IAEA
International Atomic Energy Agency

INDC(EUR)-0032
Distr. G+J

INDC International Nuclear Data Committee

Results of time-of-flight neutron capture measurements of ^{176,177,178,179}Hf-enriched and ^{nat}Hf samples at 10 m, 30 m and 60 m stations of GELINA

T.C. Ware, C.J. Dean
AMEC, Dorset Green Technology Park, Dorchester, UK

A. Borella, S. Kopecky, A. Moens, P. Schillebeeckx
Joint Research Institute for Reference Materials and Measurements
European Commission, Geel, Belgium

N. Janeva
Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

and

M.C. Moxon
Hyde Copse, Marcham, Oxfordshire, UK

April 2014

IAEA Nuclear Data Section, Vienna International Centre, A-1400 Vienna, Austria

Selected INDC documents may be downloaded in electronic form from
http://www-nds.iaea.org/publications/
or sent as an e-mail attachment.
Requests for hardcopy or e-mail transmittal should be directed to
nds.contact-point@iaea.org
or to:

Nuclear Data Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
A-1400 Vienna
Austria

Produced by the IAEA in Austria
April 2014

INDC(EUR)-0032
Distr. G+J

Results of time-of-flight neutron capture measurements of ^{176,177,178,179}Hf-enriched and ^{nat}Hf samples at 10 m, 30 m and 60 m stations of GELINA

T.C. Ware, C.J. Dean
AMEC, Dorset Green Technology Park, Dorchester, UK

A. Borella, S. Kopecky, A. Moens, P. Schillebeeckx
Joint Research Institute for Reference Materials and Measurements
European Commission, Geel, Belgium

N. Janeva
Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

and

M.C. Moxon
Hyde Copse, Marcham, Oxfordshire, UK

April 2014

Results of time-of-flight neutron capture measurements of ^{176,177,178,179}Hf-enriched and ^{nat}Hf samples at 10 m, 30 m and 60 m stations of GELINA

T.C. Ware[a,*], A. Borella[b], C.J. Dean[c,†], N. Janeva[c,†], S. Kopecky[b], A. Moens[b], M.C. Moxon[d] and P. Schillebeeckx[b]

[a]AMEC, Kimmeridge House, Dorset Green Technology Park, Dorchester, DT2 8ZB, UK

[b]European Commission, Joint Research Centre, Institute for Reference Materials and Measurements, Retieseweg 111, B-2440 Geel, Belgium

[c]Institute for Nuclear Research and Nuclear Energy, BG-1784 Sofia, Bulgaria

[d]3 Hyde Copse, Marcham, Oxfordshire, OX13 6PT, UK

Abstract

Neutron capture measurements have been performed at the time-of-flight facility GELINA to determine neutron resonance parameters for ^{174,176,177,178,179,180}Hf. In total, 16 distinct experiments were conducted at the 12 m, 28 m and 58 m capture stations using C_6D_6 detectors with a moderated neutron beam and the accelerator operating at 50 Hz or 800 Hz. Measurements were performed with ^{nat}Hf metallic samples and oxide samples enriched in ^{176}Hf, ^{177}Hf, ^{178}Hf and ^{179}Hf. This report describes the experimental details required to deliver the experimental capture yields 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.

* Measurements and data reduction were performed whilst a PhD student registered at the School of Physics, University of Birmingham, Birmingham, B15 2TT, UK

† Deceased

1. Introduction

In order 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. In order 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.

The TOF facility GELINA [1] 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 ten 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 [2]. The electron beam hits a mercury-cooled uranium target producing Bremsstrahlung and subsequently neutrons via photonuclear reactions [3]. 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 thermalised 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 neutron capture measurements performed at GELINA with natural metallic and enriched oxide hafnium samples are described. The main objective of this report is to provide the information that is required to extract resonance parameters for the Hf isotopes in a least squares adjustment to the data using resonance shape analysis codes such as REFIT [4]. The description of the data follows the recommendations resulting from a consultants' meeting organized by the Nuclear Data Section of the IAEA [5].

2. Experimental conditions

Measurements were performed with four natural Hf metallic discs and five oxide powders enriched in ^{176}Hf, ^{177}Hf, ^{178}Hf and ^{179}Hf. The main characteristics of these samples are given in Table 1. The natural samples were obtained from Goodfellow [6]. The enriched oxide powders were kindly loaned from INRNE Sofia and compressed into aluminium cans at the EC-JRC-IRMM. The isotopic composition of the natural samples was taken from [7] and the composition 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.

As seen in Table 1, uncertainty information on the enrichments of the oxide samples is incomplete. The simultaneous analysis of the different samples with REFIT [4] gave confidence in these values with the exceptions of the ^{176}Hf content of the ^{178}Hf samples being ~0.1% and the ^{177}Hf content of the ^{179}Hf sample being ~0.9%.

The aluminium cans were shown to contain a manganese impurity (visible as an increase in the between-resonance yield due to the ^{55}Mn resonance at 337 eV). Carbon fibre frames were used to suspend all samples in the neutron beam. However, at least one of the holders used with some of enriched oxide samples were shown to contain a detectable amount of bromine (visible due to resonance structures of ^{79}Br and ^{81}Br). These resonances are observable in the affected capture yields for the configurations hfe2-0810, hfe3-0810, hfe4-0810, hfe3-0830, and hfe1-50hz listed in Table 2.

The samples described in Table 1 were used in several different experimental configurations, given in Table 2. For all experiments, the moderated neutron spectrum was used with a shadow bar made of Cu and Pb placed close to the uranium target to reduce the intensity of the γ-ray flash and the fast neutron component. The angle to moderator is the angle to the direction normal to the face of the moderator viewing the flight path. The sample and detector were placed in a climate-controlled room to keep them at a constant temperature of 22°C.

Table 1: Characteristics of the samples used for the capture yields measurements performed at GELINA. Diameter is that of the metallic disc / internal diameter of oxide can, as appropriate. Mass is that of Hf metal / HfO_2 powder, as appropriate. To calculate the areal density the Avogadro constant was taken as $N_A = 6.0221367\times10^{23}$ mol^{-1} and the atomic masses were taken from [8]. The areal densities of the natural samples assume 97.0% purity [6], with the balance being zirconium. The quoted uncertainties are standard uncertainties at one standard deviation.

Sample ID	Isotopic Composition (at% Hf content)	Thickness (mm)	Diameter (mm)	Mass (g)	Areal density (at/b)
Natural Metallic Samples					
hfn1 ^{nat}Hf	^{174}Hf: 0.16 ± 0.01 ^{176}Hf: 5.26 ± 0.07 ^{177}Hf: 18.60 ± 0.09 ^{178}Hf: 27.28 ± 0.07 ^{179}Hf: 13.62 ± 0.02 ^{180}Hf: 35.08 ± 0.16	1.0810 ± 0.0018	54.995 ± 0.040	33.3600 ± 0.0001	4.6053×10^{-3} $\pm 6.75\times10^{-6}$
hfn2 ^{nat}Hf		0.2566 ± 0.0092	80.04 ± 0.01	16.1961 ± 0.0001	1.0532×10^{-3} $\pm 2.63\times10^{-7}$
hfn3 ^{nat}Hf		0.079 ± 0.0009	80.04 ± 0.02	5.0697 ± 0.0001	3.2969×10^{-4} $\pm 1.65\times10^{-7}$
hfn4 ^{nat}Hf		0.0244 ± 0.0010	80.04 ± 0.02	1.4849 ± 0.0001	9.6565×10^{-5} $\pm 4.83\times10^{-8}$
Enriched Oxide Samples					
hfe1 ^{176}Hf	^{174}Hf: <0.05 ^{176}Hf: 65.0 ^{177}Hf: 22.9 ^{178}Hf: 6.3 ^{179}Hf: 1.8 ^{180}Hf: 4.0	2.0620 ± 0.0379	30.1300 ± 0.0387	5.3424 ± 0.0001	2.17×10^{-3} $\pm 5.57\times10^{-6}$
hfe2 ^{177}Hf	^{174}Hf: <0.05 ^{176}Hf: 1.0 ^{177}Hf: 85.4 ^{178}Hf: 11.3 ^{179}Hf: 0.9 ^{180}Hf: 1.4	3.2230 ± 0.0498	30.0900 ± 0.0082	4.7070 ± 0.0001	1.91×10^{-3} $\pm 1.04\times10^{-6}$
hfe3 ^{178}Hf	^{174}Hf: <0.05 ^{176}Hf: 0.8 ^{177}Hf: 1.9 ^{178}Hf: 92.4 ± 0.2 ^{179}Hf: 3.3 ^{180}Hf: 1.6	2.5020 ± 0.1125	30.0600 ± 0.0141	4.4570 ± 0.0001	1.80×10^{-3} $\pm 1.69\times10^{-6}$
hfe4 ^{178}Hf	^{174}Hf: <0.05 ^{176}Hf: 0.8 ^{177}Hf: 1.9 ^{178}Hf: 92.4 ± 0.2 ^{179}Hf: 3.3 ^{180}Hf: 1.6	1.0520 ± 0.0097	20.0300 ± 0.005	0.9006 ± 0.0001	0.82×10^{-3} $\pm 0.42\times10^{-6}$
hfe5 ^{179}Hf	^{174}Hf: <0.05 ^{176}Hf: 0.2 ^{177}Hf: 1.3 ^{178}Hf: 4.1 ^{179}Hf: 72.1 ± 0.4 ^{180}Hf: 22.3	2.4520 ± 0.0558	30.0600 ± 0.0238	5.3175 ± 0.0001	2.14×10^{-3} $\pm 3.39\times10^{-6}$

The partially thermalised 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 75 mm at the sample position. Before the sample position, an automatic filter changer was placed containing several beam filters. An anti-overlap filter (^{10}B or ^{nat}Cd) was used to absorb slow neutrons from previous bursts. In some configurations, a 8 mm thick Pb filter was used to reduce the impact of the γ-ray flash on the detectors. Fixed background filters (Na or S) were used to establish the background at energies above the Hf resolved resonance range via the black resonance technique [9]. In all configurations, runs with low-energy background filters (Ag, Bi, Co, or W) were also performed, again to establish the background.

In the capture measurements, the sample was positioned in the neutron beam with 2 or 4 γ-ray detectors facing the sample at angles of 125° with respect to the neutron flux direction. These detectors were C_6D_6-based liquid scintillators [10], of 10 cm diameter and 7.5 cm height, coupled to a photo-multiplier tube (PMT). The detectors' energy calibration was verified based upon measurements of the 2.6 MeV γ-ray from the ^{232}Th decay chain, before and after the Hf measurements. The Analysis of Geel List-mode (AGL) code [11] was used to verify the calibrations of all detectors were aligned.

The energy dependence of the neutron flux below 150 keV was continuously measured with a Frisch-gridded ^{10}B ionisation chamber placed ~1 m in front of the sample. The detector consists of 1 or 2 layers of ^{10}B evaporated on an aluminium backing, with a diameter of 84 mm [12]. The chamber operates with a continuous flow of a mixture of argon (90%) and methane (10%) at atmospheric pressure as detector gas [12].

Table 2: Different measurements configurations for the capture yield measurements performed with the samples specified in Table 1

Sample / Configuration ID		**Flight path length**	**Angle to moderator**	**LINAC frequency**	**Detectors: C_6D_6 / ^{10}B-ion**	**Overlap filters**	**Background filters**
hfn2-0710	^{nat}Hf	12.89 m	18°	50 Hz	4 / 2	-	Na, Bi, Co
hfn3-0710	^{nat}Hf	12.89 m	18°	50 Hz	4 / 2	-	Na, Bi, Co
hfn4-0710	^{nat}Hf	12.89 m	18°	50 Hz	4 / 2	-	Na, Bi, Co
hfn1-0760	^{nat}Hf	58.586 m	9°	800 Hz	4 / 6	^{10}B	S
hfe2-0810	^{177}Hf	12.95 m	18°	800 Hz	2 / 2	^{10}B	Pb, Na
hfe3-0810	^{178}Hf	12.95 m	18°	800 Hz	2 / 2	^{10}B	Pb, Na
hfe4-0810	^{178}Hf	12.95 m	18°	800 Hz	2 / 2	^{10}B	Pb, Na
hfe5-0810	^{179}Hf	12.95 m	18°	800 Hz	2 / 2	^{10}B	Pb, Na
hfn1-0810	^{nat}Hf	12.95 m	18°	800 Hz	2 / 2	^{10}B	Pb, Na
hfe1-0830	^{176}Hf	28.82 m	0°	800 Hz	2 / 2	^{10}B	S
hfe2-0830	^{177}Hf	28.82 m	0°	800 Hz	2 / 2	^{10}B	S
hfe3-0830	^{178}Hf	28.82 m	0°	800 Hz	2 / 2	^{10}B	S
hfe5-0830	^{179}Hf	28.82 m	0°	800 Hz	2 / 2	^{10}B	S
hfn1-0830	^{nat}Hf	28.82 m	0°	800 Hz	2 / 2	^{10}B	S
hfe1-50hz	^{176}Hf	28.82 m	0°	50 Hz	2 / 2	^{nat}Cd	Na
hfe5-50hz	^{179}Hf	28.82 m	0°	50 Hz	2 / 2	^{nat}Cd	Na, Co

The output signals of the detectors were connected to conventional analogue electronics. The anode pulses of the C_6D_6 PMTs were each 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 9th dynode was shaped by a spectroscopic amplifier to determine the energy deposited by the γ-rays 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 = 2600 - 2900 ns (depending on configuration) was continuously monitored by recording the time interval between successive pulses.

