FROM RESEARCH TO INDUSTRY

SHIELDING A NEUTRON SOURCE : A TOUGH JOB BUT POSSIBLE

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TEORETICAL OUTLINE

What Sylvain Desert ask me to do

Part 1 Theory

- Types of radiation
- Radiation from different sources
- How shielding works
- Shielding materials (for different uses)
- Thickness approximation (Sullivan hand calcs)
- Leak paths
- Activation

Part 2 Engineering consideration

- Cost
- Structural issues (stability/seismic/floor load)
- Disposal
- Construction techniques
- Ease of manufacture

Part 3 Shielding (Low energy) ie out of line of sight (similar reactor – spallation)

- Instrument caves
- Beamline shielding
- Use of materials (cost/performance/ease of use/disposal)
- Applicable Construction techniques (cast in place/blocks)
- Worked example
    - Reactor source
    - Spallation source

PRATICAL OUTLINE

What I will do

Part 1 Theory

- Why a shielding ?
- Workers protection regulations
- Blue green yellow orange and red zones
- The different radiations
- Activation example
- Neutron specificity
- Detector protections

Part 2 Engineering consideration

- Basic formulae
- Cross sections issues
- Materials to use
- Transmission / absorption measurements

Part 3 Shielding

- Gamma shielding
- Neutron absorption
- Fast neutron absorption

Part 4 Various

- Other common materials

WHY SHIELDING : WORKERS AND DETECTORS CASES

Two different jobs for shielding

- Shielding for people : enable them to work within authorized dose limits
- Shielding for detectors : detect only neutrons scattered from the sample

People protection parameters

- Distance
- Time of work
- Shielding
- Classification of people

Detectors protection parameters

- Absoption of unwanted particules
- Efficiency of detection of unwanted particules by the detectors

PROTECTION OF WORKERS : DOSE LIMITS

May depend a bit on local regulations, though quite homogeneous through europe.

In France, 3 categories of workers on installations with ionizing radiations and their dose limits :

- **A** : 20 mSv/year
- **B** : 6 mSv/year *(CEA : <200 µSv/day)*
- **Non classified worker (NE)**: 1 mSv/year *(CEA : 1 µSv/day and dose rates > 10 µSv/h not allowed)*

(In a monochromatic beam on the sample in Orphée : 5 Sv/h)

Deal with 2 types of workers

- Staff of the installation : **B** (to give them a specific medical survey)
- Users : **NE**

PROTECTION OF WORKERS : ZONES

Access control and limits will depend on the radiation doses present in the different areas of the buildings

Design buildings and shieldings so that users may have access to what they need as non classsified workers (NE) :

Experiment cabin and cave, pathways and preparation laboratories : blue < 7.5 μSv/h (~200 n/cm^2/s)

Equipment necessary for the source operation : green < 25 μSv/h

Zone	Limits	Access
Non exposed	< 0.5 μSv/h	No limitation of access
Blue	< 7.5 μSv/h	Controlled access; no limitations
Green	< 25 μSv/h	Controlled acces with restrictions for NE
Yellow	< 2 mSv/h	Regulated access, no NE
Orange	< 100 mSv/h	Access submitted to authorizations
Red	> 100 mSv/h	Forbidden access

DIFFERENT TYPE OF RADIATIONS

To calculate exposition and dose rates, sum up all radiations

Particles that mainly go straight and just transfer their energy

- **Alpha** (^4He); stopped by a sheet of paper. Danger in case of contamination and internal exposure. Do not allow to drink or eat; access prohibited with open wound; control radioactivity in air.
- **Beta** (e-); stopped by a few mm of any material (metal, glass, plastic, …)
- **Gamma** high energy photon; needs mass to be stopped (lead, tungsten, water, …). ***! At high energy, may break a nucleus and expel neutrons !***

Neutrons

- Low interaction with matter, large mean free path, energetic ones difficult to stop
- Bounce on atoms before being absorbed ⇨ random walk : thermal neutrons are like a gas; beware of leaks
- Absorption creates activation ⇨ **with 25 meV you may obtain 1MeV** at a different place and time

ACTIVATION EXAMPLE

Air contains 0.9% of ^{40}Ar. Under thermal neutron irradiation, you create radioactive ^{41}Ar with half life 1.8 hour

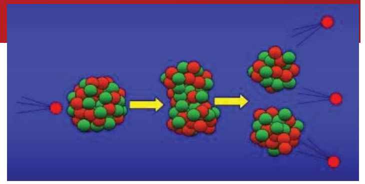
In **Orphée** : part of beam of 10^8 n/cm^2/s in air of the 14 instruments create around 10^5 Bq/h of ^{41}Ar. If confined and breathed by a user during 15mn, it might create an internal exposure of 1 μSv

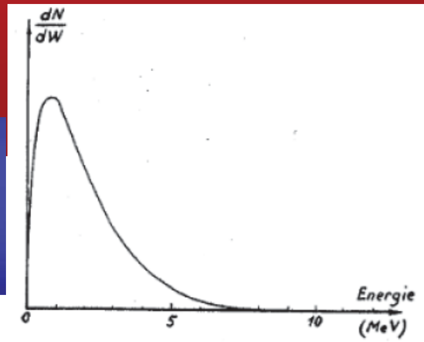
ESS Magic : 10^9 n/cm^2/s on sample, create 10^6 Bq/h, might induce a dose of 10 μSv in 15mn by breathing. This is 10 time the day dose limit for NE in CEA.

Solutions

- Avoid air irradiation; put beam under vacuum
- Vent the experimental caves
- Be prepared to have questions of the safety authorities

NEUTRONS SPECIFICITY





Fission fast neutrons (> 1eV)

- Low interaction, low detection, cross everything, no capture, no creation of radio-isotope, low energy deposition, go straight

But

- High slowing down interaction with light atoms and goes to thermal neutrons : beginning of pb

Thermal neutrons (< 1eV)

- Lots of interactions with atoms, multi bounces, a gaz of neutrons; no leaks is a challenge
- lots of activation channels of nearly all atoms, espeacially the heavy ones
- To avoid pb : choose carrefully materials to be used and pay a lot of attention to additives or impurities !!!!!!
- 1 μg of Co in 1g of Si irradiated 1 day with 10^{13}n/cm^2/s. 1 month later : 0 Bq of Si, but 1352 Bq of ^{60}Co with 5.3 year half life. Think of the Pb with 1 ton of shielding !!!!!!!

Long and time consuming efforts to decrease instrument background

- My targets :
  source on, beam off : 10 times the electronic background
  source on, beam on : 100 times the electronic background

- Obtained by protection against outside neutrons : shielding of the cave and the detector vessel with neutron absorbers

- Special attention for fast neutrons : low efficiency of detection ($< 10^{-6}$ for 1 MeV fast neutrons) but always there.

