Neutron self-shielding in the thermal range

Things used to be so simple....

Nuclear data for Activation Analysis

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March 18, 2005

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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)

Φ_0 is the incoming conventional neutron flux nv_0 ($m^{-2}s^{-1}$)

N is the number of atoms

$\sigma_{0,a}$ is the microscopic absorption cross section (m^2)

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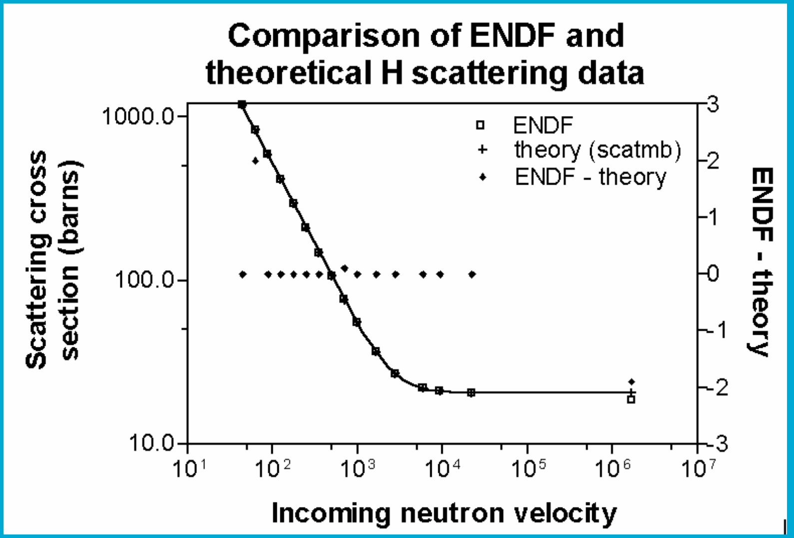
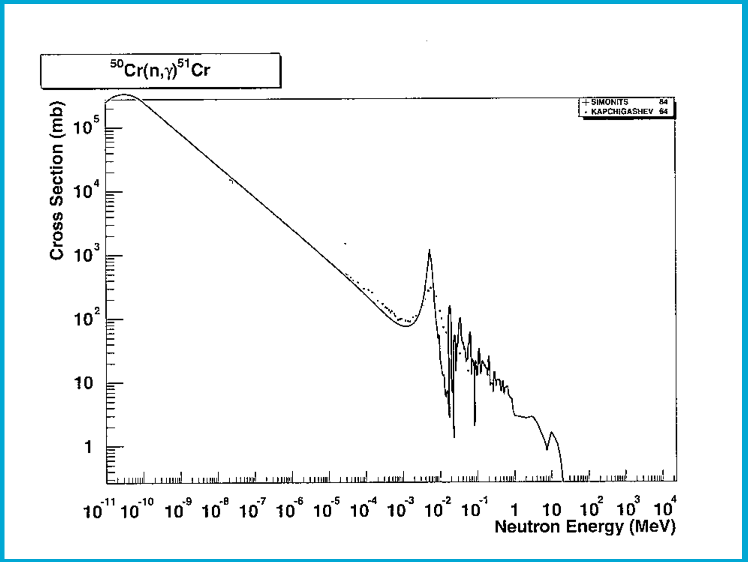
Absorption and scattering as a function of neutron velocity

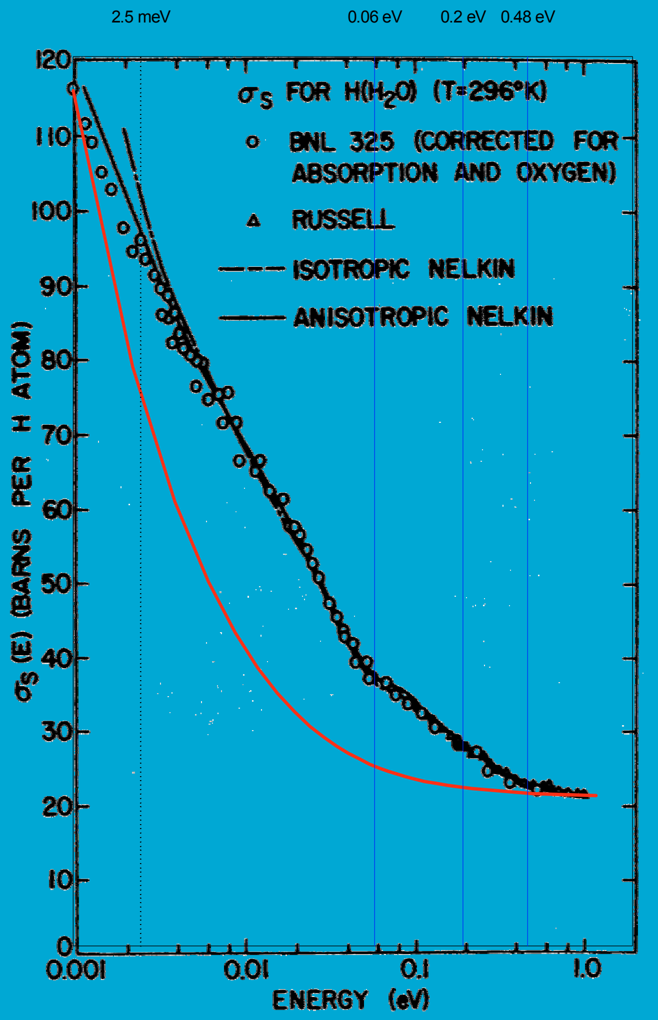


Interaction rate



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 hν of H_2O.



