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Abstract. Transmission measurements have been performed at the time-of-flight facility GELINA to provide data for a new evaluation of neutron resonance parameters for ^{142}Ce. The measurements were carried out at a 50 m transmission station using a Li-glass scintillator with the accelerator operating at 400 Hz. This report provides the experimental details required to deliver the data to the EXFOR data library, maintained by the International Network of Nuclear Reaction Data Centres (NRDC). 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][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 covering a neutron energy region from 10 meV to 20 MeV. The GELINA facility can host up to 10 experiments at measurement stations located between 10 m and 400 m from the neutron production target. The electron linear accelerator provides a pulsed electron beam with a maximum energy of 150 MeV, a maximum 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 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 production 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 the monitors is used to normalize the time-of-flight spectra to the same neutron intensity. The measurement stations are equipped with air conditioning systems to reduce electronic drifts in the detection chains due to temperature changes. The temperature in the measurement stations is continuously monitored.

This report describes the transmission measurements carried out at GELINA with a ^{142}Ce enriched powder sample encapsulated in an aluminum container to complement the measurements performed with ^{nat}Ce samples [6]. Measurements with an empty aluminum container equivalent to the one of the enriched powder sample were used to estimate the beam attenuation due to the sample container. 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 report provides the information required for extracting ^{142}Ce resonance parameters by using the resonance shape analysis code REFIT [7]. In the description of the data, the recommendations resulting from a consultant's meeting organized by the Nuclear Data Section of the IAEA (NDS/IAEA) have been followed [8].

2 Experimental conditions

The transmission experiments were performed at the 50 m measurement station of flight path 4 with the accelerator operating at 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 9° 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 20°C. A schematic view of the experimental set-up is shown in Figure 1.

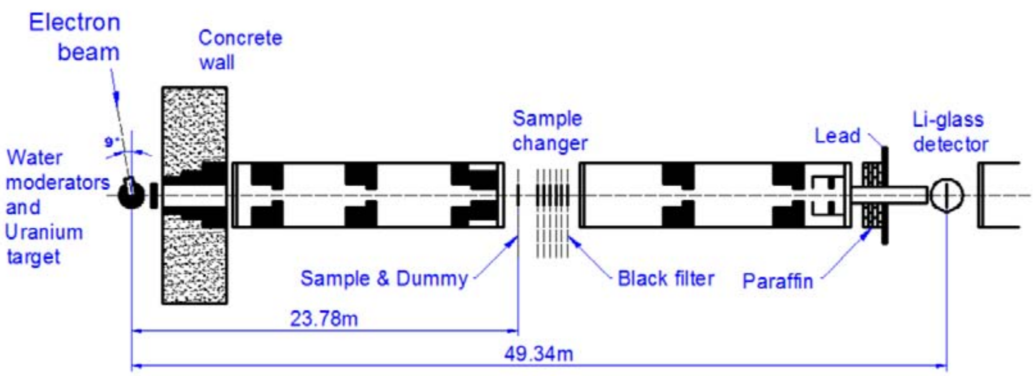

Figure 1. Schematic representation of the transmission set-up at the 50 m station of GELINA.

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 45 mm at the sample position. Additional lithium and B_4C collimators were installed to absorb neutrons that are scattered by the collimators.

A ^{10}B overlap filter with an areal density of about 0.08 at/b was placed close to the neutron target to minimize the contribution of slow neutrons coming from previous accelerator bursts. The impact of the γ-ray flash in the neutron detector was reduced by a 16 mm thick Pb filter placed in the beam.

The sample and the empty container were placed in independent and automatic sample changers at a distance of approximately 24 m from the neutron source. The neutron beam passing through the sample and filters was further collimated and detected by a 6.35 mm x 151.6 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 perpendicular to its axis. The detector was placed at about 48 m from the neutron target and the diameter of the neutron beam at the detector position was about 90 mm.