➢ Thermalization with concrete or PEHD

➢ Absorption with Cd of B_4C

➢ Beware of the holes !!!

Think if it is useful before thermalizing

SHIELDING FOR FAST NEUTRON

Not to do !

- Fast neutrons present between guides 4 and 5
- You think that neutrons comes from the reactor
- Install a wall of PEHD / B4C to thermalized and absorb them

- No change !!!

Neutron dose
before adding a wall

4 μSv/h fast
4 μSv/h thermal

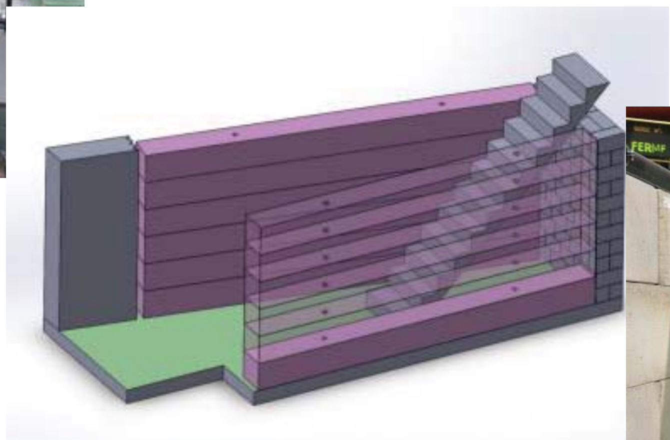
Neutron dose
with the wall

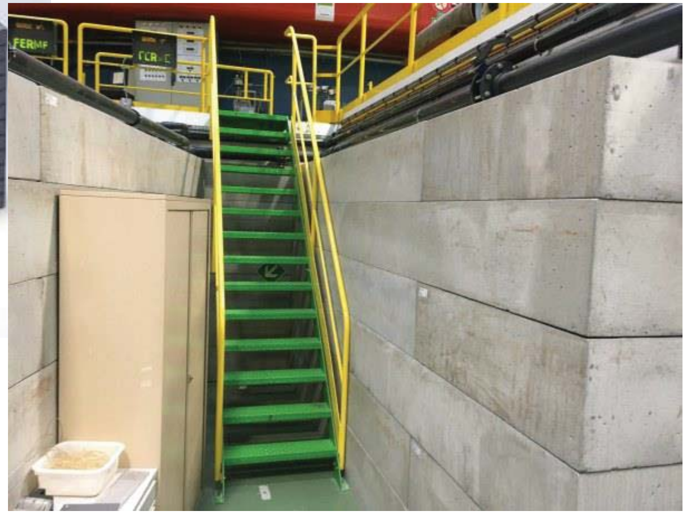
4 μSv/h fast
4 μSv/h thermal

SHIELDING FOR FAST NEUTRON

To do !

Put absorber (concrete) everywhere !





Absorbs neutrons coming from outside

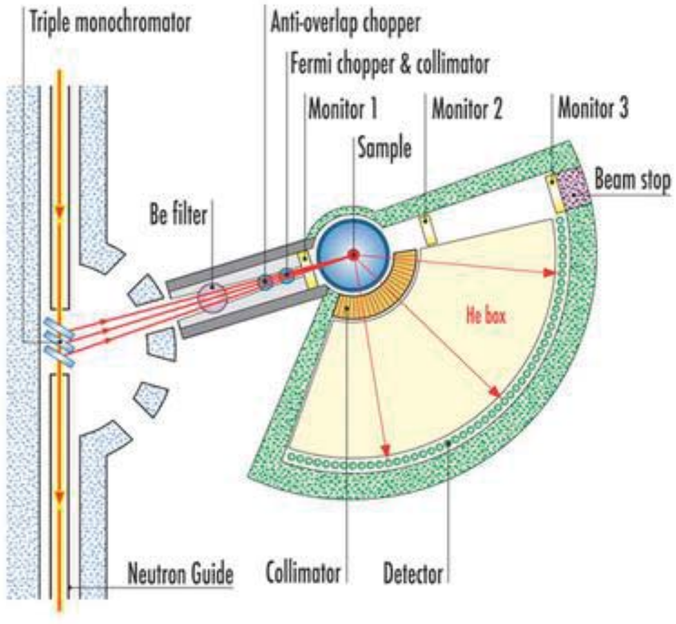
- Cover the detector vessel and sample vessel with neutron absorbers
- Add PEHD outside if ***too much**** fast neutrons around

**** : too much*** depends on the spectrometer. In Orphée, high fast neutron level betwwen G4 and G5 (2.5 μSv/h). Pb for reflectometer, not for powder diffractometer.

Detectors must see only the sample

- Use collimators in front of the detector (fixed or moving) : Gd, Cd, B
- Put nothing except sample in the neutron beam (windows create neutron scattering)

