# New measurements of the $^{63}$Cu($\alpha,\gamma$)$^{67}$Ga reaction compared with improved calculations

*Maria* Peoviti[1,2,*], *Michail* Axiotis[1], *Nikolas* Patronis[2], *Paraskevi* Dimitriou[3], *Varvara* Foteinou[4], *Sotirios* Harissopulos[1], *Fotios* Maragkos[4,5], and *Detlef* Rogalla[4]

[1]Tandem Accelerator Laboratory, Institute of Nuclear Physics, NCSR "Demokritos", 15310 Aghia Paraskevi, Athens, Greece
[2]Department of Physics, University of Ioannina, 45110 Ioannina, Greece
[3]Nuclear Data Section, Division of Physical and Chemical Sciences, Department of Nuclear Sciences and Applications, International Atomic Energy Agency, POB 100, Vienna, Austria
[4]Central Unit for Ion Beams and Radionuclides, Ruhr-University Bochum, 44801, Bochum, Germany
[5]Department of Physics, National Technical University of Athens, Zografou Campus, 15780 Athens, Greece

**Abstract.** One of the challenges of nuclear astrophysics is understanding the observed abundances of the p-process nuclei. Nucleosynthesis calculations typically employ an extended reaction network involving tens of thousands of reactions and thousands of isotopes. As it is impossible to experimentally investigate such a vast number of reactions, these calculations rely heavily on cross sections derived from the Hauser-Feshbach (HF) theory. To improve the predictive power of the HF theory, it is important to provide updated parameterization of the incorporated models, validated comprehensively using experimental data. In this paper, we report on a new measurement of the $^{63}$Cu($\alpha,\gamma$)$^{67}$Ga reaction cross-section, at energies relevant to the p-process nucleosynthesis. The purpose of the measurement was to further improve the global $\alpha$-nucleus Optical Model Potential ($\alpha$OMP). HF calculations were performed with the TALYS code (version 1.96) probing the sensitivity to all the important ingredients of the calculations including the Optical Model Potentials (OMP), Nuclear Level Densities (NLD), and $\gamma$-ray Strength Functions ($\gamma$SF). New optimized parameters are proposed for the global semi-microscopic $\alpha$OMP. The results are preliminary.

## 1 Introduction

The production of elements heavier than iron is largely governed by two nucleosynthetic processes: the s- and r-process. However, these mechanisms cannot account for the formation of 35 proton-rich nuclei, known as p-nuclei. To address this, a third mechanism, the p-process, is proposed. Although few in number, p-nuclei hold particular significance in nuclear astrophysics due to the inconsistency between predicted and observed abundances. Calculating these abundances requires cross-section data for a vast nuclear reaction network, involving around 20000 reactions and 2000 stable and unstable nuclei. Measuring every cross section is practically impossible. For this reason, the reaction rates needed for nucleosynthesis calculations rely largely on predictions of the Hauser-Feshbach theory. Accordingly, the continuous improvement of the parameterization of the incorporated models is important. In this framework, in the present work, the cross-section of the $^{63}$Cu($\alpha,\gamma$)$^{67}$Ga reaction was measured within the Gamow Window [1], the energy range of interest for nuclear astrophysics. The results were then compared with refined theoretical models to improve the accuracy of the parametrization used in these calculations[2].

## 2 Experimental Details

The experiment was conducted at the Central Unit for Ion Beams and Radionuclides, Ruhr University Bochum, Germany. The $4\pi$ $\gamma$-summing method [3] was employed using the 12×12 inch single-crystal NaI(Tl) scintillator, depicted in Fig. 1.

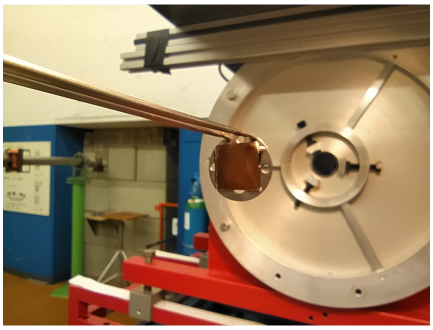

**Figure 1.** View of the sample and the detector used in the experiment.

The target used for the measurements consisted of a thin $^{63}$Cu layer ($349 \pm 28 \mu g/cm^2$) deposited through evaporation onto Ta substrate. A thick Au foil was placed behind the target to minimize the background. The thickness

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[*] e-mail: marpeoviti@gmail.com

of Cu, was measured at the Tandem Laboratory of NCSR "Demokritos", Greece, employing the X-ray fluorescence (XRF) technique. The cross-section was measured at seventeen beam energies, ranging from 5.3 to 8.6 MeV (in lab).

Figure 2 shows a typical experimental spectrum. In the same figure the corresponding "background" spectrum is presented for the same beam energy. The "background" spectrum was recorded by removing the target and irradiating the Au foil. Apart from the $^{63}$Cu($\alpha,\gamma$)$^{67}$Ga reaction sum peak ($\gamma_\Sigma$), several peaks were observed, originating from natural radiation ($^{40}$Ka and $^{208}$Tl), as well as peaks resulting from reactions between the beam and elements present in the beamline, such as C and Al.

