advanced neutron imaging
Vienna
Vienna

Berlin
Helmholtz Zentrum
Vienna

Berlin, 1935 – 1938

H. Kallmann & Kuhn
with Ra-Be and neutron generator

Berlin

Helmholtz Zentrum
Vienna

Berlin, 1935 – 1938
H. Kallmann & Kuhn
with Ra-Be
and neutron generator

Berlin
Helmholtz Zentrum

Lund
Copenhagen
ESS
Baseline parameters:
14 Hz
2.86 ms
Time average flux of ILL
7 day one instruments
2019
22 instruments 2025
Contrast

neutron interaction with matter
Contrast

neutron interaction with matter
Introduction Neutron imaging

Some advantages:
High penetration power
High sensitivity to Hydrogen
Low radiation damage
Introduction Neutron imaging

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High penetration power
High sensitivity to Hydrogen
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Introduction Neutron imaging

Some advantages:
High penetration power
High sensitivity to Hydrogen
Low radiation damage
Isotope sensitive
Contrast
Contrast
Contrast

Fig. a: Neutron radiography of a camera
Fig. b: Radiographic image of a camera made X-rays
Contrast
Contrast

Resolution
Contrast          Resolution
Contrast

- Radiation used
- Materials examined
- Instrumentation

Resolution
Contrast

- Radiation used
- Materials examined
- Instrumentation

Resolution

- Instrumentation
- Detectors
Contrast

Interaction of neutrons with matter:

**Scattering & Absorption**

Cross sections:

- Microscopic cross sections: \( \sigma = \sigma_a + \sigma_s \)

\[
\frac{d\sigma}{d\Omega}
\]

Unit of \( \sigma \): 1 barn = \( 10^{-24} \) cm\(^2\)

**Macroscopic cross section** : \( \Sigma \) (i.e. \( \mu \) linear attenuation coefficient)

\[ \Sigma = N \cdot \sigma , \quad N = \text{number of nuclei per cm}^3 . \]

Unit of \( \Sigma \) is [cm\(^{-1}\)].
Interaction of neutrons with matter:

**Scattering & Absorption**

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Contrast

Interaction of neutrons with matter: Scattering & Absorption

Cross sections:
Microscopic cross sections: \( \sigma = \sigma_a + \sigma_s \)

Unit of \( \sigma \): 1 barn = \(10^{-24}\) cm\(^2\)

Macroscopic cross section: \( \Sigma \) (i.e. \( \mu \) linear attenuation coefficient)

\[ \Sigma = N \cdot \sigma, \quad N = \text{number of nuclei per cm}^3. \]

Unit of \( \Sigma \) is [cm\(^{-1}\)].

\[
I = I_0 e^{-\int \Sigma(x) dx}
\]
Total neutron cross section

Summing up the individual cross sections

\[ \sigma_{coh}^{el}(\lambda) = \frac{\lambda^2}{2V_1} \sum_{\lambda < \lambda} \frac{d_{hkkl}^2}{d_{hkkl}=0} |F_{hkkl}|^2 \]

\[ \sigma_{inc}^{el}(\lambda) = \bar{\sigma}_{inc} \sum_n \frac{\lambda^2}{2B_{iso,n}} (1 - e^{-\frac{2B_{iso,n}}{\lambda^2}}) \]

\[ \sigma_{inel}^{total}(\lambda) = (\bar{\sigma}_{coh} + \bar{\sigma}_{inc}) \left( \frac{M/m}{M/m + 1} \right)^2 \sum_n \left( 1 + \frac{9 \varphi_3(\theta) \varphi_3(\theta) \lambda^2}{2M^2/m^2B_{iso}} \right) \]

\[ \sigma_{abs}(\lambda) = B \cdot \frac{m \lambda}{h} = \frac{\sigma_{abs}}{1.798 \text{Å}} \cdot \lambda \]

