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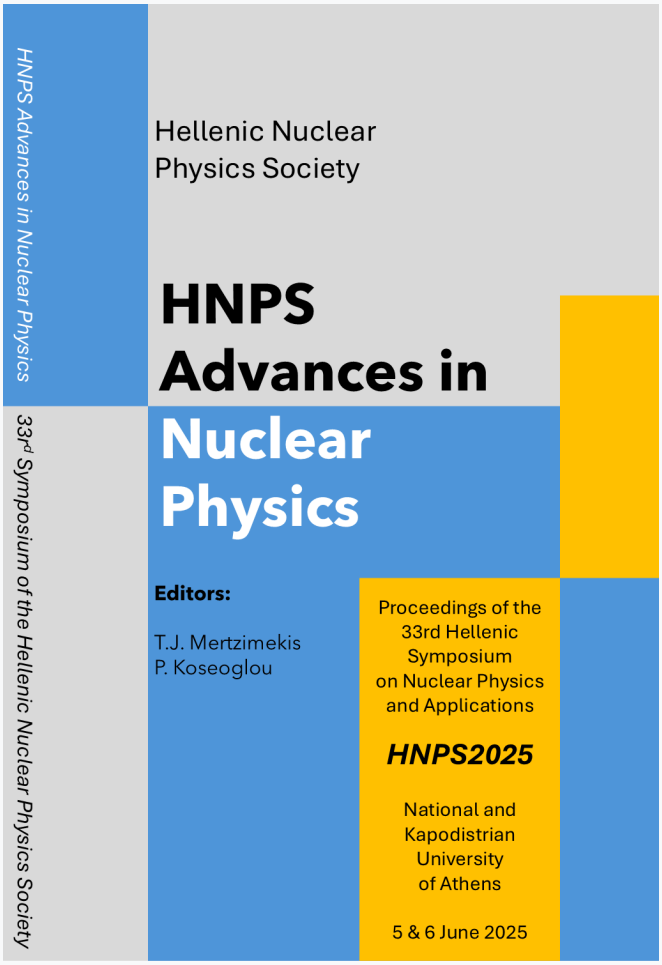

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Anna Karakaxi, Carlos Paradela, Maria Diakaki, Gilles Noguere, Georgios Gkatis, Stefan Kopecky, A. J. M. Plompen, Peter Schillebeeckx

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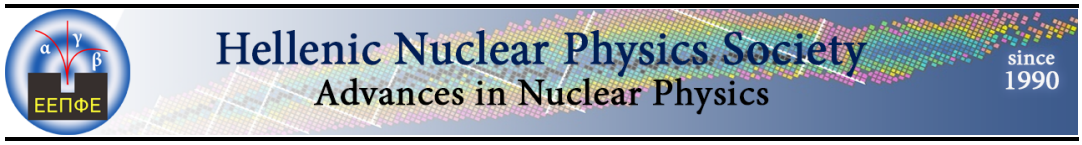

ARTICLE

Transmission measurements on ^{nat}Cu samples at GELINA

A. Karakaxi,[*,1,2] C. Paradela,[3] M. Diakaki,[2] G. Noguere,[1] G. Gkatis,[3] S. Kopecky,[3] A. J. M. Plompen,[3] and P. Schillebeeckx[3]

[1]CEA/DES/IRESNE/DER/SPRC/LEPh, Cadarache, 13108 Saint Paul Lez Durance, France
[2]Department of Physics, National Technical University of Athens, Zografou campus, 15780 Athens, Greece
[3]European Commission, Joint Research Centre, 2440 Geel, Belgium
*Corresponding author: Georgia-Anna.KARAKAXI@cea.fr

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Abstract

Natural copper is a key structural material in critical assembly configurations and fusion reactor systems. Discrepancies observed between experimental and evaluated data for neutron-induced total cross-section measurements of the two stable copper isotopes (^{63}Cu and ^{65}Cu) highlight the need for new neutron transmission experiments on copper.

In this study, neutron transmission measurements were carried out at the GELINA facility of JRC-Geel using several samples composed of natural copper (^{nat}Cu). The objective was to validate the Resolved Resonance Parameters and total cross section of copper within the energy range of 1 to 100 keV. Data analysis was performed using the AGS code [1] and following the guidelines described in Ref. [2, 3].

