Measurements of $^{13}C + {}^{12}C$ and $^{4}He + {}^{64}Zn$ fusion cross section at deep sub-barrier energies in IFIN-HH

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Introduction

The origin of chemical elements in the Universe:
- Big Bang Nucleosynthesis
- Stellar Nucleosynthesis

Nuclear Physics for Astrophysics (NPA) - to determine reaction rates in the stars

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} S(E_0) \int_0^\infty exp\left(-\frac{E}{kT} - \frac{b}{E^{1/2}}\right) dE$$

E_0 is the Gamow energy

$$E_0 = \left(\frac{bkT}{2}\right)^{2/3} = 1.22(Z_1^2 Z_2^2 \mu T_6^2)^{1/3}\ keV$$

Δ is the energy window width

$$\Delta = \frac{4}{3^{1/2}}(E_0 kT)^{1/2}$$
$$= 0.749\left(Z_1^2 Z_2^2 \mu T_6^5\right)^{1/6}\ keV$$

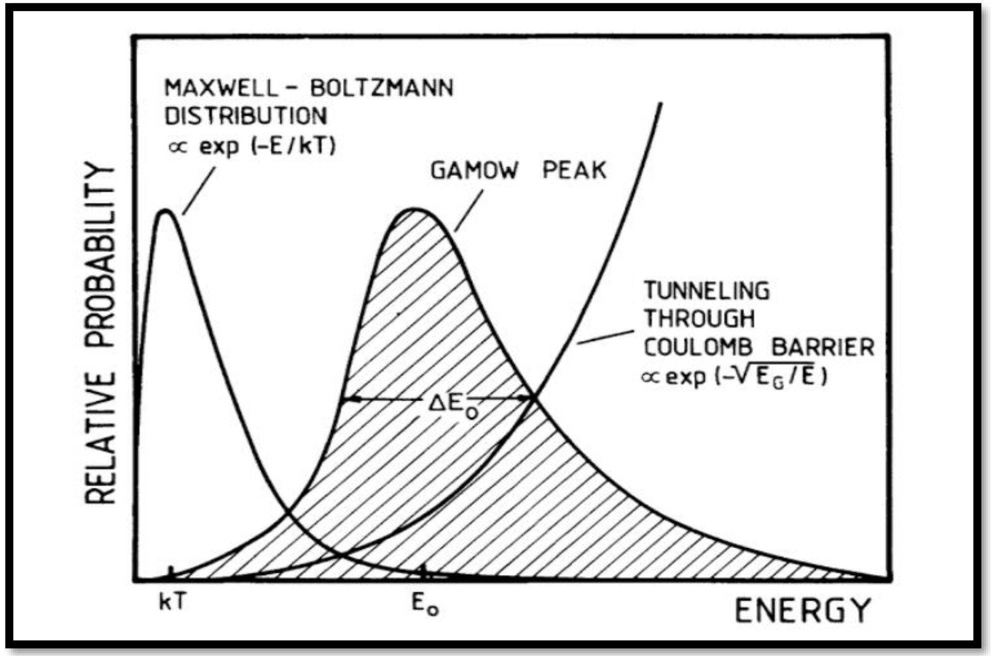


Figure 1. Gamow peak, the region where reactions relevant for nuclear astrophysics occur. Claus E. Rolfs and William S. Rodney [1].

Motivation

Possibility for direct nuclear astrophysics measurements induced by light ions at IFIN-HH, with:

- 3 MV Tandetron accelerator!
  - high currents
  - stability of beam energies
  - appropriate energy range

- main problems in direct measurements are:
  - low reaction cross sections
  - high radiation background

Despite this, we benefit of an Ultra low background at μBq laboratory placed in Unirea salt mine!

- Low background laboratory: GammaSpec

- NAG (Nuclear Astrophysics Group) laboratory in IFIN-HH

The $^{13}C+^{12}C$ Experiment

•**Important reaction in nuclear astrophysics**: $^{12}C+^{12}C$ (carbon burning scenario)

•Very difficult to measure, cross section fluctuating due to resonances!

