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Study of $^{17}O(p,\alpha)^{14}N$ reaction via the Trojan Horse Method for application to ^{17}O Nucleosynthesis

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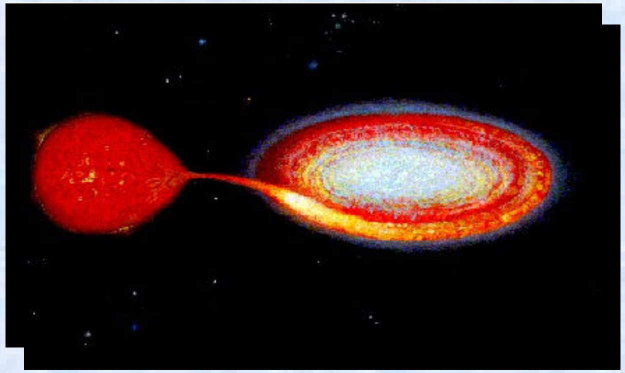
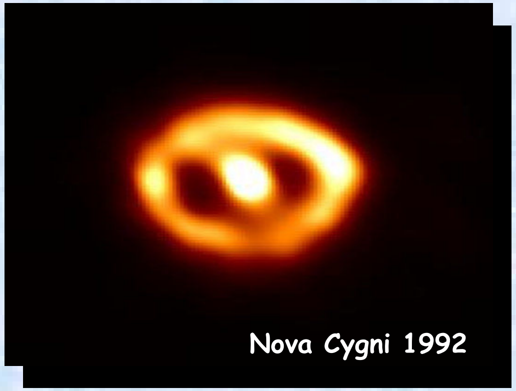
Role of ^{17}O: astrophysical scenarios

1) It is one of the very few isotopes whose nucleosynthetic origin can be attributed to Novae, stellar explosion occurring in close binary system that contain White Dwarf (WD) as a compact object and a companion star.



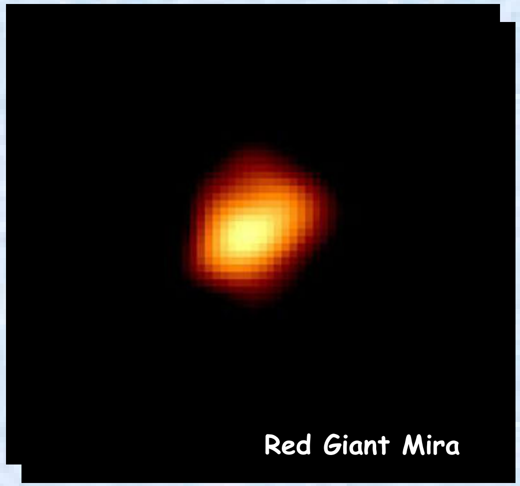


In novae, ^{17}O is produced in one of the two paths of CNO cycles leading to ^{18}F production which is of special interest for gamma ray astronomy.

→ 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.

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



^{17}O production & destruction

In nova ^{17}O is produced starting with the ^{16}O isotope found at the surface of the WD progenitor.

^{16}O nuclei can be processed in a two different competing cycles:

CNO2 cycle

$^{16}O(p,\gamma)^{17}F(\beta+)^{17}O(p,\alpha)^{14}N(p,\gamma)^{15}O(\beta+)^{15}N(p,\gamma)^{16}O$

HCNO2 cycle

$^{16}O(p,\gamma)^{17}F(\beta+)^{17}O(p,\gamma)^{18}F(p,\alpha)^{15}O(\beta+)^{15}N(p,\gamma)^{16}O$

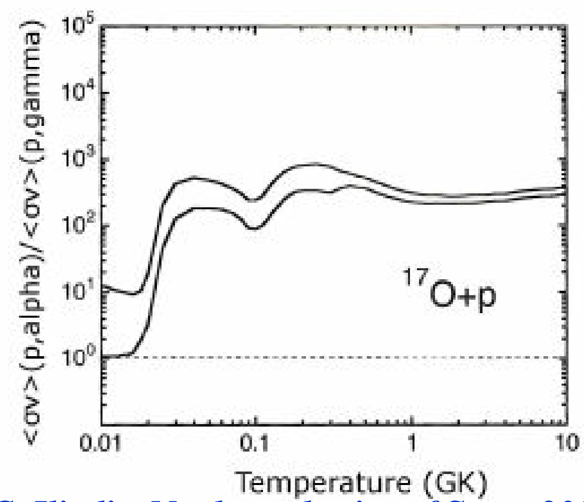
Production:

$^{16}O(p,\gamma)^{17}F$: reaction rate well known in literature (NACRE)

Destruction:

$^{17}O(p,\gamma)^{18}F$: important for ^{18}F production in novae

$^{17}O(p,\alpha)^{14}N$: dominant channel for ^{17}O destruction



C. Iliadis, Nuclear physics of Stars, 2007

Stellar temperatures of primary importance for nucleosynthesis:

T=0.01-0.1 GK for red giant, AGB, and massive stars;

T=0.01- 0.4 GK for classical nova explosion (peak temperatures of 0.35 GK can be easily achieved in explosion hosting very massive white dwarfs.)

