IX incontro nazionale dei

Gruppi **I**taliani di **A**strofisica

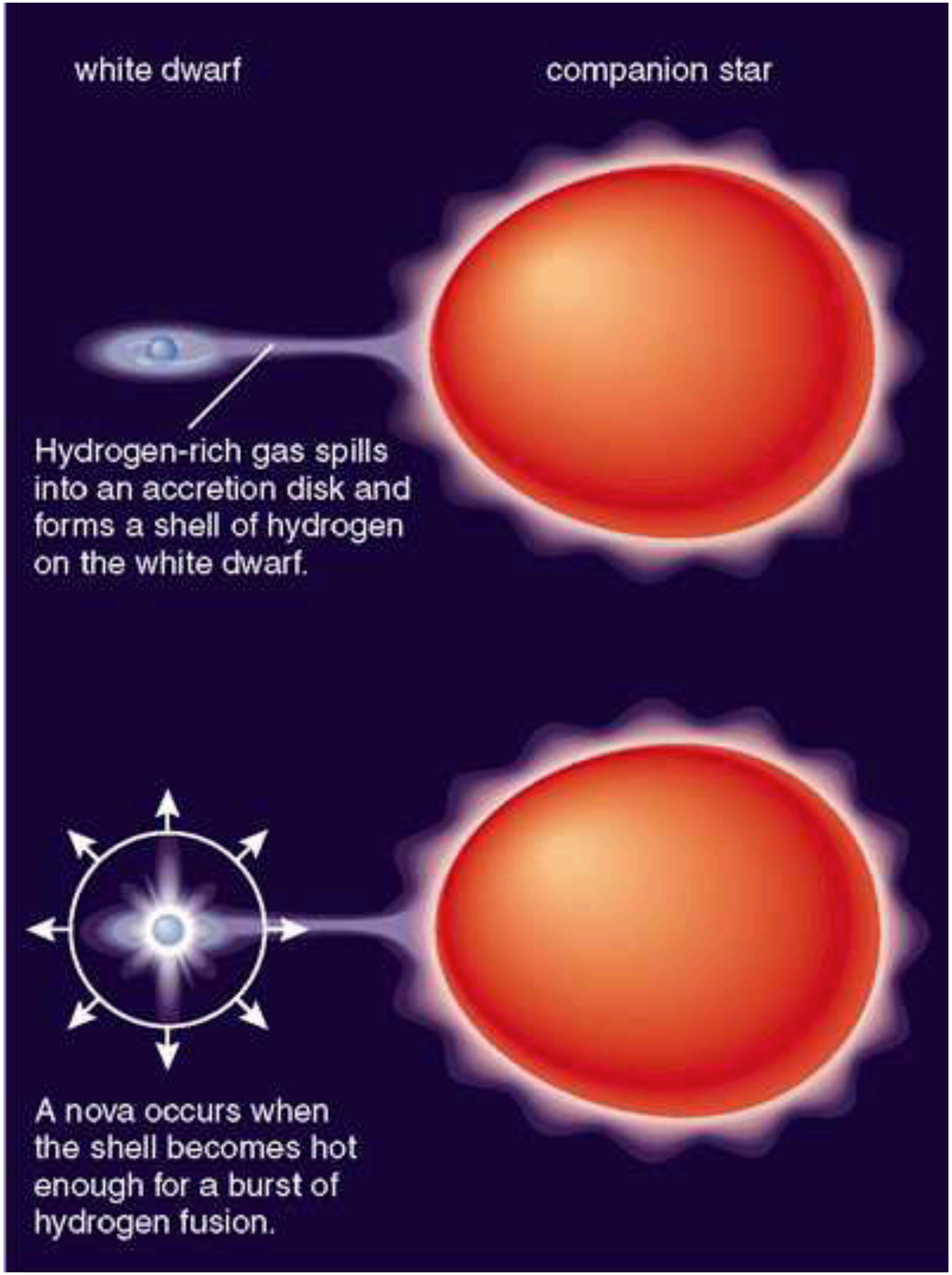
Nucleare **T**eorica e **S**perimentale

5-6 ottobre 2017

Palazzo Poggi, Bologna

H-burning in nova scenario

Maria Letizia Sergi
On behalf of the ASFIN group
Università degli Studi di Catania & LNS-INFN



Hydrogen-rich gas spills into an accretion disk and forms a shell of hydrogen on the white dwarf.

A nova occurs when the shell becomes hot enough for a burst of hydrogen fusion.

Classical Nova

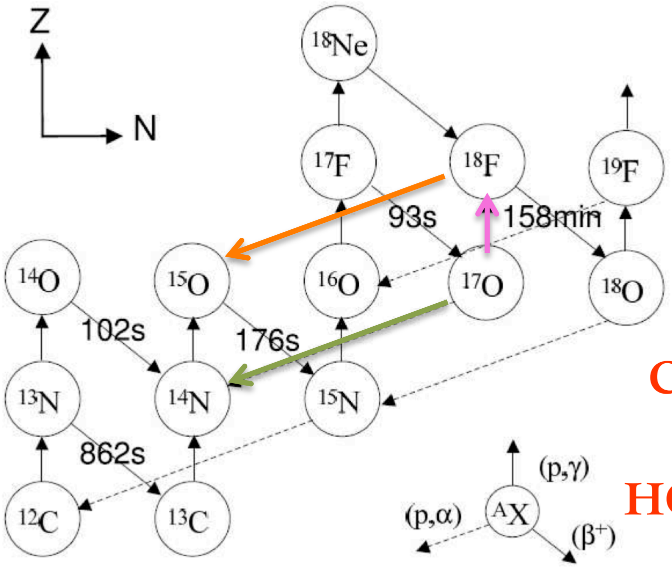
- The companion star transfers matter onto the white dwarf star

- hydrogen-rich material from companion can accumulate on surface.

- The temperature and density of the accumulated layers increase with time until it undergoes runaway fusion.

γ-ray emission

Novae Nucleosyntesis: $^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}$ and $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$



^{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.

CNO2 cycle: $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}(\beta+)^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}(\beta+)^{15}\mathrm{N}(p,\gamma)^{16}\mathrm{O}$

HCNO2 cycle : $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}(\beta+)^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}(\beta+)^{15}\mathrm{N}(p,\gamma)^{16}\mathrm{O}$

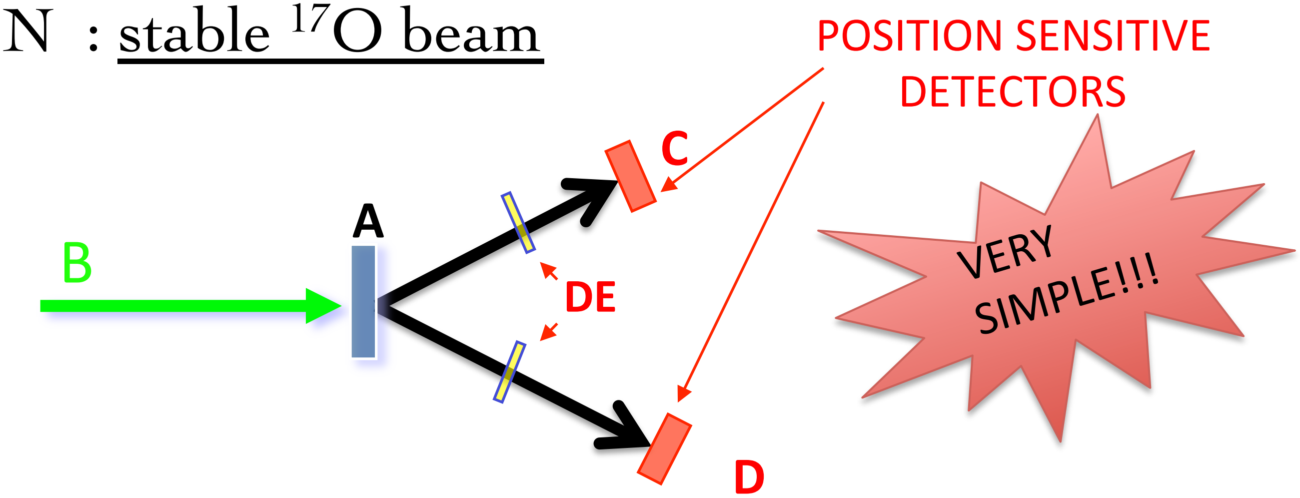
Positrons emitted by ^{18}F may have the special feature to be emitted (and then quickly annihilated) in the moment, 158 minutes, (life-time of ^{18}F) when the novae envelope starts to be transparent to the gamma-radiation.

