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Results of time-of-flight transmission measurements for ^{63,65}Cu and ^{nat}Cu at a 50 m station of GELINA

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Abstract
Transmission measurements have been performed at the time-of-flight facility GELINA to determine neutron resonance parameters for ^{63}Cu and ^{65}Cu. The experiments have been carried out at a 50 m transmission station at a moderated neutron beam using a Li-glass scintillator with the accelerator operating at 800 Hz. Measurements were performed with a ^{nat}Cu metallic sample and metallic samples enriched in ^{63}Cu and ^{65}Cu. This report describes the experimental details required to deliver the experimental transmission to the EXFOR data library which is maintained by the Nuclear Energy Agency of the OECD and the Nuclear Data Section of the IAEA. The experimental conditions and data reduction procedures are described. In addition, the full covariance information based on the AGS concept is given, such that resonance parameters together with their covariances can be derived in a least squares adjustment to the data.

1 Introduction

To study the resonance structure of neutron induced reaction cross sections, neutron spectroscopic measurements are required which determine with a high accuracy the energy of the neutron that interacts with the material under investigation. To cover a broad energy range such measurements are best carried out with a pulsed white neutron source, which is optimized for time-of-flight (TOF) measurements [1].

The TOF facility GELINA [2] has been designed and built for high-resolution cross section measurements in the resolved (RRR) and unresolved (URR) resonance region. It is a multi-user TOF facility, providing a white neutron source with a neutron energy range from 10 meV to 20 MeV. Up to 10 experiments can be performed simultaneously at measurement stations located between 10 m to 400 m from the neutron production target. The electron linear accelerator provides a pulsed electron beam with a maximum energy of 150 MeV and a repetition rate ranging from 50 Hz to 800 Hz. A compression magnet reduces the width of the electron pulses to less than 1 ns [3]. The electron beam hits a mercury-cooled uranium target producing Bremsstrahlung and subsequently neutrons via photonuclear reactions [4]. Two water-filled beryllium containers mounted above and below the neutron production target are used to moderate the neutrons. By applying different neutron beam collimation conditions, experiments can use either a fast or a thermalized neutron spectrum. The neutron production rate is constantly monitored by BF_3 proportional counters which are mounted in the ceiling of the target hall. The output of the monitors is used to normalize the time-of-flight spectra to the same neutron intensity. The measurement stations are equipped with air conditioning to reduce electronic drifts in the detection chains due to temperature changes.

In this report results of transmission measurements carried out at GELINA with natural and enriched Cu metallic samples are described. To reduce bias effects due to e.g. dead time and background, the measurement and data reduction procedures described in ref. [1] have been followed. The main objective of this report is to provide the information that is required to extract resonance parameters for

^{63}Cu and ^{65}Cu in a least squares adjustment to the data [1] using e.g. the resonance shape analysis code REFIT [5]. In the description of the data the recommendations resulting from a consultant's meeting organized by the Nuclear Data Section of the IAEA have been followed [6].

2 Experimental conditions

The transmission experiments were performed at the 50 m measurement station of flight path 4 with the accelerator operating at 800 Hz. The moderated neutron spectrum was used. A shadow bar made of Cu and Pb was placed close to the uranium target to reduce the intensity of the γ-ray flash and the fast neutron component. The flight path forms an angle of 9° with the direction normal to the face of the moderator viewing the flight path. The sample and detector were placed in a climatised room to keep them at a constant temperature of 22°C.

The partially thermalized neutrons scattered from the moderators were collimated into evacuated pipes of 50 cm diameter with annular collimators. A combination of Li-carbonate plus resin, Pb and Cu-collimators was used to reduce the neutron beam to a diameter of about 35 mm at the sample position. The sample was placed in an automatic sample changer at a distance of approximately 24 m from the neutron source. Close to the sample position a ^{10}B overlap filter, with an areal density of about 0.02 at/b, was placed to absorb slow neutrons from previous bursts. The impact of the γ-ray flash was reduced by a 8 mm thick Pb filter. Additional black resonance filters were mounted in an automatic filter changer close to the sample position to determine the background with the black resonance technique [1].

The neutron beam passing through the sample and filters was further collimated and detected by a 6.35 mm thick and 101.6 mm diameter NE912 Li-glass scintillator. The scintillator was connected through a boron-free quartz window to a 127 mm EMI 9823 KQB photomultiplier (PMT), which was placed outside the neutron beam and perpendicularly to its axis. The front face of the detector was placed at a distance of 47.587 m from the centre of the moderator. The diameter of the neutron beam at the detector position was about 45 mm.

The output signals of the detector were connected to conventional analog electronics. The anode pulse of the PMT was fed into a constant fraction discriminator to create a fast logic signal which defines the time the neutron has been detected. The signal of the 9^{th} dynode was shaped by a spectroscopic amplifier to determine the energy deposited by the ^{6}Li(n,t)α reaction in the detector. A module was included to produce a fixed dead time in the whole electronics chain directly after the detection of an event. This dead time t_d = 2050 (10) ns was continuously monitored by recording the time interval between successive pulses. The time-of-flight (TOF) of the detected neutron was determined by the time difference between the start signal (T_0), given at each electron burst, and the stop signal (T_s) derived from the anode pulse of the PMT. This time difference was measured with a multi-hit fast time coder with a 1 ns time resolution [7]. The TOF and pulse height of a detected event were recorded in list mode using a multi-parameter data acquisition system developed at the EC-JRC-IRMM [8]. Each measurement was subdivided in different cycles. Only cycles for which the ratio between the total counts in the transmission detector and in the neutron monitor deviated by less than 0.5% were selected. This selection was done with a code that is described in ref. [9].

Measurements were carried out with a 10.0 mm thick natural Cu metallic disc and with metallic discs enriched in ^{63}Cu and ^{65}Cu. The main characteristics of these samples are given in table 1. The natural samples were produced at the EC-JRC-IRMM, while the enriched samples were produced at the Oak Ridge National Laboratory. The isotopic composition of the natural samples was taken from ref. [10], the one of the enriched samples was provided by the supplier. The areal density of both the natural and enriched samples was derived at the EC-JRC-IRMM from a measurement of the weight and the effective area. The latter was determined by an optical surface inspection with a microscope measurement system from Mitutoyo. Regular sample-in and sample-out measurements were performed with a fixed Na and fixed Co filter and without background filters.

Table 1: Characteristics of the samples used for the transmission measurements performed at GELINA. All samples were in the form of a metallic disc with a 80 mm nominal diameter. The first column is the reference number. To calculate the areal density the Avogadro constant was taken as $N_A = 6.0221367 \times 10^{23}$ mol^{-1} and the atomic mass for ^{63}Cu as m$_a$ = 62.9296 u and for ^{65}Cu as m$_u$ = 64.9278 u. The abundance for natural Cu was taken from [10]. The quoted uncertainties are standard uncertainties at 1 standard deviation.