The obtained results were compared with the theoretical transmission factors, calculated using the JEFF-3.3 evaluated cross-section data [4] and the REFIT code [5]. The results indicate notable discrepancies, particularly at higher neutron energies, emphasizing the necessity for updated and more precise experimental data using thick targets. Such improvements would enhance nuclear data libraries and benefit various applications, including reactor design, safety assessments, and benchmarking studies, especially in contexts where copper serves as a structural material. The analysis methodology and corresponding results are presented and discussed.

Keywords: transmission; copper; GELINA; REFIT; nuclear data

1. Introduction

Copper is an important structural material in some nuclear reactor and critical assemblies, thus the neutron-induced reactions on both stable isotopes (^{63}Cu,^{65}Cu) significantly contribute to the corresponding neutron transport calculations. More specifically, the nuclear data of both isotopes play a critical role in modelling thick copper reflectors used to suppress neutron leakage in fast

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reactors—examples include the TAPIRO facility at ENEA in Italy [6], as well as in critical assemblies, such as the COMET vertical-lift assembly at LANL in the United States [7]. Integral benchmark experiments conducted at these facilities show a strong sensitivity to the nuclear data of copper, particularly to its neutron scattering cross sections. Indirectly, the knowledge of the nuclear data of copper has a strong impact on the evaluation of important nuclides.

The study of neutron-induced reactions and their resonance shape requires high-resolution neutron spectroscopic measurements, ideally performed using a pulsed neutron source, such as the one available at the GELINA facility. GELINA is optimized for neutron time-of-flight measurements in the neutron resonance region. This report presents transmission measurements carried out at GELINA using three natural copper (^{nat}Cu) metallic samples, in the energy range of 1 to 100 keV. To minimize systematic effects such as dead time and background contributions, the measurement and data reduction procedures recommended in Ref. [8] were followed. Finally, the results are presented and compared to the theoretical transmission calculated with JEFF-3.3, with the use of REFIT.

2. The GELINA Facility and the Experimental Setup

The GELINA facility is based on an electron linear accelerator, located in Geel, Belgium, at the European Commission Joint Research Centre, which has been designed for high-resolution cross section measurements in the resonance region. It is capable of producing a white pulsed neutron beam with a neutron energy from 10 meV to 20 MeV. Different experiments can take place simultaneously at the 10 flight paths, with measurement stations located between 10 m to 400 m from the neutron producing target. The neutron beam is produced when the electron beam hits a uranium target, with a mercury cooling system, producing Bremsstrahlung and subsequently, via photonuclear reactions, neutrons [9]. Two beryllium containers filled with water and placed above and below the neutron producing target are used to produce a moderated neutron beam.

Table 1. Characteristics of the samples used for the transmission measurements.

ID	Thickness (mm)	Mass (g)	Area (mm^2)	Areal Density $(atoms/barns)$
1. (99.5wt% Cu)	29.86(1)	317.016(1)	1189.9(3)	0.2502(1)
2. (2.22 (5) wt% Cu)	26.07(1)	276.735(1)	1189.5(1)	0.2025(1)
3. (Cu alloy with 39 wt% Zn and 3 wt% Pb)	29.90(1)	299.417(1)	1189.8(4)	0.1378(1)

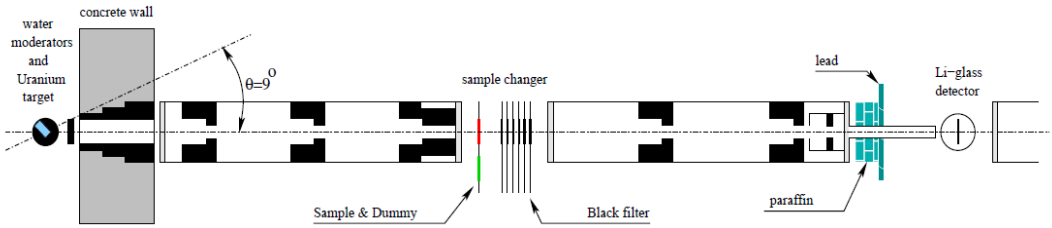


Figure 1. Schematic view of the transmission experimental setup at GELINA.

