https://doi.org/10.61092/iaea.kyqd-kmp8

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INDC(EUR)-0037
Distr. G+J

INDC International Nuclear Data Committee

Results of time-of-flight transmission measurements for ^{155,157}Gd at a 10 m station of GELINA

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September 2020

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Produced by the IAEA in Austria
September 2020

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Abstract. Transmission measurements have been performed at the time-of-flight facility GELINA to determine neutron resonance parameters for ^{155,157}Gd. The measurements have been carried out at a 10 m transmission station equipped with a Li-glass scintillator as neutron detector. The accelerator was operated at two frequencies, i.e. 400 Hz and 50 Hz, to cover a broad energy region of the moderated neutron beam. This report provides the experimental details required to deliver the data to the EXFOR data library which is maintained by the International Network of Nuclear Reaction Data Centres (NRDC). In this document, the experimental conditions and data reduction procedures are described. In addition, the full covariance information based on the AGS concept is given such that nuclear reaction model 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 that 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][3] has been designed and built for high-resolution cross-section measurements in the resonance region. It is a multi-user 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 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, a peak current of 10 A and a repetition rate ranging from 50 Hz to 800 Hz. A compression magnet reduces the width of the electron pulses to a Full Width at Half Maximum (FWHM) of about 2 ns [4]. The electron beam hits a mercury-cooled uranium target producing Bremsstrahlung and subsequently neutrons via photonuclear reactions [5]. Two water-filled beryllium containers mounted above and below the neutron-producing target are used to moderate the neutrons. By applying different neutron beam collimation conditions, experiments can use either a fast or a moderated neutron spectrum. The neutron production rate is monitored by BF_3

proportional counters, which are mounted in the ceiling of the target hall. The output of these 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. The temperature in the measurement stations is continuously monitored.

In this report, results of transmission measurements carried out at GELINA with ^{155,157}Gd metallic samples are described. To reduce bias effects due to e.g. dead time and background, the measurement and data reduction procedures recommended 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 ^{155,157}Gd in a least squares adjustment to the data using e.g. the resonance shape analysis code REFIT [6]. 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 [7].

2 Experimental conditions

The transmission experiments were performed at the 10 m measurement station of flight path 13 with the accelerator operating at 50 Hz and 400 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 18° with the direction normal to the face of the moderator viewing the flight path. The samples and detector were placed in an acclimatized room to keep them at a temperature of about 20°C.

The neutrons scattered from the moderators were collimated into the flight path through an evacuated aluminum pipe of 50 cm diameter with annular collimators, consisting of borated wax, copper and lead. A set of Pb, Ni and Cu annular collimators was used to reduce the neutron beam to a diameter of 10 mm at the sample position. Additional lithium and B_4C collimators were installed to absorb neutrons that are scattered by the collimators [8]. The impact of the γ-ray flash was reduced by a Pb filter placed at the entrance of the station. The samples were placed at 7.7 m distance from the neutron source. The neutron beam passing through the sample and filters was further collimated and detected by a 6.35 mm x 76 mm x 76 mm Scionix Li-glass scintillator. The detector was placed at about 11 m from the neutron target.

Permanent Co and Na black resonance filters were used to continuously monitor the background at 132 eV and 2850 eV, respectively, and to account for the impact of the sample on the background [1]. Additional Ag (5.2 eV) and W (21.1 eV) black resonance filters were included during short cycles to estimate the background shape at lower neutron energies. A 4 mm thick Cd overlap filter was placed in front of the sample position with the accelerator operating at 400 Hz to absorb slow neutrons from a previous burst. The measurements with the accelerator operating at 50 Hz were performed without the overlap filter. The TOF-dependence of the background under these conditions was verified by additional measurements with Rh (1.3 eV), Ag and W black resonance filters in the beam.

The TOF of the detected neutron was derived from the time difference between the stop signal T_s, obtained from the anode pulse of the PMT, and the start signal T_0, given at each electron burst. This time difference was processed with a multi-hit fast time coder with a 1 ns time resolution. The TOF and the pulse height of each detected event were recorded in list mode using a multi-parameter data acquisition system developed at the EC-JRC [9]. 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 1 % were selected. The dead time of the detection chain t_d = 3510 (10) ns was derived from a spectrum of the time interval between successive events. The maximum dead time correction was less than 20 %. In Ref. [1], it is demonstrated that uncertainties for such dead time corrections are very small and can be neglected.

Measurements were performed with $^{155,157}Gd$ metallic samples of two different thicknesses. They were sandwiched in two Mylar foils of 6 μm thickness. The thicker samples were measured at an accelerator frequency of 400 Hz to study the low energy resonances, while the thinner samples were measured at 50 Hz to cover the neutron energy region from 10 meV to about 100 eV. The main characteristics of the samples are reported in Table 1 and Table 2. One of the gadolinium samples is shown in Figure 1. The areal density of the samples was derived from a measurement of the weight and the area with an uncertainty better than 0.1 %. The area was determined by an optical surface inspection with a microscope system from Mitutoyo [10]. The sample-out measurements were performed using a dummy Mylar sample made from the same batch that was used to cover the Gd samples.

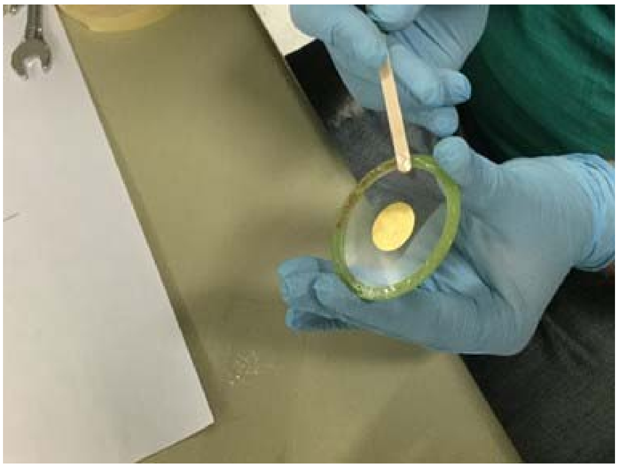

Figure 1. Picture of one of the gadolinium samples used for the transmission measurements described in this report.