Sample ID		^{63}Cu at%	^{65}Cu at%	Thickness mm	Area mm^2	Weight g	Areal density at/b
NP2012-12-06	^{63}Cu	99.86	0.14	1.05	5000.3 (1.4)	46.03 (0.01)	8.809×10^{-3}
NP2012-12-05	^{65}Cu	0.30	99.70	1.07	5019.7 (0.2)	48.63 (0.01)	8.986×10^{-3}
NP2012-12-01	^{nat}Cu	63.17	30.83	9.60	3861.7 (0.1)	329.92 (0.01)	8.608×10^{-2}

Table 2: Different measurements configurations for the transmission measurements carried out with the samples specified in table 1

Configuration ID	Sample ID		^{10}B overlap filter	Pb filter x	Background filters Co	Na
1	NP2012-12-06	^{63}Cu	x	x		
2	NP2012-12-06	^{63}Cu	x	x		x
3	NP2012-12-06	^{63}Cu	x	x	x	x
4	NP2012-12-05	^{65}Cu	x	x		
5	NP2012-12-05	^{65}Cu	x	x	x	x
6	NP2012-12-01	^{nat}Cu	x	x	x	x

An overview of the different experimental configurations is given in table 2. For all these configurations an experimental transmission was deduced. For the measurements in the configuraion ID = 1 -3 the average current of the accelerator was about 70 μA. The current for the configurations ID = 4 - 6 was about a factor 3 lower.

3 Data reduction

The experimental transmission T_{exp} as a function of TOF was obtained from the ratio of a sample-in measurement C_{in} and a sample-out measurement C_{out}, both corrected for their background contributions B_{in} and B_{out}, respectively:

$$T_{exp} = N \frac{C_{in} - KB_{in}}{C_{out} - KB_{out}} \,. \tag{1}$$

The TOF-spectra (C_{in}, B_{in}, C_{out} and B_{out}) in eq. (1) were corrected for losses due to the dead time in the detector and electronics chain, and all spectra were normalized to the same TOF-bin width structure and neutron beam intensity. The latter was derived from the response of the BF_3 beam monitors. To avoid systematic effects due to slow variations of both the beam intensity and detector efficiency as a function of time, data were taken by alternating sample-in and sample-out measurements in cycles of about 1200 seconds each. Such a procedure reduces the uncertainty on the normalization to the beam intensity to less than 0.25%. This uncertainty was evaluated from the ratios of counts in the ^{6}Li transmission detector and in the flux monitors. To account for the uncertainty on the normalization due to the beam intensity the factor N = 1.0000 $\pm$ 0.0025 was introduced in eq. (1). The background as a function of TOF is an

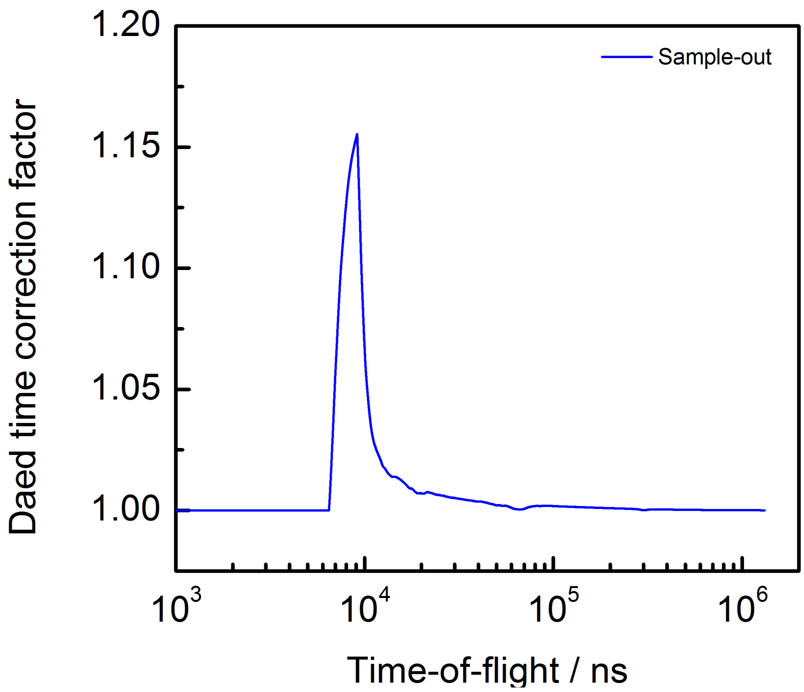

Fig. 1: Dead time correction factor as a function of time-of-flight for both a sample-in and sample-out measurement.

analytical expression determined by applying the black resonance technique [1]. The factor K in eq. (1) introduces a correlated uncertainty component accounting for systematic effects due to the background model. This factor was set to 1.00 $\pm$ 0.04 for measurements with at least one black resonance filter and to 1.00 $\pm$ 0.08 for measurements without black resonance filter. These uncertainties were derived from a statistical analysis of the difference between the observed black resonance dips and the estimated background.

3.1 Time-off set and flight path length

The time-of-flight t of a neutron creating a signal in the neutron detector was determined by the time difference between the start T_0 and stop T_s signal:

$$t = (T_s - T_0) + t_0 \; , \tag{2}$$

with t_0 a time-offset which was determined by a measurement of the γ-ray flash. The flight path distance L = 47.587 m, i.e. the distance between the centre of the moderator viewing the flight path and the front face of the detector, was derived previously from results of transmission measurements for ^{238}U using the 6.673(0.001) eV resonance of ^{238}U as a reference. The parameters of this resonance have been evaluated by Derrien *et al.* [11].

3.2 Dead time correction

To derive the experimental transmission and propagate both the correlated and uncorrelated uncertainties the AGS (Analysis Of Geel Spectra) package was used [12]. The dead time correction in the AGS code is based on the formula of Moore [13], which accounts for possible variations in the beam intensity. The maximum dead time correction for time-of-flight > 9500 ns (neutron energy < 130 keV) was less than 10% as can be seen in fig. 1, which shows the dead time correction for a sample-out measurement

Table 3: Parameters for the analytical expressions of the background correction for the different measurements configurations defined in table 2.

ID		$b_0/10^{-2}$ ns^{-1}	b_1 ns^{-1}	$\lambda_1/10^{-5}$ ns^{-1}	b_2 ns^{-1}	$\lambda_2/10^{-6}$ ns^{-1}	b_3 ns^{-1}	$\lambda_3/10^{-6}$ ns^{-1}
1	C_{in}	3.09	0.690	3.45	0.100	3.50	1.102	3.35
1	C_{out}	3.16	0.725	3.45	0.105	3.50	1.121	3.32
2	C_{in}	2.96	0.493	3.45	0.0715	3.50	1.060	3.49
2	C_{out}	2.94	0.523	3.45	0.0751	3.50	1.085	3.44
3	C_{in}	2.92	0.505	3.45	0.0692	3.50	1.007	3.44
3	C_{out}	2.96	0.575	3.45	0.0670	3.50	1.061	3.44
4	C_{in}	0.937	0.286	3.45	0.0262	3.50	0.164	3.50
4	C_{out}	0.940	0.271	3.45	0.0249	3.50	0.169	3.40
5	C_{in}	0.850	0.190	3.45	0.0181	3.50	0.130	3.37
5	C_{out}	0.850	0.196	3.45	0.0191	3.50	0.143	3.35
6	C_{in}	1.05	0.147	3.45	0.0168	3.50	0.127	3.29
6	C_{out}	1.19	0.213	3.45	0.0243	3.50	0.248	3.43

as a function of TOF. It has been demonstrated in ref. [1] that bias effects resulting from such corrections are negligible. Therefore, uncertainties related to the dead time correction were neglected and not propagated.