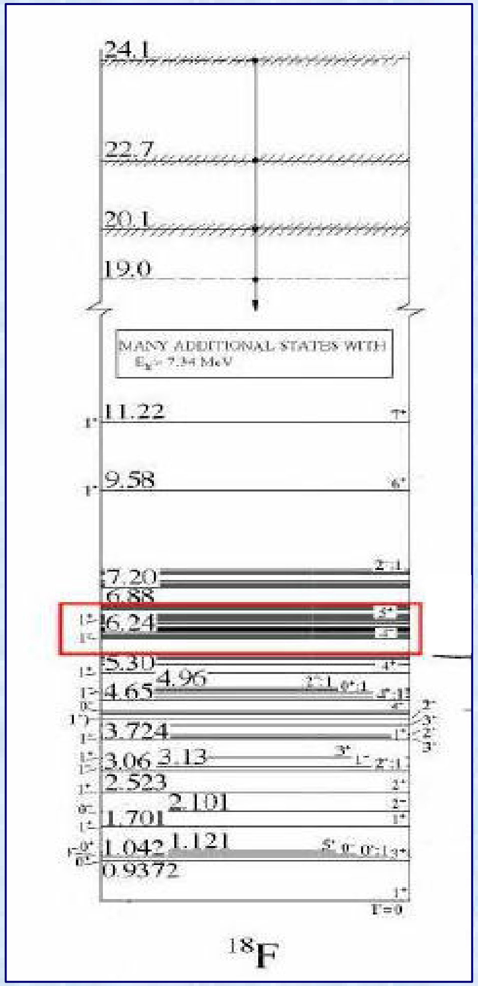
Energetic Region of astrophysical interest for the $^{17}O(p,\alpha)^{14}N$ reaction

T=0.01-0.4 GK: $^{17}O(p,\alpha)^{14}N$ and $^{17}O(p,\gamma)^{18}F$ reaction cross section have 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.



Two sub-threshold levels at

$E_X(J^{\pi})$=5.605 MeV (1^{-}) and $E_X(J^{\pi})$=5.603 MeV (1^{+})

could also play a significant role in the reaction rate through the high-energy tail of the levels.

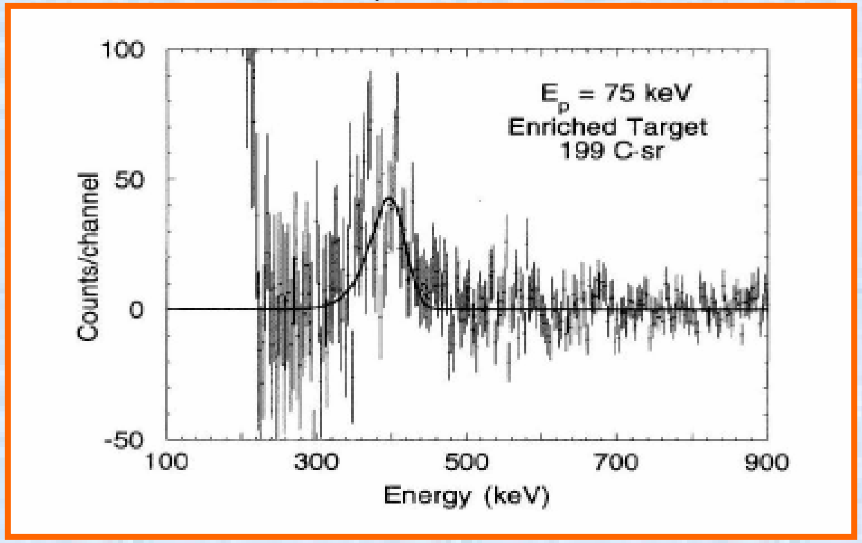
Possible interference effects between 5.673 MeV level and 5.605 MeV level

Status of the Art

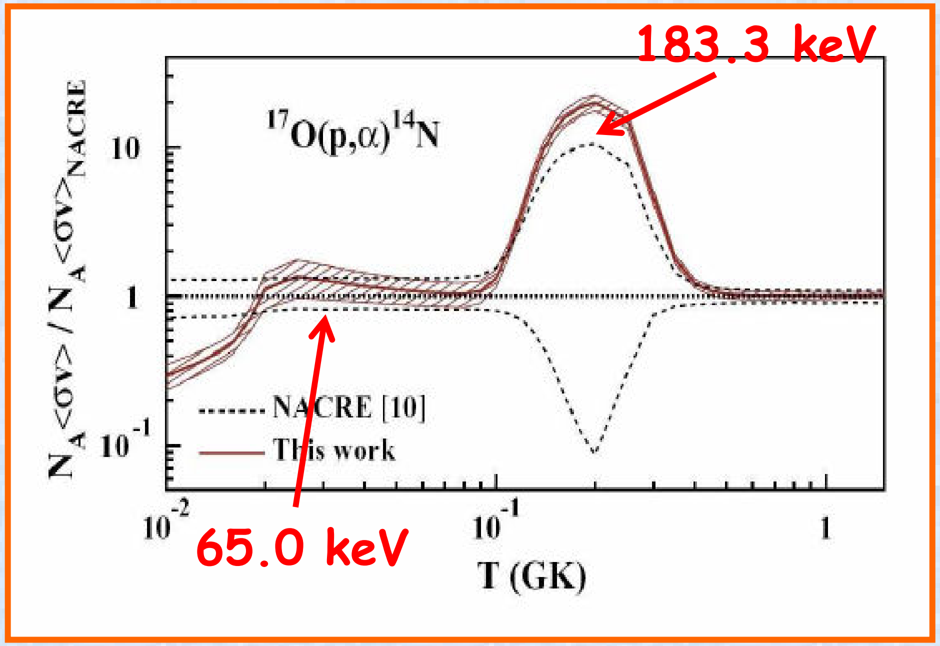
In the last years several efforts to measure the cross section for the $^{17}O(p,\alpha)^{14}N$ at astrophysical energies were made in order to reduce the indetermination on reaction rate.