Beckurts & Wirtz

"Neutron Physics"
by
K.H. Beckurts,
K. Wirtz
(Springer Verlag,
1958), probably from
E. Fermi, "Sul moto
dei Neutroni nelle
sostanza idrogenate",
Ricera Scientifica
7(2) 1936.

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.

$$\frac{M_{eff}}{1+M_{eff}}\frac{1+M}{M}=\sqrt{\frac{\sigma\left(M_{eff}\right)}{\sigma_0}}$$

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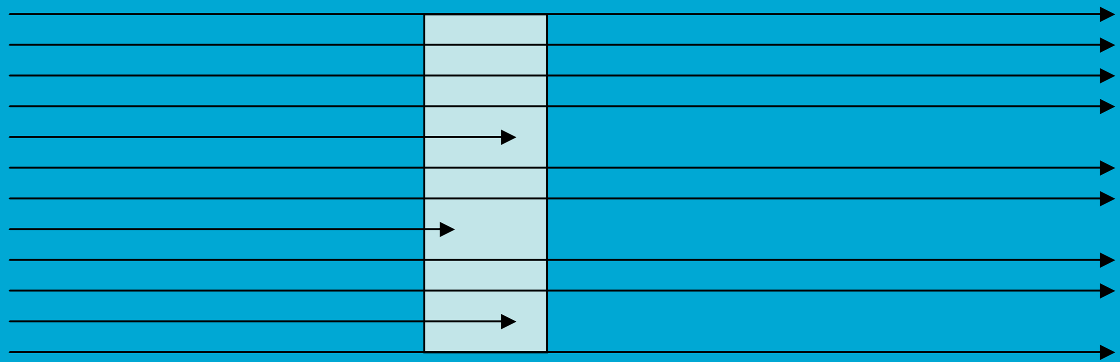
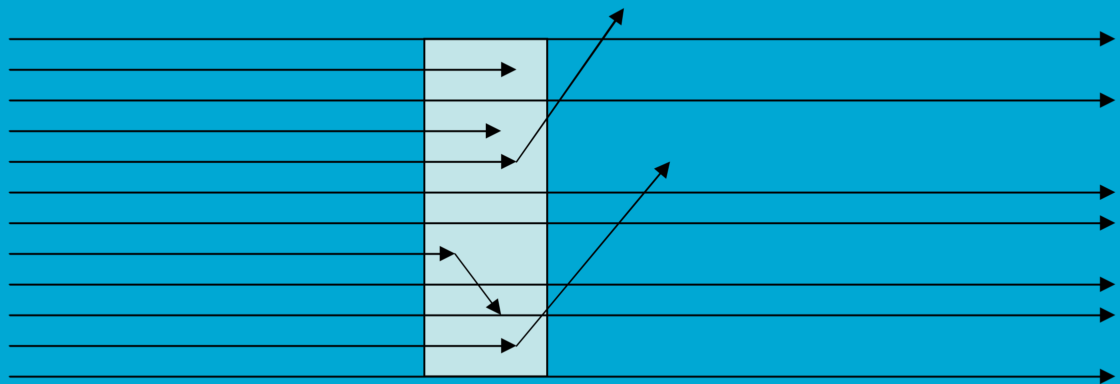
At 2200 m/s, absorption only, in a beam



$$f = \frac{\left(1 - e^{-\Sigma_{0,a} d}\right)}{\Sigma_{0,a} d}$$

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 !!!!!!!

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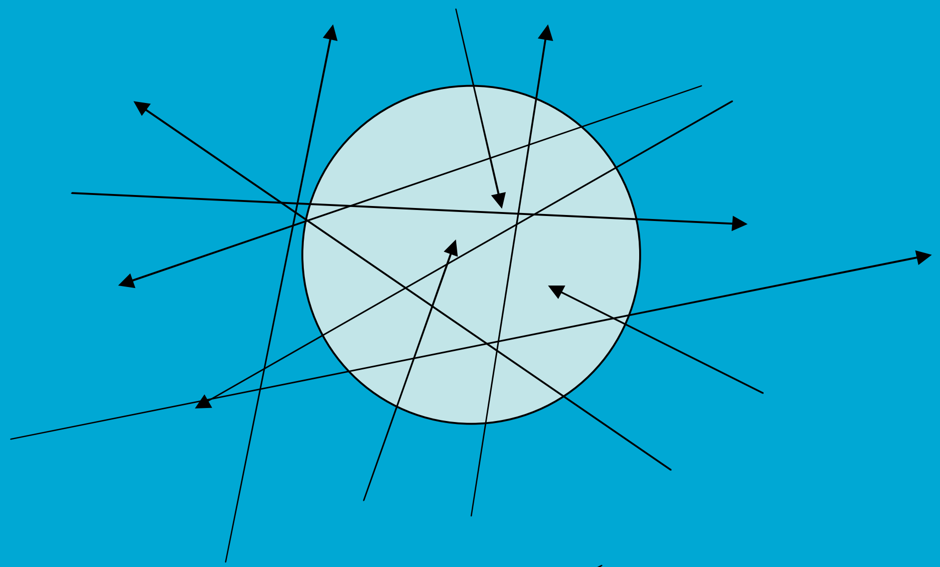
At 2200 m/s, absorption only, isotropic