3.3 Background correction

The background as a function of TOF was parameterized by an analytical expression consisting of a constant and three exponentials:

$$B(t) = b_0 + b_1 e^{-\lambda_1 t} + b_2 e^{-\lambda_2 t} + b_3 e^{-\lambda_3 (t+t_0)} \,. \tag{3}$$

The parameter b_0 is the time independent contribution. The first exponential is due to the detection of 2.2 MeV γ-rays resulting from neutron capture in hydrogen present in the moderator. The time dependence of this background component was verified by Monte Carlo simulations and confirmed by measurements with polyethylene filters in the beam. The second exponential originates predominantly from neutrons scattered inside the detector station. The third exponential is due to slow neutrons from previous accelerator cycles. This contribution was estimated by an extrapolation of the TOF-spectrum at the end of the cycle. The parameter t_0 is related to the operating frequency of the accelerator (*i.e.* $t_0 =$ 1.25 ms for 800 Hz). The time dependence of the background was derived from the measurements with the 10 mm sample and the Na and Co black resonance filters in the beam and verified with measurements using a 3 mm thick Au sample. During some of the sample-in and sample-out runs Na and Co black resonance filters were kept in the beam to monitor the background at 2.85 keV and 132 eV and to account for the dependence of the background level on the presence of the sample [1]. The dead time corrected sample-in and sample-out TOF-spectra together with the background contributions for the measurements with the ^{nat}Cu sample and a Co and Na filter in the beam are shown in fig. 2 and 3, respectively. In these figures the contributions of the different background components are also given. These figures illustrate that the smallest contribution results from overlap neutrons. The parameters for the background corrections for both the sample-in and sample-out measurements in the different configurations specified in table 2 are given in table 3.

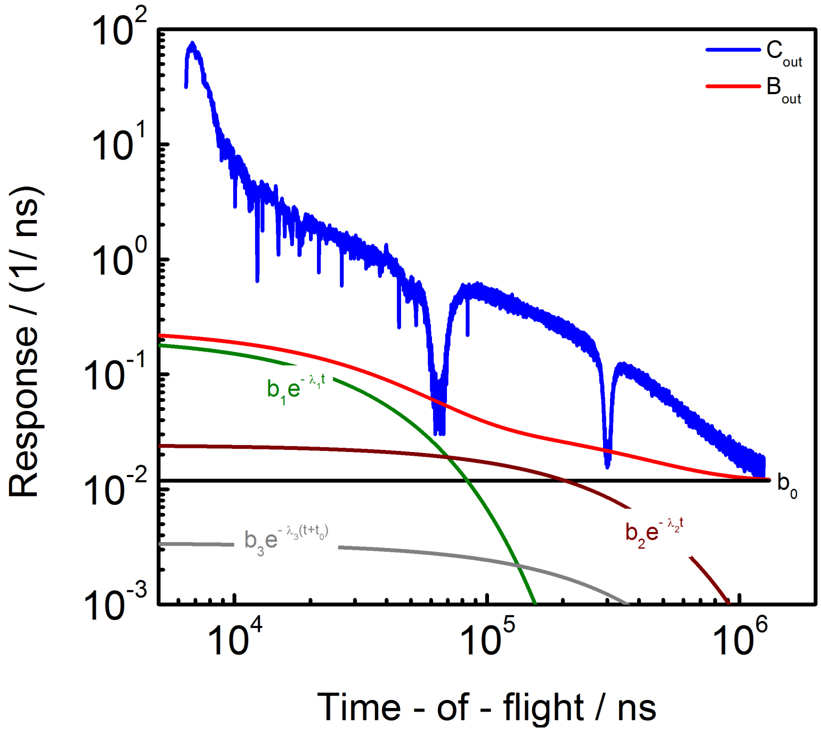

Fig. 2: Time-of-flight spectrum without sample in the beam (C_{out}) together with the total background (B_{out}). The different contributions to the background are also given.The Na and Co filters were placed in the beam.

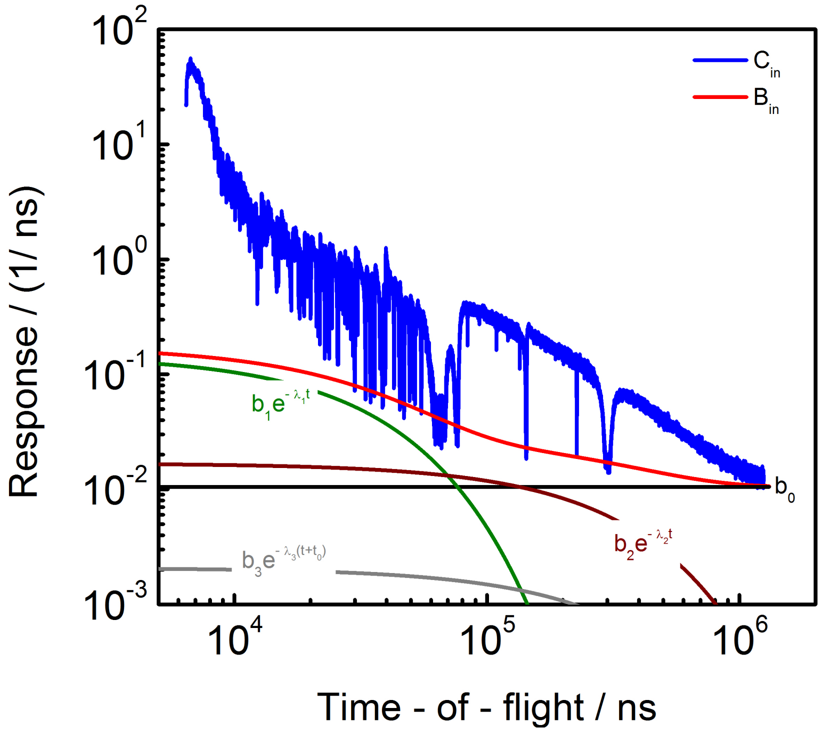

Fig. 3: Time-of-flight spectrum with the ^{nat}Cu sample in the beam (C_{in}) together with the total background (B_{in}). The different contributions to the background are also given. The Na and Co filters were placed in the beam.

