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# Measurements of the thermal neutron cross-sections and resonance integrals for $^{186}$W $(n,\gamma)$ $^{187}$W and $^{98}$Mo $(n,\gamma)$ $^{99}$Mo reactions

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**Abstract** The thermal neutron cross-sections and resonance integrals of the $^{186}$W $(n,\gamma)$ $^{187}$W and $^{98}$Mo $(n,\gamma)$ $^{99}$Mo reactions in the thermal and $1/E$ regions, respectively, of a thermal reactor neutron spectrum have been experimentally determined by the activation method using $^{197}$Au $(n,\gamma)$ $^{198}$Au reaction as a single comparator. The high purity natural W, Mo, and Zr foils; and Au wire diluted in aluminum, were irradiated without Cd shield in two neutron irradiation sites, characterized with different values for the thermal-to-epithermal flux ratios, $f$ at the Second Egyptian Research Reactor (ETRR-2). The induced activities in the samples were measured by high-resolution $\gamma$-ray spectrometry with a calibrated germanium detector. Thermal neutron cross-sections for 2200 m/s neutrons and resonance integrals for the $^{186}$W $(n,\gamma)$ $^{187}$W and $^{98}$Mo $(n,\gamma)$ $^{99}$Mo reactions have been obtained relative to the reference values, $\sigma_0 = 98.65 \pm 0.09$ b and $I_0 = 1500 \pm 28$ b for the $^{197}$Au $(n,\gamma)$ $^{198}$Au reaction. The necessary correction factors for thermal neutron and resonance neutron self-shielding effects, and the epithermal flux index ($\alpha$) were taken into account in the determinations. The results obtained were: $\sigma_0 = 38.43 \pm 0.4$ b and $I_0 = 502 \pm 65$ b for $^{186}$W $(n,\gamma)$ $^{187}$W, and $\sigma_0 = 0.137 \pm 0.014$ band $I_0 = 6.47 \pm 0.8$ for $^{98}$Mo $(n,\gamma)$ $^{99}$Mo. These results are discussed and compared with previous measurements and evaluated data in literature. The traditional method of determining thermal cross-sections and resonance integrals via neutron irradiation with and without Cd shield in one irradiation position was avoided in this work by neutron irradiation without Cd shield in at least two different neutron irradiation positions. This method provides alternative way for determining thermal cross-sections and resonance integrals simultaneously.

**Keywords** Cross-section · Resonance integral · Self shielding · Flux ratio

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## Introduction

Tungsten (W) and Molybdenum (Mo) are important structural materials for fusion reactors, accelerator-driven systems and isotope productions [1]. W is used as the target material of the electron accelerator for producing bremsstrahlung and neutrons [1]. Rhenium-188, ($^{188}$Re, $t_{1/2} = 16.8$ h) is available from the $^{188}$W/$^{188}$Re generator system, made via double neutron capture on $^{186}$W [2, 3]. Mo is very useful as a refractory and corrosion resistant material in accelerator applications [4, 5]. $^{99}$Mo ($t_{1/2} = 65.94$ h) is produced by the $^{98}$Mo $(n,\gamma)$ $^{99}$Mo reaction [5, 6]. It decays by beta emission to $^{99m}$Tc ($t_{1/2} = 6.015$ h). $^{99m}$Tc is the most important nuclide used for diagnostic purposes.

The knowledge of the thermal neutron cross-sections and the resonance integrals for $^{186}$W $(n,\gamma)$ $^{187}$W and $^{98}$Mo $(n,\gamma)$ $^{99}$Mo reactions are important, because these data is used in the production of $^{99}$Tc and $^{188}$Re and may also used in other studies related to the interaction of neutrons with matter. The thermal neutron cross-section and resonance integral of the $^{186}$W $(n,\gamma)$ $^{187}$W reaction are important in the calculations of decay heat data and evaluating the radiation damage of the material [7–9]. There are some discrepancies among the experimental

data for thermal neutron cross-sections and the resonance integrals for the $^{186}$W $(n,\gamma)$ $^{187}$W and $^{98}$Mo $(n,\gamma)$ $^{99}$Mo reactions [10–17], especially among the resonance integral values.