γ-ray line fluxes measurement would shed light into the physical processes that occur in the early phases of the explosion (line at energy of 511 keV)

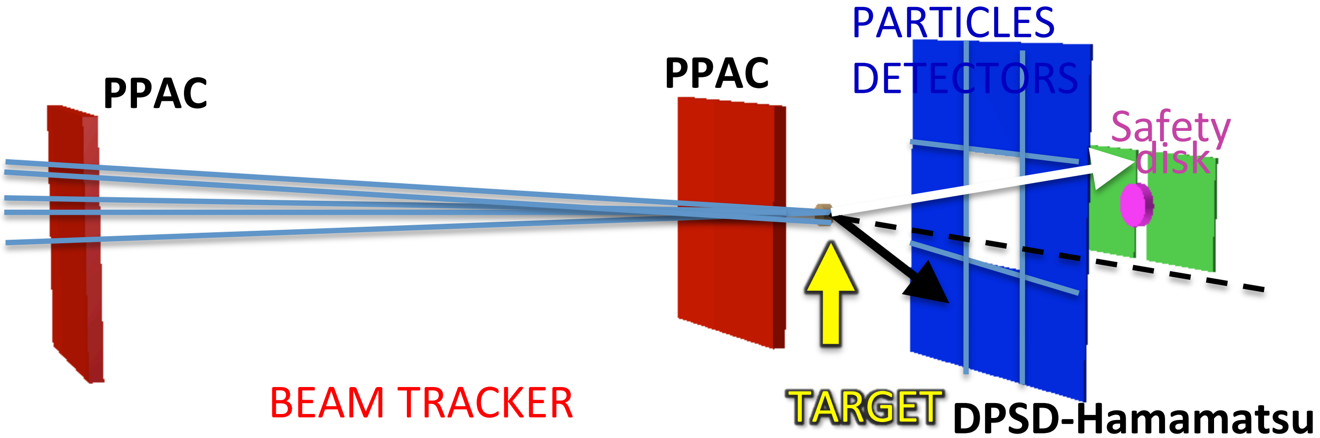
$^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}$: important channel for ^{18}F production
$^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}$: dominant channel for ^{17}O destruction
$^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$: dominant channel for ^{18}F destruction

Study of $^{17}O(p,\alpha)^{14}N$ and $^{18}F(p,\alpha)^{15}O$ by using the Trojan Horse Method

$^{17}O(p,\alpha)^{14}N$: stable ^{17}O beam



$^{18}F(p,\alpha)^{15}O$: radioactive ^{18}F beam



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

Stellar temperatures of primary importance for nucleosynthesis:
T=0.01-0.1 GK for red giant, AGB, and massive stars;
T=0.1- 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

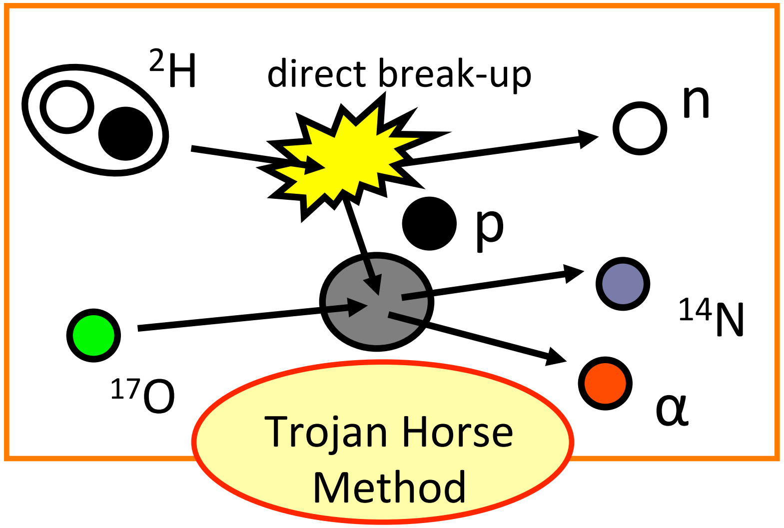
T=0.01-0.4 GK: **$^{17}O(p,\alpha)^{14}N$ and $^{17}O(p,\gamma)^{18}F$ reaction cross section have to be precisely known in the center-of-mass energy range $E_{c.m.}$=0.017-0.37 MeV.**

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.**

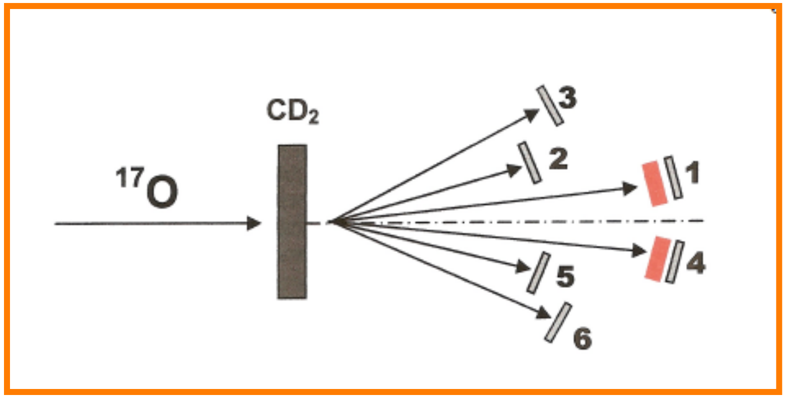
The experiment via the THM



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

$\Downarrow$

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



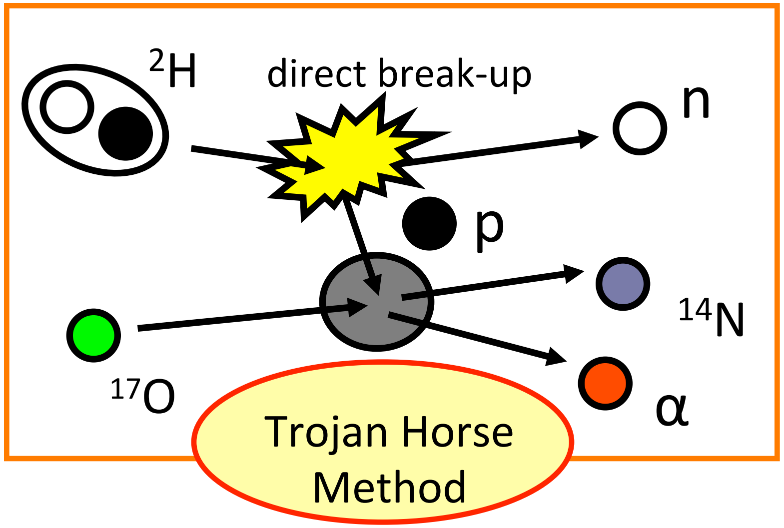
Two different measurement runs:

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

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°

The experiment via the THM



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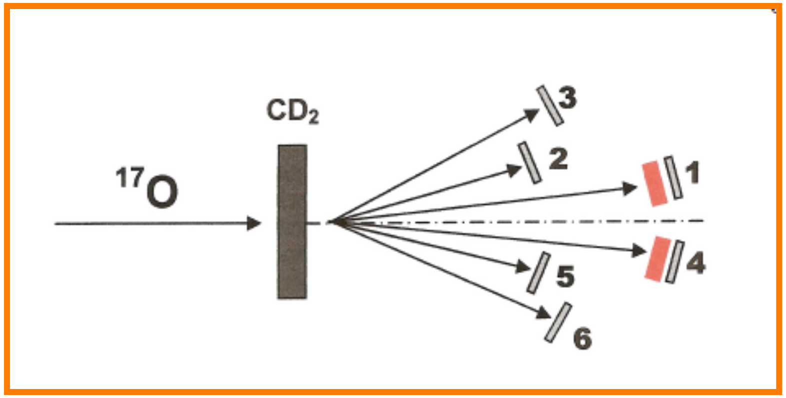

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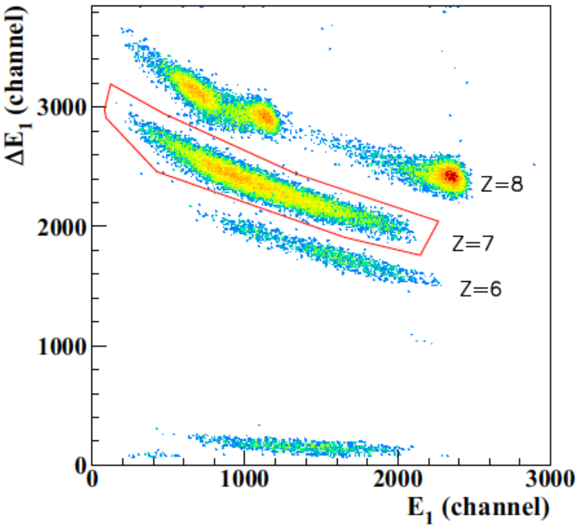
ADVANTAGE OF THM APPLICATION vs DIRECT MEASUREMENTS:

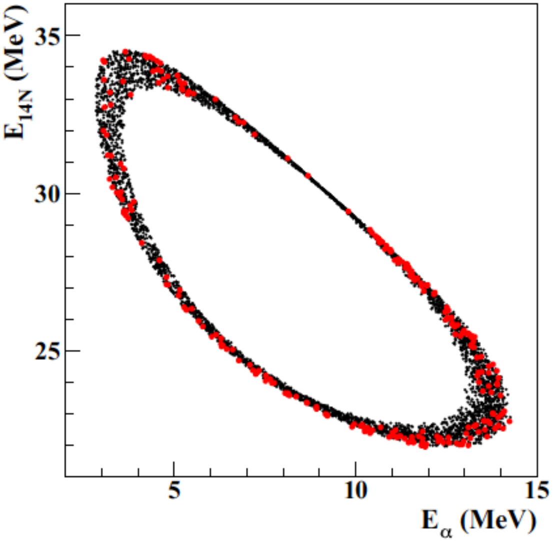
- NO ELECTRON SCREENING EFFECT → BARE NUCLEUS CROSS SECTION MEASUREMENT
- NO BACKGROUND CONTAMINATION

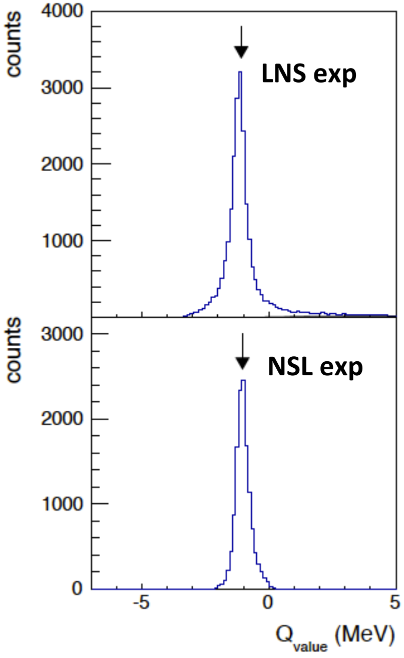
Selection of the $^{2}H(^{17}O, \alpha^{14}N)n$ reaction channel

✓ 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

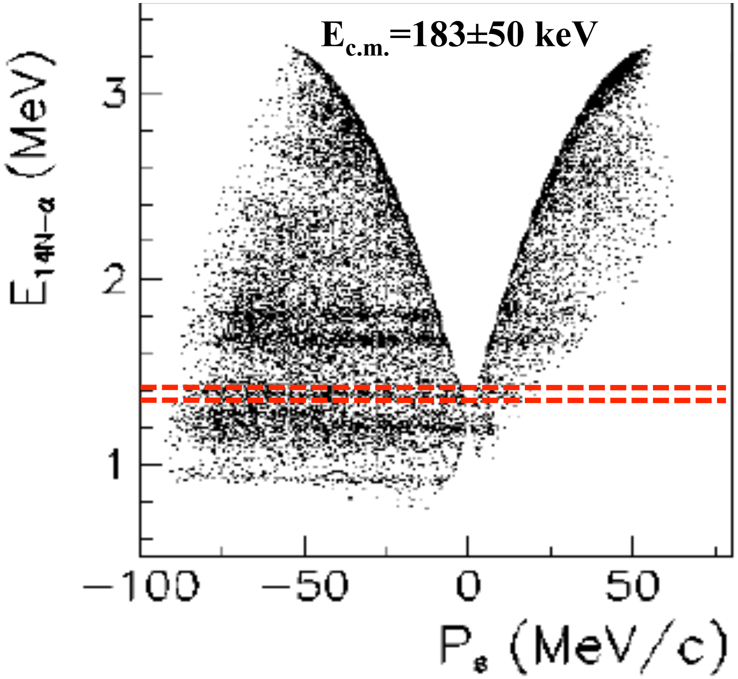
✓ Good detector calibration procedure!!