ID	Isotope	Thickness /mm	Mass/mg	Area/mm^2	Areal Density (at/b)
1	^{155}Gd	0.0040 (4)	10.0 (1)	313.7 (2)	1.238 (12) x 10^{-5}
2	^{155}Gd	0.040 (4)	100.6 (1)	316.4 (1)	12.353 (12) x 10^{-5}
3	^{157}Gd	0.0020 (2)	4.7 (1)	315.51 (4)	0.571 (12) x 10^{-5}
4	^{157}Gd	0.080 (8)	191.6 (1)	315.8 (1)	23.272 (12) x 10^{-5}

Table 1. Characteristics of the samples used for the transmission measurements described in this report. The areal densities were derived from a measurement of the weight and area.

Sample	^{152}Gd	^{154}Gd	^{155}Gd	^{156}Gd	^{157}Gd	^{158}Gd	^{160}Gd
^{155}Gd	0.03%	0.63%	91.74%	5.12%	1.14%	0.94%	0.4%
^{157}Gd	<0.01%	0.04%	0.29%	1.68%	88.32%	9.10%	0.57%

Table 2. Isotopic composition of the enriched gadolinium samples. The data are given in wt%.

3 Data reduction

The AGS code [11][12], developed at JRC-Geel, was used to derive the experimental transmission from the TOF-spectra. The code is based on a compact formalism to propagate both correlated and uncorrelated uncertainties starting from uncorrelated uncertainties due to counting statistics.

3.1 Experimental transmission

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:

$$T_{exp} = N \frac{C_{in} - KB_{in}}{C_{out} - KB_{out}}. \quad (3.1)$$

The TOF spectra (C_{in}, C_{out}, B_{in}, B_{out}) were corrected for losses due to the dead time in the detector and electronics chain. 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. 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 this uncertainty the factor N= 1.0000 (25) was introduced in Eq. (3.1). The background as a function of TOF was approximated by an analytic expression applying the black resonance technique [1]. The factor K = 1.00 (3) in Eq. (3.1) was introduced to account for systematic effects due to the background model. Its uncertainty was derived from a statistical analysis of the difference between the observed black resonance dips and the estimated background [13]. This uncertainty is only valid for measurements with at least two fixed black resonance filters placed in the beam [1].

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

$$t = (T_s - T_0) + t_0, \quad (3.2)$$

with t_0 a time-offset which was determined by a measurement of the γ-ray flash. The flight path distance L = 10.861 (1) m, i.e. the distance between the center of the moderator viewing the flight path and the front face of the detector, was derived from results of transmission measurements using a uranium sample and the resonance energies for ^{238}U+n reported by Derien et al. [14].

3.2 Background correction

The background contribution for the transmission measurements was approximated by an analytical function applying the black resonance technique [1]. The analytical function was a sum of a time-independent and three time-dependent components:

$$B\,(t) = b_0 + b_1 e^{-\lambda_1 t} + b_2 e^{-\lambda_2 t} + b_3 e^{-\lambda_3 (t+\tau_0)}. \quad (3.3)$$

The time-independent component b_0 is related to the ambient radiation and background contributions that lost any time correlation. The first exponential term is due to the detection of 2.2 MeV γ-rays resulting from neutron capture in hydrogen present in the moderator. The second exponential term originates predominantly from neutrons scattered inside the detector station. The third one is attributable 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 time shift τ_0 is the inverse of the accelerator frequency, i.e. τ_0 = 2.5 ms for 400 Hz and τ_0 = 20 ms for 50 Hz. The decay constants λ_1 and λ_2 were derived from results of measurements with additional background filters in the beam combined with the data of measurements with a 3 mm thick Au sample. The dead time corrected sample-in TOF-spectrum together with the background contributions resulting from the measurements with the thin ^{157}Gd sample and Na, Co, W, Ag and Rh black resonance filters is shown in Figure 2. These data were obtained with the accelerator operating at 50 Hz. The TOF-spectrum resulting from measurements with the thick ^{155}Gd sample and Na, Co, W and Ag filters with the accelerator operated at 400 Hz is shown in Figure 3. The parameters of the background components for the measurements discussed in this report are given in Table 3 – Table 6.

ID	$b_0/10^{-9}$ ns^{-1}	$b_1/10^{-6}$ ns^{-1}	$\lambda_1/10^{-5}$ ns^{-1}	$b_2/10^{-8}$ ns^{-1}	$\lambda_2/10^{-6}$ ns^{-1}	$b_3/10^{-6}$ ns^{-1}	$\lambda_3/10^{-7}$ ns^{-1}
B_{in}	1.29	1.00	3.00	7.14	2.18	1.91	5.27
B_{out}	1.29	1.06	3.00	7.89	2.18	2.36	4.26

Table 3. Parameters for the analytical expressions of the background components for sample-in (0.004 mm thick ^{155}Gd sample) and sample-out measurements. The parameters are derived from results of measurements with Na and Co black resonance filters in the beam and the accelerator operating at 50 Hz.

ID	$b_0/10^{-9}$ ns^{-1}	$b_1/10^{-7}$ ns^{-1}	$\lambda_1/10^{-5}$ ns^{-1}	$b_2/10^{-8}$ ns^{-1}	$\lambda_2/10^{-6}$ ns^{-1}	$b_3/10^{-6}$ ns^{-1}	$\lambda_3/10^{-7}$ ns^{-1}
B_{in}	1.26	9.47	3.00	7.35	2.29	1.53	5.96
B_{out}	1.26	9.24	3.00	7.56	2.29	2.26	4.30

Table 4. Parameters for the analytical expressions of the background components for sample-in (0.002 mm thick ^{157}Gd sample) and sample-out measurements. The parameters are derived from results of measurements with Na and Co black resonance filters in the beam and the accelerator operating at 50 Hz.

ID	$b_0/10^{-9}$ ns^{-1}	$b_1/10^{-6}$ ns^{-1}	$\lambda_1/10^{-5}$ ns^{-1}	$b_2/10^{-7}$ ns^{-1}	$\lambda_2/10^{-6}$ ns^{-1}	$b_3/10^{-8}$ ns^{-1}	$\lambda_3/10^{-7}$ ns^{-1}
B_{in}	1.29	1.09	2.40	3.51	4.50	9.44	5.31
B_{out}	1.29	1.08	2.40	3.63	4.50	9.47	5.31

Table 5. Parameters for the analytical expressions of the background components for sample-in (0.04 mm thick ^{155}Gd sample) and sample-out measurements. The parameters are derived from results of measurements with a Cd overlap filter and Na and Co black resonance filters in the beam and the accelerator operating at 400 Hz.

