



Partial gamma-ray production cross-sections for (n, n'γ)-reactions induced by fission neutrons

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Abstract

In order to perform chemical analysis with the FaNGaS instrument operated at the MLZ facility, the partial gamma-ray production cross-sections for (n, n'γ) reactions with fission neutrons were evaluated from the relative intensities of the gamma lines listed in the “Atlas of Gamma-rays from Inelastic Scattering of Reactor Fast Neutrons” published in 1978 by Demidov et al. The 846-keV gamma-ray of the ⁵⁶Fe(n, n'γ)⁵⁶Fe reaction was used as reference with the fission-spectrum averaged production cross section of 586 ± 41 mb measured with FaNGaS. Additionally, the detection limits were estimated for a measurement time of 12 h.

Keywords Inelastic scattering · Fission neutrons · Partial cross section · Gamma-ray

Introduction

The chemical composition of large or thick objects can be investigated by means of the Prompt Gamma Analysis based on Inelastic Neutron Scattering (PGAINS) with the FaNGaS (Fast Neutron induced Gamma-ray Spectrometry) instrument by using the fission neutrons delivered from the SR10 (Strahlrohr 10) beam tube at the research neutron source Heinz-Maier-Leibnitz (FRM II) [1–3]. However, reliable and accurate quantitative analysis requires knowledge of the yield of the gamma-rays produced by inelastic scattering or absorption of fission neutrons i.e. from (n, n'γ) or (n, pγ) and (n, αγ) reactions. So far, the energies, relative intensities and isotopic partial production cross-sections of gamma-rays induced by interaction of fission neutrons (average energy of 2.2 MeV) were only measured for 22 elements (C, O, Na, Al, Si, S, Cl, K, Ca, Ti, Fe, Ni, Cu, Zr, In, La, Ce, Pr, Nd, Sm, Tb and Dy) with the FaNGaS instrument at an angle of 90° between the detector and the neutron beam [2–12]. The relative intensities of the gamma rays were found to agree reasonably well with the values given in the “Atlas of

Gamma-rays from Inelastic Scattering of Reactor Fast Neutrons” obtained from measurements also carried out at 90° but with reactor fast neutrons (average energy of 0.6 MeV) [13].

In this work, to extend our cross-section database to the elements that have not yet been investigated with the instrument FaNGaS, the partial production cross-sections of the gamma-rays induced by fission neutrons were evaluated from the intensities of the gamma rays relative to the 846-keV gamma ray of ⁵⁶Fe given in [13] corrected by a factor related to the difference in the neutron energy spectra delivered at the sample position by the two facilities. Additionally, the detection limits for the elements are given.

Method

The isotopic partial production cross-section $\sigma_{E\gamma}$ (cm²) of a prompt gamma-ray of energy $E\gamma$ induced by a (n, n'γ) reaction can be connected to the measured net count rate $R_{E\gamma}$ (s⁻¹) of the corresponding gamma ray as follows:

$$R_{E\gamma} = \frac{m}{M} \cdot N_A \cdot h \cdot \sigma_{E\gamma} \cdot \epsilon_{E\gamma} \Phi \quad (1)$$

where m (g) is the mass of the considered element, M (g mol⁻¹) the molar mass, N_A the Avogadro number (mol⁻¹), h the isotopic abundance, $\epsilon_{E\gamma}$ the full-energy-peak efficiency including gamma-ray self-absorption and Φ (cm⁻² s⁻¹) the

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integral fast neutron flux within the sample. Note that, the $\sigma_{E\gamma}$ -values measured at 90° to the incident beam direction in our previous works [2–12] and considered in this work correspond to total production cross sections i.e. differential emission cross sections multiply by 4π ($\sigma_{E\gamma} = \frac{d\sigma_{E\gamma}}{d\Omega}(90^\circ) \times 4\pi$).

According to relation (1), the intensity $I_{E\gamma}$ of a gamma ray emitted by the isotope of a given element can be expressed relative to a gamma ray emitted by the isotope of a reference element (ref) and considering the same number of nuclei for both elements by:

$$I_{E\gamma} = \frac{(R_{E\gamma}/\varepsilon_{E\gamma})}{(R_{E\gamma,ref}/\varepsilon_{E\gamma,ref})} = \frac{h \cdot \sigma_{E\gamma}}{h_{ref} \cdot \sigma_{E\gamma,ref}} \quad (2)$$

where $R_{E\gamma,ref}$, $\varepsilon_{E\gamma,ref}$ and $\sigma_{E\gamma,ref}$ are the count rate, the full-energy-peak efficiency and the production cross section for the gamma ray of the isotope of the reference element and h_{ref} the abundance of the isotope. In the following the 846-keV gamma ray from the $^{56}\text{Fe}(n,n'\gamma)^{56}\text{Fe}$ reaction was used as the reference gamma ray (iron as the reference element) like in Demidov's Atlas [13]. The relative intensities of the main gamma rays of 22 elements (C, O, Na, Al, Si, S, Cl, K, Ca, Ti, Fe, Ni, Cu, Zr, In, La, Ce, Pr, Nd, Sm, Tb and Dy) measured with the FaNGaS instrument from irradiation with fission neutrons [2–12] are compared with the intensities determined from irradiation with reactor fast neutrons at IRT-M Baghdad reactor [13] in Table 1. Here we can assume that the observed discrepancies between the two sets of data are due to the excitation of the nuclei with different neutron energy spectra.

The neutron energy spectra of the two versions of the FaNGaS instrument [2, 3] used for the irradiation of the elements mentioned above are shown for the relevant energy range of the $(n,n'\gamma)$ reactions (1 keV–20 MeV) in Fig. 1. The values of the neutron flux are given in columns 3 and 4 of Table 2. The energy dependence of the neutron flux $\Phi(E_n)$ of the IRT-M Baghdad reactor was reevaluated and expressed in [15] by:

$$\Phi(E_n) = \Phi_1(E_n) + \frac{1 + \tanh[K \cdot (E_n - 1.5)]}{2} \cdot (\Phi_2(E_n) - \Phi_1(E_n)) \quad (3)$$

with E_n is the neutron energy in MeV and $K=1.0$. $\Phi_1(E_n)$ is the neutron flux for the low-energy region ($1 \text{ keV} \leq E_n < 1.5 \text{ MeV}$) of the spectrum and was represented by a Maxwellian distribution:

$$\Phi_1(E_n) = 2A_1 \sqrt{\frac{E_n}{\pi(kT)^3}} \cdot e^{-\frac{E_n}{kT}} \quad (4)$$

with $A_1=84,500 \text{ (cm}^{-2} \text{ s}^{-1})$ and $kT=0.39 \text{ MeV}$. For the high-energy region ($E_n \geq 1.5 \text{ MeV}$) of the spectrum the

Table 1 Intensities $I_{E\gamma}$ of the main gamma rays induced by $(n,n'\gamma)$ reactions for the investigated elements relative to the 846-keV gamma ray of ^{56}Fe and measured at an angle of 90° relative to the neutron beam axis

Isotope	h (%)	$E\gamma$ (keV)	From FaNGaS measurement [2–12] $I_{E\gamma}$ (%)	From IRT-M measurement [13] $I_{E\gamma}$ (%)
^{12}C	98.93	4439	2.65 ± 0.29	1.27 ± 0.21
^{18}O	0.205	1982	0.077 ± 0.008	0.11 ± 0.04
^{23}Na	100	440	94 ± 8	139 ± 28
^{27}Al	100	1014	25 ± 2	28 ± 3
^{28}Si	92.2297	1779	32 ± 3	27.0 ± 2.5
^{32}S	94.93	2230	13.9 ± 1.2	15.1 ± 2.0
^{35}Cl	75.78	1219	8.2 ± 0.9	5.2 ± 0.5
^{39}K	93.2581	2814	4.7 ± 0.4	2.6 ± 0.4
^{40}Ca	96.941	3904	1.95 ± 0.21	2.2 ± 0.4
^{48}Ti	73.72	983	86 ± 7	77 ± 8
^{56}Fe	91.754	846	100	100
^{58}Ni	68.0769	1454	43 ± 4	40 ± 5
^{63}Cu	69.17	962	53 ± 6	54 ± 6
^{92}Zr	17.15	934	34 ± 3	25 ± 3
^{115}In	95.71	934	39 ± 3	46 ± 5
^{139}La	99.910	1420	15.2 ± 1.3	17.8 ± 2.0
^{140}Ce	88.450	1596	109 ± 12	96 ± 11
^{141}Pr	100	1126	20 ± 2	33 ± 6
^{144}Nd	23.8	696	64 ± 5	32 ± 5
^{148}Sm	11.24	550	32 ± 6	52 ± 7
^{159}Tb	100	331	53 ± 6	76 ± 12
^{164}Dy	28.18	755	12.6 ± 2.2	14.5 ± 1.9

h is the isotopic abundance, $E\gamma$ the energy of the gamma ray [14]. The elements Al, Ti, Fe, Ni, Cu, Zr and In were investigated with the second version of the FaNGaS instrument (FaNGaS II [2]) and the elements C, O, Na, Si, S, Cl, K, Ca, La, Ce, Pr, Nd, Sm, Tb and Dy with the current version (FaNGaS III [3])

neutron flux $\Phi_2(E_n)$ was represented by a simple exponential function:

$$\Phi_2(E_n) = A_2 \cdot e^{-\beta \frac{E_n}{kT}} \quad (5)$$

with $A_2=36,600 \text{ (cm}^{-2} \text{ s}^{-1})$ and $\beta=0.76$. The neutron energy spectrum of the IRT-M Baghdad reactor was calculated with the same energy bins as the FaNGaS spectrum and is shown in Fig. 1. The flux values are given in column 5 of Table 2.