Measuring thermal neutron cross-sections, $\sigma_0$ and resonance integrals, $I_0$ are often performed by the activation method. It is based on irradiation target samples with and without Cd shield in the neutron field from either a reactor or a neutron source. Neutron spectrum parameters characterizing irradiation position should be well-known. There is an alternative scheme to measure simultaneously thermal neutron cross-sections and resonance integrals without irradiation under Cd shield. The target samples can be irradiated in different positions having different values for thermal-to-epithermal flux ratios, $f$. Measuring the induced activities provides coupled equation systems, where $\sigma_0$ and $I_0$ are unknown variables and can be obtained.

Aim of this work is determining thermal neutron cross-sections and resonance integrals for $^{186}$W $(n,\gamma)$ $^{187}$W and $^{98}$Mo $(n,\gamma)$ $^{99}$Mo reactions. The method of neutron irradiations of the target samples without Cd shield in two positions is used as an alternative and instead of the neutron irradiations of the target samples with and without Cd shield in one position. The correction factors of thermal neutron self-shielding ($G_{th}$), and resonance neutron self-shielding ($G_e$) effects, and the epithermal neutron spectrum shape factor ($\alpha$) were taken into account.

## Theory

The flux density in a thermal reactor can be characterized by two components, a temperature dependent Maxwellian thermal neutron component and an epithermal neutron slowing down component with an ideal $1/E$ distribution. A number of formalisms [18–20] have been suggested to describe the reaction rates. A simple convention proposed by Høgdahl [18] for $1/v$ nuclides is used for the present purpose. According to it, the reaction rate per target nuclei, $R$, of a sample irradiated by reactor neutrons is described by [21, 22]:

$$R = R_{th} + R_e = G_{th}\phi_{th}\sigma_o + G_e\phi_e I_o(\alpha), \quad (1)$$

where $R_{th}$ $(=\phi_{th}\ \sigma_o)$ is the reaction rate induced by pure thermal, $R_e$ $(=\phi_e\ I_0\ (\alpha)))$ is the reaction rate induced by epithermal neutrons, $G_{th}$ and $G_e$ are the thermal and epithermal neutrons self shielding correction factors respectively, and the parameter $\alpha$,which is independent on the neutron energy [21, 22], corrects for the deviation of the epithermal neutrons from the ideal $1/E$ law.

The reaction rate is measured by Ge detector using the expression:

$$R = (N_p M)/(N_a t_m WSDC\varepsilon_p\theta\gamma), \quad (2)$$

where $N_p$ is the net number of counts in the full-energy peak, $W$ is the weight of the sample, $t_m$ is the measuring time, $S = 1 - \exp(-\lambda t_{irr})$, $\lambda$ is the decay constant, $t_{irr}$ is the irradiation time, $D = \exp(-\lambda t_D)$, $t_D$ is the decay time, $C = 1 - \exp(-\lambda t_m)/\lambda t_m$, $M$ is the atomic weight, $\gamma$ is gamma ray intensity, $\varepsilon_p$ is the full-energy peak detection efficiency, $\theta$ is the isotopic abundance and $N_a$ is Avogadro's number. Similarly the reaction rate for Au as a comparator can be written. Thermal neutron cross-section as a function of the resonance integral for any element $x$, with respect to Au as a comparator is given by:

$$\sigma_{0,x} = [(G_{th,au}\sigma_{0,au}/G_{th,x}) + ((G_{e,au}\sigma_{0,au}I_{0,au}(\alpha))/(fG_{th,x}))]K - (G_{e,x}I_{0,x}(\alpha)/fG_{th,x}), \quad (3)$$

where $f$ is the thermal to epithermal neutron flux ratio, and the factor $K$ is given by the relation:

$$K = [(N_p/t_m WSDC\varepsilon_p)_x/(N_p/t_m WSDC\varepsilon_p)_{au}](M_x\theta_{au}\gamma_{au})/(M_{au}\theta_x\gamma_x) \quad (4)$$