ID	$b_0/10^{-9}$ ns^{-1}	$b_1/10^{-6}$ ns^{-1}	$\lambda_1/10^{-5}$ ns^{-1}	$b_2/10^{-7}$ ns^{-1}	$\lambda_2/10^{-6}$ ns^{-1}	$b_3/10^{-8}$ ns^{-1}	$\lambda_3/10^{-7}$ ns^{-1}
B_{in}	1.29	1.07	2.40	3.51	4.50	9.23	5.28
B_{out}	1.29	1.07	2.40	3.56	4.50	9.27	5.29

Table 6. Parameters for the analytical expressions of the background components for sample-in (0.08 mm thick ^{157}Gd sample) and sample-out measurements. The parameters are derived from results of measurements with a Cd overlap filter and Na and Co black resonance filters in the beam and the accelerator operating at 400 Hz.

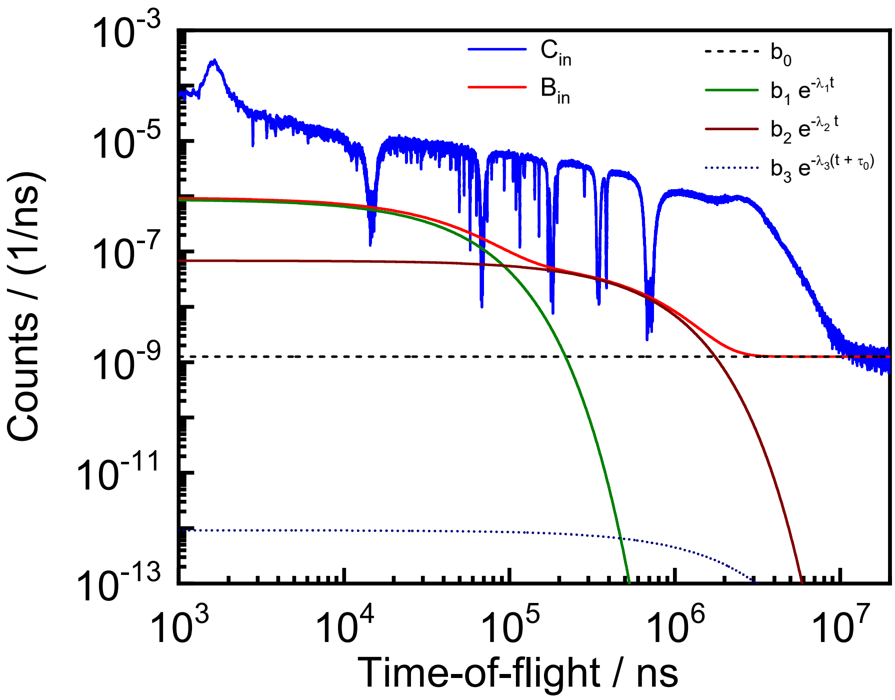

Figure 2. TOF-spectrum resulting from measurements with the ^{157}Gd sample and Na, Co, W, Ag and Rh black resonance filters in the beam and the accelerator operated at 50 Hz. The sample-in spectrum (C_{in}) is shown together with the total background (B_{in}) and its components.

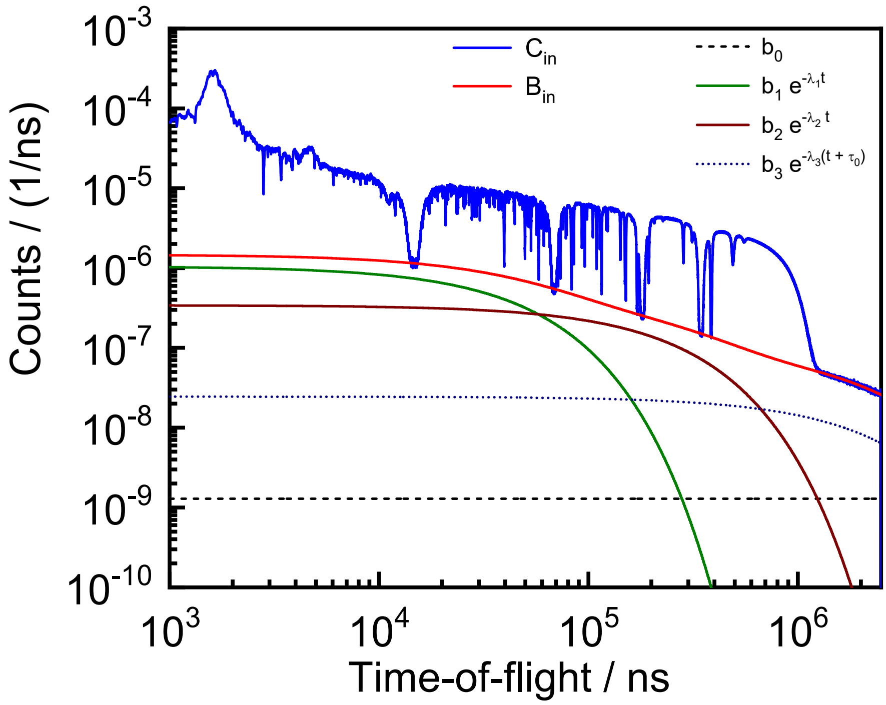

Figure 3. TOF-spectrum resulting from measurements with the ^{155}Gd sample, Na, Co, W and Ag black resonance filters and Cd overlap filter in the beam and the accelerator operated at 400 Hz. The sample-in spectrum (C_{in}) is shown together with the total background (B_{in}) and its components.

4 Results

The AGS code [11][12] was used to derive the experimental transmission and propagate both the correlated and uncorrelated uncertainties. 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 NDS/IAEA [7] to prepare the experimental observables, including their full covariance information, for storage into the EXFOR data library [15][16].

The format in which the numerical data is stored in the EXFOR data library is illustrated in the Appendix. The data 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 and background subtraction. Applying the AGS concept the covariance matrix V of the experimental transmission can be calculated by:

$$V = U_u + S(\eta)S(\eta)^T, \tag{4.2}$$

where U_u is a diagonal matrix containing the contribution of all uncorrelated uncertainty components. The matrix S contains the contribution of the components $\eta = \{N, K\}$ creating correlated components. The uncertainty due to the dead time correction can be neglected. The experimental details, which are required to perform a resonance analysis on the data, are summarized in the Appendix.