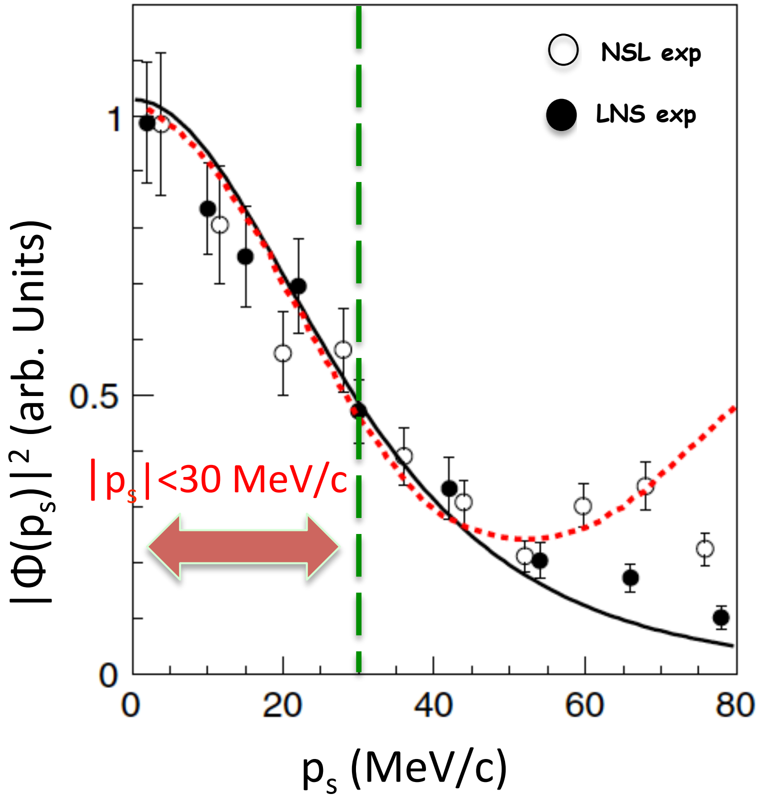
✓ Good reaction channel selection!!

QF selection via Momentum Distribution investigation: PWIA vs DWBA

✓ The PWIA approach allows one to exctract the experimental momentum distribution via the relation:

$$|\Phi(\vec{p}_s)|^2 \propto \frac{\dfrac{d^3\sigma}{d\Omega_\alpha\, d\Omega_{14N}\, dE_{cm}}}{KF}$$



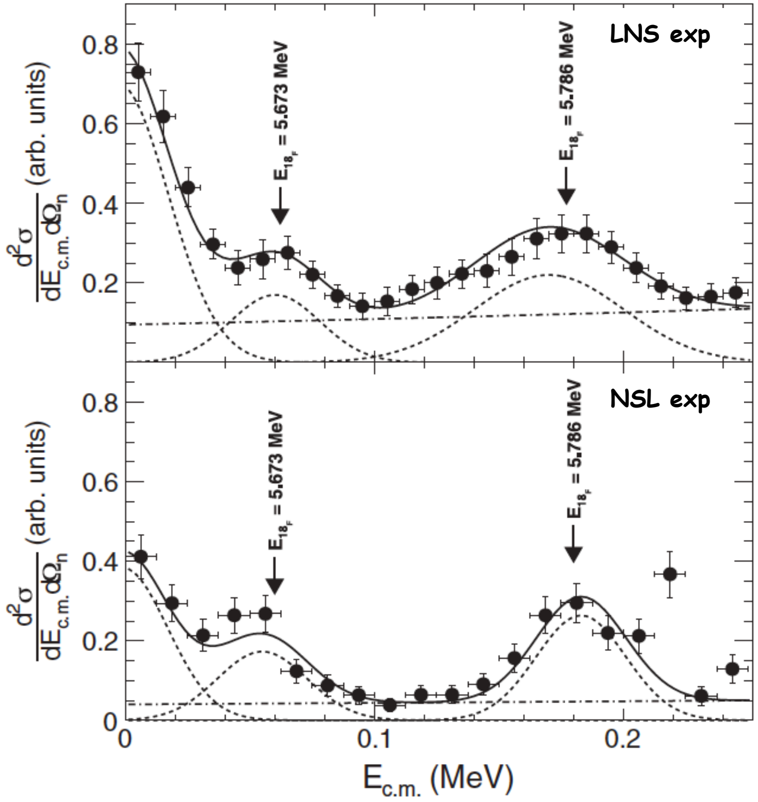


—— Hulthén→ FWHM=60 MeV/c

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

- - - - DWBA → FRESCO CODE

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.

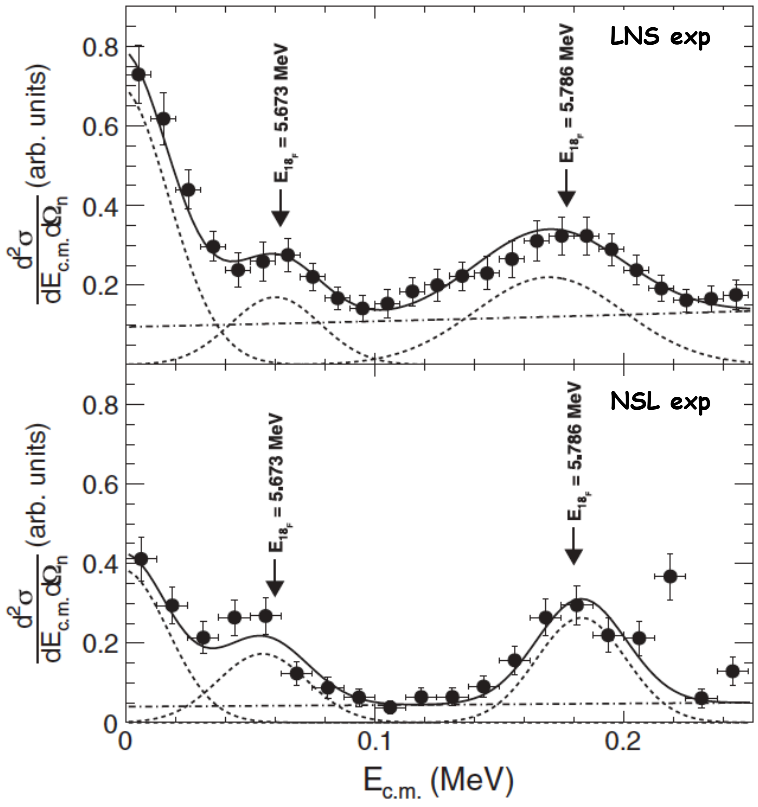
In order to separate the different contributions on this cross section, a fit of the nuclear cross section has been performed.

Extraction of:

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

Experiment	E_{R_1}	E_{R_2}	N_1	N_2
LNS	60±5 keV	175±5 keV	$0.1700 \pm 0.0250_{stat.}$ $\pm 0.0040_{back.} \pm 0.0003_{corr.}$	$0.2200 \pm 0.0310_{stat.}$ $\pm 0.0060_{back.} \pm 0.0002_{corr.}$
NSL	55±13 keV	183±13 keV	$0.1703 \pm 0.0290_{stat.}$ $\pm 0.0040_{back.} \pm 0.0003_{corr.}$	$0.2640 \pm 0.0340_{stat.}$ $\pm 0.0070_{back.} \pm 0.0002_{corr.}$

Trojan Horse Cross section



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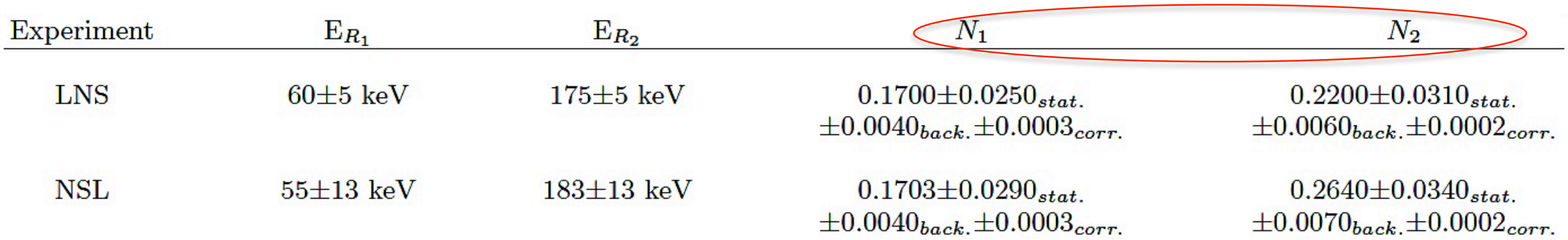