Based on relation (2), the isotopic partial production cross section, $\sigma_{E\gamma}$, for a gamma ray produced by irradiation of a sample with fission neutrons at the FaNGaS instrument was evaluated from the relative intensity, $I_{E\gamma,IRT}$, of the same line determined from irradiation with reactor fast neutrons at IRT-M Baghdad reactor [13] by:

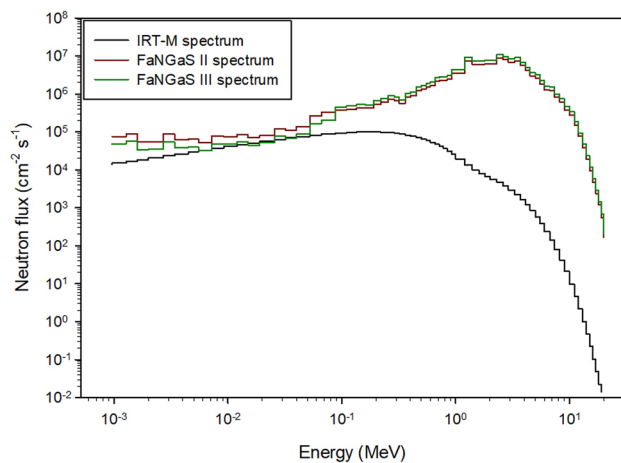


Fig. 1 Comparison of the neutron spectra in the energy range from 1 keV to 20 MeV at the sample position for measurements with the FaNGaS instrument at FRM II [2, 3] and for measurements at the IRT-M Baghdad reactor [15]

$$\sigma_{E\gamma} = \frac{h_{ref}}{h} \cdot \sigma_{E\gamma,ref} \cdot I_{E\gamma,IRT} \cdot S \quad (6)$$

where $\sigma_{E\gamma,ref} = 586 \pm 41$ mb [2] for the 846-keV reference gamma ray of ^{56}Fe measured with FaNGaS, and S is a factor that accounts for the difference in the neutron energy spectra at the sample position of the two irradiation facilities.

The relative intensities of the gamma rays (relative to the main gamma-ray of the considered element) measured with FaNGaS [2–12] were found to agree well with the relative intensities measured at the IRT-M Baghdad reactor. Considering the gamma rays only with relative intensities higher than 1% the average value of the intensity ratios was 1.00 ± 0.29 (gamma rays of Sm and Dy were not included since most of them were strongly affected by interferences of capture gamma rays making the comparison between the two sets of data complicated [12]). This value suggests in both cases nearly the same anisotropy factor for a considered gamma ray. Thus, correction for the anisotropy of the gamma-ray emission due to the different neutron energy spectra was neglected. The fact that both measurements are performed at the same angle of 90° between detector and neutron beam direction facilitates this statement.

The factor S was calculated as:

$$S = \left(\frac{\sigma_{ref,FaNGaS}}{\sigma_{ref,IRT}} \right) / \left(\frac{\sigma_{FaNGaS}}{\sigma_{IRT}} \right) \quad (7)$$

where $\sigma_{ref,FaNGaS}$ and $\sigma_{ref,IRT}$ are the neutron-spectrum averaged isotopic (effective) cross-sections of the $^{56}\text{Fe}(n,n'\gamma)^{56}\text{Fe}$ reaction and σ_{FaNGaS} and σ_{IRT} the effective cross section of the considered $(n,n'\gamma)$ reaction for the FaNGaS and IRT-M neutron spectrum, respectively.

Each effective cross-section was determined as follows:

$$\sigma = \frac{\sum_{i=m}^n \sigma(E_i) \cdot \Phi(E_i)}{\sum_{i=m}^n \Phi(E_i)} \quad (8)$$

where $\Phi(E_i)$ denotes the neutron flux in the neutron energy bin i and $\sigma(E_i)$ the neutron-bin-averaged cross-section. The value $i=m$ is the first neutron energy bin corresponding to the energy threshold of the $(n, n'\gamma)$ reaction and $i=n$ is the last neutron energy bin corresponding to a mean neutron energy of 19.5 MeV. The $\sigma(E_i)$ -values were produced from the ENDF/B-VIII.0 [16] and JEFF-3.3 [17] nuclear data library using the RECONR, BROADR and GROUPT modules of the NJOY Nuclear Data Processing System (Version 2016) [18]. The ENDF/B-VIII.0 and JEFF-3.3 databases provide uncertainties only for some elements. For the binning of the uncertainties of the cross-sections, a specific Python script [19, 20] was developed. The data for this was retrieved from the JANIS database (Java-based Nuclear Information System) [21]. Considering the uncertainties of the reaction cross-sections upper and lower values of the effective cross sections were calculated by mean of Eq. (8) from which average effective cross sections with standard deviations were derived. In the case when uncertainties of the cross-section data are not available, no uncertainty was attached to the effective cross section.

For the investigated $(n, n'\gamma)$ reactions of the isotopes listed in Table 1, the effective reaction cross-sections σ determined using Eq. (8) from the ENDF/B-VIII.0 and JEFF-3.3 databases and the corresponding factors S obtained by means of Eq. (7) are given in Tables 3 and 4. For both cases of the neutron energy spectra, the two databases produce comparable effective reaction cross-sections, except for ^{18}O , ^{32}S and ^{39}K where the values obtained from JEFF-3.3 are around 2 times higher than these from ENDF/B-VIII.0. However, the two databases produce similar S -values. The resulting isotopic partial cross sections $\sigma_{E\gamma}$ for production of the gamma rays of interest calculated with Eq. (6) are compared with the measured values in Tables 3 and 4. The uncertainties on the $\sigma_{E\gamma}$ -values are obtained by propagating the uncertainties of the reference production cross section $\sigma_{E\gamma,ref}$, the relative intensity $I_{E\gamma,IRT}$ and the correction factor S . The $\sigma_{E\gamma}$ -values calculated from each cross-section database are almost comparable with a mean ratio of $\sigma_{E\gamma}(\text{ENDF/B-VIII.0})/\sigma_{E\gamma}(\text{JEFF-3.3}) = 0.96 \pm 0.04$. The relationship between calculated $\sigma_{E\gamma,cal}$ and measured $\sigma_{E\gamma,meas}$ values is shown in Fig. 2 and can be expressed by:

$$\sigma_{E\gamma,cal} = a \cdot (\sigma_{E\gamma,meas})^b \quad (9)$$

with $a = 1.05 \pm 0.47$ and $b = 0.97 \pm 0.08$ for the values calculated with the ENDF/B-VIII.0 database and, $a = 1.11 \pm 0.48$ and $b = 0.96 \pm 0.08$ for the ones obtained from the JEFF-3.3

Table 2 Neutron flux Φ (E_i) at the sample position for measurements with the FaNGaS instrument at FRM II and measurements at the IRT-M Baghdad reactor