For each detected event in the C_6D_6 or ^{10}B-ion detectors, the time-of-flight (TOF) of the incident 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 0.5 ns time resolution [13]. The gamma flash from the target is used as a reference for measuring the actual timing of the electron burst and the overall time resolution of the detection chain (i.e. the detectors, cabling and electronics), which is about 2.5 ns [14].

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 [15]. Each measurement was subdivided in different cycles. Only cycles for which the ratio between the total counts in each capture detector and in the neutron monitor deviated by less than 0.5% were selected. The selection was performed with the AGL code.

3. Data reduction

The experimental capture yield $Y_{exp}(T_n)$ as a function of TOF was obtained from the ratio of the observed γ-rays from the sample $C_S(T_n)$ to those observed $C_\phi(T_n)$ from the incident neutron flux detector, both corrected for their background contributions B_S and B_ϕ, respectively:

$$Y_{exp}(T_n) = N_C \frac{C_S(T_n) - B_S(T_n)}{C_\phi(T_n) - B_\phi(T_n)} F_\phi(T_n) Y_\phi(T_n) \tag{1}$$

The TOF-spectra (C_S, B_S, C_ϕ and B_ϕ) in Eqn. (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.

The Normalisation factors N_C were determined using the saturated, low energy ^{177}Hf resonances. For the measurements where the low ^{177}Hf resonances were not visible or not saturated, the REFIT code was used with a self-normalised yield as reference.

The correction factor F_ϕ arises from the difference in the flux spectrum entering the flux detector and that entering the sample which is a result of neutron absorption in the ^{10}B of the flux detector and the attenuation of the beam by the detector exit window and the ~1 m of air between the detector and sample face. The dominant feature of F_ϕ is the $^1/v$ absorption, calculated from the JEF2.2 ^{10}B cross section. Y_ϕ is the theoretical capture yield of the ionisation chamber, calculated using the JEF2.2 ^{10}B (n,α) and total cross sections.

The Pulse Height Weighting Technique [10] was applied to the events recorded by C_6D_6 detectors. Detector response functions derived from Monte-Carlo N-Particle (MCNP) code [16] photon transport calculations were used to apply a weighting function to the pulse height of each event, making the detection efficiency proportional to the energy release of the capture event. Therefore, the efficiency of detecting capture in a specific nuclide is proportional to the binding energy of that nuclide.

Hence, the detector efficiency of these capture yields should be accounted for during the resonance analysis process. It is noted that the capture in ^{178}Hf should account for decay to the ^{179m}Hf isomer state (branching ~0.63) where the total initial energy release is the binding energy less the isomer energy level.

Self-absorption of γ-rays within the Hf samples has not been accounted for during the data reduction. However, the samples used are relatively thin and absorption effects should be minimal.

The AGL code was used to convert the list mode data into 30720 time-of-flight channels with channel width increases in discrete steps with increasing time-of-flight.

The dead time correction performed for each detector spectrum was based on the formula of Moore [17], which accounts for possible variations in the beam intensity. At GELINA, the dead time of the capture and flux detectors are monitored continuously by registering the distribution of the TOF differences between consecutive events. The dead time correction for the Hf capture measurements at the 12 m station was less than 6% and for the 30 m and 60 m measurements, it was less than 1%. It has been demonstrated in [9] that bias effects resulting from such corrections are negligible. Therefore, uncertainties related to the dead time correction were neglected and not propagated.

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 lengths i.e. the distance between the centre of the moderator viewing the flight path and the front face of the detector and specified in Table 2, were verified by a REFIT calculation to be within ±0.003 m of Table 2 values, except for the hfe4-0810 measurement which was ±0.007 m.

All the measurement configurations included subsidiary runs with black resonance filters in the beam in order that a “sample in” background could be determined using the black resonance technique [9]. In addition, measurements of only the carbon fibre sample holder and aluminium can (in the case of the oxide samples) were performed. These measurements were used to derive background spectra for both the capture and flux measurements.

The capture background as a function of TOF was parameterized by an analytical expression consisting of a power function plus a constant:

$$B(t) = at^b + k \tag{3}$$

where t is the time-of-flight and k is a time-independent constant. The flux background as a function of TOF was parameterized by an analytical expression consisting of a constant and two exponentials:

$$B(t) = a_1 \exp(-b_1 t) + a_2 \exp(-b_2 t) + c \tag{4}$$

where t is the time-of-flight and k is a time-independent constant.

4. Results

To derive the experimental capture yield and propagate both the correlated and uncorrelated uncertainties the AGS (Analysis of Geel Spectra) package [18] was used. AGS was used to import the TOF-spectra produced by AGL, apply the dead-time corrections, sum the spectra and subtract the backgrounds, and finally compute the capture yields from the corrected count rates and the flux attenuation factors.

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, vector-like form. 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 [19] to prepare the experimental observables, including their full covariance information, for storage into the EXFOR data library [20]. The format in which the numerical data is stored in the EXFOR data library is illustrated in Table 3, which includes 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 Normalisation and backgrounds. Applying the AGS concept described in [18] the covariance matrix V_{Texp} of the experimental capture yield can be calculated by:

$$V_{Texp} = U_u + S(\eta)S^T(\eta) \quad (5)$$

where U_u is a diagonal matrix containing the contribution of all uncorrelated uncertainty components and $S(\eta)$ is a matrix representing the contribution of components $\eta = \{u_{Bs}, u_{B\phi}, N\}$ creating a correlated contribution.

Table 3: Example capture yield (Y_{exp}) and total uncertainty derived from the Hf capture data. The information to derive the full covariance matrix based on the AGS concept (Eqn. (5)) is given: the diagonal elements of the uncorrelated components, $u_u = \sqrt{U_u}$ are in column 6 whereas columns 7 and 8 give the background counts used to calculated the correlated uncertainties due to the background models. The correlated uncertainty due to the normalisation model is constant.

E (eV)	t_l (ns)	t_h (ns)	Y_{exp}	u_t	u_u	B_S	B_ϕ
0.56462	1240283	1240539	0	0	0	0	0
0.56486	1240027	1240283	0.12678	0.05540	0.05540	26.5208	0.01186
ǀ	ǀ	ǀ	ǀ	ǀ	ǀ	ǀ	ǀ
9.904×10^6	298	299	7.811×10^{-4}	5.543×10^{-6}	5.543×10^{-6}	489.860	0.12881
9.972×10^6	297	298	0	0	0	0	0

The full meaningful TOF range of each data set is given. The authors deem the following energy ranges suitable for resonance analysis (i.e. where experimental resolution is of sufficient quality);

- 60 m yield: 20 – 1000 eV
- 30 m yields: 5 – 1000 eV
- 10 m yields: 0.5 – 250 eV.

The experimental details, which are required to perform a resonance analysis of the data, are summarized in Appendices A to P. The information given is based on the recommendation resulting from a consultant's meeting organized by the NDS-IAEA [5] in October 2013. An example of a resonance shape analysis with REFIT [4] on the capture yield obtained with the ^{177}Hf, ^{179}Hf and ^{nat}Hf samples is shown in Figure 1.

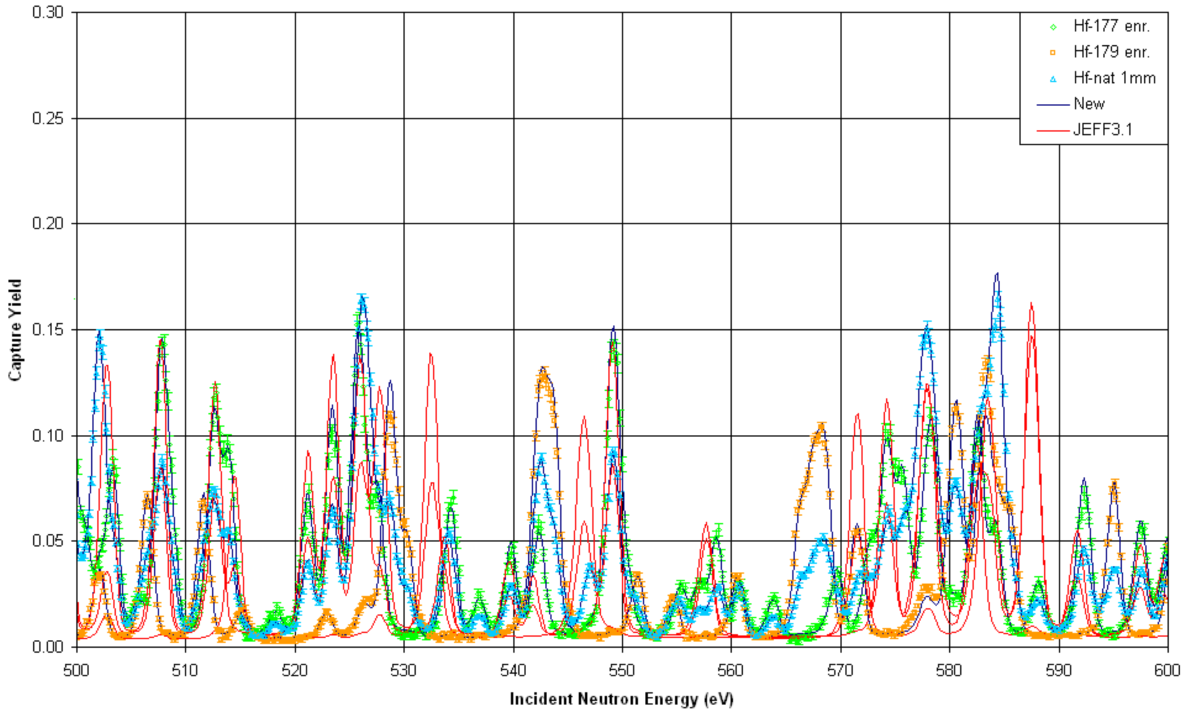

Figure 1: Experimental capture yield as a function of time-of-flight resulting from measurements with the ^{177}Hf, ^{179}Hf and ^{nat}Hf samples. The experimental yield is compared with the yields calculated with the parameters in the JEFF3.1 data library and with those resulting from fitting to the new measured data.

5. References

[1] W. Mondelaers, P. Schillebeeckx, "GELINA, a neutron time-of-flight facility for high-resolution neutron data measurements", Notiziario Neutroni e Luce di Sincrotrone 11 no.2, 19 (2006).

[2] D. Tronc, J.M. Salome, K.H. Böckhoff, "A new pulse compression system for intense relativistic electron beams", Nucl. Inst. Meth. A 228, 217 (1985). DOI: 10.1016/0168-9002(85)90263-3

[3] A. Bensussan, J.M.Salome, "GELINA: A modern accelerator for high resolution neutron time of flight experiments", Nucl. Instr. Meth., 155, 11 (1978). DOI: 10.1016/0029-554X(78)90181-73

[4] M.C. Moxon, T.C. Ware, C.J. Dean, "REFIT-2009: A Least-Square Fitting Program for Resonance Analysis of Neutron Transmission, Capture, Fission and Scattering Data; Users' Guide for REFIT-2009-10", UKNSF(2010)P243

[5] Consultants' Meeting, 8 to 10 October 2013, IAEA Headquarters, Vienna, Austria. https://www-nds.iaea.org/index-meeting-crp/CM-RF-2013/ (2013).