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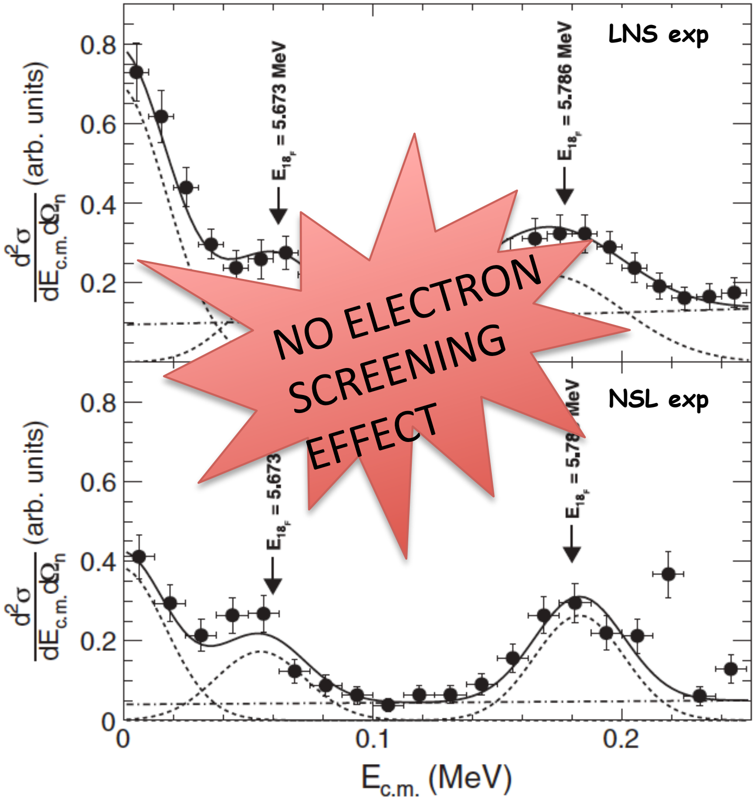

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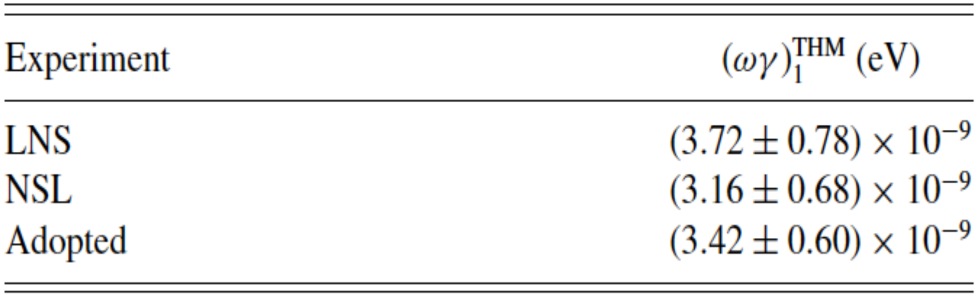
The ωγ parameter for the 65 keV resonant level

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

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



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)

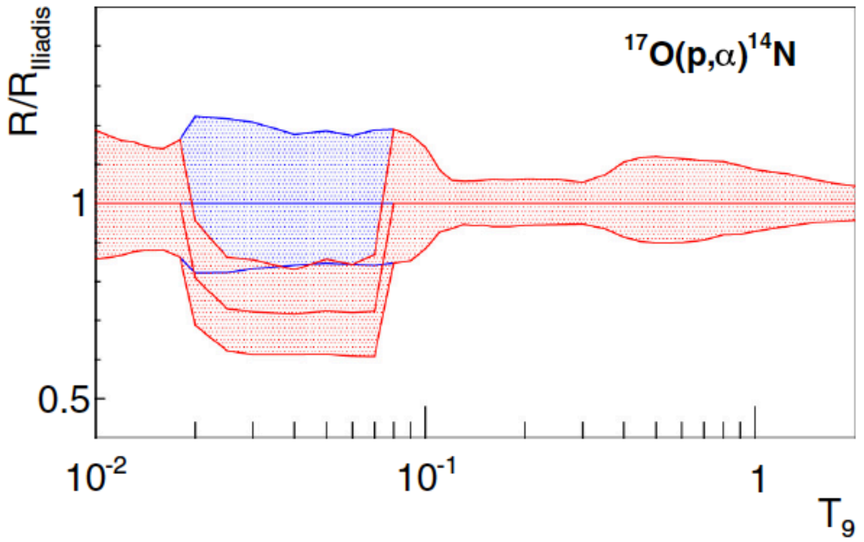
✓ with the $(4.7 \pm 0.8) \cdot 10^{-9}$ eV calculated by using the value of Γ_α and Γ_p reported in Chafa’07

They are in disagreement with the $10.0 \pm 1.4_{\mathrm{stat}} \pm 0.7_{\mathrm{syst}} \cdot 10^{-9}$ eV reported in Bruno et al. PRL 117, 142502 (2016)

Reaction rate determination

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

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



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:

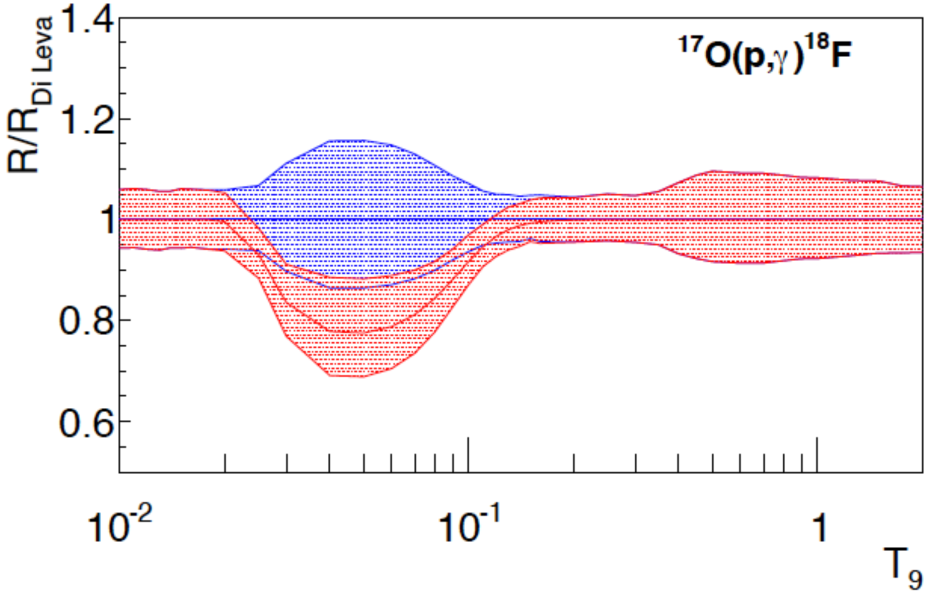
$$(\omega\gamma)_i = \frac{2J_{^{18}F_i}+1}{(2J_{^{17}O}+1)(2J_p+1)}\frac{\Gamma_{(p^{17}O)_i}(E_{R_i})\Gamma_{(\alpha^{14}N)_i}(E_{R_i})}{\Gamma_i(E_{R_i})}$$

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

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

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

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



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

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

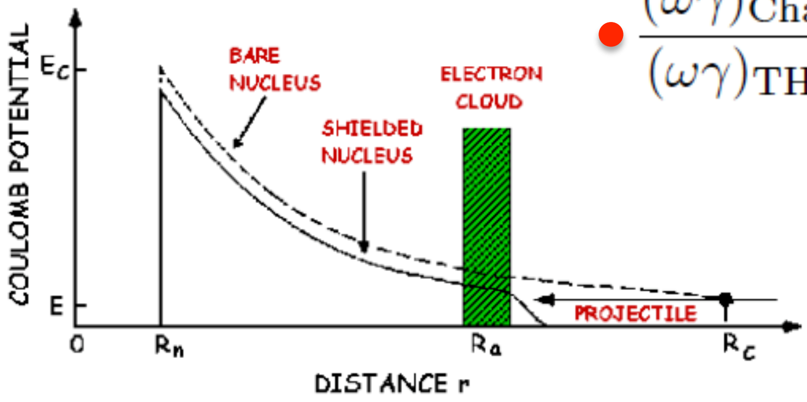
T=0.03-0.09 GK: the differences between the rate adopted in literature and the total rate calculated, if one considers the $N_A\langle\sigma v\rangle_{65}^{THM}$ extracted as explained before, is ∼20%.

Are direct data affected by electron screening?

Strengths of the 65 keV resonance in the (p,α) channel:

$$(\omega\gamma)_{Chafa} = (4.7 \pm 0.8)\cdot 10^{-9} \qquad (\omega\gamma)_{THM} = (3.40 \pm 0.60)\cdot 10^{-9}$$

In the hypothesis of electron screening effect



- $$\frac{(\omega\gamma)\mathrm{Chafa}}{(\omega\gamma)\mathrm{THM}} = \frac{\sigma_s(E)}{\sigma_b(E)} = f_{enh}(E) = 1.38 \pm 0.34,$$