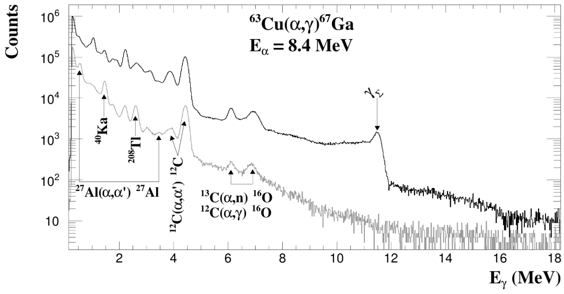

**Figure 2.** A typical spectrum of the foil at beam energy $E_{lab}$ = 8.4$MeV$ is presented by the black line, while the backing spectrum is shown in gray.

The results of this work are presented in Fig. 3, alongside all datasets available in literature [4], [5]. The current results are overall in good agreement with prior activation measurements [4].

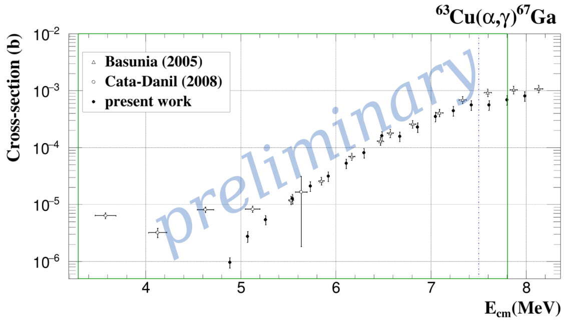

**Figure 3.** Cross-section values determined in the present work alongside previous experimental data sets [4], [5]. The green rectangle indicates the reaction's Gamow Window, while the blue dotted line corresponds to the ($\alpha$,n) reaction threshold.

## 3 Theoretical Calculations

All available TALYS (version 1.96) [6] proton Optical Model Potential (pOMP), $\alpha$-nucleus Optical Model Potential ($\alpha$OMP), Nuclear Level Densities (NLD), and $\gamma$-ray Strength Function ($\gamma$SF) (E1 and M1) models were employed for the calculations, with a focus on two specific model combinations: one fully phenomenological and one fully semi-microscopic. The phenomenological combination consisted of Koning-Delaroche (KD) + Avrigeanu (AV) + Constant Temperature Fermi Gas (CTFG) + Simplified Modified Lorentzian (SMLO), while the semi-microscopic combination included Jeukenne-Lejeune-Mahaux (JLM) + $\alpha$OMP-III + Hartree-Fock-Bogoliubov (HFB) + Gogny D1M Hartree-Fock-Bogoliubov-quasiparticle random-phase approximation (D1M/HFB/QRPA). As shown in Fig. 4, the semi-microscopic combination significantly and systematically underestimates the experimental data.

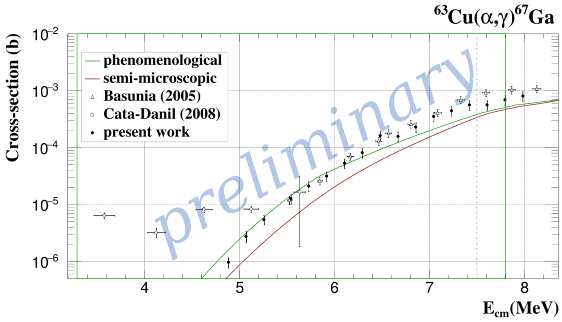

**Figure 4.** Experimental cross-section plotted as points, along with the two TALYS combinations used in this work. The phenomenological combination is represented by the green line and the semi-microscopic combination by the red line.

To address this issue, the first step was identifying which parameter caused this discrepancy. After a thorough investigation, the main source of uncertainty was found to be the $\alpha$OMP. The $\alpha$OMP model involves six parameters: three related to the volume imaginary potential (geometry: $a_v$, $r_v$ and depth: $w_1$) and three related to the surface imaginary potential (geometry: $a_w$, $r_w$ and depth: $d_1$). By varying the surface-related parameters whithin the allowed by the program range, it was determind that they have virtualy no effect on the calculation. On the other hand, Fig. 5 depicts the range of minimum and maximum cross-section values from the calculations as the three volume parameters were scaled by a factor ranging from 0.5 to 1.5 in steps of 0.05, while the surface parameters remain at their default value. It is evident that changes in these three parameters significantly affect the calculation results.

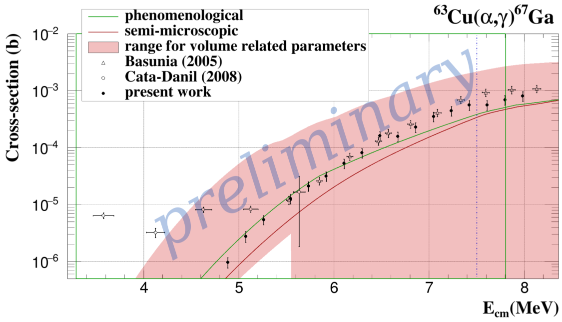

**Figure 5.** The red shaded area corresponds to the range of the cross-section calculations while varying only the three volume related parameters: $r_v$, $a_v$ and $w_1$.