Na, Co, W and Ag black resonance filters were mounted in automatic filter changers to determine the background contribution at 2850 eV, 132 eV, 18 eV and 5.9 eV, respectively, and to obtain its time dependence. The Co filter was permanently in the beam to continuously monitor the background level and to account for the impact of the sample or other filters placed in the beam [1].

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 = 3300 (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.

The measurements were performed with a cerium oxide (CeO_2) powder sample, enriched in ^{142}Ce (92.07 %). The detailed characteristics of the sample are reported in Table 1. The sample is encapsulated in an aluminum canning of a total thickness of 0.896 (7) mm and an internal diameter of 60.22 mm. The areal density was derived from the mass and the can dimensions reported by the provider with an uncertainty better than 0.1 %.

Sample	Thickness /mm	Mass/g	Area/mm2	Areal Density (at/b)
^{142}Ce	2.852 (8)	37.0143 (1)	2848.5 (15)	0.4504 (3) x 10^{-3}

Table 1 Characteristic of the ^{142}Ce sample used for the transmission measurements. The areal density n_d was derived from the mass and area provided by the manufacturer.

3 Data reduction

The AGS code [10][11], developed at the JRC Geel, was used to derive the experimental transmission from the TOF-spectra. The code is based on a compact formalism to propagate all 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} and C_{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 of about 600 seconds. 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 [12]. This uncertainty is only valid for measurements with at least two fixed black resonance filters 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 = 47.669 (4) 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 using a uranium sample [12] and the resonance energies for ^{238}U+n reported by Derien et al. [13].

3.2 Background correction

The background contribution for the transmission measurements was approximated by an analytical function, consisting of the 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 time-dependent component is due to 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 last component 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. The other terms of the analytical function were obtained applying the black resonance technique [1]. The time dependence of the first and the second time-dependent background components was studied by including short cycles with Na, Co, W and Ag filters in the beam. The decay constants λ_1 and λ_2 were previously derived from results of measurements including additional black resonance filters such as S. A permanent Co filter was in the beam to monitor continuously the background level and to account for the impact of the sample on the background. An example of dead-time corrected and normalized sample-in spectrum together with the background contributions from Eq. (3.3) is shown in Figure 2.