No resonances observed in 13C+12C!
Obs: for most energies, the 12C+12C cross sections are suppressed!

•Only at resonant energies, the 12C+12C cross sections match with those of 12C+13C and 13C+13C!

• **Proposed tests using $^{13}C+^{12}C$, measured in the Gamow window.**

Therefore, the study of $^{13}C+^{12}C$ in the Gamow energy region would be useful to understand the reaction dynamics at such low energies

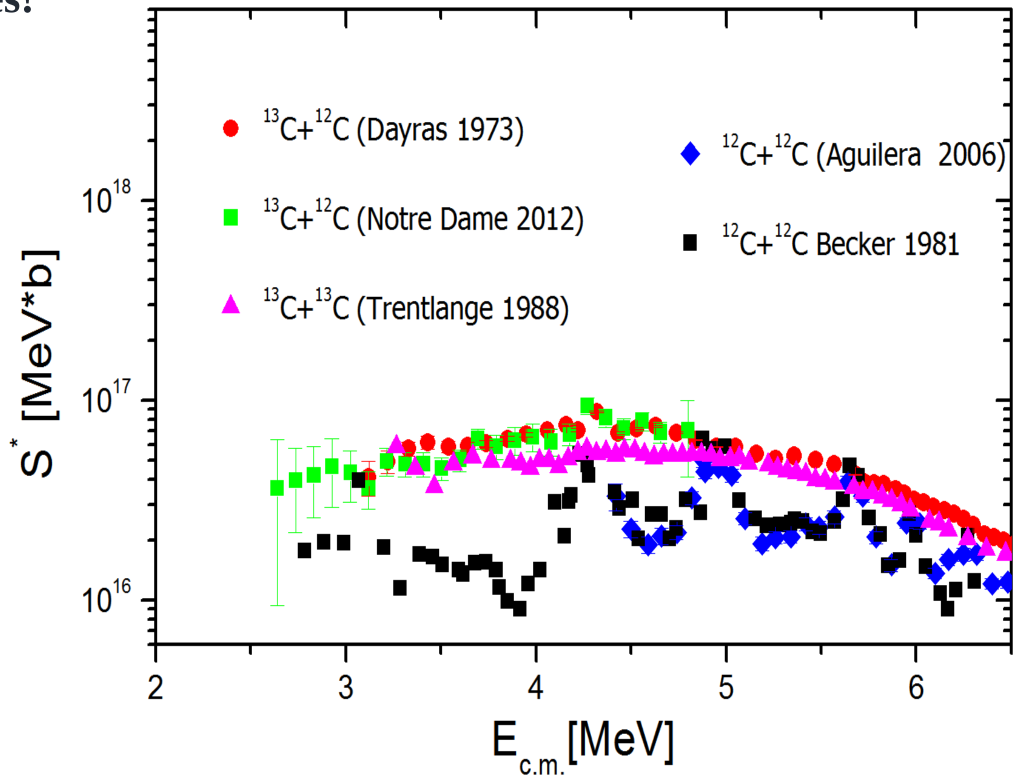
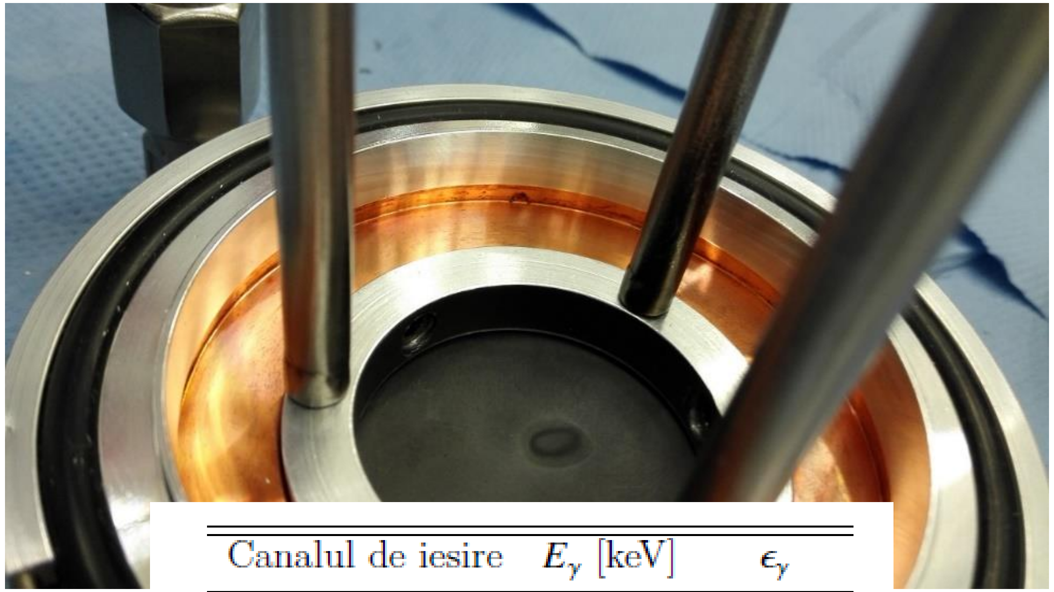


