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Epithermal neutron self-shielding factors in foils for collimated beams

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Abstract

An epithermal neutron self-shielding factor must be introduced to take into account the absorption of a neutron beam crossing a sample. This factor depends on the geometry and dimension of the sample, as well as on the physical and nuclear properties of the nuclides. On the basis of a dimensionless variable, which includes the relevant characteristics of the sample, universal curves for monoenergetic and $1/E$ collimated neutron beams are proposed, which enable the determination of the self-shielding factor for isolated resonances of high absorber nuclides.

Keywords: Epithermal neutrons; Resonance self-shielding factor; MCNP code

1. Introduction

The authors have recently introduced an universal curve of the resonance self-shielding factor, G_{res}, valid for all nuclides and various samples geometries (wires, foils, spheres and cylinders), the samples being immersed into an isotropic epithermal neutron field (Martinho et al., 2003; Gonçalves et al., 2004).

In the present paper, the work is extended to non-isotropic epithermal neutron beams. Specifically, foils irradiated by monoenergetic and $1/E$ collimated neutron beams are studied.

2. Methodology

Neutron auto-absorption and multi-scattering are the effects that determine the resonance self-shielding factor. The energy self-shielding factor, $G(E_0, t)$, for incident neutron energy E_0 and foil thickness t is calculated as the ratio between the reaction rates per atom in a real sample and in a similar and infinitely diluted sample. Thus,

$$G(E_0, t) = \frac{\int_{E_1}^{E_2} \Phi(E)\sigma_\gamma(E)\,\mathrm{d}E}{\int_{E_1}^{E_2} \Phi_0(E)\sigma_\gamma(E)\,\mathrm{d}E}, \tag{1}$$

where $\Phi_0(E)$ is the non-perturbed neutron flux per unit energy interval (inside the infinitely diluted sample), $\Phi(E)$ is the perturbed neutron flux inside the real sample, $\sigma_\gamma(E)$ designates the (n,γ) cross-section, and E_1 and E_2 are, respectively, the lower and the upper limits of the neutron energy due to multi-scattering inside the sample. The total neutron cross-section has been adopted in the calculation of the perturbed neutron flux, which takes into account the neutron scattering in the sample. In all calculations the density for infinite dilution was assumed to be $\rho = 10^{-6}\rho_0$, ρ_0 representing the density of the real sample.

An analogous equation can be used to define the epithermal neutron resonance self-shielding factor, $G_{res}(t)$. In this case, $\Phi_0(E) \propto E^{-1}$ and E_1 and E_2 are, respectively, the lower and the upper limits around the resonance energy E_{res}.

For a given nuclide and foil thickness, $G(E_0, t)$ and $G_{res}(t)$ were calculated by using the MCNP Monte Carlo transport code (Briesmeister, 2000). The nuclides studied

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Table 1
Some physical and nuclear properties of ^{232}Th, ^{197}Au and ^{56}Fe

Nuclide	A (g mol $^{-1}$)	ρ (g cm^{-3})	E_{res} (eV)	$\sigma_t(E_{res})$ (barn)	$\sigma_\gamma(E_{res})$ (barn)	$\sigma_s(E_{res})$ (barn)	Γ_γ (eV)	Γ_n (eV)	$\Gamma = \Gamma_\gamma + \Gamma_n$ (eV)	Γ_γ/Γ (%)
Th-232	232.04	11.72	21.81	1925	1770	155	0.025	0.0021	0.0271	92.4
			23.46	3183	2770	413	0.027	0.0038	0.0308	87.4
			59.52	837	715	122	0.024	0.0038	0.0278	86.3
			69.23	6751	2343	4408	0.023	0.0432	0.0662	34.7
Au-197	197.0	19.3	4.91	3.08×10^4	2.74×10^4	3.4×10^3	0.124	0.015	0.139	89.2
Fe-56	55.4	7.86	1.15	78.8	62.9	15.9	0.574	0.062	0.636	90.3

Γ_γ, Γ_n and Γ are the radiative, scattering and total resonance widths, respectively.

were ^{232}Th, ^{197}Au and ^{56}Fe. Relevant physical and nuclear properties for these nuclides are given in Table 1.