Energy bin (MeV)	E_i (MeV)	FaNGaS II [2] $\Phi(E_i)$ ($\text{cm}^{-2} \text{s}^{-1}$)	FaNGaS III [3] $\Phi(E_i)$ ($\text{cm}^{-2} \text{s}^{-1}$)	IRT [13, 14] $\Phi(E_i)$ ($\text{cm}^{-2} \text{s}^{-1}$)
9.60 10^{-4} –1.28 10^{-3}	1.12 10^{-3}	$(5.58 \pm 0.86) \times 10^4$	$(8.88 \pm 1.39) \times 10^4$	$(1.41 \pm 0.14) \times 10^4$
1.28 10^{-3} –1.60 10^{-3}	1.44 10^{-3}	$(3.40 \pm 0.54) \times 10^4$	$(5.51 \pm 0.89) \times 10^4$	$(1.58 \pm 0.16) \times 10^4$
1.60 10^{-3} –2.00 10^{-3}	1.80 10^{-3}	$(3.48 \pm 0.57) \times 10^4$	$(5.53 \pm 0.90) \times 10^4$	$(1.75 \pm 0.18) \times 10^4$
2.00 10^{-3} –2.70 10^{-3}	2.35 10^{-3}	$(5.46 \pm 0.89) \times 10^4$	$(8.69 \pm 1.43) \times 10^4$	$(1.97 \pm 0.20) \times 10^4$
2.70 10^{-3} –3.40 10^{-3}	3.05 10^{-3}	$(3.89 \pm 0.63) \times 10^4$	$(6.18 \pm 1.01) \times 10^4$	$(2.21 \pm 0.22) \times 10^4$
3.40 10^{-3} –4.50 10^{-3}	3.95 10^{-3}	$(4.01 \pm 0.64) \times 10^4$	$(6.37 \pm 1.04) \times 10^4$	$(2.50 \pm 0.25) \times 10^4$
4.50 10^{-3} –5.50 10^{-3}	5.00 10^{-3}	$(3.24 \pm 0.51) \times 10^4$	$(5.15 \pm 0.82) \times 10^4$	$(2.77 \pm 0.28) \times 10^4$
5.50 10^{-3} –7.20 10^{-3}	6.35 10^{-3}	$(4.84 \pm 0.76) \times 10^4$	$(7.70 \pm 1.22) \times 10^4$	$(3.09 \pm 0.31) \times 10^4$
7.20 10^{-3} –9.20 10^{-3}	8.20 10^{-3}	$(4.68 \pm 0.72) \times 10^4$	$(7.44 \pm 1.16) \times 10^4$	$(3.47 \pm 0.35) \times 10^4$
9.20 10^{-3} –0.012	0.0106	$(5.42 \pm 0.83) \times 10^4$	$(8.62 \pm 1.33) \times 10^4$	$(3.90 \pm 0.39) \times 10^4$
0.012–0.015	0.0135	$(4.42 \pm 0.67) \times 10^4$	$(7.03 \pm 1.08) \times 10^4$	$(4.35 \pm 0.44) \times 10^4$
0.015–0.019	0.017	$(5.14 \pm 0.78) \times 10^4$	$(8.18 \pm 1.26) \times 10^4$	$(4.81 \pm 0.48) \times 10^4$
0.019–0.0255	0.0223	$(7.71 \pm 1.17) \times 10^4$	$(1.23 \pm 0.19) \times 10^5$	$(5.40 \pm 0.54) \times 10^4$
0.0255–0.032	0.0288	$(6.86 \pm 1.05) \times 10^4$	$(1.09 \pm 0.17) \times 10^5$	$(6.02 \pm 0.60) \times 10^4$
0.032–0.04	0.036	$(8.77 \pm 1.33) \times 10^4$	$(1.39 \pm 0.21) \times 10^5$	$(6.60 \pm 0.66) \times 10^4$
0.04–0.0525	0.0463	$(1.63 \pm 0.25) \times 10^5$	$(2.59 \pm 0.40) \times 10^5$	$(7.25 \pm 0.23) \times 10^4$
0.0525–0.066	0.0593	$(2.04 \pm 0.31) \times 10^5$	$(3.24 \pm 0.50) \times 10^5$	$(7.92 \pm 0.79) \times 10^4$
0.066–0.088	0.077	$(4.52 \pm 0.69) \times 10^5$	$(3.66 \pm 0.56) \times 10^5$	$(8.58 \pm 0.86) \times 10^4$
0.088–0.11	0.099	$(4.80 \pm 0.73) \times 10^5$	$(3.89 \pm 0.60) \times 10^5$	$(9.18 \pm 0.92) \times 10^4$
0.11–0.135	0.1225	$(5.34 \pm 0.81) \times 10^5$	$(4.33 \pm 0.67) \times 10^5$	$(9.59 \pm 0.96) \times 10^4$
0.135–0.16	0.1475	$(5.15 \pm 0.78) \times 10^5$	$(4.18 \pm 0.64) \times 10^5$	$(9.84 \pm 0.98) \times 10^4$
0.16–0.19	0.175	$(6.69 \pm 1.02) \times 10^5$	$(5.42 \pm 0.83) \times 10^5$	$(9.96 \pm 1.00) \times 10^4$
0.19–0.22	0.205	$(7.57 \pm 1.15) \times 10^5$	$(6.13 \pm 0.94) \times 10^5$	$(9.95 \pm 1.00) \times 10^4$
0.22–0.255	0.2375	$(8.84 \pm 1.34) \times 10^5$	$(7.16 \pm 1.10) \times 10^5$	$(9.82 \pm 0.98) \times 10^4$
0.255–0.29	0.2725	$(8.11 \pm 1.23) \times 10^5$	$(6.57 \pm 1.00) \times 10^5$	$(9.58 \pm 0.96) \times 10^4$
0.29–0.32	0.305	$(6.90 \pm 1.04) \times 10^5$	$(5.59 \pm 0.85) \times 10^5$	$(9.30 \pm 0.93) \times 10^4$
0.32–0.36	0.34	$(1.02 \pm 0.15) \times 10^6$	$(8.22 \pm 1.25) \times 10^5$	$(8.94 \pm 0.85) \times 10^4$
0.36–0.4	0.38	$(1.12 \pm 0.17) \times 10^6$	$(9.05 \pm 1.38) \times 10^5$	$(8.49 \pm 0.85) \times 10^4$
0.4–0.45	0.425	$(1.50 \pm 0.22) \times 10^6$	$(1.21 \pm 0.18) \times 10^6$	$(7.96 \pm 0.80) \times 10^4$
0.45–0.5	0.475	$(1.65 \pm 0.24) \times 10^6$	$(1.34 \pm 0.20) \times 10^6$	$(7.36 \pm 0.74) \times 10^4$
0.5–0.55	0.525	$(1.88 \pm 0.27) \times 10^6$	$(1.52 \pm 0.22) \times 10^6$	$(6.77 \pm 0.68) \times 10^4$
0.55–0.6	0.575	$(2.08 \pm 0.30) \times 10^6$	$(1.68 \pm 0.24) \times 10^6$	$(6.20 \pm 0.62) \times 10^4$
0.6–0.66	0.63	$(2.66 \pm 0.37) \times 10^6$	$(2.15 \pm 0.31) \times 10^6$	$(5.60 \pm 0.56) \times 10^4$
0.66–0.72	0.69	$(2.76 \pm 0.38) \times 10^6$	$(2.24 \pm 0.31) \times 10^6$	$(4.99 \pm 0.50) \times 10^4$
0.72–0.78	0.75	$(2.84 \pm 0.37) \times 10^6$	$(2.30 \pm 0.31) \times 10^6$	$(4.44 \pm 0.44) \times 10^4$
0.78–0.84	0.81	$(3.02 \pm 0.38) \times 10^6$	$(2.45 \pm 0.31) \times 10^6$	$(3.93 \pm 0.39) \times 10^4$
0.84–0.92	0.88	$(4.37 \pm 0.51) \times 10^6$	$(3.54 \pm 0.43) \times 10^6$	$(3.41 \pm 0.34) \times 10^4$
0.92–1	0.96	$(4.36 \pm 0.48) \times 10^6$	$(3.53 \pm 0.39) \times 10^6$	$(2.90 \pm 0.29) \times 10^4$
1–1.2	1.1	$(9.06 \pm 0.90) \times 10^6$	$(7.34 \pm 0.76) \times 10^6$	$(2.23 \pm 0.22) \times 10^4$
1.2–1.4	1.3	$(7.44 \pm 0.67) \times 10^6$	$(6.03 \pm 0.56) \times 10^6$	$(1.53 \pm 0.15) \times 10^4$
1.4–1.6	1.5	$(7.46 \pm 0.59) \times 10^6$	$(6.04 \pm 0.50) \times 10^6$	$(1.12 \pm 0.11) \times 10^4$
1.6–1.8	1.7	$(7.74 \pm 0.53) \times 10^6$	$(6.27 \pm 0.45) \times 10^6$	$(8.75 \pm 0.88) \times 10^3$
1.8–2	1.9	$(7.69 \pm 0.45) \times 10^6$	$(6.23 \pm 0.39) \times 10^6$	$(7.30 \pm 0.73) \times 10^3$
2–2.3	2.15	$(1.09 \pm 0.05) \times 10^7$	$(8.83 \pm 0.49) \times 10^6$	$(6.16 \pm 0.62) \times 10^3$
2.3–2.6	2.45	$(9.79 \pm 0.41) \times 10^6$	$(7.93 \pm 0.38) \times 10^6$	$(5.11 \pm 0.51) \times 10^3$
2.6–2.9	2.75	$(8.42 \pm 0.30) \times 10^6$	$(6.82 \pm 0.30) \times 10^6$	$(4.24 \pm 0.42) \times 10^3$
2.9–3.3	3.1	$(9.07 \pm 0.29) \times 10^6$	$(7.35 \pm 0.29) \times 10^6$	$(3.37 \pm 0.34) \times 10^3$
3.3–3.7	3.5	$(6.89 \pm 0.20) \times 10^6$	$(5.58 \pm 0.21) \times 10^6$	$(2.54 \pm 0.25) \times 10^3$
3.7–4.1	3.9	$(5.08 \pm 0.14) \times 10^6$	$(4.11 \pm 0.15) \times 10^6$	$(1.89 \pm 0.19) \times 10^3$
4.1–4.5	4.3	$(3.66 \pm 0.10) \times 10^6$	$(2.97 \pm 0.11) \times 10^6$	$(1.40 \pm 0.14) \times 10^3$

