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**First results from the  $^{63}\text{Cu}(\alpha,\gamma)^{67}\text{Ga}$  reaction study for nuclear astrophysics purposes**

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# First results from the $^{63}\text{Cu}(\alpha,\gamma)^{67}\text{Ga}$ reaction study for nuclear astrophysics purposes

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**Abstract** The  $^{63}\text{Cu}(\alpha,\gamma)^{67}\text{Ga}$  reaction cross-section was measured in the energy range between 5 and 9 MeV, which is relevant to p-process nucleosynthesis. The experiment was conducted at the Dynamitron Tandem Laboratory, of the Ruhr-University Bochum in Germany, by applying the  $4\pi$   $\gamma$ -summing method, using a  $12'' \times 12''$  NaI(Tl) single crystal scintillator. The preliminary results are compared with previous measurements and theoretical TALYS calculations as well.

**Keywords** p-process,  $(\alpha,\gamma)$  cross-section,  $4\pi$   $\gamma$ -summing method

## INTRODUCTION

Stellar nucleosynthesis of elements heavier than Fe proceeds primarily through the slow (s-) and rapid (r-) processes by means of neutron capture reactions. However, 35 neutron-deficient isotopes, known as “p-nuclei” cannot be synthesized through these two processes. Their production requires pre-existing neutron-rich nuclei, referred to as “seed nuclei”. Under certain, very high temperature conditions, imposed during or just before a supernova explosion, the “seed nuclei” can undergo neutron, proton or  $\alpha$ -particle photodisintegrations, accompanied in many cases by  $\beta^+$ -decays, producing this way a p-nucleus. This nucleosynthetic mechanism is referred to as the “p-process” [1,2].

P-process nucleosynthesis is of key importance for the understanding of the formation mechanism of our solar system, since the p-nuclei abundances are the signatures of its creation. Up to date, these abundances cannot be satisfactorily reproduced by the existing astrophysical p-process models. The observed discrepancies however, between model predicted and measured solar p-nuclei abundances, may also be due to insufficient information on cross-sections of a huge number of nuclear reactions entering the abundance calculations as a network consisting of more than 20000 nuclear reactions, involving almost 2000 stable and unstable isotopes, rendering the experimental knowledge of every single cross-section unachievable. Thus, abundance calculations rely almost entirely on cross-section calculations using the Hauser-Feshbach (HF) theory.

Under these conditions, uncertainties in theoretical calculations may arise due to uncertainties in the nuclear parameters entering the HF theory, i.e., the Optical Model Potentials (OMPs), the Nuclear Level Densities (NLDs) and the  $\gamma$ -ray Strength Functions ( $\gamma$ -SFs). Consequently, the predictive power of the models describing these nuclear parameters must be tested at energies relevant to p-process nucleosynthesis, which in the case of  $(\alpha,\gamma)$  reactions range from 6 to 12 MeV, with a purpose to optimize the parametrization of the HF theory.

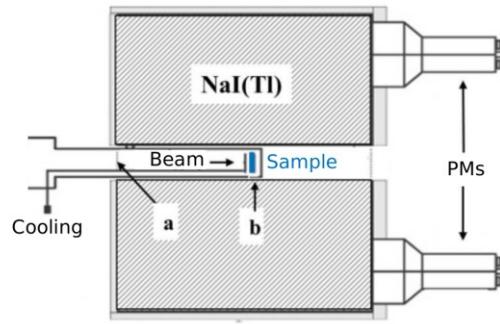
The present work reports on preliminary results of the cross-section measurement of the  $^{63}\text{Cu}(\alpha,\gamma)^{67}\text{Ga}$  reaction, at beam energies within the corresponding Gamow window, between 5 and 9 MeV. The Gamow energy window for the reaction under study was calculated to be between 3.5 and

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8.3 MeV (lab), with the corresponding ( $\alpha, n$ ) channel threshold at 7.98 MeV.