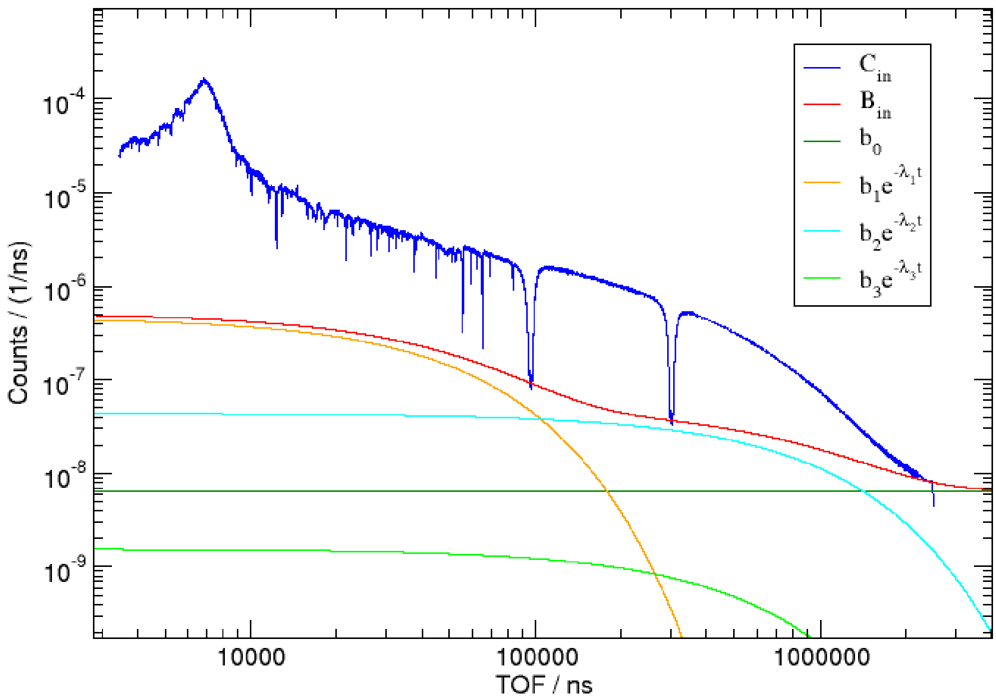

Figure 2. TOF-spectrum resulting from measurements with the ^{142}Ce sample and the Co black resonance filter in the beam and the accelerator operated at 400 Hz. The sample-in spectrum (C_{in}) is shown together with the total background (B_{in}) and its components defined in Eq. (3.3).

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}	$b_3/10^{-7}$ ns^{-1}	$\lambda_3/10^{-6}$ ns^{-1}
B_{in}	5.80	3.92	-2.4	3.66	-1.35	4.80	-2.35
B_{out}	6.03	4.27	-2.4	3.95	-1.35	5.07	-2.35

Table 2. Parameters for the analytical expressions of the background correction for the sample-in and sample-out measurements. The parameters are derived from results of measurements with the Na, Co, W and Ag black resonance filters in the beam and the accelerator operating at 400 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}	$b_3/10^{-7}$ ns^{-1}	$\lambda_3/10^{-6}$ ns^{-1}
B_{in}	6.50	4.66	-2.4	4.35	-1.35	5.53	-2.35
B_{out}	6.78	5.00	-2.4	4.68	-1.35	5.88	-2.35

Table 3. Parameters for the analytical expressions of the background correction for the sample-in and sample-out measurements. The parameters are derived from results of measurements with the Co black resonance filter in the beam and the accelerator operating at 400 Hz.

4 Results

The AGS code [10][11] 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 [8] to prepare the experimental observables, including their full covariance information, for storage into the EXFOR data library [14][15].