Table 4: Tranmission (T_{exp}) and total uncertainty derived from the transmission data with a 10.0 mm thick natural Cu sample. The information to derive the full covariance matrix based on the AGS concept (eq. (4)) is given: the diagonal elements of the uncorrelated components, $u_u = \sqrt{U_u}$ are in column 6 whereas columns 7 and 8 represent the matrix $S_{\vec{\eta}=\{K,N\}}$. A high precision is given to ensure that the resulting covariance matrix can be inverted. The values in column 1 are set to -1 for $t_l < 159$ ns.

E / eV	t_l /ns	t_h / ns	T_{exp}	u_t	AGS		
					u_u	S_K	S_N
-1	0	1	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
-1	158	159	0	0	0	0	0
8.6535×10^9	159	160	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
131168.75	9499	9500	0	0	0	0	0
131196.38	9500	9501	0.628	0.0479	0.0479	-0.00030242	0.00156946
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
51.37	480000	480064	0.554	0.083	0.083	-0.00681106	0.00138567
51.35	480064	480128	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
6.85	1314688	1314816	0	0	0	0	0

4 Results

The AGS code [12], developed at the EC-JRC-IRMM, was used to derive the experimental transmission. The code is based on a compact formalism to propagate all uncertainties starting from uncorrelated uncertainties due to counting statistics. It stores the full covariance information after each operation in a concise, vectorized way. The AGS formalism results in a substantial reduction of data storage volume and provides a convenient structure to verify the various sources of uncertainties through each step of the data reduction process. The concept is recommended by the Nuclear Data Section of the IAEA [14] to prepare the experimental observables, including their full covariance information, for storage into the EXFOR data library [15].

The experimental transmissions resulting from measurements with the samples enriched in ^{63}Cu and ^{65}Cu and without filters in the beam are shown in figs. 4 and 5, respectively. The format in which the numerical data is stored in the EXFOR data library is illustrated in table 4. For time-of-flight values with t < 9500 and t > 480064 ns and TOF regions corresponding to the positions of the black resonance regions the data were put to zero. The data in table 4 include the full covariance information based on the AGS concept. The total uncertainty and the uncertainty due to uncorrelated components are reported, together with the contributions due to the normalization to the neutron beam intensity (N) and background model (K). Applying the AGS concept described in ref. [12] the covariance matrix $\boldsymbol{V}_{T_{exp}}$ of the experimental transmission can be calculated by:

$$\boldsymbol{V}_{T_{exp}} = \boldsymbol{U}_u + \boldsymbol{S}(\vec{\eta})\boldsymbol{S}^T(\vec{\eta}), \tag{4}$$

where $\boldsymbol{U}_u$ is a diagonal matrix containing the contribution of all uncorrelated uncertainty components and $\boldsymbol{S}(\vec{\eta})$ is a matrix representing the contribution of components $\vec{\eta} = \{K, N\}$ creating a correlated contribution.

The experimental details, which are required to perform a resonance analysis of the data, are summarized in Appendix A - F. The information given is based on the recommendation resulting from

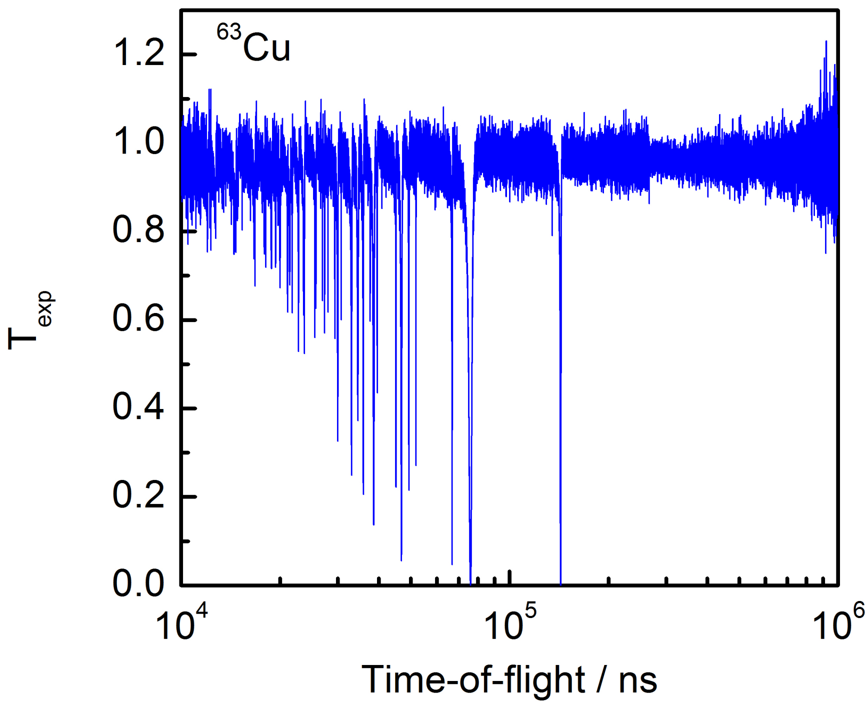

Fig. 4: Experimental transmission as a function of time-of-flight resulting from measurements with the ^{63}Cu enriched sample and without filters in the beam.

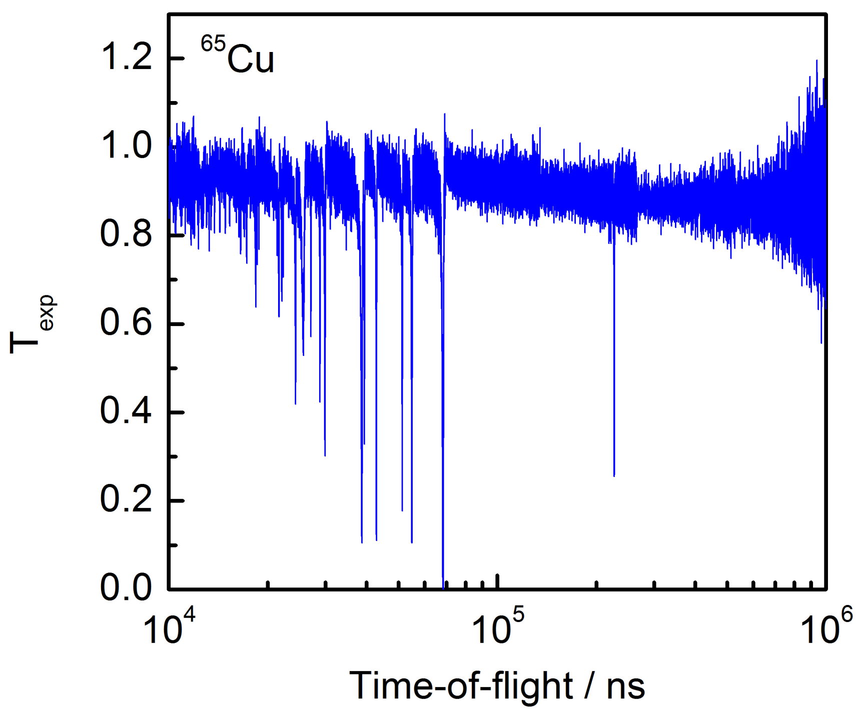

Fig. 5: Experimental transmission as a function of time-of-flight resulting from measurements with the ^{65}Cu enriched sample and without filters in the beam.