$$\Psi = R\Sigma_a$$

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

This equation for sphere only, others available for other shapes

Stuart’s formula

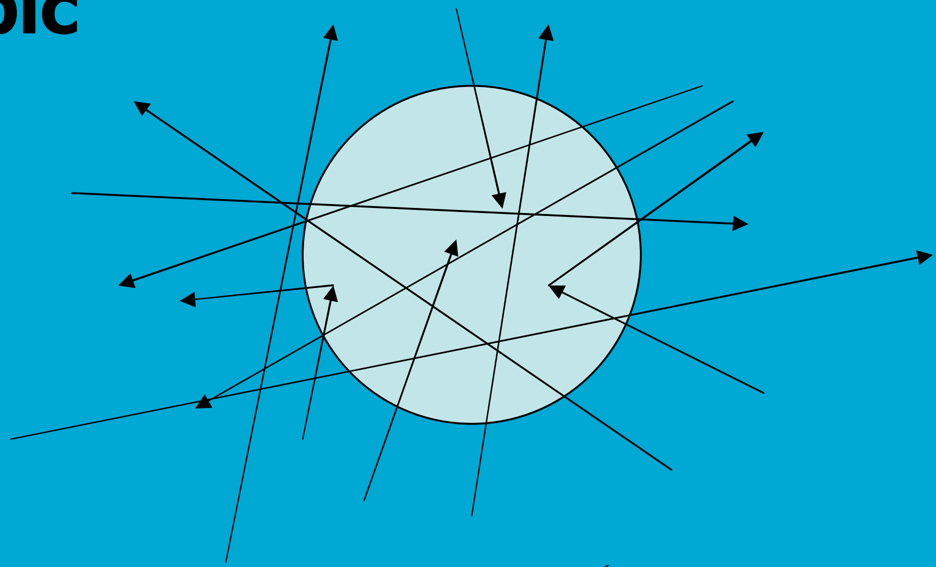
For use in thermal isotropic flux only

$$f = \frac{f_0}{1 - \frac{\Sigma_s}{\Sigma_t}\left(1 - f_0\right)}$$

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

M. Blaauw, “The derivation and proper use of Stewart’s formula for thermal neutron self-shielding in scattering media”, Nuc.Sci.Eng., **124** (1996) 431-435

At 2200 m/s, absorption and scattering, isotropic



$$\Psi = R\Sigma_t$$

$$f_0 = \frac{3}{4\Psi^3}\left(\Psi^2 + \left(\frac{1}{2} + \Psi\right)e^{-2\Psi} - \frac{1}{2}\right)$$

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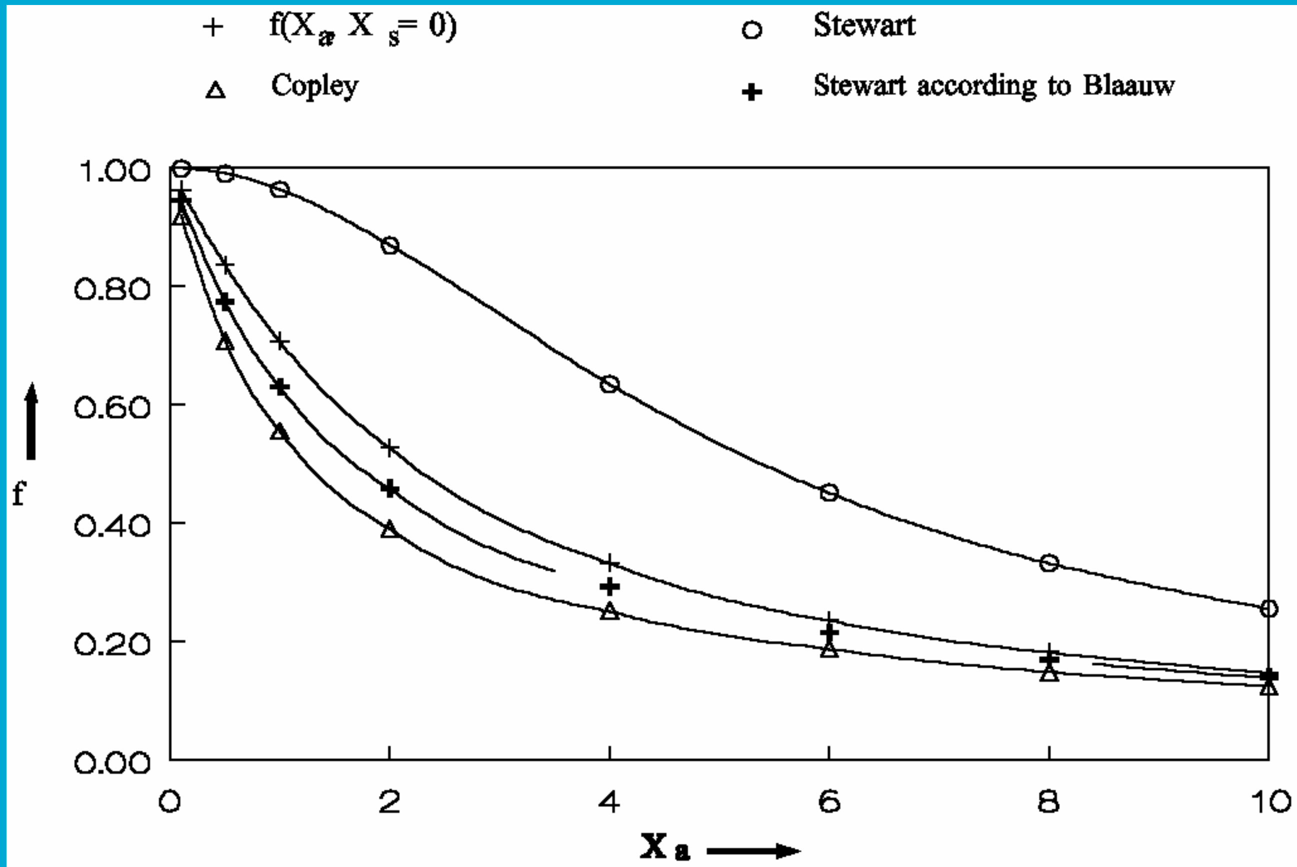
Stuart, Copley and Blaauw