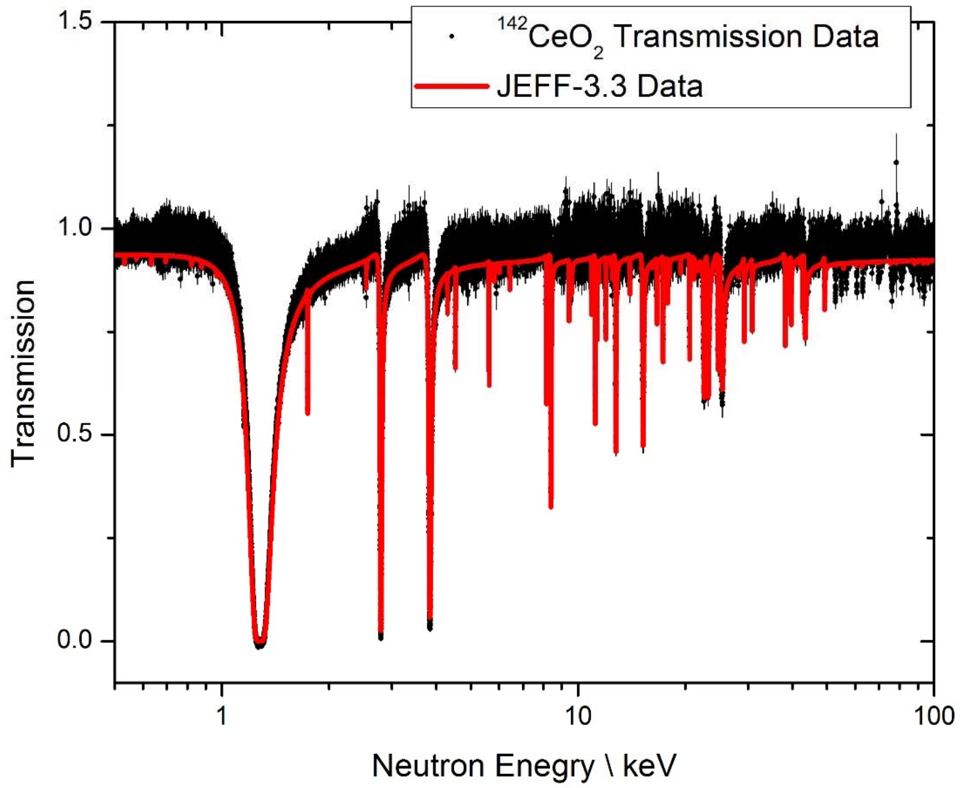

Figure 3. Transmission as a function of time-of-flight resulting from measurements with the ^{142}Ce sample and the accelerator operating at 400 Hz. The experimental transmission (T_{exp}) is compared with the calculated transmission (T_M) using the parameters recommended in the JEFF-3.3 library.

The experimental transmission resulting from the measurement with the ^{142}Ce sample is shown in Figure 3 and Figure 4. The experimental transmission is compared with the transmission calculated with the resonance parameters in the JEFF-3.3 library and ENDF/B-VIII.0, respectively. The theoretical transmission is expressed as:

$$T_M\,(t) = \int R(t,E)e^{-n\sigma_{tot}(E)}dE \quad (4.1)$$

with $R(t,E)$ the response function of the TOF spectrometer, representing the probability that a neutron with energy E is detected with a time-of-flight t, n the areal density of the sample and $\sigma_{tot}(E)$ the Doppler broadened total cross section as a function of energy. The response function $R(t,E)$ is the convolution of the duration of the accelerator burst, the time response function due to the neutron transport in the neutron target and the time response of the neutron detector [1][16]. The results in Figure 3 and Figure 4 reveal that the best agreement between experimental and theoretical transmission is obtained for the parameters in JEFF-3.3.