Table 2 (continued)

Energy bin (MeV)	E_i (MeV)	FaNGaS II [2] $\Phi(E_i)$ ($\text{cm}^{-2} \text{s}^{-1}$)	FaNGaS III [3] $\Phi(E_i)$ ($\text{cm}^{-2} \text{s}^{-1}$)	IRT [13, 14] $\Phi(E_i)$ ($\text{cm}^{-2} \text{s}^{-1}$)
4.5–5	4.75	$(3.21 \pm 0.09) \times 10^6$	$(2.60 \pm 0.09) \times 10^6$	$(1.01 \pm 0.10) \times 10^3$
5–5.5	5.25	$(2.20 \pm 0.06) \times 10^6$	$(1.79 \pm 0.06) \times 10^6$	$(6.89 \pm 0.69) \times 10^2$
5.5–6	5.75	$(1.55 \pm 0.04) \times 10^6$	$(1.26 \pm 0.04) \times 10^6$	$(4.71 \pm 0.47) \times 10^2$
6–6.7	6.35	$(1.51 \pm 0.04) \times 10^6$	$(1.22 \pm 0.04) \times 10^6$	$(3.04 \pm 0.30) \times 10^2$
6.7–7.4	7.05	$(1.00 \pm 0.02) \times 10^6$	$(8.10 \pm 0.26) \times 10^5$	$(1.79 \pm 0.18) \times 10^2$
7.4–8.2	7.8	$(7.45 \pm 0.13) \times 10^5$	$(6.03 \pm 0.18) \times 10^5$	$(1.02 \pm 0.10) \times 10^2$
8.2–9	8.6	$(4.66 \pm 0.08) \times 10^5$	$(3.78 \pm 0.11) \times 10^5$	$(5.56 \pm 0.56) \times 10^1$
9–10	9.5	$(3.43 \pm 0.07) \times 10^5$	$(2.78 \pm 0.09) \times 10^5$	$(2.87 \pm 0.28) \times 10^1$
10–11	10.5	$(1.83 \pm 0.05) \times 10^5$	$(1.48 \pm 0.05) \times 10^5$	$(1.34 \pm 0.13) \times 10^1$
11–12	11.5	$(9.41 \pm 0.32) \times 10^4$	$(7.63 \pm 0.32) \times 10^4$	(6.29 ± 0.63)
12–13	12.5	$(4.76 \pm 0.20) \times 10^4$	$(3.86 \pm 0.18) \times 10^4$	(2.94 ± 0.29)
13–14	13.5	$(2.38 \pm 0.12) \times 10^4$	$(1.92 \pm 0.11) \times 10^4$	(1.37 ± 0.14)
14–15	14.5	$(1.18 \pm 0.07) \times 10^4$	$(9.54 \pm 0.61) \times 10^3$	$(6.43 \pm 0.64) \times 10^{-1}$
15–16	15.5	$(5.84 \pm 0.40) \times 10^3$	$(4.73 \pm 0.34) \times 10^3$	$(3.01 \pm 0.30) \times 10^{-1}$
16–17	16.5	$(2.91 \pm 0.23) \times 10^3$	$(2.36 \pm 0.19) \times 10^3$	$(1.41 \pm 0.14) \times 10^{-1}$
17–18	17.5	$(1.46 \pm 0.13) \times 10^3$	$(1.18 \pm 0.11) \times 10^3$	$(6.58 \pm 0.66) \times 10^{-2}$
18–19	18.5	$(6.91 \pm 0.68) \times 10^2$	$(5.59 \pm 0.57) \times 10^2$	$(3.08 \pm 0.31) \times 10^{-2}$
19–20	19.5	$(2.05 \pm 0.22) \times 10^2$	$(1.66 \pm 0.18) \times 10^2$	$(1.44 \pm 0.14) \times 10^{-2}$

E_i is the mean neutron energy of the bin. An uncertainty of 10% was attached to the flux values of the IRT-M spectrum

database. The average values of the ratios $\sigma_{E\gamma,cal}/\sigma_{E\gamma,meas}$ are 0.97 ± 0.42 and 1.11 ± 0.46 , respectively, indicating a reasonable agreement between calculated and measured values. Rejection of ^{18}O , ^{32}S , ^{40}Ca , ^{115}In and ^{144}Nd data points (subject to large discrepancies), leads with average ratios of 0.90 ± 0.23 and 0.93 ± 0.23 to a good agreement with a better precision (25% against 40%). From this precision we derive a conservative uncertainty of 25% for the further calculated isotopic partial cross-sections. The significant disagreements observed for ^{18}O , ^{32}S , ^{40}Ca , ^{144}Nd can be attributed to the inaccuracy of the cross-section values in the databases and scarce experimental data that can be used for comparison. In the case of ^{115}In the cross sections agree reasonably with the experimental data at neutron energies lower than 1 MeV while above 1 MeV they are by a factor 5 higher than the experimental values [22].

Results

The partial cross-sections for production of the main gamma rays for the elements that have not yet been investigated with FaNGaS were evaluated with the method described above. The energy of the gamma-rays and their relative intensities, $I_{E\gamma,IRT}$ [13], the effective reaction cross-sections, σ_{FaNGaS} and σ_{IRT} and the corrections factors S obtained from both databases ENDF/B-VIII.0 and JEFF-3.3 are given in Table 5. For the gamma rays produced by more than one isotope (case of Pd,

Ag, Hf and Re) the, σ_{FaNGaS} and σ_{IRT} -values were obtained by weighing the reaction cross-section of each isotope with the corresponding isotopic abundance. The resulting $\sigma_{E\gamma}$ -values are given together with the mean values in Table 6. The latter were used to determine the elemental detection limits (DL) corresponding here to the smallest mass of elements that can be detected with the FaNGaS instrument. The gamma rays induced by fast neutron reactions are measured with a well shielded n-type high purity germanium detector of 50% relative efficiency. The sample-to-detector distance is 67 cm. The detection limits were calculated by means of Eq. (1) from the minimum net count rate $R_{E\gamma}(c)$ of the gamma line of interest which can be expressed according to [23] by

$$R_{E\gamma}(c) = \frac{1}{c} \cdot \sqrt{\frac{2 \cdot B_{E\gamma}}{t}} \quad (10)$$

where $B_{E\gamma}$ is the count rate of the background below the gamma line, t is the counting time and $c=0.5$ corresponds to an uncertainty of 50% for the net count rate of the gamma line. In the case of the presence of an interfering gamma line $R_{E\gamma}(c)$ can be given by

$$R_{E\gamma}(c) = \frac{1}{c} \cdot \sqrt{\frac{2 \cdot (2 \cdot B_{E\gamma} + R_{int})}{t}} \quad (11)$$

where R_{int} is the count rate of the interfering gamma line. The values of $B_{E\gamma}$ and R_{int} were determined from the analysis

Table 3 Effective reaction cross sections σ for (n, n' γ) reactions calculated by mean of Eq. (8), correction factor S obtained by Eq. (7) and isotopic partial cross-section for production of the gamma ray of interest $\sigma_{E\gamma,cal}$ calculated by Eq. (6) by using the ENDF/B-VIII.0 database