To solve Eq. 3, which has two unknown variables, $\sigma_{0,x}$ and $I_{0,x}(\alpha)$, two coupled equations are necessary. This is achieved by neutron irradiation of the target samples in at least two positions characterized with different values for the flux ratio $f$. The solution can be obtained graphically, from the plots of $\sigma_{0,x}$ versus $I_{0,x}(\alpha)$, which intersect in a unique point giving simultaneously the values of $\sigma_{0,x}$ and $I_{0,x}(\alpha)$.

Experimental measurements of the reaction rates of activation detectors with well-known nuclear data lead to the determination of the neutron flux parameters at the irradiation site and consequently to the measurement of thermal neutron cross-section and resonance integral of the element of interest. It is to be noted that the conversion of $I_0(\alpha)$ to $I_0$ is necessary to provide a resonance integral independent of the irradiation position, which can then be compared to literature values. This conversion can be made by using the following expression:

$$I = \bar{E}_r\alpha\left[I_0(\alpha) - \left(0.316\,\sigma_0/\sqrt{E_{cd}}\right) \times((1/(2\alpha+1)E_{cd}^{\alpha}) - \bar{E}_r^{\alpha})\right], \quad (5)$$

where $\bar{E}_r$ is the effective resonance energy and $E_{cd}$ is the cadmium cut off energy (=0.55 eV).

The necessary corrections factors for thermal and epithermal neutron self shielding are take into account. The thermal neutron self-shielding correction factor for thin slabs was calculated as follows [23]

$$G_{th} = (1 - \mathrm{Exp}(-\zeta))/\zeta, \quad (6)$$

where $\zeta = 2/\sqrt{\pi}\sum_0 t, \sum_0$ is the macroscopic cross-section for thermal neutrons ($E = 0.025$ eV), and $t$ is foil thickness. The epithermal neutron self-shielding factor was calculated as follows [24]:

$$G_e = 0.94/(1 + (z/2.7)^{0.82}) + 0.06, \quad (7)$$

where, $z = \sum_{tot}(E_{res})\Gamma\ 1.5t\ (\Gamma_\gamma/\Gamma)^{1/2}$ is a dimensionless variable, which converts the dependence of $G_e$ on the dimension and physical and nuclear parameters into an unique curve and $\sum_{tot}(E_{res}) = (\rho N_a \sigma_{res}/M)$ is the macroscopic cross-section at resonance peak ($E_{res}$) (where $\rho$ is the density, $N_a$ is Avogadro' s number; $M$ is the atomic weight; $\sigma_{res}$ is the microscopic cross-section at $E_{res}$), $t$ is the foil thickness, and $\Gamma$ is the total resonance width ($\Gamma = \Gamma_\gamma + \Gamma_n$, where $\Gamma_\gamma$ and $\Gamma_n$ are resonance widths for $(n,\gamma)$ and $(n,n')$ reactions).

## Sample irradiations and measurements

Natural W, Mo, and Zr metallic foils of the purity 99.99%; and 0.23 mm, 0.15 mm and 125 μm in thickness altogether with Au samples which are diluted in Al (0.1%) were wrapped with aluminum foils and irradiated without Cd shield in two different positions at the ETRR-2. The irradiation time varied from 2 to 3 h. After proper cooling times, the aluminum foils surrounding the activated samples were removed and the samples were transferred into clean polyethylene vials for gamma ray measurements. The gamma ray spectra were collected using a p-type coaxial EG&G Ortec HPGe detector, with 29.4% relative efficiency and 1.66 keV FWHM at 1332.5 keV of $^{60}$Co. A Canberra 10 cm thickness ultra low background lead shield with low carbon steel casing is used in shielding the detector. A genie card of 16384 channels ADC is mounted on PC for data acquisition and analysis. The measurements were performed at a distance far from the detector head (10–15 cm) to minimize true coincidence effects. The neutron spectrum parameters characterizing the irradiation positions $f$ and $\alpha$ were determined using the activated sets $^{198}$Au, $^{97}$Zr/$^{97}$Nb and $^{95}$Zr/$^{95}$Nb.