3. Results and discussion

3.1. Results for ^{232}Th foils

Fig. 1 shows the energy self-shielding factor, $G(E,t)$, for ^{232}Th foils of different thicknesses as a function of the incident neutron energy. Three conclusions can be drawn:

1. For neutron energies far away from the resonances, $G(E,t)$ is practically equal to unity for all thicknesses. This means that the auto-absorption and the multi-scattering are insignificant.
2. For $E = E_{res}$, $G(E,t) < 1$ and decreases as the thickness increases. The auto-absorption is very important, specially for $E_{res} = 23.5$ and 69.2 eV—higher capture cross sections.
3. For energies greater than E_{res} (but near E_{res}), $G(E,t)$ becomes greater than unity and increases as the thickness increases, attaining values higher than 2.5. In this case, multi-scattering predominates. Neutrons impinging on the foil with $E > E_{res}$ can suffer one or more scattering interactions before their capture at a lower energy, where the capture cross-section is higher. It should be noted that the peak position moves towards the right (higher energies) as the thickness increases.

Fig. 2 shows $G(E_{res}, t)$ of the four resonances, as a function of the foil thickness. For small thicknesses, it is practically equal to unity. For thick foils, $G(E_{res}, t)$ decreases as the thickness increases. For a given thickness, $G(E_{res}, t)$ depends on E_{res}, i.e. on the cross-sections. The decrease is more pronounced for the resonances with higher capture cross-sections. The curves can be adjusted by the following equations:

$$G(E_{res} = 21.8; t) = \frac{1}{1 + (t/0.00099)^{1.085}}, \quad (2)$$

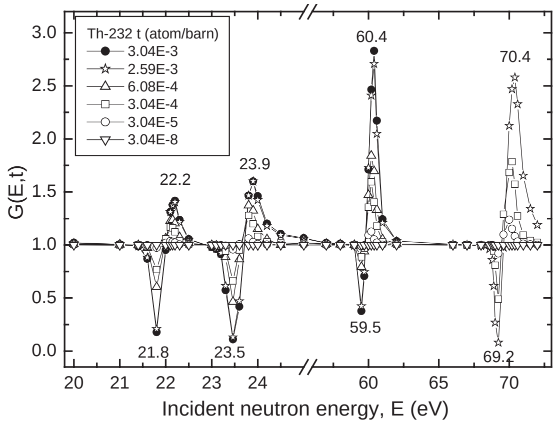

Fig. 1. Energy self-shielding factor for different incident neutron energies and ^{232}Th foil thicknesses.

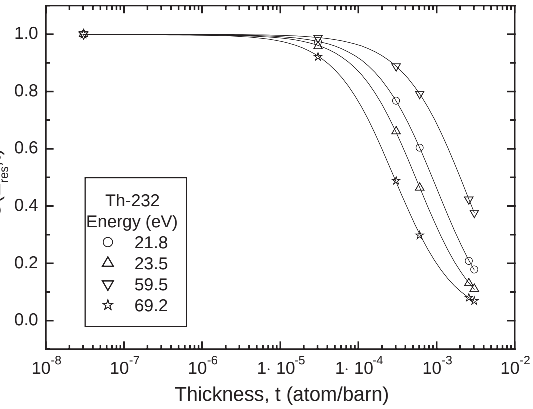

Fig. 2. Energy self-shielding factor for the resonance energies as a function of the ^{232}Th foil thickness.

$$G(E_{res} = 23.5; t) = \frac{1}{1 + (t/0.00056)^{1.126}}, \quad (3)$$

$$G(E_{res} = 59.5; t) = \frac{1}{1 + (t/0.00259)^{1.043}}, \quad (4)$$

$$G(E_{res} = 69.2; t) = \frac{1}{1 + (t/0.0029)^{1.122}}. \qquad (5)$$

Fig. 3 shows $G(E, t)$ for the energies corresponding to the peaks seen in Fig. 1 as a function of the thickness ($E' \approx E_{res} + \overline{\Delta E}$—where $\overline{\Delta E}$ is the average energy lost in one scattering event). $G(E, t)$ is always equal to or higher than unity and increases as the thickness increases due to an increase in multi-scattering events. The multi-scattering predominates over the absorption and the neutrons are absorbed with energies smaller than the incident energy.

3.2. Results for ^{197}Au foils

Fig. 4 shows the energy self-shielding factor, $G(E, t)$, for ^{197}Au foils. Two conclusions can be drawn:

1. For neutron energies far away from the resonance, $G(E, t)$ is practically equal to unity for all thicknesses.
2. For $E = E_{res}$, $G(E, t) < 1$ and decreases as the thickness increases. The auto-absorption is very important.