Isotope	h (%)	$E\gamma$ (keV)	$\sigma_{E\gamma, meas}$ (mb)	$I_{E\gamma,IRT}$ (%)	From ENDF/B-VIII.0 database				
					σ_{IRT} (mb)	σ_{FaNGaS} (mb)	S	$\sigma_{E\gamma,cal}$ (mb)	R
^{12}C	98.93	4439	14.4 ± 3.3	1.27 ± 0.21	117 ± 22	152 ± 23	1.30 ± 0.32	9.0 ± 2.7	0.62 ± 0.23
^{18}O	0.205	1982	202 ± 28	0.11 ± 0.04	143	184	1.32 ± 0.09	381 ± 143	1.88 ± 0.76
^{23}Na	100	439	507 ± 25	139 ± 28	255 ± 43	602 ± 45	0.72 ± 0.14	538 ± 132	1.06 ± 0.26
^{27}Al	100	1014	136 ± 8	28 ± 3	195 ± 30	427 ± 34	0.77 ± 0.14	116 ± 26	0.85 ± 0.20
^{28}Si	92.2297	1779	189 ± 9	27.0 ± 2.5	389	447	1.48 ± 0.10	233 ± 131	1.23 ± 0.69
^{32}S	94.93	2230	79 ± 4	15.1 ± 2.0	257	278	1.57 ± 0.11	134 ± 22	1.70 ± 0.29
^{35}Cl	75.78	1219	58 ± 5	5.2 ± 0.5	213	348	1.04 ± 0.07	38 ± 5	0.66 ± 0.11
^{39}K	93.2581	2814	27.1 ± 1.3	2.6 ± 0.4	113	145	1.32 ± 0.09	20 ± 4	0.73 ± 0.14
^{40}Ca	96.941	3904	10.8 ± 0.9	2.2 ± 0.4	226	253	1.52 ± 0.10	19 ± 4	1.76 ± 0.40
^{48}Ti	73.72	983	627 ± 27	77 ± 8	697 ± 122	922 ± 81	1.29 ± 0.27	724 ± 177	1.15 ± 0.29
^{56}Fe	91.754	846	586 ± 41	100	553 ± 33	940 ± 32	1		
^{58}Ni	68.0769	1454	338 ± 16	40 ± 5	564	690	1.39 ± 0.10	439 ± 70	1.30 ± 0.22
^{63}Cu	69.17	962	410 ± 41	54 ± 6	374	1090	0.58 ± 0.04	243 ± 36	0.59 ± 0.11
^{92}Zr	17.15	934	1068 ± 46	25 ± 3	947 ± 151	1410 ± 112	1.14 ± 0.22	893 ± 212	0.84 ± 0.20
^{115}In	95.71	934	222 ± 11	46 ± 5	125	1089	0.20 ± 0.01	52 ± 7	0.23 ± 0.03
^{139}La	99.910	1420	82 ± 4	17.8 ± 2.0	381 ± 178	1355 ± 224	0.48 ± 0.24	46 ± 24	0.56 ± 0.29
^{140}Ce	88.450	1596	666 ± 56	96 ± 11	1277	1594	1.36 ± 0.09	794 ± 154	1.19 ± 0.25
^{141}Pr	100	1126	110 ± 5	33 ± 6	519 ± 214	1550 ± 283	0.53 ± 0.24	94 ± 46	0.85 ± 0.42
^{144}Nd	23.8	696	1450 ± 68	32 ± 5	907	1824	0.84 ± 0.06	607 ± 113	0.42 ± 0.08
^{148}Sm	11.24	550	1558 ± 251	52 ± 7	600	1941	0.53 ± 0.04	1318 ± 223	0.85 ± 0.20
^{159}Tb	100	331	285 ± 24	76 ± 12	794	1971	0.68 ± 0.05	278 ± 52	0.97 ± 0.20
^{164}Dy	28.18	755	241 ± 38	14.5 ± 1.9	1140	2628	0.74 ± 0.05	205 ± 33	0.85 ± 0.19

h is the isotopic abundance, $E\gamma$ the energy of the gamma ray [14], $\sigma_{E\gamma, meas}$ the gamma-ray production cross-section measured with the FaNGaS instrument at FRM II, $I_{E\gamma,IRT}$ the relative intensity from measurements at IRT-M reactor given in Demidov's Atlas [13], σ_{IRT} the effective cross-section for the IRT-M neutron spectrum, σ_{FaNGaS} the effective cross-section for the FaNGaS neutron spectrum and R the calculated-to-measured ratio for the isotopic partial cross-section

of the measured beam background spectrum [3]. The detection limits determined for a counting time of 12 h and a fast neutron flux at sample position of $1.13 \cdot 10^8 \text{ cm}^{-2} \text{ s}^{-1}$ are given in the last column of Table 6.

Conclusions

The isotopic partial production cross -sections of gamma rays induced by (n,n' γ) reactions with fission neutrons were evaluated using the intensities relative to the 846-keV gamma line of ^{56}Fe obtained from irradiation with reactor

fast neutrons [13] and a production cross section of 586 ± 41 mb [2] for the 846-keV gamma ray. Corrections for the difference in the neutron spectra were performed determining the neutron spectrum averaged cross-sections of the (n,n' γ) reactions using the ENDF/B-VIII.0 and JEFF-3.3 databases. The calculated and measured cross sections for the gamma rays of the elements investigated with fissions neutrons using the FaNGaS instrument were found to agree reasonably (1.5σ level) indicating the reliability of the proposed method considering an uncertainty of 25% in the evaluation of the cross sections. Furthermore, the detection limits were estimated for a measurement time of 12 h.

Table 4 Effective reaction cross-sections σ for (n, γ) reactions calculated by mean of Eq. (8), factor S obtained by Eq. (7) and isotopic partial cross-section for production of the gamma ray of interest $\sigma_{E\gamma,cal}$ calculated by Eq. (6) by using the JEFF-3.3 database

Isotope	h (%)	$E\gamma$ (keV)	$\sigma_{E\gamma, meas}$ (mb)	$I_{E\gamma, IRT}$ (%)	From JEFF-3.3 database				R
					σ_{IRT} (mb)	σ_{FaNGaS} (mb)	S	$\sigma_{E\gamma, cal}$ (mb)	
^{12}C	98.93	4439	14.4 ± 3.3	1.27 ± 0.21	119	154	1.35 ± 0.08	9.3 ± 1.8	0.65 ± 0.19
^{18}O	0.205	1982	202 ± 28	0.11 ± 0.04	336 ± 24	388 ± 27	1.52 ± 0.17	438 ± 170	2.17 ± 0.89
^{23}Na	100	439	507 ± 25	139 ± 28	244 ± 12	552 ± 15	0.78 ± 0.06	583 ± 132	1.15 ± 0.27
^{27}Al	100	1014	136 ± 8	28 ± 3	195 ± 13	427 ± 16	0.80 ± 0.08	120 ± 20	0.88 ± 0.15
^{28}Si	92.2297	1779	189 ± 9	27.0 ± 2.5	363	419	1.52 ± 0.09	239 ± 31	1.26 ± 0.17
^{32}S	94.93	2230	79 ± 4	15.1 ± 2.0	437 ± 31	460 ± 33	1.67 ± 0.19	143 ± 27	1.81 ± 0.36
^{35}Cl	75.78	1219	58 ± 5	5.2 ± 0.5	213	348	1.07 ± 0.06	39 ± 5	0.68 ± 0.11
^{39}K	93.2581	2814	27.1 ± 1.3	2.6 ± 0.4	216 ± 17	268 ± 21	1.41 ± 0.18	21 ± 4	0.78 ± 0.17
^{40}Ca	96.941	3904	10.8 ± 0.9	2.2 ± 0.4	224 ± 40	252 ± 47	1.56 ± 0.41	19 ± 6	1.76 ± 0.59
^{48}Ti	73.72	983	627 ± 27	77 ± 8	697 ± 71	932 ± 67	1.31 ± 0.18	736 ± 137	1.17 ± 0.22
^{56}Fe	91.754	846	586 ± 41	100	481 ± 24	843 ± 24	1		
^{58}Ni	68.0769	1454	338 ± 16	40 ± 5	526	666	1.38 ± 0.08	436 ± 67	1.29 ± 0.21
^{63}Cu	69.17	962	410 ± 41	54 ± 6	321 ± 35	933 ± 43	0.60 ± 0.07	252 ± 52	0.61 ± 0.14
^{92}Zr	17.15	934	1068 ± 46	25 ± 3	976 ± 453	1493 ± 599	1.15 ± 0.71	901 ± 570	0.84 ± 0.53
^{115}In	95.71	934	222 ± 11	46 ± 5	143	1204	0.21 ± 0.01	54 ± 7	0.24 ± 0.03
^{139}La	99.910	1420	82 ± 4	17.8 ± 2.0	381 ± 178	1355 ± 224	0.49 ± 0.24	47 ± 24	0.57 ± 0.29
^{140}Ce	88.450	1596	666 ± 56	96 ± 11	1180 ± 121	1483 ± 127	1.39 ± 0.20	811 ± 160	1.22 ± 0.26
^{141}Pr	100	1126	110 ± 5	33 ± 6	484 ± 210	1544 ± 275	0.55 ± 0.26	97 ± 50	0.89 ± 0.45
^{144}Nd	23.8	696	1450 ± 68	32 ± 5	907	1824	0.87 ± 0.05	629 ± 113	0.43 ± 0.08
^{148}Sm	11.24	550	1558 ± 251	52 ± 7	600	1941	0.54 ± 0.03	1343 ± 217	0.86 ± 0.20
^{159}Tb	100	331	285 ± 24	76 ± 12	1063	2394	0.78 ± 0.04	319 ± 57	1.12 ± 0.22
^{164}Dy	28.18	755	241 ± 38	14.5 ± 1.9	1045 ± 138	2474 ± 126	0.74 ± 0.11	205 ± 43	0.85 ± 0.22

h is the isotopic abundance, $E\gamma$ the energy of the gamma ray [14], $\sigma_{E\gamma, meas}$ the gamma-ray production cross-section measured with the FaNGaS instrument, $I_{E\gamma, IRT}$ the relative intensity from measurements at IRT-M reactor given in Demidov's Atlas [13], σ_{IRT} the effective cross-section for the IRT neutron spectrum, σ_{FaNGaS} the effective cross-section for the FaNGaS neutron spectrum and R the calculated-to-measured ratio for the isotopic partial cross-sections

