

**Marco La Cognata**

# Reaction Measurements at Astrophysical Energies

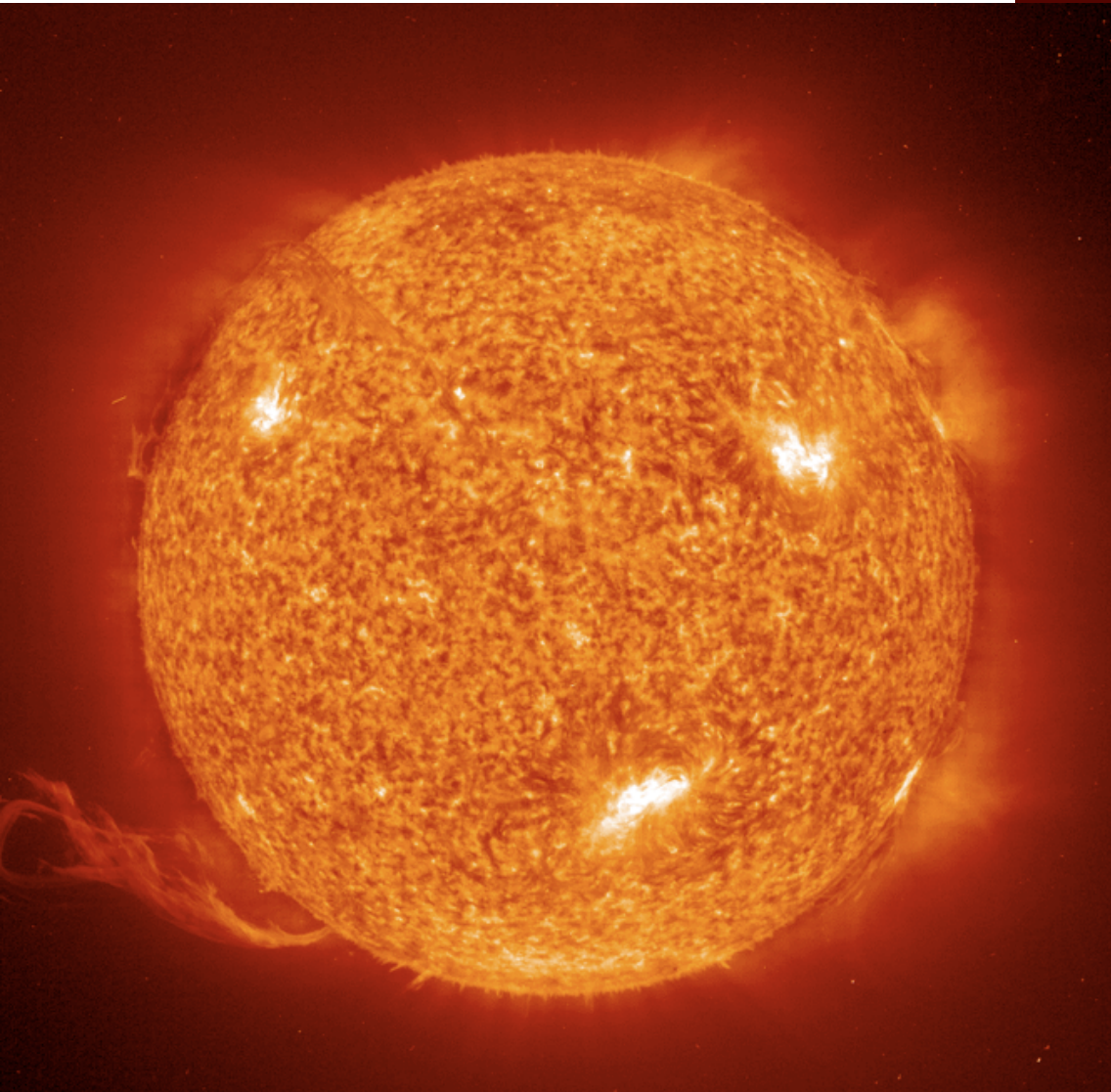


**Elba XII Workshop  
Electron-Nucleus Scattering XII  
Elba International Physics Center  
June 25-29, 2012**

# Outline

- 1. Why is nuclear astrophysics important?**
- 2. What has to be measured?**
- 3. How are the measurements performed?**
- 4. A few examples**

## 1. Introduction



Solar and Heliospheric Observatory (SOHO)

Life on Earth depends on nuclear processes deep inside the Sun

How do other stars produce energy? How do they evolve?

Fusion of H to He:

Bethe & Critchfield (1938)

[pp chains]

Bethe 1939; von Weizsaecker 1938

[CNO cycle]

Nobel prize to Hans Bethe (1967)

Accurate nuclear physics information is crucial for understanding of stars

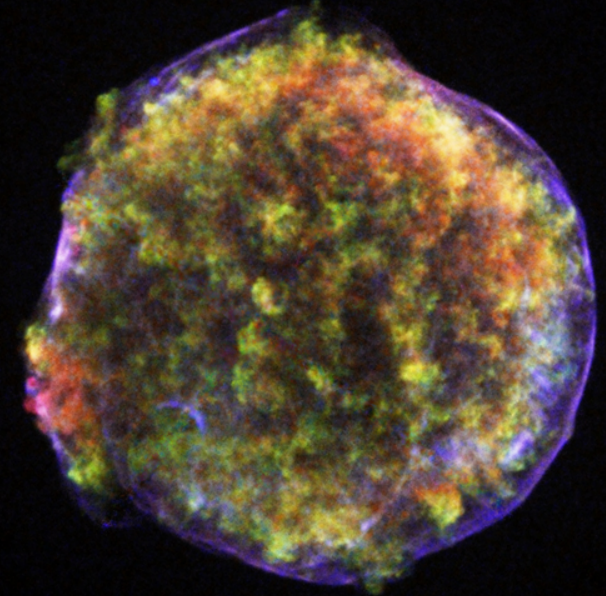
Sun did not produce elements found on Earth...

Supernova 1994D in galaxy NGC 4526



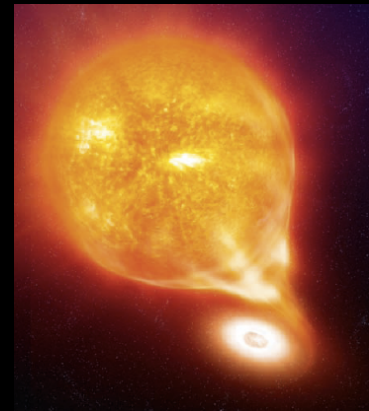
Credit: NASA/ESA

Remnant of Tycho's supernova



Credit: NASA/CXC

- smaller fraction (approximately 15%) of supernovae are **type Ia supernovae**
- believed to occur in binary stars: CO white dwarf + other star
- high mass accretion onto white dwarf surface (to avoid classical nova!)
- white mass grows to near Chandrasekhar limit ( $1.4M_{\text{sol}}$ )
- carbon ignites under degenerate conditions (thermonuclear runaway)
- nuclear energy release disrupts white dwarf, no remnant left behind
- nucleosynthesis in hottest zone: produces mainly  $^{56}\text{Ni}$  via NSE at low neutron excess
- outer regions attain smaller temperatures: explosive Si and O burning



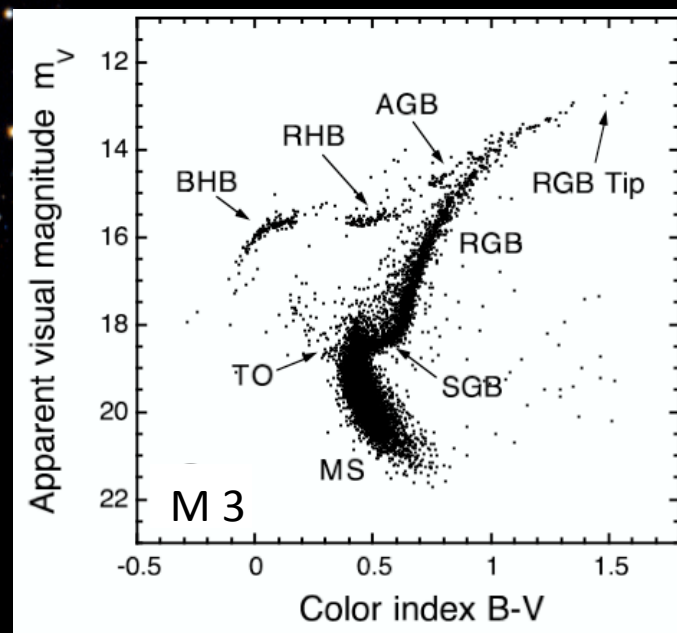
# Globular cluster M 10



**Red giant stars:**  
H→He via CNO cycles in  
H shell surrounding He core  
S-process → synthesis of nuclei  
beyond the Fe-peak

**Horizontal branch stars:**  
He→C, O in core  
H→He in shell

**Main sequence stars:**  
H→He via pp chains in core



# Direct and indirect measurements I

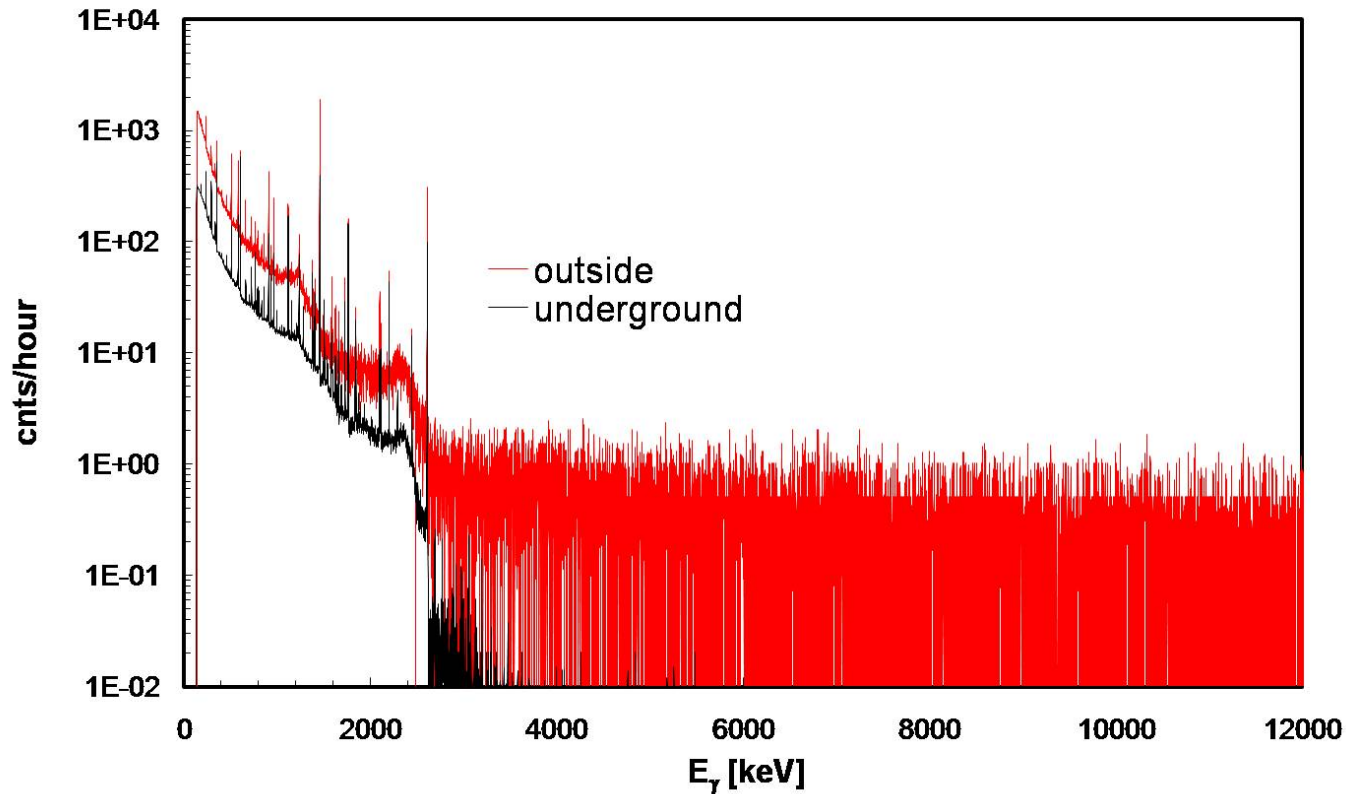
## Direct measurements:

### **Straightforward but complicated**

- ✓ Coulomb barrier exponentially suppresses the cross section ( $E < 100$  keV)
  - 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 been determined accurately

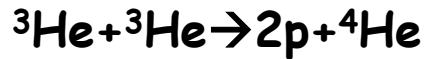
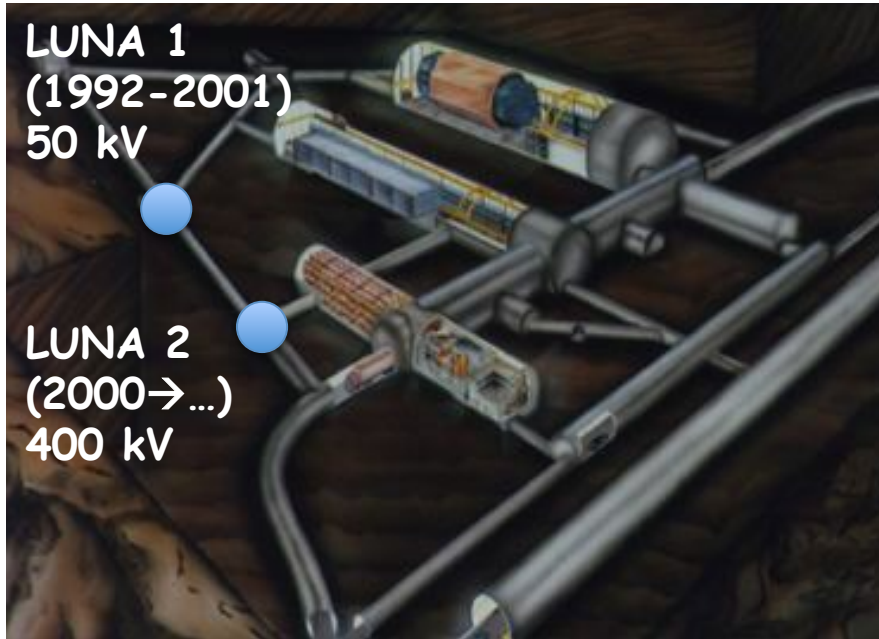
# Why underground laboratories



Therefore, the advantage of an underground environment is evident for high Q-value reactions such as  $d(p,\gamma)^3\text{He}$ ,  $^{14}\text{N}(p,\gamma)^{15}\text{O}$ ,  $^{15}\text{N}(p,\gamma)^{16}\text{O}$ ,  $^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$ ...

