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Laboratory for Neutron Scattering and Imaging

Erice School *Neutron Science and Instrumentation*, IV course

Neutron Precession Techniques
Erice, Sicily, Italy, 01. – 08. 07. 2017

Solid State Polarisers
and

Focussing Neutron Optics
basics
○ reflectometry
○ supermirrors
○ polarising coatings

polarisers
○ overview
○ reflective coatings
○ comparison

focusing optics
○ refractive
○ reflective
basics

- reflectometry
- supermirrors
- polarising coatings

polarisers

- overview
- reflective coatings
- comparison

focusing optics

- refractive
- reflective
analogy to visible light

*flat* surfaces partly reflect light

→ image of the boot

some media also transmit light

→ ground below the water

reflectivity of a surface

function of index of refraction $n$

$$q_z = 2|k_0| \sin \omega$$
analogy to visible light

*flat* surfaces partly reflect light

→ image of the boot

some media also transmit light

→ ground below the water

parallel interfaces cause interference

→ colourful soap bubbles

**reflectivity of plane parallel interfaces**

interference pattern $I(q_z, n_i, d_i)$
simulated reflectivity of a surface

\[ R \propto \left( \frac{q}{q_c} \right)^4 \text{ for } q \gg q_c \]

critical edge $\Rightarrow n_{\text{substrate}}$
simulated reflectivity of a thin layer

\[ \log_{10}[R(q_z)] \]

amplitude \( \Rightarrow \Delta n_{\text{layer,substrate}} \)

minimum \( \Rightarrow d_{\text{layer}} \)
simulated reflectivity of a thick layer

\[ \log_{10}[R(qz)] \]

- amplitude $\Rightarrow \Delta n_{layer,\text{substrate}}$
- minimum $\Rightarrow d_{layer}$
simulated reflectivity of a **periodic stack of layers**

$= \text{multilayer, ml}$
simulated reflectivity of a stack of mls
simulated reflectivity of a stack with thickness gradient
= supermirror, sm

\[ \log_{10}[R(q_z)] \]

\[ q_z/\text{Å}^{-1} \]
simulated reflectivity of a **sm** and of **Ni**

\[
q_{\text{Ni}}^c \quad \text{critical edge of Ni} \\
q_{\text{Sm}}^c := m q_{\text{Ni}}^c \quad \text{critical edge of sm}
\]
index of refraction

\[ n := \frac{|k_i|}{|k_0|} \]

\[ \approx 1 - \frac{V}{2E_{\text{kin}}} \]

\[ V = \frac{2\pi \hbar^2}{m_n} (\rho^b \pm \mu_n B) \]

\[ := \frac{2\pi \hbar^2}{m_n} (\rho^b \pm \rho^m) \]

\[ q_z = 2|k_0| \sin \omega \]

\[ |k| = 2\pi/\lambda \]
reflectometry

polarising sm

\[ \log_{10}[R(q)] \]

\[ q_z / \text{Å}^{-1} \]

\[ \rho^b - \rho^p \approx \rho_s \]

\[ \rho^b > \rho_s \]

\[ \rho^b + \rho^p \gg \rho_s \]
### polarising sm coatings

<table>
<thead>
<tr>
<th>FM</th>
<th>spacer</th>
<th>substrate</th>
<th>pro</th>
<th>con</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe$<em>{89}$Co$</em>{11}$</td>
<td>Si</td>
<td>Si</td>
<td>high transmission</td>
<td>Co</td>
</tr>
<tr>
<td>Fe</td>
<td>Si : N</td>
<td></td>
<td>low activation $q_c^{(-)}$</td>
<td></td>
</tr>
<tr>
<td>FeCoV</td>
<td>Ti : N</td>
<td>absorber</td>
<td>$q_c^{(-)} &lt; 0 \text{ Å}^{-1}$</td>
<td>Co</td>
</tr>
<tr>
<td>Fe$<em>{0.5}$Co$</em>{0.5}$</td>
<td></td>
<td></td>
<td>Co</td>
<td>Co</td>
</tr>
</tbody>
</table>

Co gets activated $\Rightarrow$ avoid whenever possible!
**off-specular scattering**

\[ \rho = \rho(x, z) \]

\[ \Rightarrow R(q_x) \neq 0! \]

\[ \Rightarrow \text{dilution of phase space background losses} \]

\[ \rho^{\text{magnetic}}(x, y) \neq 0 \]

\[ \Rightarrow \text{spin flip} \]