The individual impact of the three volume parameters is depicted along with the experimental data in Fig. 6. The ranges were calculated by varying the parameter under investigation within the specified range, while keeping all other parameters at their default values. Optimal values for the $\alpha$OMP parameters were determined through $\chi^2$ calculations, using only the experimental points below the ($\alpha$,n) channel threshold. Additionally, optimal values were established for the semi-microscopic combination using KD for the pOMP. The results are presented in Fig. 7 for both the cross-section and S-factor.

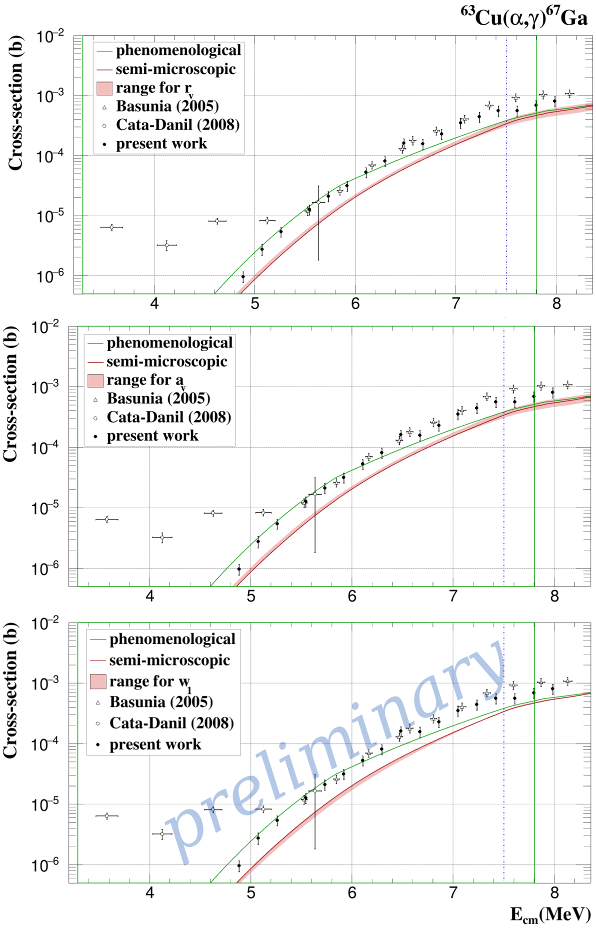

**Figure 6.** The range of the minimum and maximum cross-section calculations was determined by varying only one of the three volume related parameters at a time, while keeping the rest at their default values.

## 4 Conclusions

Within the present work, the cross-section of the $^{63}$Cu$(\alpha,\gamma)^{67}$Ga reaction was measured at the RUBION Institute using the $4\pi$ $\gamma$-summing method at seventeen energies relevant to nuclear astrophysics. The results in general are in good agreement with previous activation measurements. The agreement with previous data is very good at higher beam energies, while at lower energies the present data deviate from the previous ones by following the expected trend. Cross-section calculations were performed using TALYS 1.96, aiming to optimize the parametrization of the $\alpha$OMP model. Optimal parameter values were determined through $\chi^2$ calculations, considering only the experimental points below the ($\alpha$,n) channel threshold. The optimized model accurately reproduces both the reaction cross-section and the S-factor.

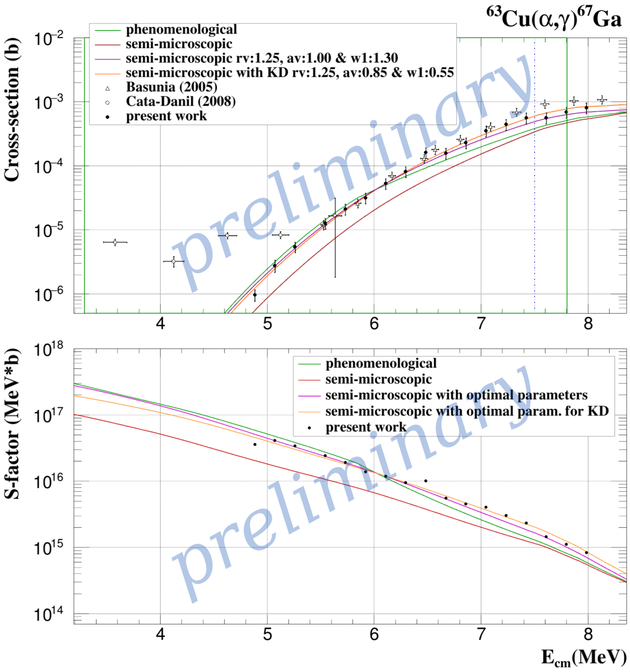

**Figure 7.** The cross-sections and S-factors calculated with the optimal values of the semi-microscopic $\alpha$OMP are represented by the purple curves. The orange curves correspond to the calculations using the semi-microscopic $\alpha$OMP with all semi-microscopic models, but employing the KD model for pOMP.

## References

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