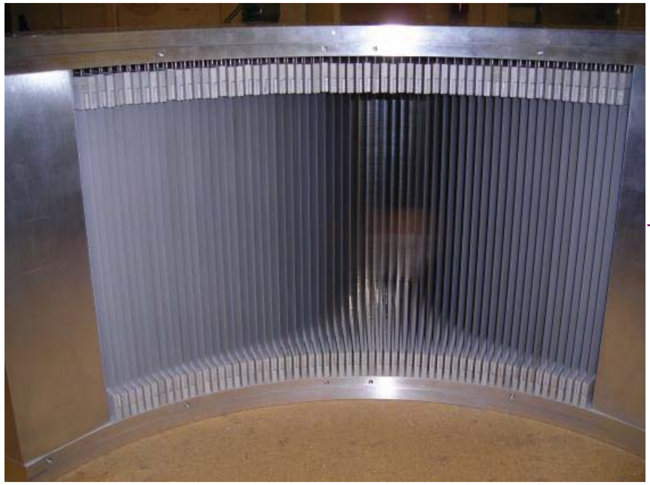
RADIAL COLLIMATORS AND BEAM SETUP

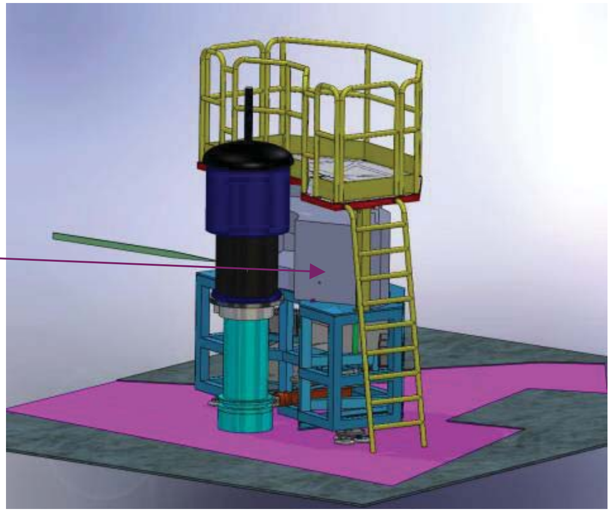


Shield flight tank with neutron absorber

Avoid anything in the beam in view of detectors

5C1 collimator

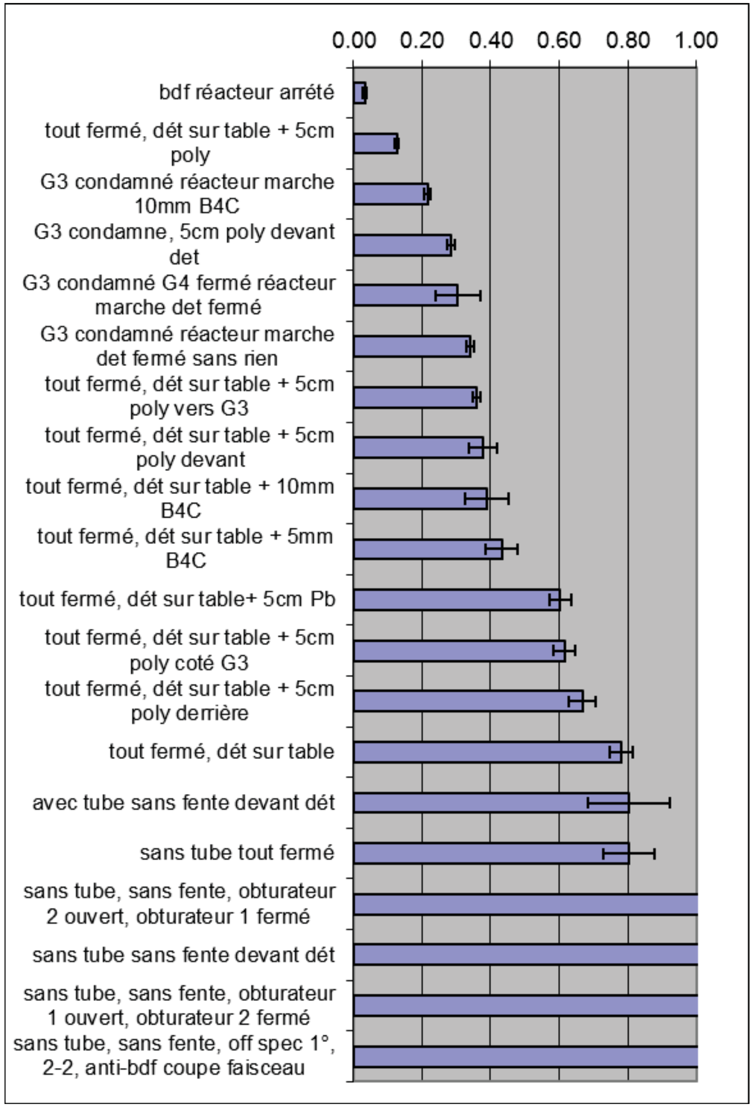


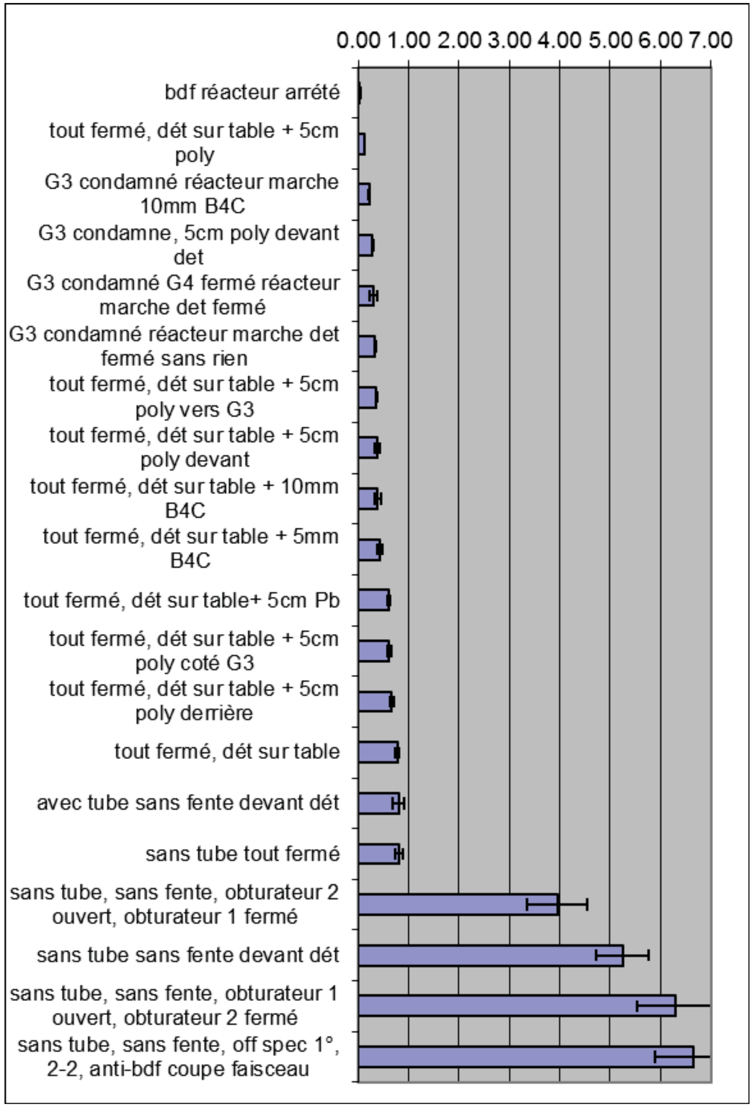


SHIELDING FOR DETECTORS :OPTIMIZATION

A long work

Counts/hour/ time channel on a reflectometer





Source off
Electronic noise

Beam off
Different
conditions

Beam on with sample

WHAT TO USE AND WHERE ?