The transmission experiment, on which this work focuses on, took place in flight path 4, 47.670(8) m. A set of annular collimators were employed to reduce the neutron beam diameter at the sample location. To reduce the contribution of slow neutrons from earlier accelerator bursts, a ^{10}B overlap filter was positioned close to the neutron target. Additionally, in the same spot, a thick Pb filter was employed to lessen the impact of the *γ-flash* in the neutron detector. The measurements were performed on three thick samples, two metallic cylinders composed predominantly of natural copper

and one brass alloy containing 39% natural zinc. The main characteristics of the samples are reported in Table 1. The three samples were placed in an automatic sample changer. Close to the sample position, three filters of Na, Co and W were placed to determine the background at 2850 eV, 132 eV and 18 eV, respectively. The neutron beam was finally detected by a 6.35 mm x 151.6 mm diameter NE912 Li-glass scintillator.

3. Data Analysis

3.1 Data Reduction

The experimental transmission, as a function of time-of-flight (TOF), is obtained from the ratio between the sample-in (C_{in}) and sample-out (C_{out}) count rates, both corrected for their respective background contributions (B_{in}, B_{out}). Earlier, the count rates have been corrected for losses associated with detector and electronics dead time and normalized to the same time-integrated neutron beam intensity. Thus, the experimental transmission was calculated using the following expression:

$$T_{exp}(t_m) = N_T \frac{C_{in}(t_m) - k_{in}B_{in}(t_m)}{C_{out}(t_m) - k_{out}B_{out}(t_m)} \tag{1}$$

where $N_T = 1.0000(25)$ is a factor accounting for the uncertainty in the beam monitor normalization. The parameters $k_{in} = 1.00(3)$ and $k_{out} = 1.00(5)$ introduce correlated uncertainties arising from systematic effects in the background model and t_m indicates the time of flight. The TOF was determined from the difference between a start T_0 and a stop t_n signal, as follows: $t_m = t_n - T_0$. The flight path length, measured as 47.670(8) m –the distance between the center of the moderator viewing the flight path and the detector front face– was initially determined from transmission experiments using uranium standard references [10]. The extraction of the experimental transmission T_{exp} was carried out using the AGS (Analysis of Geel Spectra) code [1, 3], developed at JRC-Geel. This software provides functionalities for operating with TOF spectra and performing dead-time correction, background fitting and subtraction, and data normalization. Furthermore, it implements a compact formalism for propagating all uncertainties, starting from the uncorrelated uncertainties associated with counting statistics.

3.2 Background Determination

The main focus of the analysis of transmission data is the background determination. The background of a transmission measurement can be estimated with the following formula:

$$B(t_m) = b_0 + b_1 e^{-\lambda_1 t_m} + b_2 e^{-\lambda_2 t_m} + b_3 e^{-\lambda_3 (t_m + \tau_0)} \tag{2}$$

The formula includes three time-dependent exponential terms and one time-independent term. The latter, denoted as b_0, accounts for ambient radiation and background contributions lacking time correlation. The first time-dependent term originates from 2.2 MeV γ-rays produced by neutron capture in the hydrogen of the moderator. At the GELINA facility, this component has been thoroughly studied through measurements with polyethylene beam filters and Monte Carlo simulations, where polyethylene significantly increases the γ-ray-to-neutron intensity ratio by scattering neutrons out of the beam path. The second exponential term represents neutrons scattered along the transmission line and various flight paths, while the final term results from slow neutrons from previous accelerator pulses overlapping with the subsequent burst. Additionally, the accelerator's operating frequency determines the timeshift parameter τ_0, which is $\tau_0 = 2.5$ ms for the 400 Hz repetition rate.

The first step in the analysis is to define the overlap component. In order to do that, we extrapolate the behaviour of the time of flight spectra for times larger than 2.5 ms, corresponding to the time difference between consecutive pulses for an operating frequency of 400 Hz. By fitting the TOF spectra in the range above 1 ns, we can estimate the amplitudes b_0 and b_3 and the decay constant λ_3.

To study the time-dependence of the other two background components, short cycles with additional Na, Co and W filters in the beam were included in the measurements. These filters are chosen, as they have the characteristic of absorbing all the neutrons at certain energies. The absorption is reflected as resonance dips in the experimental TOF spectrum. Na, Co and W filters present *black* resonances, in which all neutrons are absorbed, at the energy of 2850 eV, 132 eV and 18 eV respectively. The black resonances allow us to obtain the parameters λ_1 and λ_2. In addition, the black resonance technique allows us to adjust the amplitudes b_1 and b_2, using the b_1/b_2 ratio, obtained in the short cycles. During the measurements, the Co filter was permanently in the beam.