J.C. Blackmon et al., Phys. Rev. Lett. 74, 2642, (1995)

The first direct measurement of the $^{17}O(p,\alpha)^{14}N$ at low energy →



LARGE UNCERTAINTIES !!



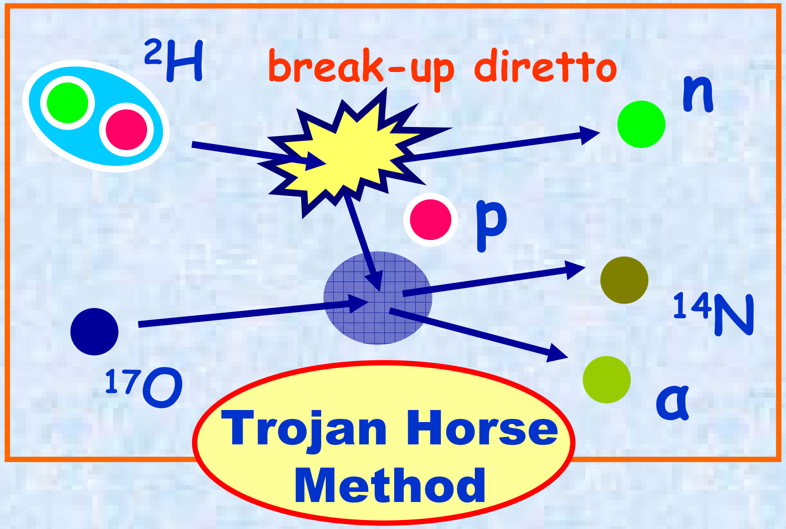
A. Chafa et al., Phys. Rev. C 75, 035810, (2007)

To reduce the uncertainties

↓

INDIRECT MEASUREMENT

Experimental Set-up

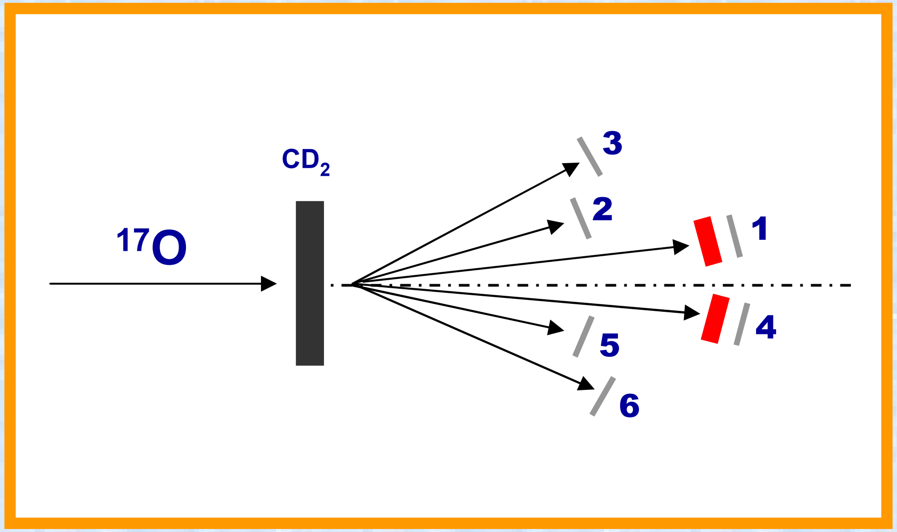


$^{17}O + d \longrightarrow {}^{14}N + \alpha + n$

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

L.N.S - Catania

Detectors	Thickness [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



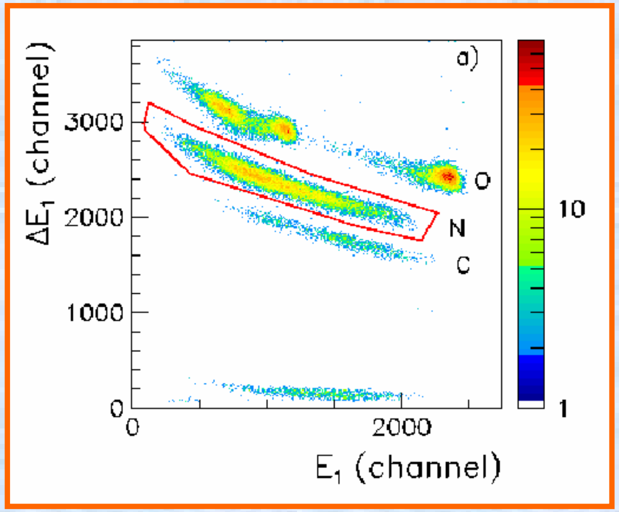
Two ionization chambers filled with 60 mbar of isobuthan gas as ΔE detector were in front of PSD1 and PSD4 detector