Materials for spectrometers

Materials for shieldings

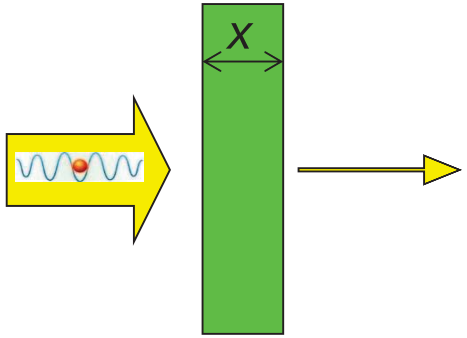
Special materials

BASIC FORMULAE

Transmission through a thickness x :

$$t = e^{-\sigma\rho x}$$

t : transmission (absorption a = 1-*t*)
σ : cross section
ρ : density
x : thickness



For gases :

$$t = e^{-\frac{\sigma P x}{37300}}$$

σ : cros section in barns
x : thickness in cm
P : pressure in bars

Example : 5 bars ^{3}He on 1cm
σ: 5333 barns
t = 0.49 gives a=0.51

For solids :

$$t = e^{-\frac{0.6\sigma\rho x}{M}}$$

σ : cross section in barns
ρ : density in g/cm^3
x : thickness in cm
M : molar mass in g

Example : 1cm Al
M=27g; σ=0.23barns; ρ=2.7g/cm^3
t = 0.986 gives a=0.014

WHICH CROSS SECTION ?

σ_a : absorption cross section : prop. to λ

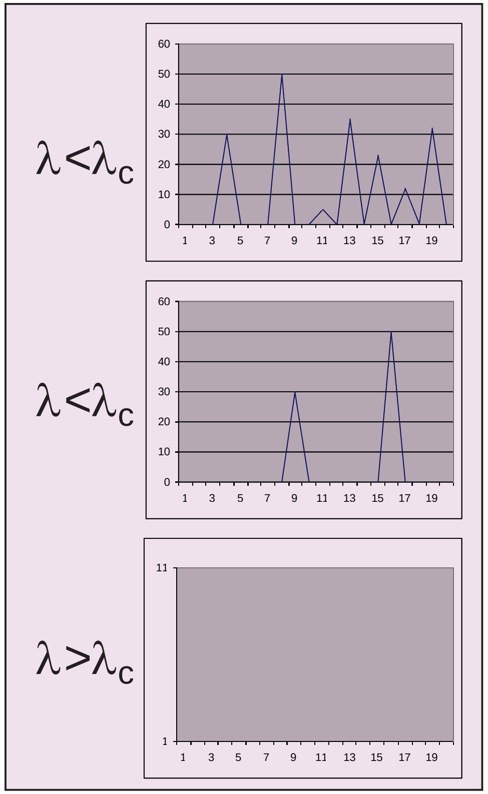
σ_c : coherent scattering cross section : constant with λ for $\lambda<\lambda_c$

At least a Bragg peak must be there for single crystals

σ_i : incoherent scattering cross section : constant

λ_c given by 2d $\sin(\theta/2)=\lambda_c$ with $\theta=180°$ scattering angle

for d=2.5Å (max distance between atomic planes) it gives λ_c=5Å



<u>Example</u> : Al

σ_a = 0.23 barns σ_c = 1.495 barns σ_i = 0.008 barns

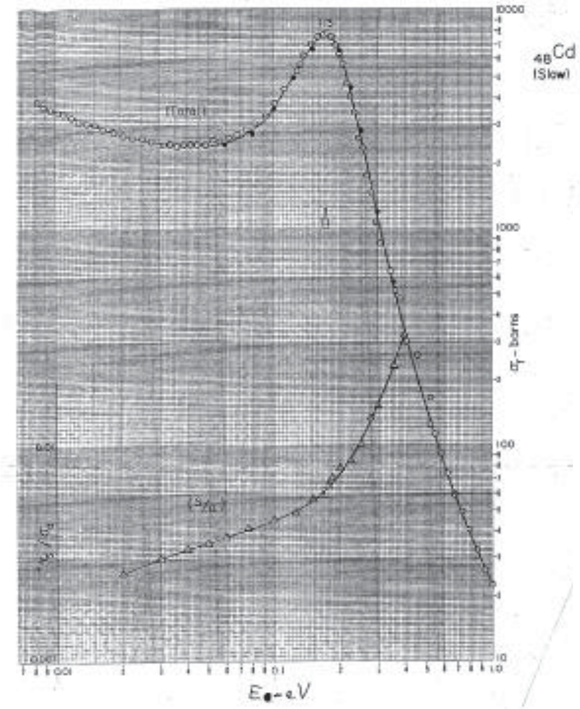
<u>Beware :</u>

Cross sections at 2200 m/s in tables (1.8 Å thermal neutrons)
Correction $\sigma_a(\lambda)$: $\lambda^* \sigma_a /1.8$