[6] Goodfellow Product Catalogue: www.goodfellow.com

[7] J.K. Tuli, "Nuclear Wallet Cards", Brookhaven National Laboratory, Upton, NY, 2005

[8] A.H. Wapstra, G. Audi, C. Thibault, “The AME2003 atomic mass evaluation (I). Evaluation of input data, adjustment procedures”, Nuclear Physics, Section A, 729 (2003) 129-336

[9] 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, K. Volev, “Determination of Resonance Parameters and their Covariances from Neutron Induced Reaction Cross Section Data”, Nuclear Data Sheets 113, 3054-3100 (2012). DOI: 10.1016/j.nds.2012.11.005

[10] A. Borella, G. Aerts, F. Gunsing, M. Moxon, P. Schillebeeckx, R. Wynants, “The use of C_6D_6 detectors for neutron induced capture cross-section measurements in the resonance region”, Nuclear Inst. and Methods in Physics Research, A, 577 (2007) 626-640

[11] A. Borella, “AGL2 - User manual”, IRMM internal report, 2007

[12] A. Borella, K. Volev, A. Brusegan, P. Schillebeeckx, F. Corvi, N. Koyumdjieva, N. Janeva, A. A Lukyanov, “Determination of the ^{232}Th(n,γ) cross section from 4 to 140 keV at GELINA”, Nuclear Science and Engineering, 152(2006)1

[13] S. de Jonge, “Fast Time Digitizer Type 8514 A”, Internal Report GE/DE/R/24/87, IRMM, Geel

[14] A. Borella, “Determination of the neutron resonance parameters for ^{206}Pb and of the thermal neutron capture cross section for ^{206}Pb and ^{209}Bi”, PhD Thesis, Univ. Gent, 2005

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

[16] J. Briesmeister, “MCNP – A General Monte Carlo N-Particle Transport Code – Version 4C2” Los Alamos National Laboratory, Los Alamos, NM, USA, 2000

[17] M.S. Moore, “Rate dependence of counting losses in neutron time-of-flight measurements”, Nucl. Instr. Meth. 169, 245 - 247 (1980). DOI: 10.1016/0029-554X(80)90129-9

[18] B. Becker, C. Bastian, F. Emiliani, F. Gunsing, J. Heyse, K. Kauwenberghs, S. Kopecky, C. Lampoudis, C. Massimi, N. Otuka, P. Schillebeeckx, I. Sirakov, “Data reduction and uncertainty propagation of time-of-flight spectra with AGS”, JINST 7, P11002 (2012). DOI: 10.1088/^{174}8-0221/7/11/P11002

[19] N. Otuka, A. Borella, S. Kopecky, C. Lampoudis, P. Schillebeeckx, “Database for Time-of-flight Spectra Including Covariances”, J. Korean Phys. Soc. 59, 1314 - 1317 (2011). DOI: 10.3938/jkps.59.1314

[20] N. Otuka, S. Dunaeva, E. Dupont, O. Schwerer, A. Blokhin, “The Role of the Nuclear Reaction Data Centres in Experimental Nuclear Data Knowledge Sharing”, J. Korean Phys. Soc., 59, 1292 – 1297, (2011) . DOI: 10.3938/jkps.59.1292

APPENDIX A: SUMMARY OF EXPERIMENTAL DETAILS - HFN2-0710

A. Experiment Description

1.	**Main Reference**		[1]
2.	**Facility**	GELINA	[2]
3.	**Neutron production** Neutron production beam Nominal average beam energy Nominal average peak current Repetition rate (pulses per second Pulse width Primary neutron production target Nominal neutron production intensity	 Electron 100 MeV 70 µA 50 Hz 1 ns Mercury-cooled depleted uranium 3.4×10^{13} s^{-1}	
4.	**Moderator** Primary neutron source position Moderator material Moderator dimensions (internal) Density (moderator material) Temperature (K) Moderator-room decoupler	 Above and below uranium target H_2O in two Be-cans around U-target 2 × (14.6 cm × 21 cm × 3.9 cm) 1 g/cm^2 Room temperature None	
5.	**Other experimental details** Measurement type Method Flight path length Flight path direction Neutron beam diameter at sample position Overlap suppression filter Other neutron beam filters	 Neutron capture Total energy detection 12.89 m (moderator to sample face) 18° (with respect to normal of the moderator face viewing the flight path) 75 mm None. Na, Bi, Co	[3]
6.	**Detector** Type Material Surface diameter Thickness Dead time Detector position relative to neutron beam	 Scintillator × 4 C_6D_6 100 mm 75 mm 2592 ns Outside the beam	
7.	**Flux Monitor** Type Material Surface diameter Areal density of ^{10}B layer Dead time Detector position relative to neutron beam	 Frisch-gridded ionisation chamber ^{10}B (evaporated on aluminium) 84 mm 4.79×10^{-6} a/b 2535 ns In the beam	
8.	**Sample** Type (metal, powder, liquid, crystal) Chemical composition Hf isotope composition (at%) Temperature	 Metal Hf: 97.0 at%, Zr: 3.0 at% ^{174}Hf: 0.16 ± 0.01 ^{176}Hf: 5.26 ± 0.07 ^{177}Hf: 18.60 ± 0.09 ^{178}Hf: 27.28 ± 0.07 ^{179}Hf: 13.62 ± 0.02 ^{180}Hf: 35.08 ± 0.16 22°C	[4]

	Sample mass Geometrical shape Diameter Nominal thickness Areal density of Hf isotopes Containment description Additional comment	16.1961 ± 0.0001 g Disc 80.04 ± 0.01 mm 0.2566 ± 0.0092 mm $1.0532\times10^{-3} \pm 2.63\times10^{-7}$ at/b None. Suspended in carbon fibre frame. -	
9.	**Data Reduction Procedure** Dead time correction Back ground subtraction Normalisation Detector efficiency Self-shielding Time-of-flight binning	 Done (factor <1.06) Black resonance technique 0.032784 Corrected in REFIT No correction applied Zone length bin width 4096 8 ns 5120 16 ns 5120 32 ns 6144 64 ns 6144 2048 ns	
10.	**Response function** Analytical function defined in REFIT, requiring additional parameters;	 Trapazoidal pulse (top / base = 0.7) with tail = $0.0167*\exp(0.273*t*E^{-0.563})$ Uses 12cm beam diameter at moderator	 [5]

B. Data Format

Column	Content	Unit	Comment
1	Neutron Energy	eV	Relativistic relation
2	t_l	ns	-
3	t_h	ns	-
4	Y_{exp}	-	Capture yield
5	Total Uncertainty	-	-
6	Uncorrelated uncertainty	-	Uncorrelated uncertainty due to counting statistics
7	AGS-vector (B_S)	-	Background model ($u(B_S)/B_S = 5\%$)
8	AGS-vector (B_ϕ)	-	Normalisation ($u(B_\phi)/B_\phi = 5\%$)

Comments from the authors:

– The AGS concept was used to derive the experimental capture yield;

$$Y_{exp} = N\, F_\phi\, Y_\phi\, [C_S - B_S] / [C_\phi - B_\phi]$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalisation ($u(N) = 2\%$) and background models ($u(B_S)/B_S$ and $u(B_\phi)/B_\phi = 5\%$).

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

– Values in columns 4, 5, 6 and 7 have been set to zero where the corresponding value in column 4 is less than $|1\times10^{-9}|$. Values greater than 1.1 or less than -0.5 in column 4 (and are shown to be unphysical) have been set to zero.

APPENDIX B: SUMMARY OF EXPERIMENTAL DETAILS – HFN3-0710

A. Experiment Description

1.	**Main Reference**		[1]
2.	**Facility**	GELINA	[2]
3.	**Neutron production**		
	Neutron production beam	Electron	
	Nominal average beam energy	100 MeV	
	Nominal average peak current	70 µA	
	Repetition rate (pulses per second	50 Hz	
	Pulse width	1 ns	
	Primary neutron production target	Mercury-cooled depleted uranium	
	Nominal neutron production intensity	3.4×10^{13} s^{-1}	
4.	**Moderator**		
	Primary neutron source position	Above and below uranium target	
	Moderator material	H_2O in two Be-cans around U-target	
	Moderator dimensions (internal)	2 × (14.6 cm × 21 cm × 3.9 cm)	
	Density (moderator material)	1 g/cm^2	
	Temperature (K)	Room temperature	
	Moderator-room decoupler	None	
5.	**Other experimental details**		
	Measurement type	Neutron capture	
	Method	Total energy detection	[3]
	Flight path length	12.89 m (moderator to sample face)	
	Flight path direction	18° (with respect to normal of the moderator face viewing the flight path)	
	Neutron beam diameter at sample position	75 mm	
	Overlap suppression filter	None.	
	Other neutron beam filters	Na, Bi, Co	
6.	**Detector**		
	Type	Scintillator × 4	
	Material	C_6D_6	
	Surface diameter	100 mm	
	Thickness	75 mm	
	Dead time	2592 ns	
	Detector position relative to neutron beam	Outside the beam	
7.	**Flux Monitor**		
	Type	Frisch-gridded ionisation chamber	
	Material	^{10}B (evaporated on aluminium)	
	Surface diameter	84 mm	
	Areal density of ^{10}B layer	4.79×10^{-6} a/b	
	Dead time	2535 ns	
	Detector position relative to neutron beam	In the beam	
8.	**Sample**		
	Type (metal, powder, liquid, crystal)	Metal	
	Chemical composition	Hf: 97.0 at%, Zr: 3.0 at%	[4]
	Hf isotope composition (at%)	^{174}Hf: 0.16 ± 0.01 ^{176}Hf: 5.26 ± 0.07 ^{177}Hf: 18.60 ± 0.09 ^{178}Hf: 27.28 ± 0.07 ^{179}Hf: 13.62 ± 0.02 ^{180}Hf: 35.08 ± 0.16	
	Temperature	22°C	

	Sample mass Geometrical shape Diameter Nominal thickness Areal density of Hf isotopes Containment description Additional comment	5.0697 ± 0.0001 g Disc 80.04 ± 0.02 mm 0.079 ± 0.0009 mm $3.2969 \times 10^{-4} \pm 1.65 \times 10^{-7}$ at/b None. Suspended in carbon fibre frame. -	
9.	**Data Reduction Procedure** Dead time correction Back ground subtraction Normalisation Detector efficiency Self-shielding Time-of-flight binning	 Done (factor <1.06) Black resonance technique 0.03284 Corrected in REFIT No correction applied Zone length bin width 4096 8 ns 5120 16 ns 5120 32 ns 6144 64 ns 6144 2048 ns	
10.	**Response function** Analytical function defined in REFIT, requiring additional parameters;	 Trapazoidal pulse (top / base = 0.7) with tail = $0.0167 \cdot \exp(0.273 \cdot t \cdot E^{-0.563})$ Uses 12cm beam diameter at moderator	 [5]

B. Data Format

Column	Content	Unit	Comment
1	Neutron Energy	eV	Relativistic relation
2	t_l	ns	-
3	t_h	ns	-
4	Y_{exp}	-	Capture yield
5	Total Uncertainty	-	-
6	Uncorrelated uncertainty	-	Uncorrelated uncertainty due to counting statistics
7	AGS-vector (B_S)	-	Background model ($u(B_S)/B_S = 5\%$)
8	AGS-vector (B_ϕ)	-	Normalisation ($u(B_\phi)/B_\phi = 5\%$)

Comments from the authors:

– The AGS concept was used to derive the experimental capture yield;

$$Y_{exp} = N\, F_\phi\, Y_\phi\, [C_S - B_S] / [C_\phi - B_\phi]$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalisation ($u(N) = 2\%$) and background models ($u(B_S)/B_S$ and $u(B_\phi)/B_\phi = 5\%$).

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

– Values in columns 4, 5, 6 and 7 have been set to zero where the corresponding value in column 4 is less than $|1 \times 10^{-9}|$. Values greater than 1.1 or less than -0.5 in column 4 (and are shown to be unphysical) have been set to zero.