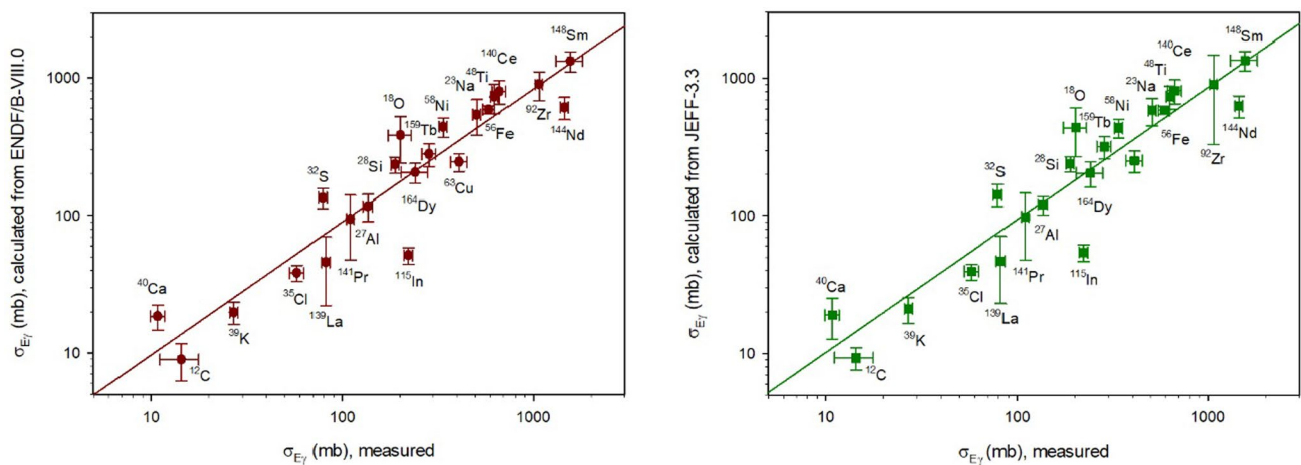


Fig. 2 Relationship between calculated and measured gamma-ray production cross sections. Left: cross sections calculated from the ENDF/B-VIII.0 database. Right: cross sections calculated from the JEFF-3.3 database. The solid line represents the fit of the data with

Eq. (9). The coefficient of determination is $R^2=0.885$ for ENDF/B-VIII.0 database and $R^2=0.881$ for the JEFF-3.3 database. Without the ^{18}O , ^{32}S , ^{40}Ca , ^{115}In and ^{144}Nd data a better fit is obtained with $R^2=0.958$ and $R^2=0.951$, respectively

Table 5 Effective reaction cross-sections σ for (n, n' γ) reactions calculated by mean of Eq. (8) and correction factor S obtained by Eq. (7) from the ENDF/B-VIII.0 and JEFF-3.3 databases, respectively, for the elements that have not yet been investigated with the instrument FaNGaS using fission neutrons

Isotope	h (%)	From ENDF/B-VIII.0 database			From JEFF-3.3 database		
		σ_{IRT} (mb)	σ_{FaNGaS} (mb)	S	σ_{IRT} (mb)	σ_{FaNGaS} (mb)	S
⁷ Li	92.41	86 ± 3	209 ± 7	0.70 ± 0.06	86 ± 3	209 ± 7	0.72 ± 0.05
¹¹ B	80.1	62 ± 4	86 ± 4	1.22 ± 0.13	62 ± 4	86 ± 4	1.26 ± 0.12
¹⁴ N	99.632	18	30.0 ± 0.1	1.02 ± 0.07	18	30.0 ± 0.1	1.05 ± 0.06
¹⁹ F	100	1395 ± 290	902 ± 134	2.63 ± 0.70	1395 ± 290	902 ± 134	2.71 ± 0.71
²⁴ Mg	78.99	484 ± 43	615 ± 41	1.34 ± 0.17	484 ± 43	615 ± 41	1.38 ± 0.17
³¹ P	100	317 ± 20	497 ± 23	1.08 ± 0.11	394 ± 20	541 ± 23	1.28 ± 0.11
⁴⁵ Sc	100	132 ± 30	772 ± 93	0.29 ± 0.07	184 ± 20	952 ± 91	0.34 ± 0.05
⁵¹ V	99.75	347 ± 37	839 ± 47	0.70 ± 0.10	354 ± 37	930 ± 46	0.67 ± 0.09
⁵² Cr	83.789	699 ± 12	876 ± 10	1.36 ± 0.10	723 ± 12	874 ± 10	1.47 ± 0.09
⁵⁵ Mn	100	618	1055 ± 10	0.99 ± 0.07	595	972 ± 8	1.07 ± 0.06
⁵⁹ Co	100	634	994 ± 10	1.08 ± 0.07	701	1110 ± 12	1.11 ± 0.06
⁶⁴ Zn	48.63	827 ± 42	1117 ± 50	1.26 ± 0.12	800 ± 42	1142 ± 49	1.27 ± 0.11
⁶⁹ Ga	60.1089	225 ± 57	922 ± 88	0.41 ± 0.11	350 ± 57	1189 ± 87	0.52 ± 0.10
⁷⁴ Ge	36.28	622 ± 76	1366 ± 109	0.77 ± 0.12	713 ± 76	1418 ± 10	0.88 ± 0.11
⁷⁵ As	100	813 ± 132	1715 ± 170	0.80 ± 0.16	674 ± 132	1557 ± 167	0.76 ± 0.17
⁸⁰ Se	49.61	547 ± 55	1162 ± 72	0.80 ± 0.11	757 ± 55	1493 ± 72	0.89 ± 0.09
⁸¹ Br	49.31	607 ± 111	1478 ± 186	0.70 ± 0.16	598 ± 111	1613 ± 181	0.65 ± 0.15
⁸⁷ Rb	27.83	463 ± 99	1018 ± 104	0.77 ± 0.19	590 ± 99	1358 ± 99	0.76 ± 0.15
⁸⁸ Sr	82.58	873 ± 111	1040 ± 113	1.43 ± 0.26	953 ± 111	1112 ± 113	1.50 ± 0.25
⁸⁹ Y	100	385 ± 50	1005 ± 104	0.65 ± 0.12	385 ± 50	1005 ± 104	0.67 ± 0.12
⁹³ Nb	100	98 ± 13	1354 ± 85	0.12 ± 0.02	105 ± 13	1411 ± 85	0.13 ± 0.02
⁹⁸ Mo	24.13	809 ± 117	1465 ± 134	0.94 ± 0.17	895 ± 117	1692 ± 130	0.93 ± 0.15
¹⁰⁰ Ru	12.6	554 ± 66	1380 ± 87	0.68 ± 0.10	783 ± 66	1681 ± 87	0.82 ± 0.09
¹⁰³ Rh	100	545 ± 121	1807 ± 208	0.51 ± 0.13	522 ± 47	1785 ± 78	0.51 ± 0.06
¹⁰² Pd	1.02	591 ± 62	1303 ± 81	0.77 ± 0.11	811 ± 62	1602 ± 79	0.89 ± 0.10
¹⁰⁴ Pd	11.14	646	1451 ± 19	0.76 ± 0.05	646	1451 ± 19	0.78 ± 0.05
^{102,104} Pd	12.16	641 ± 5	1438 ± 19	0.76 ± 0.05	660 ± 5	1464 ± 19	0.79 ± 0.05
¹⁰⁷ Ag	51.839	496 ± 155	1673 ± 111	0.50 ± 0.17	740 ± 155	2143 ± 215	0.60 ± 0.14
¹⁰⁹ Ag	48.161	584 ± 71	1857 ± 117	0.54 ± 0.08	542 ± 71	1754 ± 118	0.54 ± 0.09
^{107,109} Ag	100	538 ± 87	1762 ± 80	0.52 ± 0.09	645 ± 87	1955 ± 125	0.58 ± 0.09
¹¹⁴ Cd	28.73	984	1762 ± 15	0.95 ± 0.07	984	1762 ± 15	0.98 ± 0.06
¹²⁰ Sn	32.58	719	1201 ± 15	1.00 ± 0.07	882	1323 ± 15	1.09 ± 0.06
¹²¹ Sb	42.79	487	1294 ± 26	0.64 ± 0.05	563	1442 ± 27	0.68 ± 0.04
¹²⁸ Te	31.74	525 ± 119	1204 ± 181	0.74 ± 0.21	573 ± 119	1341 ± 178	0.75 ± 0.19
¹²⁷ I	100	788 ± 143	1770 ± 217	0.76 ± 0.17	584 ± 143	1550 ± 214	0.66 ± 0.19
¹³³ Cs	100	434 ± 108	1574 ± 217	0.49 ± 0.14	484 ± 108	1574 ± 217	0.48 ± 0.14
¹³⁸ Ba	71.698	997	1386 ± 10	1.22 ± 0.08	827	1186 ± 10	1.22 ± 0.07
¹⁵¹ Eu	47.81	1153	2540 ± 25	0.77 ± 0.05	971	2221 ± 27	0.77 ± 0.05
¹⁵⁸ Gd	24.84	949 ± 285	2583 ± 388	0.62 ± 0.21	718 ± 285	1630 ± 405	0.77 ± 0.36
¹⁶⁵ Ho	100	1191	2671 ± 18	0.76 ± 0.05	1191	2671 ± 18	0.78 ± 0.04
¹⁶⁸ Er	26.78	923 ± 143	2278 ± 362	0.69 ± 0.16	1066 ± 179	2506 ± 196	0.74 ± 0.14
¹⁶⁹ Tm	100	1501 ± 392	2484 ± 272	1.03 ± 0.30	1751 ± 392	2945 ± 263	1.04 ± 0.26
¹⁷³ Yb	16.13	1331 ± 154	2884 ± 141	0.78 ± 0.11	1500 ± 154	2863 ± 143	0.92 ± 0.12
¹⁷⁵ Lu	97.41	1433 ± 53	2040 ± 65	1.19 ± 0.10	1523 ± 53	2914 ± 54	0.92 ± 0.06
¹⁷⁸ Hf	27.28	1171 ± 264	2798 ± 568	0.71 ± 0.22	1081 ± 264	2608 ± 571	0.73 ± 0.24
¹⁷⁹ Hf	13.62	1261 ± 215	2751 ± 315	0.78 ± 0.17	1223 ± 215	2670 ± 318	0.80 ± 0.18
¹⁸⁰ Hf	35.08	1170 ± 379	2870 ± 279	0.69 ± 0.24	1104 ± 379	2672 ± 318	0.72 ± 0.26
^{178,179,180} Hf	76.08	1185 ± 202	2819 ± 247	0.71 ± 0.14	1116 ± 202	2645 ± 157	0.74 ± 0.15
¹⁸¹ Ta	99.988	1415	2730 ± 27	0.88 ± 0.06	743	2224 ± 34	0.58 ± 0.03

