# Experimental and theoretical study of the $^{65}$Cu$(n,p)^{65}$Ni reaction cross section from threshold to 25 MeV energies

R. K. Singh*[1], N. L. Singh*[1], Rakesh Chauhan[1], Mayur Mehta[2], S. V. Suryanarayana[3], Rajnikant Makwana[1], S. Mukherjee[1], B. K. Nayak[3], H. Naik[4], J. Varmuza[5], K. Katovsky[5]

[1]*Department of Physics, Faculty of Science, The M. S. University of Baroda, Vadodara -390002, INDIA*
[2]*Institute for Plasma Research, Gandhinagar-382428, INDIA*
[3]*Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai, INDIA*
[4]*Radiochemistry Division, Bhabha Atomic Research Centre, Mumbai, INDIA*
[5]*Department of Electrical Power Engineering, Brno University of Technology, Brno-61600, Czech Republic*
**E-mail: -ratankumar339@gmail.com/nl.singh-phy@msubaroda.ac.in*

## Introduction

The use of copper as a first wall material has been considered in reactor designs that have high thermal loads on the first wall or require a shield of high electrically conductive material surrounding the plasma to help stabilize its location. The ones that generate gaseous elements such as hydrogen and helium by reactions $(n,xp)$ and $(n,x\alpha)$ are of prime concern for studying the structural stability of reactor materials from the multiple neutron induced reactions that take place within a fusion reactor. These reactions cause damage to the first wall, structural and blanket material of the fusion reactor. Nuclear data is very important in nuclear research, such as the design of fusion devices, fission power plants, accelerators, environmental, space dosimetry and isotopes production [1].

In the present work, the cross section of the $^{65}$Cu$(n,p)^{65}$Ni reaction was measured above 13 MeV incident neutron energies relative to the $^{27}$Al$(n,\alpha)^{24}$Na reference reaction by activation and offline γ-ray spectrometric technique. The present results were compared with the literature data taken from the EXFOR [2] database and evaluated data of the ENDF/B-VIII.0,JEFF-3.3, JENDL4.0/HE, CENDL-3.2, TENDL-2019 and FENDL-3.2 libraries [3]. The statistical reaction TALYS (ver. 1.9) code [4] were used for the cross section calculation using the different optical potential, level density and pre-equilibrium models.

## Experimental procedure

The irradiation of the samples were performed at the 14UD Pelletron Linac accelerator facility of Bhabha Atomic Research Centre and Tata Institute of Fundamental Research, Mumbai, India. The neutron was produced via the $^{7}$Li$(p,n)$ reaction using the proton of 16, 19 and 22 MeV energies. Initially, the proton was accelerated and hit on the natural lithium (Li) foil of a thickness of ≈6.8 mg/cm$^2$, which was sandwiched between the two tantalum (Ta) foil. The front tantalum foil which faced the proton beam is the thinnest one with a thickness of ≈4 mg/cm$^2$, whereas the proton beam stop was served by a 0.1 mm thick layer of tantalum. The sample holder was placed at 0° with respect to the incident proton beam direction at a distance of 21 mm from the Ta-Li-Ta targets configuration. High-purity (99.5 % pure) pellets of natural copper material weight of ≈0.3 g each were prepared using a pelletizer. In addition, an aluminium metal foil (99.99 % pure) of weight ≈0.03 g was used along with the each copper target. During the irradiations process the copper sample was sandwiched between monitor foil (Al). After irradiation, the γ-ray activates from the decay of $^{65}$Ni and $^{24}$Na were measured using a pre-calibrated 16% relative efficiency high-purity Germanium (HPGe) detector connected to a PC based multichannel analyser and γ-ray counts under each photo peak were determined by the Canberra Genie gamma analysis software. The detector efficiency and energy calibration were carried out using a standard $^{152}$Eu radioactive source and obtained energy resolution of the HPGe detector was 3.305 keV at 1408 keV γ-ray energy of the $^{152}$Eu source.

## Data analysis

The activation cross section of the $^{65}$Cu$(n,p)^{65}$Ni reaction was estimated relative to the reference $^{27}$Al$(n,\alpha)^{24}$Na monitor reaction using the standard activation equation given by,

$$\langle\sigma_r\rangle=\langle\sigma_m\rangle\left(\frac{C_r\lambda_r Wt_m AM_r Abu_m \varepsilon_m I_m f_m}{C_m\lambda_m Wt_r AM_m Abu_r \varepsilon_r I_r f_r}\right)\times\frac{(C_{attn}*C_{low}*C_g)_r}{(C_{attn}*C_{low}*C_g)_m}$$

Where $r$ and $m$ in subscript stand for sample and monitor reaction. $\sigma$ is the reaction cross sections, $C$ is the γ-ray peak counts, $\lambda$ is the decay constant, $\varepsilon$ is the efficiency for characteristic γ-ray of radionuclide, $I$ is the γ-ray abundance, $Wt$ is the weight, $Abu$ is the isotopic abundance, $AM$ is the atomic mass, $f$ is the time factor, $C_{low}$ is the low energy background neutron correction factor, $C_{attn}$ is the γ-ray self-attenuation correction factor, $C_g$ is the geometry correction factor. The reference cross sections $\langle\sigma_m\rangle$ of the monitor reaction $^{27}\mathrm{Al}(n,\alpha)^{24}\mathrm{Na}$ were obtained using International Reactor Dosimetry and Fusion File (IRDFF-1.05) database.