Ni/Ti multilayer
Keep in mind:

\[ R(q_z) = R(n(z), B(z)) \]

\[ = 1 \quad \forall \ q_z < q_c \]

\[ = 1 \ldots 0.55 \quad \text{for} \ q_z < q_{sm} \]

\[ \propto q_z^{-4} \quad \forall \ q_z \gg q_c \]

- Typical numbers:

<table>
<thead>
<tr>
<th></th>
<th>( \rho^b / 10^{-6} \AA^{-2} )</th>
<th>( q_c / \AA^{-1} )</th>
<th>( \omega_c ) @4 Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si, Fe(^-)</td>
<td>2.1</td>
<td>0.010</td>
<td>0.18°</td>
</tr>
<tr>
<td>Fe(^+)</td>
<td>13.9</td>
<td>0.026</td>
<td>0.47°</td>
</tr>
<tr>
<td>Ni</td>
<td>9.4</td>
<td>0.022</td>
<td>0.40°</td>
</tr>
<tr>
<td>Ti</td>
<td>-3.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \Rightarrow \text{small angles} \Rightarrow \text{geometrical constraints} \]

- Roughness \( \Rightarrow \) off-specular scattering \( \Rightarrow \) background & depolarisation
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transmission through polycrystalline Fe
6 mm Fe: $P = 33\%$ at $\lambda = 3.6\,\text{Å}$

Heusler alloy
crystal monochromator

$^3\text{He}$
→ talk by E. Babcock
Heusler alloy monochromator / analyser

Cu$_2$MnAl single crystals

- $\lambda \in [0.8, 6.5] \, \text{Å}$
- $\Delta \lambda / \lambda \approx 1\%$
- $P \approx 95\%$

used for triple-axis spectrometers

with $F_{\text{magnetic}}(111) = \pm F_{\text{nuclear}}(111)$

$\Rightarrow F(111)$ reflex strong for $\mu_n \uparrow\uparrow B$
weak for $\mu_n \downarrow\uparrow B$

Using Reflected beam

- trajectory is inclined
- high polarisation
  \( P_R \approx 96\% - 99\% \)

\[ P_R = \frac{R_{\uparrow} - R_{\downarrow}}{R_{\uparrow} + R_{\downarrow}} \]

\[ P_R \approx 1 - \frac{R_{\downarrow}}{R_{\uparrow}} \]
single, falt mirror

switchable remanent polariser

\[ H_M \approx 200 \text{ Oe}, \quad H_g < 40 \text{ Oe} \]
polarisers - based on SM

|−⟩ |+⟩ |+⟩

|−⟩

|+⟩

too large \(\delta \theta\)

garland reflections of |−⟩

too high \(\lambda\)

\[
\frac{\text{length}}{\text{width}} \approx 150
\]

optimum parameters
S-bender

- almost straight trajectory
- garland-problem is solved

$$\frac{\text{length}}{\text{width}} \approx 250$$
polarisers - based on SM

application: solid-state S-bender

Si wafers (150 µm) used as channel
- thin and short channels
- $q_c \langle - \rangle < 0 \text{ Å}^{-1}$
- no dark region due to substrate
- higher absorption

this principle also applies to benders

polarisers - based on SM

using Transmitted beam

- straight trajectory

- moderate polarisation

\[ P_T \approx 60\% - 80\% \]
polarisers - based on SM

using Transmitted beam

- straight trajectory
- high polarisation 
  \( P_T \approx 96\% - 99\% \)

\[
\begin{align*}
T^{|+\rangle} & = T^-|+\rangle - T^-|\rangle \\
T^-|\rangle & = T^{|+\rangle} + T^-|+\rangle
\end{align*}
\]

increase of efficiency by multiple transmission:
- both sides of substrates coated
- several substrates in sequence
  \( \Rightarrow \) reduced intensity
transmission bender + collimator

- straight trajectory
- dark areas due to substrates

T. Krist: solid-state transmission bender + collimator

\[
\frac{\text{length}}{\text{width}} \approx 300
\]
polarisers - based on SM

The cavity

| + \rangle | | - \rangle | | - \rangle |

optimum parameters

too large $\delta \theta$

too high $m_{\text{channel}}$

\[
\frac{\text{length}}{\text{width}} \approx 50
\]
Polarisers - based on SM

Cavity

\[
|+\rangle, \quad |\pm\rangle, \quad |\mp\rangle
\]

Optimum parameters

Too low \(\lambda\)