Radiation	LNGS/out
muons	$10^{-6}$
neutrons	$10^{-3}$

# The LUNA experiment: an example

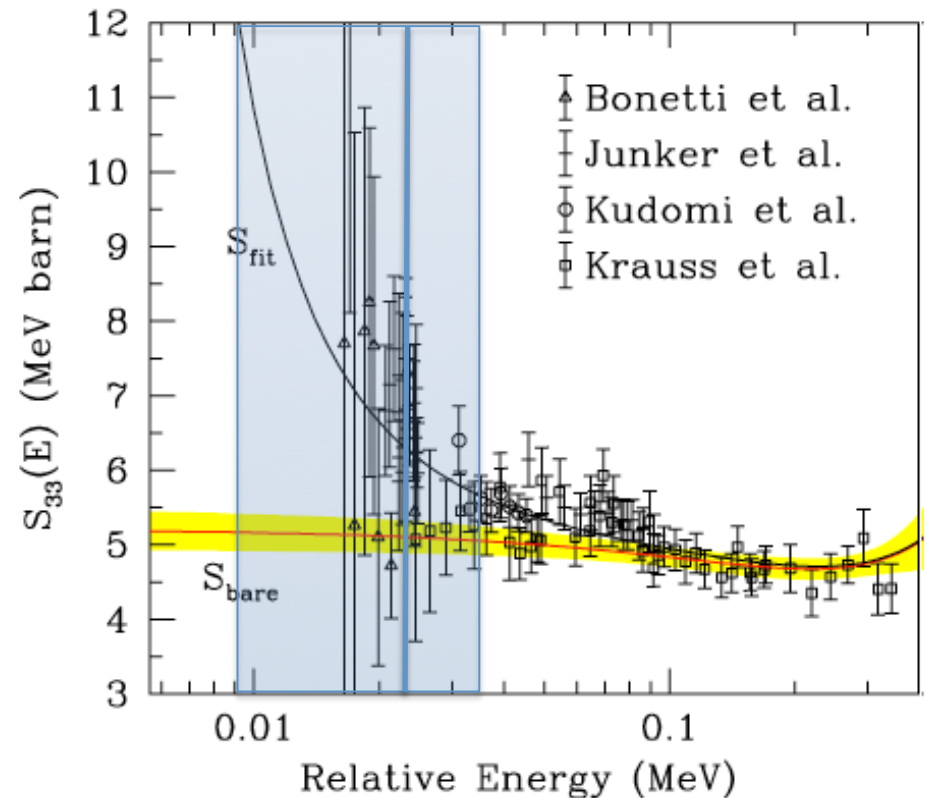


First measurement spanning the astrophysical energy range, namely the **Gamow peak**

$$E_G = 9 - 34 \text{ keV}$$

$$\sigma(E) = \frac{1}{E} \exp(-31.29 Z_1 Z_2 \sqrt{\mu/E}) S(E)$$

**Astrophysical factor: useful for more accurate extrapolation**



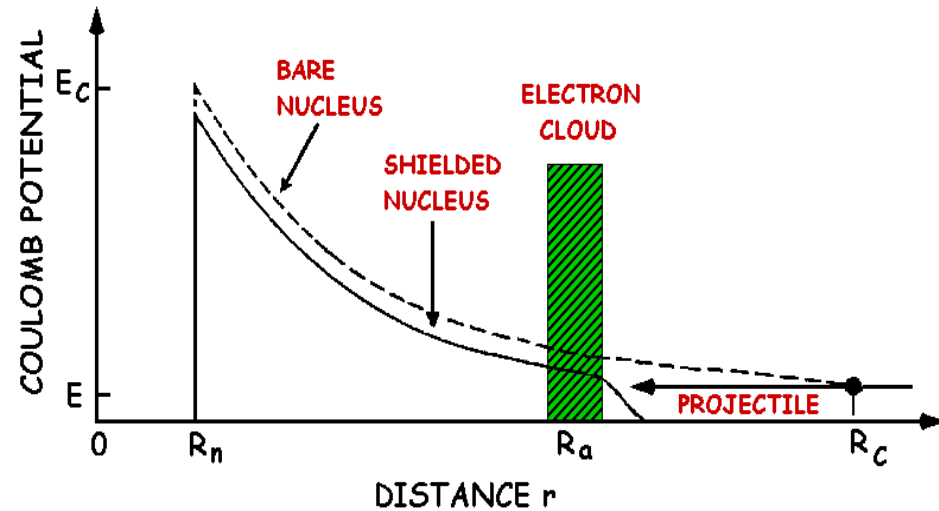


# The electron screening effect.

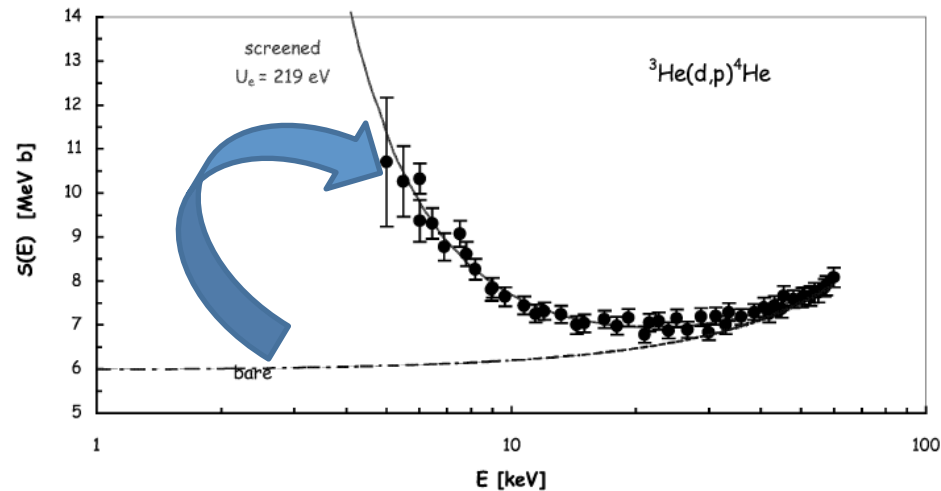
Thanks to recent experimental developments, measurements have been extended to the energies of interest for several reactions.

This led to the discovery of electron screening: at such low energies atomic degrees of freedom cannot be neglected.

Pictorial view:



Experimentally:



The electron cloud shields the nuclear charge thus the projectile meets a reduced Coulomb barrier  $\rightarrow$  enhancement of the reaction probability as tunneling is more likely.

**Exponential enhancement!**

$$\sigma_s(E)/\sigma_b(E) \propto \exp(\pi \eta U_e/E),$$

# Direct and indirect measurements II

## 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 the bare nucleus cross section down to astrophysical energies with the present day facilities

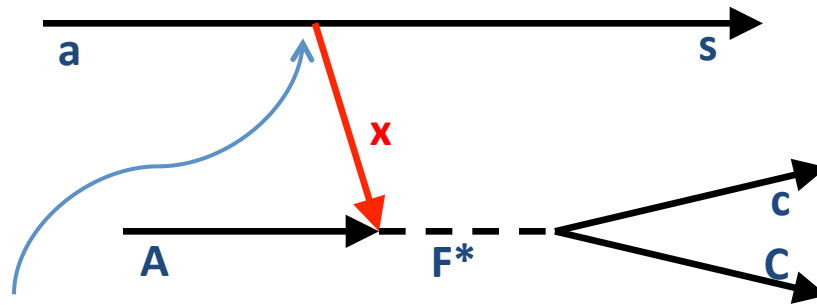
### Nuclear reaction theory required

- cross checks of the methods needed
- possible spurious contribution
- additional systematic errors (is the result model independent?)

... Indirect techniques are complementary to direct measurements  
Examples: Coulomb dissociation, ANC and Trojan horse method

# The Trojan horse method for resonant reactions

In the “Trojan Horse Method” (THM) the astrophysically relevant reaction, in particular  $A(x,c)C$ , is studied through the  $2 \rightarrow 3$  direct process  $\rightarrow A(a,c)C$ s:



Upper vertex: direct  $a$  breakup

The process is a transfer to the continuum where  $x$  is the transferred particle, e.g. a proton or an alpha particle

Standard R-Matrix approach cannot be applied to extract the resonance parameters of the  $A(x,c)C$  reaction because  $x$  is virtual  $\rightarrow$  Modified R-Matrix is introduced instead

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

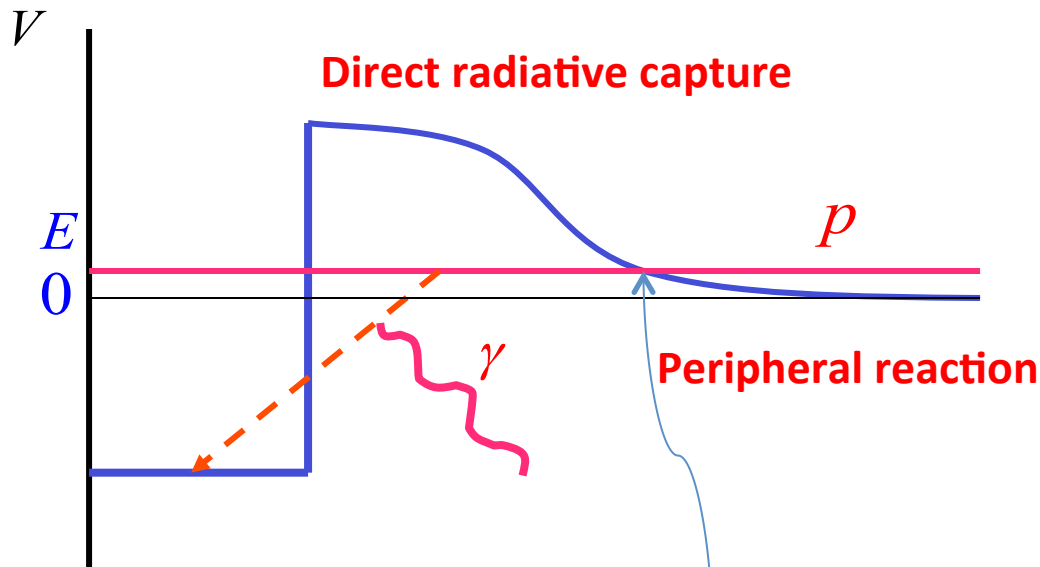
$$\frac{d^2\sigma}{dE_{Cc} d\Omega_s} \propto \frac{\Gamma_{(Cc)_i}(E) |M_i(E)|^2}{(E - E_{R_i})^2 + \Gamma_i^2(E)/4}$$

$M_i(E)$  is the amplitude of the transfer reaction (upper vertex) e.g. from FRESKO  
 $\rightarrow$  The resonance parameters can be extracted and in particular the strength

# Asymptotic Normalization Coefficient (ANC)

**Radiative  $p$  ( $\alpha$ ) capture** at stellar energies

- Classical **barrier penetration** problem



- **low energies**  $\Rightarrow$  capture at **large radii**
- **very small** cross sections

The cross section is determined by ANCs

$$\sigma \propto |M|^2$$

$$M = \left\langle I_{Bp}^A(r_{Bp}) \left| \hat{O}(r_{Bp}) \right| \psi_i^{(+)}(r_{Bp}) \right\rangle$$

$$I_{Bp}^A(r_{Bp}) \Big|_{r_B > R_N} \approx C_{Bp}^A \frac{W_{-\eta_A, l+1/2}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

**ANC  $\Rightarrow$  amplitude for tail of overlap function**

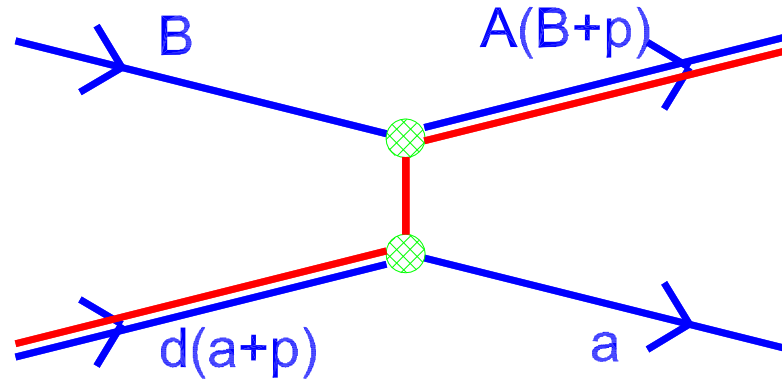
$$\sigma_{capture} \propto (C_{Bp}^A)^2$$

ANCs determine the capture cross section at low energies.

