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Neutron Self-Shielding in the Thermal Range

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Things used to be so simple....

Neutron self-shielding in the thermal range
Overview

• definition of self-shielding
• principles of cross section dependence on velocity
• self-shielding at 2200 m/s
  • absorption only
  • with scattering
• self-shielding in a thermal neutron spectrum
  • absorption only
  • with scattering
• self-shielding in reality
  • three experiments
• Conclusions
A definition of $1/v$ self-shielding

$$f = \frac{R}{V\Sigma_{0,a} \Phi_0} = \frac{R}{N\sigma_{0,a} \Phi_0}$$

where

- $f$ is the self-shielding factor
- $R$ is the activation rate (captures per second)
- $V$ is the sample volume
- $\Sigma_{0,a}$ is the macroscopic absorption cross section ($m^2/m^3$)
- $\Phi_0$ is the incoming conventional neutron flux $n\nu_0$ ($m^{-2}s^{-1}$)
- $N$ is the number of atoms
- $\sigma_{0,a}$ is the microscopic absorption cross section ($m^2$)
Absorption and scattering as a function of neutron velocity

Comparison of ENDF and theoretical H scattering data

Interaction rate
Free-gas and the real thing

BNL 325, in “Reactor Physics”, proc. ANS topical meeting, MIT press (1966), and the same data as on the previous sheet for the M=1, free-gas model.

The vertical blue lines indicate the $h\nu$ of H$_2$O.
The ratio of the bound atom scattering cross section to the free atom scattering cross section is the square of the ratio of the corresponding reduced masses.

\[
\frac{M_{\text{eff}}}{1 + M_{\text{eff}}} \cdot \frac{1 + M}{M} = \sqrt{\frac{\sigma(M_{\text{eff}})}{\sigma_0}}
\]
At 2200 m/s, absorption only, in a beam

\[ f = \frac{1 - e^{-\Sigma_{0,a}d}}{\Sigma_{0,a}d} \]

This equation for slab only, others available for other shapes
At 2200 m/s, absorption and scattering, in a beam

Average neutron path length in sample may increase.

That means \( f > 1 \) !!!!!!
At 2200 m/s, absorption only, isotropic

\[ \Psi = R \Sigma_a \]

\[ f = \frac{3}{4 \Psi^3} \left( \Psi^2 + \left( \frac{1}{2} + \Psi \right) e^{-2\Psi} - \frac{1}{2} \right) \]

This equation for sphere only, others available for other shapes
Stuart’s formula

For use in thermal isotropic flux only

\[ f = \frac{f_0}{1 - \frac{\sum_s}{\sum_t} (1 - f_0)} \]

\( f_0 \) to be calculated using the standard formula for the object shape in question and the total macroscopic cross section.

At 2200 m/s, absorption and scattering, isotropic

\[
\Psi = R \Sigma_t \\
\begin{align*}
\mathcal{f}_0 &= \frac{3}{4 \Psi^3} \left( \Psi^2 + \left( \frac{1}{2} + \Psi \right) e^{-2\Psi} - \frac{1}{2} \right)
\end{align*}
\]
Stuart, Copley and Blaauw

\[ f(X, X_s = 0) \]

- Stewart
- Copley
- Stewart according to Blaauw

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Thermal flux, absorption only, in a beam

\[ f = \frac{\left(1 - e^{-\langle \Sigma_a \rangle d}\right)}{\langle \Sigma_a \rangle d} \]

thin: \[ \langle \Sigma_a \rangle = \frac{2}{\sqrt{\pi}} \frac{T_0}{T} \Sigma_{0,a} \]

thick: \[ \langle \Sigma_a \rangle = \frac{2}{\sqrt{\pi}} \frac{T_0}{T} \Sigma_{0,a} \]

Same for other shapes: Just use the right average

Thermal flux, absorption and scattering, in a beam
Thermal flux, absorption and scattering, in a beam

Average neutron path length in sample increases. Purely thermal flux: No moderation effect. That means $f > 1$ !!!!
Thermal flux, absorption and scattering, isotropic

No simple equations known! If flux is purely thermal, 2200 m/s approximation with $\langle \Sigma_a \rangle$ is good. If epithermal component present, moderation kicks in...
Self-shielding in reality

• Gradient flux effect on scattering, slab-shaped samples
• Effect of scattering samples on gradient
• BISNIS experiences
Gradient flux effect on scattering, slab-shaped samples

- If \( f \) can be larger than unity in a slab, in a purely thermal beam, what could happen in a strong gradient?

Unpublished work by Lindstrom and Blaauw
Results for SXS/ XSX ratios

- Experimental
  - In beam: $1.150 \pm 0.005$
  - In gradient: $0.993 \pm 0.001$

- Monte Carlo
  - In isotropic: $0.999 \pm 0.002$
  - In gradient: $0.998 \pm 0.002$
  - In beam: $1.118 \pm 0.002$

Conclusion: Gradient fields are ok
Effect of scattering samples on gradient

Lindstrom and Blaauw

Core

flux

distance from core

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BI SNI S experiences

Overwater,
Bode,
Baas,
Blaauw

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Sample container and sample
Neutron self-shielding
Neutron self-shielding
Results per layer compared to ordinary INAA

Analysis method:
- REDNAILS:
  - 0 Neighbours
  - 1 Neighbour
  - 2 Neighbours
- INAA

Analysis of Fe per voxel (g)

Analysis of Sc per voxel (μg)

Analysis of Cr per voxel (mg)
Conclusions

• Keep your samples small
• Always sandwich between monitors
• If in a beam, either use spherical shape or do internal standardization
• In an isotropic flux, make sure you use the right, temperature-corrected averaged capture cross section.
• For hydrogenous materials, try to use a very thermal flux. Otherwise, Cd-cover may be essential to check for the epithermal-moderated contribution.