APPENDIX C: SUMMARY OF EXPERIMENTAL DETAILS – HFN4-0710

A. Experiment Description

1.	**Main Reference**		[1]
2.	**Facility**	GELINA	[2]
3.	**Neutron production**		
	Neutron production beam	Electron	
	Nominal average beam energy	100 MeV	
	Nominal average peak current	70 μA	
	Repetition rate (pulses per second	50 Hz	
	Pulse width	1 ns	
	Primary neutron production target	Mercury-cooled depleted uranium	
	Nominal neutron production intensity	3.4×10^{13} s^{-1}	
4.	**Moderator**		
	Primary neutron source position	Above and below uranium target	
	Moderator material	H_2O in two Be-cans around U-target	
	Moderator dimensions (internal)	2 × (14.6 cm × 21 cm × 3.9 cm)	
	Density (moderator material)	1 g/cm^2	
	Temperature (K)	Room temperature	
	Moderator-room decoupler	None	
5.	**Other experimental details**		
	Measurement type	Neutron capture	
	Method	Total energy detection	[3]
	Flight path length	12.89 m (moderator to sample face)	
	Flight path direction	18° (with respect to normal of the moderator face viewing the flight path)	
	Neutron beam diameter at sample position	75 mm	
	Overlap suppression filter	None.	
	Other neutron beam filters	Na, Bi, Co	
6.	**Detector**		
	Type	Scintillator × 4	
	Material	C_6D_6	
	Surface diameter	100 mm	
	Thickness	75 mm	
	Dead time	2592 ns	
	Detector position relative to neutron beam	Outside the beam	
7.	**Flux Monitor**		
	Type	Frisch-gridded ionisation chamber	
	Material	^{10}B (evaporated on aluminium)	
	Surface diameter	84 mm	
	Areal density of ^{10}B layer	4.79×10^{-6} a/b	
	Dead time	2535 ns	
	Detector position relative to neutron beam	In the beam	
8.	**Sample**		
	Type (metal, powder, liquid, crystal)	Metal	
	Chemical composition	Hf: 97.0 at%, Zr: 3.0 at%	[4]
	Hf isotope composition (at%)	^{174}Hf: 0.16 ± 0.01 ^{176}Hf: 5.26 ± 0.07 ^{177}Hf: 18.60 ± 0.09 ^{178}Hf: 27.28 ± 0.07 ^{179}Hf: 13.62 ± 0.02 ^{180}Hf: 35.08 ± 0.16	
	Temperature	22°C	

	Sample mass Geometrical shape Diameter Nominal thickness Areal density of Hf isotopes Containment description Additional comment	1.4849 ± 0.0001 g Disc 80.04 ± 0.02 mm 0.0244 ± 0.0010 mm $9.6565\times10^{-5} \pm 4.83\times10^{-8}$ at/b None. Suspended in carbon fibre frame. -	
9.	**Data Reduction Procedure** Dead time correction Back ground subtraction Normalisation Detector efficiency Self-shielding Time-of-flight binning	 Done (factor <1.06) Black resonance technique 0.032867 Corrected in REFIT No correction applied Zone length bin width 4096 8 ns 5120 16 ns 5120 32 ns 6144 64 ns 6144 2048 ns	
10.	**Response function** Analytical function defined in REFIT, requiring additional parameters;	 Trapazoidal pulse (top / base = 0.7) with tail = $0.0167*\exp(0.273*t*E^{-0.563})$ Uses 12cm beam diameter at moderator	[5]

B. Data Format

Column	Content	Unit	Comment
1	Neutron Energy	eV	Relativistic relation
2	t_l	ns	-
3	t_h	ns	-
4	Y_{exp}	-	Capture yield
5	Total Uncertainty	-	-
6	Uncorrelated uncertainty	-	Uncorrelated uncertainty due to counting statistics
7	AGS-vector (B_S)	-	Background model ($u(B_S)/B_S = 5\%$)
8	AGS-vector (B_ϕ)	-	Normalisation ($u(B_\phi)/B_\phi = 5\%$)

Comments from the authors:

– The AGS concept was used to derive the experimental capture yield;

$$Y_{exp} = N\, F_\phi\, Y_\phi\, [C_S - B_S] / [C_\phi - B_\phi]$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalisation ($u(N) = 2\%$) and background models ($u(B_S)/B_S$ and $u(B_\phi)/B_\phi = 5\%$).

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

– Values in columns 4, 5, 6 and 7 have been set to zero where the corresponding value in column 4 is less than $|1\times10^{-9}|$. Values greater than 1.1 or less than -0.5 in column 4 (and are shown to be unphysical) have been set to zero.

APPENDIX D: SUMMARY OF EXPERIMENTAL DETAILS – HFN1-0760

A. Experiment Description

1.	**Main Reference**		[1]
2.	**Facility**	GELINA	[2]
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	
	Nominal neutron production intensity	3.4×10^{13} s^{-1}	
4.	**Moderator**		
	Primary neutron source position	Above and below uranium target	
	Moderator material	H_2O in two Be-cans around U-target	
	Moderator dimensions (internal)	2 × (14.6 cm × 21 cm × 3.9 cm)	
	Density (moderator material)	1 g/cm^2	
	Temperature (K)	Room temperature	
	Moderator-room decoupler	None	
5.	**Other experimental details**		
	Measurement type	Neutron capture	
	Method	Total energy detection	[3]
	Flight path length	58.586 m (moderator to sample face)	
	Flight path direction	9° (with respect to normal of the moderator face viewing the flight path)	
	Neutron beam diameter at sample position	75 mm	
	Overlap suppression filter	^{10}B	
	Other neutron beam filters	S	
6.	**Detector**		
	Type	Scintillator × 4	
	Material	C_6D_6	
	Surface diameter	100 mm	
	Thickness	75 mm	
	Dead time	2700 ns	
	Detector position relative to neutron beam	Outside the beam	
7.	**Flux Monitor**		
	Type	Frisch-gridded ionisation chamber	
	Material	^{10}B (evaporated on aluminium)	
	Surface diameter	84 mm	
	Areal density of ^{10}B layer	1.25×10^{-5} a/b	
	Dead time	3400 ns	
	Detector position relative to neutron beam	In the beam	
8.	**Sample**		
	Type (metal, powder, liquid, crystal)	Metal	
	Chemical composition	Hf: 97.0 at%, Zr: 3.0 at%	[4]
	Hf isotope composition (at%)	^{174}Hf: 0.16 ± 0.01 ^{176}Hf: 5.26 ± 0.07 ^{177}Hf: 18.60 ± 0.09 ^{178}Hf: 27.28 ± 0.07 ^{179}Hf: 13.62 ± 0.02 ^{180}Hf: 35.08 ± 0.16	
	Temperature	22°C	

	Sample mass Geometrical shape Diameter Nominal thickness Areal density of Hf isotopes Containment description Additional comment	33.3600 ± 0.0001 g Disc 54.995 ± 0.040 mm 1.081 ± 0.0018 mm $4.6053 \times 10^{-3} \pm 6.75 \times 10^{-6}$ at/b None. Suspended in carbon fibre frame. -	
9.	**Data Reduction Procedure** Dead time correction Back ground subtraction Normalisation Detector efficiency Self-shielding Time-of-flight binning	 Done (factor <1.01) Black resonance technique 1.0134 Corrected in REFIT No correction applied Zone length bin width 3072 2 ns 3072 4 ns 3072 8 ns 3072 16 ns 3072 32 ns 3072 64 ns 3072 128 ns 1024 256 ns	
10.	**Response function** Analytical function defined in REFIT, requiring additional parameters;	 Trapazoidal pulse (top / base = 0.7) with tail = $0.0167 \cdot \exp(0.273 \cdot t \cdot E^{-0.563})$ Uses 12cm beam diameter at moderator	 [5]

B. Data Format

Column	Content	Unit	Comment
1	Neutron Energy	eV	Relativistic relation
2	t_l	ns	-
3	t_h	ns	-
4	Y_{exp}	-	Capture yield
5	Total Uncertainty	-	-
6	Uncorrelated uncertainty	-	Uncorrelated uncertainty due to counting statistics
7	AGS-vector (B_S)	-	Background model ($u(B_S)/B_S = 5\%$)
8	AGS-vector (B_ϕ)	-	Normalisation ($u(B_\phi)/B_\phi = 5\%$)

Comments from the authors:

– The AGS concept was used to derive the experimental capture yield;

$$Y_{exp} = N\, F_\phi\, Y_\phi\, [C_S - B_S] / [C_\phi - B_\phi]$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalisation ($u(N) = 2\%$) and background models ($u(B_S)/B_S$ and $u(B_\phi)/B_\phi = 5\%$).

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

– Values in columns 4, 5, 6 and 7 have been set to zero where the corresponding value in column 4 is less than $|1 \times 10^{-9}|$. Values greater than 1.1 or less than -0.5 in column 4 (and are shown to be unphysical) have been set to zero.

APPENDIX E: SUMMARY OF EXPERIMENTAL DETAILS – HFE2-0810

A. Experiment Description

1.	**Main Reference**		[1]
2.	**Facility**	GELINA	[2]
3.	**Neutron production** Neutron production beam Nominal average beam energy Nominal average peak current Repetition rate (pulses per second Pulse width Primary neutron production target Nominal neutron production intensity	 Electron 100 MeV 70 μA 800 Hz 1 ns Mercury-cooled depleted uranium 3.4×10^{13} s^{-1}	
4.	**Moderator** Primary neutron source position Moderator material Moderator dimensions (internal) Density (moderator material) Temperature (K) Moderator-room decoupler	 Above and below uranium target H_2O in two Be-cans around U-target 2 × (14.6 cm × 21 cm × 3.9 cm) 1 g/cm^2 Room temperature None	
5.	**Other experimental details** Measurement type Method Flight path length Flight path direction Neutron beam diameter at sample position Overlap suppression filter Other neutron beam filters	 Neutron capture Total energy detection 12.95 m (moderator to sample face) 18° (with respect to normal of the moderator face viewing the flight path) 75 mm ^{10}B Pb, Na	 [3]
6.	**Detector** Type Material Surface diameter Thickness Dead time Detector position relative to neutron beam	 Scintillator × 2 C_6D_6 100 mm 75 mm 2835 ns Outside the beam	
7.	**Flux Monitor** Type Material Surface diameter Areal density of ^{10}B layer Dead time Detector position relative to neutron beam	 Frisch-gridded ionisation chamber ^{10}B (evaporated on aluminium) 84 mm 4.79×10^{-6} a/b 6735 ns In the beam	
8.	**Sample** Type (metal, powder, liquid, crystal) Chemical composition Hf isotope composition (at%) Temperature Sample mass	 Powder Hf: 33.3 at%, O: 66.7 at% ^{174}Hf: <0.05 ^{176}Hf: 1.0 ^{177}Hf: 85.4 ^{178}Hf: 11.3 ^{179}Hf: 0.9 ^{180}Hf: 1.4 22°C 4.7070 ± 0.0001 g	

	Geometrical shape Diameter Nominal thickness Areal density of Hf isotopes Containment description Additional comment	Disc 30.09 ± 0.0082 mm 3.223 ± 0.0498 mm $1.91\times10^{-3} \pm 1.04\times10^{-6}$ at/b Al can 31mm outer diam., 0.45mm windows, mass 6.2g. Suspended in carbon fibre frame. Trace bromine in carbon fibre frame.	
9.	**Data Reduction Procedure** Dead time correction Back ground subtraction Normalisation Detector efficiency Self-shielding Time-of-flight binning	 Done (factor <1.06) Black resonance technique 1.050 Corrected in REFIT No correction applied Zone length bin width 3072 2 ns 3072 4 ns 3072 8 ns 3072 16 ns 3072 32 ns 3072 64 ns 3072 128 ns 2048 256 ns	
10.	**Response function** Analytical function defined in REFIT, requiring additional parameters;	 Trapazoidal pulse (top / base = 0.7) with tail = $0.0167*\exp(0.273*t*E^{-0.563})$ Uses 12cm beam diameter at moderator	 [5]

B. Data Format

Column	Content	Unit	Comment
1	Neutron Energy	eV	Relativistic relation
2	t_l	ns	-
3	t_h	ns	-
4	Y_{exp}	-	Capture yield
5	Total Uncertainty	-	-
6	Uncorrelated uncertainty	-	Uncorrelated uncertainty due to counting statistics
7	AGS-vector (B_S)	-	Background model ($u(B_S)/B_S = 5\%$)
8	AGS-vector (B_ϕ)	-	Normalisation ($u(B_\phi)/B_\phi = 5\%$)

Comments from the authors:

– The AGS concept was used to derive the experimental capture yield;

$$Y_{exp} = N\, F_\phi\, Y_\phi\, [C_S - B_S] / [C_\phi - B_\phi]$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalisation ($u(N) = 2\%$) and background models ($u(B_S)/B_S$ and $u(B_\phi)/B_\phi = 5\%$).