## Results and discussion

The neutron spectrum parameter $f$ and $\alpha$ characterizing the two irradiation positions were determined using the activated isotopes of Zr and Au standards—details will be reported elsewhere. The results are shown in Table 1. The determined values of $f$ and $\alpha$ for the two irradiation positions were used in Eq. 3 to determine the thermal neutron cross-sections and resonance integrals of the reactions $^{186}$W $(n,\gamma)$ $^{187}$W and $^{98}$Mo $(n,\gamma)$ $^{99}$Mo simultaneously relative to that $^{197}$Au $(n,\gamma)$ $^{198}$Au.

The results are shown in Figs. 1 and 2. As one can see, the curves intercept in unique points giving simultaneously $\sigma_0$= 38.43 b and $I_0(\alpha) = 425$ b for $^{186}$W $(n,\gamma)$ $^{187}$W; and $\sigma_0 = 0.137$ b and $I_0\ (\alpha) = 4.75$ b for $^{98}$Mo $(n,\gamma)$ $^{99}$Mo. The values of the resonance integrals determined from the curves were corrected for the value of the parameter $\alpha$ in the two irradiation positions with average values of 502 b and 6.47 b for the reactions $^{186}$W $(n,\gamma)$ $^{187}$W and $^{98}$Mo $(n,\gamma)$ $^{99}$Mo respectively—see Table 1. The thermal and epithermal neutron self shielding corrections were taken into

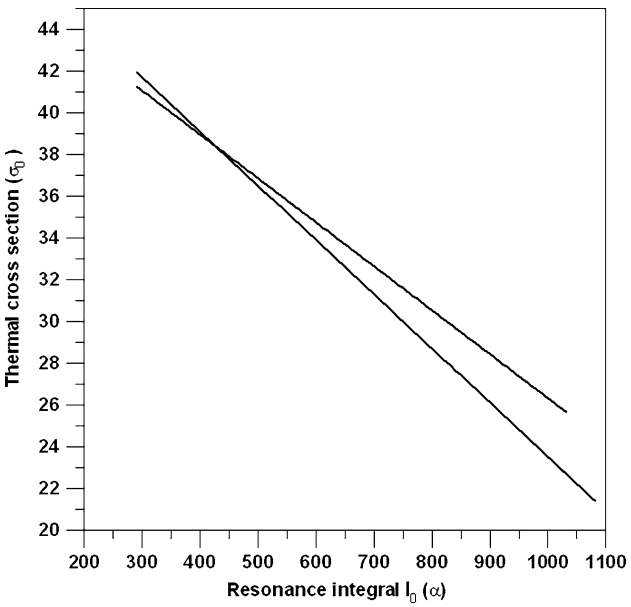


**Fig. 1** Thermal cross-section and resonance integral of $^{186}$W $(n,\gamma)$ $^{187}$W

**Table 1** Determined neutron spectrum parameters, thermal neutron cross-sections and resonance integrals in the two irradiation positions

| $f$ | $\alpha$ | $^{186}$W $(n,\gamma)$ $^{187}$W | | | $^{98}$Mo $(n,\gamma)$ $^{99}$Mo | | |
|---|---|---|---|---|---|---|---|
| | | $\sigma_0$ (b) | $I_0$ ($\alpha$) (b) | $I_0$ (b) | $\sigma_0$ (b) | $I_0$ ($\alpha$) (b) | $I_0$ (b) |
| 13.7 | 0.053 | 38.43 | 425 | 497 | 0.137 | 4.75 | 6.33 |
| 17.3 | 0.06 | | | 508 | | | 6.603 |
| | | | | Average = 502 | | | Average = 6.47 |