Examples of experimental transmissions as a function of neutron energy are shown in Figure 4 and Figure 5. The experimental data obtained in this work are compared with results of calculations using the resonance shape analysis code REFIT with the resonance parameters recommended in ENDF/B-VIII.0 [17], JEFF-3.3 [18] and JENDL-4.0 [19]. For these calculations the TOF-response functions of GELINA reported in Ref. [20] were used. The experimental transmission obtained with the 0.002 mm thick ^{157}Gd sample and the accelerator operated at 50 Hz is shown in Figure 4 together with the calculated ones. Figure 5 compares the experimental and calculated transmission through the 0.04 mm thick ^{155}Gd sample for an accelerator frequency of 400 Hz. The residuals in these figures reveal that a new evaluation is required to describe the experimental data reported in this work.

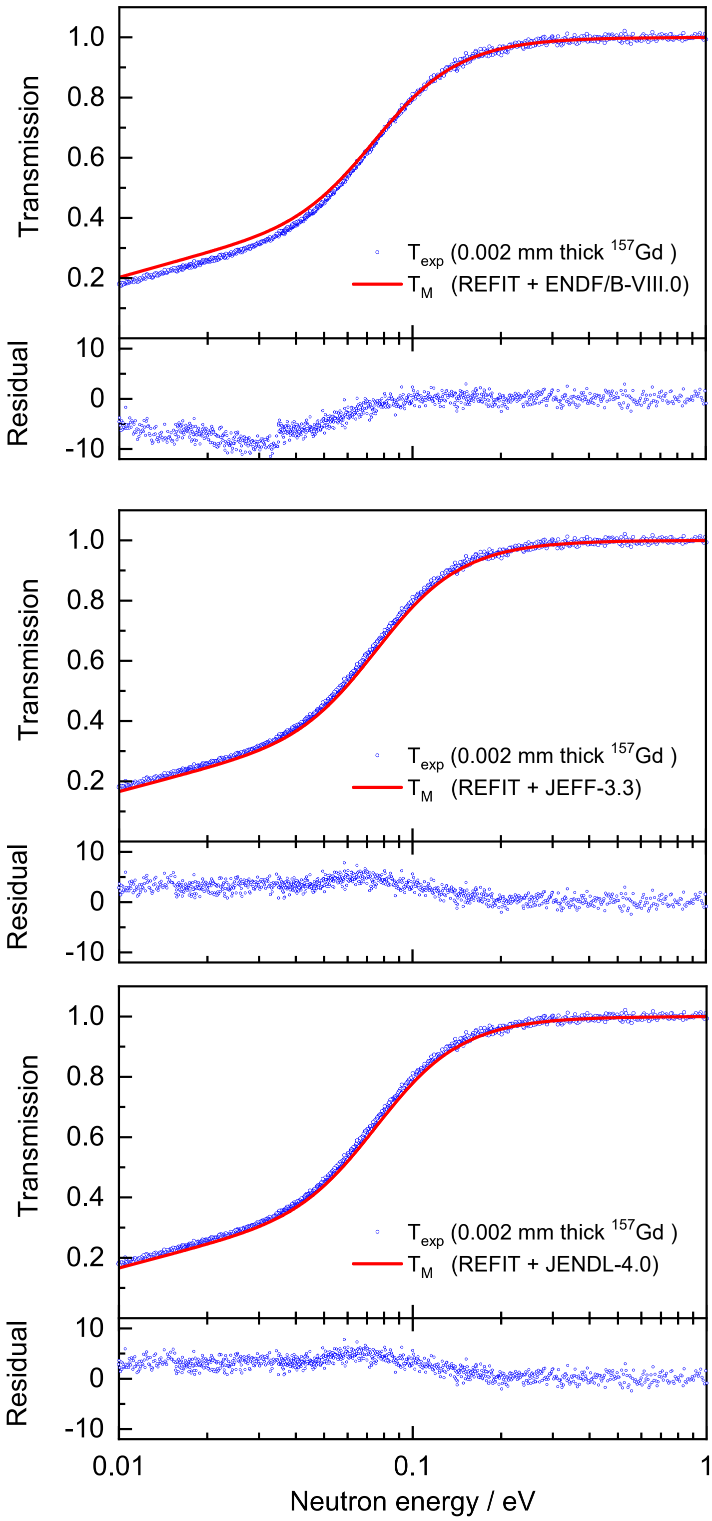

Figure 4. Transmission as a function of neutron energy resulting from measurements with the 0.002 mm thick ^{157}Gd sample and the accelerator operated at 50 Hz. The experimental transmission (T_{exp}) is compared with the calculated transmission (T_M) using the parameters recommended in the ENDF/B-VIII.0, JEFF-3.3 and JENDL-4.0 libraries. The REFIT code was used to obtain the calculated transmissions.