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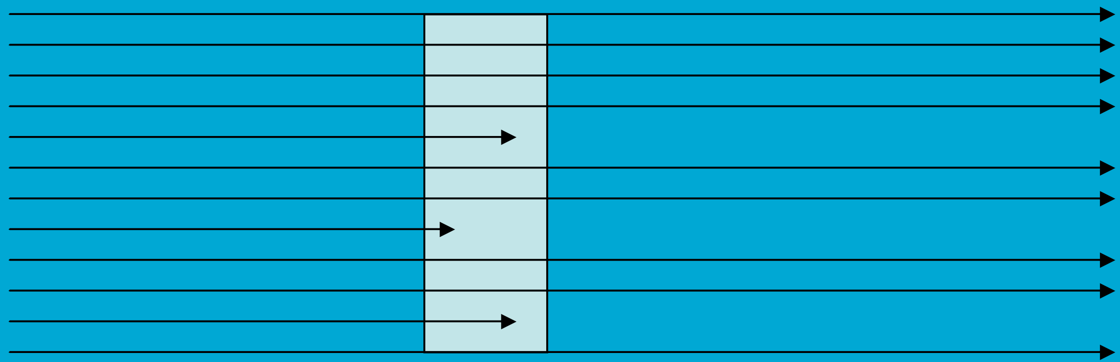
Thermal flux, absorption only, in a beam



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

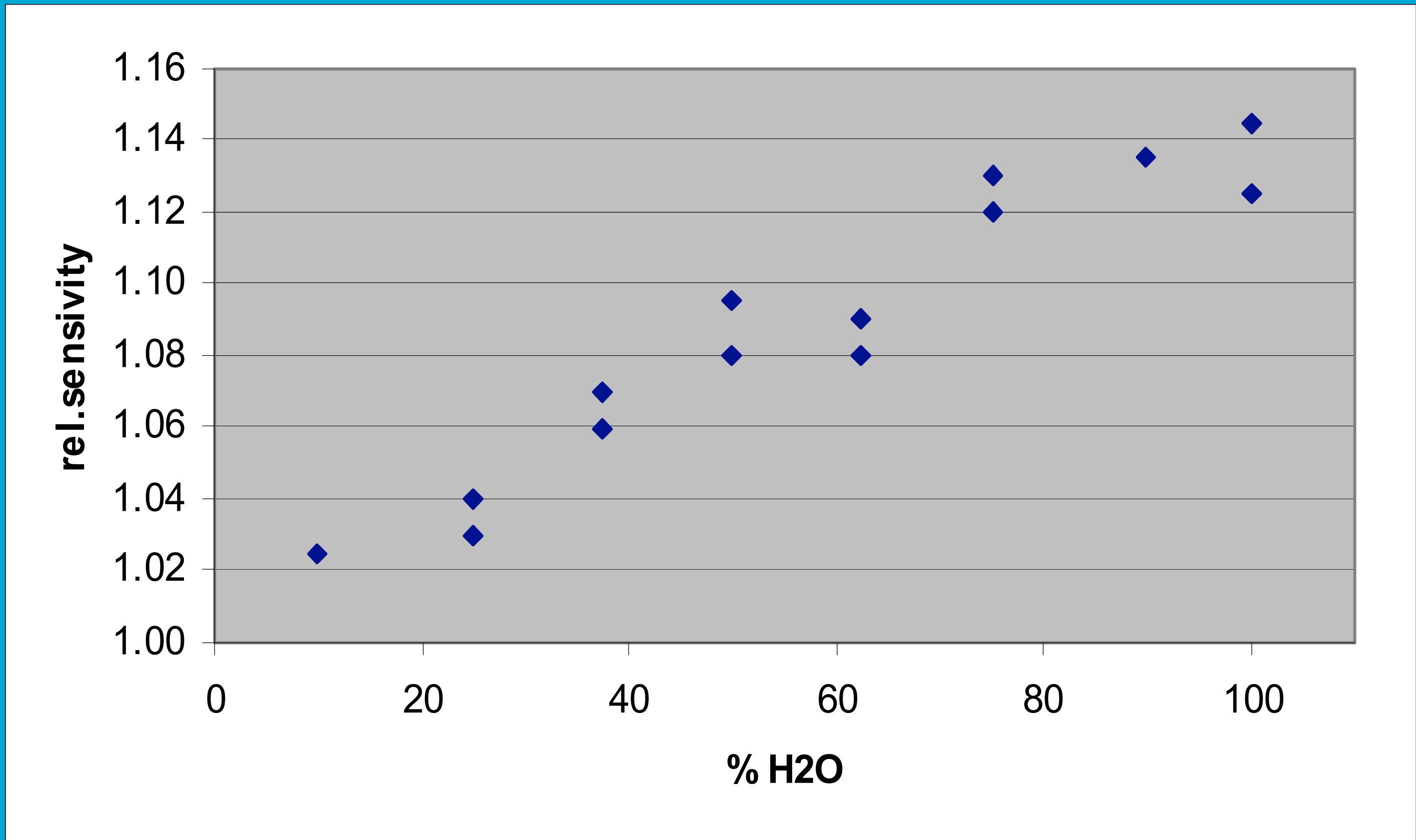
thin: $< \Sigma_a > = \frac{2}{\sqrt{\pi}} \sqrt{\frac{T_0}{T}} \Sigma_{0,a}$

