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Extension to cylindrical samples of the universal curve of resonance neutron self-shielding factors

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Abstract

Resonance neutron self-shielding factors for cylindrical samples of nuclides used as activation detectors or as targets for radionuclide production have been calculated using the MCNP code. These factors depend on the sample dimensions, as well as on the physical and nuclear properties of the nuclides. However, defining a dimensionless variable, which includes the relevant characteristics of the samples, it is possible to extend to cylinders a previously deduced universal curve for isolated resonances of any nuclide and samples of other geometries (foils, wires and spheres).

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1. Introduction

The presence of a sample in an epithermal neutron field originates a flux perturbation due to neutron absorption inside the sample. The resonance neutron self-shielding factor, G_{res} depends mainly on material properties, reaction cross-section and thickness (for foils) or radius (for wires and spheres).

It has been shown recently that (a) a dimensionless variable, z, can be introduced which converts the dependence of G_{res} on physical and nuclear parameters of the samples into an universal curve, valid for isolated resonances of any nuclide and various geometries (foils, wires and spheres) [1] and (b) the universal curve can be generalised for a group of isolated resonances, by weighting its individual contributions [2].

The present work extends the universal curve to cylindrical samples. The MCNP code [3] was used to calculate G_{res} values of the following nuclides: ^{55}Mn, ^{59}Co, ^{63}Cu, ^{115}In, ^{185}Re and ^{197}Au.

2. Methodology of calculation

Following the methodology proposed in previous works [4–6], the resonance neutron self-shielding factor in cylinders of radius R and height h, $G_{res}(R,h)$, is defined as the ratio between the reaction rates per atom in the real sample and in a similar and infinitely diluted sample. Thus

$$G_{res}(R,h) = \frac{\int_{E_1}^{E_2} \Phi(E)\sigma_{n\gamma}(E)\,dE}{\int_{E_1}^{E_2} \Phi_0(E)\sigma_{n\gamma}(E)\,dE}, \tag{1}$$

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Table 1
Physical and nuclear parameters of the studied nuclides [7,8]

Nuclide	A (g mol^{-1})	ρ (g cm^{-3})	θ (%)	E_{res} (eV)	σ_{tot} (E_{res}) (barn)	Γ_γ (eV)	Γ_n (eV)	$\Gamma = \Gamma_\gamma + \Gamma_n$ (eV)	Γ_γ/Γ_n (%)
^{197}Au	196.97	19.3	100	4.91	30 770	0.1225	0.0152	0.1377	89.0
^{59}Co	58.93	8.9	100	132	10 370	0.47	5.27	5.74	8.2
^{63}Cu	63.55	8.96	69.17	579	918	0.485	0.59	1.075	45.1
^{115}In	114.82	7.31	95.71	1.46	31 150	0.072	0.00304	0.07504	95.9
^{55}Mn	54.94	7.32	100	337	3290	0.31	21.99	22.30	1.4
^{185}Re	186.2	21.02	37.40	2.16	24 550	0.0549	0.00283	0.05773	95.1

where $\Phi_0(E) \propto E^{-1}$ is the original, non-perturbed, epithermal neutron flux per unit energy interval inside the infinitely diluted sample, $\Phi(E)$ represents the perturbed epithermal neutron flux inside the real sample, $\sigma_{n\gamma}(E)$ designates the (n, γ) cross-section and E_1 and E_2 are, respectively, the lower and the upper limits around the resonance energy E_{res}. The total neutron cross-section has been adopted in the calculation of the perturbed neutron flux $\Phi(E)$, thus taking into account the neutron scattering in the sample. A fictitious density $\rho = 10^{-6}\rho_0$ has been adopted in the simulation of infinite dilution to calculate the non-perturbed reaction rate, ρ_0 representing the density of the real sample.

The MCNP code was used to calculate G_{res} values of the following nuclides: ^{55}Mn, ^{59}Co, ^{63}Cu, ^{115}In, ^{185}Re and ^{197}Au. Table 1 shows the physical and nuclear properties of these isotopes. For each of the 3 cylinder radii used in the calculations ($R = 0.001$, 0.01 and 0.1 cm), 3 heights were considered, corresponding to $h = 1R$, $2R$ and $3R$.

The dimensionless variable depends, for this geometry, on its two linear dimensions, R and h. According to a suggestion of Gilat and Gurfinkel [9], the one-dimensional parameter adopted for cylinders was

$$x = \frac{R \cdot h}{R + h}, \qquad (2)$$

which has the dimension of a length.