This has to be compared with the theoretical value:

$$f_{enh}^{th} = 1.148$$

H. Assenbaum, K. Langanke, and C. Rolfs, Z. Phys. 327, 461 (1987).

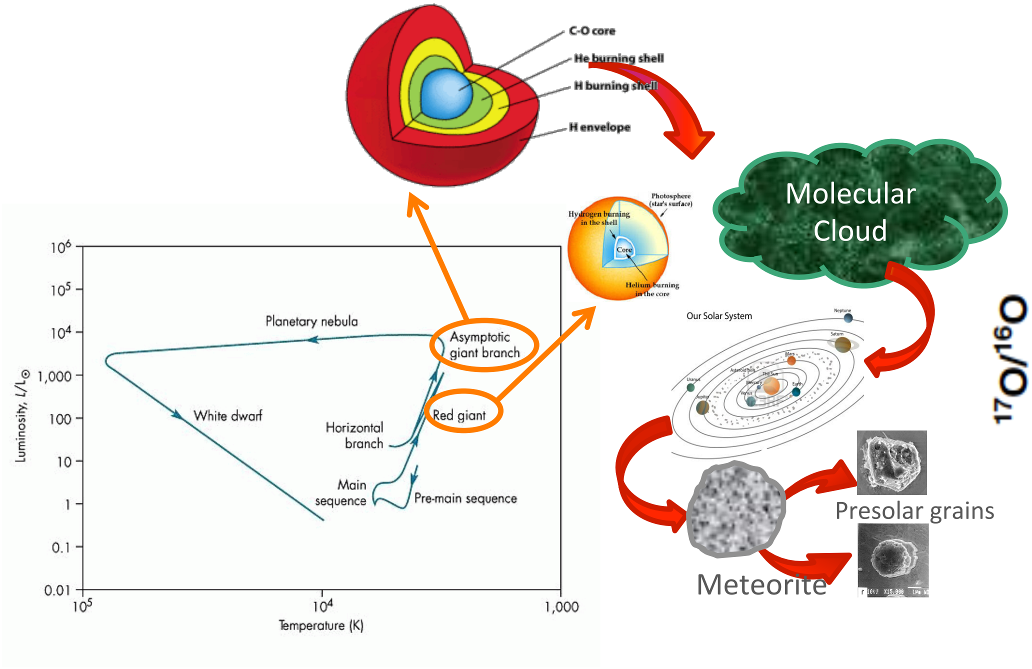
- An estimate of the electron screening potential U_e^{THM} leads to:

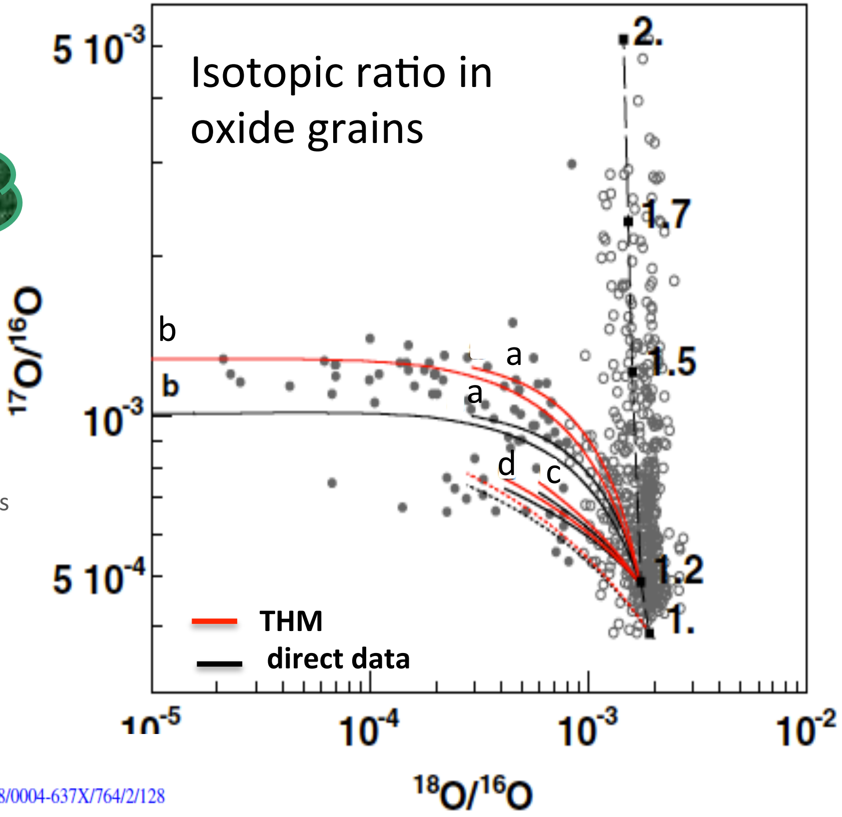
$$f_{enh}(E) = \frac{\sigma_s(E)}{\sigma_b(E)} = e^{\pi\eta(E_{R_i})\frac{U_e}{E_{R_i}}} \quad \Rightarrow \quad U_e^{THM} = \frac{\log[f_{enh}(E)]\cdot E_{R_i}}{\pi\eta(E_{R_i})} = 1387\mathrm{eV}$$

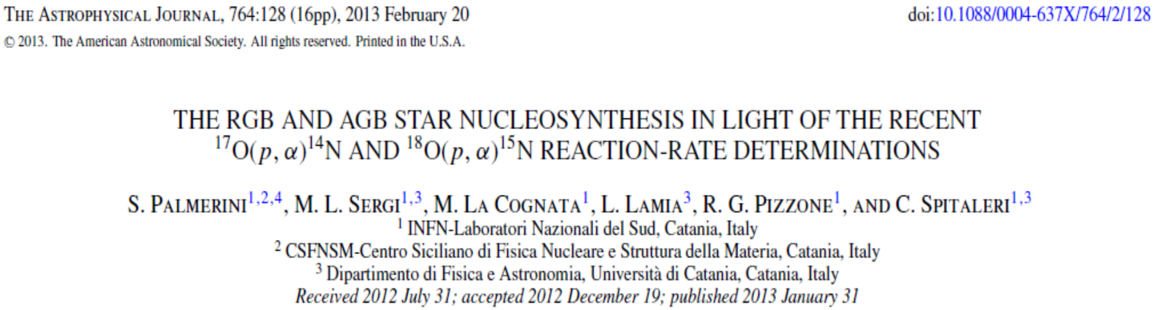
a factor 2.3 larger than the adiabatic upper limit U_e^{ad}= 594 eV

Further confirmation of the discrepancy between experimental and theoretical data for U_e values

$^{17}O(p,\alpha)^{14}N$ reaction rate variations






The Astrophysical Journal, 764:128 (16pp), 2013 February 20 doi:10.1088/0004-637X/764/2/128

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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

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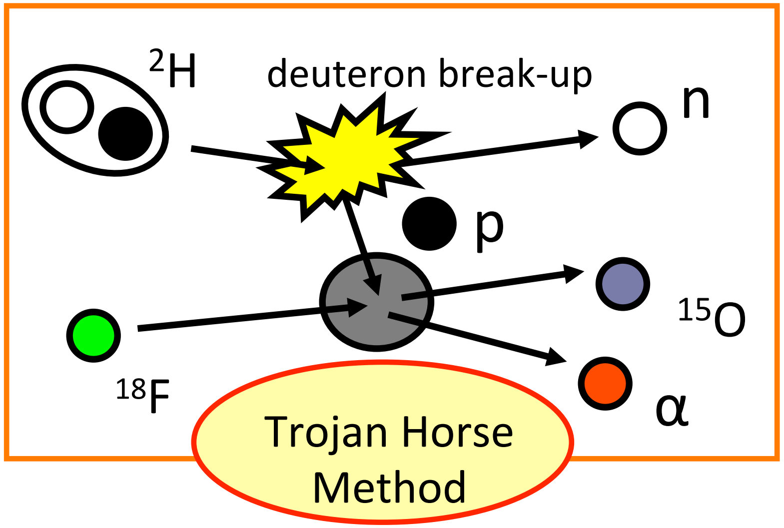
$^{18}F(p,\alpha)^{15}O$: RIBs and THM measurements

$^{18}F+p \rightarrow ^{15}O + \alpha$ @ CRIB-RIKEN - JP

$^{18}F+p \rightarrow ^{15}O + \alpha$ @ TAMU - TEXAS



$^{18}F+d \rightarrow ^{15}O+ \alpha +n$

$\Downarrow$

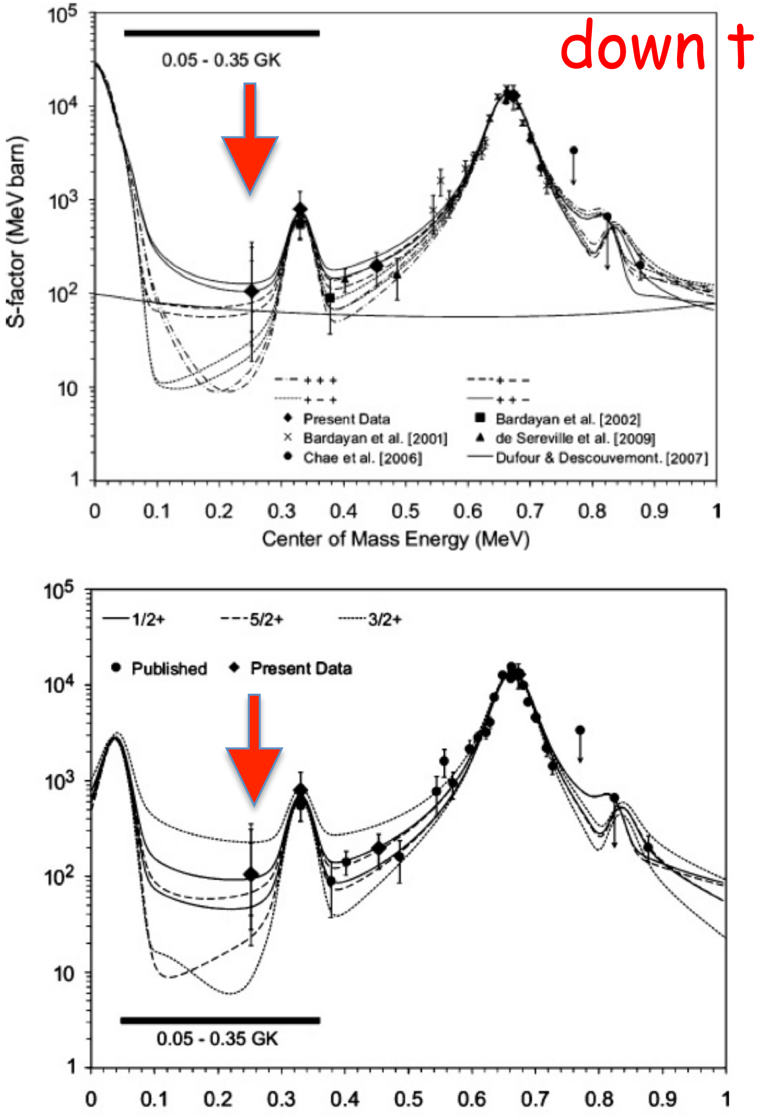
$^{18}F+p \rightarrow ^{15}O+ \alpha$

SOME ADVANTAGES

- lower intensities (10^5-10^6 pps) and short beam time (15-20 days) because of qf reaction cross sections;
- use of an only monoenergetic beam.