**How can we measure them?**

# Where do we get the ANCs from?

Transfer reactions



Transition amplitude:

$$M = \sum \langle \chi_f^{(-)} I_{Bp}^A | \Delta V | I_{ap}^d \chi_i^{(+)} \rangle$$

Peripheral transfer:

$$I_{Bp}^A \approx C_{Bp}^A \frac{W_{-n_A, l + \frac{1}{2}}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

$$\frac{d\sigma}{d\Omega} = (C_{Bp l_A j_A}^A)^2 (C_{ap l_d j_d}^d)^2 \frac{\sigma_{l_A j_A l_d j_d}^{DW}}{b_{Bp l_A j_A}^2 b_{ap l_d j_d}^2}$$

The transfer cross section is proportional to the needed ANCs  
 → From a measurement @ several tens of MeV one can get the zero energy S-factor for a radiative capture reaction

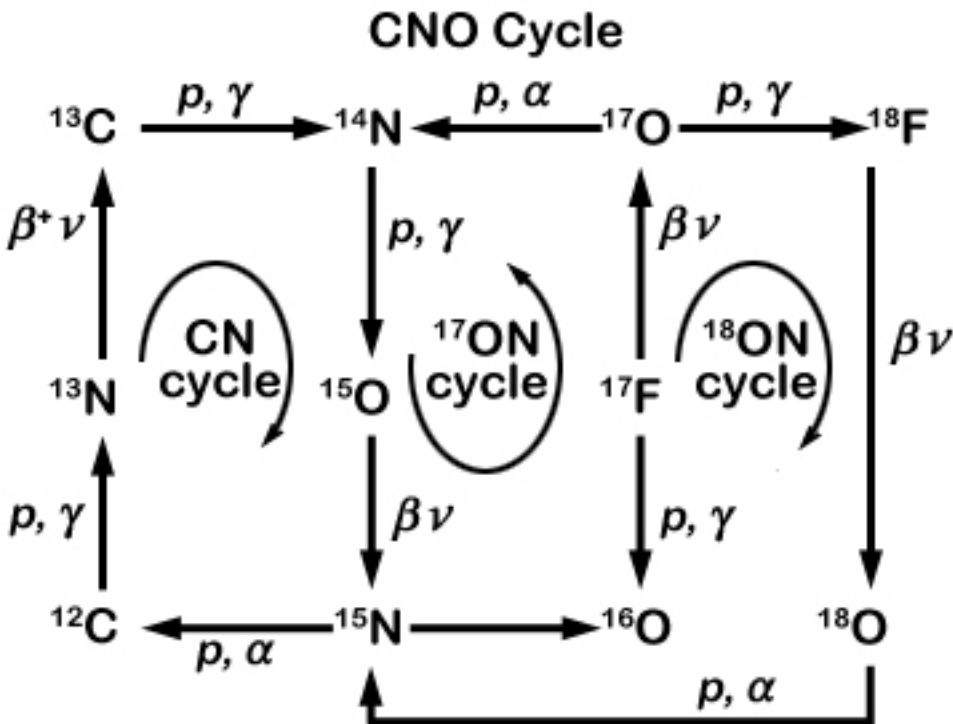
## Solar fusion cross sections. II. The $pp$ chain and CNO cycles

(Received 21 April 2010; published 12 April 2011)

The available data on nuclear fusion cross sections important to energy generation in the Sun and other hydrogen-burning stars and to solar neutrino production are summarized and critically evaluated. Recommended values and uncertainties are provided for key cross sections, and a recommended spectrum is given for  $^8\text{B}$  solar neutrinos. Opportunities for further increasing the precision of key rates are also discussed, including new facilities, new experimental techniques, and improvements in theory. This review, which summarizes the conclusions of a workshop held at the Institute for Nuclear Theory, Seattle, in January 2009, is intended as a 10-year update and supplement to 1998, *Rev. Mod. Phys.* **70**, 1265.

DOI: [10.1103/RevModPhys.83.195](https://doi.org/10.1103/RevModPhys.83.195)

PACS numbers: 26.20.Cd, 26.65.+t, 96.60.Jw, 25.10.+s



In the following, we will focus on recent results on nuclear reactions forming the CNO cycle

- H-burning in the core of main-sequence massive stars
- Nucleosynthesis at the bottom of the convection envelope (cool bottom process)

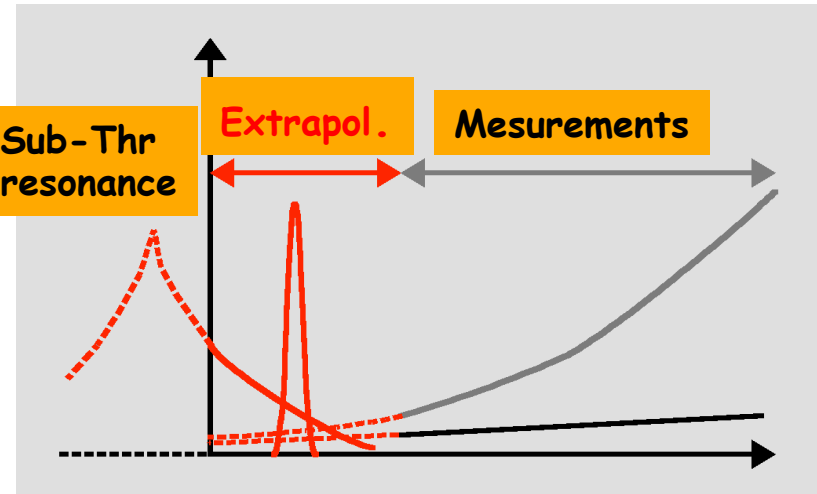
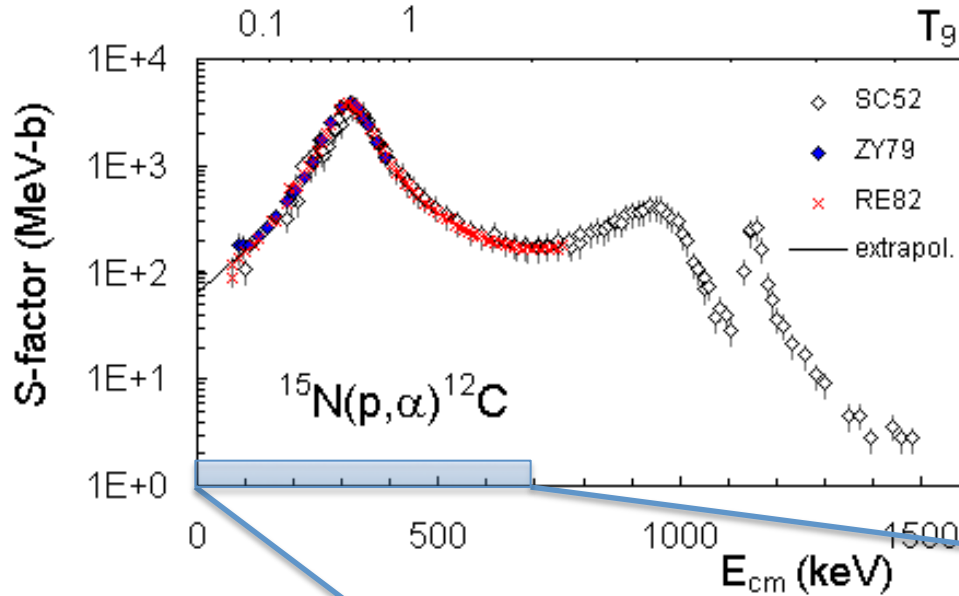


**Let's review some recent important results!**

# The $^{15}\text{N}(p,\alpha)^{12}\text{C}$ reaction

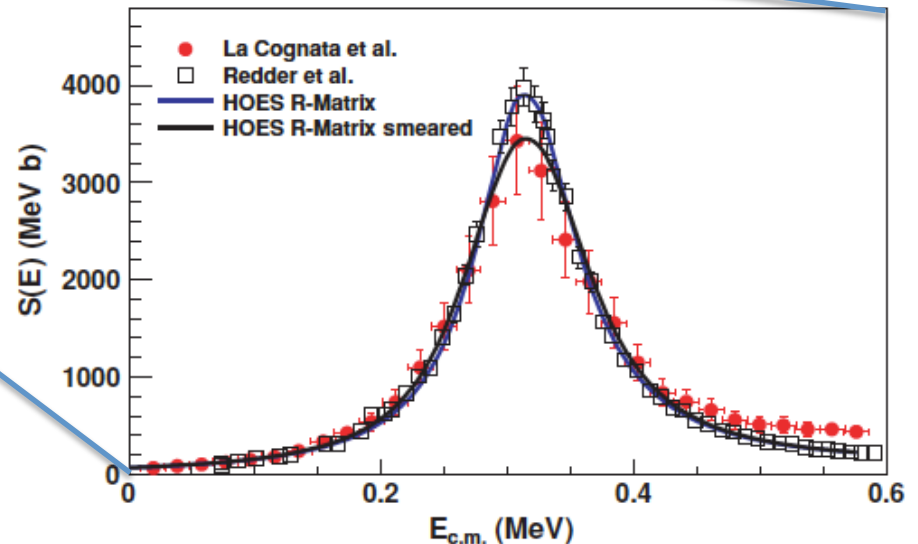
Angulo et al, Nucl Phys A656 (1999) 3

Gamow window: 13-40 keV  
Direct data stop at 70 keV



Two effects have to be taken into account:

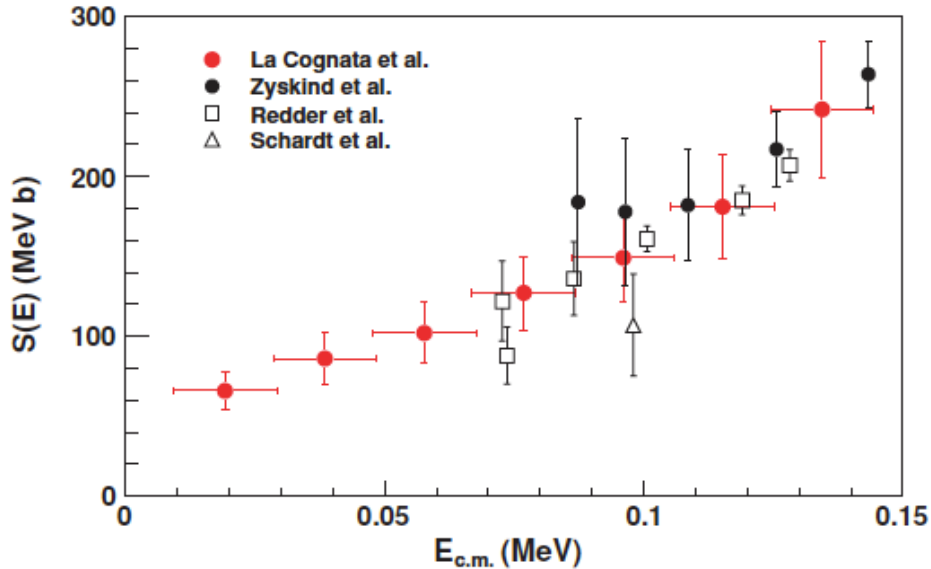
1. Energy resolution broadening experimental resonances
2. Non quasi-free effects at higher energies introducing spurious contributions not present in direct data



La Cognata et al, Phys Rev C 80 (2009) 012801



# The $^{15}\text{N}(p,\alpha)^{12}\text{C}$ reaction



**Gamow window: 13-40 keV**  
**Direct data stop at 70 keV**

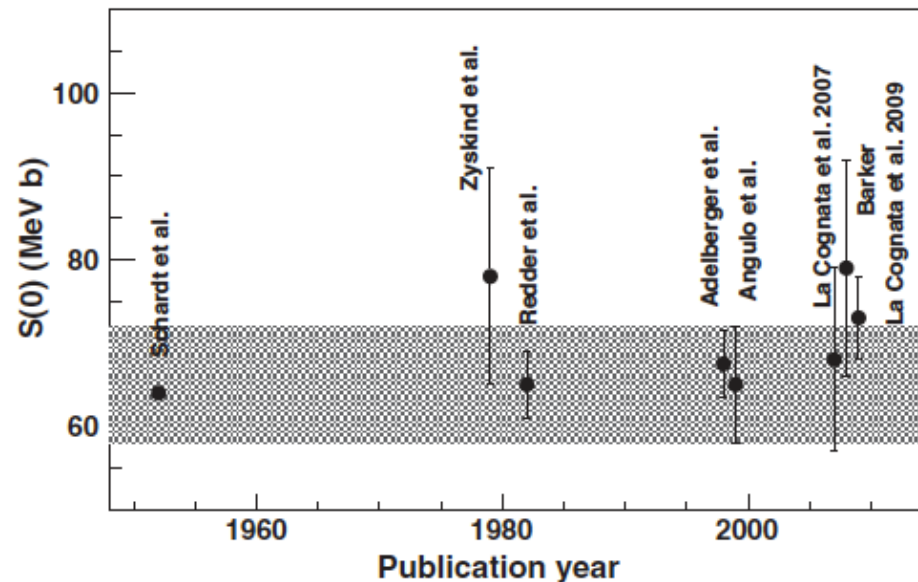
→ The cross section at 20 keV is about  $10^{-10}$  times smaller than at 70 keV so there is no way to measure the cross section inside the Gamow window

Summary of the available measurements of  $S(0)$  showing values as originally reported on the dates indicated.

