Fundamental Research with Neutrons

Andrew Jackson

European Spallation Source

Delivered by Wim Bouwman, Delft University of Technology

75 years of nuclear reactors: A chain reaction of applications
KIVI-NNS Symposium, 3rd November 2017

The Neutron

1932 Discovery of the neutron by Chadwick (prediction by Rutherford 1920)

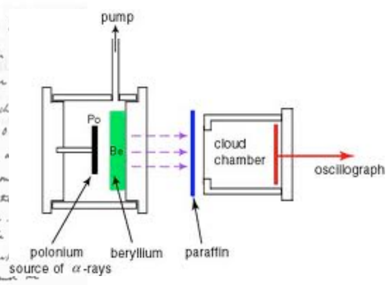
"Whatever the radiation from Be may be,
it has most remarkable properties"

Cavendish Laboratory,
Cambridge.
24 February 1932.

Dear Bohr,
I enclose the proof of a letter I have written to "Nature" and which will appear either this week or next. I thought you might like to know about it beforehand.
The suggestion is that α particles eject from beryllium (and also from boron) particles which have no nett charge, and which probably have a mass about equal to that of ... put this forward ... the evidence is ... the radiation fr... remarkable prope... experiments whi...

letter to "Nature" and they can all ... interpreted readily on the assumption ... the particles are neutrons. Feather ... taken some pictures in the expansion ch... and we have already found about 20 ... of recoil atoms. About 4 of these show a ... fork head (and it is almost certain that this one ... of this fork represents a recoil atom and the ... some other particle, probably an α particle ... are disintegrations due to the capture of the ... by N_{14} or O_{16}. I enclose two photographs ... one of which shows the simple recoil atom, and the other what we suppose is a disintegration. The photographs are not very good but they were printed in a hurry.

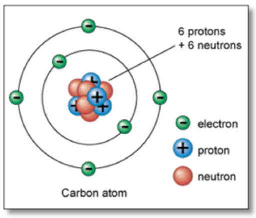
With best regards
Yours sincerely
J. Chadwick.



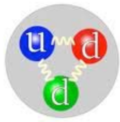
1932: $^{4}_{2}He + ^{9}_{4}Be \Rightarrow ^{12}_{6}C + {}^{1}_{0}n$ neutrons

The Neutron

The neutron:
- Is a spin 1/2 sub-atomic particle
- Has a mass equivalent to 1839 electrons (1.674928×10^{-27} kg or 939.57 MeV)
- Has a magnetic moment of $-1.9130427\ \mu_n$ ($-9.6491783 \times 10^{27} JT^{-1}$)
- Has a lifetime of 15 minutes (885.9 s).



Neutrons are baryons
Three quarks (udd) = neutron



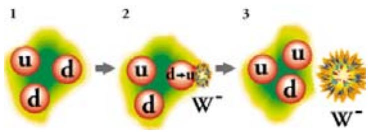
Waveparticle duality

Particle and a Wave

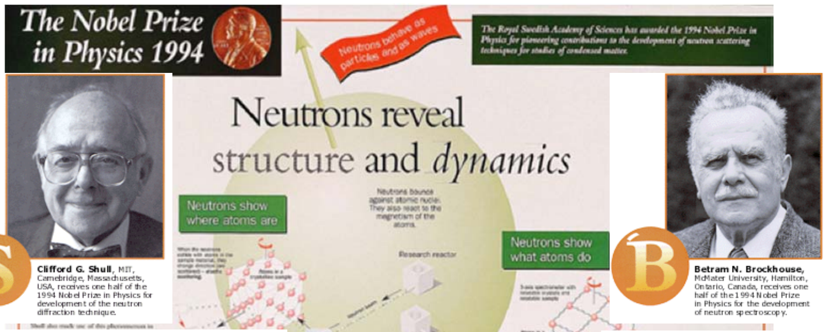
- Reflection
- Diffraction
- Refraction
- Focussing

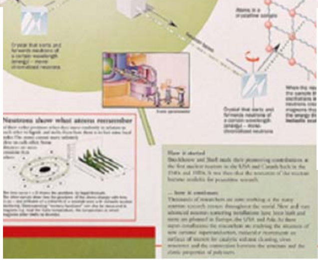
Neutron decays into proton + electron +antineutrino (of the electron type)

$$n \rightarrow p^+ e^- \bar{\nu}_e$$



Why Neutrons for Research?



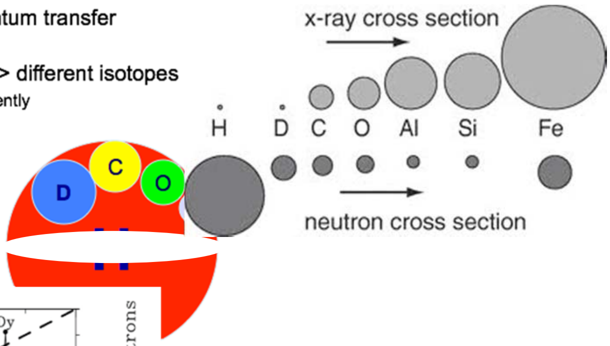


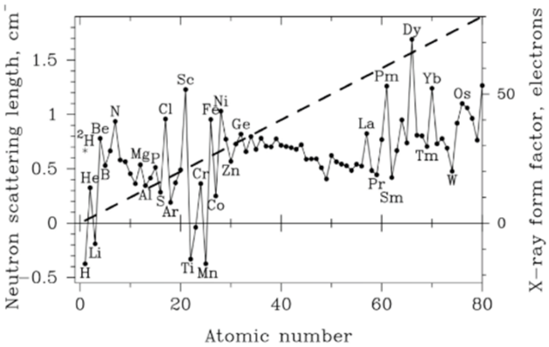
Because of the wave nature of neutrons, a diffraction pattern can be recorded which indicates where in the sample the atoms are situated. Even the placing of light elements such as hydrogen in metallic hydrides, or hydrogen, carbon and oxygen in organic substances can be determined. The pattern also shows how atomic dipoles are oriented in magnetic materials, since neutrons are affected by magnetic forces. Shull also made use of this phenomenon in his neutron diffraction technique.

With his 3-axis spectrometer Brockhouse measured energies of phonons (atomic vibrations) and magnons (magnetic waves). He also studied how atomic structures in liquids change with time.

Why Neutrons for Research?

1) Ability to measure both energy *and* momentum transfer
   Geometry of motion
2) Neutrons scatter by a nuclear interaction => different isotopes scatter differently
   H and D scatter very differently
3) Simplicity of the interaction allows easy interpretation of intensities
   Easy to compare with theory and models
4) Neutrons have a magnetic moment





$$V(r) = \frac{h^2}{2\pi m}\left\langle \sum_i b_i \delta(\mathbf{R}-\mathbf{r_i})\right\rangle$$

Interaction of neutron and nucleus is described by the pseudo-potential developed by Fermi

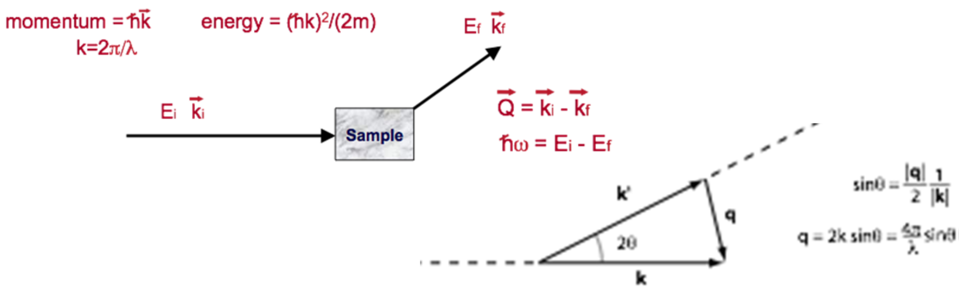
Contrast matching to make parts structure (in)visible

Morna Fisken, Britlab
https://youtu.be/OZxtwIc3ieM

Many materials transparent for neutrons In situ during processing

Anders Kaestner, PSI
https://youtu.be/VESMU7JfVHU

What do we measure?