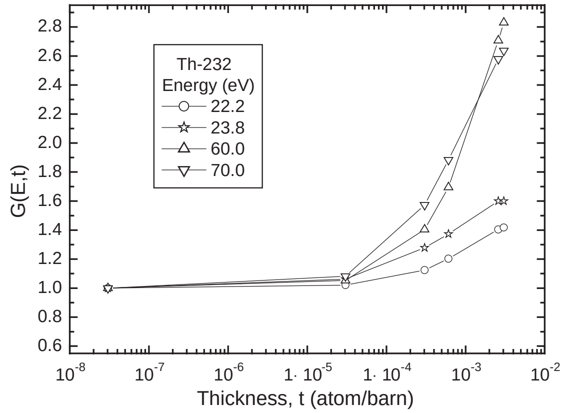

Fig. 3. Energy self-shielding factor for different energies as a function of the thickness.

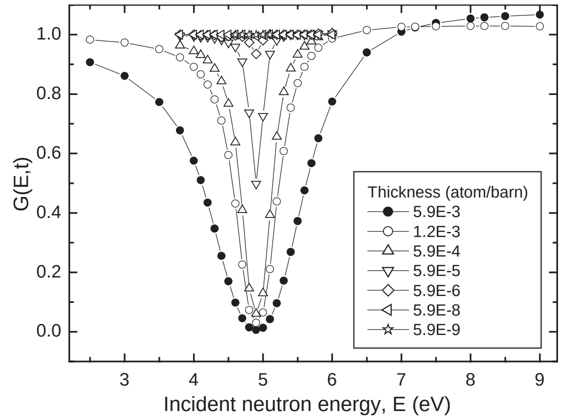

Fig. 4. Energy self-shielding factor for ^{197}Au foils as a function of the incident neutron energies, for different thicknesses.

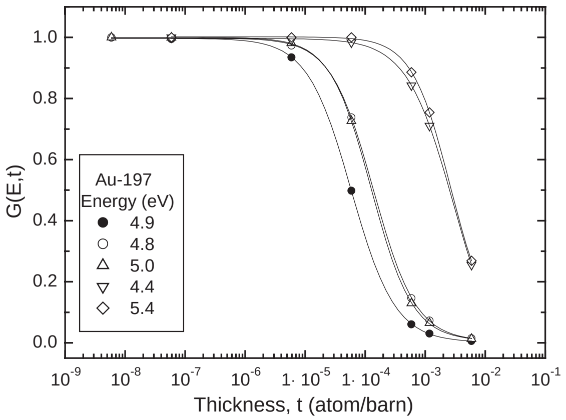

Fig. 5. Energy self-shielding factor for ^{197}Au foils for different neutron energies as a function of the thickness.

Fig. 5 shows $G(E, t)$ corresponding to five neutron energies as a function of the foil thickness. For small thicknesses, it is practically equal to unity. For thick foils, $G(E, t)$ decreases as the thickness increases. For the resonance energy, $G(E_{res}, t)$ can be fitted by the equation

$$G(E_{res}, t) = \frac{1}{1 + (t/0.00006)^{1.187}}. \qquad (6)$$

3.3. Results for ^{56}Fe foils

Fig. 6 shows the energy self-shielding factor, $G(E, t)$, for ^{56}Fe foils. Three conclusions can be drawn:

1. For neutron energies far away from the resonance, $G(E, t)$ tends to unity for all thicknesses.
2. For $E = E_{res}$, $G(E, t) < 1$ and decreases as the thickness increases. The auto-absorption is very important.
3. For $E > E_{res}$, the behaviour of $G(E, t)$ is very interesting, attaining very high values. For $t = 9.7\text{E} - 4$ atom/b (0.1 mm), the peak has a maximum at 1.20 keV; this result means that neutrons have suffered, on average, one scattering event before absorption ($\overline{\Delta E} \approx 0.04$ keV) and its final energy corresponds to the maximum of the capture cross-section. The number of scattering events increases with the thickness and, consequently, the peak dislocates its position towards higher incident neutron energies.