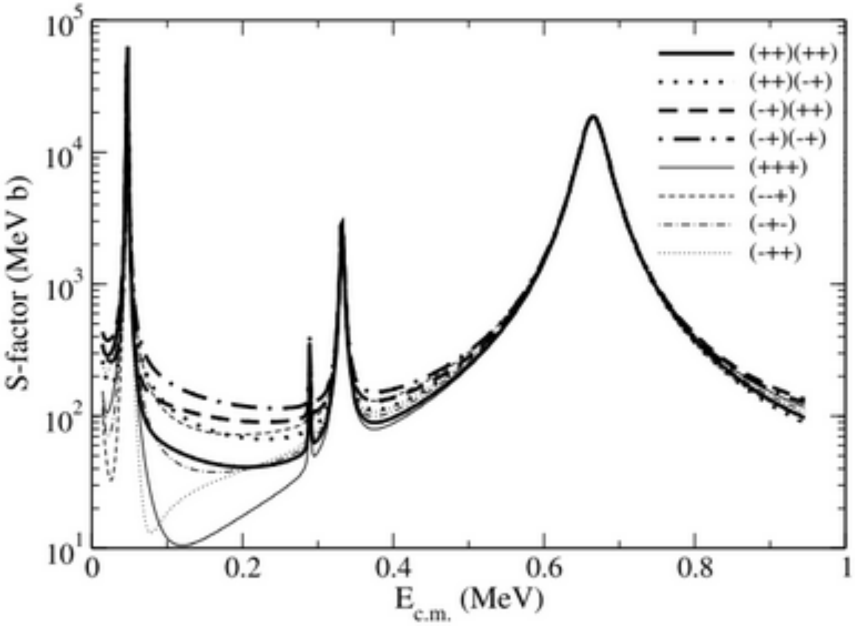
Study of the $^{18}F(p,\alpha)^{15}O$ reaction: direct data

Direct data
down to 250 keV



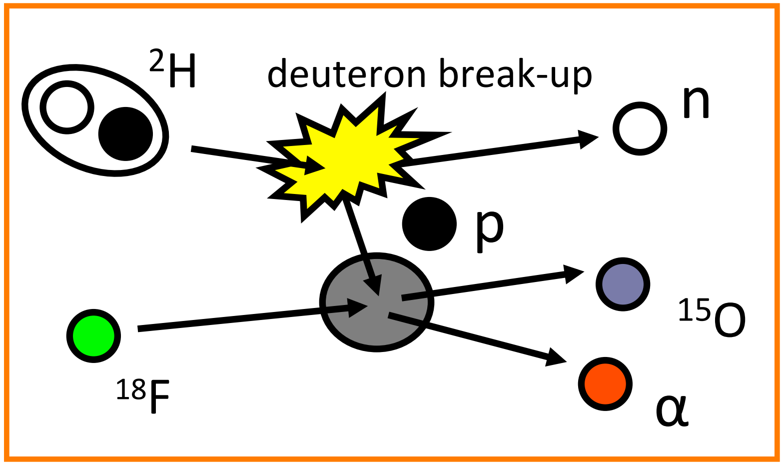
C. E. Beer et al. PRC 83, 042801(R) (2011)

Only theoretical calculation at lower energies



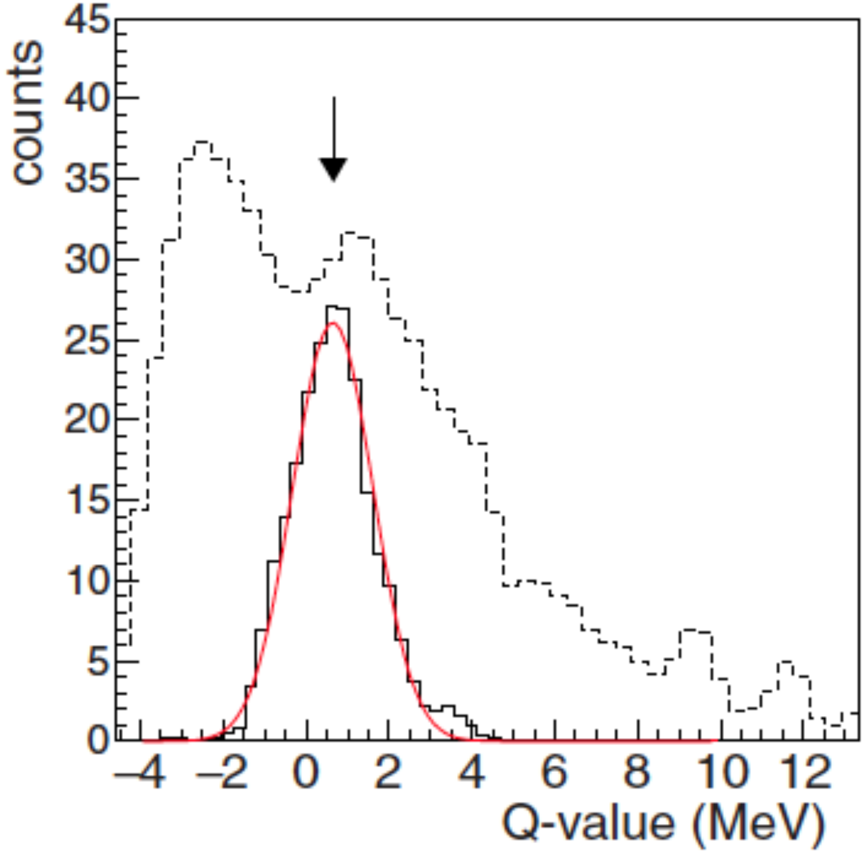
D.W. Bardayan et al. PLB 751, 311 (2015)