thick: $< \Sigma_a > = \frac{\sqrt{\pi}}{2} \sqrt{\frac{T_0}{T}} \Sigma_{0,a}$

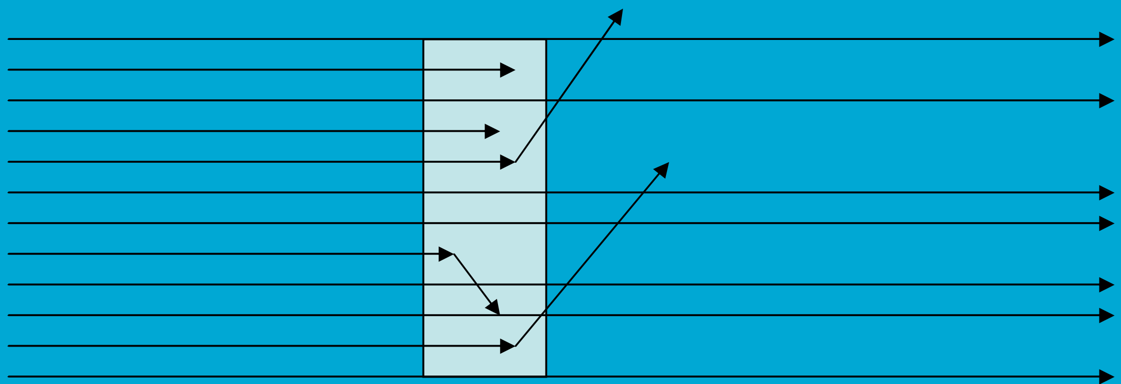
Same for other shapes: Just use the right average

M. Blaauw, "The confusing issue of the neutron capture cross-section to use in thermal neutron self-shielding computations", Nucl.Instr.Meth. A356 (1995) 403-407

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 !!!!!!!

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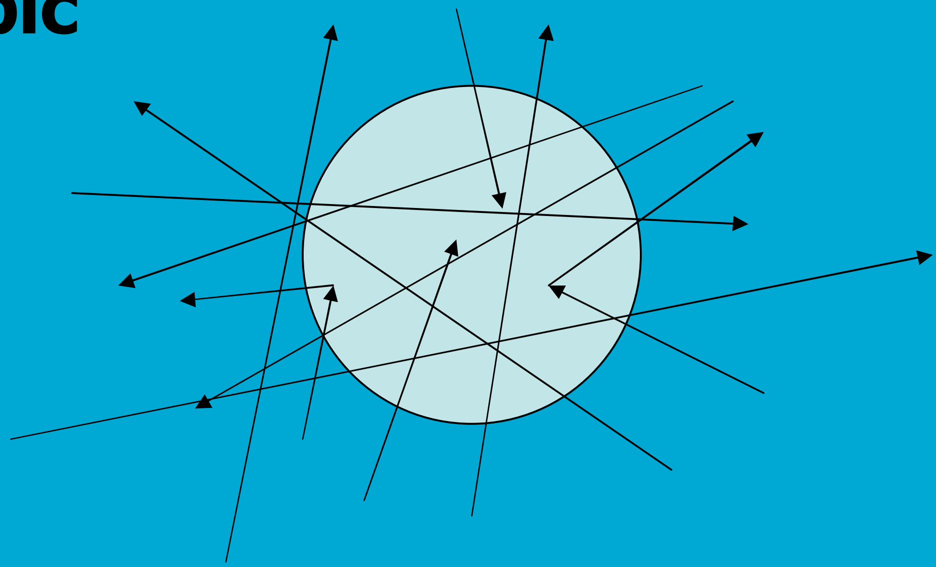
Thermal flux, absorption and scattering, isotropic



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...

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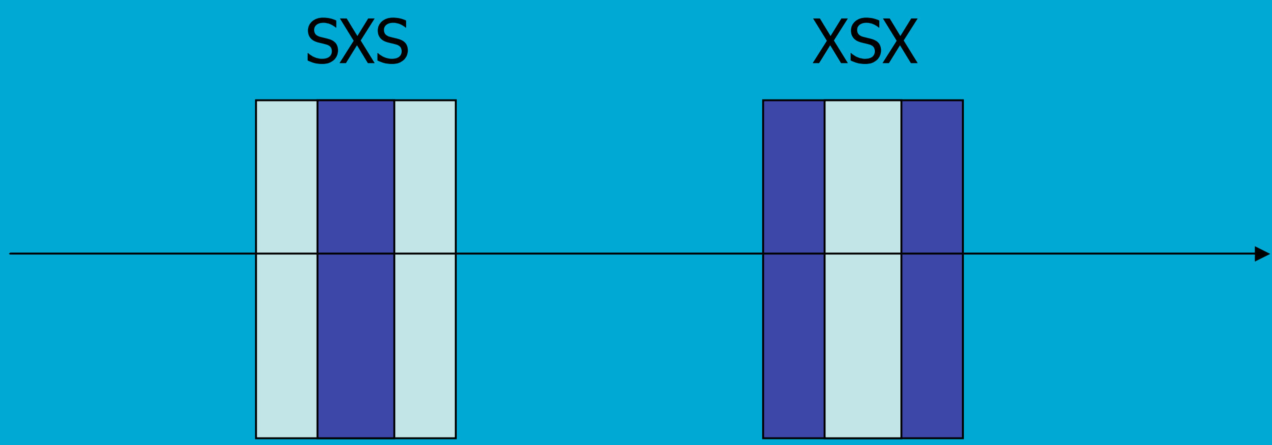
Self-shielding in reality

- 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

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Results for SXS/XSX ratios

- Experimental
- In beam: 1.150 ± 0.005
- In gradient: 0.993 ± 0.001

- Monte Carlo
- In isotropic: 0.999 ± 0.002
- In gradient: 0.998 ± 0.002
- In beam: 1.118 ± 0.002