Fig. 7 shows $G(E,t)$ corresponding to different energies as a function of the foil thickness. For $E < E_{res}$ and thin foils, it is practically equal to unity, whereas for thick foils, $G(E,t)$ decreases as the thickness increases (Fig. 7(a)). For $E > E_{res}$ and thin foils, it is practically equal to unity and, as the thickness and energy increase, $G(E,t)$ also increases (Fig. 7(b)). The behaviour of the curve for $E = 1.23\,\text{keV}$ means that, for $t > 2 \times 10^{-2}$ atom/b, there is more than one collision before capture. For the resonance energy, $G(E_{res},t)$ can be fitted by the equation

$$G(E_{res},t) = \frac{1}{1+(t/0.026)^{1.134}}. \tag{7}$$

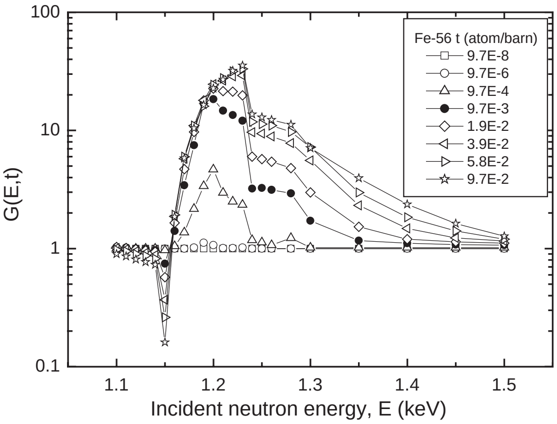

Fig. 6. Energy self-shielding factor for ^{56}Fe for different incident neutron energies and thicknesses.

3.4. Comparison of results

As referenced above, the authors have shown that the dependence of the resonance neutron self-shielding factor for foils immersed in an isotropic neutron field on physical and nuclear parameters can be converted into an unique curve by the introduction of the dimensionless variable, z,

$$z = \Sigma_{tot}(E_{res})t\sqrt{\frac{\Gamma_\gamma}{\Gamma}}, \tag{8}$$

where Γ_γ and Γ are the radiative and total resonance widths, respectively.

The same formalism is now applied to foils in collimated neutron beams. The energy self-shielding factors for ^{56}Fe, ^{197}Au and ^{232}Th are plotted in Fig. 8 as a function of the dimensionless variable z. The points can be fitted by the curve:

$$G(E_{res},z) = \frac{1}{1+(z/1.58)^{1.157}}. \tag{9}$$

The $G_{res}(E)$ of foils submitted to a $1/E$ collimated neutron beam perpendicular to the foil (Gonçalves et al., 2002) can also be fitted with the sigmoid

$$G_{res}(z) = \frac{1}{1+(z/3.57)^{0.948}} + 0.090. \tag{10}$$

As in the case of a $1/E$ isotropic neutron field impinging on a foil, the fitted curves show that the dimensionless variable converts the dependence of the neutron self-shielding factors on physical and nuclear parameters into universal curves valid for isolated resonances of strong neutron absorbers.

Fig. 9 compares self-shielding factors of foils irradiated by monoenergetic and $1/E$ collimated neutron beams with the resonance self-shielding factor for a $1/E$

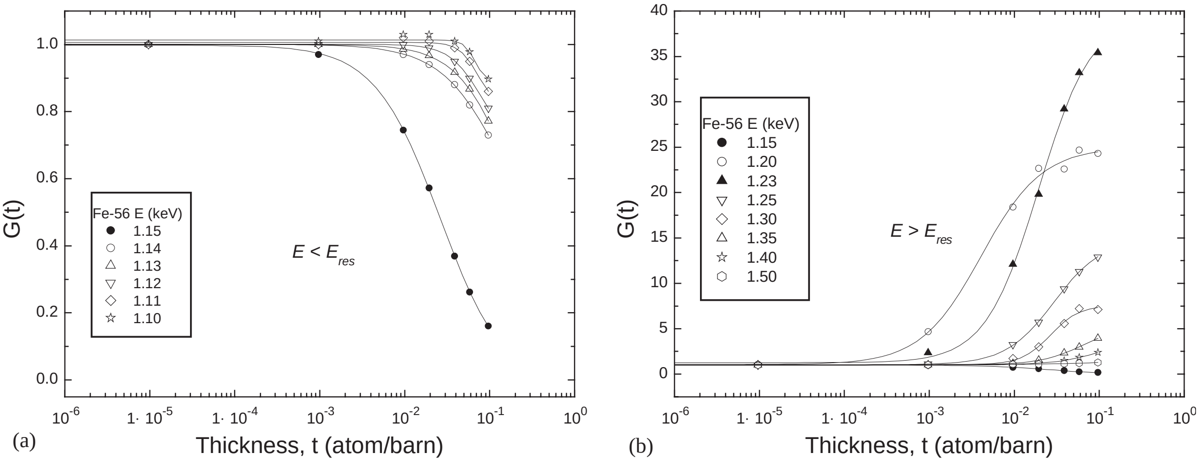

Fig. 7. Energy self-shielding factor for ^{56}Fe for the different energies as a function of the thickness; (a) $E < E_{res}$ and (b) $E > E_{res}$.