Study of the $^{18}F(p,\alpha)^{15}O$ reaction by THM

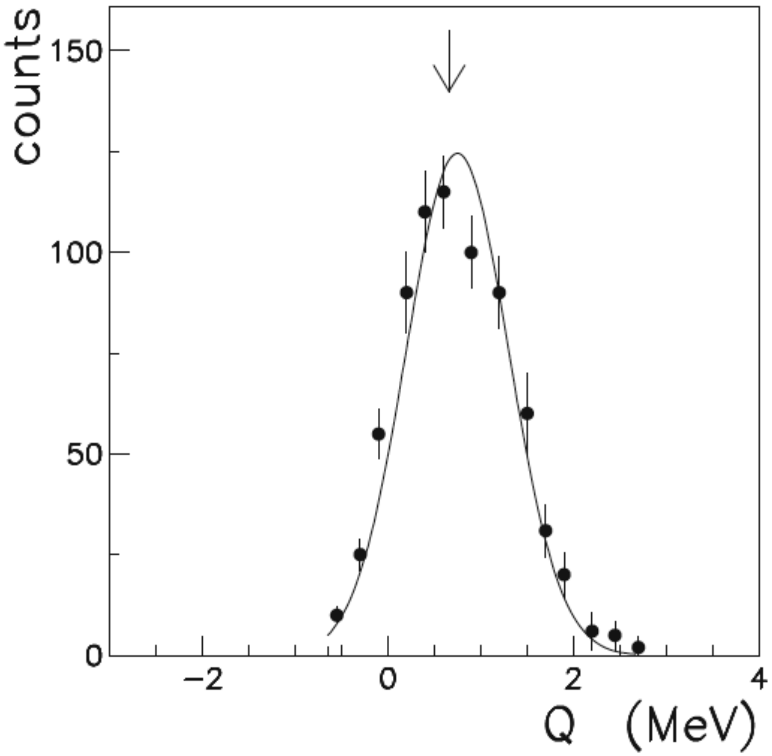


Q-value spectra

@ CRIB – RIKEN - JP



@ TAMU - TEXAS



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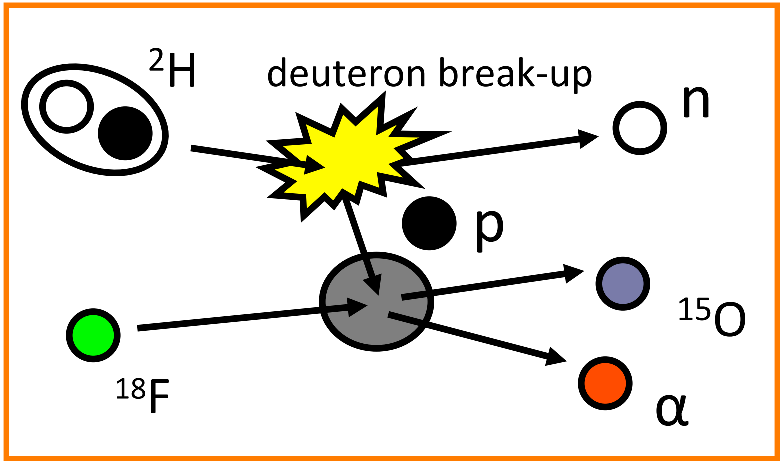
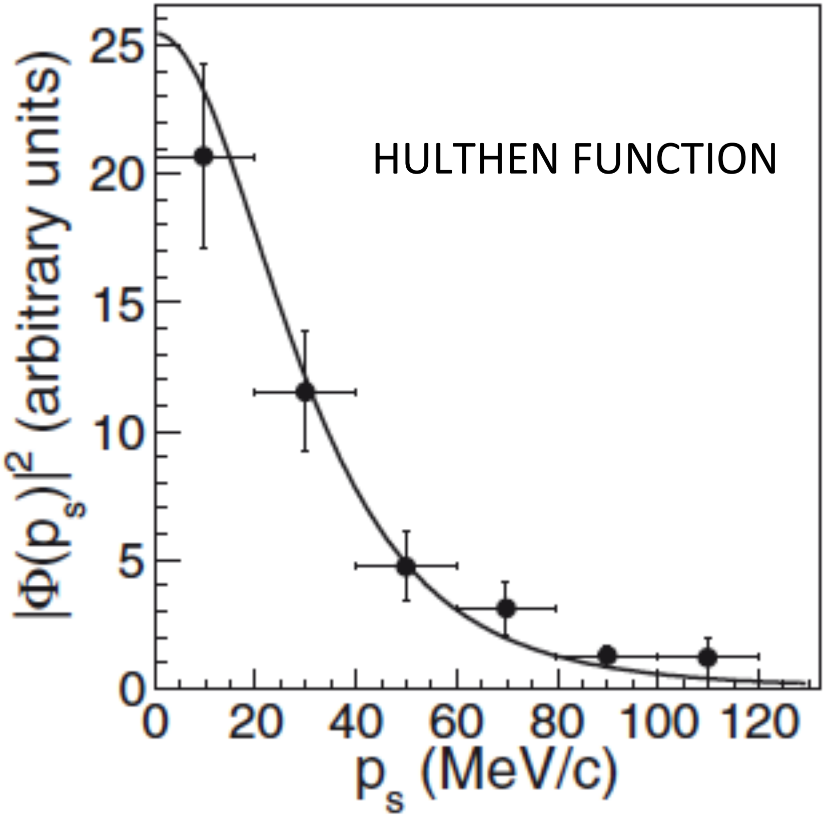
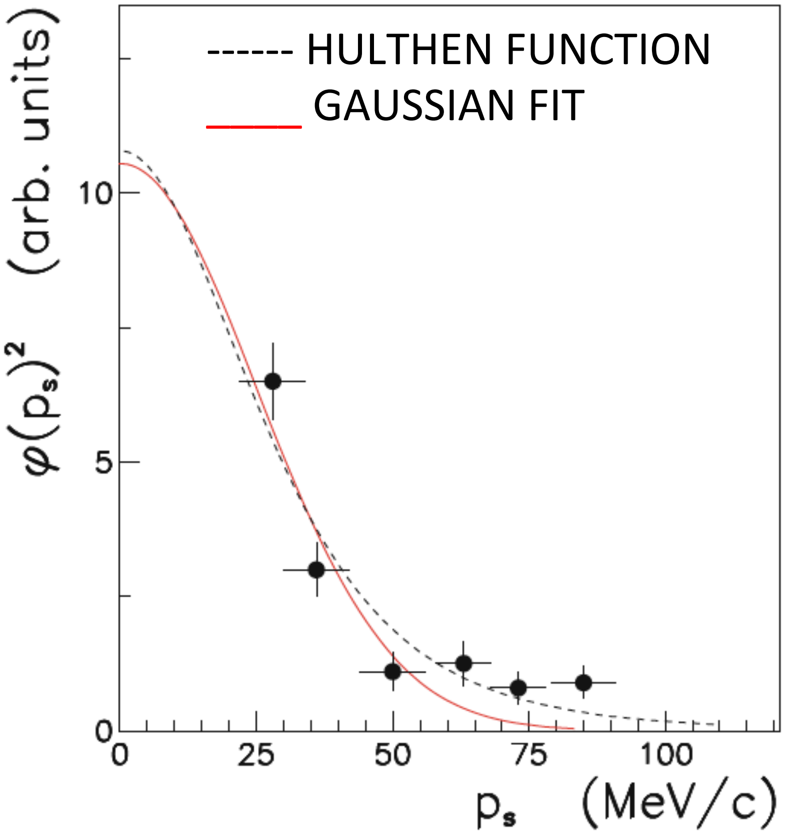


Search for the quasi-free reaction mechanism

@ CRIB – RIKEN - JP

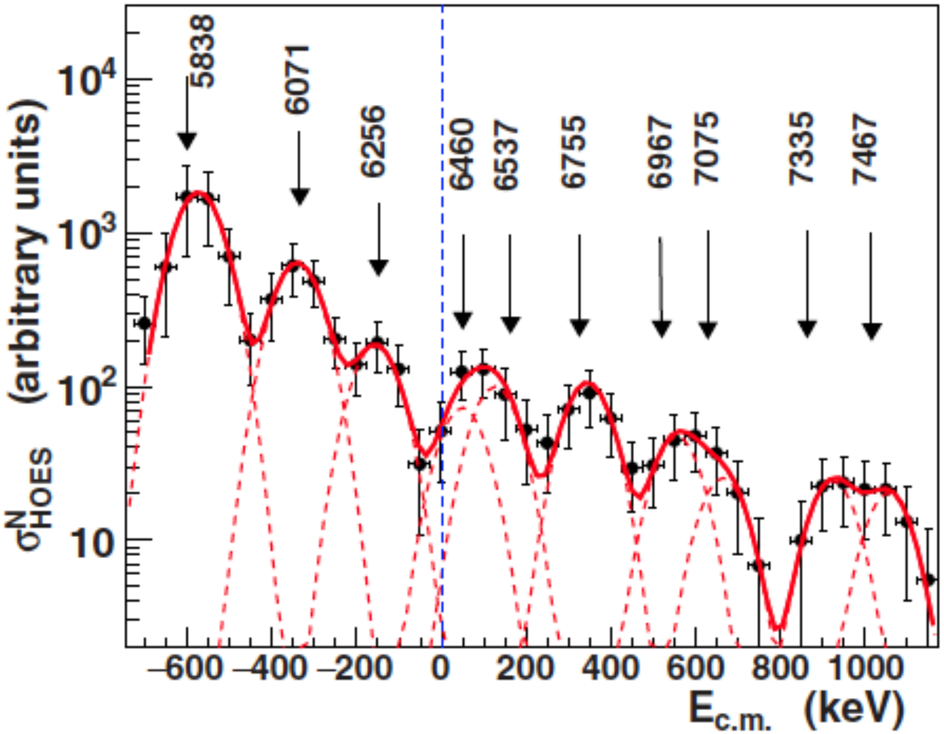


@ TAMU - TEXAS



Study of the $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$ reaction by THM

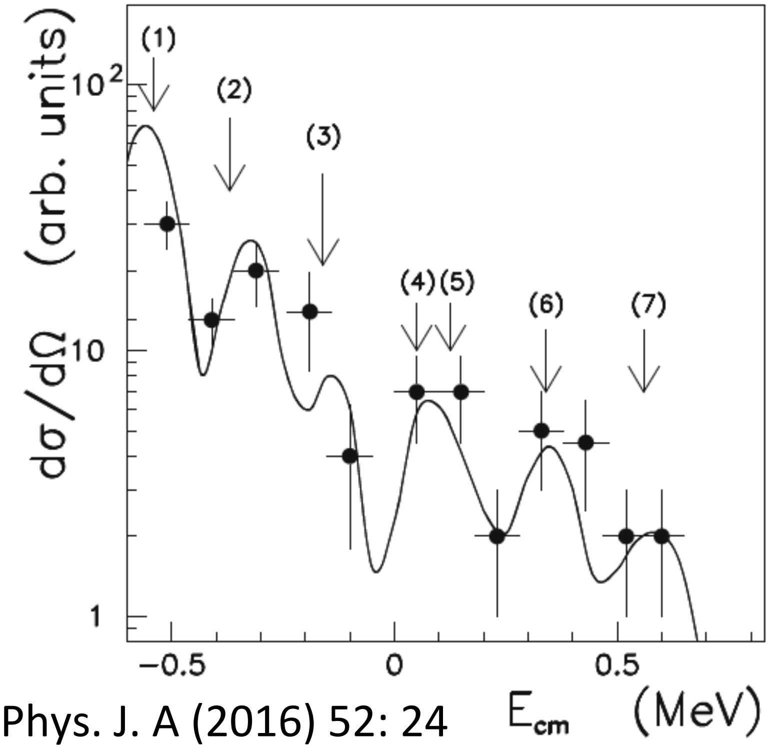
Bare nucleus cross section $\frac{d^3\sigma}{dE_b d\Omega_b d\Omega_B} \propto KF\left(\frac{d\sigma}{d\Omega}\right)\cdot\left|\Phi(p_s)\right|^2$



@ CRIB – RIKEN - JP

Cherubini et al., PRC 92, 015805 (2015)