Figure 2. Modified astrophysical S factor

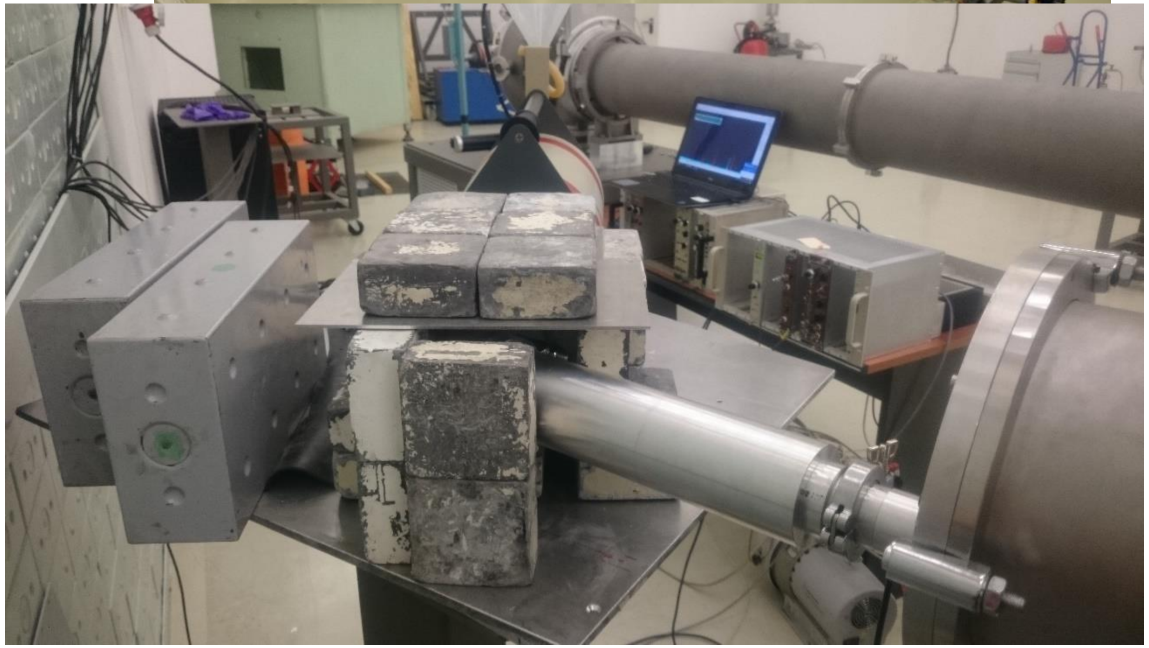
The $^{13}C+^{12}C$ Experiment

- ^{13}C beam energy 11 – 4.6 MeV (E_{cm}=5,3 – 2.2 MeV), in steps of 0.2 MeV