3. Results and discussion

The resonance neutron self-shielding factor depends on the sample properties, namely geometry, dimensions, density (ρ) atomic mass (A), natural abundance (θ) and resonance neutron cross-section $[\Sigma_{tot}(E_{res})]$. In a previous work [1], the authors have shown that a dimensionless variable, z,

$$z = \Sigma_{tot}(E_{res}) \cdot y \cdot \sqrt{\frac{\Gamma_\gamma}{\Gamma}} \qquad (3)$$

can be introduced which converts the dependence of the resonance neutron self-shielding factor of wires, foils and spheres on physical and nuclear parameters into an universal curve valid for isolated resonances of any nuclide. Γ_γ and Γ are the radiative and total resonance widths, respectively and y is a geometrical parameter: $y = 2R$ for wires, $y = 1.5t$ for foils and $y = R$ for spheres, where R and t designate the appropriate radius and the thickness of the samples, respectively.

The universal curve of G_{res} is a sigmoid given by

$$G_{res}(z) = \frac{A_1 - A_2}{1 + \left(\frac{z}{z_0}\right)^p} + A_2, \qquad (4)$$

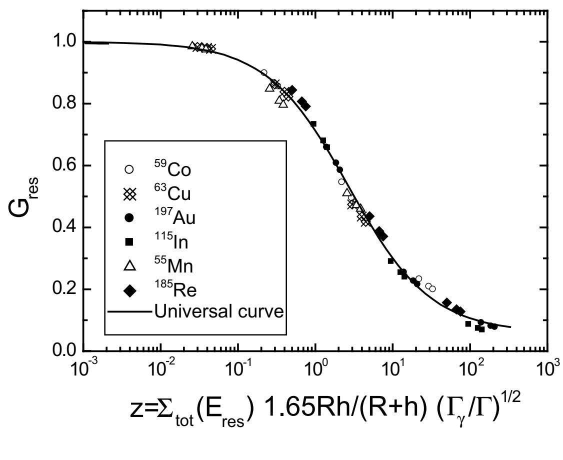

Fig. 1. Extension of the universal curve of G_{res} to cylindrical samples.

Table 2
Applicability of the universal curve of $G_{res}(z)$ for the various geometries

$$G_{res}(z) = \frac{A_1 - A_2}{1 + \left(\frac{z}{z_0}\right)^p} + A_2 \qquad z = \Sigma_{tot}(E_{res}) \cdot y \cdot \sqrt{\frac{\Gamma_y}{\Gamma}}$$

Geometry (typical dimensions)	Geometrical parameter y (cm)	Parameters of the universal curve			
		A_1	A_2	z_0	p
Wires (radius = R)	$y = 2R$	1.000 ± 0.005	0.060 ± 0.011	2.70 ± 0.09	0.82 ± 0.02
Cylinders (radius = R; height = h)[a]	$y = 1.65\frac{Rh}{R+h}$				
Foils (thickness = t)	$y = 1.5t$				
Spheres (radius = R)	$y = R$				

[a] $1 \leqslant h/R \leqslant 3$.

where $A_1 = 1.000 \pm 0.005$, $A_2 = 0.060 \pm 0.011$, $z_0 = 2.70 \pm 0.09$, $p = 0.82 \pm 0.02$.

Using the dimensionless variable z^* given by

$$z^* = \Sigma_{tot}(E_{res}) \cdot \frac{R \cdot h}{R + h} \cdot \sqrt{\frac{\Gamma_\gamma}{\Gamma}}, \tag{5}$$

a sigmoid was fitted to the fifty-four calculated values of G_{res} for cylinders (6 nuclides and 9 cylinders/nuclide). The parameters of the adjusted sigmoid are as follows:

$$A'_1 = 1.011 \pm 0.011; \quad A'_2 = 0.051 \pm 0.011;$$
$$z'_0 = 1.622 \pm 0.077 \quad \text{and} \quad p' = 0.781 \pm 0.032.$$

Attending to the error bars (1σ), the values of A'_1, A'_2 and p' are compatible with the corresponding values of the universal curve. Fixing these parameters and using the least squares method, the adjusted value of z'_0 is $z_{0,cyl} = 1.635$. This means that it is possible to translate the sigmoid curve for cylinders into the universal curve by making the variable transformation:

$$z = (z_0/z_{0,cyl}) \cdot z^* = 1.65 \cdot z^*. \tag{6}$$

Then, a good agreement is obtained between the universal curve and G_{res} values of cylindrical samples, as is shown in Fig. 1.

Table 2 summarises the conditions of applicability of the universal curve for spheres, foils, wires and cylinders. Note that the "form factor" corresponding to cylinders (1.65) lies between 1.5 (foils) and 2 (wires), which reveals the consistency of the results.

4. Conclusion

The results presented in this work show that the universal curve of G_{res} which describes the behaviour of the resonance neutron self-shielding factor of foils, wires and spheres, can be extended to cylinders. In this case, the dimensionless variable is a function of the cylinder radius and height. The curve is valid for isolated resonances of any nuclide.

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