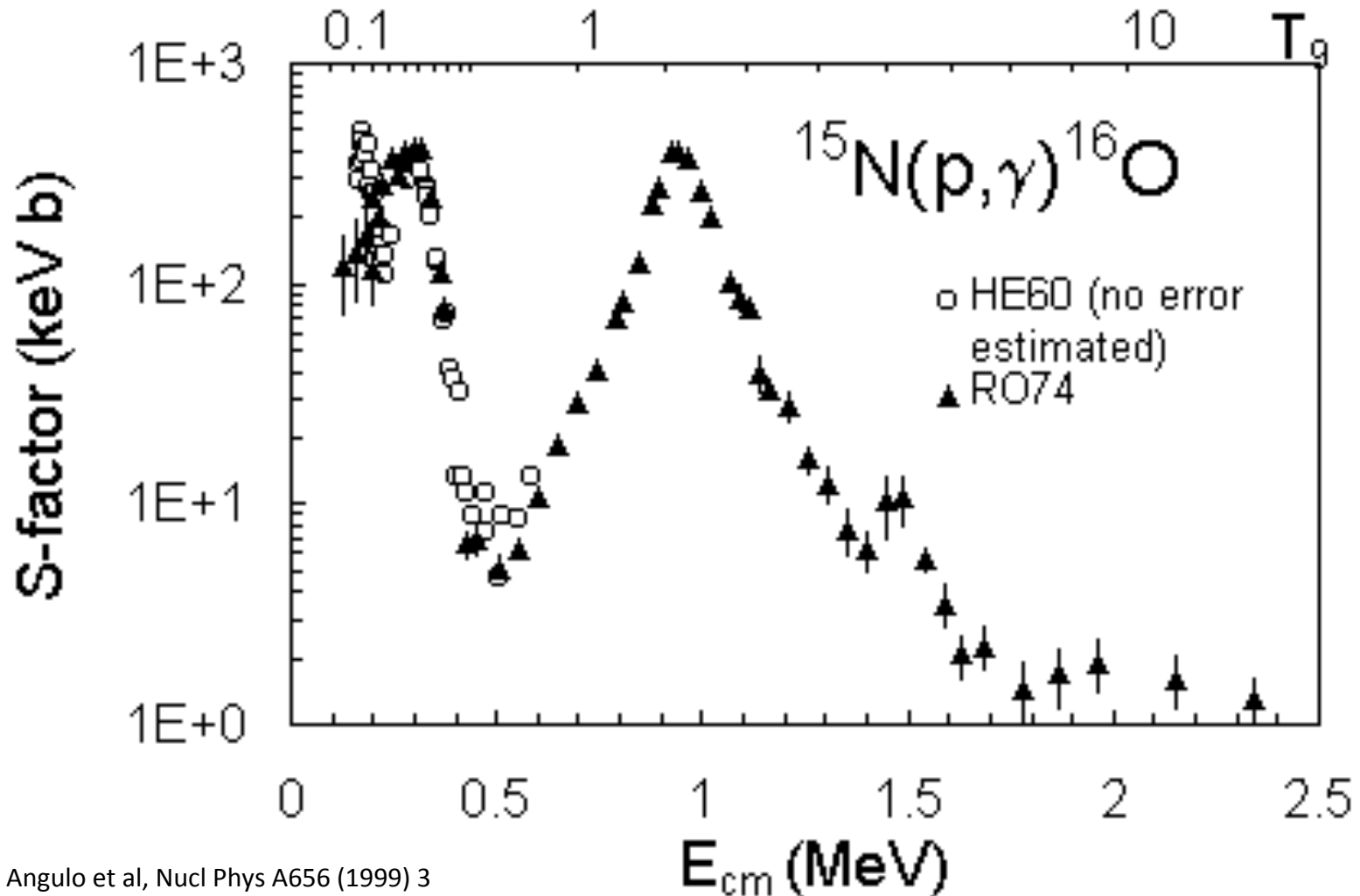
The shaded band corresponds to the NACRE compilation (Angulo et al., 1999).

The result from indirect measurements is slightly larger than given in compilations

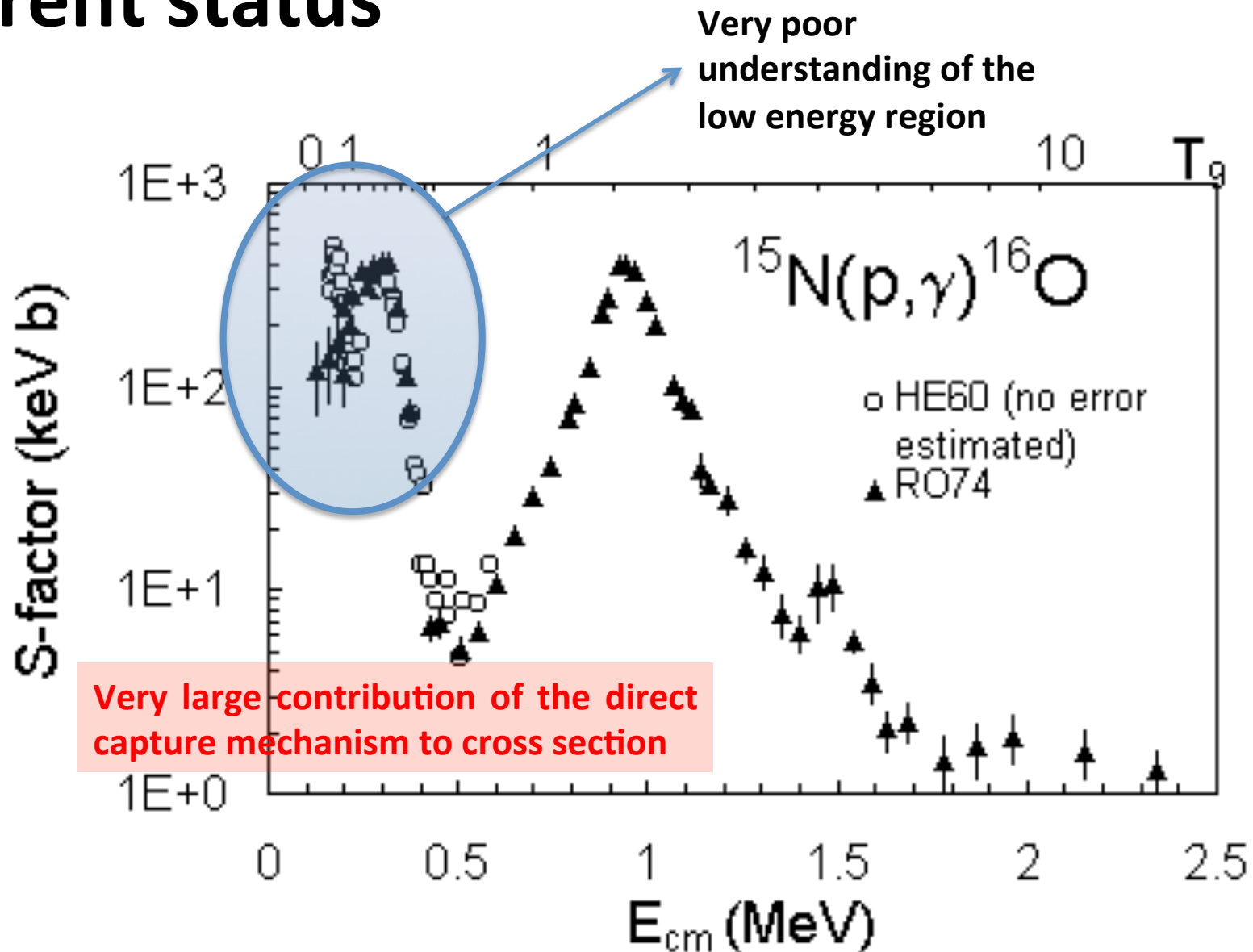
La Cognata et al, Phys Rev C 80 (2009) 012801



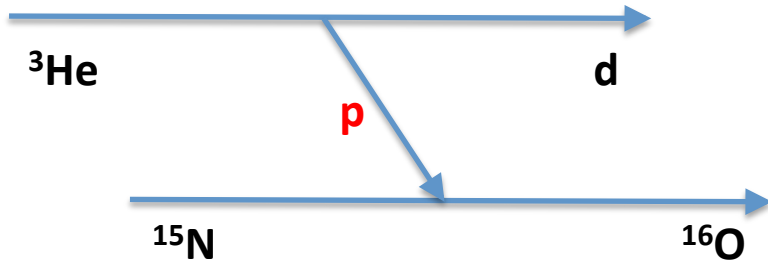
# The $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction: Current status



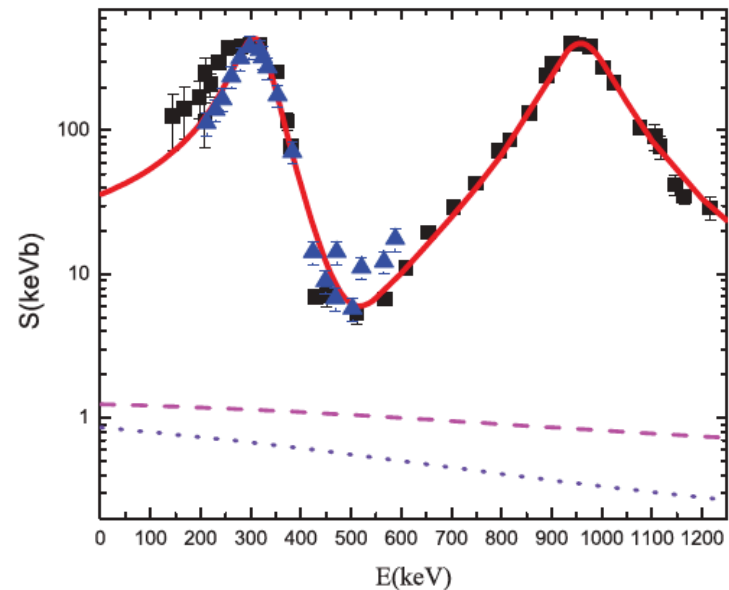
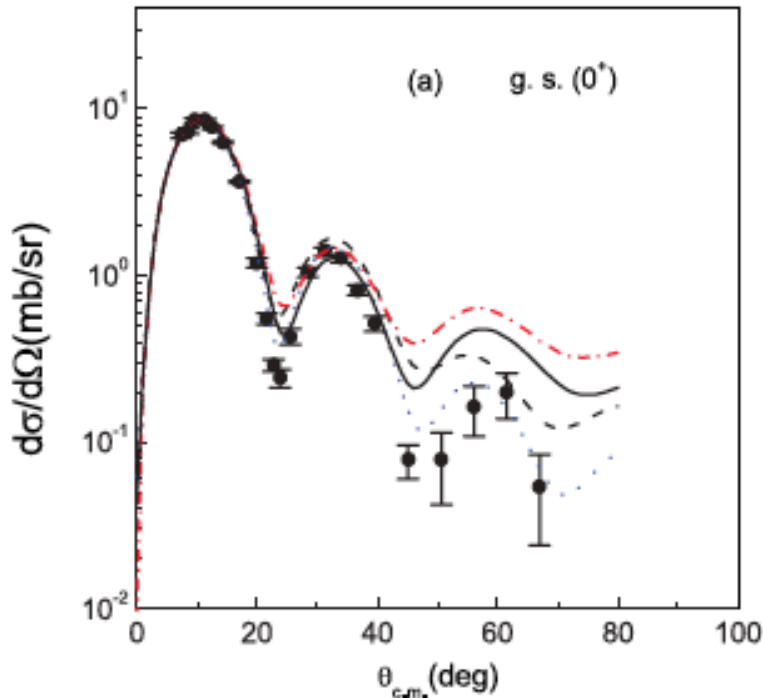
# The $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction: Current status



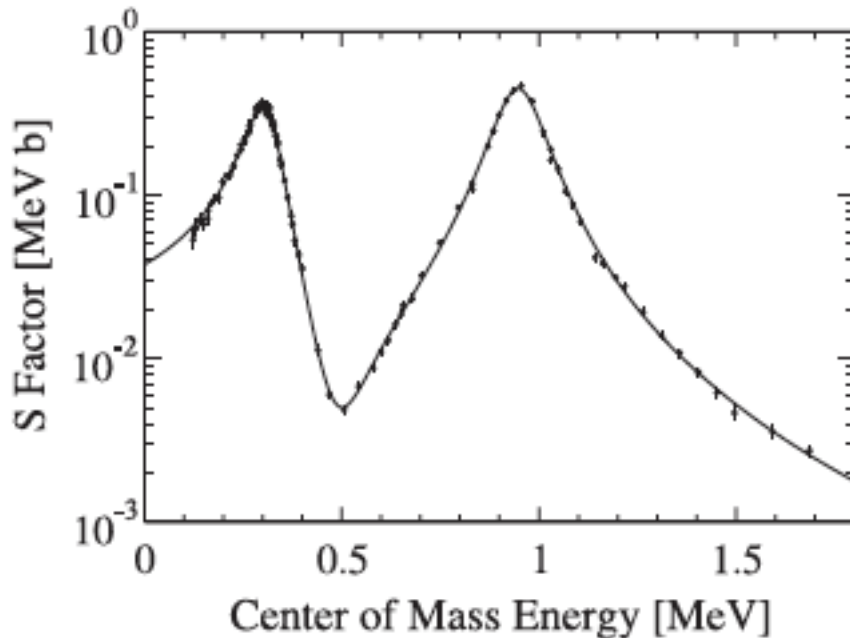
# The $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction: Indirect measurement through ANC



From the measurement of the angular distributions for the  $^{15}\text{N}(^3\text{He},\text{d})^{16}\text{O}$  reaction the ANC for the the  $^{16}\text{O} \rightarrow \text{p} + ^{15}\text{N}$  system can be deduced fixing the direct contribution to the total cross section

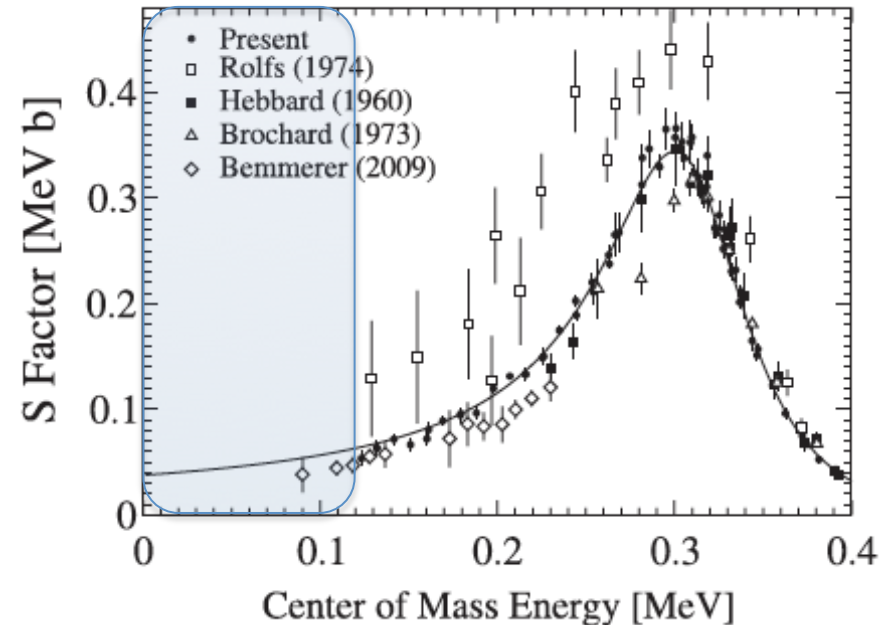


# The $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction: Direct measurement



High accuracy data used to perform R-matrix fitting to extrapolate the astrophysical  $S(E)$  factor down to the energies of interest