Conclusion: Gradient fields are ok

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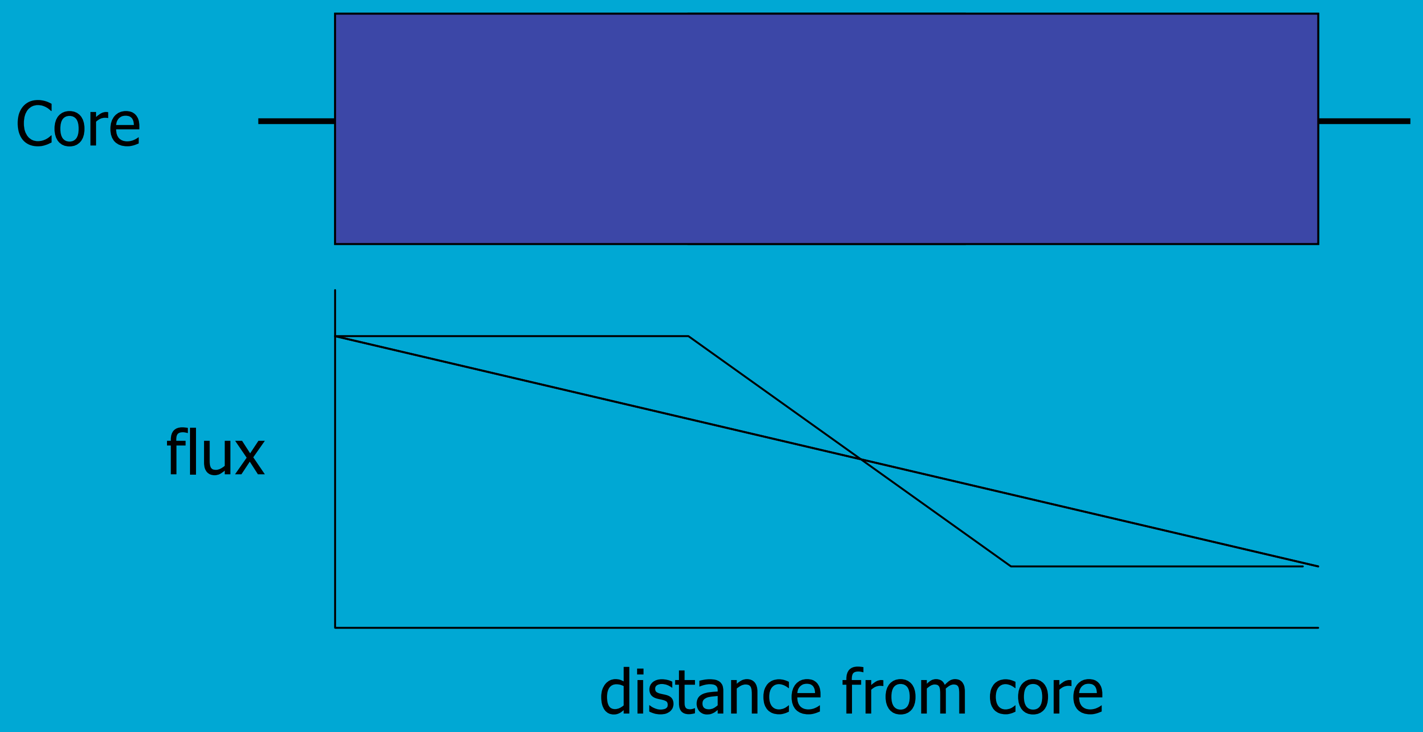
Effect of scattering samples on gradient

Lindstrom and Blaauw



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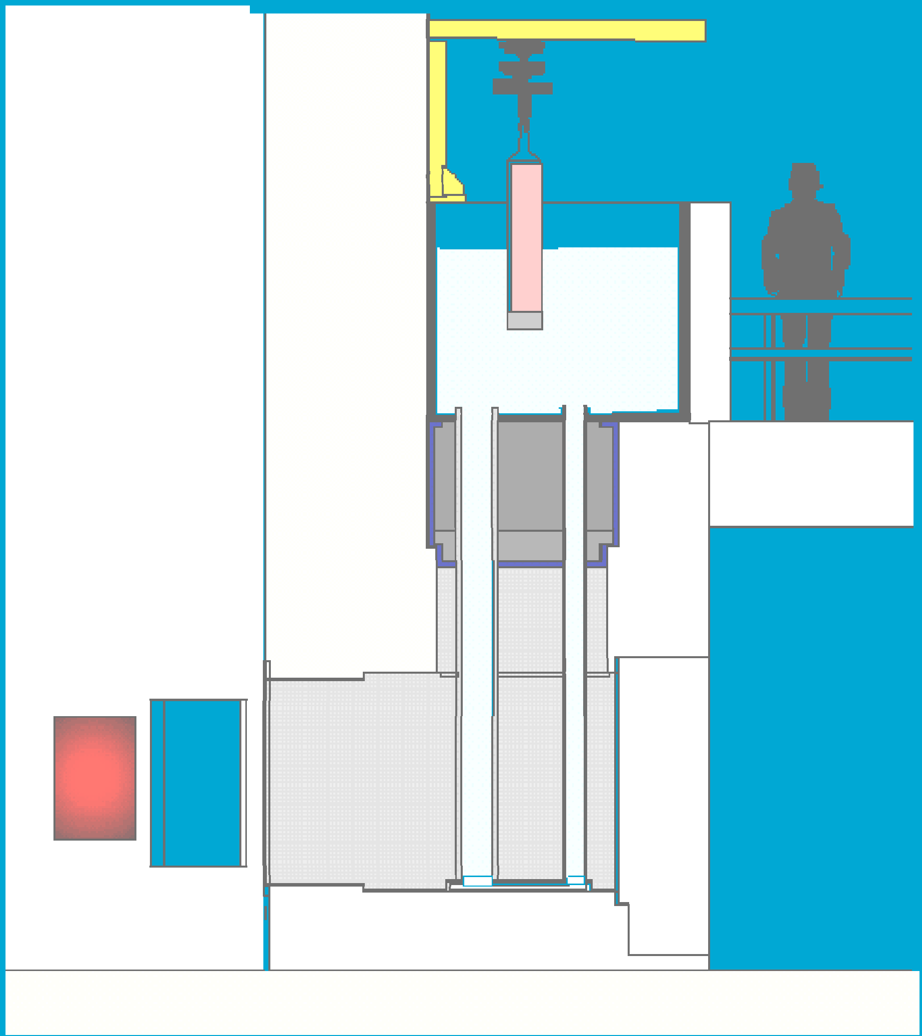
BISNIS experiences