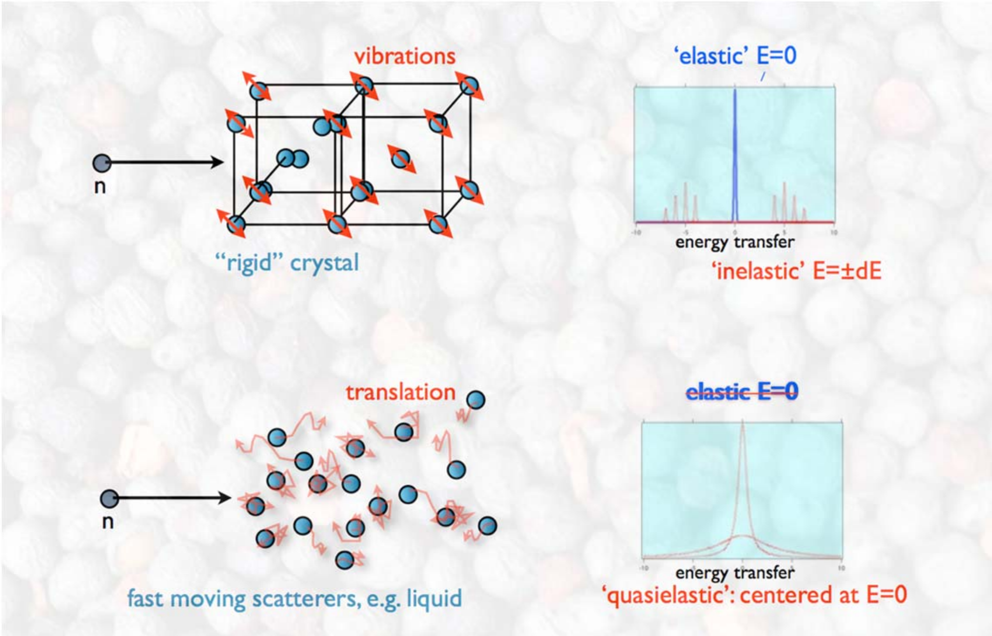


Measure number of neutrons scattered as function of Q and ω

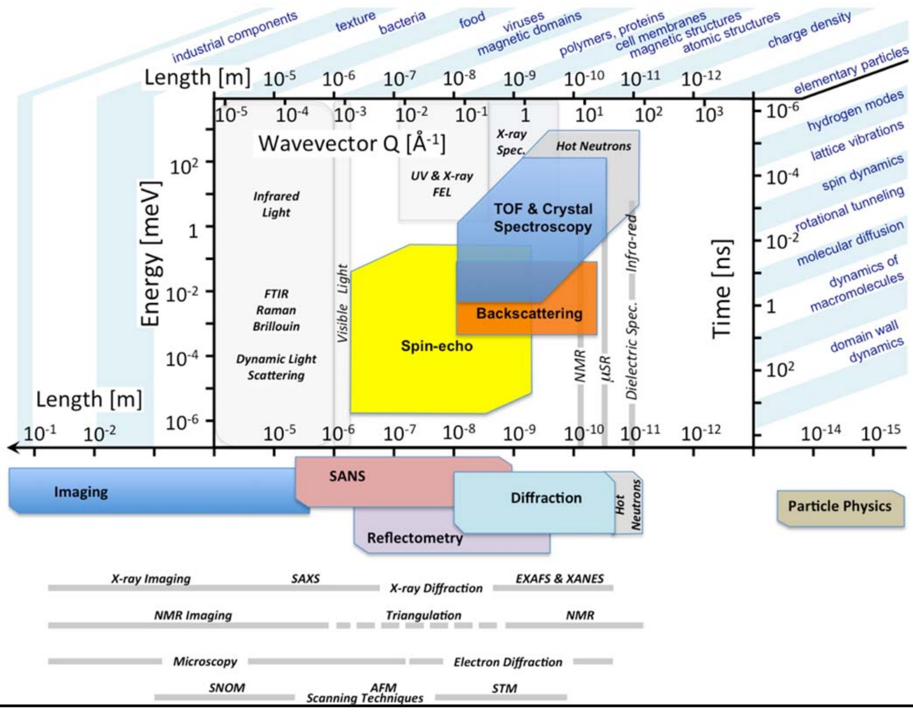
Intensity of scattering as function of Q is related to the Fourier transform of the spatial arrangement of matter in the sample => Correlations in Space

Intensity of scattering as function of ω is related to the Fourier transform of the temporal arrangement of matter in the sample => Correlations in Time

Elastic vs Inelastic

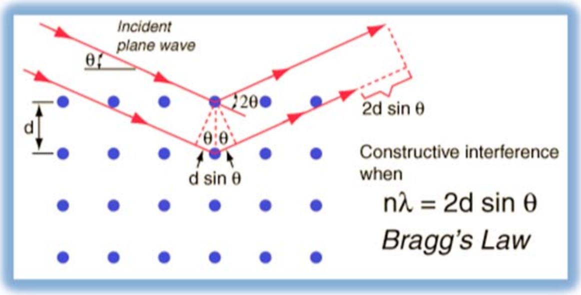


Neutron Scattering Techniques



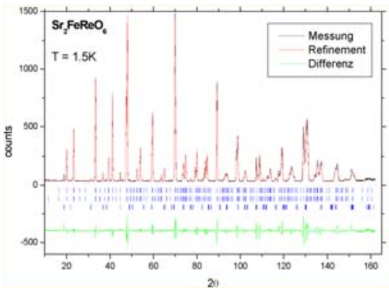
Diffraction

Sizes probed = "atomic structures" = 0.1 nm - 10 nm



BT1 Diffractometer at NCNR

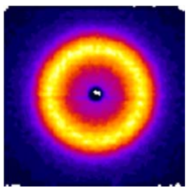
Position and intensity of diffraction peaks gives atomic positions

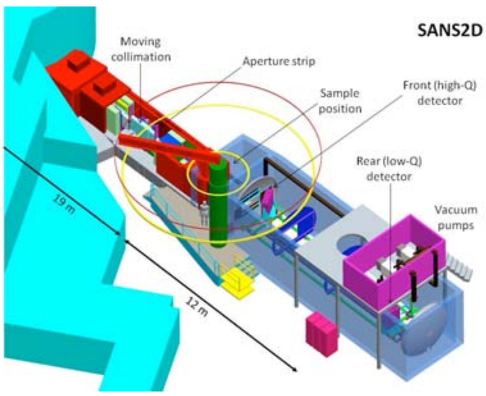


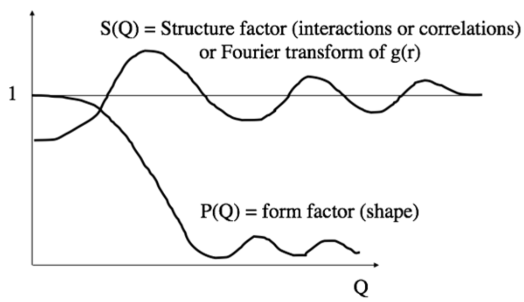
Diffraction pattern image from :http://www.uni-mainz.de/FB/Physik/IPH/Forschungsbericht02/KOMETex/KOMET_330_/NeutronDiffraction.html

Small Angle Scattering

Sizes probed = "large-scale structures" = 1 nm - 10 μm

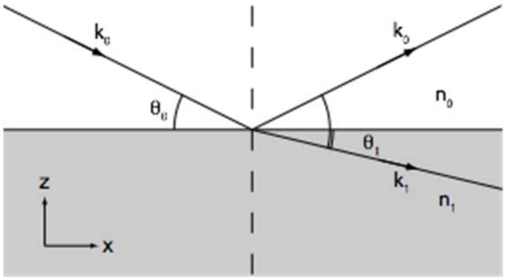




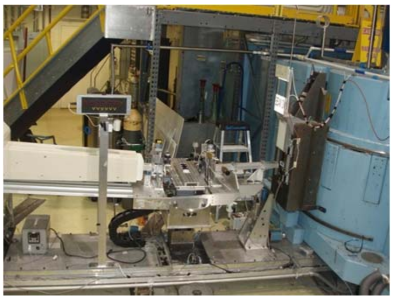


Reflectometry

Sizes probed = 1 nm - 100 nm



$k_z = k_0 \sin\theta_0$
$q_z = 2k_z = 4\pi/\lambda \sin\theta_0$



NG7 Reflectomter at NCNR

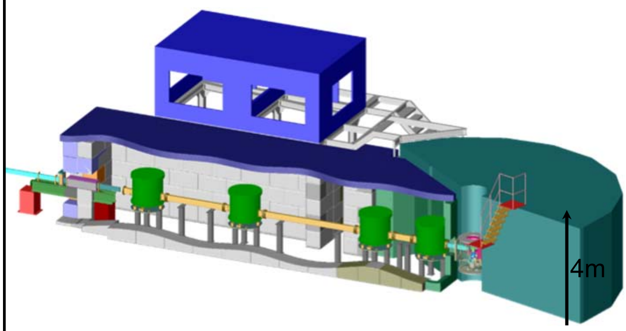
Specular = Incident and Reflected Angles Equal => Structure perpendicular to surface

Offspecular = Incident and Reflected Angles Not Equal => Structure in plane of surface

Reflection of neutrons first shown by Fermi and Zinn in the mid 1940's

Neutron Spectroscopy

Example : TOFTOF @ FRMII



Measure the change in energy of neutrons as a function of Q to obtain information about atomic or molecular motions

Methods include:
- Triple-axis spectrometry
- Backscattering spectroscopy
- Time-of-flight spectroscopy
- Neutron Spin Echo spectroscopy

Time and spatial resolution are well matched

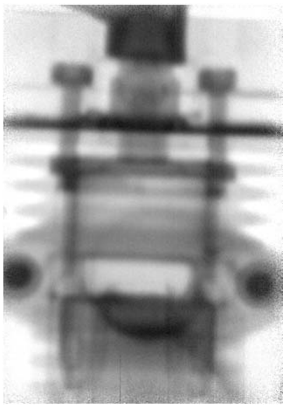
Useful for investigation of diffusive versus confined motion

Imaging

Mainly radiographic technique

Sizes probed = 100 μm and larger

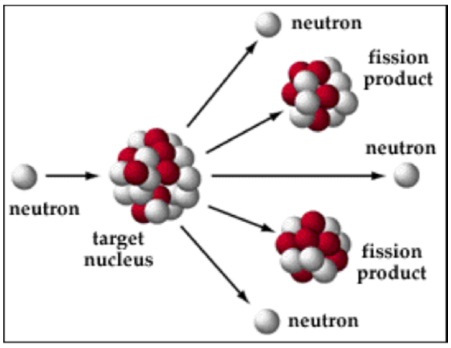
New methods are developing that give spatial mapping of diffraction or small angle scattering signals