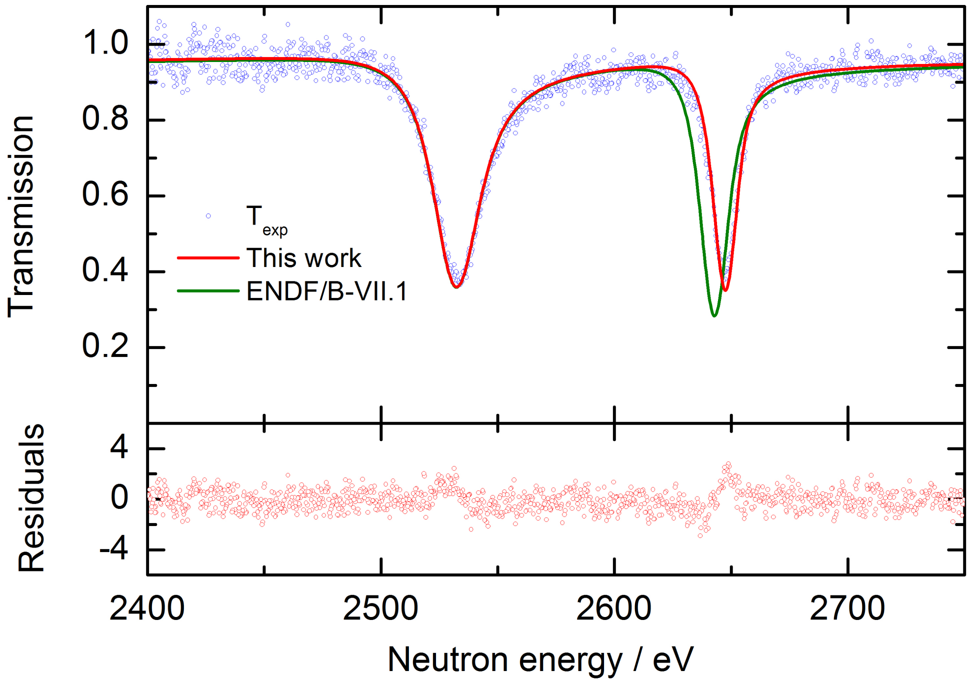

Fig. 6: Experimental transmission as a function of energy resulting from measurements with the ^{63}Cu enriched sample. The experimental transmission is compared with the transmission calculated with the parameters in the ENDF/B-VII.1 data library and with those resulting from an adjustment to the ^{nat}Cu data.

a consultant's meeting organized by the NDS-IAEA [6] in October 2013. It is recommended that only the data between 50 eV and 130 keV is used for a resonance shape analysis. An example of a resonance shape analysis with REFIT [5] on the transmission obtained with the sample enriched in ^{63}Cu is shown in fig. 6.

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APPENDIX A: SUMMARY OF EXPERIMENTAL DETAILS - ID1

A. EXPERIMENT DESCRIPTION

1. Main Reference		[1]
2. Facility	GELINA	[3]
3. Neutron production		
Neutron production beam	Electron	
Nominal average beam energy	100 MeV	
Nominal average peak current	70 μA	
Repetition rate (pulses per second)	800 Hz	
Pulse width	1 ns	
Primary neutron production target	Mercury cooled depleted uranium	
Target nominal neutron production intensity	3.4×10^{13} s^{-1}	
4. Moderator		
Primary neutron source position in moderator	Above and below uranium target	
Moderator material	2 H_2O filled Be-containers around U-target	
Moderator dimensions (internal)	2 x (14.6 cm x 21 cm x 3.9 cm)	
Density (moderator material)	1g/cm^2	
Temperature (K)	Room temperature	
Moderator-room decoupler (Cd, B, ...)	None	
5. Other experimental details		
Measurement type	Transmission	
Method (total energy, total absorption, ...)	Good transmission geometry	[4]
Flight Path length (moderator – detector: centre to face distance)	L = 47.587 m	
Flight path direction	9° with respect to normal of the moderator face viewing the flight path	
Neutron beam dimensions at sample position	35 mm in diameter	
Neutron beam profile	–	
Overlap suppression	$^{10}B_4C$ overlap filter (^{10}B: 0.02 at/b)	
Other fixed beam filters	Pb (8 mm)	
6. Detector		
Type	Scintillator (NE912)	
Material	Li-glass	
Surface Dimensions	101.6 mm in diameter	
Thickness	6.35 mm in thick	
Distance from samples	25 m	
Detector(s) position relative to neutron beam	In the beam	
Detector(s) solid angle		
7. Sample		
Type (metal, powder, liquid, crystal)	Metal	
Chemical composition	^{63}Cu (99.86 at%), ^{65}Cu (0.14 at%)	
Sample composition (at/b)	^{63}Cu: 8.81×10^{-3} at/b	
Temperature	22°C	
Sample mass	46.03 (0.01) g	
Geometrical shape (cylinder, sphere, ...)	cylinder	
Surface dimension	5000.3 (1.4) mm^2	
Nominal thickness	1.05 mm	
Containment description	None	
Additional comment	enriched ^{63}Cu	

8. Data Reduction Procedure		[4, 5]
Dead time correction	Done (< factor 1.2)	
Back ground subtraction	Black resonance technique	
Flux determination (reference reaction, ...)	–	
Normalization	1.000 – 0.0025	
Detector efficiency	–	
Self-shielding	–	
Time-of-flight binning	Zone length bin width	
	2048 4 ns	
	4096 1 ns	
	4096 2 ns	
	4096 4 ns	
	4096 8 ns	
	4096 16 ns	
	4096 32 ns	
	4096 64 ns	
	6144 128 ns	
9. Response function		
Initial pulse	Normal distribution, FWHM = 2 ns	
Target / moderator assembly	Numerical distribution from MC simulations	[6, 7]
Detector	Analytical function defined in REFIT manual	[8]

B. DATA FORMAT

Column	Content	Unit	Comment
1	Energy	eV	Relativistic relation using a fixed FP length of 47.587 m
2	t_l	ns	
3	t_h	ns	
4	T_{exp}		Transmission
5	Total Uncertainty		
6	Uncorrelated uncertainty		Uncorrelated uncertainty due to counting statistics
7	AGS-vector (K)		Background model (u_K/K = 8%)
8	AGS-vector (N)		Normalization (u_N/N = 0.25%)

Comments from the authors:

- The AGS concept was used to derive the experimental transmission:

$$T_{exp} = N \frac{C_{in} - K\ B_{in}}{C_{out} - K\ B_{out}}$$

  and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalization (u_N/N = 0.25%) and background model (u_K/K = 4% or 8%, depending if a fixed black resonance filter was used).
- The quoted uncertainties are standard uncertainties at 1 standard deviation.
- The values in column 1 are set to -1 for: $t_h \leq L \times c$.