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

– Values in columns 4, 5, 6 and 7 have been set to zero where the corresponding value in column 4 is less than $|1\times10^{-9}|$. Values greater than 1.1 or less than -0.5 in column 4 (and are shown to be unphysical) have been set to zero.

APPENDIX F: SUMMARY OF EXPERIMENTAL DETAILS – HFE3-0810

A. Experiment Description

1.	**Main Reference**		[1]
2.	**Facility**	GELINA	[2]
3.	**Neutron production** Neutron production beam Nominal average beam energy Nominal average peak current Repetition rate (pulses per second Pulse width Primary neutron production target Nominal neutron production intensity	 Electron 100 MeV 70 µA 800 Hz 1 ns Mercury-cooled depleted uranium 3.4×10^{13} s^{-1}	
4.	**Moderator** Primary neutron source position Moderator material Moderator dimensions (internal) Density (moderator material) Temperature (K) Moderator-room decoupler	 Above and below uranium target H_2O in two Be-cans around U-target 2 × (14.6 cm × 21 cm × 3.9 cm) 1 g/cm^2 Room temperature None	
5.	**Other experimental details** Measurement type Method Flight path length Flight path direction Neutron beam diameter at sample position Overlap suppression filter Other neutron beam filters	 Neutron capture Total energy detection 12.95 m (moderator to sample face) 18° (with respect to normal of the moderator face viewing the flight path) 75 mm ^{10}B Pb, Na	 [3]
6.	**Detector** Type Material Surface diameter Thickness Dead time Detector position relative to neutron beam	 Scintillator × 2 C_6D_6 100 mm 75 mm 2835 ns Outside the beam	
7.	**Flux Monitor** Type Material Surface diameter Areal density of ^{10}B layer Dead time Detector position relative to neutron beam	 Frisch-gridded ionisation chamber ^{10}B (evaporated on aluminium) 84 mm 4.79×10^{-6} a/b 6735 ns In the beam	
8.	**Sample** Type (metal, powder, liquid, crystal) Chemical composition Hf isotope composition (at%) Temperature Sample mass	 Powder Hf: 33.3 at%, O: 66.7 at% ^{174}Hf: <0.05 ^{176}Hf: 0.8 ^{177}Hf: 1.9 ^{178}Hf: 92.4 ± 0.2 ^{179}Hf: 3.3 ^{180}Hf: 1.6 22°C 4.4570 ± 0.0001 g	

	Geometrical shape Diameter Nominal thickness Areal density of Hf isotopes Containment description Additional comment	Disc 30.06 ± 0.0141 mm 2.502 ± 0.1125 mm $1.80\times10^{-3} \pm 1.69\times10^{-6}$ at/b Al can 31mm outer diam., 0.45mm windows, mass 6.2g. Suspended in carbon fibre frame. Trace bromine in carbon fibre frame.	
9.	**Data Reduction Procedure** Dead time correction Back ground subtraction Normalisation Detector efficiency Self-shielding Time-of-flight binning	 Done (factor <1.06) Black resonance technique 0.80954 Corrected in REFIT No correction applied Zone length bin width 3072 2 ns 3072 4 ns 3072 8 ns 3072 16 ns 3072 32 ns 3072 64 ns 3072 128 ns 2048 256 ns	
10.	**Response function** Analytical function defined in REFIT, requiring additional parameters;	 Trapazoidal pulse (top / base = 0.7) with tail = $0.0167*\exp(0.273*t*E^{-0.563})$ Uses 12cm beam diameter at moderator	 [5]

B. Data Format

Column	Content	Unit	Comment
1	Neutron Energy	eV	Relativistic relation
2	t_l	ns	-
3	t_h	ns	-
4	Y_{exp}	-	Capture yield
5	Total Uncertainty	-	-
6	Uncorrelated uncertainty	-	Uncorrelated uncertainty due to counting statistics
7	AGS-vector (B_S)	-	Background model ($u(B_S)/B_S = 5\%$)
8	AGS-vector (B_ϕ)	-	Normalisation ($u(B_\phi)/B_\phi = 5\%$)

Comments from the authors:

– The AGS concept was used to derive the experimental capture yield;

$$Y_{exp} = N\, F_\phi\, Y_\phi\, [C_S - B_S] / [C_\phi - B_\phi]$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalisation ($u(N) = 2\%$) and background models ($u(B_S)/B_S$ and $u(B_\phi)/B_\phi = 5\%$).

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

– Values in columns 4, 5, 6 and 7 have been set to zero where the corresponding value in column 4 is less than $|1\times10^{-9}|$. Values greater than 1.1 or less than -0.5 in column 4 (and are shown to be unphysical) have been set to zero.

APPENDIX G: SUMMARY OF EXPERIMENTAL DETAILS – HFE4-0810

A. Experiment Description

1.	**Main Reference**		[1]
2.	**Facility**	GELINA	[2]
3.	**Neutron production** Neutron production beam Nominal average beam energy Nominal average peak current Repetition rate (pulses per second Pulse width Primary neutron production target Nominal neutron production intensity	 Electron 100 MeV 70 μA 800 Hz 1 ns Mercury-cooled depleted uranium 3.4×10^{13} s^{-1}	
4.	**Moderator** Primary neutron source position Moderator material Moderator dimensions (internal) Density (moderator material) Temperature (K) Moderator-room decoupler	 Above and below uranium target H_2O in two Be-cans around U-target 2 × (14.6 cm × 21 cm × 3.9 cm) 1 g/cm^2 Room temperature None	
5.	**Other experimental details** Measurement type Method Flight path length Flight path direction Neutron beam diameter at sample position Overlap suppression filter Other neutron beam filters	 Neutron capture Total energy detection 12.95 m (moderator to sample face) 18° (with respect to normal of the moderator face viewing the flight path) 75 mm ^{10}B Pb, Na	 [3]
6.	**Detector** Type Material Surface diameter Thickness Dead time Detector position relative to neutron beam	 Scintillator × 2 C_6D_6 100 mm 75 mm 2835 ns Outside the beam	
7.	**Flux Monitor** Type Material Surface diameter Areal density of ^{10}B layer Dead time Detector position relative to neutron beam	 Frisch-gridded ionisation chamber ^{10}B (evaporated on aluminium) 84 mm 4.79×10^{-6} a/b 6735 ns In the beam	
8.	**Sample** Type (metal, powder, liquid, crystal) Chemical composition Hf isotope composition (at%) Temperature Sample mass	 Powder Hf: 33.3 at%, O: 66.7 at% ^{174}Hf: <0.05 ^{176}Hf: 0.8 ^{177}Hf: 1.9 ^{178}Hf: 92.4 ± 0.2 ^{179}Hf: 3.3 ^{180}Hf: 1.6 22°C 0.9006 ± 0.0001 g	

	Geometrical shape Diameter Nominal thickness Areal density of Hf isotopes Containment description Additional comment	Disc 20.03 ± 0.005 mm 1.052 ± 0.0097 mm $0.82\times10^{-3} \pm 0.42\times10^{-6}$ at/b Al can 21mm outer diam.,0.45mm windows, mass 3.9g. Suspended in carbon fibre frame. Trace bromine in carbon fibre frame.	
9.	**Data Reduction Procedure** Dead time correction Back ground subtraction Normalisation Detector efficiency Self-shielding Time-of-flight binning	 Done (factor <1.06) Black resonance technique 1.1463 Corrected in REFIT No correction applied Zone length bin width 3072 2 ns 3072 4 ns 3072 8 ns 3072 16 ns 3072 32 ns 3072 64 ns 3072 128 ns 2048 256 ns	
10.	**Response function** Analytical function defined in REFIT, requiring additional parameters;	 Trapazoidal pulse (top / base = 0.7) with tail = $0.0167*\exp(0.273*t*E^{-0.563})$ Uses 12cm beam diameter at moderator	[5]

B. Data Format

Column	Content	Unit	Comment
1	Neutron Energy	eV	Relativistic relation
2	t_l	ns	-
3	t_h	ns	-
4	Y_{exp}	-	Capture yield
5	Total Uncertainty	-	-
6	Uncorrelated uncertainty	-	Uncorrelated uncertainty due to counting statistics
7	AGS-vector (B_S)	-	Background model ($u(B_S)/B_S = 5\%$)
8	AGS-vector (B_ϕ)	-	Normalisation ($u(B_\phi)/B_\phi = 5\%$)

Comments from the authors:

– The AGS concept was used to derive the experimental capture yield;

$$Y_{exp} = N\, F_\phi\, Y_\phi\, [C_S - B_S] / [C_\phi - B_\phi]$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalisation ($u(N) = 2\%$) and background models ($u(B_S)/B_S$ and $u(B_\phi)/B_\phi = 5\%$).

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

– Values in columns 4, 5, 6 and 7 have been set to zero where the corresponding value in column 4 is less than $|1\times10^{-9}|$. Values greater than 1.1 or less than -0.5 in column 4 (and are shown to be unphysical) have been set to zero.

APPENDIX H: SUMMARY OF EXPERIMENTAL DETAILS – HFE5-0810

A. Experiment Description

1.	**Main Reference**		[1]
2.	**Facility**	GELINA	[2]
3.	**Neutron production** Neutron production beam Nominal average beam energy Nominal average peak current Repetition rate (pulses per second Pulse width Primary neutron production target Nominal neutron production intensity	 Electron 100 MeV 70 µA 800 Hz 1 ns Mercury-cooled depleted uranium 3.4×10^{13} s^{-1}	
4.	**Moderator** Primary neutron source position Moderator material Moderator dimensions (internal) Density (moderator material) Temperature (K) Moderator-room decoupler	 Above and below uranium target H_2O in two Be-cans around U-target 2 × (14.6 cm × 21 cm × 3.9 cm) 1 g/cm^2 Room temperature None	
5.	**Other experimental details** Measurement type Method Flight path length Flight path direction Neutron beam diameter at sample position Overlap suppression filter Other neutron beam filters	 Neutron capture Total energy detection 12.95 m (moderator to sample face) 18° (with respect to normal of the moderator face viewing the flight path) 75 mm ^{10}B Pb, Na	 [3]
6.	**Detector** Type Material Surface diameter Thickness Dead time Detector position relative to neutron beam	 Scintillator × 2 C_6D_6 100 mm 75 mm 2835 ns Outside the beam	
7.	**Flux Monitor** Type Material Surface diameter Areal density of ^{10}B layer Dead time Detector position relative to neutron beam	 Frisch-gridded ionisation chamber ^{10}B (evaporated on aluminium) 84 mm 4.79×10^{-6} a/b 6735 ns In the beam	
8.	**Sample** Type (metal, powder, liquid, crystal) Chemical composition Hf isotope composition (at%) Temperature Sample mass	 Powder Hf: 33.3 at%, O: 66.7 at% ^{174}Hf: <0.05 ^{176}Hf: 0.2 ^{177}Hf: 1.3 ^{178}Hf: 4.1 ^{179}Hf: 72.1 ± 0.4 ^{180}Hf: 22.3 22°C 5.3175 ± 0.0001 g	

	Geometrical shape Diameter Nominal thickness Areal density of Hf isotopes Containment description Additional comment	Disc 30.06 ± 0.0238 mm 2.452 ± 0.0558 mm $2.14\times10^{-3} \pm 3.39\times10^{-6}$ at/b Al can 31mm outer diam., 0.45mm windows, mass 6.2g. Suspended in carbon fibre frame. -	
9.	**Data Reduction Procedure** Dead time correction Back ground subtraction Normalisation Detector efficiency Self-shielding Time-of-flight binning	 Done (factor <1.06) Black resonance technique 1.00 Corrected in REFIT No correction applied Zone length bin width 3072 2 ns 3072 4 ns 3072 8 ns 3072 16 ns 3072 32 ns 3072 64 ns 3072 128 ns 2048 256 ns	
10.	**Response function** Analytical function defined in REFIT, requiring additional parameters;	 Trapazoidal pulse (top / base = 0.7) with tail = $0.0167*\exp(0.273*t*E^{-0.563})$ Uses 12cm beam diameter at moderator	[5]

B. Data Format

Column	Content	Unit	Comment
1	Neutron Energy	eV	Relativistic relation
2	t_l	ns	-
3	t_h	ns	-
4	Y_{exp}	-	Capture yield
5	Total Uncertainty	-	-
6	Uncorrelated uncertainty	-	Uncorrelated uncertainty due to counting statistics
7	AGS-vector (B_S)	-	Background model ($u(B_S)/B_S = 5\%$)
8	AGS-vector (B_ϕ)	-	Normalisation ($u(B_\phi)/B_\phi = 5\%$)

Comments from the authors:

– The AGS concept was used to derive the experimental capture yield;

$$Y_{exp} = N\, F_\phi\, Y_\phi\, [C_S - B_S] / [C_\phi - B_\phi]$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalisation ($u(N) = 2\%$) and background models ($u(B_S)/B_S$ and $u(B_\phi)/B_\phi = 5\%$).