3.3 Impact of thick samples

In addition to the background information obtained from the filters, we also used copper black resonances, at energies of 8556 eV, 5784 eV and 2038 eV, from Cu present in the studied samples, in order to have a more accurate estimation of the background in the high energy region. In the same context, we used the Zn resonance at 514 eV, also originating from the sample composition, to get more information in the low energy region. All the resonances we used for the background determination possess the black resonance characteristics. This method significantly helped to extract the background components with a better accuracy when the sample was in the beam, as the thick samples used in these measurements are impacting the absorption in the neutron component and the parameter λ_2.

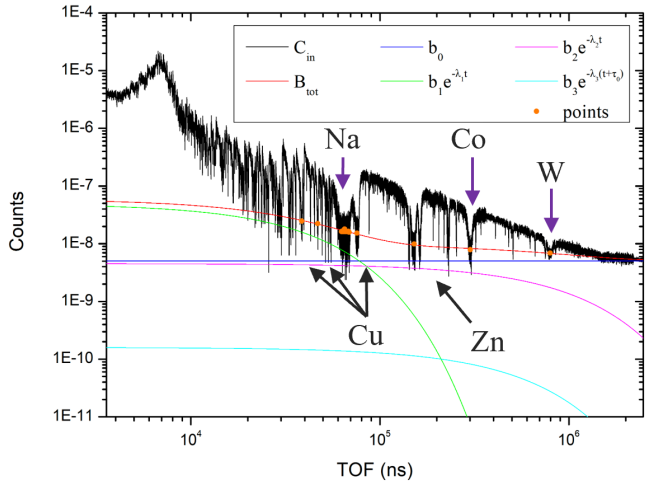
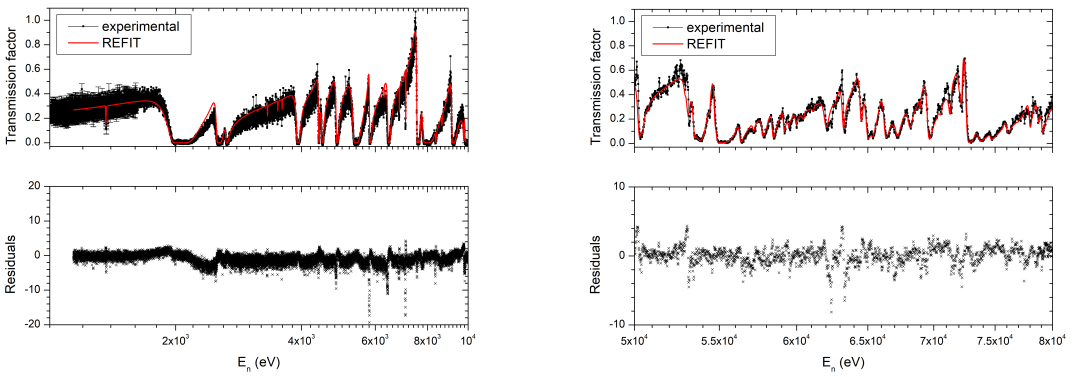


Figure 2. TOF-spectra resulting from the transmission measurement of sample No.1 at the 47.670(8) m station of GELINA. The sample-in with all the filters is presented along with its respective total background, its different components and the points of each element used in the fit.

Due to the poor statistics of the measurement with all the filters, a new analysis methodology was implemented, including the combination of the data from three different campaigns, only for the sample-out measurements. All the measurements included were performed under the same experimental conditions, including the γ-flash position and filter configuration. In this way, better statistics were obtained in the resonance dips of the filters, since that was the only contribution in the transmission spectrum. Consequently, that enforced our study of the background and allowed us to determine the background parameters with even higher accuracy.

4. REFIT Calculations and Results

The experimental results are presented and compared to the theoretical transmission calculated with the JEFF-3.3 evaluation [4], using the REFIT code [5]. REFIT is used to account for effects due to the response function of the time-of-flight spectrometer, in addition to the resolution of the detector and the accelerator. The results of the transmission measurements are presented, only for sample No.1 indicatively, as all of them follow the same trend. No fitting of resonance parameters to the experimental data has been performed; thus, the results in Fig. 3 represent a direct comparison between experiment and evaluation.



(a) Energy region of 1 - 10 keV.

(b) Energy region of 50 - 80 keV.

Figure 3. Experimental transmission obtained with sample No.1 compared with the JEFF-3.3 evaluation folded with the experimental resolution, focused in specific incident neutron energy ranges.