APPENDIX B: SUMMARY OF EXPERIMENTAL DETAILS - ID2

A. EXPERIMENT DESCRIPTION

1. Main Reference		[1]
2. Facility	GELINA	[3]
3. Neutron production		
Neutron production beam	Electron	
Nominal average beam energy	100 MeV	
Nominal average peak current	70 μA	
Repetition rate (pulses per second)	800 Hz	
Pulse width	1 ns	
Primary neutron production target	Mercury cooled depleted uranium	
Target nominal neutron production intensity	3.4×10^{13} s^{-1}	
4. Moderator		
Primary neutron source position in moderator	Above and below uranium target	
Moderator material	2 H_2O filled Be-containers around U-target	
Moderator dimensions (internal)	2 x (14.6 cm x 21 cm x 3.9 cm)	
Density (moderator material)	1 g/cm^3	
Temperature	Room temperature	
Moderator-room decoupler (Cd, B, . . .)	None	
5. Other experimental details		
Measurement type	Transmission	
Method (total energy, total absorption, . . .)	Good transmission geometry	[4]
Flight Path length (moderator – detector: centre to face distance)	L =47.587 m	
Flight path direction	9° with respect to normal of the moderator face viewing the flight path	
Neutron beam dimensions at sample position	35 mm in diameter	
Neutron beam profile	–	
Overlap suppression	$^{10}B_4C$ overlap filter (^{10}B: 0.02 at/b)	
Other fixed beam filters	Pb (8 mm), Na	
6. Detector		
Type	Scintillator (NE912)	
Material	Li-glass	
Surface Dimensions	101.6 mm in diameter	
Thickness	6.35 mm in thick	
Distance from samples	25 m	
Detector(s) position relative to neutron beam	In the beam	
Detector(s) solid angle		
7. Sample		
Type (metal, powder, liquid, crystal)	Metal	
Chemical composition	^{63}Cu (99.86 at%), ^{65}Cu (0.14 at%)	
Sample composition	^{63}Cu: 8.81×10^{-3} at/b	
Temperature	22°C	
Sample mass	46.03 (0.01) g	
Geometrical shape (cylinder, sphere, . . .)	cylinder	
Surface dimension	5000.3 (1.4) mm^2	
Nominal thickness	1.05 mm	
Containment description	None	
Additional comment	enriched ^{63}Cu	

8. Data Reduction Procedure		[4, 5]
Dead time correction	Done (< factor 1.2)	
Back ground subtraction	Black resonance technique	
Flux determination (reference reaction, ...)	–	
Normalization	1.000 – 0.0025	
Detector efficiency	–	
Self-shielding	–	
Time-of-flight binning	Zone length / bin width	
	2048 / 4 ns	
	4096 / 1 ns	
	4096 / 2 ns	
	4096 / 4 ns	
	4096 / 8 ns	
	4096 / 16 ns	
	4096 / 32 ns	
	4096 / 64 ns	
	6144 / 128 ns	
9. Response function		
Initial pulse	Normal distribution, FWHM = 2 ns	
Target / moderator assembly	Numerical distribution from MC simulations	[6, 7]
Detector	Analytical function defined in REFIT manual	[8]

B. DATA FORMAT

Column	Content	Unit	Comment
1	Energy	eV	Relativistic relation using a fixed FP length of 47.587 m
2	t_l	ns	
3	t_h	ns	
4	T_{exp}		Transmission
5	Total Uncertainty		
6	Uncorrelated uncertainty		Uncorrelated uncertainty due to counting statistics
7	AGS-vector (K)		Background model (u_K/K = 4%)
8	AGS-vector (N)		Normalization (u_N/N = 0.25%)

Comments from the authors:

– The AGS concept was used to derive the experimental transmission:

$$T_{exp} = N \frac{C_{in} - K\ B_{in}}{C_{out} - K\ B_{out}}$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalization (u_N/N = 0.25%) and background model (u_K/K = 4% or 8%, depending if a fixed black resonance filter was used).

– The quoted uncertainties are standard uncertainties at 1 standard deviation.

– The values in column 1 are set to -1 for: $t_h \leq L \times c$.

APPENDIX C: SUMMARY OF EXPERIMENTAL DETAILS - ID3

A. EXPERIMENT DESCRIPTION

1. Main Reference		[1]
2. Facility	GELINA	[3]
3. Neutron production		
Neutron production beam	Electron	
Nominal average beam energy	100 MeV	
Nominal average peak current	70 μA	
Repetition rate (pulses per second)	800 Hz	
Pulse width	1 ns	
Primary neutron production target	Mercury cooled depleted uranium	
Target nominal neutron production intensity	3.4×10^{13} s^{-1}	
4. Moderator		
Primary neutron source position in moderator	Above and below uranium target	
Moderator material	2 H_2O filled Be-containers around U-target	
Moderator dimensions (internal)	2 x (14.6 cm x 21 cm x 3.9 cm)	
Density (moderator material)	1 g/cm^3	
Temperature	Room temperature	
Moderator-room decoupler (Cd, B, . . .)	None	
5. Other experimental details		
Measurement type	Transmission	
Method (total energy, total absorption, . . .)	Good transmission geometry	[4]
Flight Path length (moderator – detector: centre to face distance)	L = 47.587 m	
Flight path direction	9° with respect to normal of the moderator face viewing the flight path	
Neutron beam dimensions at sample position	35 mm in diameter	
Neutron beam profile	–	
Overlap suppression	$^{10}B_4C$ overlap filter (^{10}B: 0.02 at/b)	
Other fixed beam filters	Pb (8 mm), Na, Co	
6. Detector		
Type	Scintillator (NE912)	
Material	Li-glass	
Surface Dimensions	101.6 mm in diameter	
Thickness	6.35 mm in thick	
Distance from samples	25 m	
Detector(s) position relative to neutron beam	In the beam	
Detector(s) solid angle		
7. Sample		
Type (metal, powder, liquid, crystal)	Metal	
Chemical composition	^{63}Cu (99.86 at%), ^{65}Cu (0.14 at%)	
Sample composition	^{63}Cu: 8.81×10^{-3} at/b	
Temperature	22°C	
Sample mass	46.03 (0.01) g	
Geometrical shape (cylinder, sphere, . . .)	cylinder	
Surface dimension	5000.3 (1.4) mm^2	
Nominal thickness	1.05 mm	
Containment description	None	
Additional comment	enriched ^{63}Cu	

8. Data Reduction Procedure		[4, 5]
Dead time correction	Done (< factor 1.2)	
Back ground subtraction	Black resonance technique	
Flux determination (reference reaction, ...)	–	
Normalization	1.000 – 0.0025	
Detector efficiency	–	
Self-shielding	–	
Time-of-flight binning	Zone length / bin width 2048 / 4 ns 4096 / 1 ns 4096 / 2 ns 4096 / 4 ns 4096 / 8 ns 4096 / 16 ns 4096 / 32 ns 4096 / 64 ns 6144 / 128 ns	
9. Response function		
Initial pulse	Normal distribution, FWHM = 2 ns	
Target / moderator assembly	Numerical distribution from MC simulations	[6, 7]
Detector	Analytical function defined in REFIT manual	[8]

B. DATA FORMAT

Column	Content	Unit	Comment
1	Energy	eV	Relativistic relation using a fixed FP length of 47.587 m
2	t_l	ns	
3	t_h	ns	
4	T_{exp}		Transmission
5	Total Uncertainty		
6	Uncorrelated uncertainty		Uncorrelated uncertainty due to counting statistics
7	AGS-vector (K)		Background model (u_K/K = 4%)
8	AGS-vector (N)		Normalization (u_N/N = 0.25%)

Comments from the authors:

– The AGS concept was used to derive the experimental transmission:

$$T_{exp} = N \frac{C_{in} - K\ B_{in}}{C_{out} - K\ B_{out}}$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalization (u_N/N = 0.25%) and background model (u_K/K = 4% or 8%, depending if a fixed black resonance filter was used).