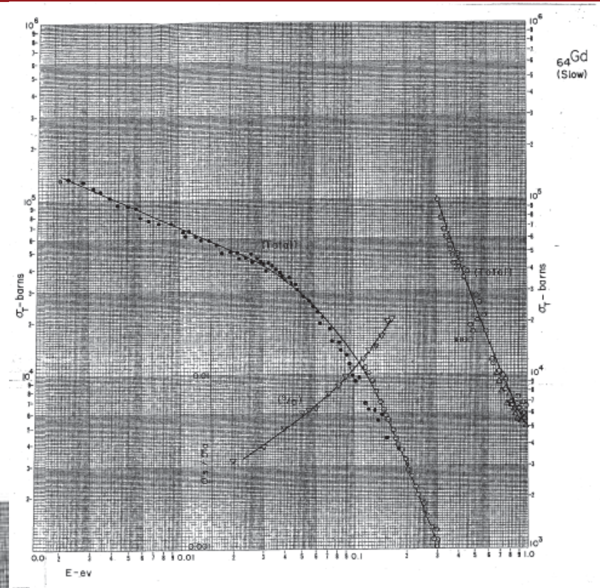
CROSS SECTIONS VARIATIONS

Not always prop. to λ

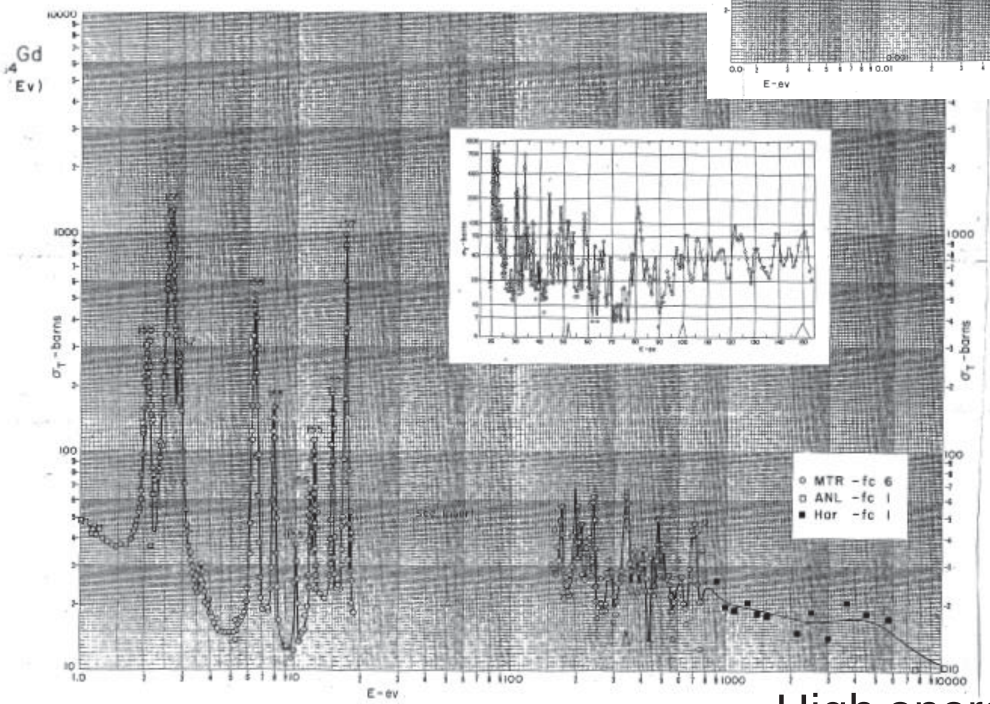
Cd



Gd



Low energy



High energy

DEPENDS OF THE MICROSTRUCTURE

This does not take into account heterogeneities small angle scattering.

Example : porous alumina made by K.Lagrene :

Al_2O_3

σ_a = 0.46 barns σ_c = 15.68 barns σ_i = 0.02 barns

- Should be transparent to neutrons
- But not at all due to SANS of pores.
- Might be reduced if you fill pores with contrast match solvent.

COMMON MATERIALS USED ON SPECTROMETERS

Al (AG3, AG3-net or AG5)

Light, easy to machine
Transparent with neutrons
Low activation (espeacilly for AG3-net), half life Al : 2.24 mn
Always wait at least 10mn before any Al sample holder manipulation after irradiation: emission of a γ of 0.8 MeV

Steel

Try to use steel without Co (it activates with a half life of **5.3 year, γ of 1.3 MeV**
Quite absorbing σ_a = 2.56 barns
Strong

Zircalloy (Zr + 2.5% Sn)

Transparent to neutrons
High strength, low activation, (emits béta)
Difficult to find

OTHER MATERIALS

Brass (Cu Zn alloy)

Easy to machine but

Zn has high activation; half life 244 days, γ of 1.3 MeV

To avoid close to the beam

Plastics

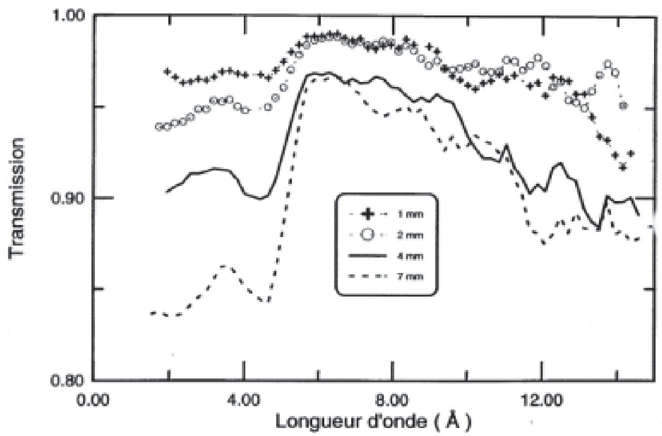
Becomes powder under γ irradiation. γ breaks double links in the molecules

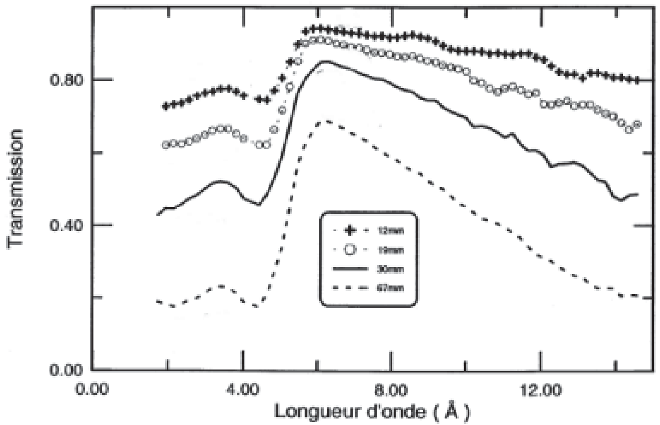
Highly absorbing because of hydrogen : σ_i = 80 barns

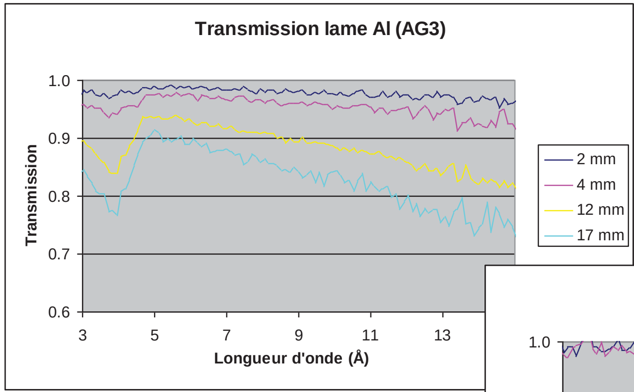
To avoid if high γ dose

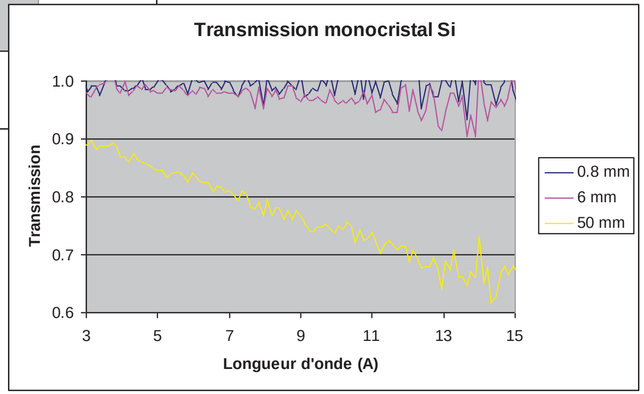
VARIOUS THERMAL NEUTRONS TRANSMISSIONS

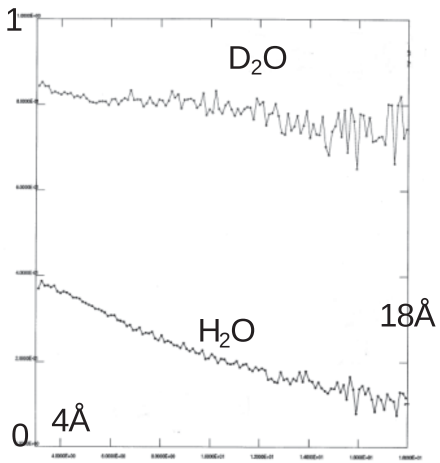
Transmission of Zircalloy windows with thickness and wavelength