Too high \(\lambda\)

Length/width \(\approx 50\)
V-cavity

- straight beam geometry

V-cavity

- Straight beam geometry phase space affected

- $\Delta \lambda / \lambda_{\text{min}} \approx 5$

- $P \approx 99\%$

polarisers - based on SM

equiangular spiral

for beams \{ \text{emerging from focused to} \} a narrow area

- same $\omega$ for all trajectories
  $\rightarrow$ flexibility for $\omega$, $m$, $\lambda$
- phase space hardly affected

prototype at PSI

using **Reflected and Transmitted** beam

- split neutron guide for 2 polarised instruments (at HMI / HZB)
  

- suggested analyser for Estia@ESS
wide-angle analysers

stack of cavities / benders / spirals pointing towards the sample

challenges:
- avoid / minimise black angles
- provide a high magnetisation field
- reduce losses

example: Hyspec analyser by PSI

60° coverage with 1000 benders

$P \approx 95\%$

transmission = 10% to 45% for $\lambda \in [2, 5] \text{Å}$
wide-angle analysers

optimisation of shape using an equiangular spiral:

study for MIEZE@ESS

\[ \lambda > 6 \text{ Å} \]

by P. Böni

\[ \lambda \in [6, 48] \text{ Å} \]
polarisers - comparison

comparison

Heusler

$^3$He

failed
focusing optics

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focusing optics

motivation

higher flux on small samples

no illumination of sample environment

control over phase space / trajectories

selection of area on / within sample

deal with small sources

remote footprint control
**focusing optics**

Reshapes the phase space of a n-beam (an ensemble of neutrons) to a **small spatial extent** at a given position.

**shading optics**

Reshapes the phase space by restricting it in space (slit).
focusing optics vs. shading optics

high costs (needs high precision)
lower transmission
convenient beam manipulation
real focusing
aberration

robust
flexible
high transmission
high background
refractive optics

\( n \approx 0.99999 \ldots 1 \) for all bulk materials

Snell’s law: \( n = \frac{\sin \alpha_{\text{ex}}}{\sin \alpha_{\text{in}}} \)

\( \Rightarrow \alpha_{\text{in}} \approx n \alpha_{\text{ex}} \) close to normal incidence

- used for SANS

M. R. Eskildsen et al. nature 391, 563 (1998)
focusing optics – reflective

reflective optics

elliptic
divergent to convergent

parabolic
parallel to convergent

hyperbolic
convergent to convergent
reflective focusing optics

elliptic
divergent to convergent
focusing optics – reflective

reflective focusing optics

elliptic
divergent to convergent

early reflections suffer the most from coma aberration
⇒ multiple reflections
⇒ non-convergent beam behind guide exit

L. Cusssen et al.: NIM A 705, 121 (2013)
reflective focusing optics
reflective focusing optics
focusing optics – reflective

coma aberration
focusing optics – reflective

coma aberration

...and its correction
focusing optics – reflective

coma aberration

... and its correction

- $I(xy)$ is restored
- $I(\theta)$ is not!
Selene guide

point-to-point focusing

with

2 subsequent elliptical reflectors

for

horizontal and vertical direction

Selene picture: ceiling painting in the Ny Carlsberg Glyptotek, København
focusing optics – reflective

Selene guide

decoupling of

• spot-size

and

• divergence
**condenser**: parabolic deflector to generate a parallel beam

- **parabola axis** $\Rightarrow$ beam direction
- **focal length** $\Rightarrow$ beam width
- **beam width** & spot size $\Rightarrow$ divergence
- no collimator needed
- tunable

**adaptive parabola** (convex)

focal spot with 170 $\mu$m reached

(PSI, early version)
**focusing optics – reflective**

**astigmatic focusing**: focusing to the detector by shifting the focal point

**hyperbolic deflector**
focusing optics – reflective

solid-state neutron lense

focusing optics - discussion

focusing results in . . .

. . . no gain in brilliance

. . . a defined footprint

. . . a clean beam

homogeneous uni-modal angular or spatial distribution

non-perfect optics \Rightarrow reduction of resolution / transmission

works best for small samples

weak aberration
thanks to J. Stahn

solid state polarisers

Erice, 07. 2017

Thomas Krist    HZB
Peter Böni     TUM
Uwe Filges    PSI
Artur Glavic    PSI

for discussions and for contributing to these slides

sonic screwdriver used by the Doctor to

reverse the polarity of the neutron flow

There must be a similar device to polarise it!