LeBlanc et al, Phys Rev C 82 (2010) 055804



**The Gamow window is not covered by the direct data stopping well above 100 keV**

**THE EXTRAPOLATION OF DIRECT DATA CONFIRMS THE RESULTS OF THE INDIRECT MEASUREMENT**

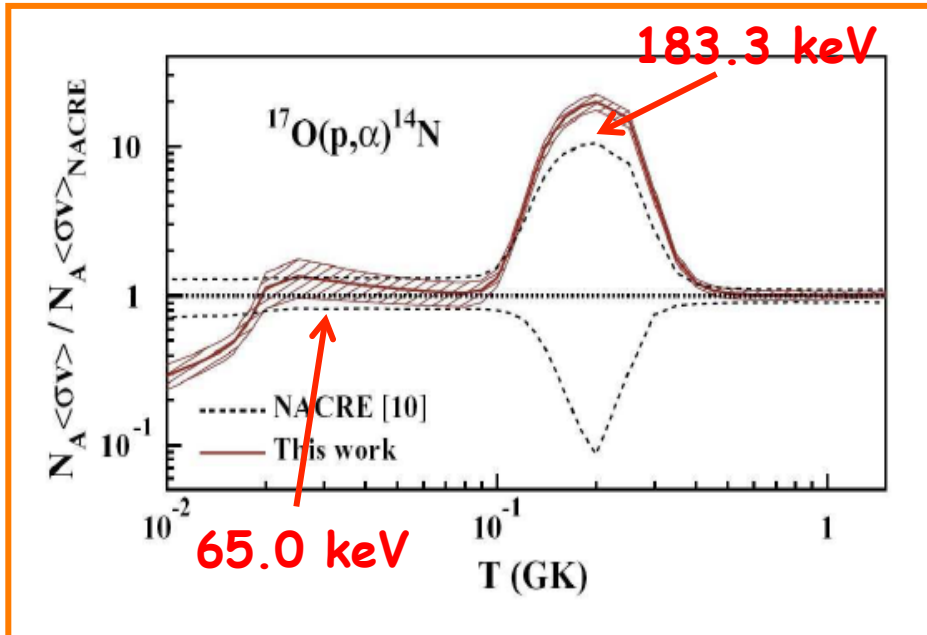
# The $^{17}\text{O}(p,\alpha)^{14}\text{N}$ reaction

## Summary of the current status

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

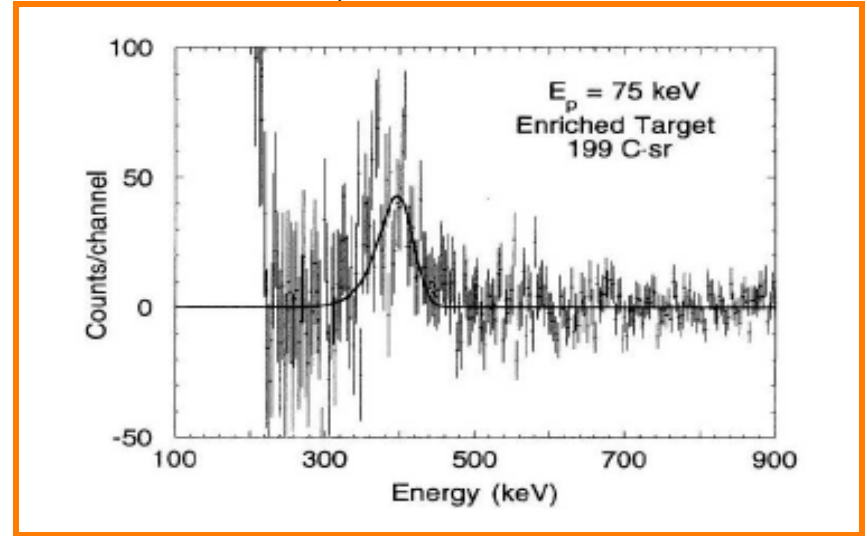


**LARGE UNCERTAINTIES !!**



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

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



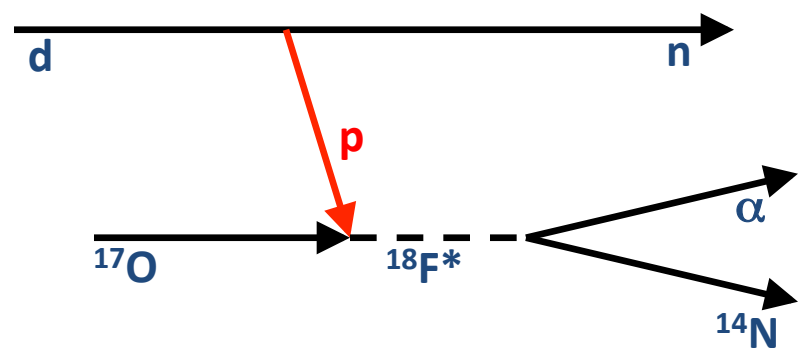
To reduce the uncertainties



**INDIRECT MEASUREMENT**

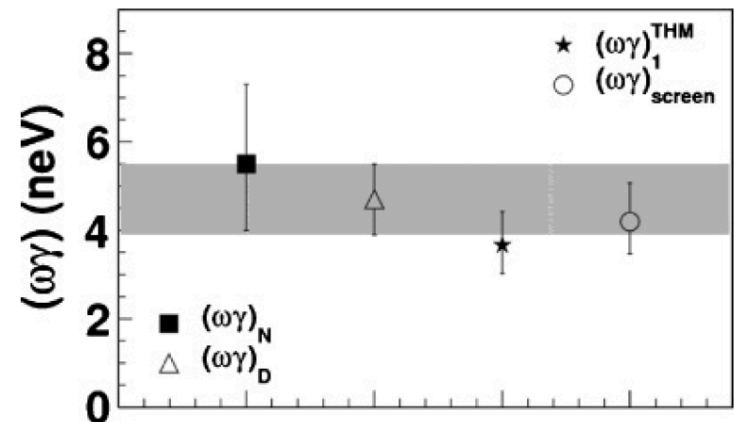
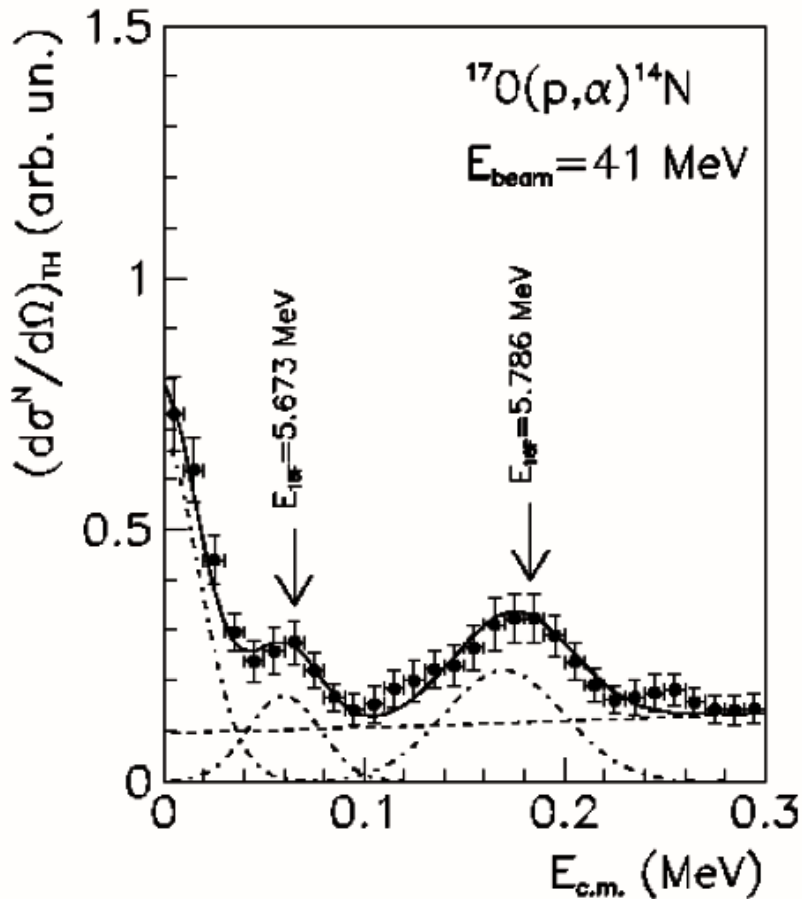
# The $^{17}\text{O}(p,\alpha)^{14}\text{N}$ reaction

Sergi et al, Phys Rev C 82 (2010) 032801

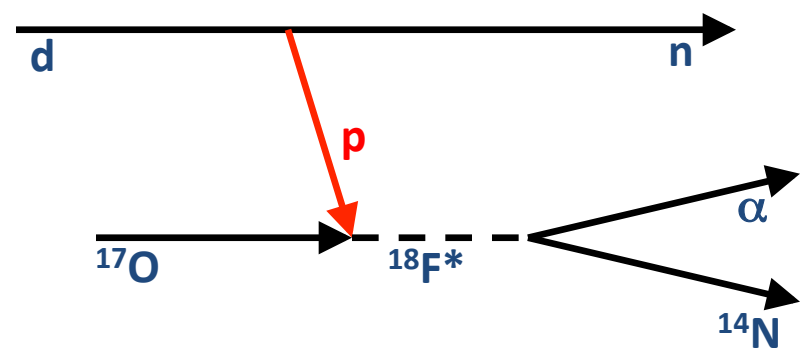


Extraction of:

- ✓ Resonance energies:  $E_{R1}=65\pm 5$  keV and  $E_{R2}=183\pm 5$  keV.
- ✓ Peak value of the two resonances:  $N_1=0.170\pm 0.025$  and  $N_2=0.220\pm 0.031$ , used to derive the resonance strengths  $\omega\gamma$  (case of narrow resonances).

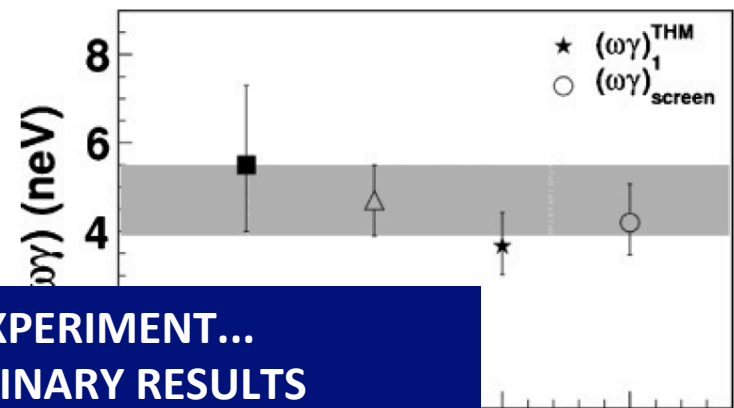
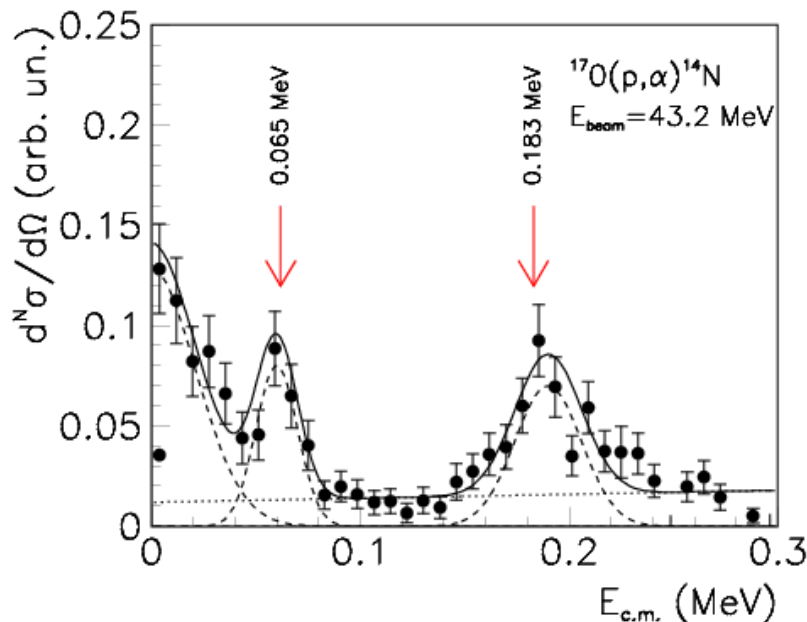
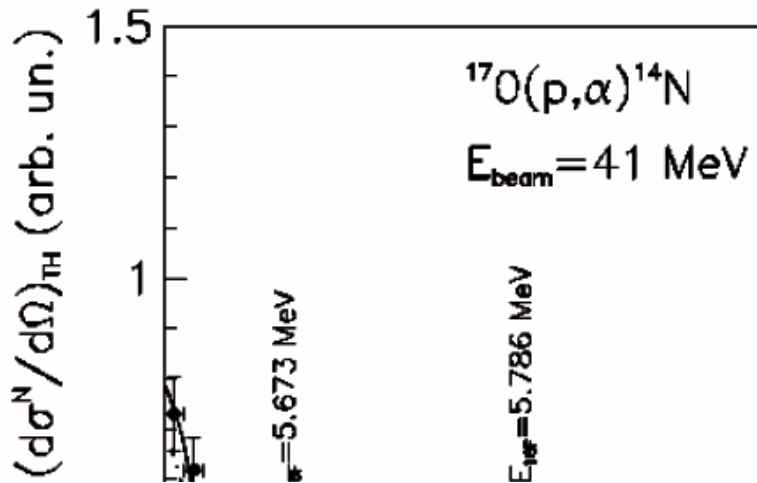


# The $^{17}\text{O}(p,\alpha)^{14}\text{N}$ reaction



Extraction of:

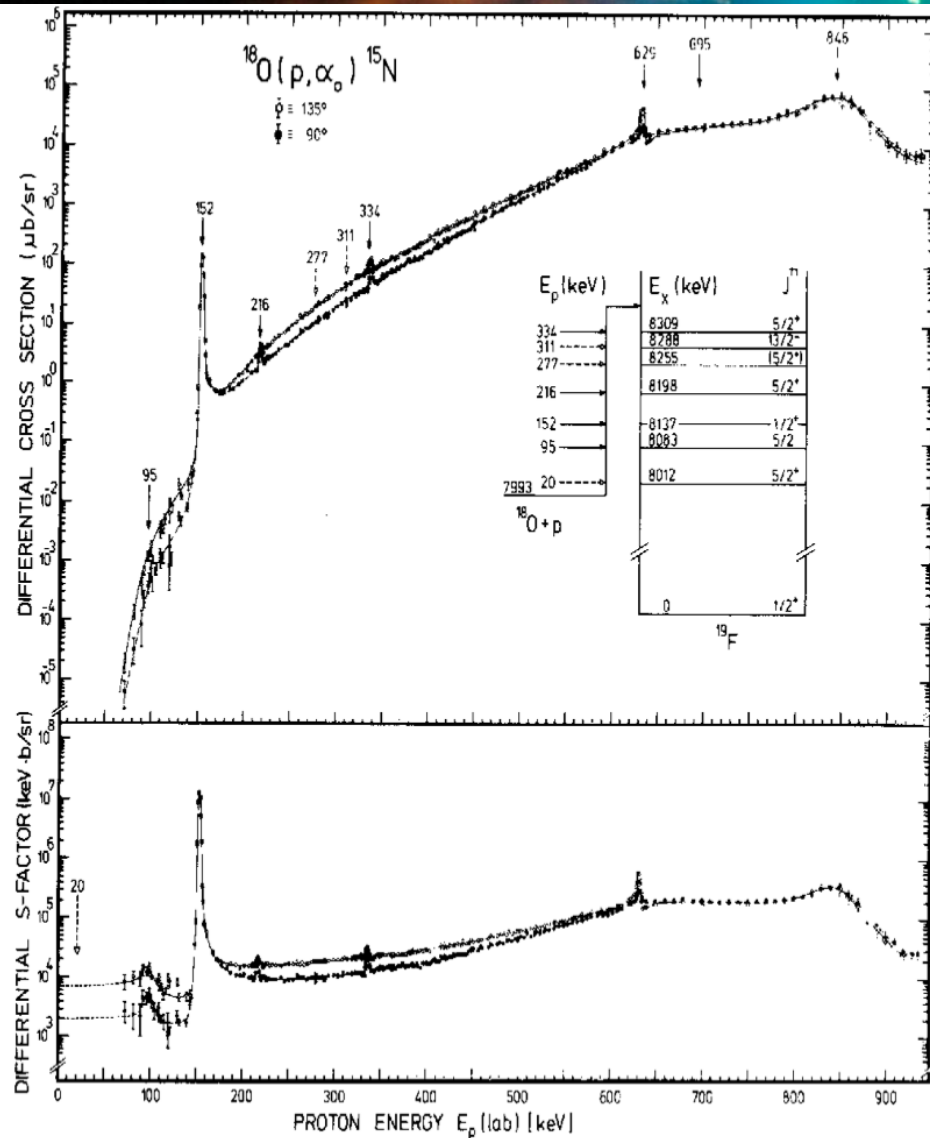
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**NEW EXPERIMENT...  
PRELIMINARY RESULTS**



# The $^{18}\text{O}(p,\alpha)^{15}\text{N}$ reaction



~50 resonances in the 0-7 MeV region

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

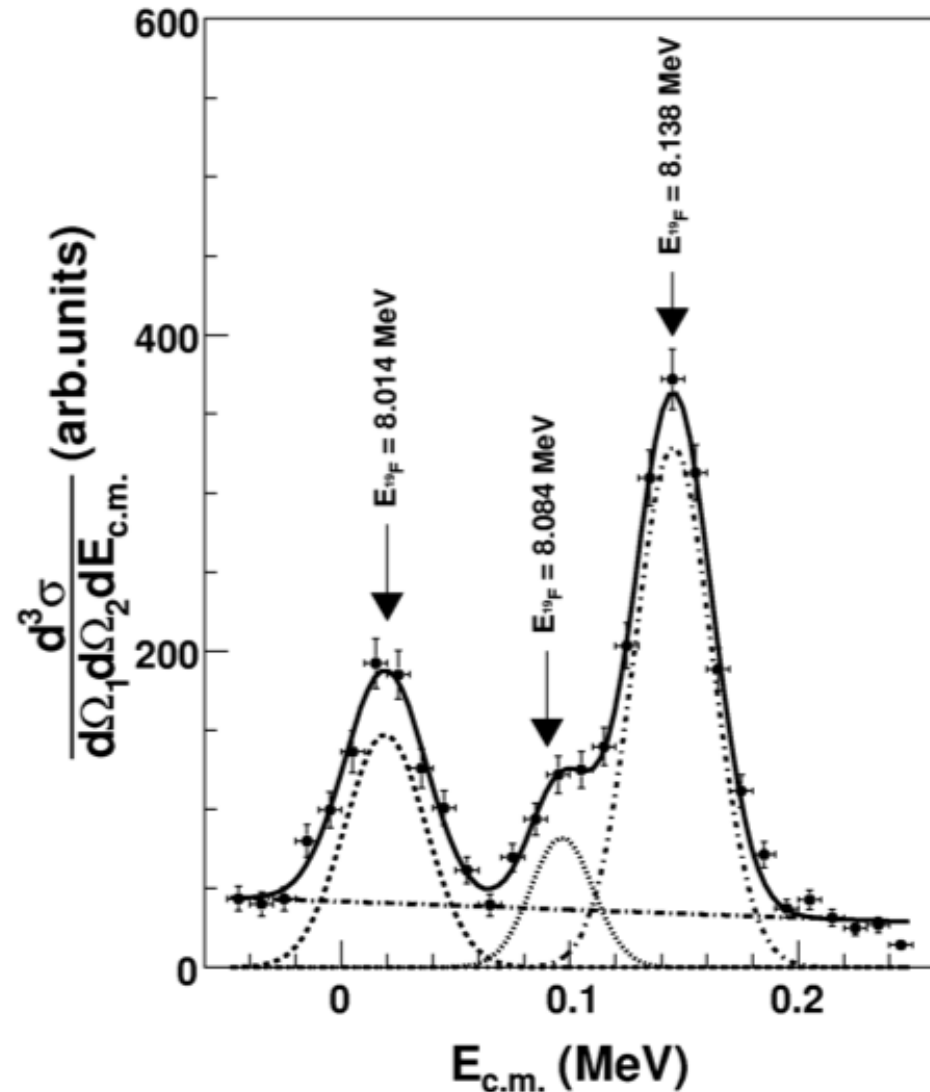
- 1- 20 keV  $J^\pi=5/2^+$
- 2- 144 keV  $J^\pi=1/2^+$  (well established)
- 3- 656 keV  $J^\pi=1/2^+$

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

**Subthreshold resonance at 7.9 MeV**

# The $^{18}\text{O}(p,\alpha)^{15}\text{N}$ reaction



Present case: narrow resonances.

THM data are smoothed out because of 17 keV energy spread

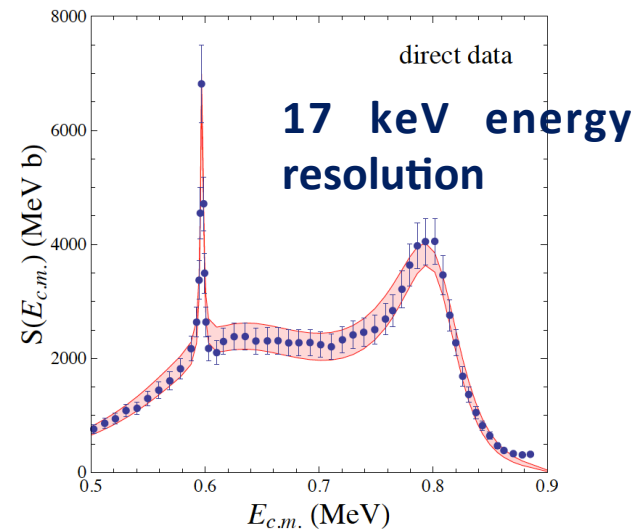
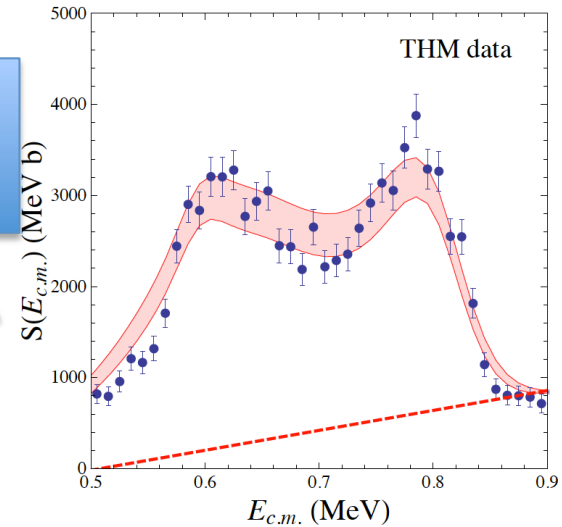
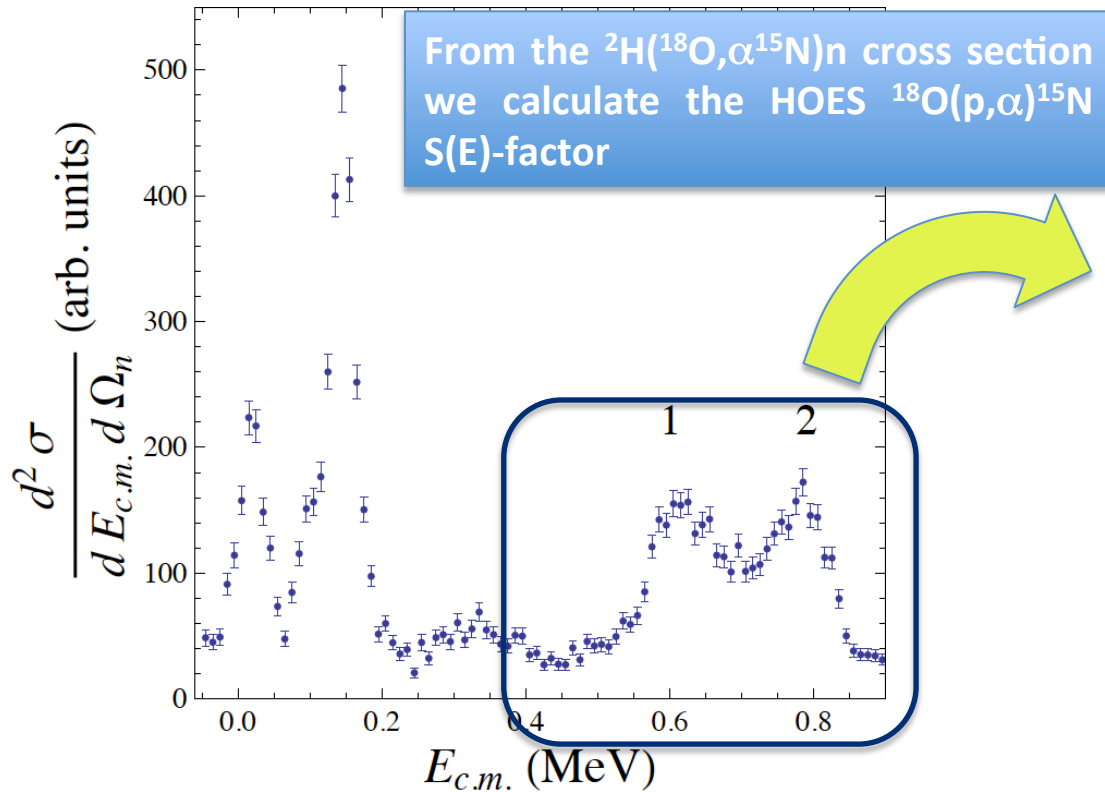
The energies and the  $\omega\gamma$  parameters are obtained from the fit of the experimental three-body cross section.