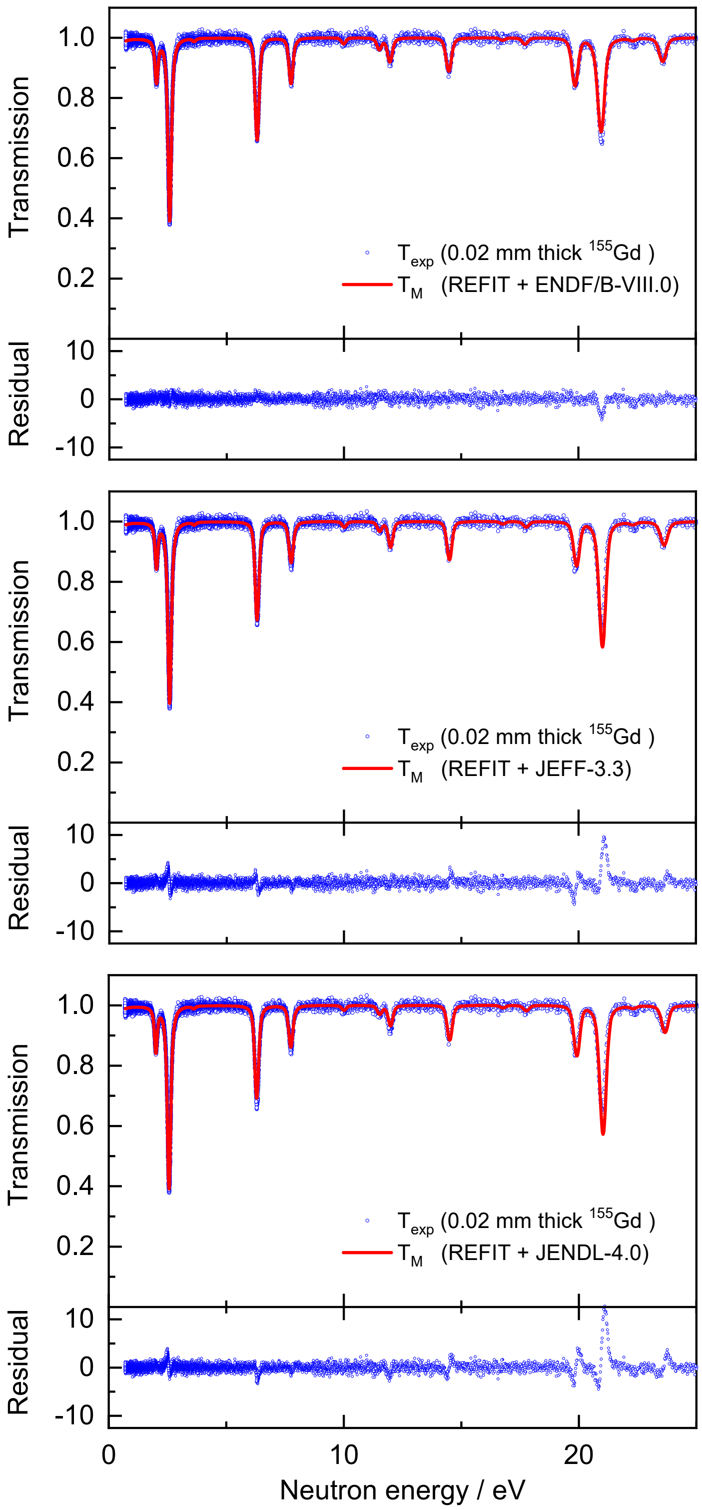

Figure 5. Transmission as a function of neutron energy resulting from measurements with the 0.04 mm thick ^{155}Gd sample and the accelerator operated at 400 Hz. The experimental transmission (T_{exp}) is compared with the calculated transmission (T_M) using the parameters recommended in the ENDF/B-VIII.0, JEFF-3.3 and JENDL-4.0 libraries. The REFIT code was used to obtain the calculated transmissions.

Acknowledgements

This work was supported by the EUFRAT open access programme of the Joint Research Centre at Geel (BE). We thank the GELINA operators for the dedicated and skilful running of the accelerator.

References

[1] P. Schillebeeckx, B. Becker,Y. Danon, K. Guber, H. Harada, J. Heyse, A.R. Junghans, S. Kopecky, C. Massimi, M.C. Moxon, N. Otuka, I. Sirakov and K. Volev, "Determination of resonance parameters and their covariances from neutron induced reaction cross section data", Nucl. Data Sheets 113 (2012) 3054 – 3100.

[2] A. Bensussan and J.M. Salomé, "GELINA: A modern accelerator for high resolution neutron time of flight experiments", Nucl. Instr. Meth. 155 (1978) 11 – 23.

[3] W. Mondelaers and P. Schillebeeckx, "GELINA, a neutron time-of-flight facility for neutron data measurements", Notiziario Neutroni e Luce di Sincrotrone 11 (2006) 19 – 25.

[4] D. Tronc, J.M. Salomé and K.H. Böckhoff, "A new pulse compression system for intense relativistic electron beams", Nucl. Instr. Meth. 228 (1985) 217 – 227.

[5] J.M. Salome and R. Cools, "Neutron producing targets at GELINA", Nucl. Instr. Meth. 179 (1981) 13 – 19.

[6] M.C. Moxon and J.B. Brisland, Technical Report AEA-INTEC-0630, AEA Technology (1991).

[7] F. Gunsing, P. Schillebeeeckx and V. Semkova, "Summary Report of the Consultants' Meeting on EXFOR Data in Resonance Region and Spectrometer Response Function", IAEA Headquarters, Vienna, Austria, 8-10 October 2013, INDC(NDS)-0647 (2013), https://www-nds.iaea.org/index-meeting-crp/CM-RF-2013/ (03/05/2016).

[8] C. Paradela, J. Heyse, S. Kopecky, P. Schillebeeckx, H. Harada, F. Kitatani, M. Koizumi and H. Tsuchiya, "Neutron resonance analysis for nuclear safeguards and security applications", EPJ Web of Conferences 146 (2017) 09002.

[9] J. Gonzalez, C. Bastian, S. de Jonge, and K. Hofmans, "Modular Multi-Parameter Multiplexer MMPM. Hardware description and user guide", Internal Report GE/R/INF/06/97, IRMM, Geel.

[10] https://www.mitutoyo.co.jp/eng/ (03/06/2016).

[11] B. Becker, C. Bastian, J. Heyse, S. Kopecky and P. Schillebeeckx, "AGS – Analysis of Geel Spectra User's Manual", NEA/DB/DOC(2014) 4.

[12] B. Becker, C. Bastian, F. Emiliani, F. Gunsing, J. Heyse, K. Kauwenberghs, S. Kopecky, C. Lampoudis, C. Massimi, N. Otuka, P. Schillebeeckx and I. Sirakov, "Data reduction and uncertainty propagation of time-of-flight spectra with AGS", J. of Instrumentation 7 (2012) 11002 – 19.

[13] I. Sirakov, B. Becker, R. Capote, E. Dupont, S. Kopecky, C. Massimi, and P. Schillebeeckx, "Results of total cross section measurements for ^{197}Au in the neutron energy region from 4 to 108 keV at GELINA", Eur. Phys. J. A 49 (144) (2013) 1.

[14] H. Derrien, L.C. Leal, N.M. Larson and A. Courcelle, "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 ORNL/TM-2005/241, Oak Ridge National Laboratory (2005).

[15] N. Otuka, E. Dupont, V. Semkova et al., "Towards a More Complete and Accurate Experimental Nuclear Reacton Data Library (EXFOR): International Collaboration

Between Nuclear Reaction Data Centres (NRDC)", Nucl. Data Sheets 120 (2014) 272 - 276.

[16] N. Otuka, A. Borella, S. Kopecky, C. Lampoudis, and P. Schillebeeckx, "Database for time-of-flight spectra with their covariances", J. Korean Phys. Soc. 59 (2011) 1314 – 1317.

[17] D.A. Brown, M.B. Chadwick, R. Capote, 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", Nuclear Data Sheets 148 (2018) 1 – 142.

[18] A. J. Plompen, O. Cabellos, C. De Saint Jean, et al., "The joint evaluated fission and fusion nuclear data library, JEFF_3.3", Eur. Phys. J. A 56 (2020) 181.

[19] K. Shibata, O. Iwamoto, T. Nakagawa, et al., "JENDL-4.0: a new library for nuclear science and engineering", Nucl. Sci. Technol., 48 (2011) 1 - 30.