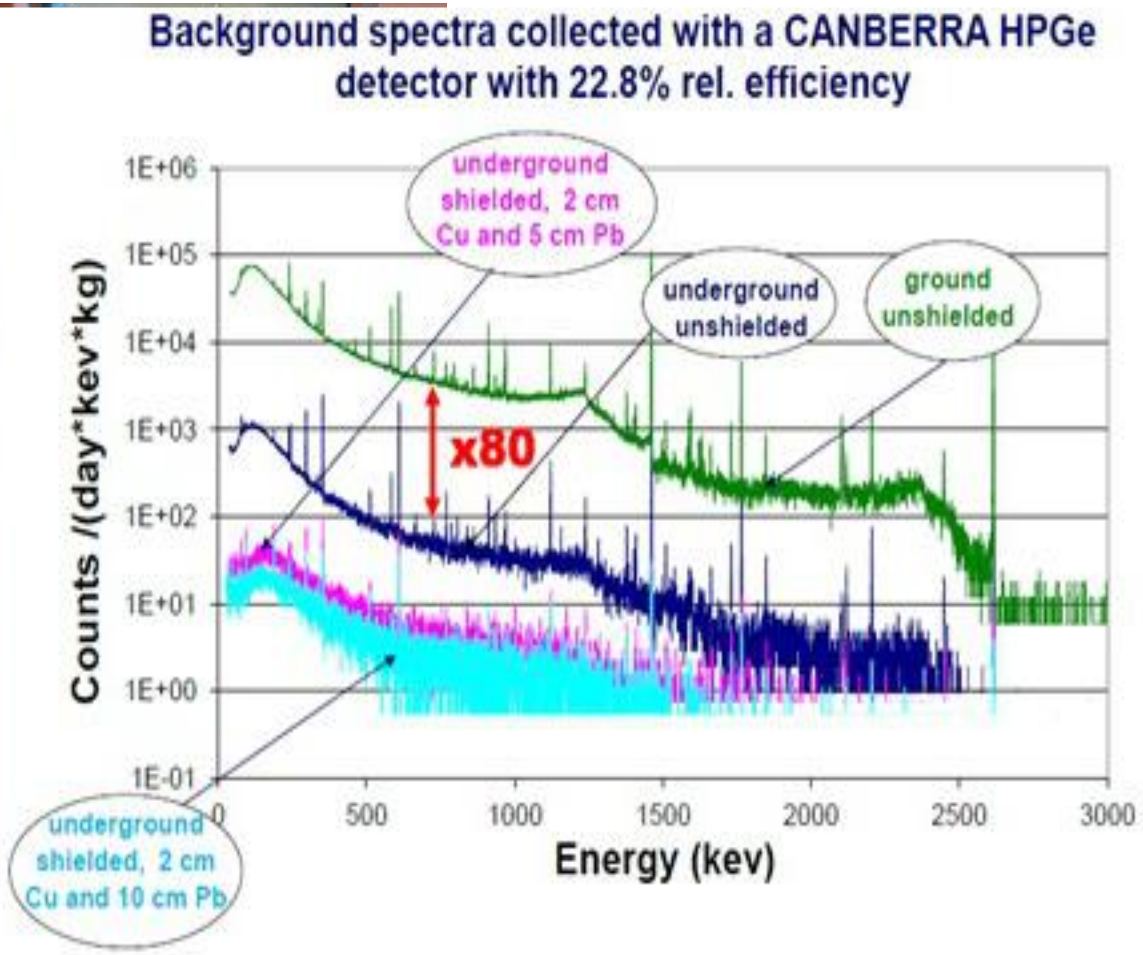


Canalul de iesire	E_γ [keV]	ϵ_γ
$^{21}Ne+\alpha$	350.7	0.182%
$^{23}Na+pn$	439.9	0.199%
$^{24}Na+p$	472.2	0.205%
$^{24}Mg+n$	1368.63	0.287%