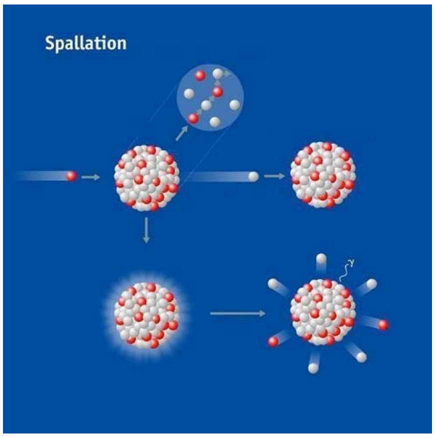
Neutron Scattering Facilities

Types of Neutron Source

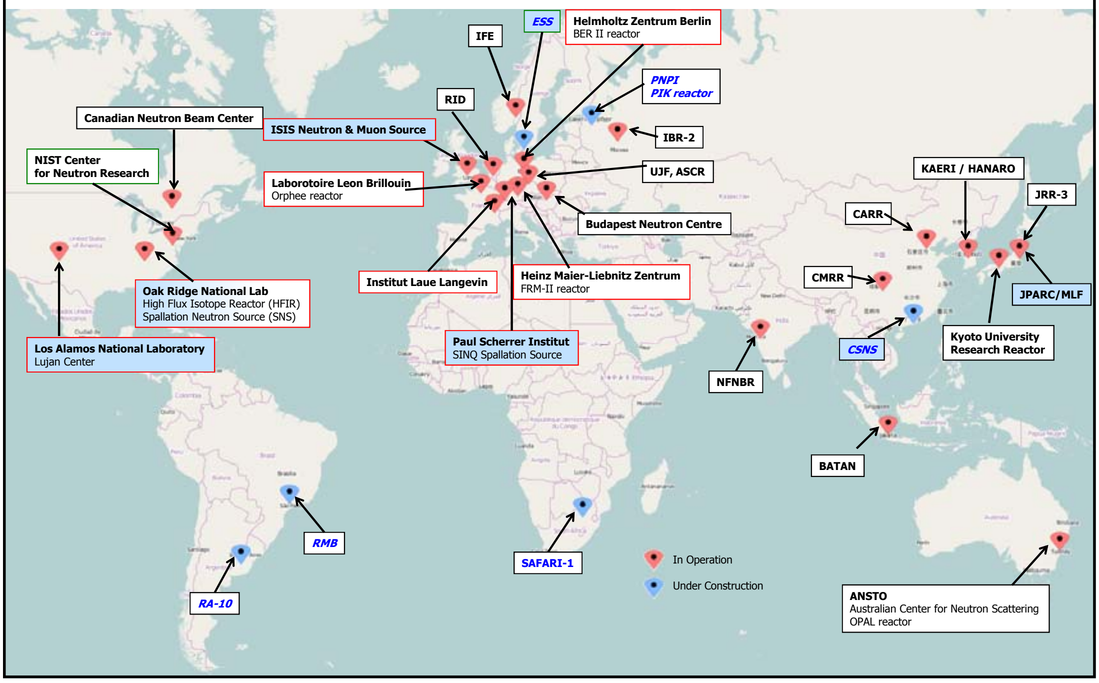
Nuclear Fission
(Reactors)



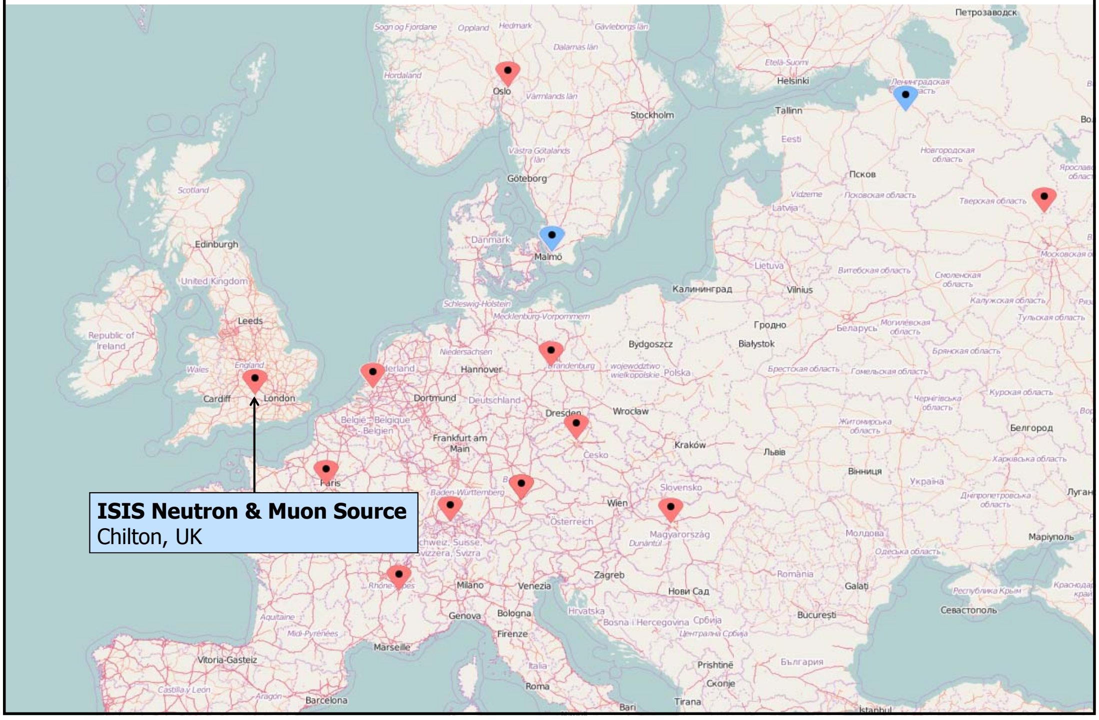
Spallation



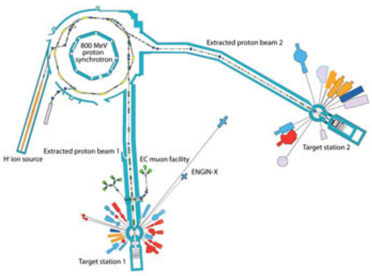
Neutron Scattering Facilities



Neutron Scattering Facilities in Europe



ISIS Neutron and Muon Source
Chilton, UK



- Short pulse spallation source
- Operating since 1984
- Linac and synchrotron ring

- 800 MeV proton beam
- 50 Hz operation

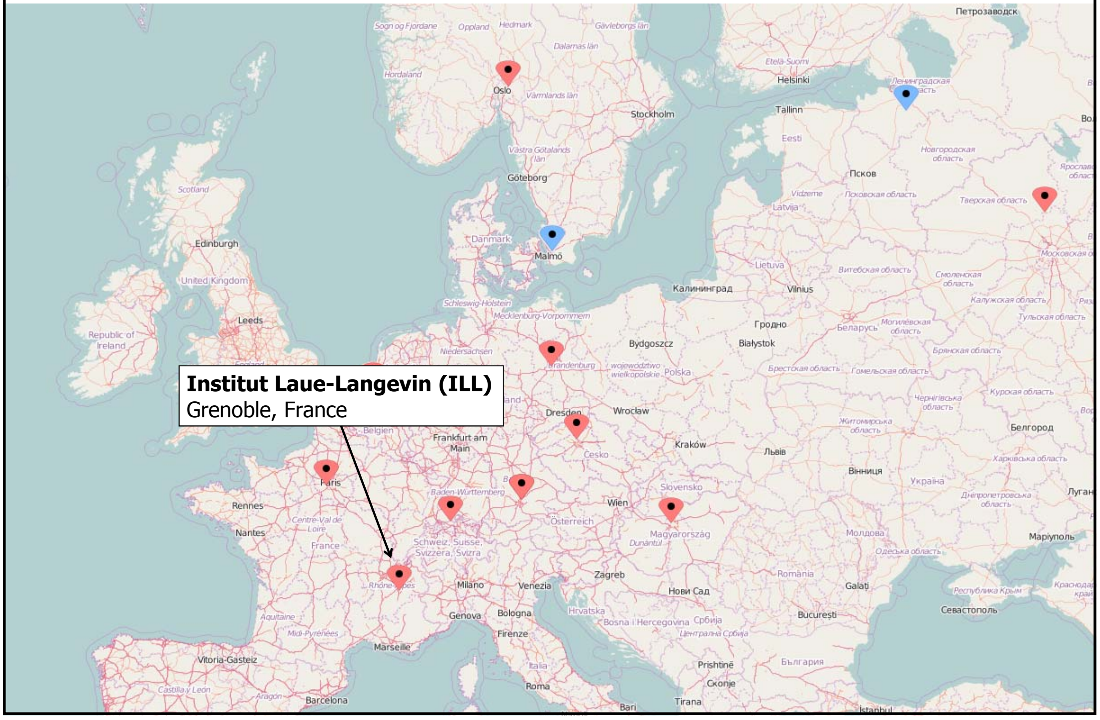
- Tungsten targets
- Hydrogen, Water and Methane moderators

- Two target stations:
- TS1 – 4/5 pulses (50hz) 160 kW
- TS2 – 1/5 pulses (10hz) 40 kW

- Recent major upgrade with TS2
- 27 Instruments with 4 in construction
- 1400 users in 3000 visits per year

http://www.isis.stfc.ac.uk

Neutron Scattering Facilities in Europe



Institut Laue-Langevin – ILL
Grenoble, France

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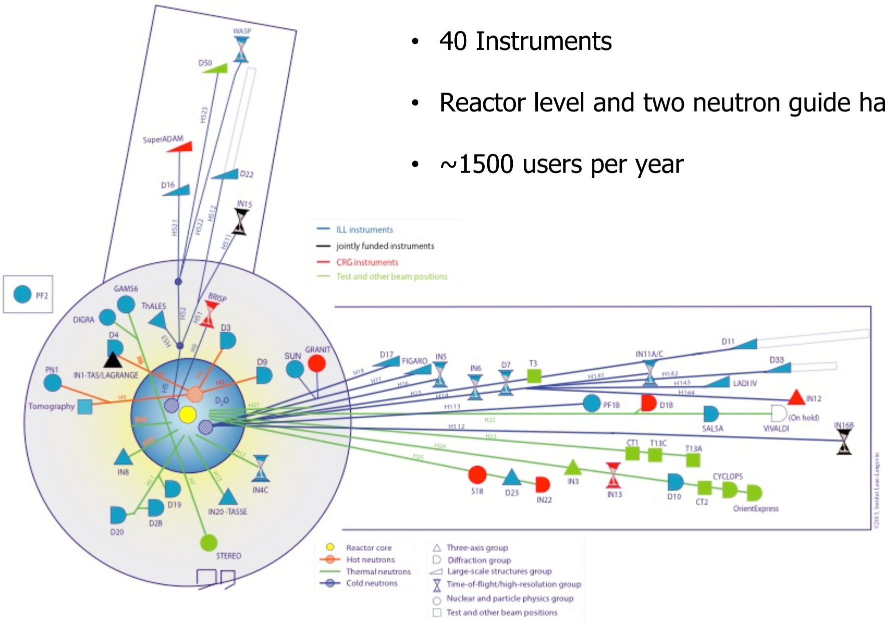
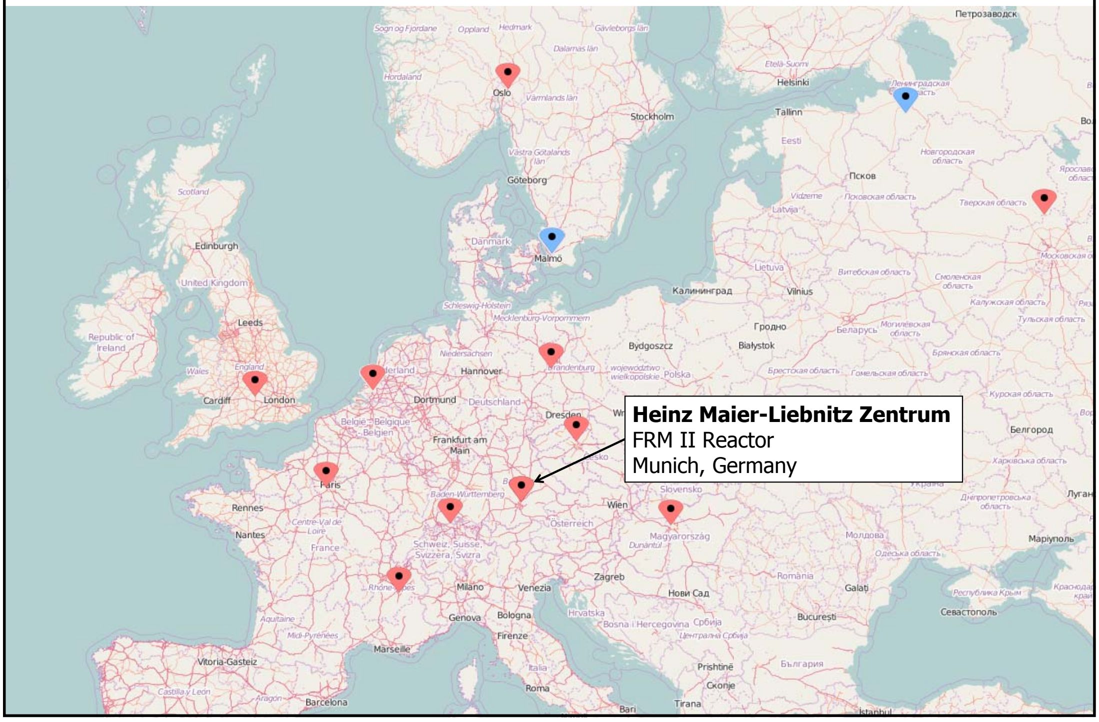