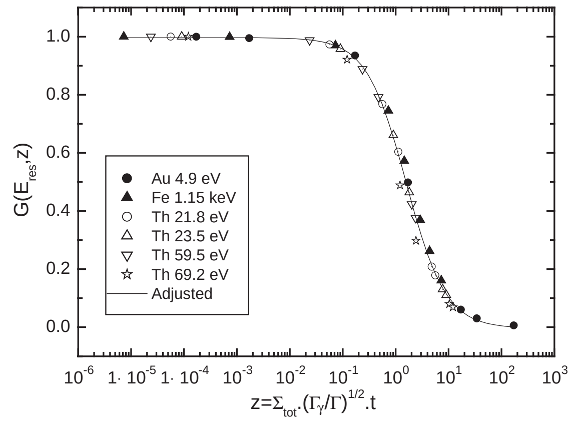

Fig. 8. Universal curve of the resonance self-shielding factor for a collimated monoenergetic neutron beam impinging perpendicularly to a foil.

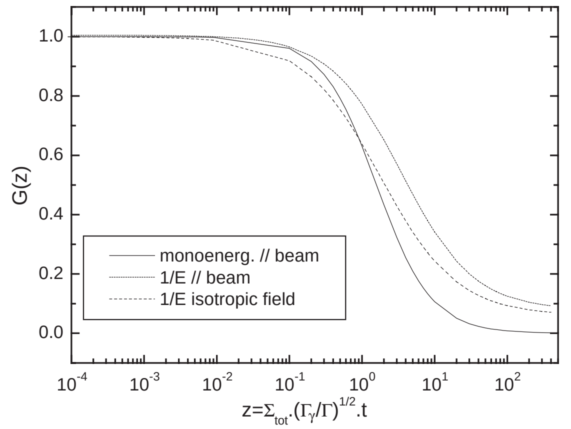

Fig. 9. Comparison of universal curves calculated for the following conditions: (i) collimated monoenergetic neutron beam (solid), (ii) $1/E$ collimated neutron beam (dotted) and (iii) $1/E$ isotropic neutron field (dashed).

isotropic neutron field. Note that in the last two cases all the energies between E_1 and E_2 contribute for the calculations. The energy resonance self-shielding factors, $G(E_{res}, t)$, of the monoenergetic collimated beam are always smaller than the resonance self-shielding factors, $G_{res}(t)$, of the $1/E$ collimated beam; the values of the $1/E$ isotropic neutron field are smaller than the corresponding values for the $1/E$ parallel beam; for $z<1$, it is observed that the values of $1/E$ isotropic neutron field are smaller than the corresponding parallel beam. Opposite effects contribute to the observed differences: greater average path length of neutrons inside the foil in the isotropic case (higher absorption and scattering); and contributions of $E \neq E_{res}$ in the $1/E$ case (lesser absorption). Comparing the monoenergetic parallel beam with the $1/E$ isotropic field, it is possible to conclude that the isotropic effect prevails for $z<1$, while for $z>1$ the neutron energy effect dominates.

4. Conclusions

The results show that there are differences between the resonance energy self-shielding factor, $G(E_{res}, t)$, and the resonance neutron self-shielding factor, $G_{res}(t)$, for a collimated neutron beam. As for a foil immersed in a $1/E$ isotropic neutron field, a dimensionless variable can be introduced that converts the dependence of $G(E_{res}, t)$ into an unique curve, valid for all nuclides. The neutron absorption in a foil immersed in an isotropic field is higher than that in a foil irradiated by a collimated beam.

References

Briesmeister, J.F. (Ed.), 2000. MCNP—A general Monte Carlo n-particle transport code. Los Alamos National Laboratory Report LA-13709 – M.

Gonçalves, I.F., Martinho, E., Salgado, J., 2004. Extension to cylindrical samples of the universal curve of resonance neutron self-shielding factors. Nucl. Instrum. Methods 213, 186–188.

Gonçalves, I.F., Martinho, E., Salgado, J., 2002. Monte Carlo calculation of epithermal neutron resonance self-shielding factors in foils of different materials. Appl. Radiat. Isot. 56, 945–951.

Martinho, E., Gonçalves, I.F., Salgado, J., 2003. Universal curve of epithermal neutron resonance self-shielding factors in foils, wires and spheres. Appl. Radiat. Isot. 58 (3), 371–375.