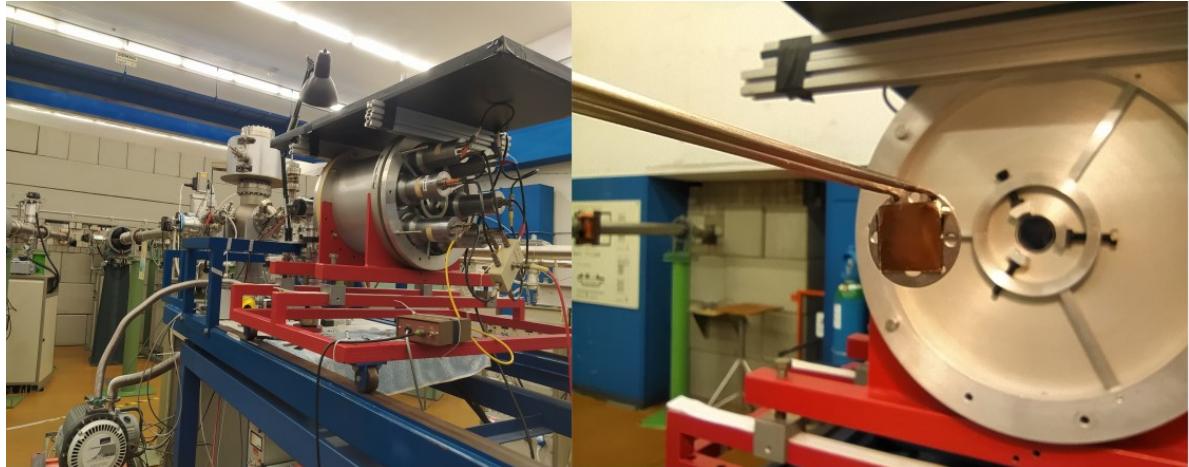
## EXPERIMENTAL DETAILS

The cross-section measurements of the  $^{63}\text{Cu}(\alpha, \gamma)^{67}\text{Ga}$  reaction were performed at the RUBION Dynamitron Tandem Laboratory of the Ruhr-University Bochum, in Germany [3]. Alpha-particles were impinging on a sample comprising a thin  $^{63}\text{Cu}$  foil, with a nominal areal density value of  $\sim 370 \text{ }\mu\text{g/cm}^2$ , mounted on Ta backing. The target was placed at the center of the large-volume NaI(Tl) summing detector shown in Fig. 1.



**Figure 1.** Schematic representation of the experimental setup used for the measurements [4]

The  $4\pi \gamma$ -summing method was adopted for the measurements, using a  $12'' \times 12''$  NaI(Tl) single crystal scintillator, equipped with six PMTs. During the measurements, the sample/holder system was positioned in the center of the detector, through the 35 mm hole along its axis (see Fig. 2). Figure 3 depicts two spectra presenting the sum-peak shift, as the beam energy changes.



**Figure 2.** Picture of the experimental line (left) and the  $^{63}\text{Cu}$  foil with the NaI(Tl) scintillator (right)

## DATA ANALYSIS

The cross-section is obtained using the formula

$$\sigma = \frac{A \cdot Y_{\Sigma}}{N_A \cdot d \cdot \varepsilon_{\Sigma}}, \quad (1)$$

where  $A$  is the atomic number of the foil,  $Y_{\Sigma}$  is the number of counts in the photopeak,  $N_A$  the Avogadro number,  $d$  the thickness of the foil and  $\varepsilon_{\Sigma}$  the efficiency of the detector.

Determining the efficiency for measurements of this kind is not trivial, since it depends not only on the energy of the sum peak ( $E_{\Sigma}$ ), but on the average multiplicity (number of photons in a cascade) as well. The RUBION detector setup has been fully characterized [4] and two different methods for the

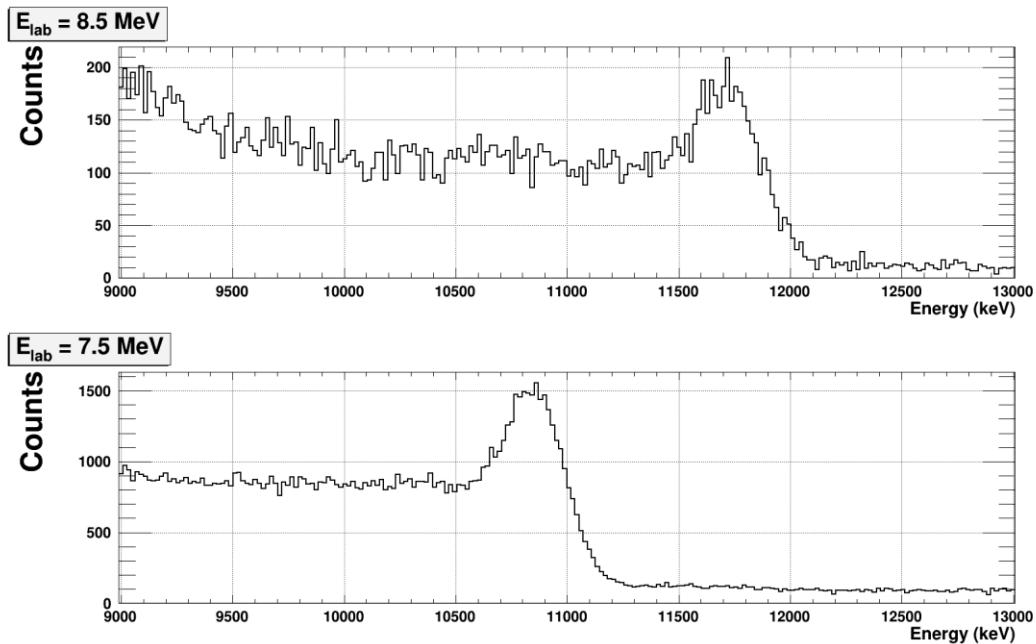
determination of the detector's efficiency exist, the “in/out” and the “global” method (see Fig. 4). The “in/out” method relies on the experimental estimation of the average multiplicity using the ratio:

$$R = \frac{\gamma_{\Sigma, in}}{\gamma_{\Sigma, out}} \quad (2)$$

and the consequent determination of the efficiency through detailed MC simulations [5]. The “global” method derives from the observation that depending on the CN type (odd-odd, odd-even, even-even) the efficiency follows the equation:

$$\varepsilon_{\Sigma} = \varepsilon_0 + a e^{E_{\Sigma}/b}. \quad (3)$$

In the present work the “global” technique was adopted, since the “in/out” method could not be applied due to the very low cross-section, and thus the unreasonably long measurement time necessary for the “out” measurement.



**Figure 3.** Experimental spectra produced by two different beam energies

## RESULTS AND DISCUSSION

The beam intensity was monitored so as to maintain the dead time below 4%. Dead time and screening effect corrections have not been applied to the results thus far, as future thickness measurements are pending. The errors that contribute to the results are the efficiency error (20%), the foil thickness error (10%) and the peak analysis error (up to 15%). The preliminary results of this work, along with previous measurements and TALYS calculations are depicted in Fig 5.

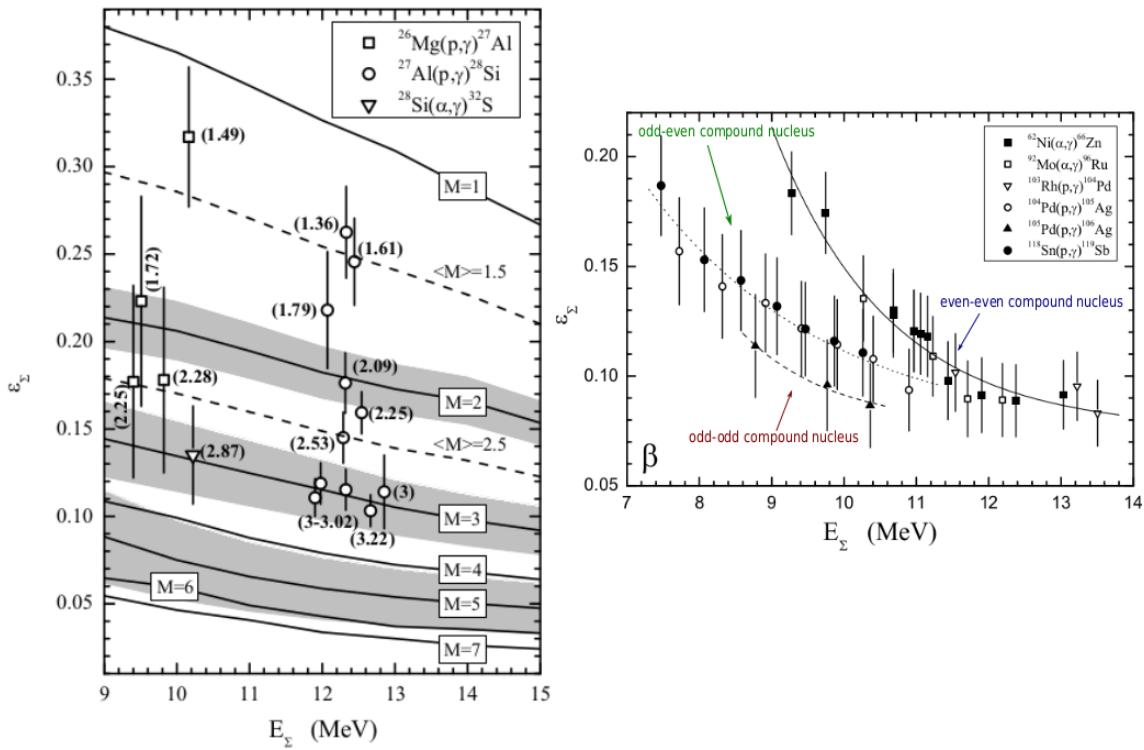
The combinations of TALYS models presented in the plot of Fig. 5 are summarized in Table 1, while all the available TALYS models are listed in Table 2.