E_{beam} = 41 MeV

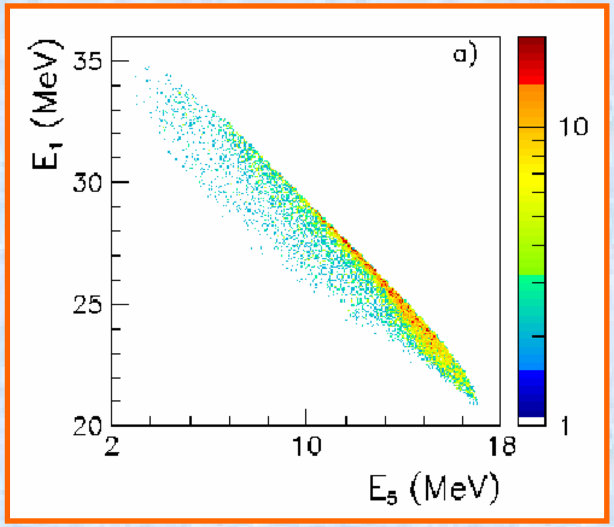
Target Thickness ~ 150 μg/cm2

Selection of the $^{2}H(^{17}O, \alpha^{14}N)n$ reaction channel

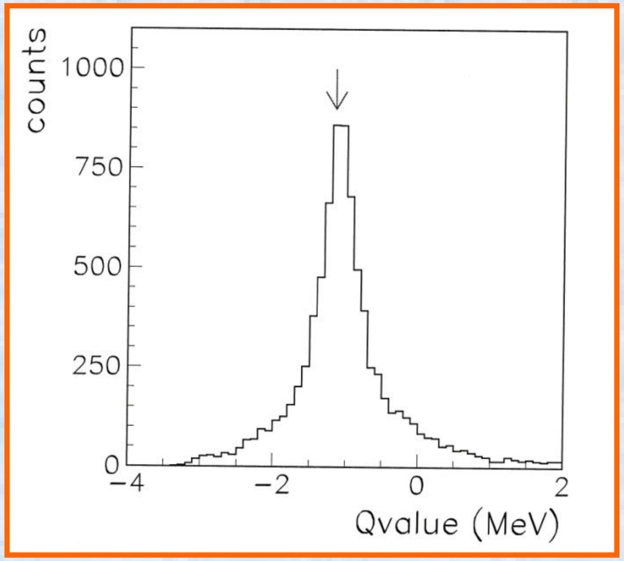
✓ N particles were selected with the standard ΔE-E technique in both telescopes 1 and 4



✓ The loci events in E_1 vs E_5 and E_4 vs E_2 for the $^{2}H(^{17}O, \alpha^{14}N)n$ reaction were deduced



Good agreement with the theoretical value -1.033 MeV



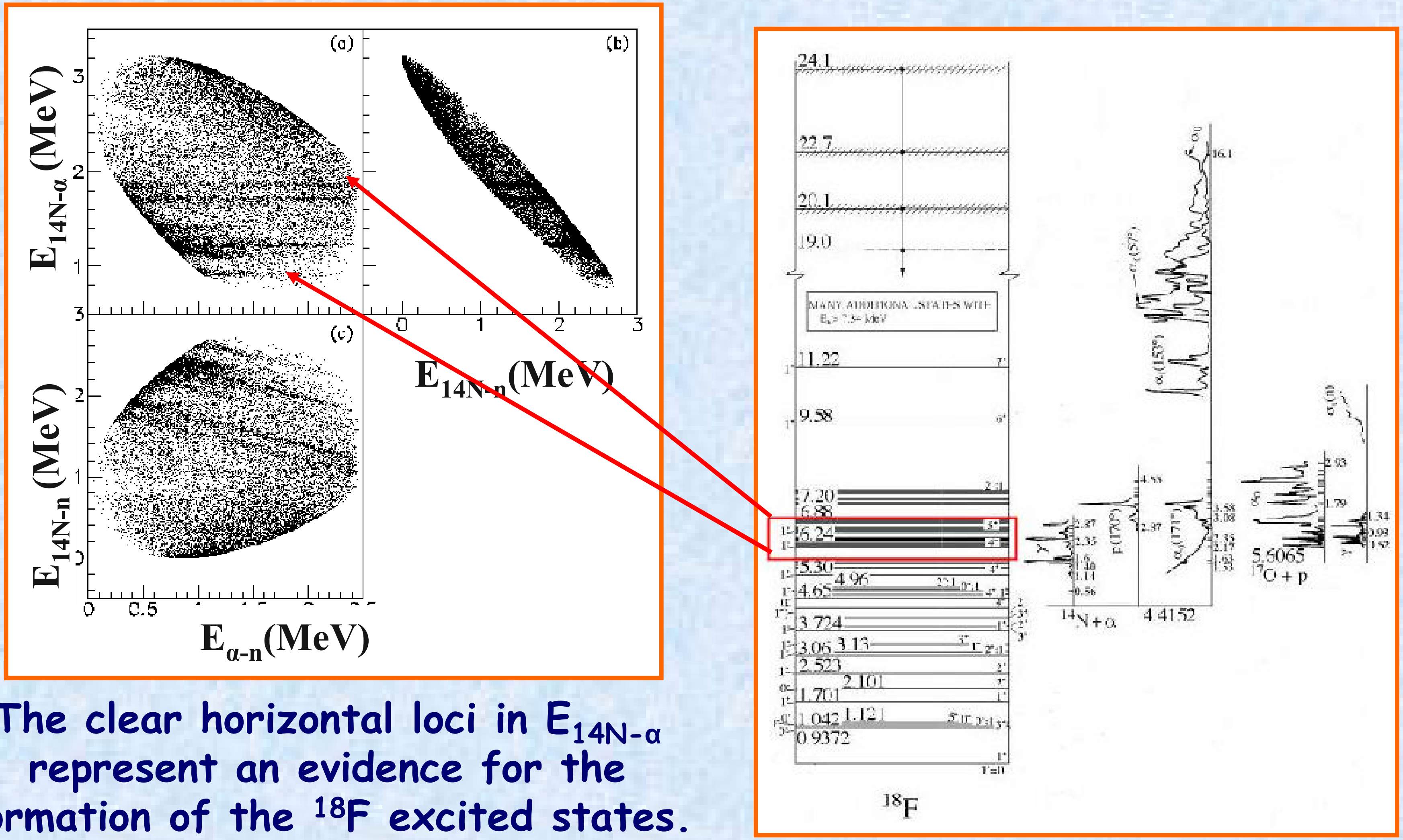
✓ Good detector calibration procedure!!