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

– Values in columns 4, 5, 6 and 7 have been set to zero where the corresponding value in column 4 is less than $|1\times10^{-9}|$. Values greater than 1.1 or less than -0.5 in column 4 (and are shown to be unphysical) have been set to zero.

APPENDIX I: SUMMARY OF EXPERIMENTAL DETAILS – HFN1-0810

A. Experiment Description

1.	**Main Reference**		[1]
2.	**Facility**	GELINA	[2]
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	
	Nominal neutron production intensity	3.4×10^{13} s^{-1}	
4.	**Moderator**		
	Primary neutron source position	Above and below uranium target	
	Moderator material	H_2O in two Be-cans around U-target	
	Moderator dimensions (internal)	2 × (14.6 cm × 21 cm × 3.9 cm)	
	Density (moderator material)	1 g/cm^2	
	Temperature (K)	Room temperature	
	Moderator-room decoupler	None	
5.	**Other experimental details**		
	Measurement type	Neutron capture	
	Method	Total energy detection	[3]
	Flight path length	12.95 m (moderator to sample face)	
	Flight path direction	18° (with respect to normal of the moderator face viewing the flight path)	
	Neutron beam diameter at sample position	75 mm	
	Overlap suppression filter	^{10}B	
	Other neutron beam filters	Pb, Na	
6.	**Detector**		
	Type	Scintillator × 2	
	Material	C_6D_6	
	Surface diameter	100 mm	
	Thickness	75 mm	
	Dead time	2835 ns	
	Detector position relative to neutron beam	Outside the beam	
7.	**Flux Monitor**		
	Type	Frisch-gridded ionisation chamber	
	Material	^{10}B (evaporated on aluminium)	
	Surface diameter	84 mm	
	Areal density of ^{10}B layer	4.79×10^{-6} a/b	
	Dead time	6735 ns	
	Detector position relative to neutron beam	In the beam	
8.	**Sample**		
	Type (metal, powder, liquid, crystal)	Metal	
	Chemical composition	Hf: 97.0 at%, Zr: 3.0 at%	[4]
	Hf isotope composition (at%)	^{174}Hf: 0.16 ± 0.01 ^{176}Hf: 5.26 ± 0.07 ^{177}Hf: 18.60 ± 0.09 ^{178}Hf: 27.28 ± 0.07 ^{179}Hf: 13.62 ± 0.02 ^{180}Hf: 35.08 ± 0.16	
	Temperature	22°C	

	Sample mass Geometrical shape Diameter Nominal thickness Areal density of Hf isotopes Containment description Additional comment	33.3600 ± 0.0001 g Disc 54.995 ± 0.040 mm 1.081 ± 0.0018 mm $4.6053\times10^{-3} \pm 6.75\times10^{-6}$ at/b None. Suspended in carbon fibre frame. -	
9.	**Data Reduction Procedure** Dead time correction Back ground subtraction Normalisation Detector efficiency Self-shielding Time-of-flight binning	 Done (factor <1.06) Black resonance technique 1.020 Corrected in REFIT No correction applied Zone length bin width 3072 2 ns 3072 4 ns 3072 8 ns 3072 16 ns 3072 32 ns 3072 64 ns 3072 128 ns 2048 256 ns	
10.	**Response function** Analytical function defined in REFIT, requiring additional parameters;	 Trapazoidal pulse (top / base = 0.7) with tail = 0.0167*exp(0.273*t*$E^{-0.563}$) Uses 12cm beam diameter at moderator	[5]

B. Data Format

Column	Content	Unit	Comment
1	Neutron Energy	eV	Relativistic relation
2	t_l	ns	-
3	t_h	ns	-
4	Y_{exp}	-	Capture yield
5	Total Uncertainty	-	-
6	Uncorrelated uncertainty	-	Uncorrelated uncertainty due to counting statistics
7	AGS-vector (B_S)	-	Background model ($u(B_S)/B_S = 5\%$)
8	AGS-vector (B_ϕ)	-	Normalisation ($u(B_\phi)/B_\phi = 5\%$)

Comments from the authors:

– The AGS concept was used to derive the experimental capture yield;

$$Y_{exp} = N\, F_\phi\, Y_\phi\, [C_S - B_S] / [C_\phi - B_\phi]$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalisation ($u(N) = 2\%$) and background models ($u(B_S)/B_S$ and $u(B_\phi)/B_\phi = 5\%$).

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

– Values in columns 4, 5, 6 and 7 have been set to zero where the corresponding value in column 4 is less than $|1\times10^{-9}|$. Values greater than 1.1 or less than -0.5 in column 4 (and are shown to be unphysical) have been set to zero.

APPENDIX J: SUMMARY OF EXPERIMENTAL DETAILS – HFE1-0830

A. Experiment Description

1.	**Main Reference**		[1]
2.	**Facility**	GELINA	[2]
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	
	Nominal neutron production intensity	3.4×10^{13} s^{-1}	
4.	**Moderator**		
	Primary neutron source position	Above and below uranium target	
	Moderator material	H_2O in two Be-cans around U-target	
	Moderator dimensions (internal)	2 × (14.6 cm × 21 cm × 3.9 cm)	
	Density (moderator material)	1 g/cm^2	
	Temperature (K)	Room temperature	
	Moderator-room decoupler	None	
5.	**Other experimental details**		
	Measurement type	Neutron capture	
	Method	Total energy detection	[3]
	Flight path length	28.82 m (moderator to sample face)	
	Flight path direction	0° (with respect to normal of the moderator face viewing the flight path)	
	Neutron beam diameter at sample position	75 mm	
	Overlap suppression filter	^{10}B	
	Other neutron beam filters	S	
6.	**Detector**		
	Type	Scintillator × 2	
	Material	C_6D_6	
	Surface diameter	100 mm	
	Thickness	75 mm	
	Dead time	2874 ns	
	Detector position relative to neutron beam	Outside the beam	
7.	**Flux Monitor**		
	Type	Frisch-gridded ionisation chamber	
	Material	^{10}B (evaporated on aluminium)	
	Surface diameter	84 mm	
	Areal density of ^{10}B layer	4.3×10^{-6} a/b	
	Dead time	3992 ns	
	Detector position relative to neutron beam	In the beam	
8.	**Sample**		
	Type (metal, powder, liquid, crystal)	Powder	
	Chemical composition	Hf: 33.3 at%, O: 66.7 at%	
	Hf isotope composition (at%)	^{174}Hf: <0.05 ^{176}Hf: 65.0 ^{177}Hf: 22.9 ^{178}Hf: 6.3 ^{179}Hf: 1.8 ^{180}Hf: 4.0	
	Temperature	22°C	
	Sample mass	5.3424 ± 0.0001 g	

	Geometrical shape Diameter Nominal thickness Areal density of Hf isotopes Containment description Additional comment	Disc 30.13 ± 0.0387 mm 2.062 ± 0.0379 mm $2.17\times10^{-3} \pm 5.57\times10^{-6}$ at/b Al can 31mm outer diam., 0.45mm windows, mass 6.2g. Suspended in carbon fibre frame. -	
9.	**Data Reduction Procedure** Dead time correction Back ground subtraction Normalisation Detector efficiency Self-shielding Time-of-flight binning	 Done (factor <1.01) Black resonance technique 0.57073 Corrected in REFIT No correction applied Zone length bin width 2048 2 ns 3072 4 ns 3072 8 ns 3072 16 ns 3072 32 ns 3072 64 ns 3072 128 ns 1024 256 ns	
10.	**Response function** Analytical function defined in REFIT, requiring additional parameters;	 Trapazoidal pulse (top / base = 0.7) with tail = $0.0167*\exp(0.273*t*E^{-0.563})$ Uses 12cm beam diameter at moderator	 [5]

B. Data Format

Column	Content	Unit	Comment
1	Neutron Energy	eV	Relativistic relation
2	t_l	ns	-
3	t_h	ns	-
4	Y_{exp}	-	Capture yield
5	Total Uncertainty	-	-
6	Uncorrelated uncertainty	-	Uncorrelated uncertainty due to counting statistics
7	AGS-vector (B_S)	-	Background model ($u(B_S)/B_S = 5\%$)
8	AGS-vector (B_ϕ)	-	Normalisation ($u(B_\phi)/B_\phi = 5\%$)

Comments from the authors:

– The AGS concept was used to derive the experimental capture yield;

$$Y_{exp} = N\, F_\phi\, Y_\phi\, [C_S - B_S] / [C_\phi - B_\phi]$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalisation ($u(N) = 2\%$) and background models ($u(B_S)/B_S$ and $u(B_\phi)/B_\phi = 5\%$).

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

– Values in columns 4, 5, 6 and 7 have been set to zero where the corresponding value in column 4 is less than $|1\times10^{-9}|$. Values greater than 1.1 or less than -0.5 in column 4 (and are shown to be unphysical) have been set to zero.

APPENDIX K: SUMMARY OF EXPERIMENTAL DETAILS – HFE2-0830

A. Experiment Description

1.	**Main Reference**		[1]
2.	**Facility**	GELINA	[2]
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	
	Nominal neutron production intensity	3.4×10^{13} s^{-1}	
4.	**Moderator**		
	Primary neutron source position	Above and below uranium target	
	Moderator material	H_2O in two Be-cans around U-target	
	Moderator dimensions (internal)	2 × (14.6 cm × 21 cm × 3.9 cm)	
	Density (moderator material)	1 g/cm^2	
	Temperature (K)	Room temperature	
	Moderator-room decoupler	None	
5.	**Other experimental details**		
	Measurement type	Neutron capture	
	Method	Total energy detection	[3]
	Flight path length	28.82 m (moderator to sample face)	
	Flight path direction	0° (with respect to normal of the moderator face viewing the flight path)	
	Neutron beam diameter at sample position	75 mm	
	Overlap suppression filter	^{10}B	
	Other neutron beam filters	S	
6.	**Detector**		
	Type	Scintillator × 2	
	Material	C_6D_6	
	Surface diameter	100 mm	
	Thickness	75 mm	
	Dead time	2874 ns	
	Detector position relative to neutron beam	Outside the beam	
7.	**Flux Monitor**		
	Type	Frisch-gridded ionisation chamber	
	Material	^{10}B (evaporated on aluminium)	
	Surface diameter	84 mm	
	Areal density of ^{10}B layer	4.3×10^{-6} a/b	
	Dead time	3992 ns	
	Detector position relative to neutron beam	In the beam	
8.	**Sample**		
	Type (metal, powder, liquid, crystal)	Powder	
	Chemical composition	Hf: 33.3 at%, O: 66.7 at%	
	Hf isotope composition (at%)	^{174}Hf: <0.05 ^{176}Hf: 1.0 ^{177}Hf: 85.4 ^{178}Hf: 11.3 ^{179}Hf: 0.9 ^{180}Hf: 1.4	
	Temperature	22°C	
	Sample mass	4.7070 ± 0.0001 g	

	Geometrical shape Diameter Nominal thickness Areal density of Hf isotopes Containment description Additional comment	Disc 30.09 ± 0.0082 mm 3.223 ± 0.0498 mm $1.91\times10^{-3} \pm 1.04\times10^{-6}$ at/b Al can 31mm outer diam., 0.45mm windows, mass 6.2g. Suspended in carbon fibre frame. -	
9.	**Data Reduction Procedure** Dead time correction Back ground subtraction Normalisation Detector efficiency Self-shielding Time-of-flight binning	 Done (factor <1.01) Black resonance technique 0.63625 Corrected in REFIT No correction applied Zone length bin width 2048 2 ns 3072 4 ns 3072 8 ns 3072 16 ns 3072 32 ns 3072 64 ns 2048 512 ns	
10.	**Response function** Analytical function defined in REFIT, requiring additional parameters;	 Trapazoidal pulse (top / base = 0.7) with tail = $0.0167*\exp(0.273*t*E^{-0.563})$ Uses 12cm beam diameter at moderator	 [5]

B. Data Format

Column	Content	Unit	Comment
1	Neutron Energy	eV	Relativistic relation
2	t_l	ns	-
3	t_h	ns	-
4	Y_{exp}	-	Capture yield
5	Total Uncertainty	-	-
6	Uncorrelated uncertainty	-	Uncorrelated uncertainty due to counting statistics
7	AGS-vector (B_S)	-	Background model ($u(B_S)/B_S$ = 5%)
8	AGS-vector (B_ϕ)	-	Normalisation ($u(B_\phi)/B_\phi$ = 5%)

Comments from the authors:

– The AGS concept was used to derive the experimental capture yield;

$$Y_{exp} = N\, F_\phi\, Y_\phi\, [C_S - B_S] / [C_\phi - B_\phi]$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalisation ($u(N)$ = 2%) and background models ($u(B_S)/B_S$ and $u(B_\phi)/B_\phi$ = 5%).