\[ \sigma_{total}(\lambda) \]
Total neutron cross section

Most significant

Defines the Bragg edge position

\[ \sigma_{\text{coh}}^e(\lambda) = \frac{\lambda^2}{2V_0} \sum_{d_{hkl}=0}^{2d_{hkl}<\lambda} |F_{hkl}|^2 d_{hkl} \]

\[ \sigma_{\text{inc}}^e(\lambda) = \bar{\sigma}_{\text{inc}} \sum_n \frac{\lambda^2}{2B_{\text{iso},n}} (1 - e^{-\left(\frac{2B_{\text{iso},n}}{\lambda^2}\right)}) \]

\[ \sigma_{\text{inel}}^{\text{total}}(\lambda) = (\sigma_{\text{coh}} + \sigma_{\text{inc}})(\frac{M/m}{M/m + 1})^2 \sum_n (1 + \frac{9 \varphi_3(\theta) \varphi_3(\theta) \lambda^2}{2M^2/m^2 B_{\text{iso}}}) \]

\[ \sigma_{\text{abs}}(\lambda) = B \cdot \frac{m\lambda}{\hbar} = \frac{\sigma_{\text{abs}}^{2200\text{m/s}}}{1.798\text{Å}} \cdot \lambda \]

\[ \sigma_{\text{total}}(\lambda) \]
consequence

\[ \ln\left(\frac{N_{\text{in}}}{N_{\text{d}}}\right) \]

Thickness of a homogeneous absorber

**Ideal case** (no spectral shifting)

**Practical case**
consequence

\[ \ln\left(\frac{N_{in}}{N_d}\right) \]

Ideal case (no spectral shifting)

Practical case

Thickness of a homogeneous absorber
Monochromatic imaging

vent tube

1.4 cm
Monochromatic imaging

vent tube

1.4 cm
Energy resolved imaging

-neutron guide
-beam stop
-upper
-lower
-sample
-rotation + tilt stage
-CCD detector
Energy resolved imaging

- Neutron guide
- Beam stop
- PCG crystals
- Monochromatic beam
- Rotation + tilt stage
- Sample
- CCD detector

[Diagram showing the above components arranged in a line process flow.]
Energy resolved imaging

neutron guide
beam stop
PCG crystals
monochromatic beam
sample
rotation + tilt stage
CCD detector
Total neutron cross section

Most significant

Defines the Bragg edge position

\[
\sigma_{coh}(\lambda) = \frac{\lambda^2}{2V_0} \sum_{2d_{hkl}} < \lambda \mid F_{hkl} \mid^2 d_{hkl}
\]

\[
\sigma_{inc}(\lambda) = \bar{\sigma}_{inc} \sum_n \frac{\lambda^2}{2B_{iso,n}} \left( 1 - e^{-\frac{2B_{iso,n}}{\lambda^2}} \right)
\]

\[
\sigma_{inel}(\lambda) = (\sigma_{coh} + \sigma_{inc}) \left( \frac{M/m}{M/m + 1} \right)^2 \sum_n \left( 1 + \frac{9\varphi_3(\theta)\varphi_3(\theta)\lambda^2}{2M^2/m^2B_{iso}} \right)
\]

\[
\sigma_{abs}(\lambda) = B \cdot \frac{m\lambda}{h} = \frac{\sigma_{abs}^{2200m/s}}{1.798\text{Å}} \cdot \lambda
\]

\[
\sigma_{total}(\lambda)
\]
Bragg scattering – coherent, elastic

\[ n\lambda = 2dsin\Theta \]
Energy resolved imaging
Energy resolved imaging

**Fe**

![Graph showing attenuation coefficient versus wavelength for Fe](image1)

**Cu**

![Graph showing attenuation coefficient versus wavelength for Cu](image2)

**Al**

![Graph showing attenuation coefficient versus wavelength for Al](image3)
Energy resolved imaging

Graphs showing the attenuation coefficient, $\Sigma$ [cm$^{-1}$], as a function of wavelength [Å] for Fe, Cu, and Al.}

- **Fe:** The graph shows a gradual increase in the attenuation coefficient with wavelength, with a sharp peak around 4 Å.
- **Cu:** The graph exhibits a more pronounced peak around 4 Å followed by a decrease in the attenuation coefficient.
- **Al:** The attenuation coefficient shows a series of peaks and valleys, with a notable peak at around 3 Å.