✓ Good reaction channel selection!!

Study of the presence of SD mechanism

The $^{14}N+\alpha+n$ exit channel can be fed through different reaction mechanism: Sequential Decay (SD) or Quasi-Free mechanism (QF).

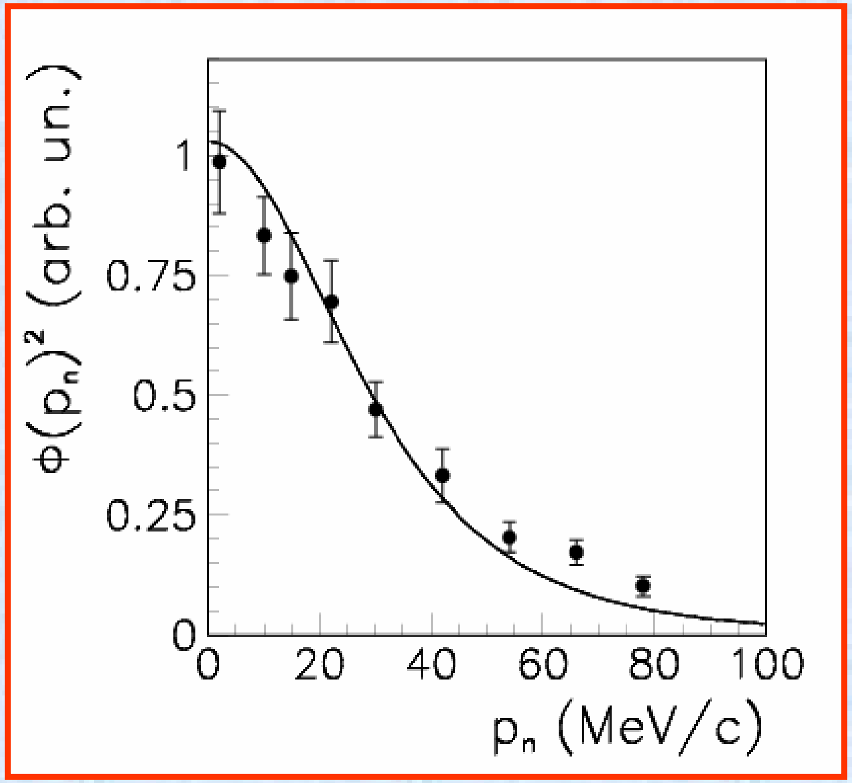
Study of relative energy spectra:



The clear horizontal loci in $E_{14N-\alpha}$ represent an evidence for the formation of the ^{18}F excited states.

Selection of the Quasi-Free mechanism: experimental momentum distribution

An observable which turns out to be more sensitive to the reaction mechanism is the shape of the experimental momentum distribution



In a energy windows of 100 keV $d\sigma/d\Omega$~const. ⇒ dividing the resulting three-body coincidence yield by the kinematic factor, the p-n momentum distribution in arbitrary units is obtained

$$|\Phi(k_s)|^2 \propto \frac{d^3\sigma}{dE_c d\Omega_c d\Omega_c} \Big/ (KF)$$

The extracted experimental momentum distribution is compared with the theoretical one, given by the Hulthén wave function in momentum space:

$$|\phi(k_S)|^2 = \frac{1}{2\pi}\sqrt{\frac{ab(a+b)}{(a-b)^2}}\left[\frac{1}{a^2+p_s^2} - \frac{1}{b^2+p_s^2}\right]$$