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	$1.8 \pm 0.3 10^{-7}$	$1.6 \pm 0.5 10^{-7}$

# Results and simultaneous R-matrix



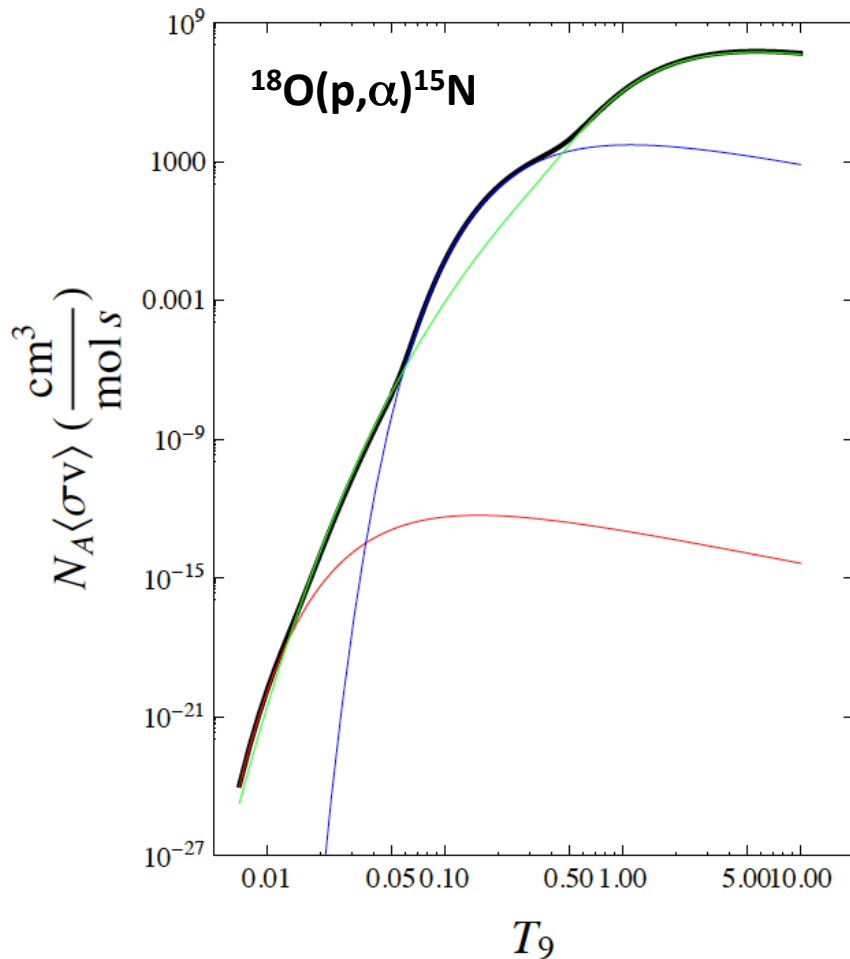
THM 2 $\rightarrow$ 3 cross section

1- 656 keV  $J^\pi=1/2^+$

2- 799 keV  $J^\pi=1/2^+$

**S t r o n g  
i n t e r f e r e n c e  
p a t t e r n**

# The reaction rate: input for astrophysical computations



**Thick black line:**  
**Total reaction rate**

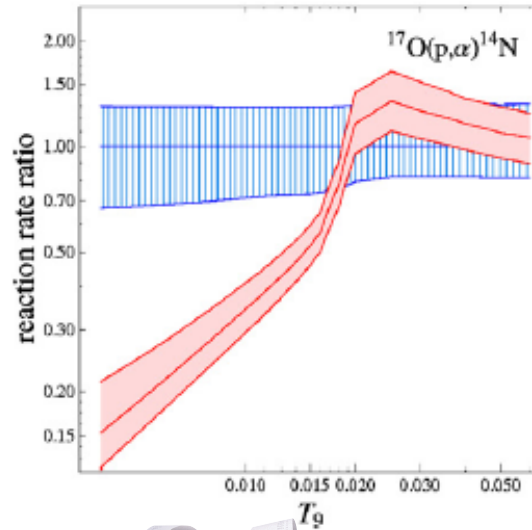
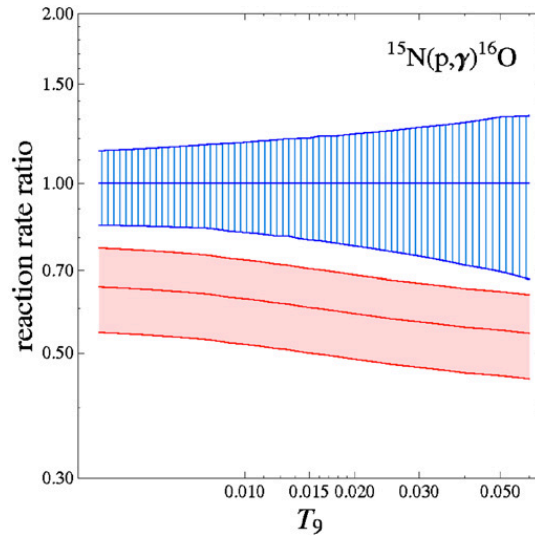
**Thin green line:**  
**656+799 keV contribution**

**Thin blue line:**  
**145 keV contribution**

**Thin red line:**  
**20 keV contribution**

**The role of the broad 656 and 799 keV resonances is important both at high and low temperatures**

# Nuclear data as an input to astrophysics



Etc. ...



THE ASTROPHYSICAL JOURNAL, 729:3 (21pp), 2011 March 1

doi:10.1088/0004-637X/729/1/3

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## DEEP MIXING IN EVOLVED STARS. I. THE EFFECT OF REACTION RATE REVISIONS FROM C TO AI

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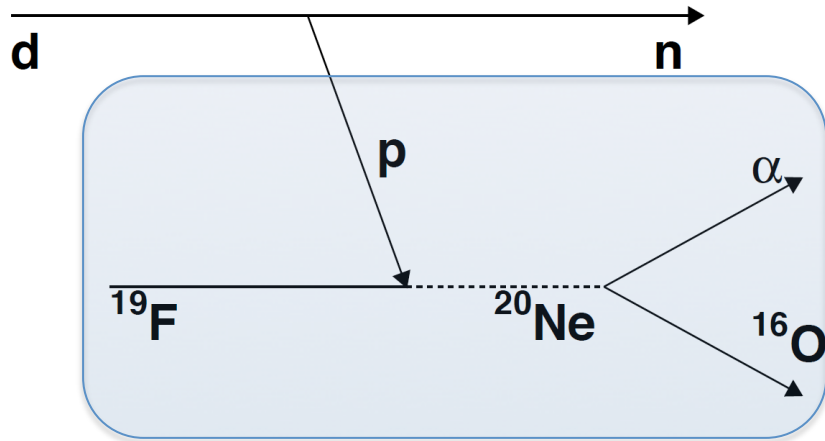
<sup>2</sup> Dipartimento di Metodologie Fisiche e Chimiche per l'Ingegneria, Università di Catania, Catania, Italy

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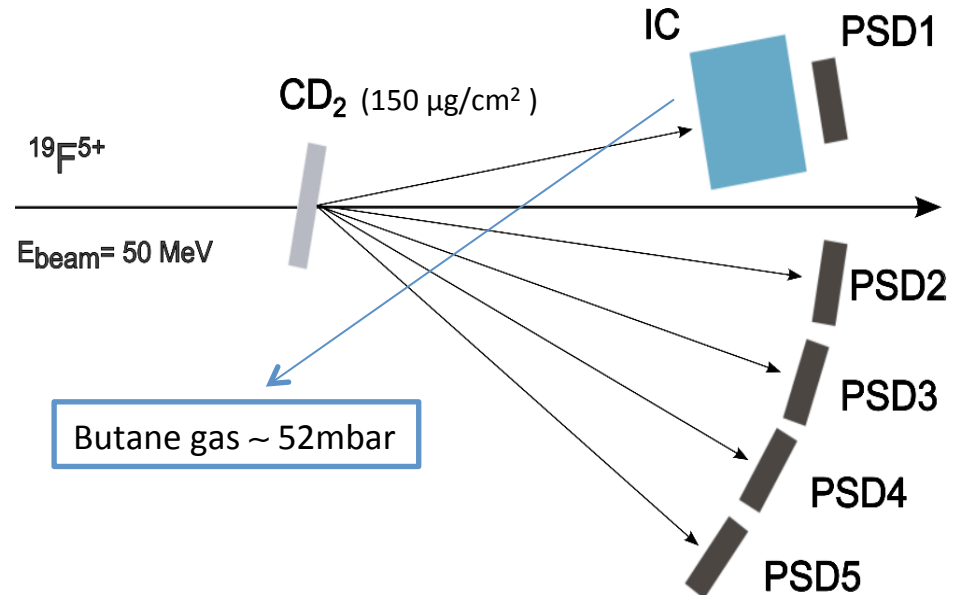
Received 2010 August 31; accepted 2010 December 17; published 2011 February 3

# From CNO to NeNa cycle: the experimental investigation of the $^{19}\text{F}(p,\alpha)^{16}\text{O}$ reaction

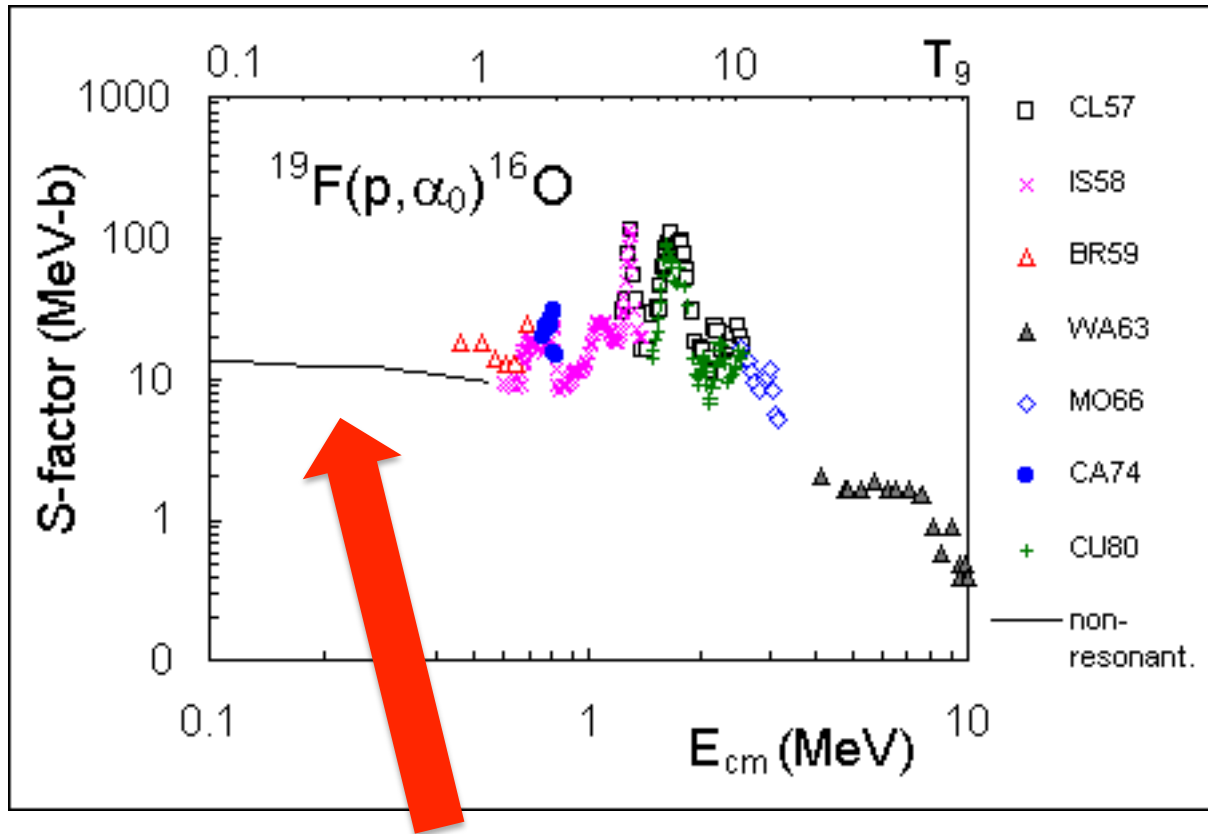


$d$ : Trojan horse nucleus  $p+n$   
 $B=2.2$  MeV  $|p_s|=0$  MeV/c  
 $n$ : spectator  
 $p$ : participant

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



# The $^{19}\text{F}(p, \alpha_0)^{16}\text{O}$ reaction



Below  $E_{cm} = 460$  keV, where data do not exist, a non resonant contribution is calculated for s-capture. The S-factor was adjusted as to the lower experimental points between 460 and 600 keV

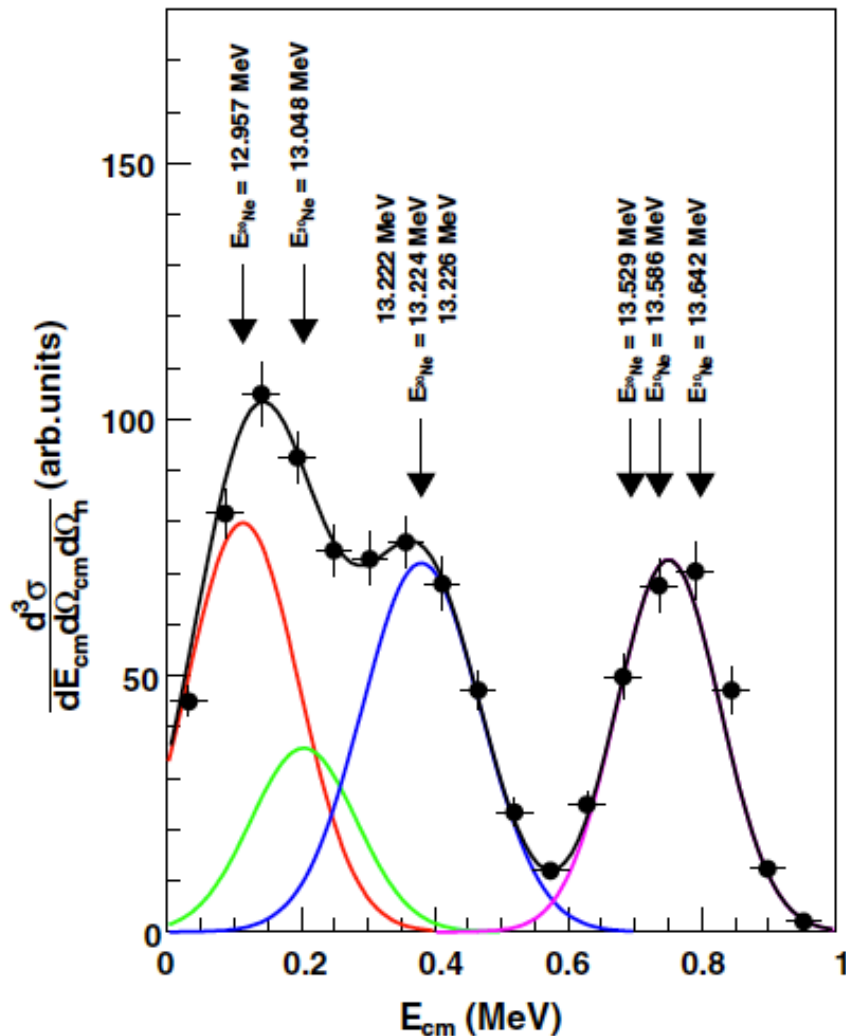
The S(E) factor shows several resonances around 1 MeV.