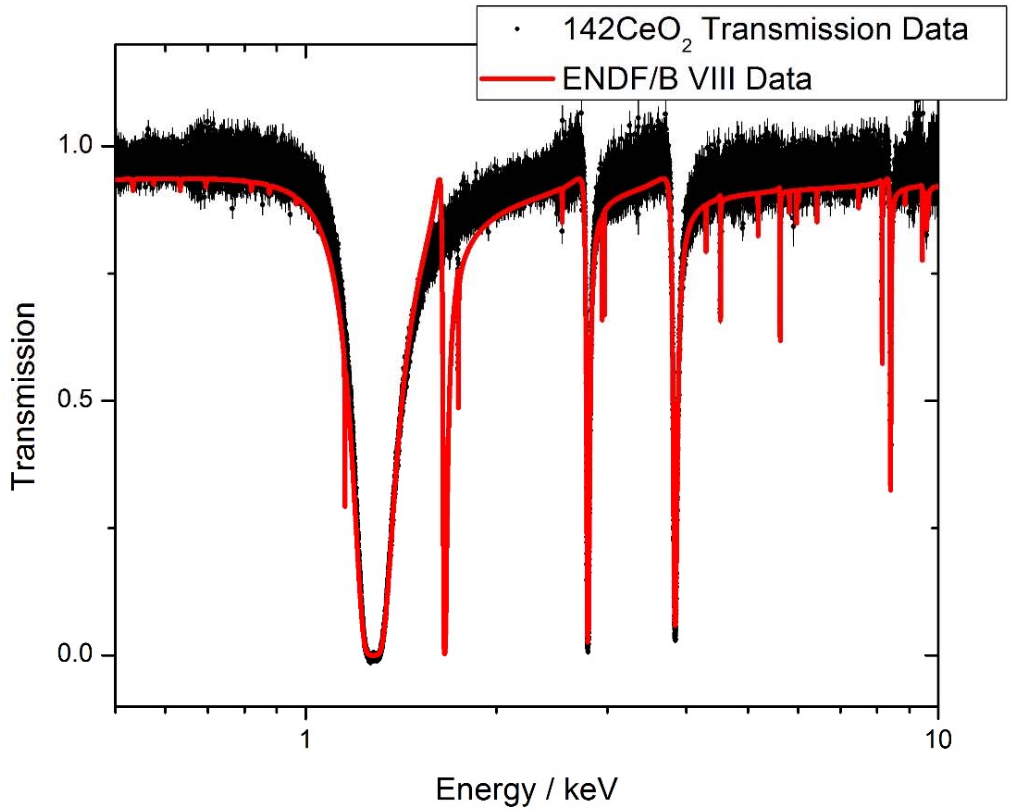

Figure 4. Transmission as a function of time-of-flight resulting from measurements with the ^{142}Ce sample and the accelerator operating at 400 Hz. The experimental transmission (T_{exp}) is compared with the calculated transmission (T_M) using the parameters recommended in the ENDF/B-VIII.0 library.

The format in which the numerical data will be 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:

$$V = U_u + S(\eta)S(\eta)^T, \quad (4.2)$$

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.

Acknowledgements

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Appendix

A. SUMMARY OF EXPERIMENTAL DETAILS

1. Main Reference		[a]
2. Facility	GELINA	[b]
3. Neutron production		
Neutron production beam	Electron	
Nominal average beam energy	100 MeV	
Nominal average current	50 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	3.4×10^{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^3	
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	[c]
Flight Path length (m) (moderator centre-detector front face)	L = 47.669 (4) m	
Flight path direction	9° with respect to normal of the moderator face viewing the flight path	
Neutron beam dimensions at sample position	45 mm in diameter	
Neutron beam profile	-	
Overlap suppression	^{10}B overlap filter	
Other fixed beam filters	Co, Pb	
6. Detector		
Type	Scintillator	
Material	Li-glass	
Surface Dimensions	152.4 mm diameter	
Thickness (cm)	6.35 mm	
Detector(s) position relative to neutron beam	In the beam	
Detector(s) solid angle	-	
Sample		
7. Type (metal, powder, liquid, crystal)	Metal	
Chemical composition	^{142}Ce (92.07 at %), ^{140}Ce (7.93 at %), ^{138}Ce (<0.02 at %), ^{136}Ce (<0.02 at %)	
Sample composition (at/b)	0.4504 (3) x 10^{-3} at/b	
Temperature	20 ℃	
Sample mass (g)	37.0143 (1) g	

Geometrical shape (cylinder, sphere, …)	Cylinder	
Surface dimension	2848.5 (15) mm^2	
Nominal thickness (mm)	2.852 mm	
Containment description	Al canning of 0.896 (7) mm thickness (base+lid)	
Data Reduction Procedure		[c][d]
8. Dead time correction	Done (< factor 1.2)	
Back ground subtraction	Black resonance technique	
Flux determination (reference reaction, …)	-	
Normalization	1.0000 (25)	
Detector efficiency	-	
Self-shielding	-	
Time-of-flight binning	Zone length bin width 12288 1 ns 12288 2 ns 8192 4 ns 8192 8 ns 6144 16 ns 4096 32 ns 4096 64 ns 4096 128 ns 4096 256 ns 2048 1024 ns	
Response function		
9. Initial pulse	Normal distribution, FWHM = 2 ns	
Target / moderator assembly	Numerical distribution from MC simulations	[e][f]
Detector	Analytical function defined in REFIT manual	[g]

B. DATA FORMAT

Column	Content	Unit	Comment
1	Energy	eV	Relativistic relation using a fixed flight path length (L = 47.67 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.

E/ keV	t_l / ns	t_h / ns	T_{exp}	u_t	AGS		
					u_u	K	N
300.033	6293	6294	0.945089	0.009057	0.008743	-0.000007	0.002363
299.938	6294	6295	0.948247	0.009247	0.008938	-0.000006	0.002371
…	…	…	…	…	…	…	…
1.25032	97464	97472	0.017701	0.003989	0.003655	-0.001596	0.000044
1.25012	97472	97480	0.012348	0.003887	0.003534	-0.001620	0.000031
…	…	…		…	…	…	…
0.20006	243648	243680	0.957977	0.015165	0.014974	-0.000073	0.002395
0.20001	243680	243712	0.949562	0.015024	0.014835	-0.000086	0.002374

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