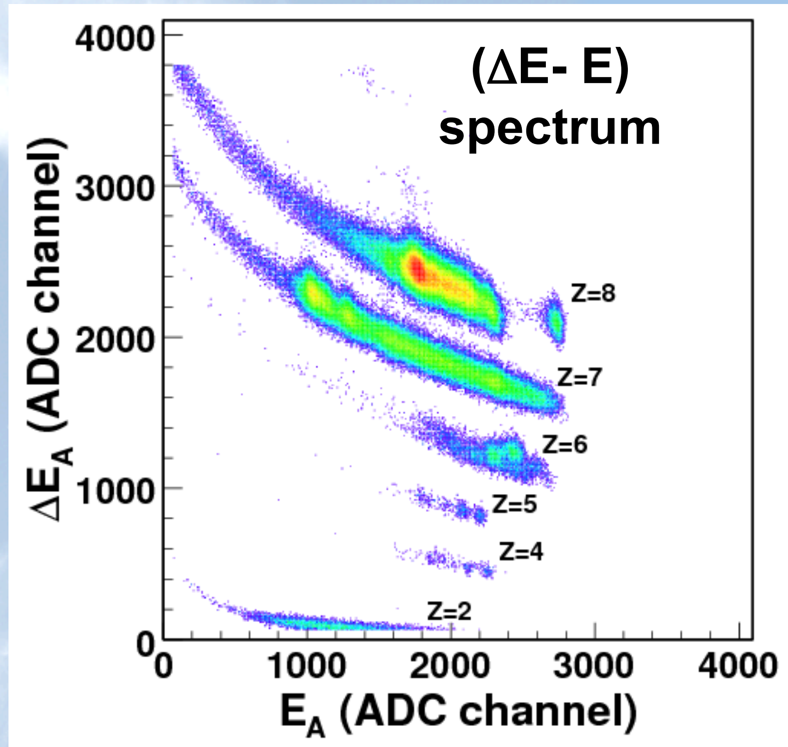
Where:
- $\omega_I = \hat{J}_i / \hat{J}_p \hat{J}_{18O}$ statistical factor
- N_i = THM resonance strength
- M_i = transfer amplitude

Advantages:
- possibility to measure down to zero energy
- No electron screening
- No spectroscopic factors in the $\Gamma_{(p18O)} / |M_i|^2$ ratio

The 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 $^{2}H(^{18}O,\alpha^{15}N)n$ reaction
Detectors placed at the QF angles

the three-body process (THM reaction) is:
$^{2}H(^{18}O,\alpha^{15}N)n$
@ E_{beam}= 54 MeV

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

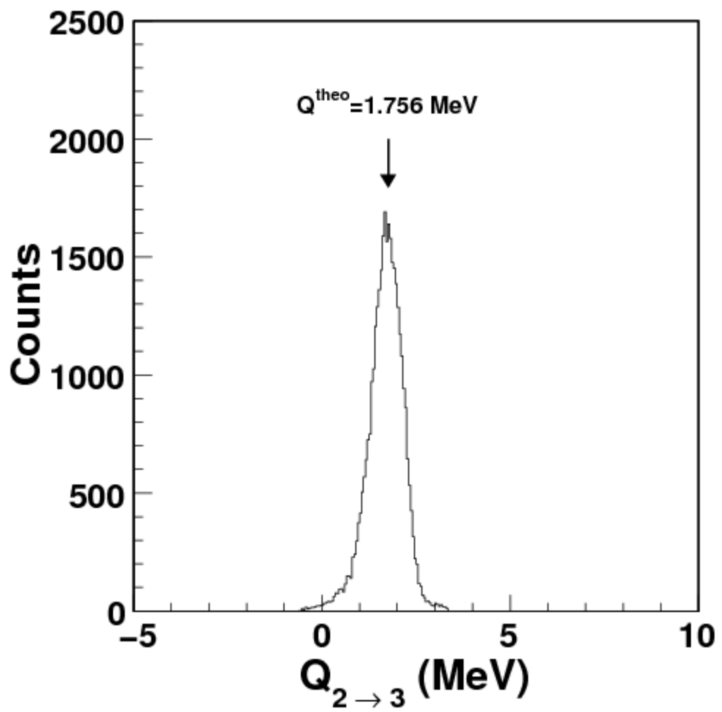
Data analysis I

Selection of the channel $^{15}N+\alpha+n$

Study of the **kinematics** of the three-body reaction

Selection of the THM reaction mechanism

Study of the **dynamics** of the three-body reaction



Comparison of the experimental Q-value spectrum and the theoretical one for the $^{18}O+d \rightarrow {}^{15}N+\alpha+n$ 2→3 process