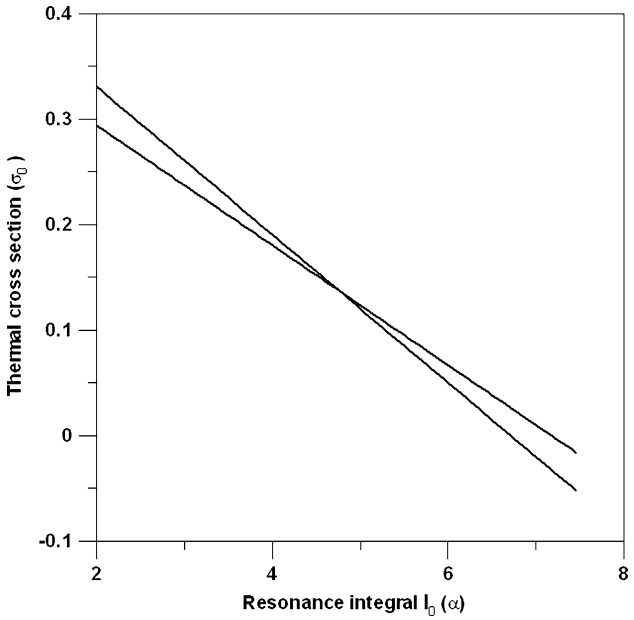


**Fig. 2** Thermal cross-section and resonance integral of $^{98}$Mo $(n,\gamma)$ $^{99}$Mo

account using Eqs. 6 and 7 respectively. These corrections and the nuclear data used in the calculation of the thermal neutron cross-sections and resonance integrals are shown in Table 2.

The results obtained were compared with previous measurements and the evaluated data in literature; and shown in Table 3. The determined thermal neutron cross-section for $^{186}$W $(n,\gamma)$ $^{187}$W reaction, agrees with most of the reported results with deviations less than 9%, however the present result deviates by −10.2 and 16.45% from the reported values in [12] and [33] respectively. The obtained resonance integral of $^{186}$W $(n,\gamma)$ $^{187}$W reaction agrees with most of the literature values with relative deviation less than 9%. Too high deviations (up to 73%) are observed between the current result and the reported values in [16, 33, 37–39].

The determined thermal neutron cross-section for the $^{98}$Mo $(n,\gamma)$ $^{99}$Mo reaction is in a very good agreement with the literature results with deviations less than 7%, however the higher deviations of 14.1 and −23.8% are observed between the present result and the results found in [14] and [15] respectively. Similarly, the obtained resonance integrals of the $^{98}$Mo $(n,\gamma)$ $^{99}$Mo reaction agrees with most values, however with some deviations—see Table 3.

Total uncertainties of the obtained cross-sections and resonance integrals are determined. The uncertainty for thermal cross-sections and resonance integrals are found less than 13% of the determined values.

In this work, the two neutron irradiation positions used in determining cross-sections and resonance integrals are in the same reactor, however, these positions can belong to two different reactors. Moreover, three or more neutron irradiation positions can be used for the same purpose. In addition, the method of two neutron irradiation positions can be extended to perform neutron activation analysis using the $k_0$ method. Namely, it can be used to determine the neutron spectrum parameters as well as elemental concentrations for any number of samples of unknown compositions using only one comparator. The details of this extension and procedures will be reported in a forthcoming paper.

