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1866-13

School on Pulsed Neutrons: Characterization of Materials

15 - 26 October 2007

Polarized Neutrons

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Methods and Techniques: Polarized Neutrons

Lecture Notes

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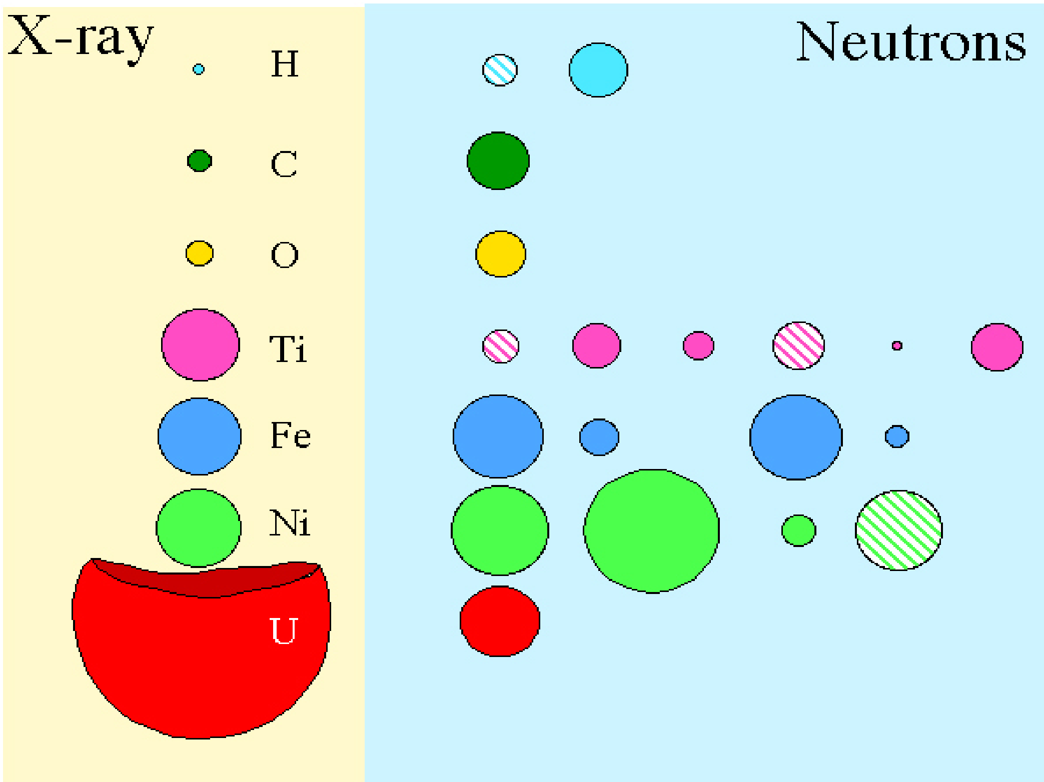
Topics

1. Introduction
2. Need for polarized neutrons
3. Basics of polarized beam technique
4. Ancillary equipment for polarization analysis
5. Heusler monochromators
6. Polarizing supermirrors
7. Spin Filters: Protons, ^{3}He
8. Instruments
9. Applications for Polarized Neutrons
10. Focusing Techniques
11. Conclusions

1. Introduction

Comparison Neutrons – X-rays



Thermal neutrons:

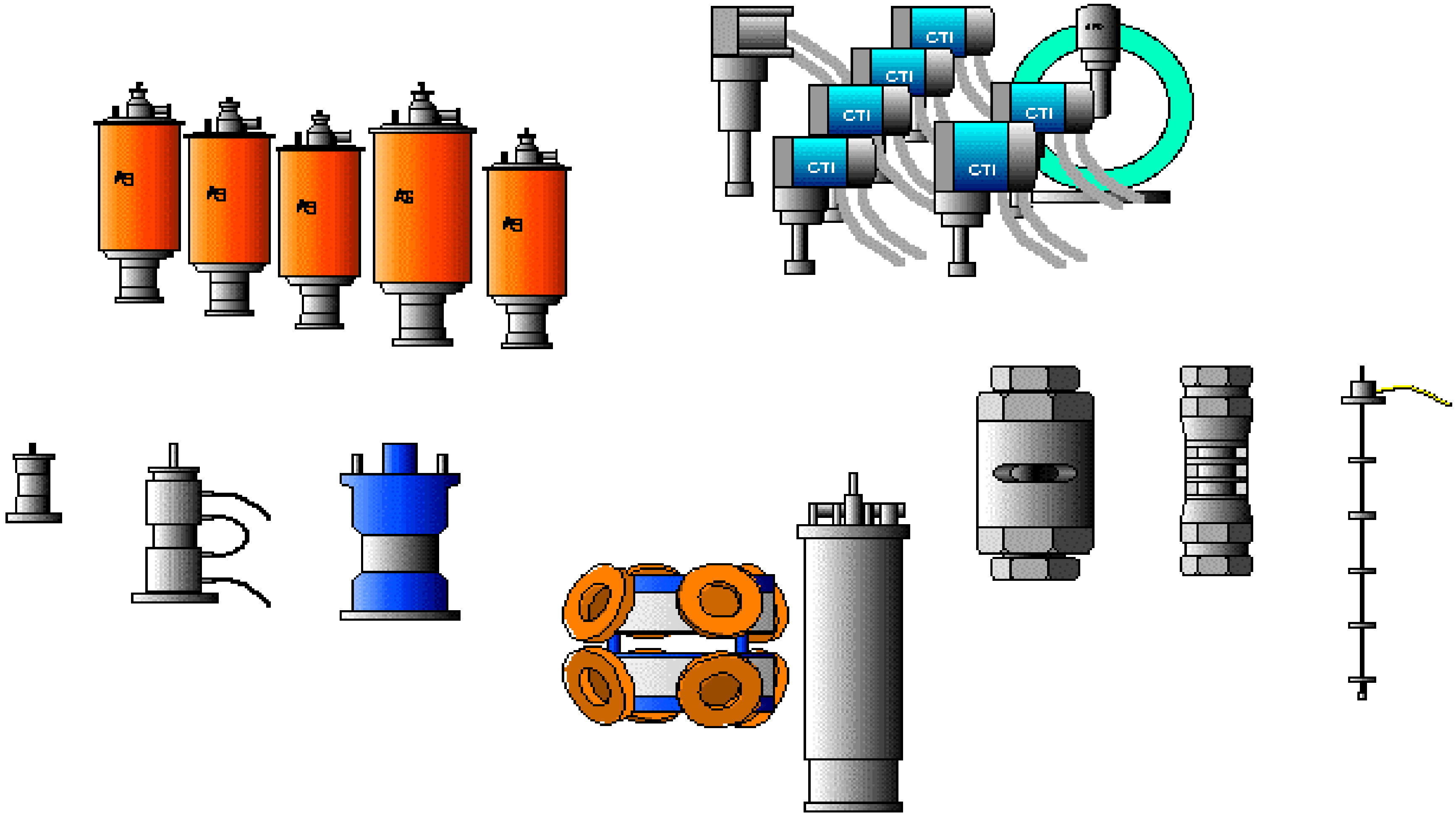
- $\lambda \cong$ lattic constant
- $E \cong$ Excitations in solid state

Interaction between neutrons and nuclei is weak:

1st Born approximation

scattering length is random	→	distinction between light and heavy elements
substitution by isotopes	→	deuteration
no charge	→	large penetration depth → volume sensitiv
magnetic moment	→	magnetic properties

Extreme sample environment



Sample environment is essential (not only the neutrons)!

Landmarks in Polarized Neutron Scattering

- 1939: Halpern and Johnson: polarized neutrons – magnetic moments

  (O. Halpern and M. R. Johnson, Phys. Rev. **55**, 898 (1939))

$$\mathbf{P}' = f(\mathbf{Q} \cdot \mathbf{P})$$

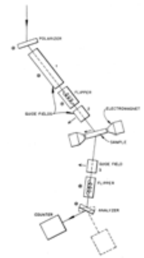
- 1957: Nathans et al.: experiment with polarized neutrons on Cr_2O_3