Single peak → a single reaction is contributing

Good agreement → accurate calibrations

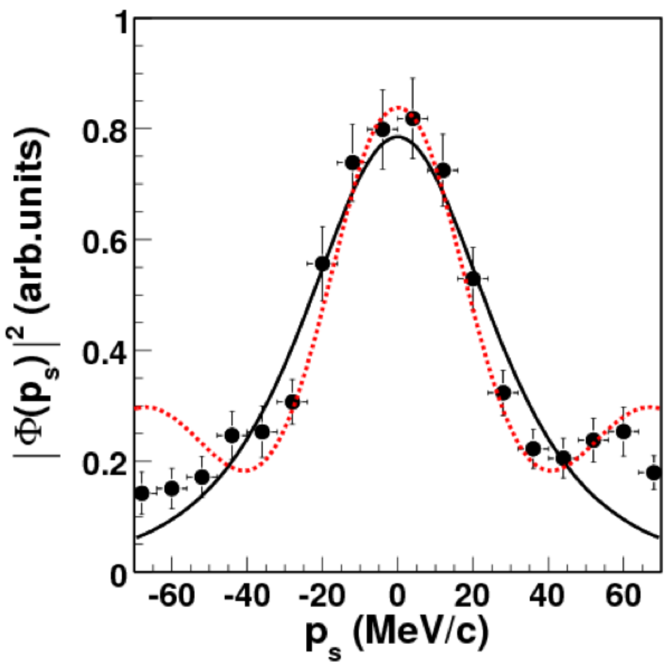
Data analysis II

Selection of the channel $^{15}N+\alpha+n$

Study of the kinematics of the three-body reaction

Selection of the THM reaction mechanism

Study of the dynamics of the three-body reaction



Deuteron Breakup → direct process

The momentum distribution should keep the same shape as inside deuteron if THM reaction

$$\varphi_a(\mathbf{p}_{sx}) = \frac{1}{\pi}\sqrt{\frac{ab(a+b)}{(a-b)^2}}\left[\frac{1}{a^2+p_{sx}^2} - \frac{1}{b^2+p_{sx}^2}\right]$$

Good agreement inside a 50 MeV/c momentum window

Data analysis II

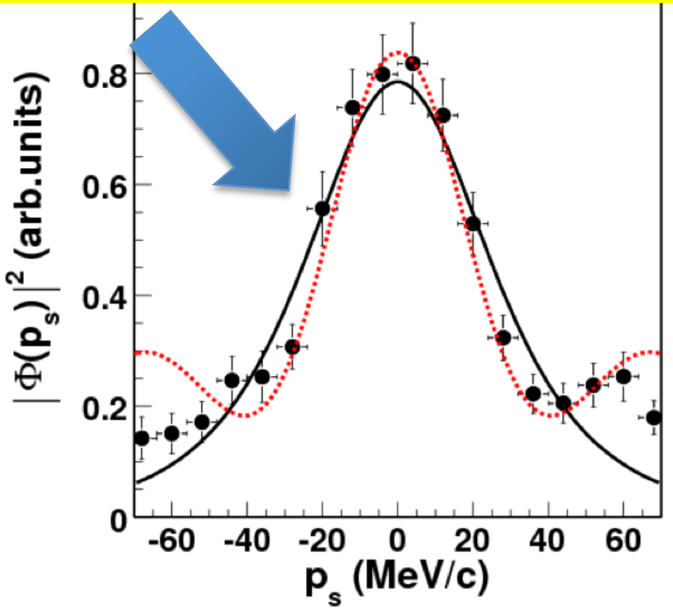
Selection of the channel $^{15}N+\alpha+n$

Study of the kinematics of the three-body reaction

Selection of the THM reaction mechanism

Study of the dynamics of the three-body reaction

DWBA momentum distribution (potential parameters from Perey & Perey) Distortions negligible below 50 MeV/c