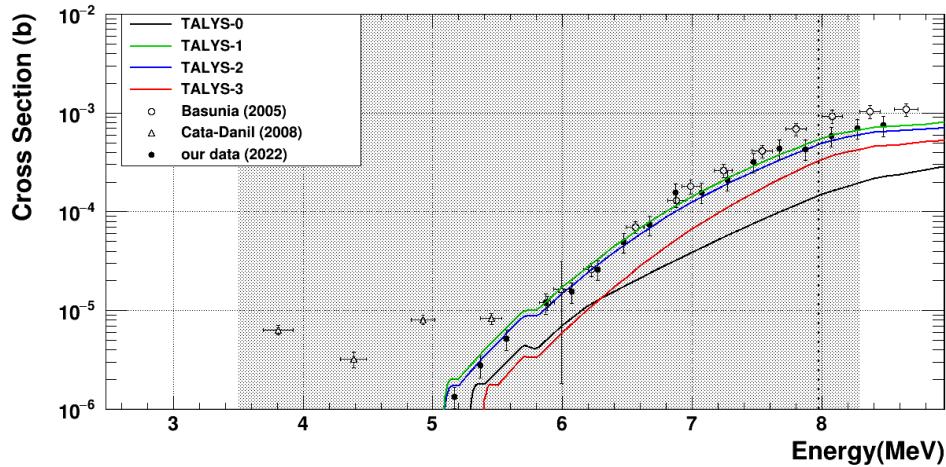
**Table 1.** The TALYS models combinations used in this work

	$\alpha$ -OMP	NLD	$\gamma$ -SF
TALYS-0	AV/I	CTFG	BA
TALYS-1	$\alpha$ -OMPI	HFBCS	HFBCS/QRPA
TALYS-2	$\alpha$ -OMPII	HFBCS	HFBCS/QRPA
TALYS-3	$\alpha$ -OMPIII	HFBCS	HFBCS/QRPA

**Table 2.** All the available TALYS models

Parameter	Phenomenological models	Semi-microscopic models
$\alpha$ -OMP	<b>WKD:</b> TALYS-specific $\alpha$ -particle–nucleus OMP [8-10] <b>McFS:</b> $\alpha$ -particle–nucleus OMP of McFadden and Satchler [11] <b>AV/I:</b> $\alpha$ -particle–nucleus OMP of Avrigeanu et al. [12] <b>Nlt:</b> $\alpha$ -particle–nucleus OMP of Nolte et al. [13] <b>AV/II:</b> $\alpha$ -particle–nucleus OMP of Avrigeanu et al. [14]	<b><math>\alpha</math>-OMPI:</b> Demetriou et al. [15] <b><math>\alpha</math>-OMPII:</b> Demetriou et al. [15] <b><math>\alpha</math>-OMPIII:</b> Demetriou et al. [15]
NLD	<b>CTFG:</b> Constant temperature Fermi gas [16] <b>BSFG:</b> Back-shifted Fermi gas [17,18] <b>GSM:</b> Generalized superfluid model [19,20]	<b>HFBCS:</b> Hartree-Fock-BCS [21] <b>HFB:</b> Hartree-Fock-Bogolyubov [22] <b>HFB/T:</b> Temperature-dependent Hartree-Fock-Bogolyubov [23]
$\gamma$ SF	<b>KU:</b> Generalized Lorentzian of Kopecky and Uhl [24] <b>BA:</b> Generalized Lorentzian of Brink and Axel [25,26]	<b>HFBCS/QRPA:</b> Hartree-Fock-BCS–quasiparticle random-phase approximation [27] <b>HFB/QRPA:</b> Hartree-Fock-Bogolyubov–quasiparticle random-phase approximation [28] <b>HG:</b> Hybrid model of Goriely [29] <b>HFB/T:</b> Temperature-dependent Hartree-Fock-Bogolyubov [28] <b>RMF/T:</b> Temperature-dependent RMF [30] <b>D1M/HFB/QRPA:</b> Gogny D1M Hartree-Fock-Bogolyubov–quasiparticle random-phase approximation [31]

**Figure 4.** The efficiency of the NaI(Tl) scintillator according to the two methods described in the text [4,5]



**Figure 5.** The results from this work (black points) along with previous measurements and TALYS calculations [6,7]

## CONCLUSIONS

The preliminary results from the cross-section measurement of the  $\alpha$ -capture reaction on  $^{63}\text{Cu}$  are presented within this work. The measurements were performed via the  $4\pi \gamma$ -summing method at the RUBION Dynamitron Tandem Laboratory [3] of the Ruhr-University Bochum, in Germany, for beam energies within the Gamow energy window. The preliminary results are compared with previous measurements and with a few TALYS calculations as well.

For the needs of a deeper interpretation based on a comparison with TALYS, some final checks, including the target thickness are in progress.

## Acknowledgements

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