## Theoretical calculations

The theoretical calculations of the $^{65}\mathrm{Cu}(n,p)^{65}\mathrm{Ni}$ reaction cross section were performed using the TALYS (ver. 1.9) [5] code from reaction threshold to 25 MeV energies. The present results and the previous ones were compared with the theoretical calculations. The calculation of cross sections using the TALYS code contributes to the compound nucleus by the Hauser-Feshbach theory. The pre-equilibrium contribution models based on exciton model and MSC/MSD were used in the calculations. In addition, the optical potential proposed by Koning-Delaroche and Bauge-Delaroche were used to obtained optical model parameters for neutron and protons from RIPL-3 database. This code uses a fixed γ-ray strength function model the Brink-Axel Lorentzian for all the transitions except from the E1. The six different nuclear level density models based on the phenomenological and microscopic calculations were used for predicting cross section. Various input parameters are adjusted in the TALYS (ver. 1.9) code to reproduce the admissible cross sections for the entire neutron energy range.

## Results and discussion

The cross section of the $^{65}\mathrm{Cu}(n,p)^{65}\mathrm{Ni}$ reaction was measured at 13.52, 16.86 and 19.89 MeV neutron energies is shown in Fig. 1 along with the available measurements and evaluated data. The measured cross sections in the present work at 13.52, 16.86 and 19.89 MeV are in agreement with the results of D. C. Santry *et al.* within the experimental uncertainties. Above 19 MeV, only one measured data is available and the present data point at 19.89 MeV is the second experimental evidence for the excitation curve of this cross section. However, the evaluated results of the ENDF/B-VIII.0,JEFF-3.3,JENDL-4.0/HE,CENDL-3.2,TENDL-2019 and FENDL-3.2 libraries above 13 MeV shows that cross section differs largely in magnitude at higher energies region.

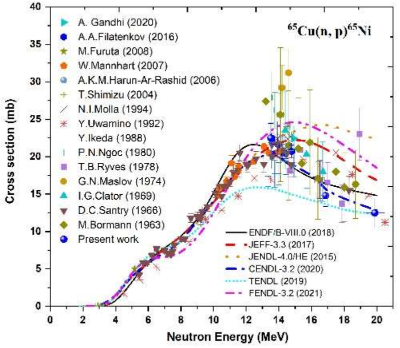

Fig. 1. Comparison of the present data and the literature data and evaluated data.

The TALYS default results of the $^{65}\mathrm{Cu}(n,p)^{65}\mathrm{Ni}$ reaction cross section adopting the phenomenological and microscopic level density models are plotted in Fig 2(a). In view of the large discrepancies between measured cross section and results from the statistical model code TALYS, using default parameters for the $^{65}\mathrm{Cu}(n,p)^{65}\mathrm{Ni}$ reaction, the theoretical calculations were revisited with adjusted parameters to fit the experimental data more accurately. The results of these calculations with adjusted-level density parameters and models are illustrated in Fig. 2(b). The present data and the previous ones were used to validate the theoretical calculations of the TALYS (ver. 1.9) code by considering the level density, optical potential and preequilibrium models.

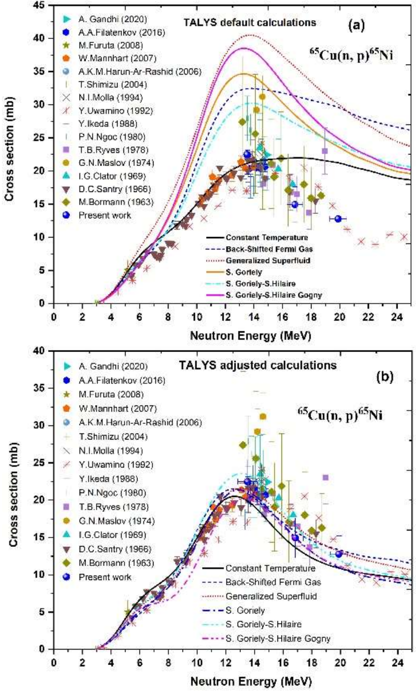

Fig. 2. The $^{65}\mathrm{Cu}(n,p)^{65}\mathrm{Ni}$ reaction cross section along with the literature, default and adjusted theoretical calculations from the TALYS (ver. 1.9) code.

## Acknowledgments

The authors gratefully acknowledge the BARC-TIFR Pelletron Accelerator Facility staff for their assistance during experiment. One of the authors R. K. Singh is thankful for financial assistance from the IUAC New Delhi (UGC-IUAC/XIII.7/UFR-60321).

## References

[1] O. K. Harling, G.P. Yu, N.J. Grant and J.E. Meyer, J. Nucl. Mater. 103 Kc 104 (1981) 127.

[2] N. Otukaa, E. Dupont, *et al.* (EXFOR), Nucl. Data Sheets Vol. 120, Pages 272-276, June (2014).

[3] ENDF, Evaluated Nuclear Reaction Data https://www-nds.iaea.org/exfor/endf.htm

[4] A. J. Koning, *et al.* , TALYS (ver. 1.9), A Nuclear reaction program, user manual, NRG-1755 ZG Petten, The Netherlands (2018).