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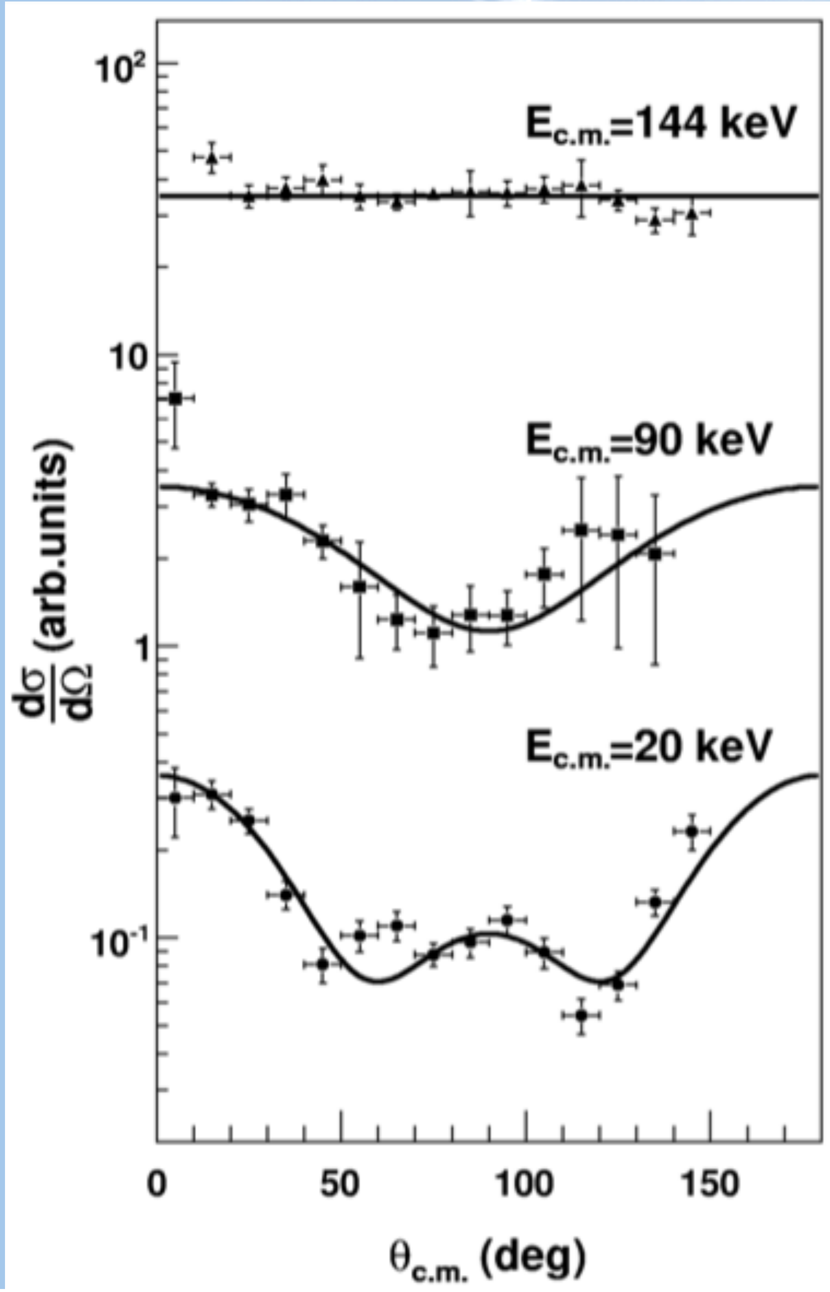
Good agreement inside a 50 MeV/c momentum window

Results – spin and parity assignment



Extraction of the angular distributions:

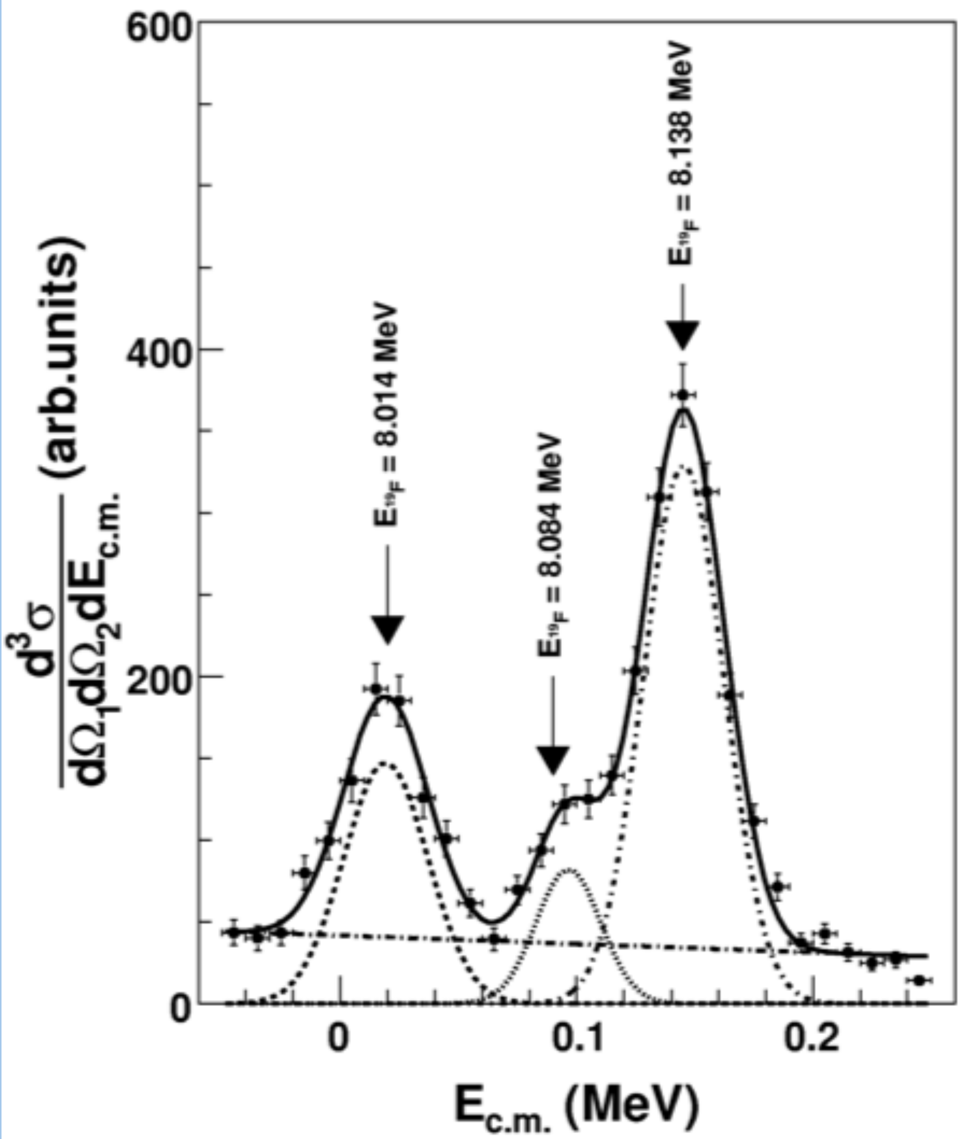
$$\theta_{c.m.} = \arccos\frac{(\mathbf{v_p}-\mathbf{v_t})\cdot(\mathbf{v_C}-\mathbf{v_\alpha})}{|\mathbf{v_p}-\mathbf{v_t}||\mathbf{v_C}-\mathbf{v_\alpha}|}$$