Overwater,
Bode,
Baas,
Blaauw



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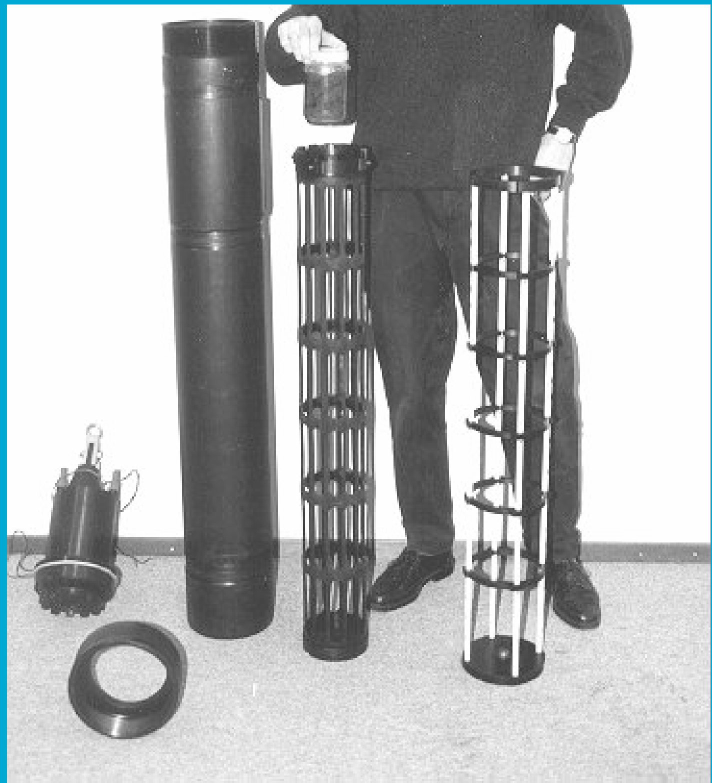
Sample container and sample



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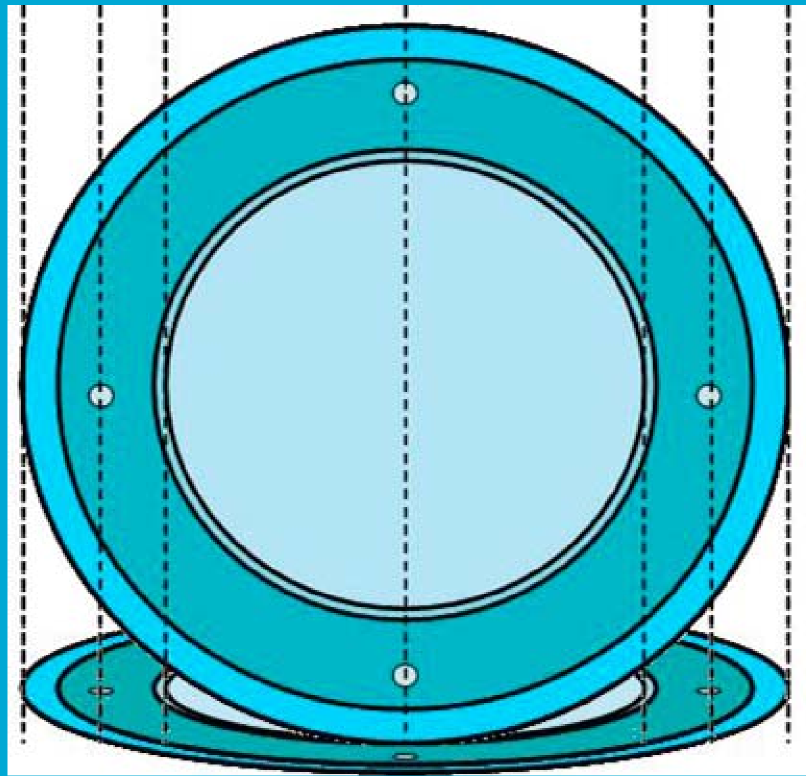
Neutron self-shielding