- 40 Instruments
- Reactor level and two neutron guide halls
- ~1500 users per year

Institut Laue-Langevin – ILL
Grenoble, France

- Recently completed a major upgrade programme with 7 new or upgraded instruments
- New programme underway to build 5 new instruments as well as enhance sample environment and data acquisition, control and data analysis software.

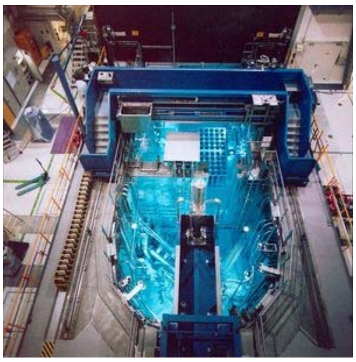
Neutron Scattering Facilities in Europe

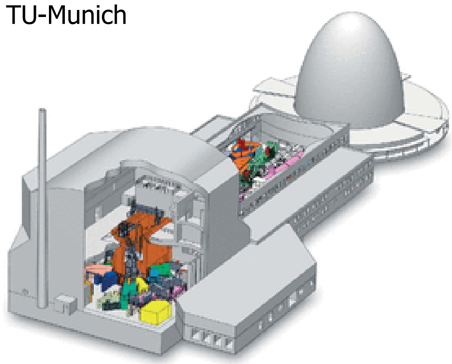


Heinz Maier-Leibnitz Zentrum – MLZ Munich, Germany

- Neutron research center based around FRM II reactor
- 20 MW open pool reactor
- Opened in 2004

- Cooperation between FZ-Julich, HZ-Geestacht and TU-Munich

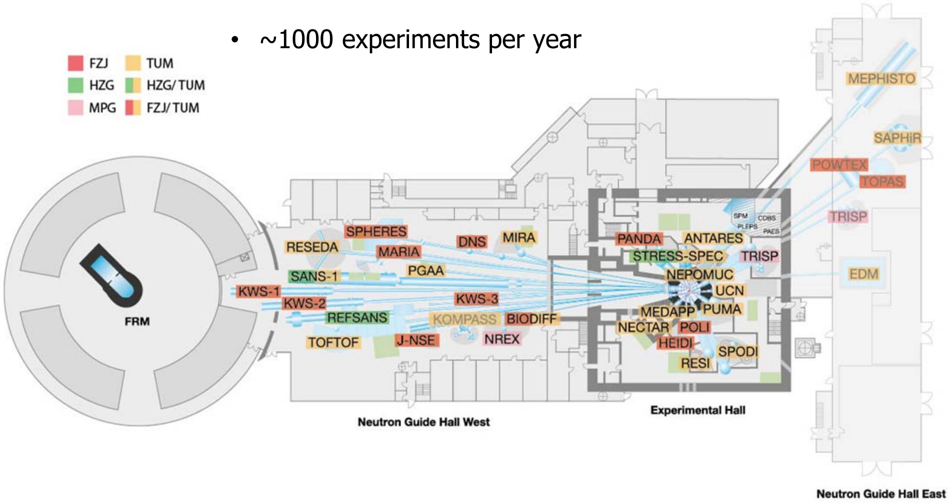




- http://www.mlz-garching.de

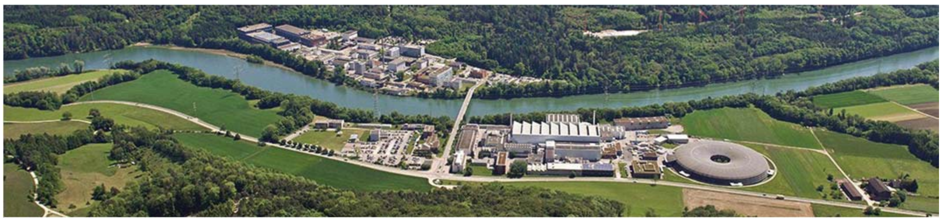
Heinz Maier-Leibnitz Zentrum – MLZ
Munich, Germany

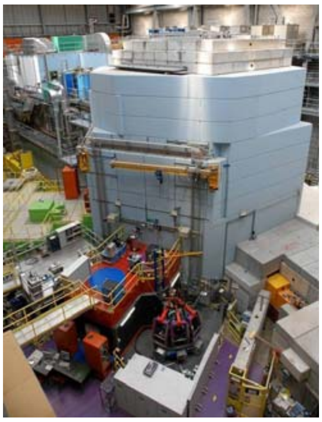
- 26 scattering instruments with 4 under construction
- ~1000 experiments per year



Neutron Scattering Facilities in Europe

SINQ at Paul Scherrer Institut
Villigen, Switzerland

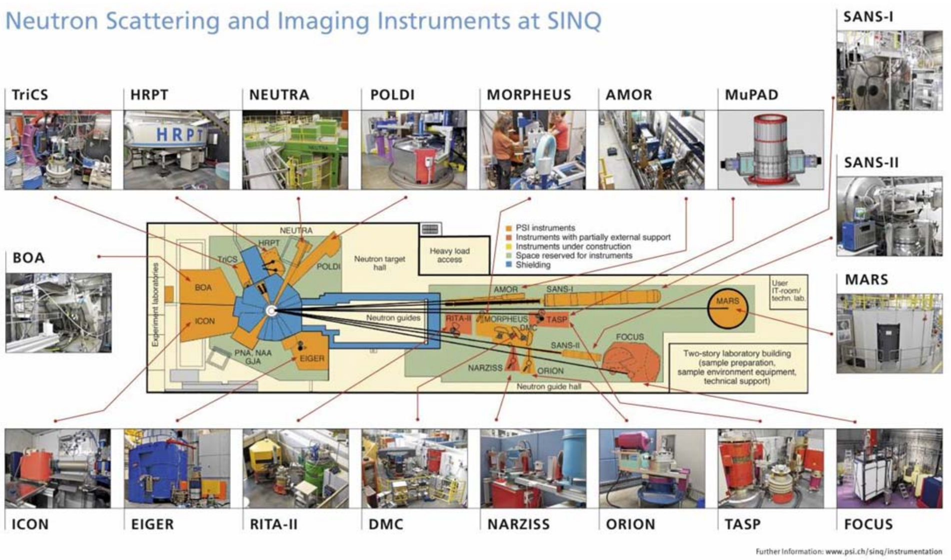




- Continuous spallation source
- 570 MeV proton beam
- 750kW
- Lead target
- Heavy water moderator and liquid deuterium cold source
- 8 Thermal beam ports plus cold guides

SINQ at Paul Scherrer Institut
Villigen, Switzerland

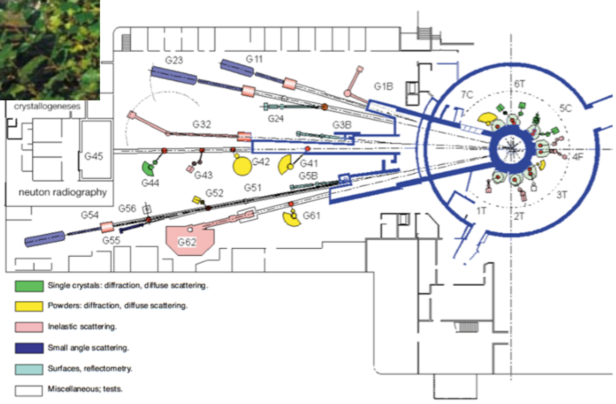
19 instruments & 4500 user visits per year