Table 5 (continued)

Isotope	h (%)	From ENDF/B-VIII.0 database			From JEFF-3.3 database		
		σ_{IRT} (mb)	σ_{FaNGaS} (mb)	S	σ_{IRT} (mb)	σ_{FaNGaS} (mb)	S
^{186}W	28.43	982 ± 280	2486 ± 191	0.67 ± 0.20	947 ± 280	3222 ± 195	0.51 ± 0.16
^{185}Re	37.40	631 ± 300	1630 ± 316	0.66 ± 0.34	1237 ± 300	2864 ± 316	0.76 ± 0.21
^{187}Re	62.60	676 ± 374	1726 ± 554	0.67 ± 0.43	1398 ± 374	2990 ± 559	0.82 ± 0.27
$^{185,187}\text{Re}$	100	659 ± 259	1690 ± 469	0.66 ± 0.32	1338 ± 259	2943 ± 369	0.80 ± 0.19
^{190}Os	26.26	1187 ± 256	2495 ± 383	0.81 ± 0.22	1223 ± 256	2890 ± 379	0.74 ± 0.19
^{193}Ir	62.70	1240 ± 392	2540 ± 504	0.83 ± 0.31	1240 ± 392	2540 ± 504	0.86 ± 0.32
^{194}Pt	32.9670	667 ± 204	1803 ± 232	0.63 ± 0.21	667 ± 204	1803 ± 208	0.65 ± 0.21
^{197}Au	100	727	2053 ± 27	0.60 ± 0.04	727	2053 ± 27	0.62 ± 0.04
^{200}Hg	23.10	717 ± 159	1802 ± 232	0.68 ± 0.18	533 ± 159	1581 ± 231	0.59 ± 0.20
^{205}Tl	70.476	367 ± 113	1420 ± 241	0.49 ± 0.16	466 ± 113	1618 ± 237	0.50 ± 0.14
^{206}Pb	24.10	645 ± 75	1550 ± 102	0.71 ± 0.11	579 ± 75	1493 ± 101	0.68 ± 0.11
^{209}Bi	100	350 ± 48	955 ± 87	0.62 ± 0.11	355 ± 49	972 ± 86	0.64 ± 0.11
^{232}Th	100	1050	2781 ± 40	0.64 ± 0.05	1050	2781 ± 40	0.66 ± 0.04
^{238}U	99.2745	1302 ± 102	2705 ± 31	0.82 ± 0.08	1174 ± 99	2686 ± 153	0.77 ± 0.09

Table 6 Isotopic partial cross-sections for production of the gamma rays [14] of interest $\sigma_{E\gamma}$ calculated by Eq. (6) with the reaction cross sections σ and correction factors S given in Table 5 for the elements that have not yet been investigated with the instrument FaNGaS

using fission neutrons. $\overline{\sigma_{E\gamma}}$ is the average of the values obtained from ENDF/B-VIII.0 and JEFF-3.3 databases. LD is the limit of detection achieved with FaNGaS instrument

Isotope	h (%)	$E\gamma$ (keV)	$I_{\gamma,IRT}$ (%)	From ENDF/B-VIII.0 $\sigma_{E\gamma}$ (mb)	From JEFF-3.3 $\sigma_{E\gamma}$ (mb)	$\overline{\sigma_{E\gamma}}$ (mb)	LD(mg)
Li	92.41	477	53 ± 0.7	216 ± 37	222 ± 37	219 ± 55	0.08
^{11}B	80.1	2124	1.25 ± 0.13	10.3 ± 1.7	10.6 ± 1.7	10.5 ± 2.6	2.6
^{14}N	99.632	2313	1.33 ± 0.16	7.3 ± 1.1	7.5 ± 1.1	7.4 ± 1.8	9.8
^{19}F	100	1236	5.9 ± 7	83 ± 25	86 ± 25	84 ± 21	0.8
^{24}Mg	78.99	1369	28 ± 3	255 ± 46	263 ± 47	259 ± 65	0.3
^{31}P	100	1266	21 ± 3	122 ± 23	144 ± 26	133 ± 37	0.4
^{45}Sc	100	364	28 ± 4	44 ± 13	51 ± 11	47 ± 13	3.1
^{51}V	99.75	320	115 ± 16	436 ± 91	413 ± 84	424 ± 107	0.3
^{52}Cr	83.789	1434	52 ± 6	453 ± 69	490 ± 72	471 ± 121	0.3
^{55}Mn	100	858	16.8 ± 1.8	90 ± 13	97 ± 13	93 ± 24	1.4
^{59}Co	100	1190	33 ± 4	192 ± 30	196 ± 30	194 ± 48	0.5
^{64}Zn	48.63	992	52 ± 5	723 ± 111	731 ± 109	727 ± 182	0.3
^{69}Ga	60.1089	574	27 ± 3	100 ± 31	125 ± 29	112 ± 33	2.2
^{74}Ge	36.28	596	108 ± 18	1239 ± 300	1411 ± 307	1325 ± 353	0.6
^{75}As	100	280	135 ± 44	585 ± 228	551 ± 223	568 ± 144	0.3
^{80}Se	49.61	666	92 ± 10	798 ± 150	886 ± 147	842 ± 219	0.3
^{81}Br	49.31	276	173 ± 43	1317 ± 457	1225 ± 419	1271 ± 324	0.3
^{87}Rb	27.83	402	65 ± 15	971 ± 335	956 ± 295	963 ± 241	1.2
^{88}Sr	82.58	1836	55 ± 6	511 ± 114	538 ± 113	524 ± 132	0.3
^{89}Y	100	909	40 ± 5	140 ± 32	145 ± 33	142 ± 36	1.3
^{93}Nb	100	744	48 ± 5	32 ± 6	34 ± 7	33 ± 8	5.9
^{98}Mo	24.13	787	33 ± 3	690 ± 150	682 ± 135	686 ± 171	1.2
^{100}Ru	12.6	539	35 ± 6	1019 ± 244	1219 ± 265	1119 ± 313	1.3
^{103}Rh	100	611	64 ± 13	176 ± 59	176 ± 43	176 ± 44	2.2
$^{102,104}\text{Pd}$	12.16	556	14.6 ± 2.5	490 ± 96	510 ± 100	500 ± 126	3.2
$^{107,109}\text{Ag}$	100	551	10.3 ± 1.2	28 ± 6	32 ± 7	30 ± 8	6.6
^{114}Cd	28.73	558	70 ± 8	1243 ± 187	1282 ± 187	1262 ± 317	0.5
^{120}Sn	32.58	1171	40 ± 4	663 ± 93	719 ± 97	691 ± 177	0.9
^{121}Sb	42.79	910	16 ± 3	129 ± 27	138 ± 29	133 ± 34	3.3
^{128}Te	31.74	743	42 ± 6	527 ± 170	533 ± 159	530 ± 132	1.5
^{127}I	100	418	57 ± 9	232 ± 67	202 ± 68	217 ± 58	2.3
^{133}Cs	100	768	21.5 ± 2.4	54 ± 17	56 ± 18	55 ± 14	4.9
^{138}Ba	71.698	1436	65 ± 6	526 ± 80	596 ± 78	561 ± 149	0.6
^{151}Eu	47.81	307	21 ± 5	182 ± 47	181 ± 46	181 ± 45	4.2
^{158}Gd	24.84	944	6.5 ± 1.1	88 ± 34	109 ± 55	98 ± 29	12
^{165}Ho	100	362	275 ± 44	1121 ± 210	1155 ± 213	1136 ± 285	0.4
^{168}Er	26.78	816	26 ± 3	360 ± 96	389 ± 92	374 ± 96	3.1
^{169}Tm	100	475	18 ± 3	99 ± 34	101 ± 31	100 ± 25	4.1
^{173}Yb	16.13	400	8.1 ± 1.6	212 ± 53	248 ± 61	230 ± 63	15
^{175}Lu	97.41	354	274 ± 56	1806 ± 418	1385 ± 314	1595 ± 498	0.4
$^{178,179,180}\text{Hf}$	76.08	214	277 ± 51	1390 ± 387	1449 ± 409	1419 ± 357	0.4
^{181}Ta	99.988	482	127 ± 15	602 ± 92	400 ± 60	501 ± 190	1.1
^{186}W	28.43	739	33 ± 4	419 ± 140	321 ± 108	370 ± 115	3.4
$^{185,187}\text{Re}$	100	646	20 ± 3	71 ± 36	86 ± 25	78 ± 22	4.9
^{190}Os	26.26	558	24 ± 3	397 ± 122	364 ± 106	380 ± 98	3.9
^{193}Ir	62.70	559	8.2 ± 1.0	58 ± 24	60 ± 24	59 ± 15	10