[20] M. Flaska, A. Borella, D. Lathouwers, L.C. Mihailescu, W. Mondelaers, A.J.M. Plompen, H. van Dam and T.H.J.J. van der Hagen, "Modeling of the GELINA neutron target using coupled electron–photon–neutron transport with the MCNP4C3 code", Nucl. Instr. Meth. A 531 (2004) 392 – 406.

Appendix

A. SUMMARY OF EXPERIMENTAL DETAILS

A. 1 Experiment description (ID 1)

1. Main Reference		[a]
2. Facility	GELINA	[b][c]
3. Neutron production		
Neutron production beam	Electron	
Nominal average beam energy	100 MeV	
Nominal average current	3 μA	
Repetition rate (pulses per second)	50 Hz	
Pulse width	2 ns	
Primary neutron production target	Mercury cooled depleted uranium	
Target nominal neutron production intensity	3.4 x10^{13} s^{-1}	
4. Moderator		
Primary neutron source position in moderator	Above and below uranium target	
Moderator material	2 water 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 (K)	Room temperature	
Moderator-room decoupler (Cd, B, …)	None	
5. Other experimental details		
Measurement type	Transmission	
Method (total energy, total absorption, …)	Good transmission geometry	[d]
Flight Path length (m) (moderator center-detector front face)	L = 10.861 (1) m	
Flight path direction	18° with respect to normal of the moderator face viewing the flight path	
Neutron beam dimensions at sample position	10 mm in diameter	
Neutron beam profile	-	
Overlap suppression	None	
Other fixed beam filters	Na, Co, Pb	
6. Detector		
Type	Scintillator	
Material	Li-glass	
Surface Dimensions	76 mm x 76 mm square	
Thickness (cm)	6.35 mm	
Detector(s) position relative to neutron beam	In the beam	
Detector(s) solid angle	-	
7. Sample		
Type (metal, powder, liquid, crystal)	Metal	
Chemical composition	Gd (100 %)	
Isotopic composition (wt%)	^{152}Gd (0.03 %),^{154}Gd (0.63 %),^{155}Gd (91.74 %),^{156}Gd (5.12 %),^{157}Gd (1.14 %),^{158}Gd (0.94 %)^{160}Gd (0.4 %)	
Sample composition (at/b)	1.238 (12) x 10^{-5} at/b of ^{155}Gd	
Temperature	20°C	

Sample mass (g) Geometrical shape (cylinder, sphere, …) Surface dimension Nominal thickness (mm) Containment description	10.0 (1) mg Disk 313.7 (2) mm^2 0.004 mm Sandwiched in 6 μm Mylar foils	
8. Data Reduction Procedure Dead time correction Background subtraction Flux determination (reference reaction, …) Normalization Detector efficiency Self-shielding Time-of-flight binning	 Done (< factor 1.2) Black resonance technique - 1.0000 (25) - - Zone length bin width 4096 2 ns 5120 4 ns 5120 8 ns 4096 16 ns 4096 32 ns 4096 64 ns 12288 128 ns 4096 512 ns 1024 2048 ns 1024 4096 ns 20480 8192 ns	[d][e]
9. Response function Initial pulse Target / moderator assembly Detector	 Normal distribution, FWHM = 2 ns Numerical distribution from MC simulations Analytical function defined in REFIT manual	 [f][g] [h]

A. 2 Experiment description (ID 2)

1. Main Reference		[a]
2. Facility	GELINA	[b][c]
3. Neutron production		
Neutron production beam	Electron	
Nominal average beam energy	100 MeV	
Nominal average current	30 μA	
Repetition rate (pulses per second)	400 Hz	
Pulse width	2 ns	
Primary neutron production target	Mercury cooled depleted uranium	
Target nominal neutron production intensity	3.4 x10^{13} s^{-1}	
4. Moderator		
Primary neutron source position in moderator	Above and below uranium target	
Moderator material	2 water 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 (K)	Room temperature	
Moderator-room decoupler (Cd, B, …)	None	
5. Other experimental details		
Measurement type	Transmission	
Method (total energy, total absorption, …)	Good transmission geometry	[d]
Flight Path length (m) (moderator center-detector front face)	L = 10.861 (1) m	
Flight path direction	18° with respect to normal of the moderator face viewing the flight path	
Neutron beam dimensions at sample position	10 mm in diameter	
Neutron beam profile	-	
Overlap suppression	4 mm Cd overlap filter	
Other fixed beam filters	Na, Co, Pb	
6. Detector		
Type	Scintillator	
Material	Li-glass	
Surface Dimensions	76 mm x 76 mm square	
Thickness (cm)	6.35 mm	
Detector(s) position relative to neutron beam	In the beam	
Detector(s) solid angle	-	
7. Sample		
Type (metal, powder, liquid, crystal)	Metal	
Chemical composition	Gd (100 %)	
Isotopic composition (wt%)	^{152}Gd (0.03 %),^{154}Gd (0.63 %),^{155}Gd (91.74 %),^{156}Gd (5.12 %),^{157}Gd (1.14 %),^{158}Gd (0.94 %)^{160}Gd (0.4 %)	
Sample composition (at/b)	12.353 (12) x 10^{-5} at/b of ^{155}Gd	
Temperature	20°C	
Sample mass (g)	100.6 (1) mg	
Geometrical shape (cylinder, sphere, …)	Disk	
Surface dimension	316.4 (1) mm^2	

Nominal thickness (mm) Containment description	0.04 mm Sandwiched in 6 μm Mylar foils	
8. Data Reduction Procedure		[d][e]
Dead time correction	Done (< factor 1.2)	
Background subtraction	Black resonance technique	
Flux determination (reference reaction, …)	-	
Normalization	1.0000 (25)	
Detector efficiency	-	
Self-shielding	-	
Time-of-flight binning	Zone length bin width 4096 2 ns 5120 4 ns 5120 8 ns 4096 16 ns 4096 32 ns 4096 64 ns 5120 128 ns 4096 512 ns 1024 2048 ns 1024 4096 ns 27648 8192 ns	
9. Response function		
Initial pulse	Normal distribution, FWHM = 2 ns	
Target / moderator assembly	Numerical distribution from MC simulations	[f][g]
Detector	Analytical function defined in REFIT manual	[h]