N: normalization parameter

$a=0.2317\ fm^{-1}$

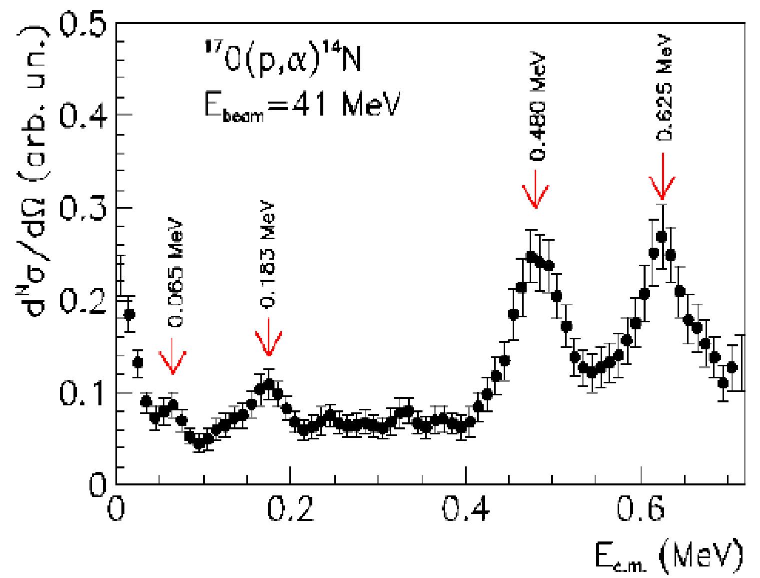
$b=1.202\ fm^{-1}$

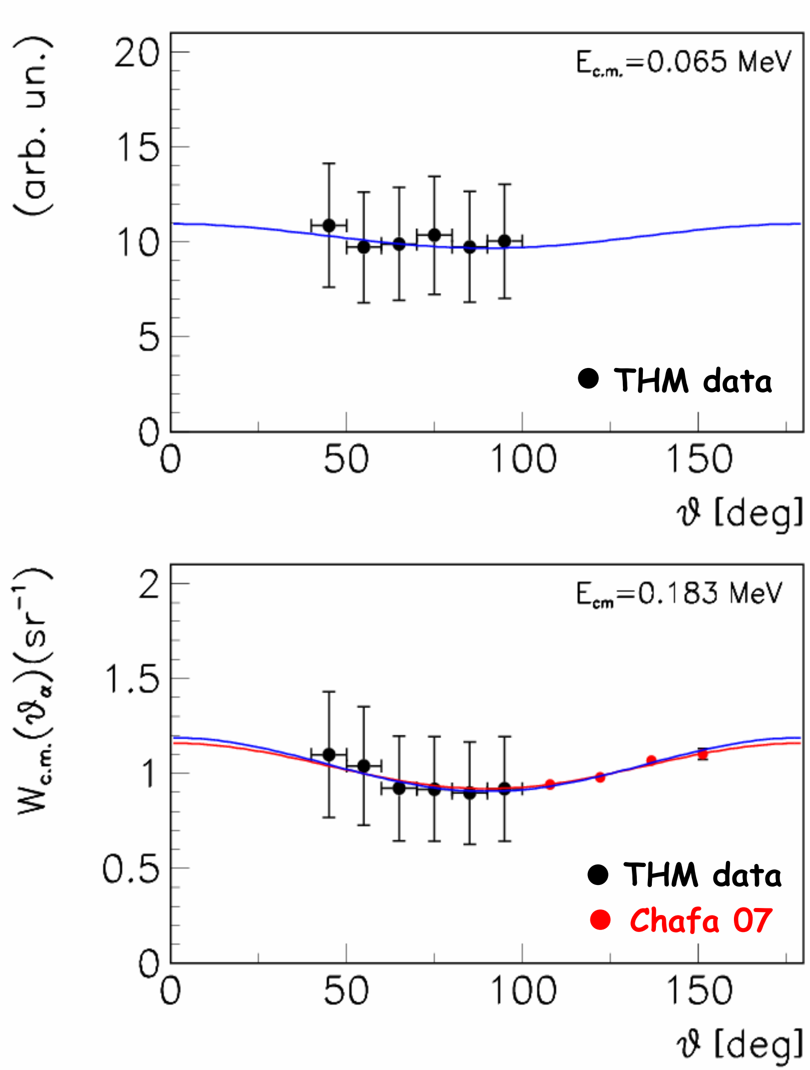
$|P_n| < 30$ MeV/c

$^{17}O(p,\alpha)^{14}N$ cross section & angular distributions

Extraction of nuclear part of the two body cross section by using the PWIA approach

$$\frac{d\sigma^N}{d\Omega} \propto \frac{\dfrac{d^3\sigma}{d\Omega_\alpha \, d\Omega_{14N} dE_{cm}}}{KF \cdot |\Phi(\overrightarrow{Ps})|^2}$$