Table 6 (continued)

Isotope	h (%)	E γ (keV)	I $_{\gamma,IRT}$ (%)	From ENDF/B-VIII.0 $\sigma_{E\gamma}$ (mb)	From JEFF-3.3 $\sigma_{E\gamma}$ (mb)	$\overline{\sigma_{E\gamma}}$ (mb)	LD(mg)
¹⁹⁴ Pt	32.9670	328	168 ± 34	1723 ± 690	1776 ± 701	1749 ± 439	0.9
¹⁹⁷ Au	100	279	108 ± 12	349 ± 52	361 ± 52	355 ± 89	1.2
²⁰⁰ Hg	23.10	368	81 ± 9	1275 ± 377	1114 ± 403	1194 ± 319	2.7
²⁰⁵ Tl	70.476	720	33 ± 4	111 ± 43	127 ± 41	119 ± 32	5.5
²⁰⁶ Pb	24.10	803	41 ± 6	647 ± 143	622 ± 140	634 ± 159	5.1
²⁰⁹ Bi	100	362	48 ± 7	161 ± 39	165 ± 39	163 ± 41	4.6
²³² Th	100	666	36 ± 4	124 ± 18	128 ± 18	126 ± 32	3.9
²³⁸ U	99.2745	635	29 ± 4	128 ± 24	120 ± 23	124 ± 31	4.8

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Data availability All data supporting the findings of this study are available upon reasonable request from the corresponding author.

Declarations

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References

- Randriamalala TH, Rossbach M, Mauerhofer E, Zs R, Söllradl S, Wagner FM (2016) FaNGaS: a new instrument for (n,n γ) reaction measurements at FRM II. Nucl Instrum Methods A 806:370–377
- Ilic Z, Mauerhofer E, Stieghorst C, Zs R, Rossbach M, Randriamalala TH, Brückel T (2020) Prompt gamma rays induced by inelastic scattering of fission neutrons on iron. J Radioanal Nucl Chem 325:641–645
- Ophoven N, Ilic Z, Mauerhofer E, Randriamalala TH, Vezhlev E, Stieghorst C, Zs R, Brückel T, Jolie J, Strub E (2022) Fast neutron induced gamma rays from (n,n'), (n,p) and (n, α) reactions on CaCO₃. J Radioanal Nucl Chem 331:5729–5740
- Mauerhofer E, Ilic Z, Stieghorst C, Zs R, Rossbach M, Li J, Randriamalala TH, Brückel T (2021) Prompt and delayed gamma rays induced by epithermal and fast neutrons with indium. J Radioanal Nucl Chem 331:535–546
- Mauerhofer E, Ilic Z, Stieghorst C, Révay Z, Vezhlev E, Ophoven N, Randriamalala TH, Brückel T (2022) Prompt gamma rays from fast neutron inelastic scattering on aluminum, titanium and copper. J Radioanal Nucl Chem 331:3987–4000
- Ophoven N, Ilic Z, Mauerhofer E, Randriamalala TH, Vezhlev E, Stieghorst C, Révay Z, Brückel T, Jolie J, Strub E (2023) Prompt gamma rays from fast neutron induced reactions on cerium and chlorine. J Radioanal Nucl Chem 332:3133–3145
- Ophoven N, Ilic Z, Mauerhofer E, Randriamalala TH, Vezhlev E, Stieghorst C, Zs R, Brückel T, Jolie J, Strub E (2023) Prompt gamma rays of terbium induced by inelastic scattering of fission neutrons. J Radioanal Nucl Chem 333:1287–1300
- Mauerhofer E, Ophoven N, Ilic Z, Stieghorst C, Révay Z, Meleshkovskii I, Randriamalala TH (2024) Gamma emission from interaction of fission neutrons on nickel and zirconium. J Radioanal Nucl Chem 333:4333–4352
- Ophoven N, Mauerhofer E, Ilic Z, Stieghorst C, Révay Z, Meleshkovskii I, Randriamalala TH (2025) Prompt gamma rays of lanthanum and praseodymium produced by inelastic scattering of fission neutrons. J Radioanal Nucl Chem 334:953–967
- Mauerhofer E, Ophoven N, Ilic Z, Stieghorst C, Révay Z, Meleshkovskii I, Randriamalala TH (2025) Prompt gamma rays induced by fission neutrons on sodium, silicon, sulfur and potassium. J Radioanal Nucl Chem 334:3227–3240
- Ophoven N, Mauerhofer E, Ilic Z, Stieghorst C, Zs R, Meleshkovskii I, Randriamalala TH (2025) Prompt gamma rays of neodymium from the (n,n γ)-reaction with fission neutrons. J Radioanal Nucl Chem 334:3227–3240
- Mauerhofer E, Ophoven N, Ilic Z, Stieghorst C, Révay Z, Meleshkovskii I, Randriamalala TH (2026) Prompt gamma rays from the inelastic scattering of fission neutrons on samarium and dysprosium. J Radioanal Nucl Chem. <https://doi.org/10.1007/s10967-026-10892-2>
- Demidov A, Govor L, Cherepantsev M, Ahmed S, Al-Najjar M, Al-Amili N, Al-Assafi N, Rammo N (1978) Atlas of gamma-ray spectra from the inelastic scattering of reactor fast neutrons. Atomizdat, Moscow
- NuDat 3.0 National Nuclear Data Center, Brookhaven National Laboratory, <https://www.nndc.bnl.gov/nudat3/>
- Hurst AM, Bernstein LA, Kawano T, Lewis AM, Song K (2021) The Baghdad Atlas: a relational database of inelastic neutron-scattering (n,n γ) data. Nucl Instrum Meth A 995:165095

16. Brown DA et al (2018) ENDF/B-VIII.0: the 8th major release of the nuclear reaction data library with CIELO-project cross sections, new standards and thermal scattering data. *Nucl Data Sheets* 148:1–142
17. Plompen AJM, Cabellos O, De Saint JC et al (2020) The joint evaluated fission and fusion nuclear data library, JEFF-3.3. *Eur Phys J A* 56:181
18. MacFarlane R, Muir DW, Boicourt RM, Kahler AC, Conlin JL (2017) The NJOY Nuclear Data Processing System, Version 2016. <https://doi.org/10.2172/1338791>
19. Python Software Foundation. Python Language Reference, version 2.7. Available at <http://www.python.org>
20. Kellerhof G (2025) Partial gamma ray cross sections for inelastic scattering of fast neutrons, Bachelorarbeit, Fachhochschule Aachen Campus Jülich
21. OECD NEA Data Bank (2020) JANIS Book of neutron-induced cross-sections <https://www.oecd-neo.org/janis/book/book-neutron-2020-09.pdf>
22. Otuka N, Dupont E, Semkova V, Pritychenko B, Blokhin AI, Aikawa M, Babykina S, Bossant M, Chen G, Dunaeva S, Forrest RA, Fukahori T, Furutachi N, Ganesan S, Ge Z, Gritzay OO, Herman M, Hlavač S, Katō K, Lalremruata B, Lee YO, Makinaga A, Matsumoto K, Mikhaylyukova M, Pikulina G, Pronyaev VG, Saxena A, Schwerer O, Simakov SP, Soppera N, Suzuki R, Takács S, Tao X, Taova S, Tárkányi F, Varlamov VV, Wang J, Yang SC, Zerkov V, Zhuang Y (2014) Towards a more complete and accurate experimental nuclear reaction data library (EXFOR): international collaboration between nuclear reaction data centres (NRDC). *Nuclear Data Sheets*, 120:272–276. Experimental Nuclear Reaction Data (EXFOR) Database Version of 2026–06–17. <https://nds.iaea.org/exfor/>
23. Zs R (2009) Determining elemental composition using prompt γ activation analysis. *Anal Chem* 81:6851–6859

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