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

– Values in columns 4, 5, 6 and 7 have been set to zero where the corresponding value in column 4 is less than $|1\times10^{-9}|$. Values greater than 1.1 or less than -0.5 in column 4 (and are shown to be unphysical) have been set to zero.

APPENDIX L: SUMMARY OF EXPERIMENTAL DETAILS – HFE3-0830

A. Experiment Description

1.	**Main Reference**		[1]
2.	**Facility**	GELINA	[2]
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	
	Nominal neutron production intensity	3.4×10^{13} s^{-1}	
4.	**Moderator**		
	Primary neutron source position	Above and below uranium target	
	Moderator material	H_2O in two Be-cans around U-target	
	Moderator dimensions (internal)	2 × (14.6 cm × 21 cm × 3.9 cm)	
	Density (moderator material)	1 g/cm^2	
	Temperature (K)	Room temperature	
	Moderator-room decoupler	None	
5.	**Other experimental details**		
	Measurement type	Neutron capture	
	Method	Total energy detection	[3]
	Flight path length	28.82 m (moderator to sample face)	
	Flight path direction	0° (with respect to normal of the moderator face viewing the flight path)	
	Neutron beam diameter at sample position	75 mm	
	Overlap suppression filter	^{10}B	
	Other neutron beam filters	S	
6.	**Detector**		
	Type	Scintillator × 2	
	Material	C_6D_6	
	Surface diameter	100 mm	
	Thickness	75 mm	
	Dead time	2874 ns	
	Detector position relative to neutron beam	Outside the beam	
7.	**Flux Monitor**		
	Type	Frisch-gridded ionisation chamber	
	Material	^{10}B (evaporated on aluminium)	
	Surface diameter	84 mm	
	Areal density of ^{10}B layer	4.3×10^{-6} a/b	
	Dead time	3992 ns	
	Detector position relative to neutron beam	In the beam	
8.	**Sample**		
	Type (metal, powder, liquid, crystal)	Powder	
	Chemical composition	Hf: 33.3 at%, O: 66.7 at%	
	Hf isotope composition (at%)	^{174}Hf: <0.05 ^{176}Hf: 0.8 ^{177}Hf: 1.9 ^{178}Hf: 92.4 ± 0.2 ^{179}Hf: 3.3 ^{180}Hf: 1.6	
	Temperature	22°C	
	Sample mass	4.4570 ± 0.0001 g	

	Geometrical shape Diameter Nominal thickness Areal density of Hf isotopes Containment description Additional comment	Disc 30.06 ± 0.0141 mm 2.502 ± 0.1125 mm $1.80\times10^{-3} \pm 1.69\times10^{-6}$ at/b Al can 31mm outer diam., 0.45mm windows, mass 6.2g. Suspended in carbon fibre frame. Trace bromine in carbon fibre frame.	
9.	**Data Reduction Procedure** Dead time correction Back ground subtraction Normalisation Detector efficiency Self-shielding Time-of-flight binning	 Done (factor <1.01) Black resonance technique 0.51545 Corrected in REFIT No correction applied Zone length bin width 2048 2 ns 3072 4 ns 3072 8 ns 3072 16 ns 3072 32 ns 3072 64 ns 2048 512 ns	
10.	**Response function** Analytical function defined in REFIT, requiring additional parameters;	 Trapazoidal pulse (top / base = 0.7) with tail = 0.0167*exp(0.273*t*E$^{-0.563}$) Uses 12cm beam diameter at moderator	 [5]

B. Data Format

Column	Content	Unit	Comment
1	Neutron Energy	eV	Relativistic relation
2	t_l	ns	-
3	t_h	ns	-
4	Y_{exp}	-	Capture yield
5	Total Uncertainty	-	-
6	Uncorrelated uncertainty	-	Uncorrelated uncertainty due to counting statistics
7	AGS-vector (B_S)	-	Background model ($u(B_S)/B_S = 5\%$)
8	AGS-vector (B_ϕ)	-	Normalisation ($u(B_\phi)/B_\phi = 5\%$)

Comments from the authors:

– The AGS concept was used to derive the experimental capture yield;

$$Y_{exp} = N\, F_\phi\, Y_\phi\, [C_S - B_S] / [C_\phi - B_\phi]$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalisation ($u(N) = 2\%$) and background models ($u(B_S)/B_S$ and $u(B_\phi)/B_\phi = 5\%$).

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

– Values in columns 4, 5, 6 and 7 have been set to zero where the corresponding value in column 4 is less than $|1\times10^{-9}|$. Values greater than 1.1 or less than -0.5 in column 4 (and are shown to be unphysical) have been set to zero.

APPENDIX M: SUMMARY OF EXPERIMENTAL DETAILS – HFE5-0830

A. Experiment Description

1.	**Main Reference**		[1]
2.	**Facility**	GELINA	[2]
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	
	Nominal neutron production intensity	3.4×10^{13} s^{-1}	
4.	**Moderator**		
	Primary neutron source position	Above and below uranium target	
	Moderator material	H_2O in two Be-cans around U-target	
	Moderator dimensions (internal)	2 × (14.6 cm × 21 cm × 3.9 cm)	
	Density (moderator material)	1 g/cm^2	
	Temperature (K)	Room temperature	
	Moderator-room decoupler	None	
5.	**Other experimental details**		
	Measurement type	Neutron capture	
	Method	Total energy detection	[3]
	Flight path length	28.82 m (moderator to sample face)	
	Flight path direction	0° (with respect to normal of the moderator face viewing the flight path)	
	Neutron beam diameter at sample position	75 mm	
	Overlap suppression filter	^{10}B	
	Other neutron beam filters	S	
6.	**Detector**		
	Type	Scintillator × 2	
	Material	C_6D_6	
	Surface diameter	100 mm	
	Thickness	75 mm	
	Dead time	2874 ns	
	Detector position relative to neutron beam	Outside the beam	
7.	**Flux Monitor**		
	Type	Frisch-gridded ionisation chamber	
	Material	^{10}B (evaporated on aluminium)	
	Surface diameter	84 mm	
	Areal density of ^{10}B layer	4.3×10^{-6} a/b	
	Dead time	3992 ns	
	Detector position relative to neutron beam	In the beam	
8.	**Sample**		
	Type (metal, powder, liquid, crystal)	Powder	
	Chemical composition	Hf: 33.3 at%, O: 66.7 at%	
	Hf isotope composition (at%)	^{174}Hf: <0.05 ^{176}Hf: 0.2 ^{177}Hf: 1.3 ^{178}Hf: 4.1 ^{179}Hf: 72.1 ± 0.4 ^{180}Hf: 22.3	
	Temperature	22°C	
	Sample mass	5.3175 ± 0.0001 g	

	Geometrical shape Diameter Nominal thickness Areal density of Hf isotopes Containment description Additional comment	Disc 30.06 ± 0.0238 mm 2.452 ± 0.0558 mm $2.14\times10^{-3} \pm 3.39\times10^{-6}$ at/b Al can 31mm outer diam., 0.45mm windows, mass 6.2g. Suspended in carbon fibre frame. -	
9.	**Data Reduction Procedure** Dead time correction Back ground subtraction Normalisation Detector efficiency Self-shielding Time-of-flight binning	 Done (factor <1.01) Black resonance technique 0.57526 Corrected in REFIT No correction applied Zone length bin width 2048 2 ns 3072 4 ns 3072 8 ns 3072 16 ns 3072 32 ns 3072 64 ns 2048 512 ns	
10.	**Response function** Analytical function defined in REFIT, requiring additional parameters;	 Trapazoidal pulse (top / base = 0.7) with tail = $0.0167*\exp(0.273*t*E^{-0.563})$ Uses 12cm beam diameter at moderator	[5]

B. Data Format

Column	Content	Unit	Comment
1	Neutron Energy	eV	Relativistic relation
2	t_l	ns	-
3	t_h	ns	-
4	Y_{exp}	-	Capture yield
5	Total Uncertainty	-	-
6	Uncorrelated uncertainty	-	Uncorrelated uncertainty due to counting statistics
7	AGS-vector (B_S)	-	Background model ($u(B_S)/B_S = 5\%$)
8	AGS-vector (B_ϕ)	-	Normalisation ($u(B_\phi)/B_\phi = 5\%$)

Comments from the authors:

– The AGS concept was used to derive the experimental capture yield;

$$Y_{exp} = N\, F_\phi\, Y_\phi\, [C_S - B_S] / [C_\phi - B_\phi]$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalisation ($u(N) = 2\%$) and background models ($u(B_S)/B_S$ and $u(B_\phi)/B_\phi = 5\%$).

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

– Values in columns 4, 5, 6 and 7 have been set to zero where the corresponding value in column 4 is less than $|1\times10^{-9}|$. Values greater than 1.1 or less than -0.5 in column 4 (and are shown to be unphysical) have been set to zero.

APPENDIX N: SUMMARY OF EXPERIMENTAL DETAILS – HFN1-0830

A. Experiment Description

1.	**Main Reference**		[1]
2.	**Facility**	GELINA	[2]
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	
	Nominal neutron production intensity	3.4×10^{13} s^{-1}	
4.	**Moderator**		
	Primary neutron source position	Above and below uranium target	
	Moderator material	H_2O in two Be-cans around U-target	
	Moderator dimensions (internal)	2 × (14.6 cm × 21 cm × 3.9 cm)	
	Density (moderator material)	1 g/cm^2	
	Temperature (K)	Room temperature	
	Moderator-room decoupler	None	
5.	**Other experimental details**		
	Measurement type	Neutron capture	
	Method	Total energy detection	[3]
	Flight path length	28.82 m (moderator to sample face)	
	Flight path direction	0° (with respect to normal of the moderator face viewing the flight path)	
	Neutron beam diameter at sample position	75 mm	
	Overlap suppression filter	^{10}B	
	Other neutron beam filters	S	
6.	**Detector**		
	Type	Scintillator × 2	
	Material	C_6D_6	
	Surface diameter	100 mm	
	Thickness	75 mm	
	Dead time	2874 ns	
	Detector position relative to neutron beam	Outside the beam	
7.	**Flux Monitor**		
	Type	Frisch-gridded ionisation chamber	
	Material	^{10}B (evaporated on aluminium)	
	Surface diameter	84 mm	
	Areal density of ^{10}B layer	4.3×10^{-6} a/b	
	Dead time	3992 ns	
	Detector position relative to neutron beam	In the beam	
8.	**Sample**		
	Type (metal, powder, liquid, crystal)	Metal	
	Chemical composition	Hf: 97.0 at%, Zr: 3.0 at%	[4]
	Hf isotope composition (at%)	^{174}Hf: 0.16 ± 0.01 ^{176}Hf: 5.26 ± 0.07 ^{177}Hf: 18.60 ± 0.09 ^{178}Hf: 27.28 ± 0.07 ^{179}Hf: 13.62 ± 0.02 ^{180}Hf: 35.08 ± 0.16	
	Temperature	22°C	

	Sample mass Geometrical shape Diameter Nominal thickness Areal density of Hf isotopes Containment description Additional comment	33.3600 ± 0.0001 g Disc 54.995 ± 0.040 mm 1.081 ± 0.0018 mm $4.6053\times10^{-3} \pm 6.75\times10^{-6}$ at/b None. Suspended in carbon fibre frame. -	
9.	**Data Reduction Procedure** Dead time correction Back ground subtraction Normalisation Detector efficiency Self-shielding Time-of-flight binning	 Done (factor <1.01) Black resonance technique 0.15217 Corrected in REFIT No correction applied Zone length bin width 2048 2 ns 3072 4 ns 3072 8 ns 3072 16 ns 3072 32 ns 3072 64 ns 2048 512 ns	
10.	**Response function** Analytical function defined in REFIT, requiring additional parameters;	 Trapazoidal pulse (top / base = 0.7) with tail = $0.0167*\exp(0.273*t*E^{-0.563})$ Uses 12cm beam diameter at moderator	 [5]

B. Data Format

Column	Content	Unit	Comment
1	Neutron Energy	eV	Relativistic relation
2	t_l	ns	-
3	t_h	ns	-
4	Y_{exp}	-	Capture yield
5	Total Uncertainty	-	-
6	Uncorrelated uncertainty	-	Uncorrelated uncertainty due to counting statistics
7	AGS-vector (B_S)	-	Background model ($u(B_S)/B_S = 5\%$)
8	AGS-vector (B_ϕ)	-	Normalisation ($u(B_\phi)/B_\phi = 5\%$)

Comments from the authors:

– The AGS concept was used to derive the experimental capture yield;

$$Y_{exp} = N\, F_\phi\, Y_\phi\, [C_S - B_S] / [C_\phi - B_\phi]$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalisation ($u(N) = 2\%$) and background models ($u(B_S)/B_S$ and $u(B_\phi)/B_\phi = 5\%$).