Assignment of spin and parity of the resonances is obtained by fitting the angular distribution with the formula

$$\frac{d\sigma}{d\Omega_{c.m.}} = \frac{d\sigma}{d\Omega_{c.m.}}(90^\circ)\left(1 + A_2(E)\cos^2\theta + A_4(E)\cos^4\theta + \ldots + A_{2L}(E)\cos^{2L}\theta\right)$$

144 keV → $1/2^+$ (isotropic angular distributions, L=0)
90 keV → $3/2^+$ (L=1)
20 keV → $5/2^+$ (L=2)
20 keV and 144 keV assignments in agreement with literature
90 keV → first time assignment

Extraction of the resonance strength



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

The energies and the ωγ 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

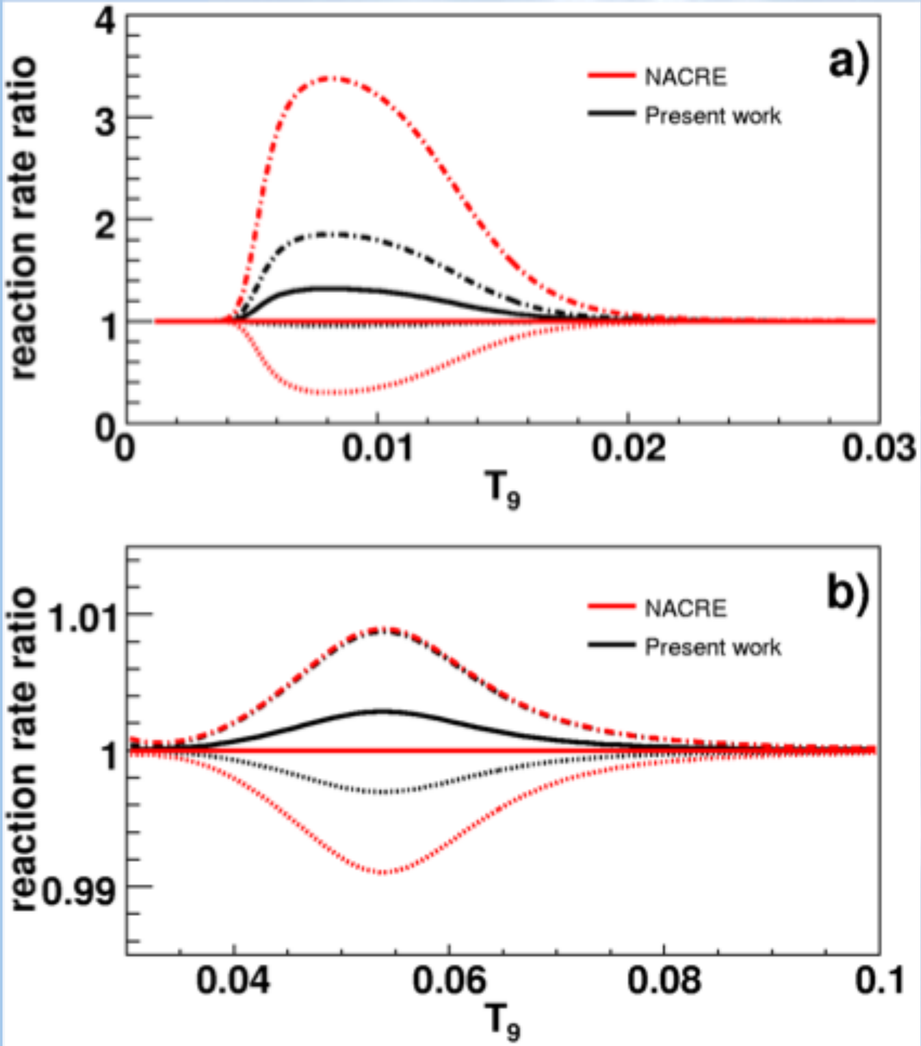
$$(\omega\gamma)_i = \frac{\omega_i}{\omega_3}\frac{\Gamma_{p_i}(E_{R_i})}{|M_i(E_{R_i})|^2}\frac{|M_3(E_{R_3})|^2}{\Gamma_{p_3}(E_{R_3})}\frac{N_i}{N_3}(\omega\gamma)_3$$