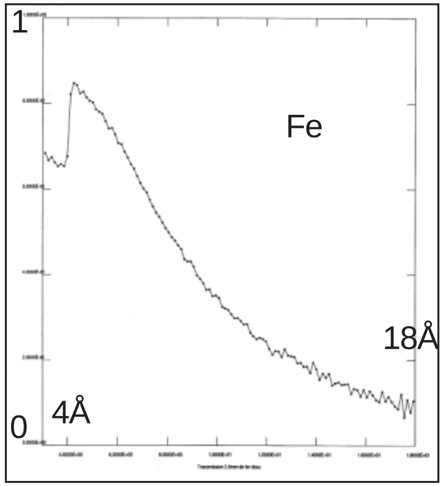












GAMMA RADIATION PROTECTION

To be protected against γ, you have to put mass !

Concrete

Contain roughly 15% of water (for fast neutrons thermalization)
Low cost, easy to handle
Various quality available
Normal concrete : 2.3 kg/dm^3
Concrete with baryty : 3.6 kg/dm^3
Heavy concrete : usual 4.4 kg/dm^3, special 6 kg/dm^3, for 2T 7 kg/dm^3
Add absorbing materials for neutrons ($B_2 0_3$) or γ (Fe, Pb, …)
May be a bit like a cooking receipe (heavy concrete for 2T)

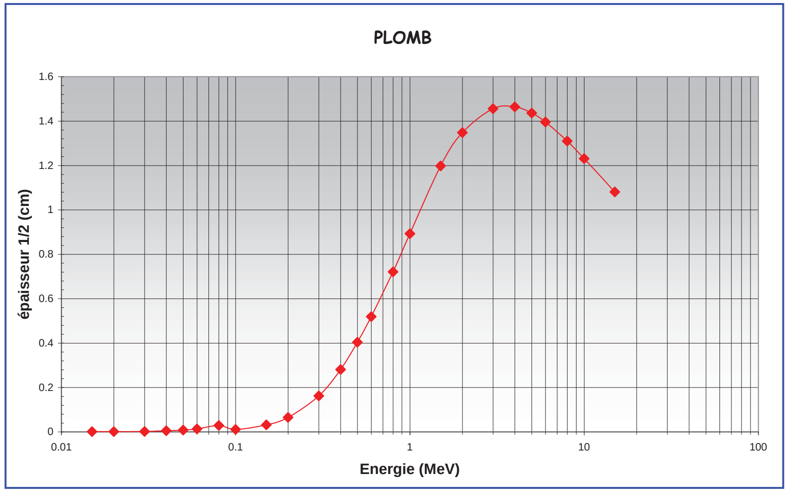
Lead

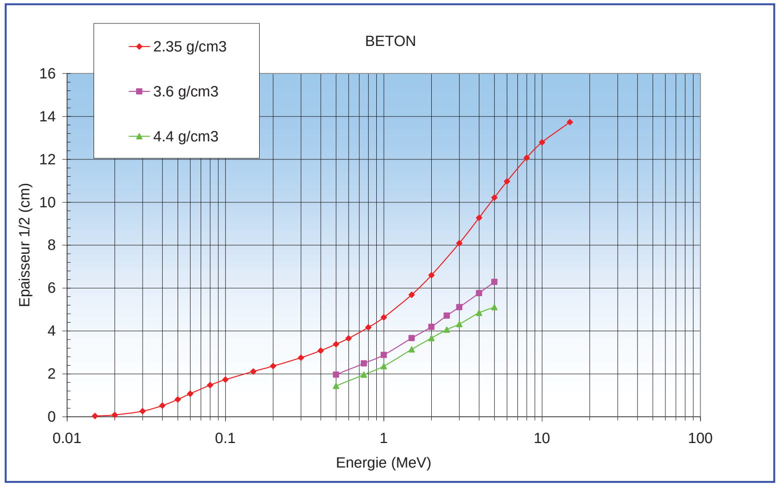
Not that expensive, easy to handle and design, available as bricks
Density : 11.3 kg/dm^3
Beware : **transparent to thermal neutrons** $\sigma_a = 0.2$ barns

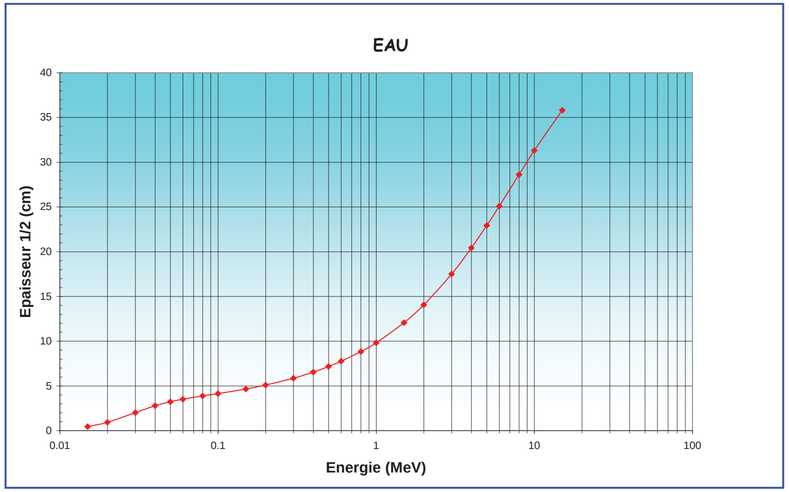
Tungsten

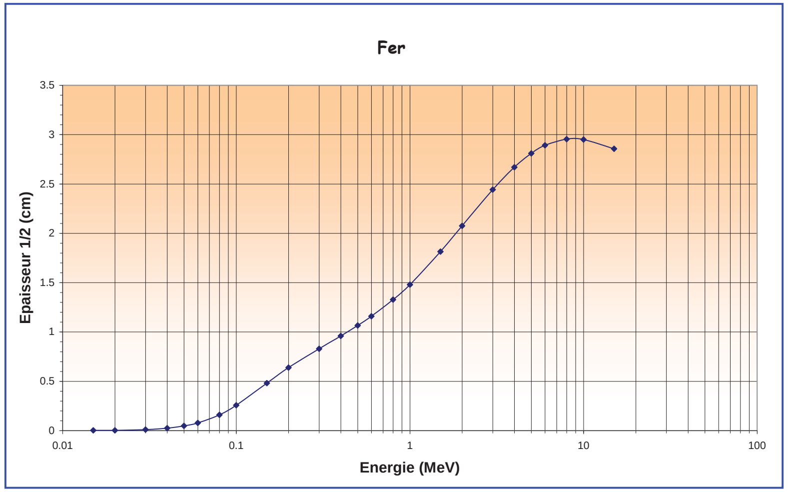
Highly absorbing; Density : 19.3 kg/dm^3; $\sigma_a = 18.3$ barns
Expensive and difficult to machine

GAMMA ABSORBING POWER









High absorption neutron cross section.