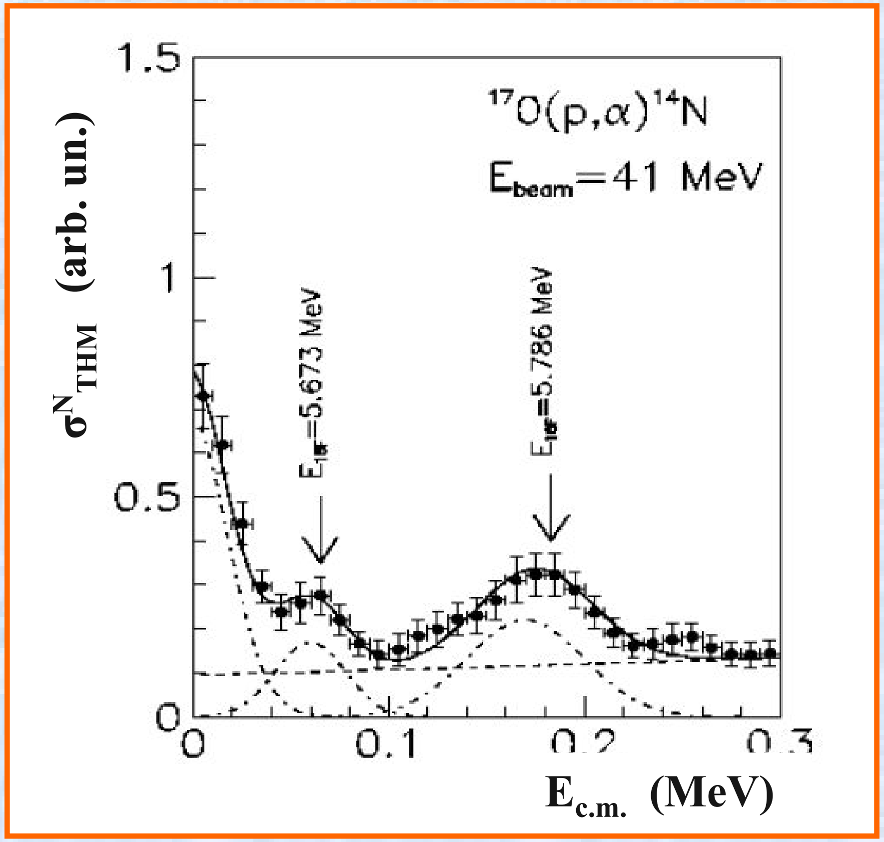


— Theoretical calculation based on Blatt (1952) theory

— Legendre polinomyal fit of direct data reported in Chafa et al., 2007 $W_{c.m.}(\theta_{c.m.})=a_1+a_2P_2(\cos\theta_{c.m.})$

Trojan Horse Cross section

The extracted two-body differential cross section has been integrated in the whole angular range, assuming that in the region where no experimental angular distribution are available, their trend is given by the fit of the obtained experimental angular distribution.



Trojan Horse cross section: horizontal error bar refers to the integration bin while the vertical one arise for the statistics (~25%)

In order to separate the different contributions on this cross section, a fit of the nuclear cross section has been performed.

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).

Reaction rate determination

KEY PARAMETER:

$$\omega\gamma = \frac{2J_{C^*}+1}{(2J_a+1)(2J_X+1)}(1+\delta_{aX})\frac{\Gamma_1\Gamma_2}{\Gamma}$$

STRENGTH OF THE RESONANCE:

We focussed on the 0-0.3 MeV energy region and in particular on both $E_{c.m.}$=65 keV and $E_{c.m.}$=183 keV, obtaining the strength of the resonance at $E_{c.m.}$=65 keV by using the available information in literature on the well measured $E_{c.m.}$=183 keV resonance.

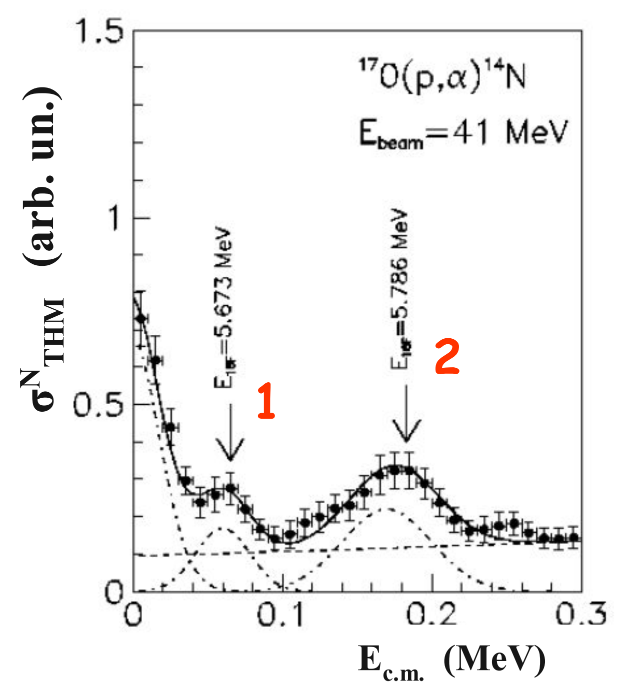
The strength of the resonance at 65 keV is given from the ratio between the peak value N_1 and N_2 through the relation:

New approach

$$(\omega\gamma)_1 = \frac{\omega_1}{\omega_2}\frac{\Gamma_{p_1}(E_{R_1})}{\Gamma_{p_2}(E_{R_2})}\frac{|M_2(E_{R_2})|^2}{|M_1(E_{R_1})|^2}\frac{N_1}{N_2}(\omega\gamma)_2$$

La Cognata et al., PRL 101, 152501, (2008)

where $M_i(E)$ is the direct transfer reaction amplitude for the binary reaction $^{17}O+d \rightarrow {}^{18}F^*+s$ populating the resonant state $^{18}F^*$ with the resonance energy E_{Ri};



Reaction rate determination II

ωγ RESULTS:

$(\omega\gamma)_1$ (eV) (Present work)	$(\omega\gamma)_2$ (eV)	$(\omega\gamma)_2$ (reference)
$(4.4\pm 1.1)\times 10^{-9}$	$(1.6\pm 0.2)\times 10^{-3}$	[Chafa07]
$(4.67\pm 1.04)\times 10^{-9}$	$(1.70\pm 0.15)\times 10^{-3}$	[Moazen07]