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

Results and discussion

The contribution to the reaction rate of each resonance is given by:

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



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

If T9 < 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**)

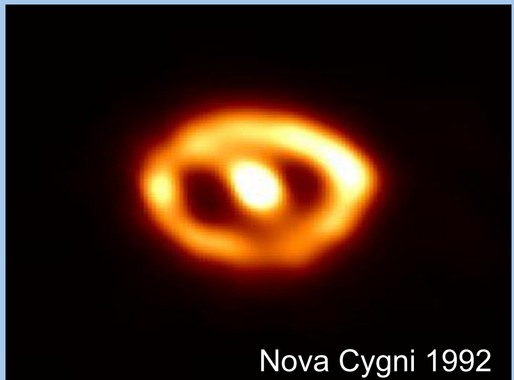
Astrophysical consequences...

…Work in progress!!!

The $^{17}O(p,\alpha)^{14}N$ Reaction in Astrophysics

The $^{17}O(p,\alpha)^{14}N$ reaction is crucial in two fields:

1. **Novae explosive nucleosynthesis**
2. **Oxygen isotopic ratios in presolar grains**

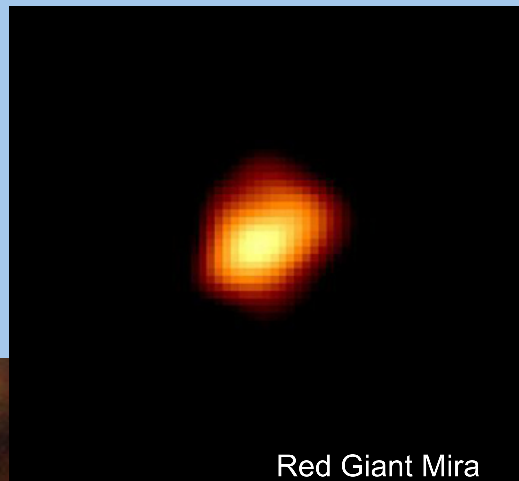

Nova Cygni 1992

1. In novae, ^{17}O is produced in one of the two paths of CNO cycles leading to ^{18}F production which is of special interest for gamma ray astronomy.

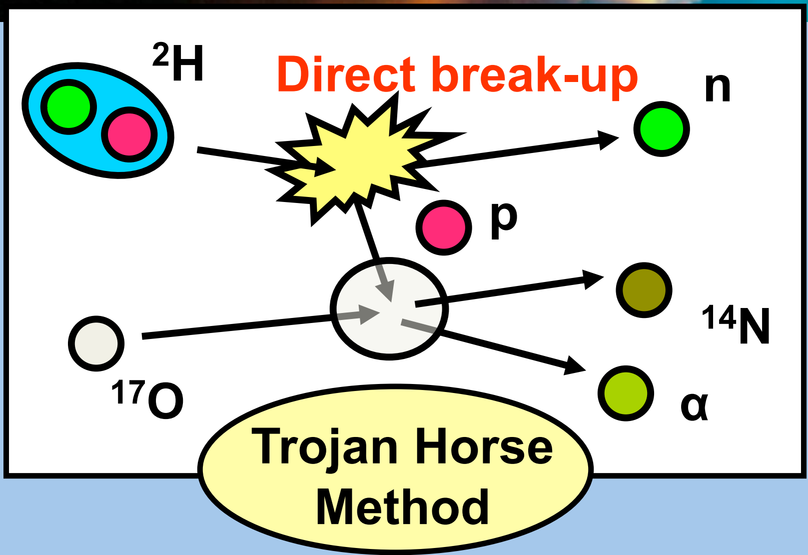
→ **γ-ray line fluxes measurement would shed light into the physical processes that occur in the early phases of the explosion.**

2. The relative abundances of the oxygen isotopes have been observed at the surface of some Red Giant (RG) stars and in meteorite grains formed in their coldest layers

→ **The change in the surface composition offers an opportunity to probe the "history" of the stellar interior.**