**Table 2** Nuclear data used for the determination of thermal neutron cross-sections and resonance integrals and correction factors for neutron self-shielding[a]

| Nuclear reaction | Half-life | Gamma-rays | | Isotopic abundance (%) | $\bar{E}_r$(eV) | $G_{th}$ | $G_e$ |
|---|---|---|---|---|---|---|---|
| | | Energy (KeV) | Intensity (%) | | | | |
| $^{186}$W $(n,\gamma)$ $^{187}$W | 23.72 h | 134.25 | 9.4 | 28.6 | 20.5 | 0.983 | 0.3578 |
| | | 479.55 | 21.8 | | | | |
| | | 551.52 | 5.08 | | | | |
| | | 618.26 | 6.28 | | | | |
| | | 625.54 | 1.17 | | | | |
| | | 685.73 | 27.3 | | | | |
| | | 772.91 | 4.41 | | | | |
| $^{98}$Mo $(n,\gamma)$ $^{99}$Mo | 2.748 d | 140.51 | 4.52 | 24.13 | 241 | 0.9815 | 0.999 |
| | | 181.06 | 5.99 | | | | |
| | | 366.44 | 1.21 | | | | |
| | | 739.50 | 12.13 | | | | |
| | | 777.92 | 4.26 | | | | |
| $^{187}$Au $(n,\gamma)$ $^{198}$Au | 2.695 d | 411.80 | 95.58 | 100 | 5.65 | 1 | 1 |

[a] Data were taken from reference [25]

**Table 3** Comparison of $\sigma_0$ and $I_0$ for $^{186}$W $(n,\gamma)$ $^{187}$W and $^{98}$Mo $(n,\gamma)$ $^{99}$Mo reactions with literature results

| Ref. | $^{186}$W $(n,\gamma)$ $^{187}$W | | | | Ref. | $^{98}$Mo $(n,\gamma)$ $^{99}$Mo | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\sigma_0$ (b) | $D$ (%) | $I_0$(b) | $D$ (%) | | $\sigma_0$ (b) | $D$ (%) | $I_0$ (b) | $D$ (%) |
| This work | 38.43 ± 4 | – | 502 ± 65 | – | This work | 0.137 ± 0.014 | – | 6.47 ± 0.8 | – |
| [1] | 37.2 ± 2.1 | 3.3 | 461 ± 39 | 8.9 | [44] | 0.136 ± 0.007 | 0.7 | 7.02 ± 0.62 | −7.8 |
| [10] | 39.5 ± 2.3 | −2.7 | 493 ± 40 | 1.8 | [14] | 0.12 ± 0.005 | 14.1 | – | |
| [26] | 41.8 ± 2.9 | −8.06 | – | – | [15] | 0.18 ± 0.02 | −23.8 | – | |
| [27] | 37 ± 2 | 3.86 | 510 ± 50 | −1.6 | [16] | – | – | 4.72 | 37.07 |
| [12] | 42.8 ± 0.8 | −10.2 | 486 ± 5 | 3.3 | [17] | 0.14 | −2.14 | 8.2 | −21.1 |
| [28] | 38.7 ± 1.9 | −0.7 | 530 ± 28 | −5.3 | [29] | 0.13 ± 0.006 | 5.4 | 7.3 ± 1.8 | −11.4 |
| [29] | 37 ± 1.5 | 3.86 | 490 ± 15 | −2.4 | [31] | 0.13 ± 0.006 | 5.4 | 6.9 ± 0.3 | −6.23 |
| [30] | 35.4 ± 0.8 | −8.55 | 534 ± 50 | −6 | [34] | 0.1307 | 4.8 | – | – |
| [31] | 37.9 ± 0.6 | 1.4 | 485 ± 15 | 3.5 | [35] | 0.13 | 5.4 | 6.553 | −1.3 |
| [32] | 37 ± 1.8 | 3.86 | 507 ± 27 | −0.1 | [36] | 0.129 | 6.2 | 6.954 | −7 |
| [33] | 33 | 16.45 | 318 | 57.8 | [40] | 0.144 ± 0.0053 | −4.9 | 7.42 ± 0.3 | −12.8 |
| [34] | 37.5 | 2.5 | 522 | −3.8 | [41] | 0.145 ± 0.015 | −5.51 | 5.2 ± 0.2 | 24.4 |
| [35] | 39.45 | −2.6 | 529 | −5.1 | [42] | 0.131 ± 0.002 | 4.6 | – | – |
| [36] | 38.27 | 0.4 | 528.6 | −4.9 | [43] | 0.14 ± 0.01 | −2.14 | – | – |
| [37] | 36.5 ± 4.2 | 5.28 | 290.3 | 73 | | | | | |
| [16] | – | – | 290 | 73 | | | | | |
| [38] | – | – | 345 | 45.5 | | | | | |
| [39] | – | – | 320 | 56.8 | | | | | |