Most commonly used :

- Li ; σ_a = 70 barns (^{6}Li ; σ_a = 940 barns , *!! nuc. mat !!*)
- B ; σ_a = 767 barns (^{10}B ; σ_a = 3835 barns)
- Cd ; σ_a = 2520 barns
- Gd ; σ_a = 49700 barns; qq μm are suffisent !

<u>Beware :</u>

Neutron absorption conduct generally to the emission of a high energy particle; usually a γ, sometime a α or a β.

The heavier the absorbing nucleus, the highest number of desexcitation paths with high energy particle emission

NEUTRON ABSORPTION

Cd (metallic foils)

- Emits γ mainly at 0.6 MeV, but also at 6 MeV
- Easy to handle and use
- Need a limited thickness
- Few neutron reflection
- Regulations for handling more and more stric (poison)

B_4C (powder, rubber, plastic, sintered, carbon)

- Difficult to machine, but may be molded and cut
- Emits γ of 0.5 MeV only
- Reflects a bit the neutrons

Boron nitrides (white friable blocs)

- Special for furnaces
- Easy to machine before heating
- Reflects a lot of neutrons

^{6}Li (plastic LiF foil or carbonate of Li powder)

- Absorbs without γ emission, but emits a α of 4.5 MeV
- Very expensive, easy to handle, use only in special cases

Gd

- Very efficient absorber
- Emits energetic γ around 0.2 MeV, 1 Mev and 6.5 MeV (use with moderation)

Boral plates (B4C between Al fols)

- Very efficient absorber
- Difficult to machine
- Difficult to find

NEUTRON ABSORPTION : ONE MORE FAST NEUTRONS PB

Be carrefull : B and Li emit fast neutrons around 2MeV.

Efficiency for B : $0.5\ 10^{-6}$
Efficiency for Li : $80\ 10^{-6}$

Be carrefull : high energy γ can extract neutrons from heavy nuclei and can emit fast neutrons

Example : neutrons/Cd/Pb or neutrons/Gd/Pb

Low efficiency : $\sim 10^{-8}$

Detection efficiency of fast neutrons by ^{3}He gaz detectors

σ_a = 0.8 barns; detection efficiency $6\ 10^{-4}$
White beam (10^9n/s) absorbed by Li, emits $8\ 10^4$n/s
30 cm^2 neutron detector at 1 m sees 600 n/s (solid angle)
Low efficency of detection ⇨ background of 0.4 n/s

You cannot avoid shielding of fast neutrons !!

STOP FAST NEUTRONS

Stop fast neutrons with thermalization !!

Best thermalizer is H atom.

<u>Various solutions tested :</u>

Water tank : leaks Pb

PEHD (CH2)n (easy to handle but will not sustain high flux)

Concrete (15% water inside)

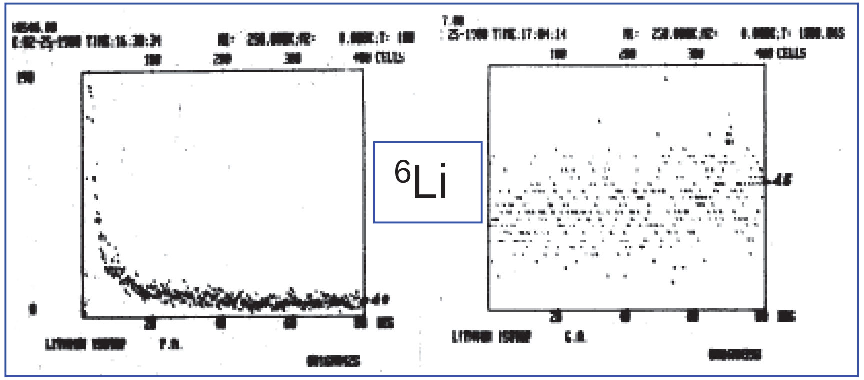
!! Do not forget to put an absorber of thermal neutrons afterwards !!

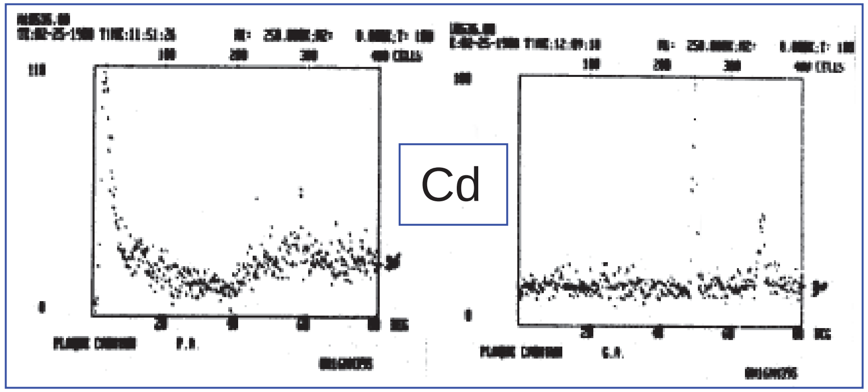
Slowing down from 2MeV to 0.025eV	H_2O	D_2O
Mean free path (cm)	0.5	2.5
Slowing down distance (cm)	5.7	11
Nb chocs	18	25

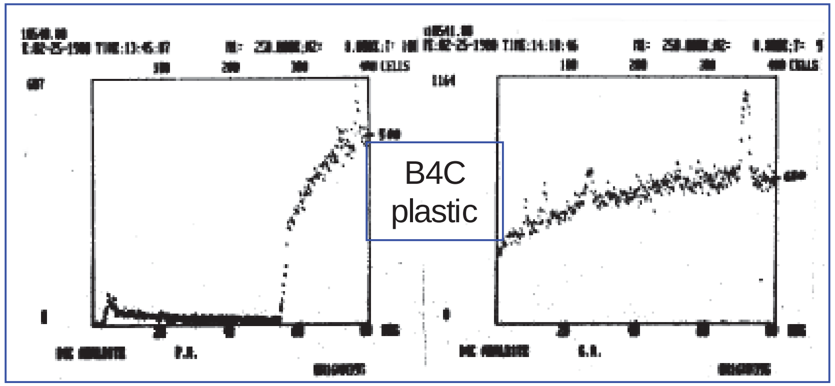
NEUTRON ABSORBERS AND BACKGROUND

All neutrons absorbers reflects more or less thermal neutrons

15mn on G61	Diffus	Peak
^{6}Li	5	5
Cd	20	170
B_4C sintered	5	700
B_4C carbon	40	1800
B_4C plastic	590	1100
Boron nitride	50	10000