– The quoted uncertainties are standard uncertainties at 1 standard deviation.

– The values in column 1 are set to -1 for: $t_h \leq L \times c$.

APPENDIX D: SUMMARY OF EXPERIMENTAL DETAILS - ID4

A. EXPERIMENT DESCRIPTION

1. Main Reference		[1]
2. Facility	GELINA	[3]
3. Neutron production		
Neutron production beam	Electron	
Nominal average beam energy	100 MeV	
Nominal average peak current	30 μA	
Repetition rate (pulses per second)	800 Hz	
Pulse width	1 ns	
Primary neutron production target	Mercury cooled depleted uranium	
Target nominal neutron production intensity	3.4×10^{13} s^{-1}	
4. Moderator		
Primary neutron source position in moderator	Above and below uranium target	
Moderator material	2 H_2O filled Be-containers around U-target	
Moderator dimensions (internal)	2 x (14.6 cm x 21 cm x 3.9 cm)	
Density (moderator material)	1 g/cm^3	
Temperature	Room temperature	
Moderator-room decoupler (Cd, B, . . .)	None	
5. Other experimental details		
Measurement type	Transmission	
Method (total energy, total absorption, . . .)	Good transmission geometry	[4]
Flight Path length (moderator – detector: centre to face distance)	L = 47.587 m	
Flight path direction	9° with respect to normal of the moderator face viewing the flight path	
Neutron beam dimensions at sample position	35 mm in diameter	
Neutron beam profile	–	
Overlap suppression	$^{10}B_4C$ overlap filter (^{10}B: 0.02 at/b)	
Other fixed beam filters	Pb (8 mm)	
6. Detector		
Type	Scintillator (NE912)	
Material	Li-glass	
Surface Dimensions	101.6 mm in diameter	
Thickness	6.35 mm in thick	
Distance from samples	25 m	
Detector(s) position relative to neutron beam	In the beam	
Detector(s) solid angle		
7. Sample		
Type (metal, powder, liquid, crystal)	Metal	
Chemical composition	^{65}Cu (99.70 at%), ^{63}Cu (0.3 at%)	
Sample composition	^{65}Cu: 8.99×10^{-3} at/b	
Temperature	22°C	
Sample mass	48.63 (0.01) g	
Geometrical shape (cylinder, sphere, . . .)	cylinder	
Surface dimension	5019.7 (0.2) mm^2	
Nominal thickness	1.065 mm	
Containment description	None	
Additional comment	enriched ^{65}Cu	

8. Data Reduction Procedure		[4, 5]
Dead time correction	Done (< factor 1.2)	
Back ground subtraction	Black resonance technique	
Flux determination (reference reaction, ...)	–	
Normalization	1.000 – 0.0025	
Detector efficiency	–	
Self-shielding	–	
Time-of-flight binning	Zone length bin width	
	2048 4 ns	
	4096 1 ns	
	4096 2 ns	
	4096 4 ns	
	4096 8 ns	
	4096 16 ns	
	4096 32 ns	
	4096 64 ns	
	6144 128 ns	
9. Response function		
Initial pulse	Normal distribution, FWHM = 2 ns	
Target / moderator assembly	Numerical distribution from MC simulations	[6, 7]
Detector	Analytical function defined in REFIT manual	[8]

B. DATA FORMAT

Column	Content	Unit	Comment
1	Energy	eV	Relativistic relation using a fixed FP length of 47.587 m
2	t_l	ns	
3	t_h	ns	
4	T_{exp}		Transmission
5	Total Uncertainty		
6	Uncorrelated uncertainty		Uncorrelated uncertainty due to counting statistics
7	AGS-vector (K)		Background model (u_K/K = 8%)
8	AGS-vector (N)		Normalization (u_N/N = 0.25%)

Comments from the authors:

- The AGS concept was used to derive the experimental transmission:

$$T_{exp} = N\frac{C_{in} - K\ B_{in}}{C_{out} - K\ B_{out}}$$

  and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalization (u_N/N = 0.25%) and background model (u_K/K = 4% or 8%, depending if a fixed black resonance filter was used).
- The quoted uncertainties are standard uncertainties at 1 standard deviation.
- The values in column 1 are set to -1 for: $t_h \leq L \times c$.

APPENDIX E: SUMMARY OF EXPERIMENTAL DETAILS - ID5

A. EXPERIMENT DESCRIPTION

1. Main Reference		[1]
2. Facility	GELINA	[3]
3. Neutron production		
Neutron production beam	Electron	
Nominal average beam energy	100 MeV	
Nominal average peak current	30 μA	
Repetition rate (pulses per second)	800 Hz	
Pulse width	1 ns	
Primary neutron production target	Mercury cooled depleted uranium	
Target nominal neutron production intensity	3.4×10^{13} s^{-1}	
4. Moderator		
Primary neutron source position in moderator	Above and below uranium target	
Moderator material	2 H_2O filled Be-containers around U-target	
Moderator dimensions (internal)	2 x (14.6 cm x 21 cm x 3.9 cm)	
Density (moderator material)	1 g/cm^3	
Temperature	Room temperature	
Moderator-room decoupler (Cd, B, . . .)	None	
5. Other experimental details		
Measurement type	Transmission	
Method (total energy, total absorption, . . .)	Good transmission geometry	[4]
Flight Path length (moderator – detector: centre to face distance)	L =47.587 m	
Flight path direction	9° with respect to normal of the moderator face viewing the flight path	
Neutron beam dimensions at sample position	35 mm in diameter	
Neutron beam profile	–	
Overlap suppression	$^{10}B_4C$ overlap filter (^{10}B: 0.02 at/b)	
Other fixed beam filters	Pb (8 mm), Na, Co	
6. Detector		
Type	Scintillator (NE912)	
Material	Li-glass	
Surface Dimensions	101.6 mm in diameter	
Thickness	6.35 mm in thick	
Distance from samples	25 m	
Detector(s) position relative to neutron beam	In the beam	
Detector(s) solid angle		
7. Sample		
Type (metal, powder, liquid, crystal)	Metal	
Chemical composition	^{65}Cu (99.70 at%), ^{63}Cu (0.3 at%)	
Sample composition	^{65}Cu: 8.99×10^{-3} at/b	
Temperature	22°C	
Sample mass	48.63 (0.01) g	
Geometrical shape (cylinder, sphere, . . .)	cylinder	
Surface dimension	5019.7 (0.2) mm^2	
Nominal thickness	1.065 mm	
Containment description	None	
Additional comment	enriched ^{65}Cu	

