OPPORTUNITIES IN THE USE OF VERY COLD NEUTRONS FOR RADIOGRAPHY TECHNIQUES.

F. OTT
LABORATOIRE LÉON BRILLOUIN CEA/CNRS
UNIV. PARIS SACLAY
WHAT DO WE AIM AT PROBING?

What science?
- Radio-tomography of microscopic structures (10µm → 200µm)
NEUTRON CROSS SECTIONS

- Lithium
- Iron
- Vanadium
- Water (hydrogen)
Most of the time incoherent scattering from hydrogenated materials

Diffraction contrast $\rightarrow$ Bragg edge imaging

SANS scattering – Refraction effects

More exotic $\rightarrow$ magnetic contrast

Rarely absorption contrast: Lithium – Boron – Gadolinium
Lithium in batteries
- Boron in metallic nuclear materials (good homogeneity)
- Gadolinium or Hafnium as a marker

Absorption contrast scales as $\lambda \rightarrow VCN$ are a priori better
- One may study thinner samples

But the absorption increases also for the surrounding materials
- For some « fixed geometry » problems, long wavelengths may be unsuitable
  - the « sample » is not sufficiently transparent anymore
    - Boron in metallic nuclear elements
    - Lithium in batteries
    - Melts (geophysics)
Bragg edge imaging relies on the diffraction on crystallites in the studied material (Fe, Ni, Cu, Al)

- Wavelengths are scattered only up to 4.2Å° (in 3d metals)
- Useful wavelength range \{ 2Å° - 5Å° \} = typical cold neutron spectrum
- It is possible to take advantage of the pulsed structure of ESS
  - The Bragg edge information is obtained « for free »
  - ESS especially suited for such studies

- Colder neutrons are a handicap
  → Bragg edge diffraction is no more possible

- Upside, no need to care about the pulse time structure anymore 😊
Incoherent scattering from hydrogen is one of the most widely used contrast in neutron radiography experiments. Liquids in porous medium (rocks, concrete, fuel cells, roots, food ...)

Incoherent scattering (on H) is a strong effect in neutron cross section.

But it is a complex process:
- Most often it is a multiple scattering process.
- It leads to inelasticity.
- The wavelength dependence is non trivial.

![Graph showing cross section against energy (meV) for water (hydrogen) with Total and Absorption lines.](image)
$A \propto \ln E_n$

Very cold neutrons are useful for very small contrasts.
SANS and refraction as a source of contrast

Neutron grating interferometry is probably easier to implement

- Phase gratings and absorption gratings are easier to build for long wavelengths
- SANS and refraction effects are higher for long wavelengths → better contrast expected

Tobias Neuwirth (MLZ)
The detection efficiency increases as $\sim \lambda$ (actually $1 - e^{-a\lambda}$) providing a direct efficiency gain.

- The gain is higher if it avoids using Gadox.

**Diagram:**
- Normalized light yield and absorption for different materials and thicknesses.
- ZnS:Cu/βLiF, Zn(Cd)S:Ag/βLiF, YAG:Ce/βLiF, ZnO:Ga/βLiF, Gd$_2$O$_2$:Pr,Ce,F/βLiF, Gd$_2$O$_2$:Pr,Ce,F.

**Legend:**
- 125µm
- 40µm @ $\lambda_0$
- 125µm @ 3$\lambda_0$
- 40µm @ 3$\lambda_0$

T. Neuwirth, J of Imaging (2020)
Currently → neutron radiography uses a pin-hole geometry

- Spatial resolution proportional to \( \frac{L}{D} \) (10µm requires \( \frac{L}{D} = 1000 \) and \( SD < 10\text{mm} \))
- Sample – detector distance is a strongly limiting factor
  - Sample environment very challenging at high resolutions (< few 10µm)

Using proper optics could significantly enhance the performances

- Neutron optics is challenging
- Inefficient + costly
- Reflective optics efficiency scales as \( \lambda \) (the total reflection angles is prop. to \( \lambda \))

- For imaging, high quality 2D optics is required
More classical optical setup

Optics solid angle scales as $\lambda^2$

Neutron use / collection (x10 – 100)
CONCLUSION

Longer wavelengths would provide
- a increased sensitivity, prop. $\lambda$ or $\ln(\lambda)$
- a better detection efficiency, prop. $\lambda$

Bragg edge imaging is no more possible if spectrum beyond cold neutrons
- no use left for pulsed beam structure

Phase contrast imaging becomes more efficient

Advanced optics is more efficient
- Wolter optics still needs to be demonstrated in « production »

Optimistic view
- Wolter optics + detection efficiency scales as $\lambda^3$ + gain in contrast
- Beware of gravity!

VCN are worth the effort (though not suitable for all problems)