@ TAMU - TEXAS

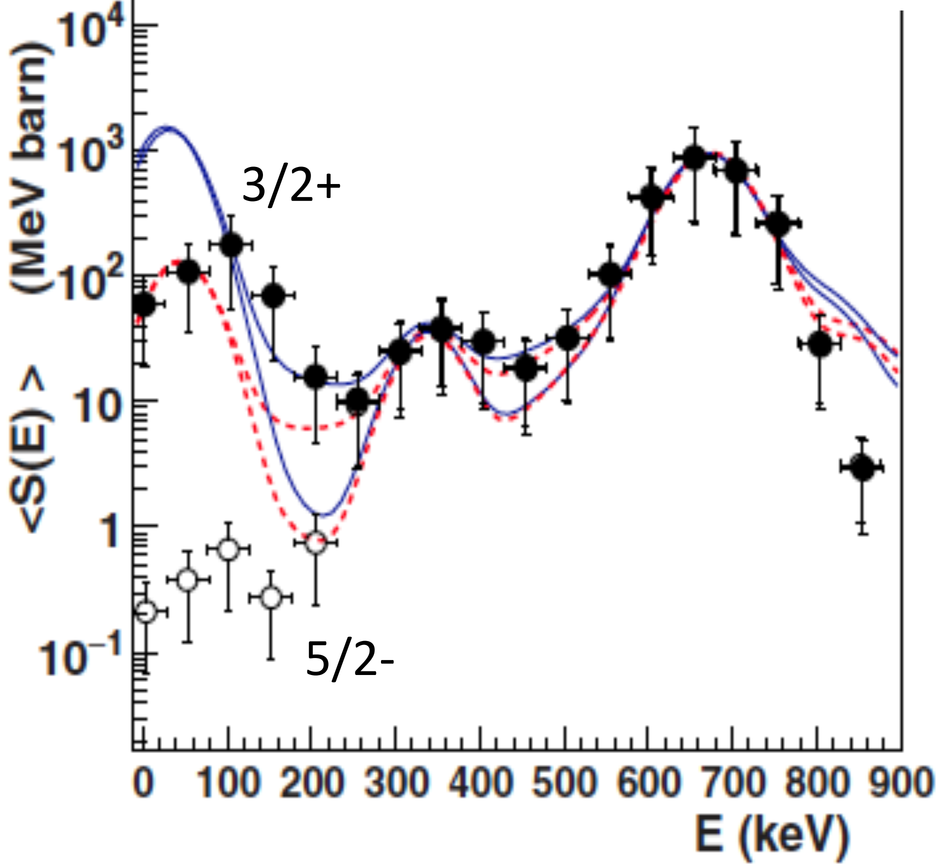


Pizzone et., Eur. Phys. J. A (2016) 52: 24

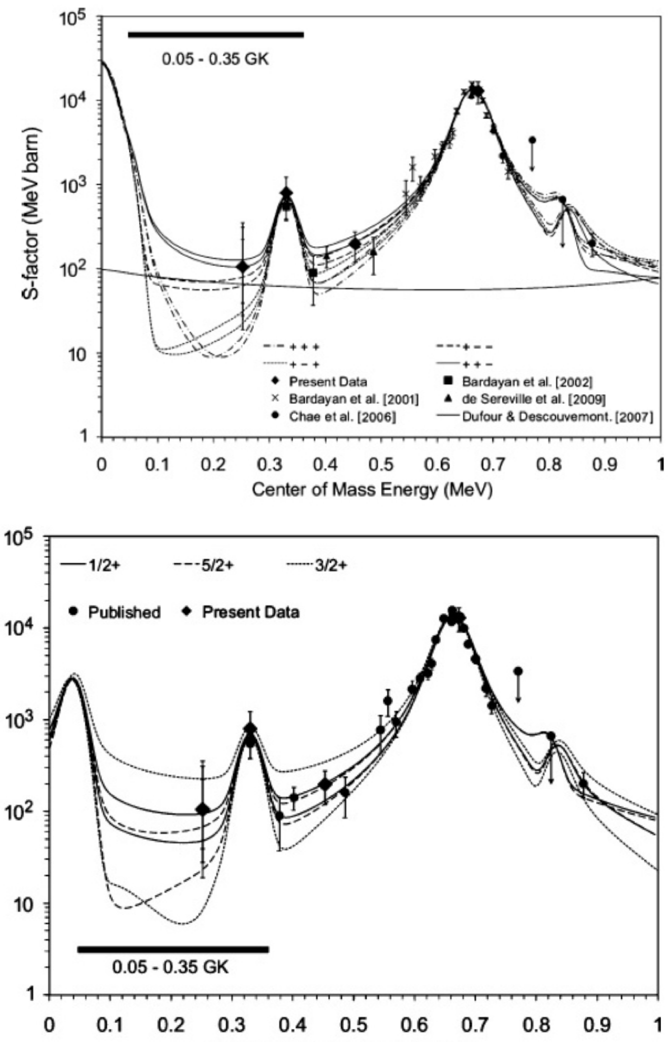
Study of the ^{18}F(p,α)^{15}O reaction by THM

Astrophysical factor

PHYSICAL REVIEW C 92, 015805 (2015)



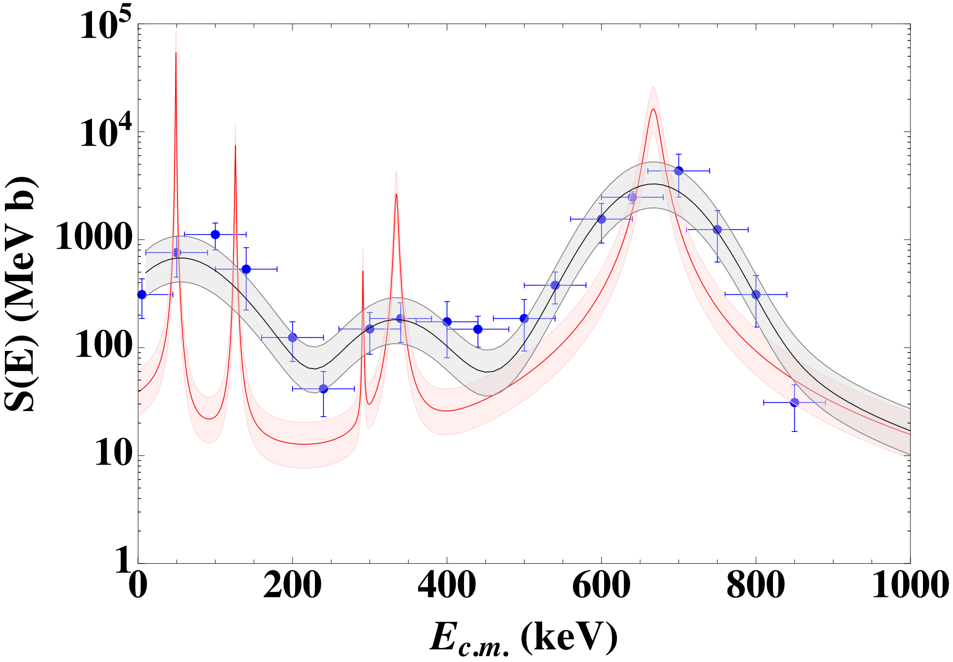
$$\left.\frac{d\sigma_{xA\to bB}}{d\Omega}\right|_{\mathrm{OES}} = P_l(E_{xA})\left.\frac{d\sigma_{xA\to bB}}{d\Omega}\right|_{\mathrm{HOES}},$$



C. E. Beer et al. PRC 83, 042801(R) (2011)

Data correction for the penetrability of the centrifugal barrier

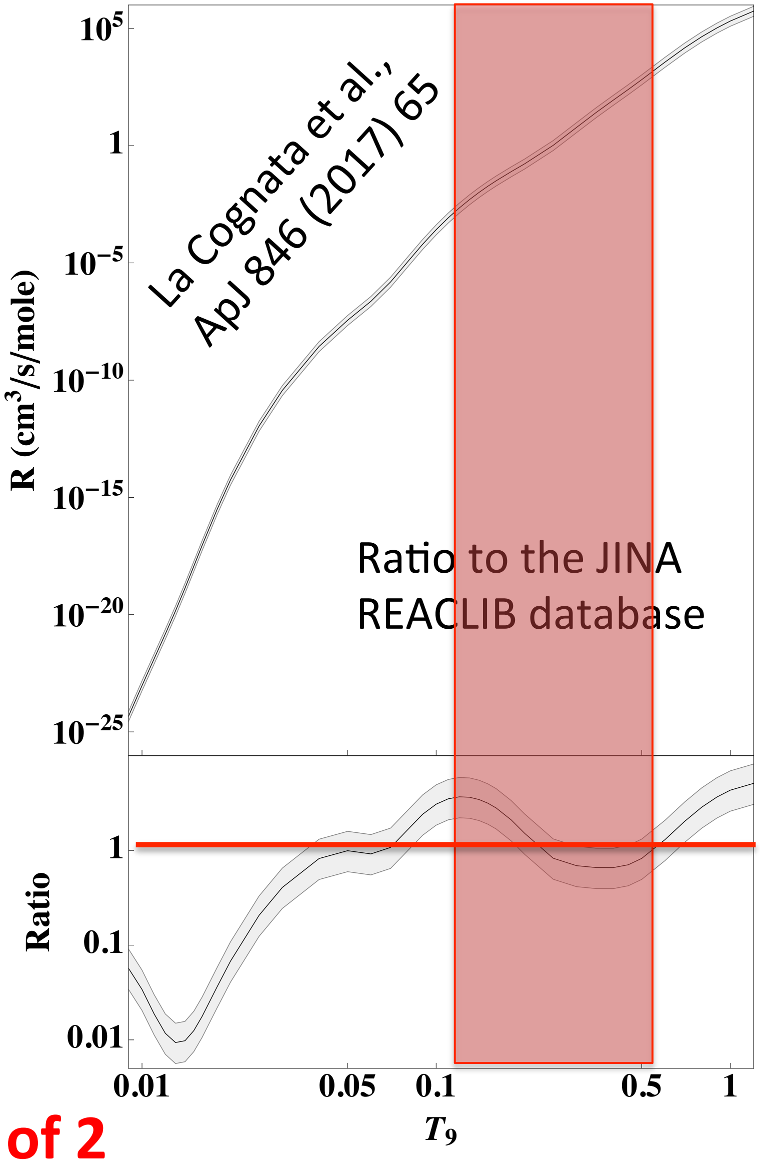
^{18}F(p,α)^{15}O: impact on Novae nucleosynthesis and observations



Experimental data down to ZERO energy!

No evidence of the 7 keV resonance
($3/2^-$ state of ^{19}Ne at 6417 keV)

Evidence of the 126 keV resonance
($7/2^+$ state of ^{19}Ne at 6537 keV)



La Cognata et al., ApJ 846 (2017) 65

Ratio to the JINA REACLIB database

REDUCTION of ^{18}F abundance by a factor of 2

Conclusions

^{17}O(p,α)^{14}N reaction

- Extraction of the 65 keV resonance strength intervening in the ^{17}O(p,α)^{14}N and ^{17}O(p,γ)^{18}F by using the 183 keV level resonance strength as normalization value;
- Evaluation of the reaction rate for both (p,α) and (p,γ) channels and comparison with the most recent ones;
- The THM reaction rates appear to be 30% lower and 25% lower with respect the ones given in the literature;
- The discrepancy between THM and direct data can be explained if electron screening effects are invoked;

^{18}F(p,α)^{15}O reaction

- Application of the THM to a reaction induced by radioactive beam;
- Measurement of the astrophysical factor down to 0 MeV;
- Reduction of the ^{18}F abundance of a factor 2.

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Thank you…