Images below the graphs illustrate the applications of energy resolved imaging, with a scale bar indicating 5 mm.
Energy resolved imaging
Energy resolved imaging

Bragg scattering analyses

neutron beam

5 mm steel

recording radiographies
scanning the spectrum
analysing Bragg edge
in every image point

Bragg cutoff position, [Å]

13 cm
Energy resolved imaging

Bragg scattering analyses

- neutron beam
- recording radiographies
- scanning the spectrum
- analysing Bragg edge in every image point

5 mm steel

Transmission, $I/I_0$

Bragg cutoff position, [Å]

13 cm
Energy resolved imaging

Bragg scattering analyses

neutron beam

5 mm steel

Recording radiographies

Scanning the spectrum

Analysing Bragg edge in every image point

Transmission, $n/n_0$

Bragg-cutoff position, [Å]

13 cm
Energy resolved imaging

Bragg scattering analyses

neutron beam

5 mm steel

Transmission, \( \frac{I}{I_0} \)

Bragg cutoff position, [\( \text{Å} \)]

13 cm

Recording radiographies

Scanning the spectrum

Analysing Bragg edge

In every image point

Fe

Attenuation coefficient, \( \Sigma \) [cm\(^{-1}\)]

Wavelength [Å]
Energy resolved imaging

Investigation on steel weld

photo

4.2 Å
Energy resolved imaging

Investigation on steel weld

resolution: 50 µm
Energy resolved imaging
Energy resolved imaging
Structural phase sensitive tomography

Bainitic sample

Martensitic sample
Energy resolved imaging

- energy selector
- monochromatic beam
- rotation + tilt stage
- sample
- CCD detector
Energy resolved imaging
Energy resolved imaging

Pulsed spallation source ESS
Strain mapping
Strain mapping
Strain mapping
3D-XRD, diffraction imaging
3D-XRD, diffraction imaging
3D-XRD, diffraction imaging
Energy resolved Bragg edge imaging

Bragg edge diffraction imaging

I. Manke, M. Strobl et al.

R. Woracek, M. Strobl et al. JAP 2011

J.R. Santistepan NIMA (2002)


E. Lehmann, N. Kardjilov et al. NIMA 2009

W. T., M. Strobl et al. APL 2006

H. Sato et al. J. Phys 2010

Nuclear and magnetic dark-field imaging

Fast and stroboscopic imaging

Polarized neutron imaging

Phase contrast, complementary x-ray, fast neutron...

Energy resolved Bragg edge imaging
What about small angles?

E.g. refraction
What about small angles?

e.g. refraction
Small angle scattering

Fig 2: Scattering from objects

$\Theta \propto \frac{1}{d}$
Phase contrast
Phase contrast

Grating Interferometer

source grating

phase grating

absorption grating
Phase contrast

Grating Interferometer

source grating

phase grating

absorption grating
Phase contrast

Grating Interferometer

source grating

phase grating

detector

absorption grating

Dark field contrast

source grating

grating interferometer
Dark field contrast

source grating

grating interferometer
Dark field contrast

source grating

grating interferometer
Dark field contrast

source grating

grating interferometer

$\delta(x, y)$
Dark field contrast
Dark field contrast

source grating

grating interferometer
Dark field contrast
Dark field contrast

Diagram 1: Graph showing modulation (amplitude/offset) against the width of the scattering curve [arcsec].

Diagram 2: Graph showing counts/min against arcsec, with curves labeled 'Instr. Curve' and 'Sample'.