Neutron Scattering Facilities in Europe

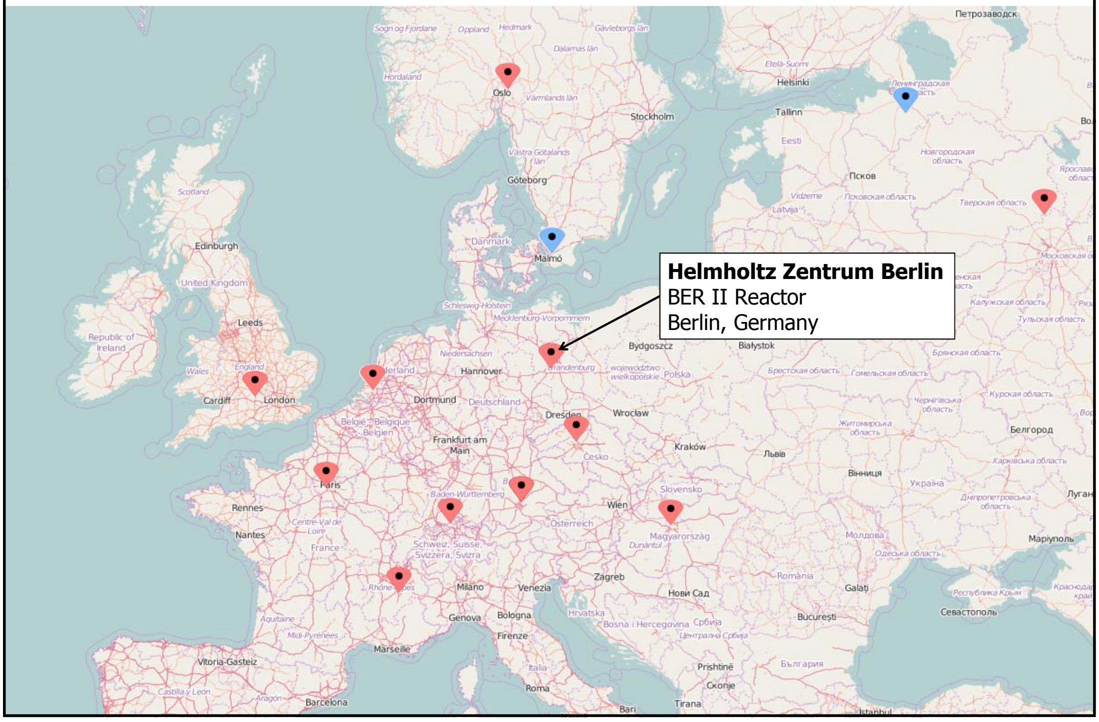
Laborotoire Leon Brillouin
Saclay, France

- 14 MW Heavy Water Reactor
- Cold source and 7 thermal beam ports
- Opened in 1980



- 25 Instruments
- ~500 users per year

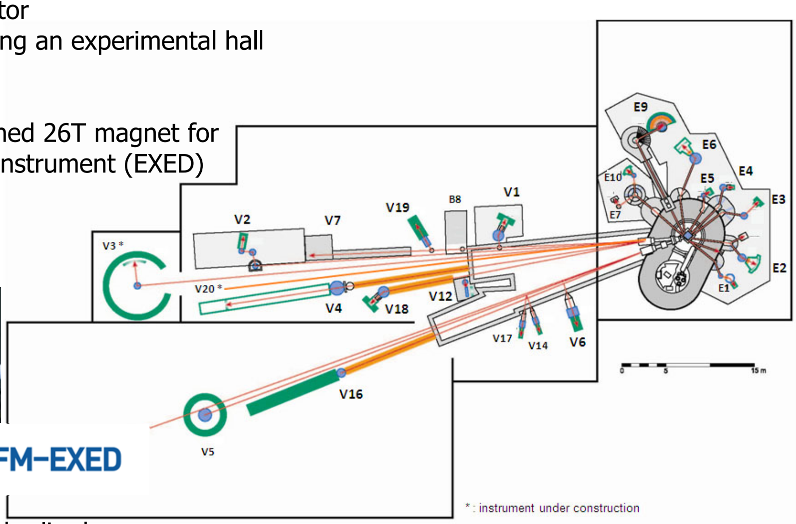
Neutron Scattering Facilities in Europe



BERII at Helmholtz Zentrum Berlin – HZB Berlin, Germany

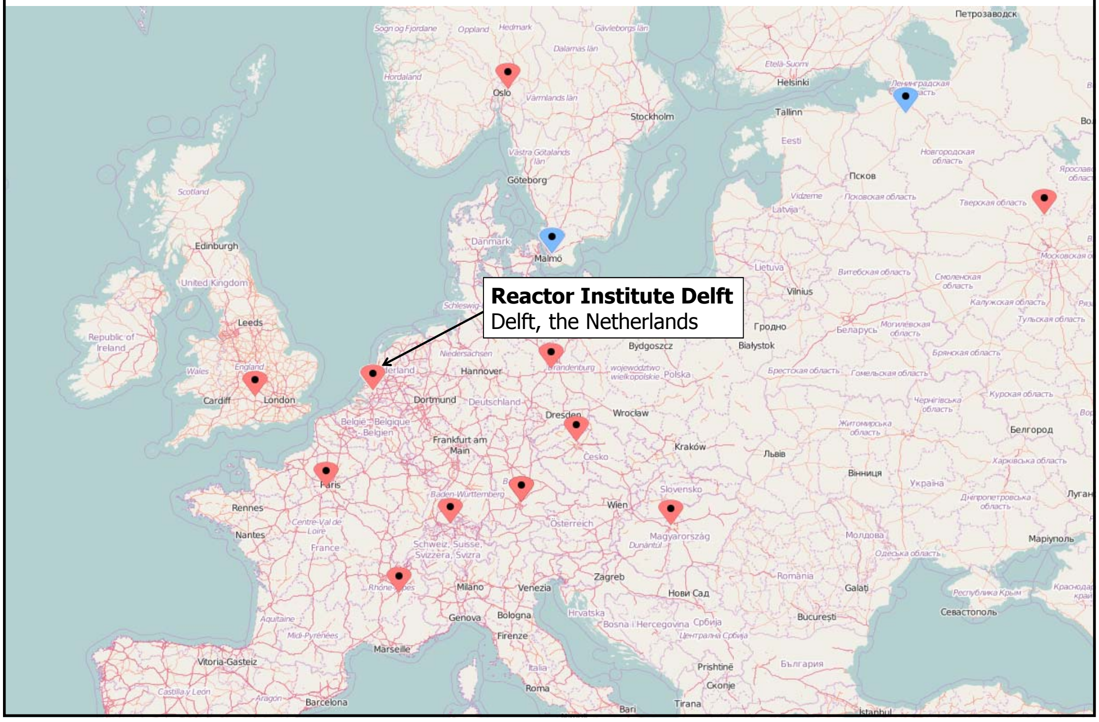
- Opened in 1972 and renovated 1991
- 10 MW open, light water moderated swimming pool reactor
- 18 beam ports feeding an experimental hall and two guide halls
- Recently commissioned 26T magnet for extreme conditions instrument (EXED)
- 21 instruments

HFM–EXED

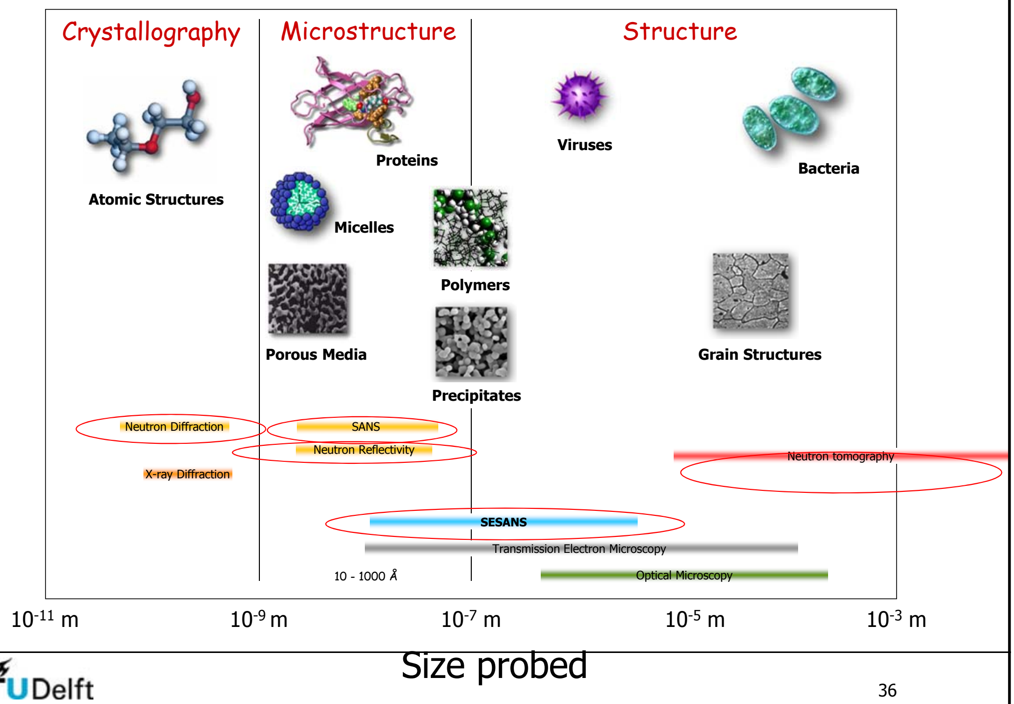


http://www.helmholtz-berlin.de

Neutron Scattering Facilities in Europe



Neutron instruments RID, Delft

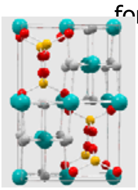


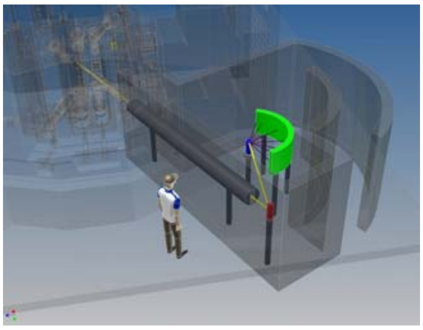
TU Delft

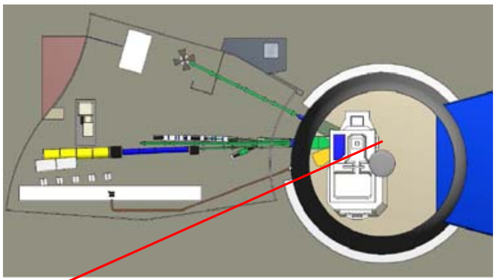
Neutron instruments RID, Delft

Pearl: powder diffractometer

for determining atomic structures







Operational since 2015

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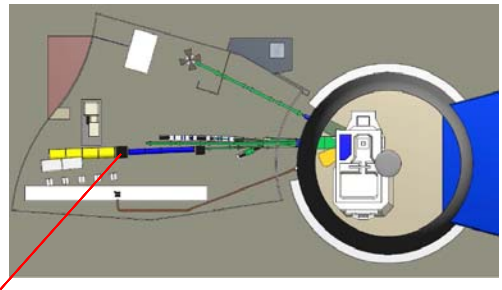
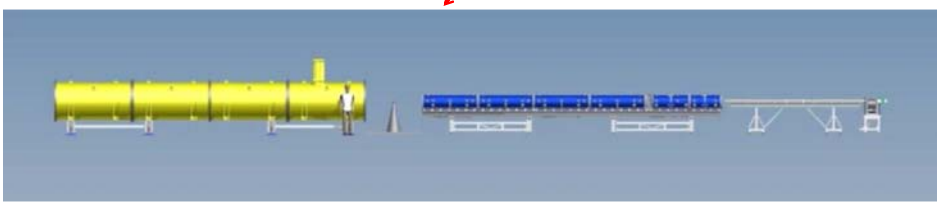
Neutron instruments RID, Delft