## Conclusions

The thermal neutron cross-sections and resonance integrals of the $^{186}$W $(n,\gamma)$ $^{187}$W and $^{98}$Mo $(n,\gamma)$ $^{99}$Mo reactions were determined via neutron irradiation without Cd shield in two different neutron irradiation positions instead of the traditional method of irradiation with and without Cd shield in one neutron irradiation position. Neutron self shielding and the deviation from the $1/E$ law corrections were taken into account. The determined cross-sections were compared with the previous measurements in literature. Good agreements are obtained for all values determined, however with some deviations for the resonance integrals of the $^{98}$Mo $(n,\gamma)$ $^{99}$Mo and $^{186}$W $(n,\gamma)$ $^{187}$W reactions.

## References


1. Nguyen D, Pham K, Kim T, Le Truong S, Guinyun YoungL, Seok K, YoungdoO Hee-SeokL, Moo-Hyun C, In Soo K, Won N (2008) Nucl Instrum Methods B 266:863–871
2. Moustapha EM, Ehrhardta JG, Smith JC, Szajek PL, Eckelman WC, Jurisson SS (2006) Nucl Med Biol 33:81–89
3. Jun Sig L, Jong-Soup L, UI-Jae P, Kwang-Jae S, Hyon-Soo H (2009) Appl Radiat Isot 67:1162–1166
4. Uddin S, Hagiwara M, Tarkanyi F, Ditroi F, Baba M (2004) Appl Radiat Isot 60:911–920
5. Ryabchikov A, Skuridin S, Nesterov V, Chibisov V, Golovkov M (2004) Nucl Instrum Methods B 213:364–368
6. Zolle I (2007) Technetium-99m radiopharmaceuticals: preparation and quality control in nuclear medicine. Springer, Berlin
7. Maekawa F, Wada M, Konno C, Kasugai Y, Ikeda Y (2000) Fusion Eng Des 51–52:809–814
8. Barabash V, Federici G, R€odig M, Snead L, Wu H (2000) J Nucl Mater 283–287:138–146
9. Barabash V, Federici GJ, Linke H, Wu (2003) J Nucl Mater 313–316:42–51
10. Karadag M, Yucel H (2004) Ann Nucl Energy 31:1285–1297
11. Gillette JH (1966) Oak Ridge National Lab, Preprint: ORNL-4013, Vol 5
12. Kafala SI, MacMahon TD, Borzakov SB (1997) J Radioanal Nucl Chem 215:193–204
13. Damle PP, Fabry A, Jacquemin R (1967) Study of the reaction $^{186}$W$(n,\gamma)^{187}$W, Report from Euratom to EANDC-76, Jan. 1967, p 107
14. Fabry A, Jacquemin R (1969) Progress Report, March 1969, p 195, Available from: Exfor Data Bank
15. Dahlberg R, Jirlow K, Johansson E (1961) J Nucl Energy 14:53–54
16. De Corte F, Speecke A, Hoste J (1971) J Radioanal Chem 9:9–17
17. De Soete D, Gijbels R, Hoste J (1972) Neutron Activation Analysis, John Wiley & Sons Ltd.
18. Høgdahl OT (1962) neutron absorption in pile neutron activation, Report MMPP-226-1, 1962
19. Westcott CH (1960) Effective cross section values for well-moderated thermal reaction spectra, Chalk River Laboratory, Atomic Energy of Canada Limited, Technical Report CRRP-960 (3rd Edition corrected) 1960
20. Stoughton RW, Halperin J (1959) Nucl Sci Eng 6:100–118
21. Ryves TB, Paul EB (1968) J Nucl Energy 22:759–775