[Graphs and data points are not transcribed due to the nature of the image representation.]
Dark field contrast

\[
P_{\theta}(t) = w(\theta, t)^2 = \int_{path} \frac{\sigma(x, y) N(x, y)}{R^2(x, y)} \, ds
\]

M. Strobl et al. PRL (2008)
Dark field contrast
Dark field contrast

Al-Si binary metallic alloys castings with varying levels of hydrogen concentrations in the initial melts

A. Hilger et al. JAP (2010)
Dark field contrast

A. Hilger et al. JAP (2010)
Dark field contrast

A. Hilger et al. JAP (2010)
Dark field contrast

A. Hilger et al. JAP (2010)
Dark field contrast

2024-T3 Al alloy fatigue test sample

A. Hilger et al. JAP (2010)
Dark field contrast

2024-T3 Al alloy fatigue test sample

A. Hilger et al. JAP (2010)
Dark field contrast

2024-T3 Al alloy fatigue test sample

A. Hilger et al. JAP (2010)
Dark field contrast

A. Hilger et al. JAP (2010)
Phase and dark field contrast

Refractive index: \( n(x, y, z, \lambda) = 1 - \delta(x, y, z, \lambda) - i\beta(x, y, z, \lambda) \)

Refractive index:  \( n(x, y, z, \lambda) = 1 - \delta(x, y, z, \lambda) - i\beta(x, y, z, \lambda) \)

Phase and dark field contrast

\[ \varphi = -k \int_{-\infty}^{z} \delta(z') \, dz \]  

\[ \frac{\partial \varphi}{\partial t} \]

Phase and dark field contrast

Refractive index: \( n(x, y, z, \lambda) = 1 - \delta(x, y, z, \lambda) - i\beta(x, y, z, \lambda) \pm \delta_\text{B}(x, y, z, \lambda, B) \)

\[
\varphi = -k \int_{-\infty}^{z} \delta(z') dz \quad \partial \varphi / \partial t
\]

Phase and dark field contrast

Refractive index: \[ n(x, y, z, \lambda) = 1 - \delta(x, y, z, \lambda) - i\beta(x, y, z, \lambda) \pm \delta_B(x, y, z, \lambda, B) \]

Phase and dark field contrast

\[ \varphi = -k \int_{-\infty}^{z} \delta(z') dz \quad \frac{\partial \varphi}{\partial t} \]

M. Strobl et al., APL (2007)
Ch. Gruenzweig et al. APL (2008)
Dark-field NI

M. Strobl et al. APL 2007
Ch. Grünzweig et al. APL 2009
Dark field contrast

I. Manke et al., Nature comm. 2010
Dark field contrast

I. Manke et al., Nature comm. 2010
Bragg edge diffraction imaging

High resolution conventional imaging

Structural and magnetic dark-field imaging

Fast and stroboscopic imaging

Polarized neutron imaging

Others: phase contrast, complementary x-ray, fast neutron,..
Dark-filed contrast

Structural and magnetic dark-field imaging


Spin echo encoding and spatial beam modulation

\[ B_1 \cdot L_1 = B_2 \cdot L_2 \]

\[ \zeta = \pi \tan \theta_0 / (c \lambda (B_2 - B_1)) \]

\[ \delta_{SE} = \lambda L_s / \zeta \]

Towards 2D SANS mapping

Dark field contrast – SEMSANS (M. Strobl, W. Boumann et al. JAP & Phys B 2012)

$L_1B_1 = L_2B_2$

$\zeta = \frac{\pi \tan \theta_0}{c \lambda (B_2 - B_1)}$

$\Delta = \frac{\lambda L_s}{\zeta}$

$2.1 \text{A}$

theoret. spatial resolution app. 1 mm

Towards 2D SANS mapping

Dark field contrast – SEMSANS (M. Strobl, W. Boumann et al. JAP & Phys B 2012)