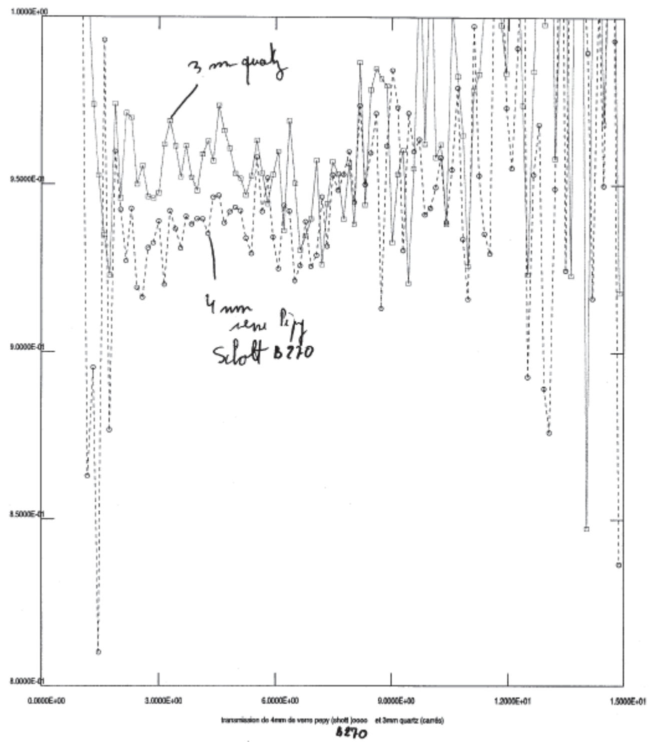
MATERIALS WITH SPECIFIC USE 1/2

Si

Large size and low price single crystals (20*20*30 cm^3).
Transparent to neutrons.
May be used at low and high T°
A bit fragile

Quartz (Si02)

Transparent to neutrons and light
Available on different size
More expensive than Si



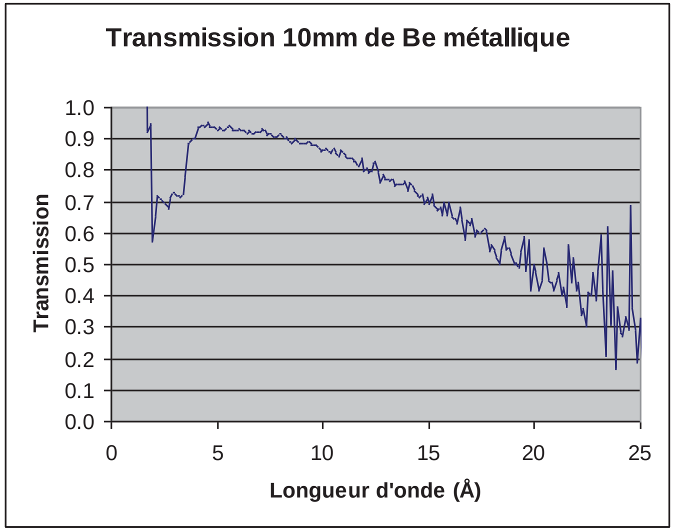
Glasses

Composition not always known with precision
Often highly absorbing
Schott glass B270 quite transparent
95% transmission after 4mm.

MATERIALS WITH SPECIFIC USE 2/2

Alumina (Al_2O_3)

Available as single crystal
Transparent for neutrons
May be used at high and low T°

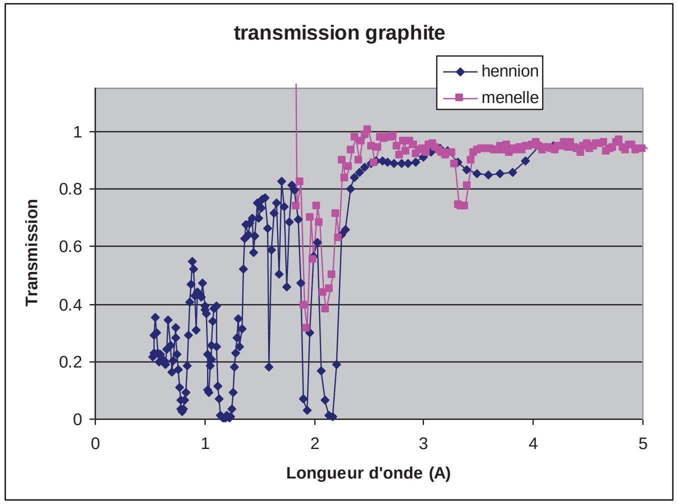


Be

Short wavelength absorber

HOPG graphite filters

Selective wavelength absorption



Fast neutrons Bi filter

High mass to stop fast neutrons (209)
low absorption : σ_a = 0.04 barns

CONCLUSION

Lots of work and tests to be done

Thank you

GLASSES FOR NEUTRON GUIDES

Rôles :

Guider les neutrons

Tenir le vide

Absorber les neutrons

Float :
Crée des γ
Peu cher
Surface de qualité
Un peu mou
Pas d'absorption neutrons

Borkron (guides du LLB):
Cher
A polir
Résistant

Borofloat :
Peu cher
Surface de qualité
Peu résistant au rayonnement

Compositions des verres à guides de neutrons en % en masse

	Float	**Borkron**	**A8866**	**Borofloat**
SiO2	70.62	62	67	83
Al2O3	0.9	0	0.9	2.7
ZnO2	0	11	0	0
Na2O	13.6	7	0.5	3.6
B2O3	0	12.5	19	12.9
CaO	9.8	0	0	0
MgO	3.85	0	0	0
K2O	0.5	0	8.3	0.6
Fe2O3	0.1	0	0	0.001
SO3	0.28	0	0	0
TiO2	0.015	0	0	0
LiO2	0	0	0.9	0
As2O3	0	0	0.2	0
ZrO2	0	0	0	0.05
	99.665	92.5	96.8	102.851

A8866 :
Alternative au Borkron, mais trop dur (difficile à polir)