SANS: small-angle neutron scattering

for determining structures on length scale 1 – 100 mm





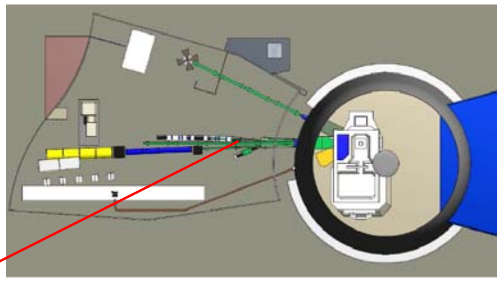
under development

TUDelft http://sans.weblog.tudelft.nl/ 38

Neutron instruments RID, Delft

SESANS: spin-echo small-angle neutron scattering

for determining structures on length scale 30 nm – 20 μm

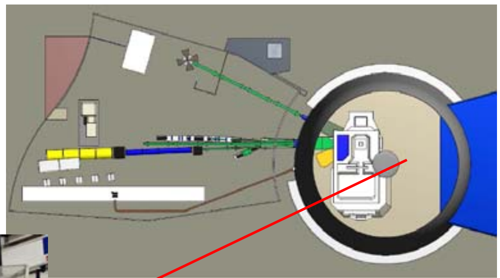


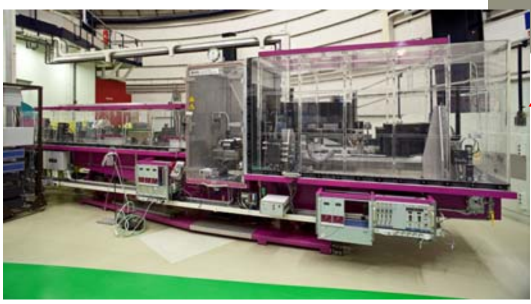
Operational since 2002

Neutron instruments RID, Delft

ROG: neutron reflectometer

for determining thin films and interfaces length scale 1 nm – 300 nm

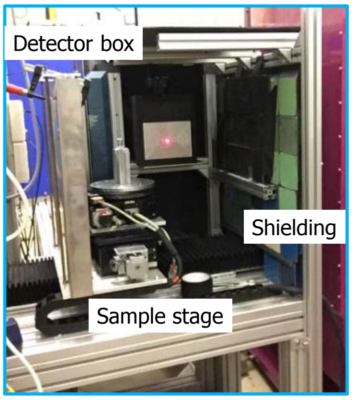


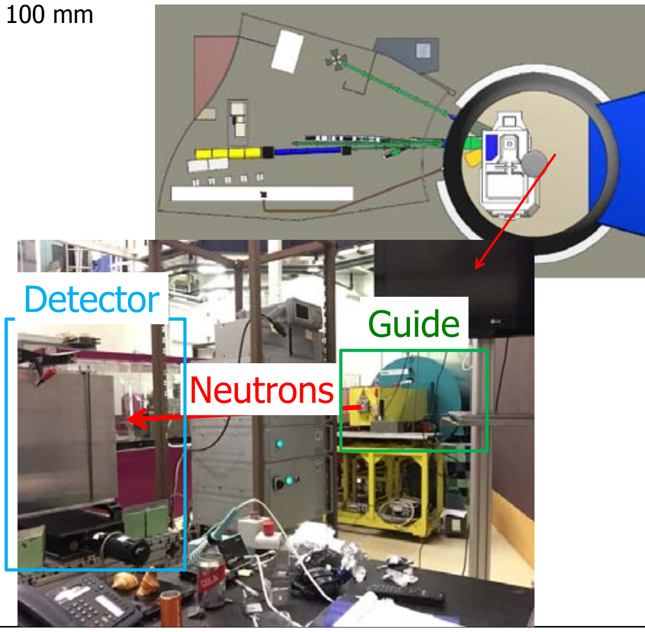


Operational since 1994

Neutron instruments RID, Delft

FISH: neutron tomography to determine structures on length scale 0.1 mm – 100 mm





Operational since 2016

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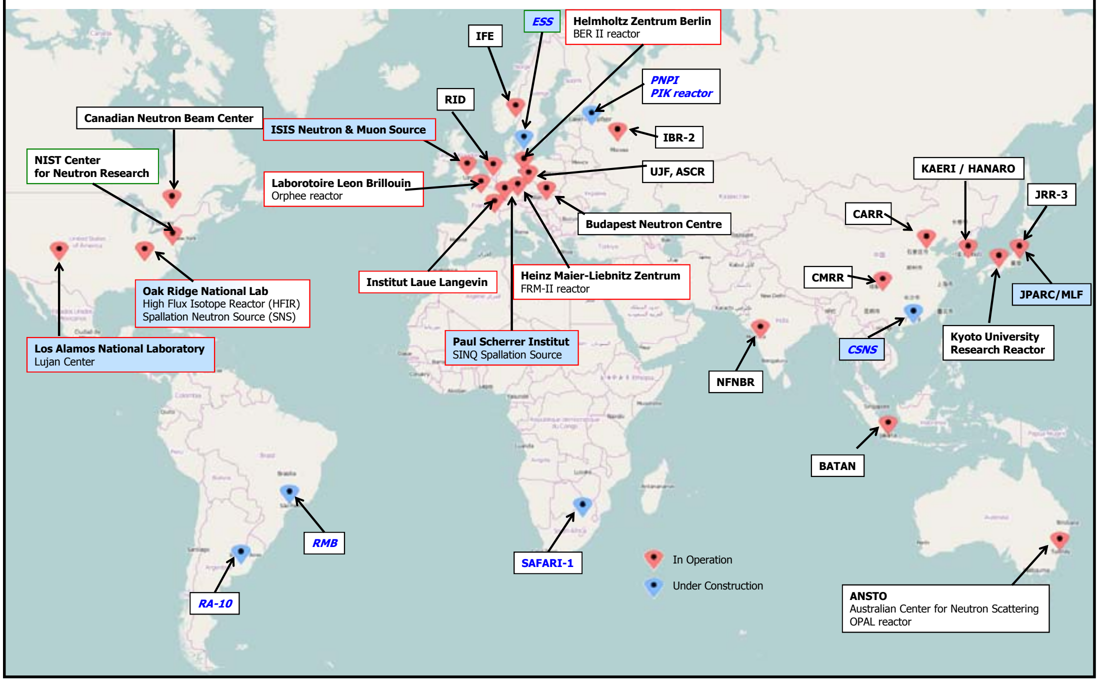
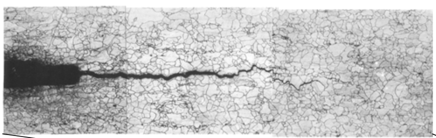
Neutron Scattering Facilities

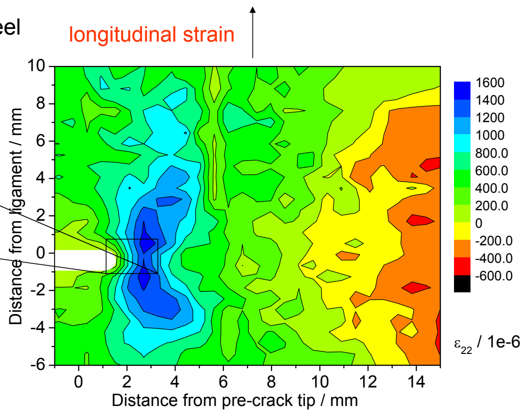


Research Examples

Stress in materials
Understanding macroscopic behaviour from nanostructure

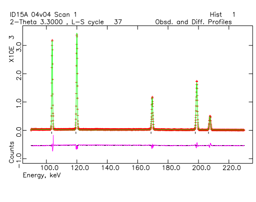
Fatigue + Creep Crack in **25mm** Austenitic steel





Aim: Exploring the boundaries of spatial resolution achievable in real materials engineering components, using combinations of in-situ techniques: imaging & diffraction, in-situ loading, high-temperature…

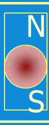
Methods: Scanning neutron diffraction and time-of-flight imaging