Red Giant Mira

The $^{17}O(p,\alpha)^{14}N$ experimental setup

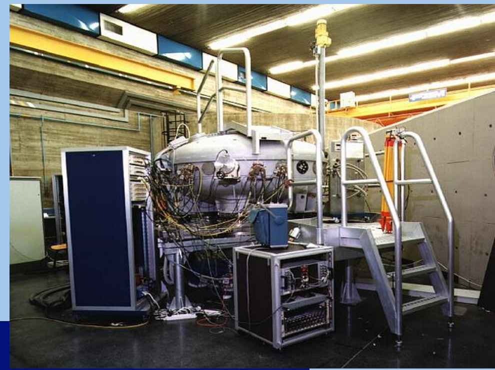


$^{17}O+d \rightarrow {}^{14}N + \alpha$

+n

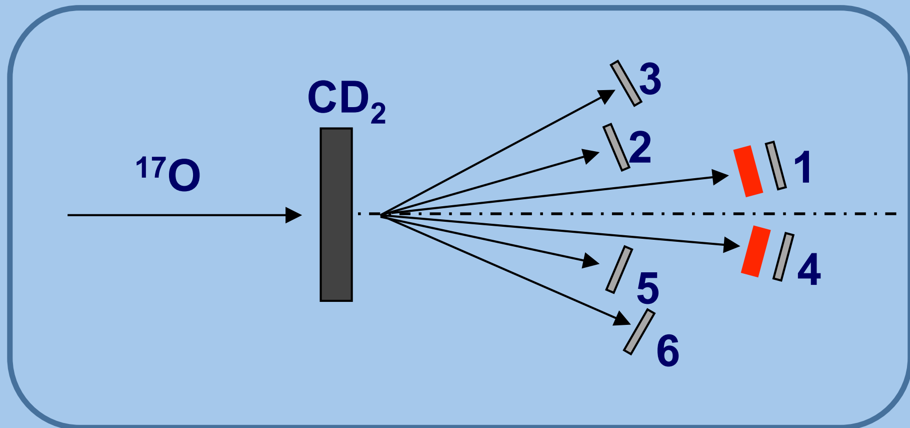
$^{17}O+p \rightarrow {}^{14}N + \alpha$

L.N.S - Catania



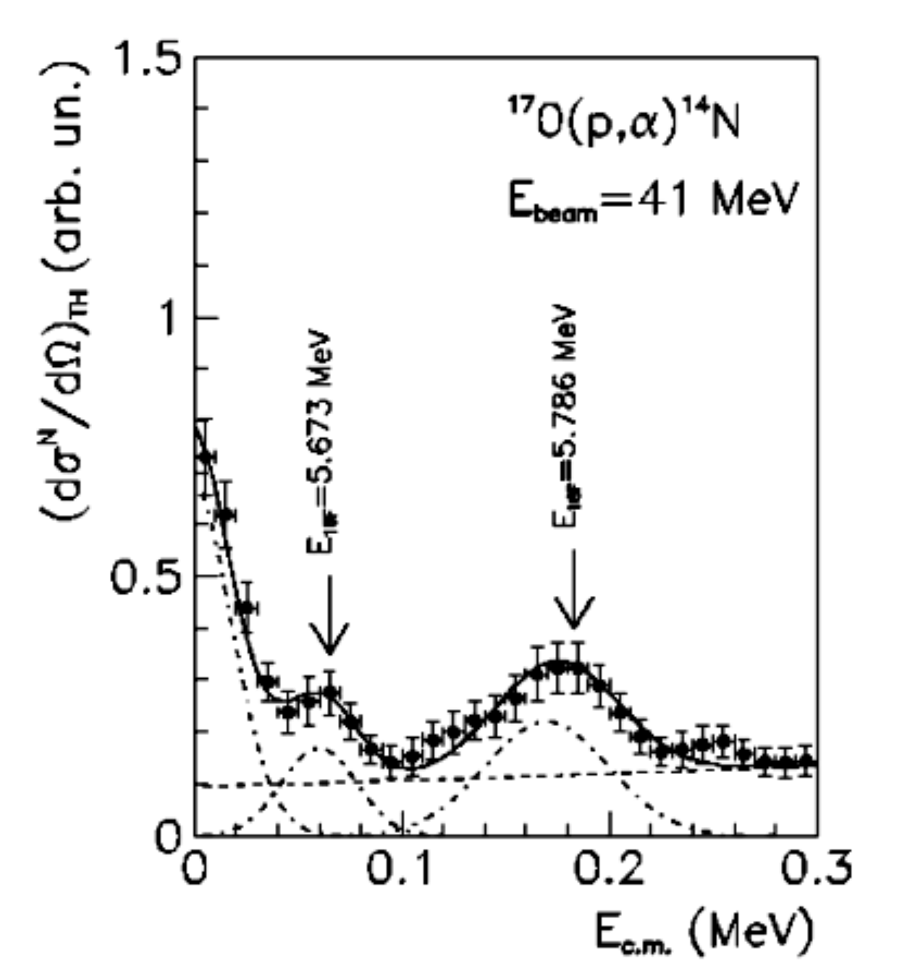
E_{beam} = 41 MeV
Target thickness ~ 150 μg/cm^2