A. 3 Experiment description (ID 3)

1. Main Reference		[a]
2. Facility	GELINA	[b][c]
3. Neutron production		
Neutron production beam	Electron	
Nominal average beam energy	100 MeV	
Nominal average current	3 μA	
Repetition rate (pulses per second)	50 Hz	
Pulse width	2 ns	
Primary neutron production target	Mercury cooled depleted uranium	
Target nominal neutron production intensity	3.4 x10^{13} s^{-1}	
4. Moderator		
Primary neutron source position in moderator	Above and below uranium target	
Moderator material	2 water 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 (K)	Room temperature	
Moderator-room decoupler (Cd, B, …)	None	
5. Other experimental details		
Measurement type	Transmission	
Method (total energy, total absorption, …)	Good transmission geometry	[d]
Flight Path length (m) (moderator center-detector front face)	L = 10.861 (1) m	
Flight path direction	18° with respect to normal of the moderator face viewing the flight path	
Neutron beam dimensions at sample position	10 mm in diameter	
Neutron beam profile	-	
Overlap suppression	None	
Other fixed beam filters	Na, Co, Pb	
6. Detector		
Type	Scintillator	
Material	Li-glass	
Surface Dimensions	76 mm x 76 mm square	
Thickness (cm)	6.35 mm	
Detector(s) position relative to neutron beam	In the beam	
Detector(s) solid angle	-	
7. Sample		
Type (metal, powder, liquid, crystal)	Metal	
Chemical composition	Gd (100 %)	
Isotopic composition (wt%)	^{152}Gd (<0.01 %),^{154}Gd (0.04 %),^{155}Gd (0.29 %),^{156}Gd (1.68 %),^{157}Gd (88.32 %),^{158}Gd (9.10 %)^{160}Gd (0.57 %)	
Sample composition (at/b)	0.571 (12) x 10^{-5} at/b of ^{157}Gd	
Temperature	20°C	
Sample mass (g)	4.7 (1) mg	
Geometrical shape (cylinder, sphere, …)	Disk	
Surface dimension	315.51 (4) mm^2	

Nominal thickness (mm) Containment description	0.002 mm Sandwiched in 6 μm Mylar foils	
8. Data Reduction Procedure		[d][e]
Dead time correction	Done (< factor 1.2)	
Background subtraction	Black resonance technique	
Flux determination (reference reaction, …)	-	
Normalization	1.0000 (25)	
Detector efficiency	-	
Self-shielding	-	
Time-of-flight binning	Zone length bin width 4096 2 ns 5120 4 ns 5120 8 ns 4096 16 ns 4096 32 ns 4096 64 ns 12288 128 ns 4096 512 ns 1024 2048 ns 1024 4096 ns 20480 8192 ns	
9. Response function		
Initial pulse	Normal distribution, FWHM = 2 ns	
Target / moderator assembly	Numerical distribution from MC simulations	[f][g]
Detector	Analytical function defined in REFIT manual	[h]

A. 4 Experiment description (ID 4)

1. Main Reference		[a]
2. Facility	GELINA	[b][c][3]
3. Neutron production		
Neutron production beam	Electron	
Nominal average beam energy	100 MeV	
Nominal average current	30 μA	
Repetition rate (pulses per second)	400 Hz	
Pulse width	2 ns	
Primary neutron production target	Mercury cooled depleted uranium	
Target nominal neutron production intensity	3.4 x10^{13} s^{-1}	
4. Moderator		
Primary neutron source position in moderator	Above and below uranium target	
Moderator material	2 water 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 (K)	Room temperature	
Moderator-room decoupler (Cd, B, …)	None	
5. Other experimental details		
Measurement type	Transmission	
Method (total energy, total absorption, …)	Good transmission geometry	[d]
Flight Path length (m) (moderator center-detector front face)	L = 10.861 (1) m	
Flight path direction	18° with respect to normal of the moderator face viewing the flight path	
Neutron beam dimensions at sample position	10 mm in diameter	
Neutron beam profile	-	
Overlap suppression	4 mm Cd overlap filter	
Other fixed beam filters	Na, Co, Pb	
6. Detector		
Type	Scintillator	
Material	Li-glass	
Surface Dimensions	76 mm x 76 mm square	
Thickness (cm)	6.35 mm	
Detector(s) position relative to neutron beam	In the beam	
Detector(s) solid angle	-	
7. Sample		
Type (metal, powder, liquid, crystal)	Metal	
Chemical composition	Gd (100 %)	
Isotopic composition (wt%)	^{152}Gd (<0.01 %),^{154}Gd (0.04 %),^{155}Gd (0.29 %),^{156}Gd (1.68 %),^{157}Gd (88.32 %),^{158}Gd (9.10 %)^{160}Gd (0.57 %)	
Sample composition (at/b)	23.272 (12) x 10^{-5} at/b of ^{157}Gd	
Temperature	20°C	
Sample mass (g)	191.6 (1) mg	
Geometrical shape (cylinder, sphere, …)	Disk	
Surface dimension	315.8 (1) mm^2	

Nominal thickness (mm) Containment description	0.08 mm Sandwiched in 6 μm Mylar foils	
8. Data Reduction Procedure		[d][e]
Dead time correction	Done (< factor 1.2)	
Background subtraction	Black resonance technique	
Flux determination (reference reaction, …)	-	
Normalization	1.0000 (25)	
Detector efficiency	-	
Self-shielding	-	
Time-of-flight binning	Zone length bin width 4096 2 ns 5120 4 ns 5120 8 ns 4096 16 ns 4096 32 ns 4096 64 ns 5120 128 ns 4096 512 ns 1024 2048 ns 1024 4096 ns 27648 8192 ns	
9. Response function		
Initial pulse	Normal distribution, FWHM = 2 ns	
Target / moderator assembly	Numerical distribution from MC simulations	[f][g]
Detector	Analytical function defined in REFIT manual	[h]

B. Data format

Column	Content	Unit	Comment
1	Energy	eV	Relativistic relation using a fixed flight path length (L = 10.861 m)
2	t_l	ns	Low bound
3	t_h	ns	High bound
4	T_{exp}		Transmission
5	Total Uncertainty		
6	Uncorrelated uncertainty		Uncorrelated uncertainty due to counting statistics
7	AGS-vector (K)		Background model uncertainty (u_K/K=3 %)
8	AGS-vector (N)		Normalization (u_N/N = 0.25 %)

Comments from the authors:

- The AGS concept was used to derive the experimental transmission

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

  and to propagate the uncertainties, both the uncorrelated due to counting statistics and the uncertainty due to the normalization and the background contributions.
- The quoted uncertainties are standard uncertainties at 1 standard deviation.