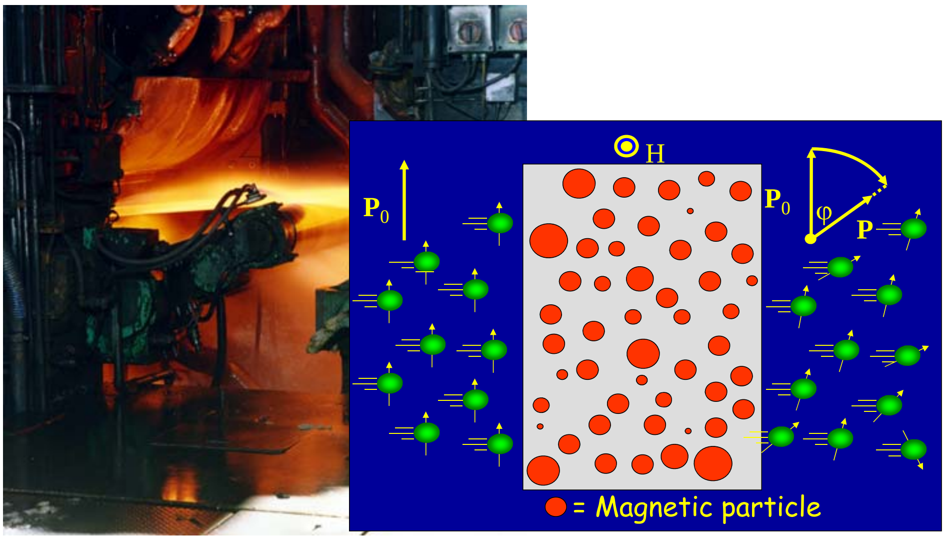
Neutron has a spin: Larmor precession

$$\frac{d}{dt}\vec{S}(t) = \gamma \vec{S}(t) \times \vec{B}(t)$$

TU Delft

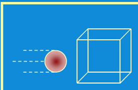


- has a magnetic moment
  - can see magnetic effects

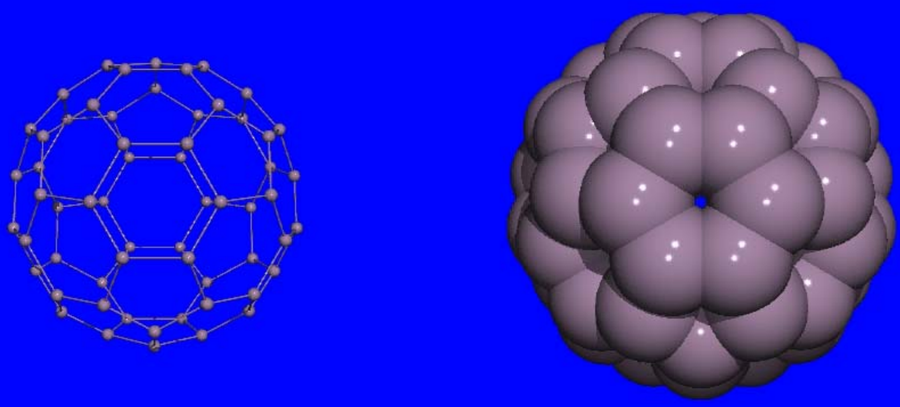


Watching ferrite grow during austenite-ferrite transition in steels

TU Delft 46

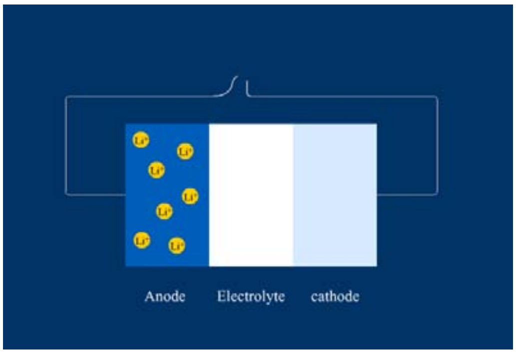


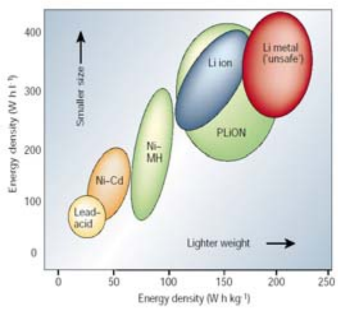
- Neutrons move at speeds similar to atoms – can study motion of atoms



Measuring and calculating nuclear motion – directly.

Example: Energy storage in Li-ion batteries





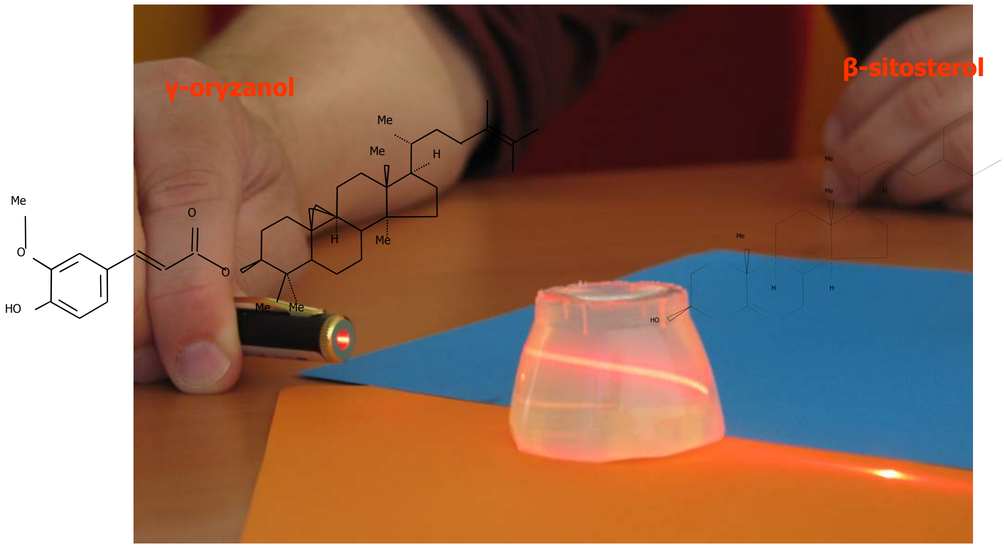
Demanded properties

- High voltage difference
- High capacity
- High power density
- Long cycle life
- Low weight

Microscopic origin

- Difference in Li-host interaction
- Amount of Li-ion stored
- Mobility of Li-ions
- Small changes in lattice parameters

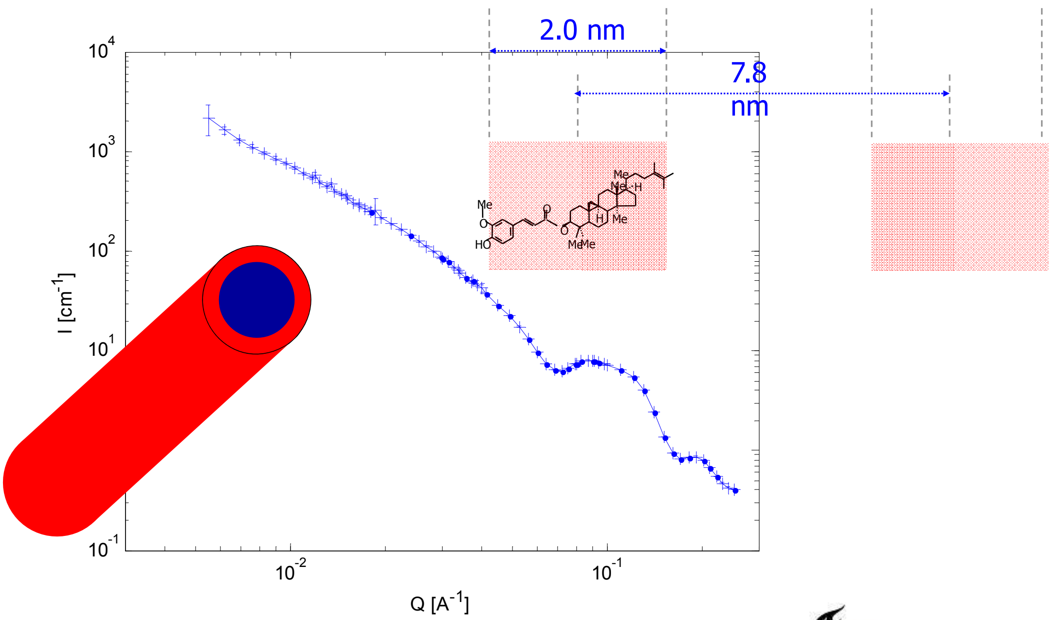
The phytosterol compounds structure oils without solid fats



A. Bot (Unilever), *et al.*
Faraday Discuss. **158**, 223-238 (2012)

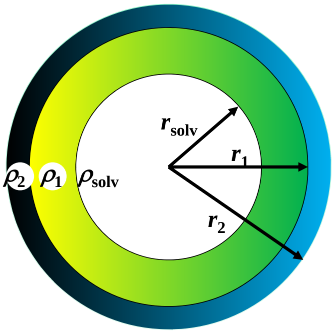
TUDelft

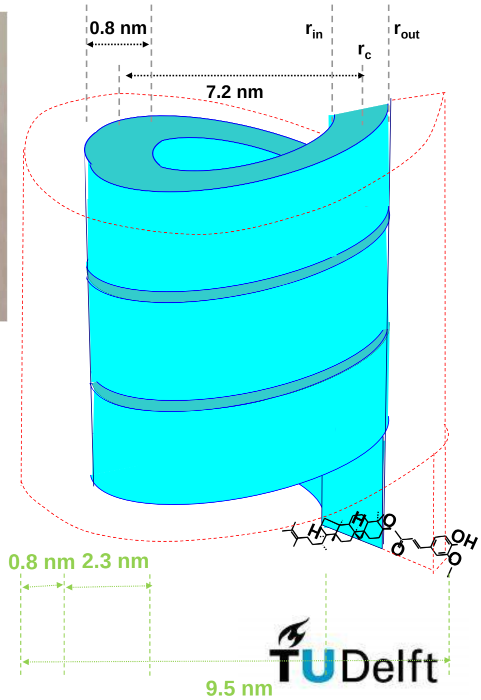
β-sitosterol and γ-oryzanol in d-decane



TUDelft

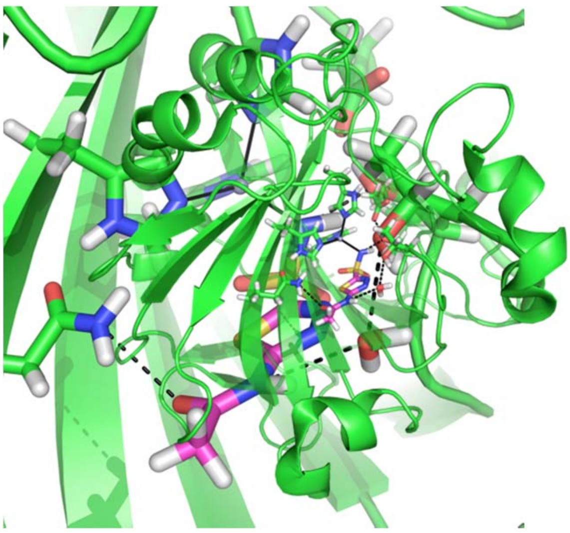
Double walled helical ribbon





TUDelft

Neutrons reveal how drugs interact with drug targets



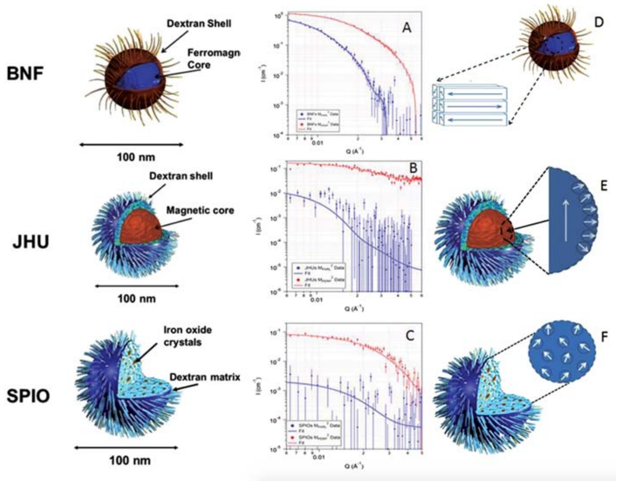
The enzyme carbonic anhydrase transports CO_2 and regulates blood acidity. It is a major player in some cancers, glaucoma, obesity and high blood pressure