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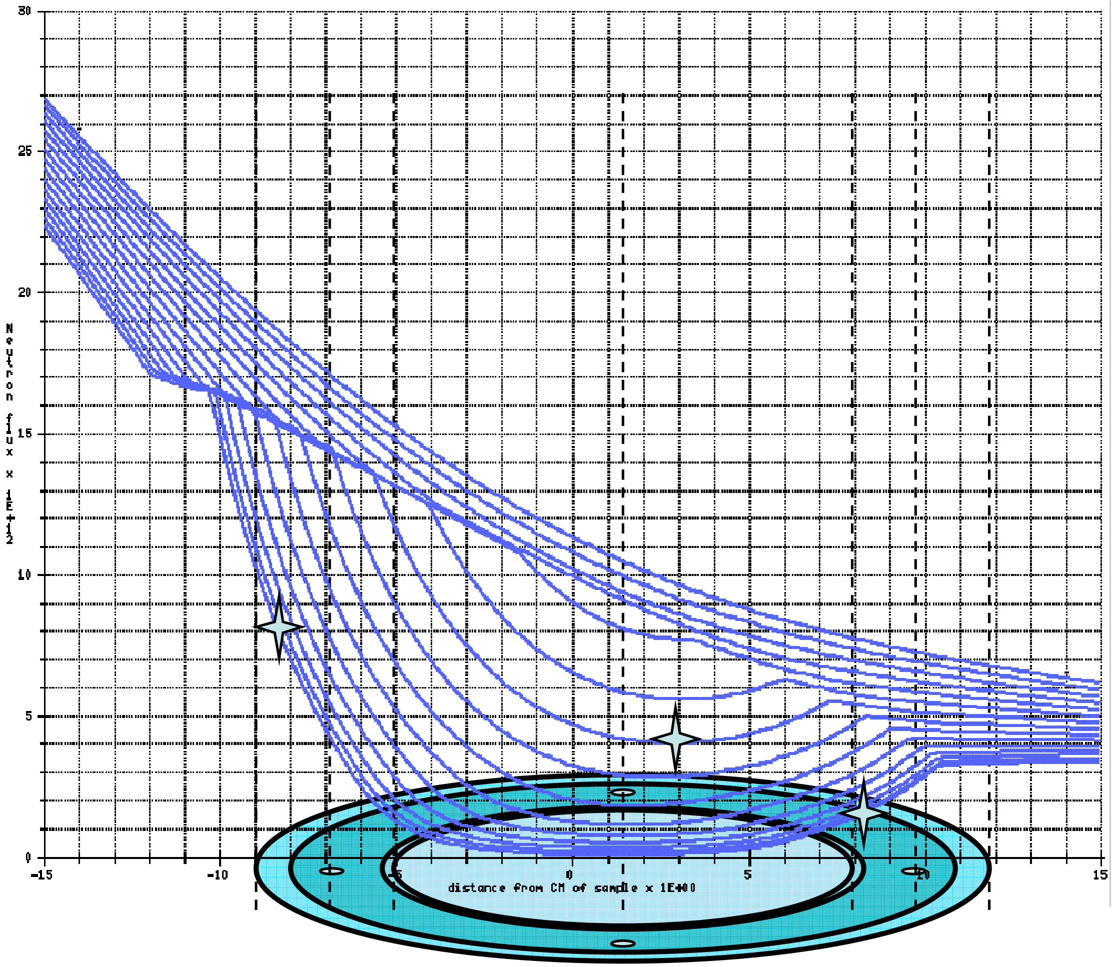
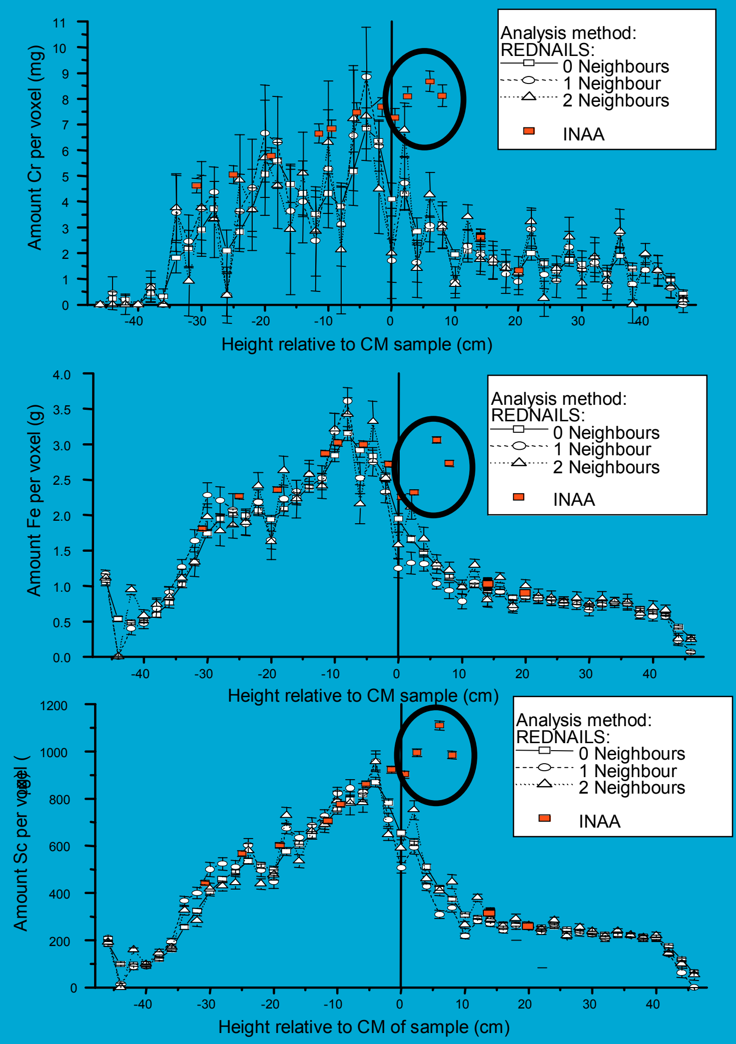
Neutron self-shielding



Results per layer compared to ordinary INAA



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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.