Detectors	Thicknes s [μm]	θ [deg]	r [mm]	Δθ [deg]
PSD1	500	8.0 ± 0.1	470	5.1
PSD2	500	17.4 ± 0.1	372	7.7
PSD3	500	27.8 ± 0.1	392	6.8
PSD4	500	8.0 ± 0.1	470	5.1
PSD5	500	17.4 ± 0.1	372	7.7
PSD6	500	27.8 ± 0.1	392	6.8



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

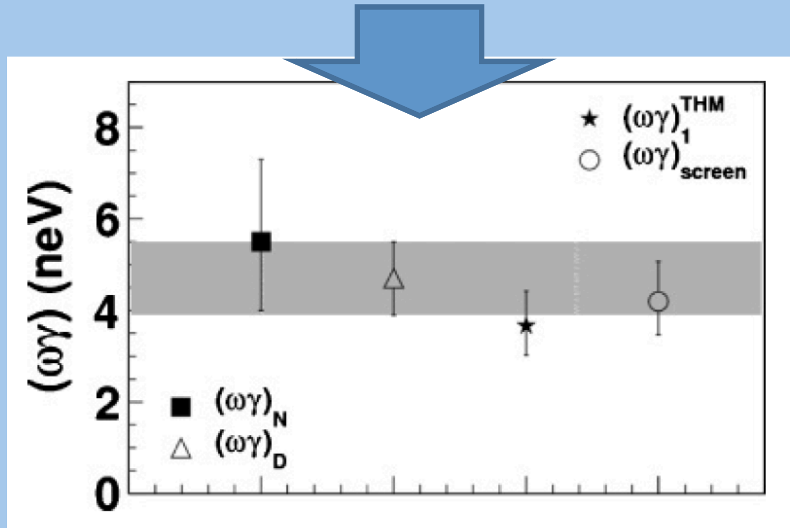
The $^{17}O(p,\alpha)^{14}N$: results



Extraction of:

✓ **Resonance energies: E_{R1}=65±5 keV and E_{R2}=183±5 keV.**

✓ **Peak value of the two resonances: N_1=0.170±0.025 and N_2=0.220±0.031, used to derive the resonance strengths ωγ (case of narrow resonances).**



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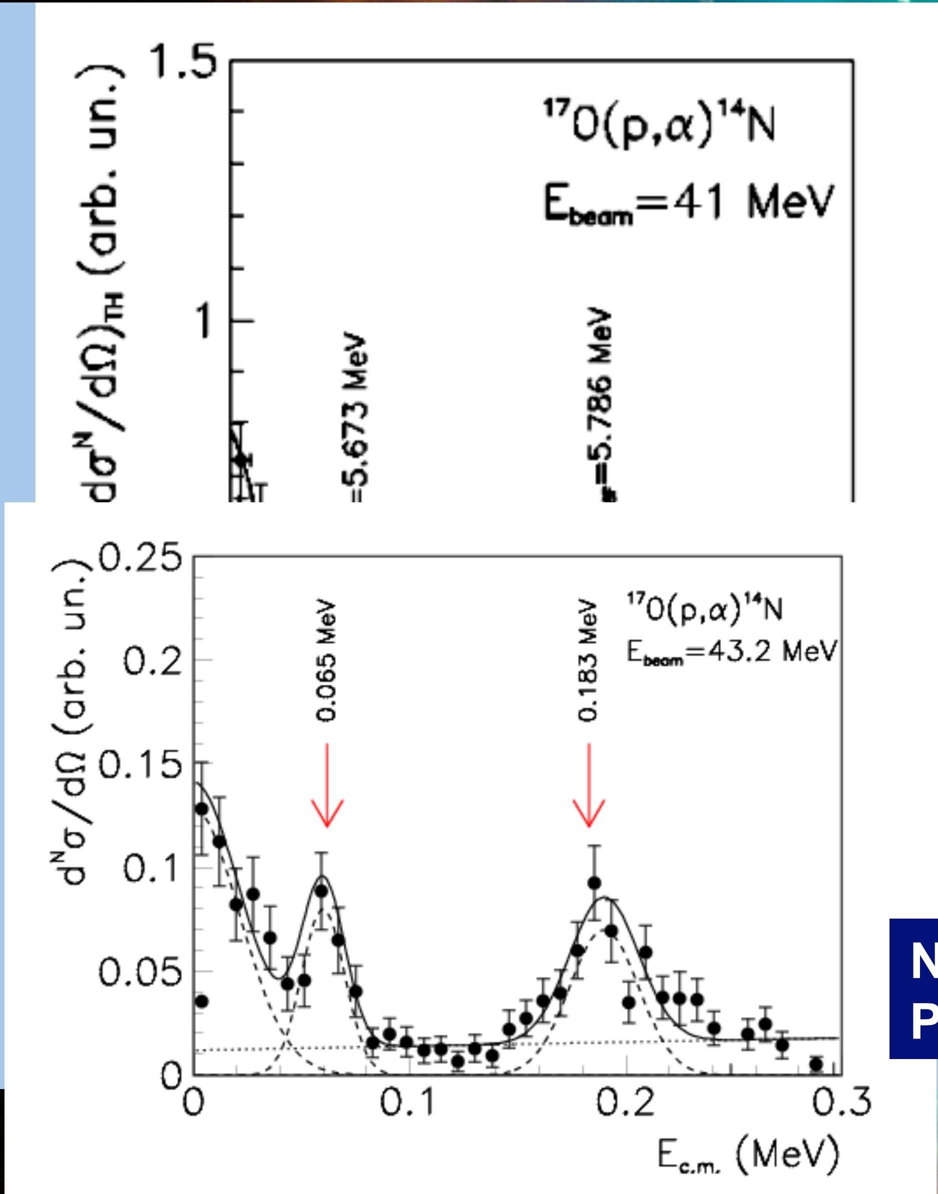