NACRE: C. Angulo et al., Nucl. Phys. A 656, 3-183 (1999)

Moazen'07: B.H. Moazen et al., Phys. Rev. C 75, 065801, (2007)

This two values are in agreement

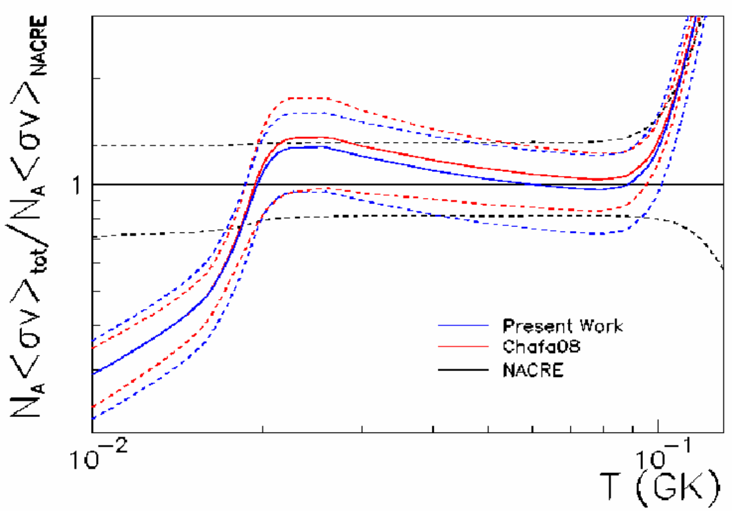
✓ each other;

✓ with the value $5.5^{+1.8}_{-1.0}\cdot 10^{-9}$ eV adopted in NACRE;

✓ with the $(4.7\pm0.8)\cdot 10^{-9}$ eV calculated by using the value of Γ_α and Γ_p reported in Chafa'07.

TOTAL REACTION RATE:

$$N_A\langle\sigma v\rangle^{THM}_{tot} = N_A\langle\sigma v\rangle^{Chafa'07}_{tot} - N_A\langle\sigma v\rangle^{Chafa'07}_{65keV} + N_A\langle\sigma v\rangle^{THM}_{65keV}$$



Ratio of the THM reaction rate to the NACRE one (blu line).

The THM reaction rate was calculated by considering the value of $\omega\gamma=(4.4\pm1.1)\times10^{-9}$ eV for the 65 keV resonance.

Ratio between the reaction rate evaluated by Chafa'07 and NACRE.

NACRE adopted reaction rate.

Reaction rate determination II

ωγ RESULTS:

$(\omega\gamma)_1$ (eV) (Present work)	$(\omega\gamma)_2$ (eV)	$(\omega\gamma)_2$ (reference)
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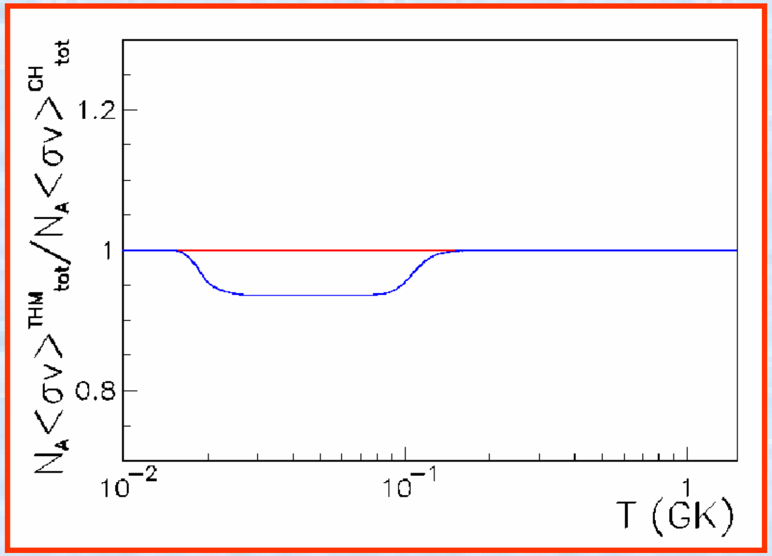
TOTAL REACTION RATE:

$$N_A\langle\sigma v\rangle_{tot}^{THM} = N_A\langle\sigma v\rangle_{tot}^{Chafa'07} - N_A\langle\sigma v\rangle_{65keV}^{Chafa'07} + N_A\langle\sigma v\rangle_{65keV}^{THM}$$



T=0.02-0.1 GK: the difference 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, are smaller than 10%.

➡ Agreement between the two sets of data

Conclusions

Main results:

1. A clear evidence of both levels at $E_{c.m.}$=65 and 183 keV is present in the excitation function.
2. Extraction of angular distributions for both levels at $E_{c.m.}$=65 (for the first time!!) and 183 keV and comparison with theoretical calculation and direct measurement (only for $E_{c.m.}$=183 keV).
3. The $^{17}O(p,\alpha)^{14}N$ reaction rate was extracted and compared with that one reported in *Chafa'07*, giving a difference of less than 10%.

… in progress:

✓ A deeper analysis of contribution of sub-threshold level is needed

✓ Our results are affected by a statistical error of ~25%.

A further experiment was performed at Physics Department of Notre Dame University (Indiana, USA) in November 2008 by using the same experimental apparatus adopted in the previous one.

Data analysis in progress