5. Conclusion

The resolved resonance region contains numerous resonances, complicating their individual analysis. In Fig. 3, where two energy regions are presented indicatively, the comparison of the experimental transmission data with the JEFF-3.3 evaluation via REFIT shows good agreement at the resonance edges but mostly underestimation in the valleys, likely due to resonance interference and poor experimental statistics.

The thick-sample results of this work aim to improve future evaluations. Further comparison with the other evaluation libraries, such as ENDF [11] and INDEN [12], and complementary measurements on a thin ^{nat}Cu target are foreseen to achieve a more complete and reliable analysis. In conclusion, measurements with thick samples provide complementary information to thin enriched ones available in EXFOR [13], revealing possible cross section discrepancies in the valley region between the resonances.

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References

[1] B. Becker, C. Bastian, J. Heyse, S. Kopecky, and P. Schillebeeckx. *AGS - Analysis of Geel Spectra Users' Manual*. NEA/DB/DOC, 2014. URL: https://www.oecd-nea.org/upload/docs/application/pdf/2020-01/db-doc2014-4.pdf.

[2] P. Schillebeeckx et al. "Determination of Resonance Parameters and their Covariances from Neutron Induced Reaction Cross Section Data". In: *Nuclear Data Sheets* 113.12 (2012). Special Issue on Nuclear Reaction Data, pp. 3054–3100. ISSN: 0090-3752. DOI: 10.1016/j.nds.2012.11.005.

[3] B. Becker et al. "Data reduction and uncertainty propagation of time-of-flight spectra with AGS". In: *Journal of Instrumentation* 7.11 (2012), P11002. DOI: 10.1088/1748-0221/7/11/P11002.

[4] A. J. M. Plompen et al. "The joint evaluated fission and fusion nuclear data library, JEFF-3.3". In: *Eur. Phys. J. A* 56.181 (2020), pp. 13–19. DOI: 10.1140/epja/s10050-020-00141-9.

[5] M. C. Moxon, T. C. Ware, and C. J. Dean. "REFIT-2009, A least-square program for resonance analysis of neutron transmission, capture, fission and scattering data users' guide for REFIT-2009-2009-10". In: *OECD/NEA* (2010).

[6] M. Sepielli, F. Pisacane, L. Ricci, A. Santagata, A. Gandini, T. Murgia, L. Cretara, V. Peluso, M. Carta, and V. Fabrizio. *Fast research reactor for generation IV technologies*. 2013. URL: https://www.academia.edu/107336681/Fast_Research_Reactor_for_Generation_IV_Technologies.

[7] N. Thompson et al. "A New Era of Nuclear Criticality Experiments: The First 10 Years of Comet Operations at NCERC". In: *Nuclear Science and Engineering* 195.sup1 (2021), S17–S36. DOI: 10.1080/00295639.2021.1947105.

[8] R. Mucciola, C. Paradela, G. Alaerts, S. Kopecky, C. Massimi, A. Moens, P. Schillebeeckx, and R. Wynants. "Evaluation of resonance parameters for neutron interactions with molybdenum". In: *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 531 (2022), pp. 100–108. ISSN: 0168-583X. DOI: 10.1016/j.nimb.2022.09.019.

[9] D. Ene, C. Borcea, S. Kopecky, W. Mondelaers, A. Negret, and A.J.M. Plompen. "Global characterisation of the GELINA facility for high-resolution neutron time-of-flight measurements by Monte Carlo simulations". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 618.1 (2010), pp. 54–68. ISSN: 0168-9002. DOI: 10.1016/j.nima.2010.03.005.

[10] H. Derrien. "Neutron Resonance Parameters of 238U and the Calculated Cross Sections from the Reich-Moore Analysis of Experimental Data in the Neutron Energy Range from 0 keV to 20 keV, report". In: *University of North Texas Libraries, UNT Digital Library* (December 5, 2005). DOI: 10.2172/885973.

[11] D.A. Brown et al. "ENDF/B-VIII.0: The 8th Major Release of the Nuclear Reaction Data Library with CIELO-project Cross Sections, New Standards and Thermal Scattering Data". In: *Nuclear Data Sheets* 148 (2018). Special Issue on Nuclear Reaction Data, pp. 1–142. ISSN: 0090-3752. DOI: 10.1016/j.nds.2018.02.001.

[12] *INDEN network*. https://www-nds.iaea.org/INDEN/.

[13] *EXFOR Database*. https://www-nds.iaea.org/exfor.