22. De Corte F, Moens L, Jovanovic S, Simonits A, De Wispelaere A (1986) J Radioanal Nucl Chem 102:37–57
23. Blaauw M (1995) Nucl Instrum Methods A 356:307–403
24. Martinho E, Goncalves F, Salgado J (2003) Appl Radiat Isot 58:371–375
25. NuDat2 (2007) The Nu Dat Program for Nuclear Data on the Web, National Nuclear Center, Brookhaven National Laboratory, Version 2.4 http://www.nndc.bnl.gov/nudat2/
26. De Corte F (2003) J Radioanal Nucl Chem 257:493–499
27. Holden E (1998) Neutron scattering and absorption properties, CRC handbook of chemistry and physics, 79th edn. CRC Press, New York
28. De Corte F, Simonits A (1989) J Radioanal Nucl Chem Artic 133:43–130
29. Gryntakis E, Cullen DE, Mundy G (1987) Handbook on nuclear activation data, IAEA Technical Reports Series 273, Vienna
30. Damle PP, Fabry A, Jacquemin R (1967) Study of the reaction $^{186}W(n,\gamma)$ $^{187}W$. Report from Euratom-Countries + Euratom to EANDC-76, 107(2)
31. Mughabghab S (1984) Neutron Cross section. Vol 1. Academic press, Inc., Santiago
32. Simonits A, De Corte F, Elnimr T, Moens L, Hoste J (1984) J Radioanal Nucl Chem Artic 81:379–415
33. Gillette JH (1966) Preprint: ORNL-4013, Vol.5, Oak Ridge National Lab. 1966
34. Chadwick MB et al (2006) ENDF/B-VII.0: next generation evaluated nuclear data library for nuclear science and technology. Nucl Data Sheets 107(2006):2931–3060
35. Shibata K et al (2002) Japanese Evaluated Nuclear Data Library Version 3 Revision-3: JENDL-3.3, J Nucl Sci Technol 39:1125–1136 http://wwwndc.tokai-sc.jaea.go.jp/endl/j33/j33.html
36. JFF Report14 (1994) Table of simple integral neutron cross section data From JEFF-2.2, ENDF/B-VI, JENDL-3.2, BROND-2 and CENDL-2, OECD, 1994
37. Garland MA, Mirzadeh S, Alexander CW, Hirtz GJ, Hobbs RW, Pertmer GA, Knapp JFF (2003) Appl Radiat Isot 59(1):63–72
38. Hayodom V, Boonkong W, Mahapanyawong S, Chaimonkon C (1969) Thai-AEC23 Progress Report, Thailand
39. Harris SP, Muehlhause CO, Thomas GE (1950) Phys Rev 79(1): 11–18
40. Herf RE (1978) A consistent set of nuclear parameter values for absolute INAA, in Conference on computers in activation analysis and gamma-ray spectroscopy, Mayaguez, Puerto Rico, 30 April–4 May, 1978, p 495
41. Gleason G (1977) Thermal Neutron (n,$\gamma$) Part2, Private Communication to NEA-Data Bank, Exfor Accession No. 10662004,1977, http://www-nds.iaea.org/exfor/exfor00.htm
42. De Corte F, Simonits A (1988) Nuclear data for science and technology (Mito 1988), In: H. Schoper (ed), JAERI 1988, Springer Verlarg, Berlin, Heidelberg, 2000, p 583
43. Babich SI, Anufriev VA (1989) Atomnaya Energiya 67:140–141
44. Nguyen D, Pham K, Kim T, Bui Van L, Rahman Md S, Kyung Sook K, Guinyun K, Youngdo O, Hee-Seok L, Moo-Hyun C, In Soo K, Won N (2009) Nucl Instrum Methods 267(3):462–468