Breuer (1959) claimed the occurrence of two resonances at around 400 keV

Unpublished data (Lorentz-Wirzba 1978) suggests that no resonance occurs

$\alpha_0$  is the dominant channel in the energy region of astrophysical interest

# From THM to OES S-factor: observed $^{20}\text{Ne}$ states



Normalized coincidence yield obtained by dividing the selected coincidence yield by the product of the phase-space factor and of the  $p$ - $n$  momentum distribution

Three resonance groups corresponding to  $^{20}\text{Ne}$  states at:

12.957 and 13.048 MeV;

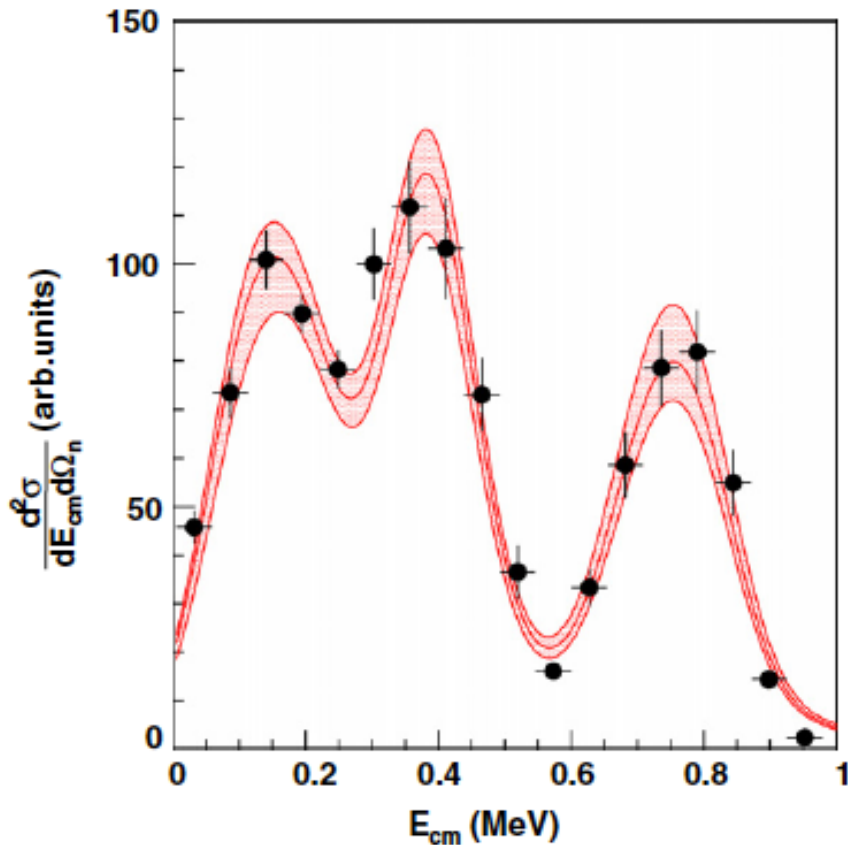
13.222, 13.224, and 13.226 MeV;

13.529, 13.586, and 13.642 MeV.

The normalized yield was fitted simultaneously with four Gaussian curves to separate the resonance contributions



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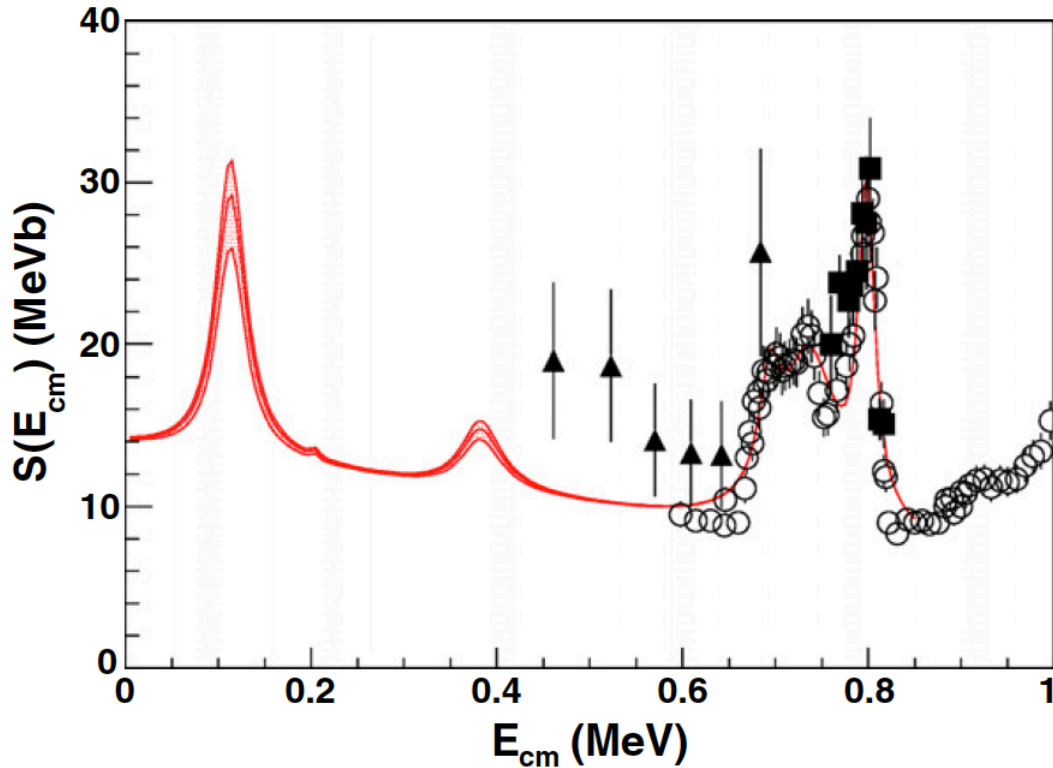
13.222, 13.224, and 13.226 MeV;

13.529, 13.586, and 13.642 MeV.

**HOES R-matrix to extract the resonance parameters**

The normalized yield was fitted simultaneously with four Gaussian curves to separate the resonance contributions

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



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

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

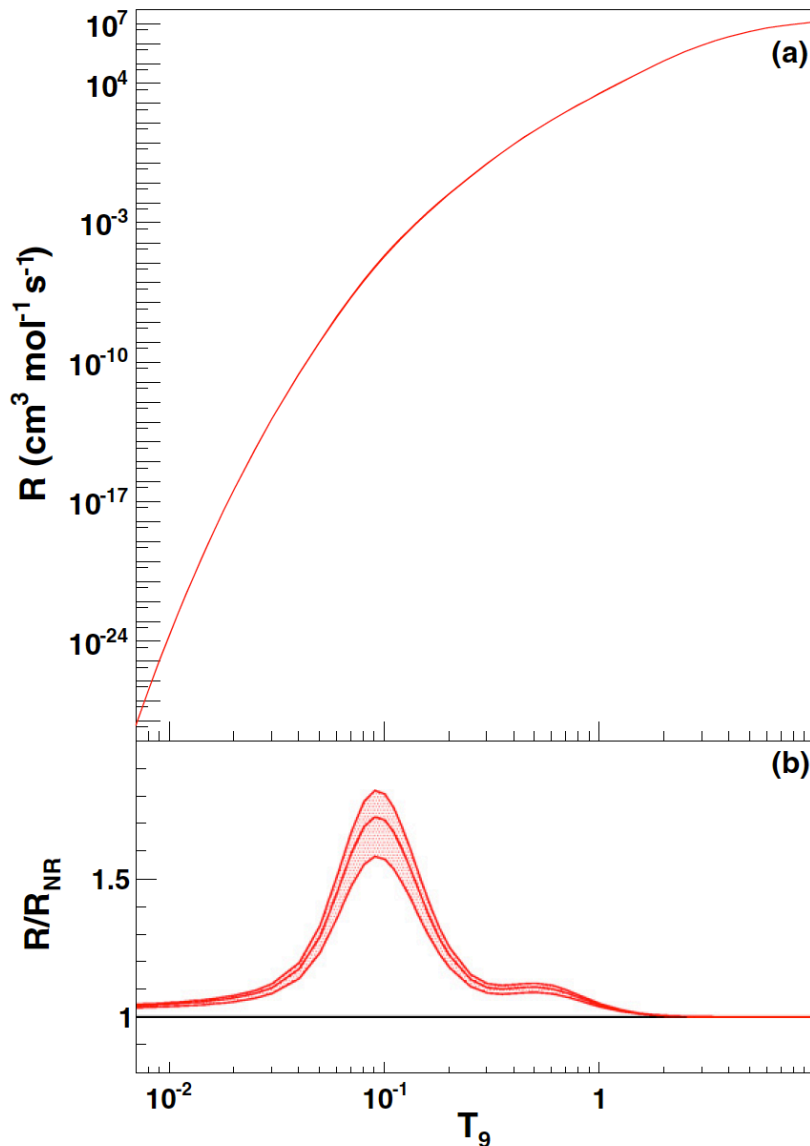
Below 0.6 MeV, the resonance parameters were obtained from the modified  $R$ -matrix fit

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

Because of spin-parity, only the resonance at 12.957 MeV provide a significant contribution

Gamow window: 27-94 keV  $\rightarrow$  this level lies right at edge of the Gamow window for extramixing in AGB stars

# $^{19}\text{F}(p,\alpha)^{16}\text{O}$ reaction reaction rate

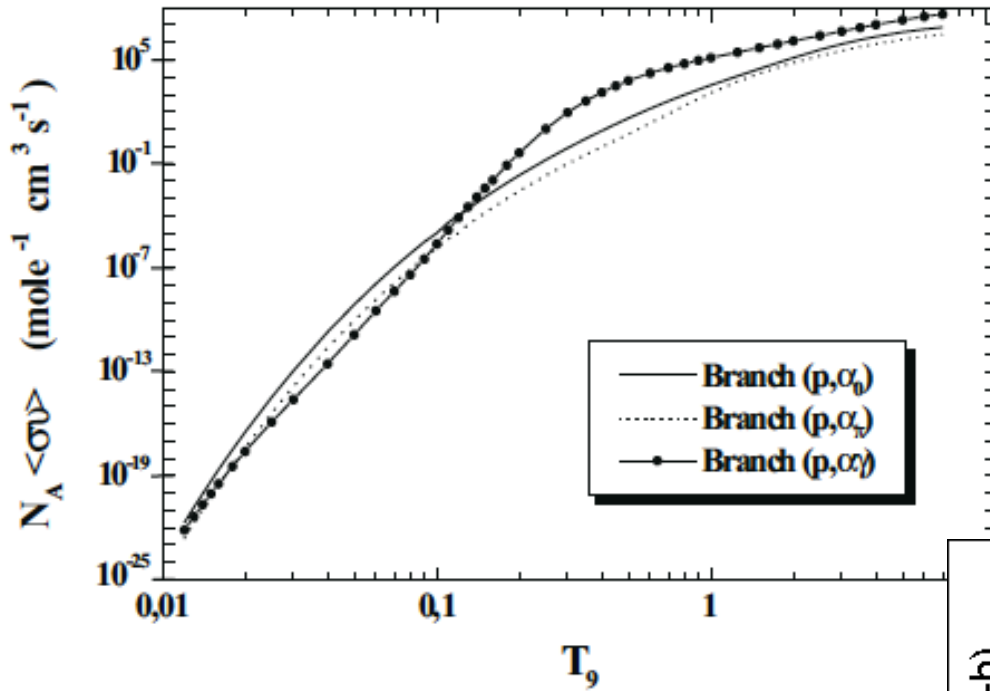


(a) Reaction rate for the  $^{19}\text{F}(p,\alpha_0)^{16}\text{O}$ . Upper and lower limits are also given, though they are barely visible because of the large rate range.

(b) Ratio of the reaction rate in panel (a) to the rate of the  $^{19}\text{F}(p,\alpha_0)^{16}\text{O}$  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 astrophysics (for instance,  $T_9 \sim 0.04$  in AGB stars)

# Perspectives

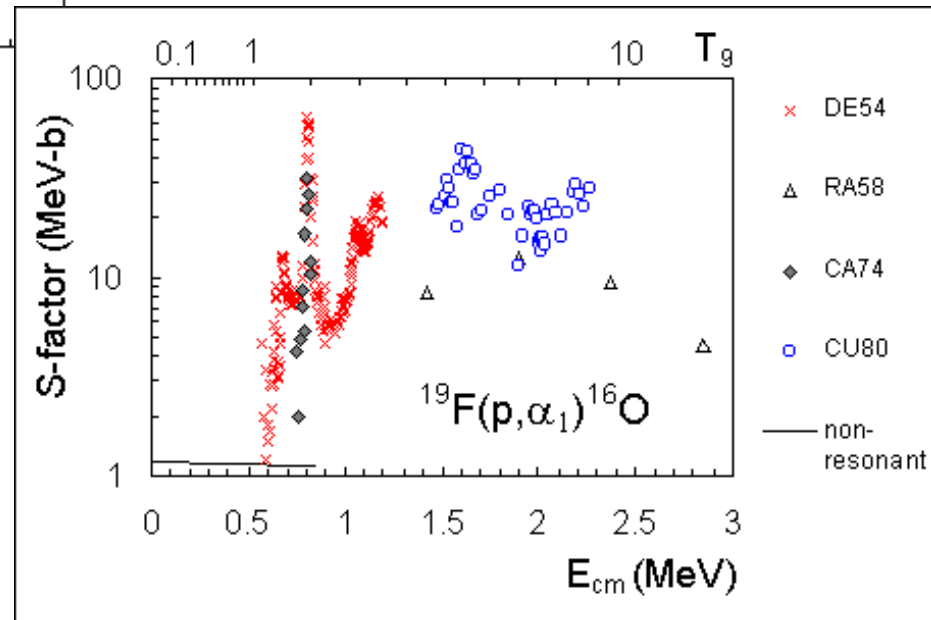


The contribution of the  $\alpha_0$  channel only has been addressed since this is currently regarded as the dominant one at temperatures relevant for AGB stars

← Spyrou et al. (2000)

**$\alpha_1$  channel is even more uncertain!**

An experimental campaign is scheduled to extract the cross section for the  $\alpha_1$  channel and to improve the spectroscopy of the resonances discussed here.



# The ASFIN Collaboration




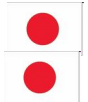











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