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

– Values in columns 4, 5, 6 and 7 have been set to zero where the corresponding value in column 4 is less than $|1\times10^{-9}|$. Values greater than 1.1 or less than -0.5 in column 4 (and are shown to be unphysical) have been set to zero.

APPENDIX O: SUMMARY OF EXPERIMENTAL DETAILS – HFE1-50HZ

A. Experiment Description

1.	**Main Reference**		[1]
2.	**Facility**	GELINA	[2]
3.	**Neutron production** Neutron production beam Nominal average beam energy Nominal average peak current Repetition rate (pulses per second Pulse width Primary neutron production target Nominal neutron production intensity	 Electron 100 MeV 70 µA 50 Hz 1 ns Mercury-cooled depleted uranium 3.4×10^{13} s^{-1}	
4.	**Moderator** Primary neutron source position Moderator material Moderator dimensions (internal) Density (moderator material) Temperature (K) Moderator-room decoupler	 Above and below uranium target H_2O in two Be-cans around U-target 2 × (14.6 cm × 21 cm × 3.9 cm) 1 g/cm^2 Room temperature None	
5.	**Other experimental details** Measurement type Method Flight path length Flight path direction Neutron beam diameter at sample position Overlap suppression filter Other neutron beam filters	 Neutron capture Total energy detection 28.82 m (moderator to sample face) 0° (with respect to normal of the moderator face viewing the flight path) 75 mm ^{nat}Cd Na	 [3]
6.	**Detector** Type Material Surface diameter Thickness Dead time Detector position relative to neutron beam	 Scintillator × 2 C_6D_6 100 mm 75 mm 2874 ns Outside the beam	
7.	**Flux Monitor** Type Material Surface diameter Areal density of ^{10}B layer Dead time Detector position relative to neutron beam	 Frisch-gridded ionisation chamber ^{10}B (evaporated on aluminium) 84 mm 4.3×10^{-6} a/b 3992 ns In the beam	
8.	**Sample** Type (metal, powder, liquid, crystal) Chemical composition Hf isotope composition (at%) Temperature Sample mass	 Powder Hf: 33.3 at%, O: 66.7 at% ^{174}Hf: <0.05 ^{176}Hf: 65.0 ^{177}Hf: 22.9 ^{178}Hf: 6.3 ^{179}Hf: 1.8 ^{180}Hf: 4.0 22°C 5.3424 ± 0.0001 g	

	Geometrical shape Diameter Nominal thickness Areal density of Hf isotopes Containment description Additional comment	Disc 30.13 ± 0.0387 mm 2.062 ± 0.0379 mm $2.17\times10^{-3} \pm 5.57\times10^{-6}$ at/b Al can 31mm outer diam., 0.45mm windows, mass 6.2g. Suspended in carbon fibre frame. Trace bromine in carbon fibre frame.	
9.	**Data Reduction Procedure** Dead time correction Back ground subtraction Normalisation Detector efficiency Self-shielding Time-of-flight binning	 Done (factor <1.01) Black resonance technique 0.98447 Corrected in REFIT No correction applied Zone length bin width 1024 4 ns 3072 8 ns 3072 16 ns 3072 32 ns 3072 64 ns 3072 128 ns 3072 256 ns 3072 512 ns	
10.	**Response function** Analytical function defined in REFIT, requiring additional parameters;	 Trapazoidal pulse (top / base = 0.7) with tail = $0.0167*\exp(0.273*t*E^{-0.563})$ Uses 12cm beam diameter at moderator	 [5]

B. Data Format

Column	Content	Unit	Comment
1	Neutron Energy	eV	Relativistic relation
2	t_l	ns	-
3	t_h	ns	-
4	Y_{exp}	-	Capture yield
5	Total Uncertainty	-	-
6	Uncorrelated uncertainty	-	Uncorrelated uncertainty due to counting statistics
7	AGS-vector (B_S)	-	Background model ($u(B_S)/B_S = 5\%$)
8	AGS-vector (B_ϕ)	-	Normalisation ($u(B_\phi)/B_\phi = 5\%$)

Comments from the authors:

– The AGS concept was used to derive the experimental capture yield;

$$Y_{exp} = N\, F_\phi\, Y_\phi\, [C_S - B_S] / [C_\phi - B_\phi]$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalisation ($u(N) = 2\%$) and background models ($u(B_S)/B_S$ and $u(B_\phi)/B_\phi = 5\%$).

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

– Values in columns 4, 5, 6 and 7 have been set to zero where the corresponding value in column 4 is less than $|1\times10^{-9}|$. Values greater than 1.1 or less than -0.5 in column 4 (and are shown to be unphysical) have been set to zero.

APPENDIX P: SUMMARY OF EXPERIMENTAL DETAILS – HFE5-50HZ

A. Experiment Description

1.	**Main Reference**		[1]
2.	**Facility**	GELINA	[2]
3.	**Neutron production**		
	Neutron production beam	Electron	
	Nominal average beam energy	100 MeV	
	Nominal average peak current	70 µA	
	Repetition rate (pulses per second	50 Hz	
	Pulse width	1 ns	
	Primary neutron production target	Mercury-cooled depleted uranium	
	Nominal neutron production intensity	3.4×10^{13} s^{-1}	
4.	**Moderator**		
	Primary neutron source position	Above and below uranium target	
	Moderator material	H_2O in two Be-cans around U-target	
	Moderator dimensions (internal)	2 × (14.6 cm × 21 cm × 3.9 cm)	
	Density (moderator material)	1 g/cm^2	
	Temperature (K)	Room temperature	
	Moderator-room decoupler	None	
5.	**Other experimental details**		
	Measurement type	Neutron capture	
	Method	Total energy detection	[3]
	Flight path length	28.82 m (moderator to sample face)	
	Flight path direction	0° (with respect to normal of the moderator face viewing the flight path)	
	Neutron beam diameter at sample position	75 mm	
	Overlap suppression filter	^{nat}Cd	
	Other neutron beam filters	Na, Co	
6.	**Detector**		
	Type	Scintillator × 2	
	Material	C_6D_6	
	Surface diameter	100 mm	
	Thickness	75 mm	
	Dead time	2874 ns	
	Detector position relative to neutron beam	Outside the beam	
7.	**Flux Monitor**		
	Type	Frisch-gridded ionisation chamber	
	Material	^{10}B (evaporated on aluminium)	
	Surface diameter	84 mm	
	Areal density of ^{10}B layer	4.3×10^{-6} a/b	
	Dead time	3992 ns	
	Detector position relative to neutron beam	In the beam	
8.	**Sample**		
	Type (metal, powder, liquid, crystal)	Powder	
	Chemical composition	Hf: 33.3 at%, O: 66.7 at%	
	Hf isotope composition (at%)	^{174}Hf: <0.05 ^{176}Hf: 0.2 ^{177}Hf: 1.3 ^{178}Hf: 4.1 ^{179}Hf: 72.1 ± 0.4 ^{180}Hf: 22.3	
	Temperature	22°C	
	Sample mass	5.3175 ± 0.0001 g	

	Geometrical shape Diameter Nominal thickness Areal density of Hf isotopes Containment description Additional comment	Disc 30.06 ± 0.0238 mm 2.452 ± 0.0558 mm $2.14\times10^{-3} \pm 3.39\times10^{-6}$ at/b Al can 31mm outer diam., 0.45mm windows, mass 6.2g. Suspended in carbon fibre frame. -	
9.	**Data Reduction Procedure** Dead time correction Back ground subtraction Normalisation Detector efficiency Self-shielding Time-of-flight binning	 Done (factor <1.01) Black resonance technique 0.5600 Corrected in REFIT No correction applied Zone length bin width 1024 4 ns 3072 8 ns 3072 16 ns 3072 32 ns 3072 64 ns 3072 128 ns 3072 256 ns 3072 512 ns	
10.	**Response function** Analytical function defined in REFIT, requiring additional parameters;	 Trapazoidal pulse (top / base = 0.7) with tail = $0.0167*\exp(0.273*t*E^{-0.563})$ Uses 12cm beam diameter at moderator	[5]

B. Data Format

Column	Content	Unit	Comment
1	Neutron Energy	eV	Relativistic relation
2	t_l	ns	-
3	t_h	ns	-
4	Y_{exp}	-	Capture yield
5	Total Uncertainty	-	-
6	Uncorrelated uncertainty	-	Uncorrelated uncertainty due to counting statistics
7	AGS-vector (B_S)	-	Background model ($u(B_S)/B_S = 5\%$)
8	AGS-vector (B_ϕ)	-	Normalisation ($u(B_\phi)/B_\phi = 5\%$)

Comments from the authors:

– The AGS concept was used to derive the experimental capture yield;

$$Y_{exp} = N\, F_\phi\, Y_\phi\, [C_S - B_S] / [C_\phi - B_\phi]$$

and to propagate the uncorrelated uncertainties due to counting statistics and the uncertainty due to the normalisation ($u(N) = 2\%$) and background models ($u(B_S)/B_S$ and $u(B_\phi)/B_\phi = 5\%$).

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

– Values in columns 4, 5, 6 and 7 have been set to zero where the corresponding value in column 4 is less than $|1\times10^{-9}|$. Values greater than 1.1 or less than -0.5 in column 4 (and are shown to be unphysical) have been set to zero.

Appendix References

[1] T.C. Ware, A. Borella, C.J Dean, N. Janeva, S. Kopecky, A. Moens, M.C. Moxon and P. Schillebeeckx, "Results of time-of-flight neutron capture measurements of ^{176,177,178,179}Hf-enriched and ^{nat}Hf samples at 10 m, 30 m and 60 m stations of GELINA", INDC(EUR)-032, (2014). [This paper.]

[2] W. Mondelaers, P. Schillebeeckx, "GELINA, a neutron time-of-flight facility for high-resolution neutron data measurements", Notiziario Neutroni e Luce di Sincrotrone 11 no.2, 19 (2006).

[3] A. Borella, G. Aerts, F. Gunsing, M. Moxon, P. Schillebeeckx, R. Wynants, "The use of C_6D_6 detectors for neutron induced capture cross-section measurements in the resonance region", Nuclear Inst. and Methods in Physics Research, A, 577 (2007) 626-640

[4] Goodfellow Product Catalogue: www.goodfellow.com

[5] M.C. Moxon, T.C. Ware, C.J. Dean, "REFIT-2009: A Least-Square Fitting Program for Resonance Analysis of Neutron Transmission, Capture, Fission and Scattering Data; Users' Guide for REFIT-2009-10", UKNSF(2010)P243

Nuclear Data Section
International Atomic Energy Agency
P.O. Box 100
A-1400 Vienna
Austria

e-mail: nds.contact-point@iaea.org
fax: (43-1) 26007
telephone: (43-1) 2600 21725
Web: http://www-nds.iaea.org/