8. Data Reduction Procedure		[4, 5]
Dead time correction	Done (< factor 1.2)	
Back ground subtraction	Black resonance technique	
Flux determination (reference reaction, ...)	–	
Normalization	1.000 – 0.0025	
Detector efficiency	–	
Self-shielding	–	
Time-of-flight binning	Zone length bin width	
	2048 4 ns	
	4096 1 ns	
	4096 2 ns	
	4096 4 ns	
	4096 8 ns	
	4096 16 ns	
	4096 32 ns	
	4096 64 ns	
	6144 128 ns	
9. Response function		
Initial pulse	Normal distribution, FWHM = 2 ns	
Target / moderator assembly	Numerical distribution from MC simulations	[6, 7]
Detector	Analytical function defined in REFIT manual	[8]

B. DATA FORMAT

Column	Content	Unit	Comment
1	Energy	eV	Relativistic relation using a fixed FP length of 47.587 m
2	t_l	ns	
3	t_h	ns	
4	T_{exp}		Transmission
5	Total Uncertainty		
6	Uncorrelated uncertainty		Uncorrelated uncertainty due to counting statistics
7	AGS-vector (K)		Background model (u_K/K = 4%)
8	AGS-vector (N)		Normalization (u_N/N = 0.25%)

Comments from the authors:

- The AGS concept was used to derive the experimental transmission:

$$T_{exp} = N \frac{C_{in} - K\ B_{in}}{C_{out} - K\ B_{out}}$$

  and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalization (u_N/N = 0.25%) and background model (u_K/K = 4% or 8%, depending if a fixed black resonance filter was used).
- The quoted uncertainties are standard uncertainties at 1 standard deviation.
- The values in column 1 are set to -1 for: $t_h \leq L \times c$.

APPENDIX F: SUMMARY OF EXPERIMENTAL DETAILS - ID6

A. EXPERIMENT DESCRIPTION

1. Main Reference		[1]
2. Facility	GELINA	[3]
3. Neutron production		
Neutron production beam	Electron	
Nominal average beam energy	100 MeV	
Nominal average peak current	30 μA	
Repetition rate (pulses per second)	800 Hz	
Pulse width	1 ns	
Primary neutron production target	Mercury cooled depleted uranium	
Target nominal neutron production intensity	3.4×10^{13} s^{-1}	
4. Moderator		
Primary neutron source position in moderator	Above and below uranium target	
Moderator material	2 H_2O filled Be-containers around U-target	
Moderator dimensions (internal)	2 x (14.6 cm x 21 cm x 3.9 cm)	
Density (moderator material)	1 g/cm^2	
Temperature	Room temperature	
Moderator-room decoupler (Cd, B, . . .)	None	
5. Other experimental details		
Measurement type	Transmission	
Method (total energy, total absorption, . . .)	Good transmission geometry	[4]
Flight Path length (moderator – detector: centre to face distance)	L = 47.587 m	
Flight path direction	9° with respect to normal of the moderator face viewing the flight path	
Neutron beam dimensions at sample position	35 mm in diameter	
Neutron beam profile	–	
Overlap suppression	$^{10}B_4C$ overlap filter (^{10}B: 0.02 at/b)	
Other fixed beam filters	Pb (8 mm), Na, Co	
6. Detector		
Type	Scintillator (NE912)	
Material	Li-glass	
Surface Dimensions	101.6 mm in diameter	
Thickness	6.35 mm in thick	
Distance from samples	25 m	
Detector(s) position relative to neutron beam	In the beam	
Detector(s) solid angle		
7. Sample		
Type (metal, powder, liquid, crystal)	Metal	
Chemical composition	^{nat}Cu (100 at%)	
Sample composition	^{nat}Cu: 8.608×10^{-2} at/b	
Temperature	22°C	
Sample mass	329.92 (0.01) g	
Geometrical shape (cylinder, sphere, . . .)	cylinder	
Surface dimension	3861.7 (0.1) mm^2	
Nominal thickness	9.59 mm	
Containment description	None	
Additional comment	63.17 at% ^{63}Cu, 30.83 at% ^{65}Cu	

8. **Data Reduction Procedure**		[4,5]
Dead time correction	Done (< factor 1.2)	
Back ground subtraction	Black resonance technique	
Flux determination (reference reaction, ...)	–	
Normalization	1.000 – 0.0025	
Detector efficiency	–	
Self-shielding	–	
Time-of-flight binning	Zone length bin width	
	2048 4 ns	
	4096 1 ns	
	4096 2 ns	
	4096 4 ns	
	4096 8 ns	
	4096 16 ns	
	4096 32 ns	
	4096 64 ns	
	6144 128 ns	
9. **Response function**		
Initial pulse	Normal distribution, FWHM = 2 ns	
Target / moderator assembly	Numerical distribution from MC simulations	[6,7]
Detector	Analytical function defined in REFIT manual	[8]

B. DATA FORMAT

Column	Content	Unit	Comment
1	Energy	eV	Relativistic relation using a fixed FP length of 47.587 m
2	t_l	ns	
3	t_h	ns	
4	T_{exp}		Transmission
5	Total Uncertainty		
6	Uncorrelated uncertainty		Uncorrelated uncertainty due to counting statistics
7	AGS-vector (K)		Background model (u_K/K = 4%)
8	AGS-vector (N)		Normalization (u_N/N = 0.25%)

Comments from the authors:

- The AGS concept was used to derive the experimental transmission:

$$T_{exp} = N\frac{C_{in} - K\ B_{in}}{C_{out} - K\ B_{out}}$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalization (u_N/N = 0.25%) and background model (u_K/K = 4% or 8%, depending if a fixed black resonance filter was used).
- The quoted uncertainties are standard uncertainties at 1 standard deviation.
- The values in column 1 are set to -1 for: $t_h \leq L \times c$.

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Title: Results of time-of-flight transmission measurements for $^{63,65}Cu$ and ^{nat}Cu at a 50 m station of GELINA

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Abstract

Transmission measurements have been performed at the time-of-flight facility GELINA to determine neutron resonance parameters for ^{63}Cu and ^{65}Cu. The experiments have been carried out at a 50 m transmission station at a moderated neutron beam using a Li-glass scintillator with the accelerator operating at 800 Hz. Measurements were performed with metallic samples enriched in ^{63}Cu and ^{65}Cu and a ^{nat}Cu metallic sample. This report describes the experimental details required to deliver the experimental transmission to the EXFOR data library which is maintained by the Nuclear Energy Agency of the OECD and the Nuclear Data Section of the IAEA. The experimental conditions and data reduction procedures are described. In addition, the full covariance information based on the AGS concept is given such that resonance parameters together with their covariances can be derived in a least squares adjustment to the data.

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