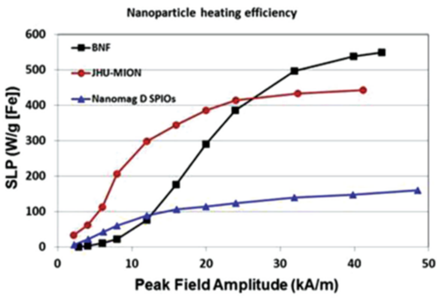
Neutron crystallography pinpoints protons and waters in the active site, showing how the drug Acetazolamide binds

Image: Fisher, S. Z. *et al.* 2012 JACS

Hyperthermia Treatment of Cancer

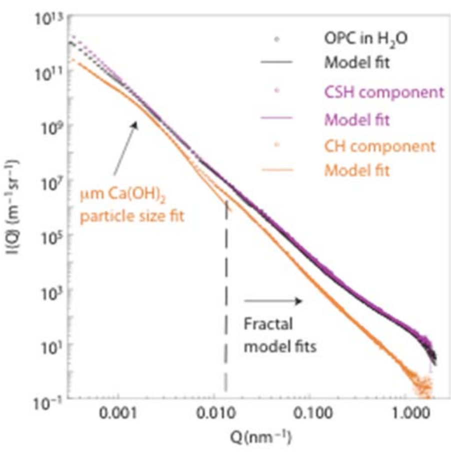
- Use magnetic nanoparticles with alternating magnetic field to locally heat tumour
- Structure of the nanoparticles has strong impact on heating response
- Use polarized neutron scattering to understand these differences

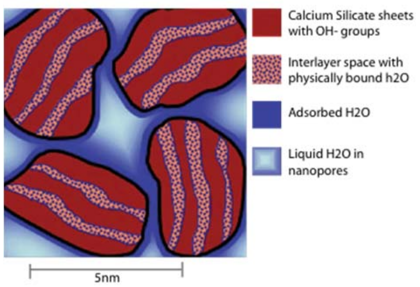




Dennis et al. *Advanced Functional Materials,* (2015), **25**, 4300

Hydration in Cement





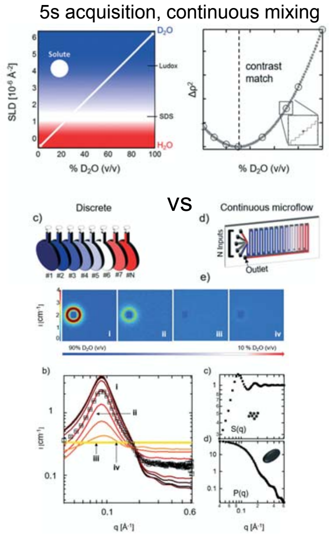
Combination of SANS/USANS and SAXS/USAXS gives detailed information about the mean formula and mass density of calcium-silicate-hydrate without drying - the first such measurement.

Allen AJ, Thomas JJ, Jennings HM. Nature Materials, 6(4), 311 (2007)

Microfluidic SANS

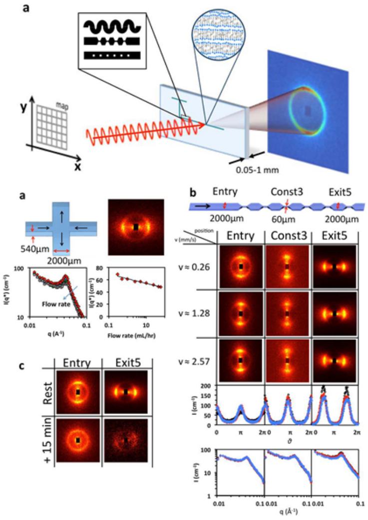
High Throughput Mixing & Tailored Flow Geometry

400 um channels, 12 mm beam avg. over 20 channels
5s acquisition, continuous mixing



Adamo, M., Poulos, A. S., Miller, R. M., Lopez, C. G., Martel, A., Porcar, L., & Cabral, J. T. (2017). *Lab Chip*, *17*(9), 1559–1569.

60um channels, 500um beam
0.01 – 0.3Å-1 – 1s - 5 min. acquisitions

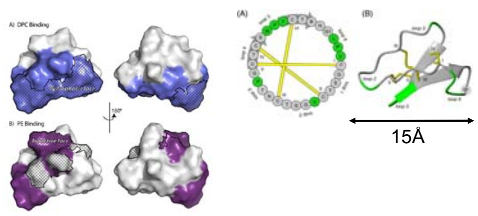


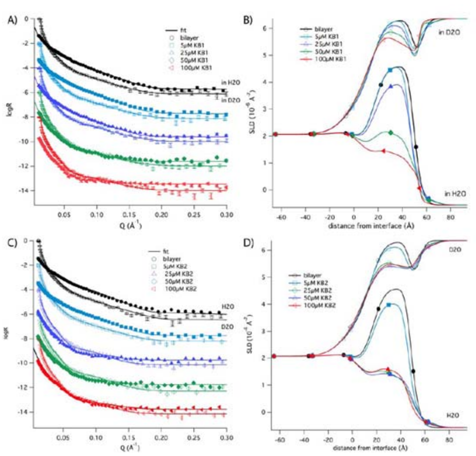
C.G. Lopez, T. Watanabe, A. Martel, L. Porcar, J.T. Cabral, Scientific Reports, 5 (2015) 7727.

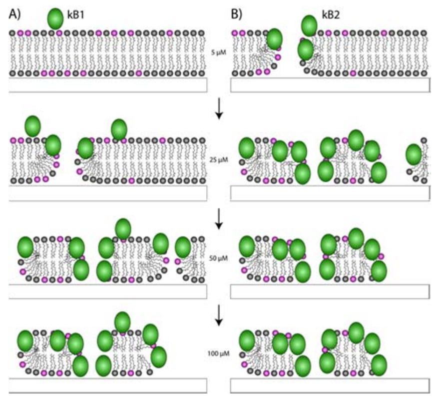
Kalata B1/B2 – plant cyclotides

Hanna Wacklin-Knecht, ESS and Conan Wang/David Craik Institute for Molecular Bioscience, UQLD Brisbane

- Circular peptides are found in many plants – antimicrobial, anti-HIV, anticancer
- Compact structures with hydrophobic patch - oligomers in solution
- How cyclotides form pores in membranes?

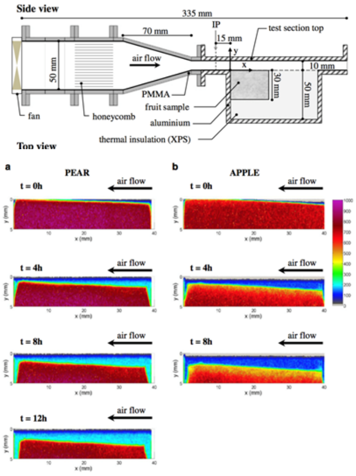






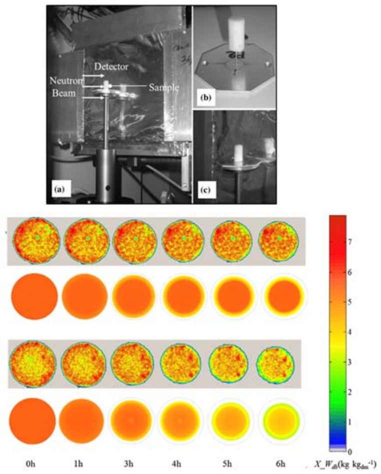
Drying of Fruit

In-Situ drying in wind tunnel using neutrons imaging to quantitatively determine water loss and water loss profile



Defraeye, T., et al. *Food and Bioprocess Technology*, *6*(12), 3353

Neutron tomography of dehydration of apple used to examine water loss and validate numerical simulations of drying



Aregawi, W., et al. (2013). *International Journal of Heat and Mass Transfer* , *67*, 173–182.

Visualising Particle Distributions

Using chemical sensitivity of neutrons to distinguish particle types

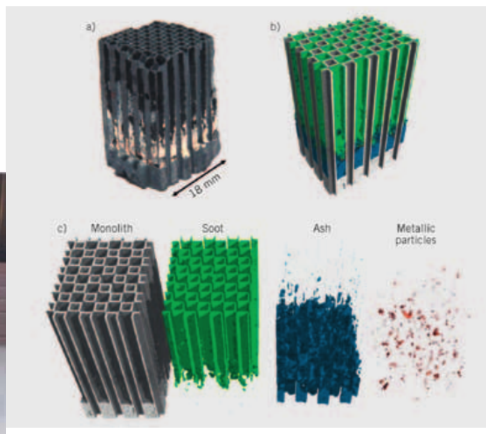
Neutron tomography used to examine particulate type and distribution in filters

AUTHORS

DR. DIPL.-PHYS. CHRISTIAN GRÜNZWEIG

VISUALISING THE SOOT AND ASH DISTRIBUTION IN DIESEL PARTICULATE FILTERS USING NEUTRON IMAGING

Neutron tomography is presently the only possibility to obtain information about



Courtesy: Ch. Gruenzweig
PSI, Switzerland

and Applied

Fundamental Research with Neutrons

Andrew Jackson

European Spallation Source

Delivered by Wim Bouwman, Delft University of Technology

75 years of nuclear reactors: A chain reaction of applications
KIVI-NNS Symposium, 3rd November 2017