$$^{12}C(^{13}C,p)^{24}Na$$



μBq laboratory



Cross section determination

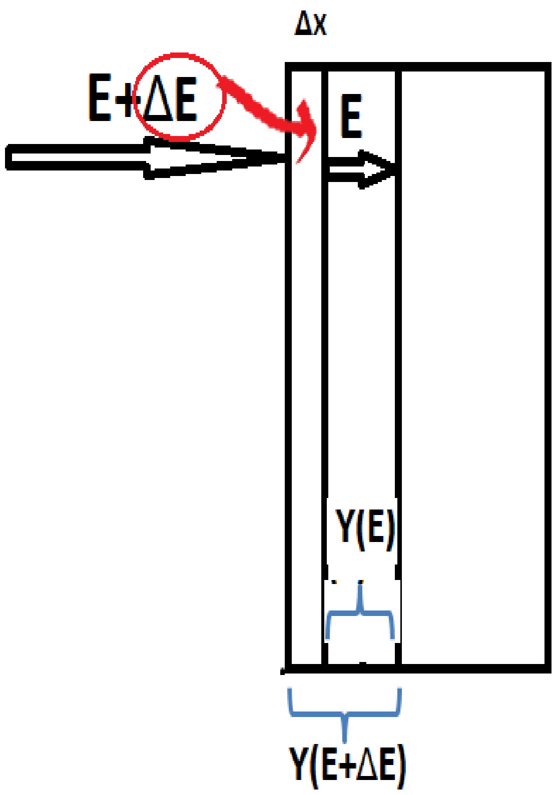
The cross sections were determined starting from the experimental yields:

$$Y(E) = \int_0^E \sigma(E) \frac{dx}{dE} \frac{N_A}{A_t} dE \quad \Leftrightarrow \quad \Lambda = \frac{N_{\gamma det}}{\epsilon_\gamma I_\gamma} \frac{\lambda e^{-\lambda \Delta t}}{(1 - e^{-\lambda t_{max}})}$$

$$\Rightarrow \quad Y(E) = \frac{\frac{\Lambda}{\lambda}}{\frac{I * \Delta t}{qe}} \qquad I = [\sum_{t_0}^{t_{ir}} I(t) e^{-\lambda(t_{ir} - t)}] \Delta t$$