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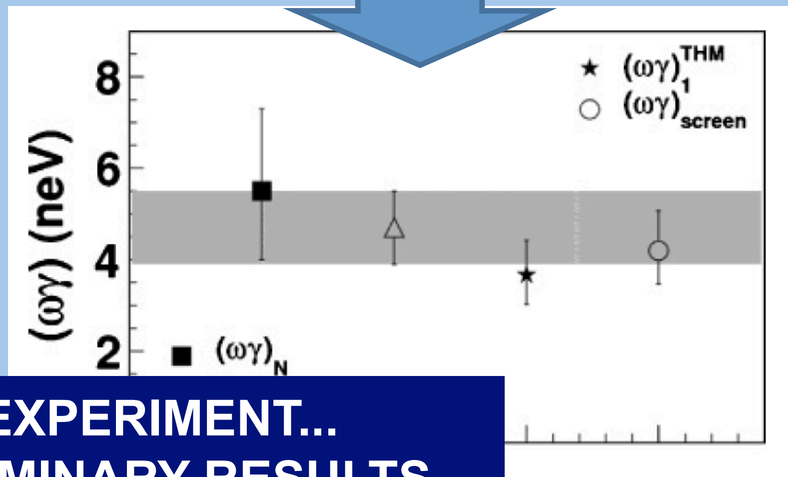

NEW EXPERIMENT...
PRELIMINARY RESULTS

PHYSICAL REVIEW C **82**, 032801(R) (2010)

New high accuracy measurement of the $^{17}O(p,\alpha)^{14}N$ reaction rate at astrophysical temperatures

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(Received 17 February 2010; published 8 September 2010)

The $^{17}O(p,\alpha)^{14}N$ reaction is of fundamental relevance in several astrophysical scenarios, such as novae, asymptotic giant branch nucleosynthesis, and γ-ray astronomy. We report on the indirect measurement of the $^{17}O(p,\alpha)^{14}N$ reaction bare-nucleus cross section in the low-energy region. In particular, the two resonances at $E_R^{c.m.} = 65$ keV and $E_R^{c.m.} = 183$ keV, which dominate the reaction rate inside the Gamow window, have been observed, and the strength of the 65 keV resonance has been deduced. The reaction rate determination and the comparison with the results of the previous measurements are also discussed.

PRL 101, 152501 (2008) PHYSICAL REVIEW LETTERS week ending 10 OCTOBER 2008

Measurement of the 20 and 90 keV Resonances in the $^{18}O(p,\alpha)^{15}N$ Reaction via the Trojan Horse Method

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(Received 13 June 2008; published 7 October 2008)

The $^{18}O(p,\alpha)^{15}N$ reaction is of primary importance in several astrophysical scenarios, including fluorine nucleosynthesis inside asymptotic giant branch stars as well as oxygen and nitrogen isotopic ratios in meteorite grains. Thus the indirect measurement of the low energy region of the $^{18}O(p,\alpha)^{15}N$ reaction has been performed to reduce the nuclear uncertainty on theoretical predictions. In particular the strength of the 20 and 90 keV resonances has been deduced and the change in the reaction rate evaluated.

Direct and indirect measurements

Direct measurements:

Straightforward but complicated

✓ **Coulomb barrier exponentially suppresses the cross section**

→ **low count rate and low statistics**

→ **high background and poor signal-to-noise ratio**

→ **no access to the low energy region**

✓ **Straggling**

→ **possible errors in energy calibration**

→ **poor energy and angular resolution**

✓ **Electron screening**

→ **trend of the bare-nucleus S-factor altered**

→ **systematic error due to poor knowledge of the process**

... even in the few cases when the low-energy S-factor has been measured the bare-nucleus S-factor has not being determined accurately

Direct and 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

But...

Nuclear reaction theory required

→ **cross checks of the methods needed**

→ **possible spurious contribution**

... Indirect techniques are complementary to direct measurements

Examples: Coulomb dissociation, ANC and Trojan horse method