$L_1-L_2$

$B_1$

$B_2$

$D$

$L_2$

$\text{ana}$

$L S$

$samp$

Cd

2D SANS mapping

Sample 1

Sample 2

$\rho = 12.4\%$

$D = 136\text{nm}$

$\text{rel. modulation amplitude}$

$SE\text{-length [\mu m]}$

$0.60$ $0.65$ $0.70$ $0.75$ $0.80$ $0.85$ $0.90$

$0.02$ $0.04$ $0.06$ $0.08$ $0.10$ $0.12$ $0.14$ $0.16$ $0.18$ $0.20$ $0.22$

$D = 136\text{nm}$

$\rho = 12.4\%$

$\text{rel. modulation amplitude}$

$SE\text{-length [\mu m]}$

$0.60$ $0.65$ $0.70$ $0.75$ $0.80$ $0.85$ $0.90$

$0.02$ $0.04$ $0.06$ $0.08$ $0.10$ $0.12$ $0.14$ $0.16$ $0.18$ $0.20$ $0.22$
Polarised neutron imaging

neutron guide

beam stop

PCG crystals

monochromatic beam

sample

rotation + tilt stage

CCD detector
Polarised neutron imaging

neutron guide
beam stop
PCG crystals
monochromatic beam
polarizer
sample
rotation + tilt stage
analyser
CCD detector
Polarised neutron imaging

\[ I(x, y) = I_0(x, y) \exp\left(-\int_{\text{path}} \sigma \, ds \right) \frac{1}{2} \left(1 + \cos \varphi(x, y)\right) \]

\[ \varphi = \int_{\text{path}} \frac{\lambda m_n \gamma_n B}{h} \, ds \]
Polarised neutron imaging

\[ I(x, y) = I_0(x, y) \times \exp(-\int_{\text{path}} \sigma \cdot ds) \times \frac{1}{2} (1 + \cos \varphi(x, y)) \]

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Polarised neutron imaging

\[ I(x, y) = I_0(x, y) \times \exp\left(-\int_{\text{path}} \sigma \times ds \times \frac{1}{2} (1 + \cos \varphi(x, y)) \right) \]

\[ I_a(x, y) \]
Polarised neutron imaging

a) \( T > T_c \)

b) \( I(x,y) \)

c) \( I(x,y) / I_a(x,y) \)

\[
I(x, y) = I_0(x, y) \exp\left(- \int_{\text{path}} \sigma \, ds \right) \frac{1}{2} \left( 1 + \cos \varphi(x, y) \right)
\]

\( I_a(x,y) \)

YBCO
Polarised neutron imaging

YBCO

(a) \( T > T_c \)

(b) \( I(x,y) \)

(c) \( I(x,y) / I_a(x,y) \)

\[ \text{YBCO} \]

100 K

20 K

1 cm
Polarised neutron imaging

Flux pinning in polycrystalline Pb superconductor
Polarised neutron imaging

Flux pinning in polycrystalline Pb superconductor
Polarised neutron imaging

Flux pinning in polycrystalline Pb superconductor

Polarised neutron imaging

Electric currents: Skin effect

I. Manke et al., JAP (2008)
Polarised neutron imaging

**Electric currents: Skin effect**

I. Manke et al., JAP (2008)
Polarized neutron imaging

Fast and stroboscopic imaging


T. Shinohara et al. (2011)
Polarised neutron imaging

\[ I(x, y) = I_0(x, y) \times \exp\left(- \int_{\text{path}} \sigma \times ds \right) \times \frac{1}{2} \left(1 + \cos \varphi(x, y)\right) \]

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Polarised neutron imaging

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Polarised neutron imaging

Quantification requires/possible through multiple wavelengths

\[ I(x, y) = I_0(x, y) \exp(-\int_{\text{path}} \sigma \, ds) \times \frac{1}{2} (1 + \cos \varphi(x, y)) \]

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Quantification requires/possible through multiple wavelengths

Polarised neutron imaging

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Quantification requires/possible through multiple wavelengths

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\varphi = \int_\text{path} \frac{\lambda m_n \gamma_n B}{h} ds