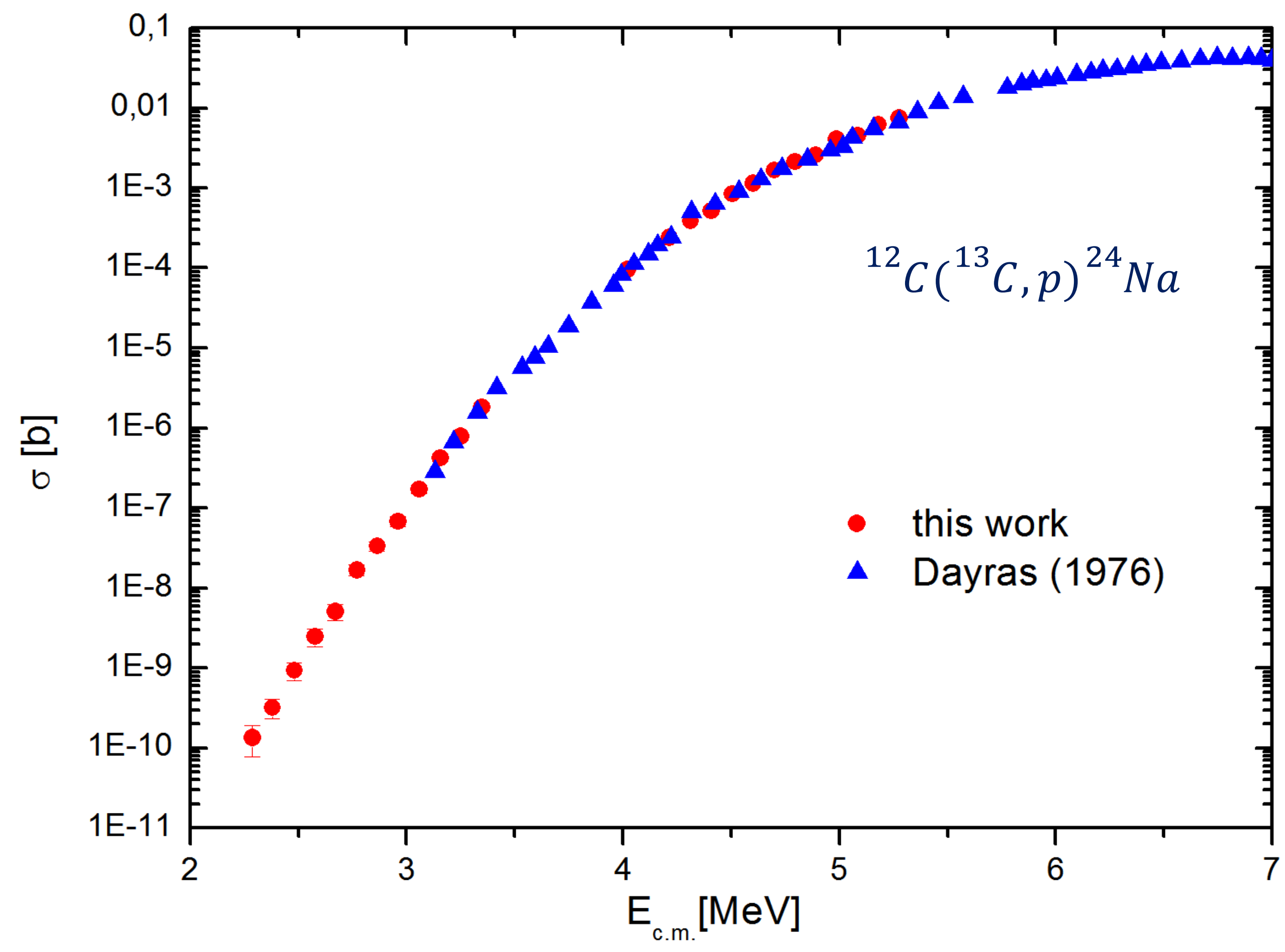
Last step was the determination of experimental cross section:

$$\sigma(\tilde{E}) = \frac{Y(E + \Delta E) - Y(E)}{n_t} \cdot 10^{24} b$$

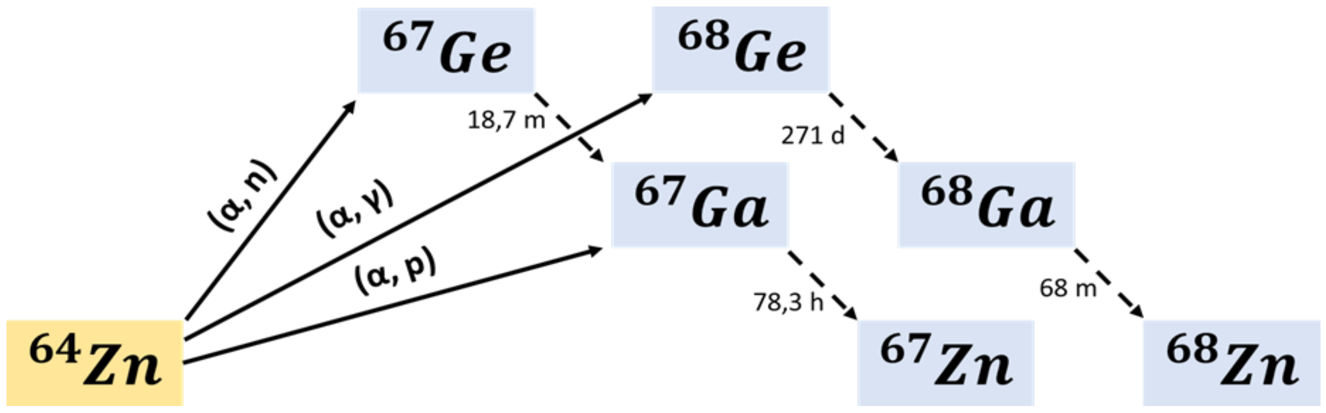


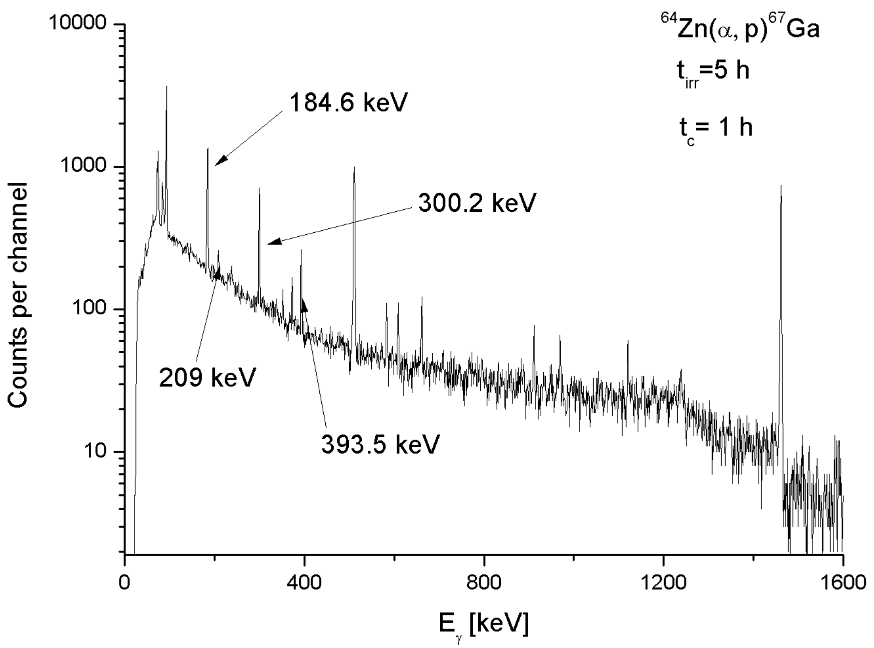
Thick target method

Cross section determination



The $^{64}Zn(\alpha,p)^{67}Ga$ reaction



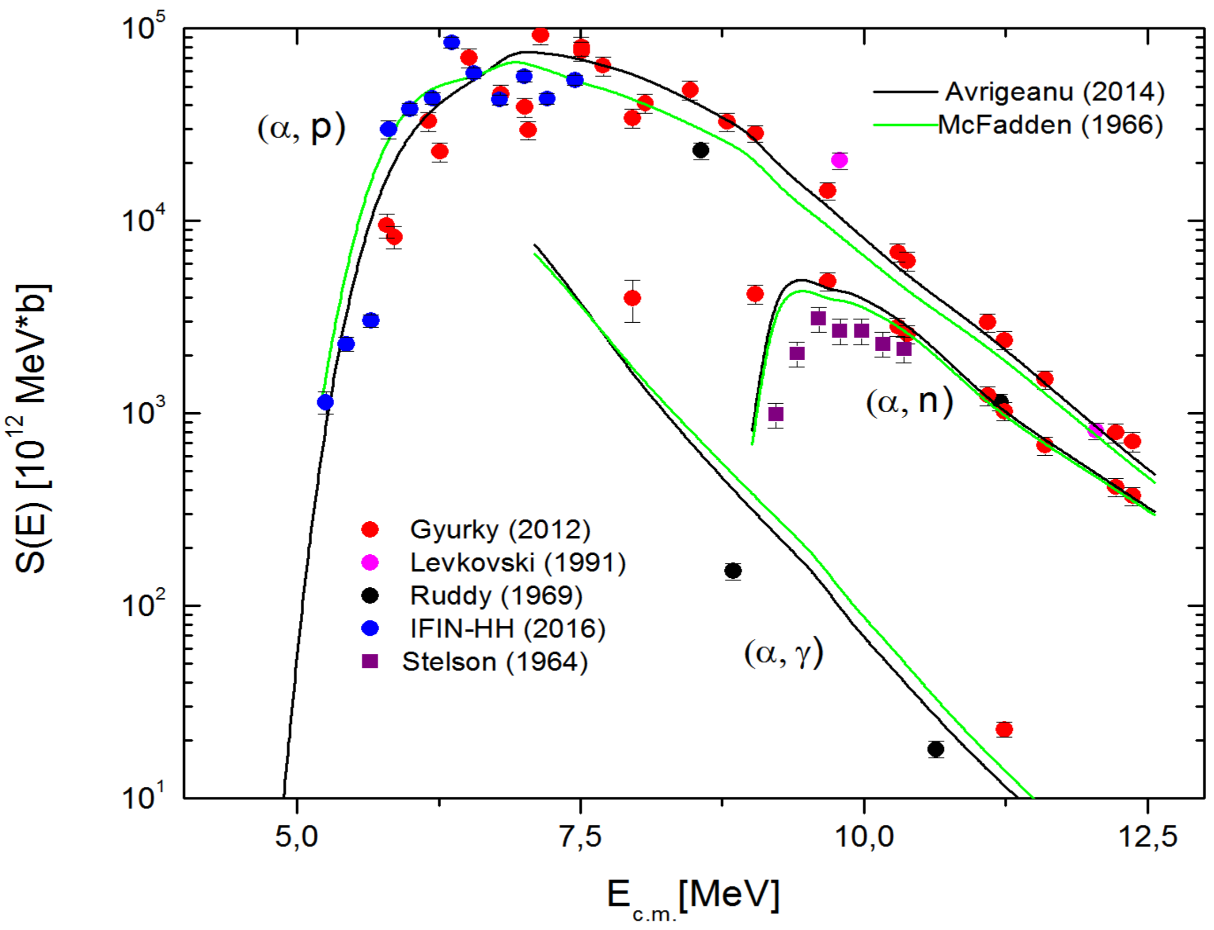


- Natural zinc targets
- E_{lab} between 5,4 – 8 MeV in steps of 0.2 and 0.25 MeV
- Beam current: 0,5 – 0,65 μA

Reaction	Product isotope	Half-life	E_γ [keV]	Relative Intensity [%]
$^{64}Zn(\alpha,p)$	^{67}Ga	3.26 d	184,6	21,41±0.01
			209.0	2.46±0.01
			300.2	16.64±0.12
			393.5	4.56±0.24

Activation measurements. Preliminary results

$$S(E) = \sigma(E) * E * \exp(2\mu\eta)$$



The astrophysical S(E) factor of experimental data obtained from ^{64}Zn (α, p)^{67}Ga, ^{64}Zn (α, n)^{67}Ge, ^{64}Zn (α, γ)^{68}Ge reaction channels in comparison with theoretical results [9, 10].

Conclusions

- We studied the **$^{12}C(^{13}C,p)^{24}Na$ and $^{64}Zn(\alpha,p)^{67}Ga$** fusion reactions in the energy range
E= 4,6-11 MeV and E= 5,4 – 8 MeV respectively.

- Measurements in different setups: NAG, GammaSpec and μBq are consistent.

- Activities of the irradiated targets measured both in the underground and surface laboratory allowed to determine the lowest cross sections of the order of 100 pb for **$^{12}C(^{13}C,p)^{24}Na$** and 30 nb for **$^{64}Zn(\alpha,p)^{67}Ga$** .

- We extended the range of measurements down into the Gamow windows, with the important conclusion that the Hindrance model does not work for 13C+12C.

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Thank you!