B.1 DATA (ID 1)

E/ eV	t_l / ns	t_h / ns	T_{exp}	u_t	AGS		
					u_u	K	N
100.030400	78496	78512	1.031059	0.125505	0.125478	0.000098	0.002578
99.989610	78512	78528	1.068249	0.129550	0.129522	0.000133	0.002671
…	…	…	…	…	…	…	…
0.025045	4960256	4962304	0.484828	0.018750	0.018711	0.000030	0.001212
0.025025	4962304	4964352	0.454227	0.017809	0.017773	0.000032	0.001136
0.025004	4964352	4966400	0.495578	0.019395	0.019355	0.000031	0.001239
0.024983	4966400	4968448	0.499244	0.019362	0.019322	0.000030	0.001248
…	…	…	…	…	…	…	…
0.005011	11087872	11096064	0.297100	0.042872	0.042842	0.001429	0.000743
0.005003	11096064	11104256	0.306371	0.040337	0.040311	0.001232	0.000766

B.2 DATA (ID 2)

E/ eV	t_l / ns	t_h / ns	T_{exp}	u_t	AGS		
					u_u	K	N
350.075600	41960	41968	1.041797	0.021763	0.021606	0.000149	0.002604
349.942200	41968	41976	0.984469	0.020488	0.020340	-0.000016	0.002461
…	…	…	…	…	…	…	…
20.97447	171424	171456	0.659020	0.009840	0.009687	-0.000529	0.001648
20.96665	171456	171488	0.658862	0.009840	0.009686	-0.000530	0.001647
…	…	…	…	…	…	…	…

6.305760	312640	312704	0.669775	0.008064	0.007876	-0.000428	0.001674
6.303179	312704	312768	0.670058	0.008091	0.007904	-0.000430	0.001675
...	...	...	...	...	...	...	...
2.571436	489600	489664	0.383917	0.006327	0.006211	-0.000727	0.000960
2.570764	489664	489728	0.386970	0.006357	0.006241	-0.000723	0.000967
...	...	...	...	...	...	...	...
1.000507	784896	785024	0.997266	0.011721	0.011453	0.000007	0.002493
1.000181	785024	785152	0.998477	0.011724	0.011455	0.000008	0.002496

B.3 DATA (ID 3)

E/ eV	t_l / ns	t_h / ns	T_{exp}	u_t	AGS		
					u_u	K	N
100.030400	78496	78512	0.939886	0.065534	0.065492	-0.000049	0.002350
99.989610	78512	78528	0.969793	0.068495	0.068452	-0.000026	0.002424
...	...	...	...	...	...	...	...
0.025025	4962304	4964352	0.291784	0.007753	0.007719	-0.000045	0.000729
0.025004	4964352	4966400	0.277983	0.007472	0.007439	-0.000046	0.000695
0.024983	4966400	4968448	0.270747	0.007379	0.007348	-0.000047	0.000677
0.024963	4968448	4970496	0.288086	0.007683	0.007649	-0.000046	0.000720
...	...	...	...	...	...	...	...
0.005011	11087872	11096064	0.107683	0.014458	0.014350	-0.001742	0.000269
0.005003	11096064	11104256	0.118903	0.014786	0.014687	-0.001682	0.000297

B.4 DATA (ID 4)

E/ eV	t_l / ns	t_h / ns	T_{exp}	u_t	AGS		
					u_u	K	N
350.075600	41960	41968	0.926577	0.017810	0.017658	-0.000194	0.002316
349.942200	41968	41976	0.932932	0.017911	0.017757	-0.000176	0.002332
...	...	...	...	...	...	...	...
44.08875	118240	118256	0.813762	0.013525	0.013367	-0.000330	0.002034
44.07682	118256	118272	0.814717	0.013569	0.013411	-0.000330	0.002037
...	...	...	...	...	...	...	...
16.78164	191648	191680	0.265490	0.005249	0.005086	-0.001118	0.000664
16.77603	191680	191712	0.278353	0.005371	0.005212	-0.001096	0.000696
...	...	...	...	...	...	...	...
2.828553	466816	466880	0.695397	0.008364	0.008174	-0.000355	0.001738
2.827778	466880	466944	0.695247	0.008377	0.008187	-0.000356	0.001738
...	...	...	...	...	...	...	...
1.000507	784896	785024	0.943179	0.010095	0.009815	-0.000072	0.002358
1.000181	785024	785152	0.954873	0.010255	0.009974	-0.000056	0.002387

References

[a] R. Mucciola, C. Paradela, G. Alaerts, J. Heyse, S. Kopecky, C. Massimi, P. Schillebeeckx and R. Wynants, "Results of time-of-flight transmission measurements for ^{155,157}Gd at a 10 m station of GELINA", INDC(EUR)-037.

[b] W. Mondelaers and P. Schillebeeckx, "GELINA, a neutron time-of-flight facility for neutron data measurements", Notiziario Neutroni e Luce di Sincrotrone 11 (2006) 19 – 25.

[c] C. Paradela, J. Heyse, S. Kopecky, P. Schillebeeckx, H. Harada, F. Kitatani, M. Koizumi and H. Tsuchiya, "Neutron resonance analysis for nuclear safeguards and security applications", EPJ Web of Conferences 146 (2017) 09002.

[d] P. Schillebeeckx, B. Becker,Y. Danon, K. Guber, H. Harada, J. Heyse, A.R. Junghans, S. Kopecky, C. Massimi, M.C. Moxon, N. Otuka, I. Sirakov and K. Volev, "Determination of resonance parameters and their covariances from neutron induced reaction cross section data", Nuclear Data Sheets 113 (2012) 3054 – 3100.

[e] B. Becker, C. Bastian, F. Emiliani, F. Gunsing, J. Heyse, K. Kauwenberghs, S. Kopecky, C. Lampoudis, C. Massimi, N. Otuka, P. Schillebeeckx and I. Sirakov, "Data reduction and uncertainty propagation of time-of-flight spectra with AGS", J. of Instrumentation 7 (2012) P11002 – 19.

[f] M. Flaska, A. Borella, D. Lathouwers, L.C. Mihailescu, W. Mondelaers, A.J.M. Plompen, H. van Dam and T.H.J.J. van der Hagen, "Modeling of the GELINA neutron target using coupled electron–photon–neutron transport with the MCNP4C3 code", Nucl. Instr. Meth. A 531 (2004) 392–406.

[g] 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-light measurements by Monte Carlo simulations", Nucl. Instr. Meth. A 618 (2010) 54 - 68.

[h] M.C. Moxon and J.B. Brisland, Technical Report AEA-INTEC-0630, AEA Technology (1991).

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