Polarized neutron imaging

3D vector quantification through multiple wavelengths

dynamic polarisation

pulsed TOF multi-wavelength measurements for quantification, vector field reconst.
M. Strobl NIMA 2009
Introduction Neutron imaging

Some advantages:
High penetration power
High sensitivity to Hydrogen
Low radiation damage
Isotope sensitive

Enrichment of fuel element
Some advantages:
High penetration power
High sensitivity to Hydrogen
Low radiation damage
Isotope sensitive
Magnetic moment

N. Kardjilov, I. Manke, M. Strobl, A. Hilger et al.
Imaging methods

- Bragg edge diffraction imaging
- High resolution conventional imaging
- Structural and magnetic dark-field imaging
- Fast and stroboscopic imaging
- Polarized neutron imaging
Imaging methods

High resolution conventional imaging

Structural and magnetic dark-field imaging

Fast and stroboscopic imaging

Polarized neutron imaging

\[
\sigma_{\text{coh}}^{\text{el}}(\lambda) = \frac{\lambda^2}{2V_0} \sum_{\lambda_B=2d_{hkl}} |F_{hkl}|^2 d_{hkl}
\]
Imaging methods

High resolution conventional imaging

Structural and magnetic dark-field imaging

Polarized neutron imaging

\[ \sigma_{coh}^{el}(\lambda) = \frac{\lambda^2}{2V_0} \sum_{2d_{hkl} < \lambda, d_{hkl} = 0} |F_{hkl}|^2 d_{hkl} \]

\[ \lambda_B = 2d_{hkl} \]
Imaging methods for ESS

\[ \sigma_{coh}^{el}(\lambda) = \frac{\lambda^2}{2V_0} \sum_{d_{hkl}=0}^{2d_{hkl}<\lambda} |F_{hkl}|^2 d_{hkl} \]

\[ \lambda_B = 2d_{hkl} \]

High resolution conventional imaging

Structural and magnetic dark-field imaging

Fast and stroboscopic imaging

Polarized neutron imaging
Imaging methods for ESS

High resolution conventional imaging

Fast and stroboscopic imaging

Polarized neutron imaging

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\[ \lambda_B = 2d_{hkl} \]

\[ Q = \frac{2\pi}{\lambda} \sin \theta \]

\[ A(\lambda)/A_0(\lambda) = \exp(\sigma t (G(\lambda)-1)) \]

- \( A \)…amplitude
- \( \sigma \)…scatt. cross section
- \( t \)…thickness, \( G \)…correlation function
Imaging methods for ESS

High resolution conventional imaging

Fast and stroboscopic imaging

A(\lambda)/A_0(\lambda)=\exp(\sigma t (G(\lambda)-1))

A...amplitude
\sigma...scatt. cross section
t...thickness, G...correlation function

Q=2\pi/\lambda \sin \theta

\lambda_B=2d_{hkl}

\sigma_{coh}^e(\lambda) = \frac{\lambda^2}{2V_0} \sum_{d_{hkl}=0}^{2d_{hkl}<\lambda} |F_{hkl}|^2 d_{hkl}

Structural and magnetic dark-field imaging

Polarized neutron imaging
Imaging methods for ESS

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\[ t \ldots \text{thickness, } G \ldots \text{correlation function} \]

\[ I(x, y) = I_0(x, y) \exp(- \int \sigma \times ds) \times \frac{1}{2} (1 + \cos \varphi(x, y)) \]

\[ \varphi = \int_{\text{path}} \frac{\lambda m_n m_n B}{h} ds \]

Polarized neutron imaging

Structural and magnetic dark-field imaging
Our vision for 2019!
Our vision for 2019!
Our vision for 2019!
Our vision for 2019!
Our vision for 2019!
Our vision for 2019!

SCIENCE CITY

Complementary world-class science facilities!
For Imaging!
Our vision for 2019!

Complementary world-class science facilities!
For Imaging!

Imaging competence centre with image processing lab?