  scattered neutrons are analyzed with magnetized block of Fe

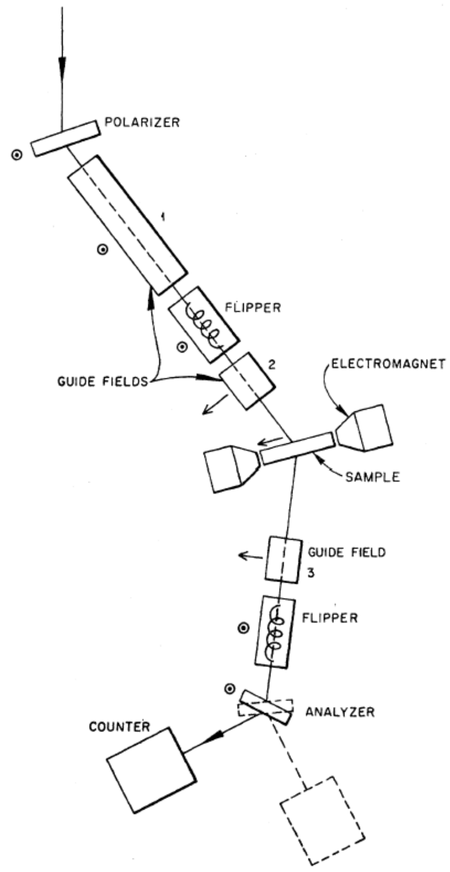
  (R. Nathans, T. Riste, G. Shirane, and C. G. Shull, Bull. Am. Phys. Soc. **2**, 1, FA4 (1957))

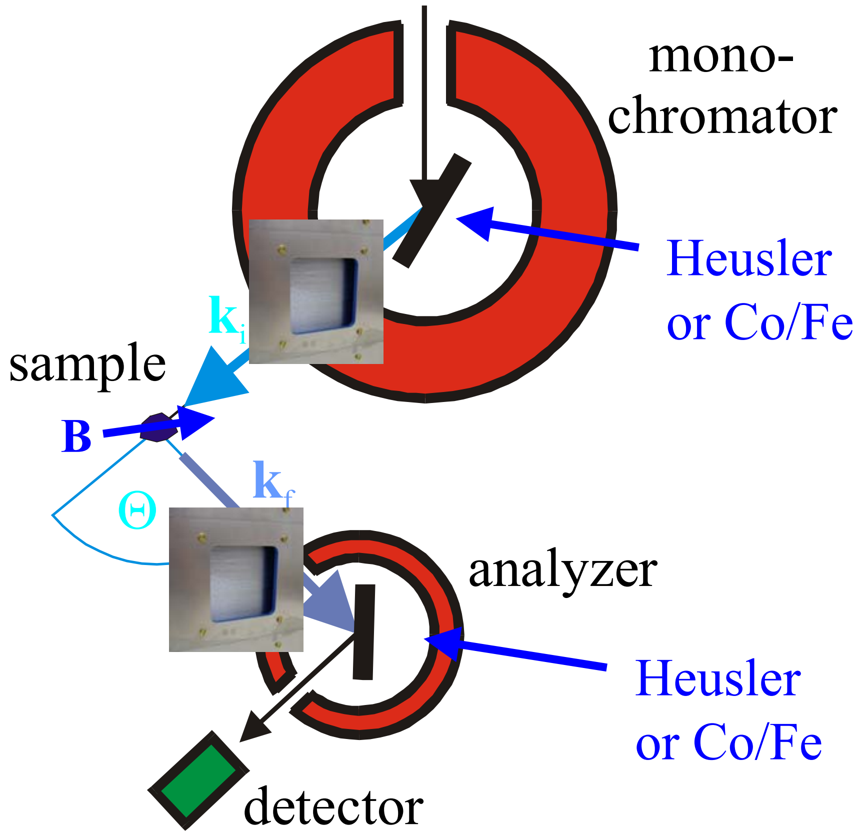
- 1969: Moon, Riste and Koehler: measurement of σ^{++}, σ^{--}, σ^{+-}, σ^{-+}

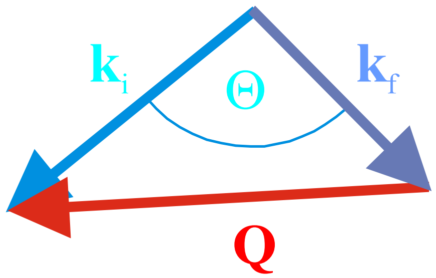
  (R. M. Moon, T. Riste, and W. C. Koehler, Phys. Rev. **181**, 920 (1969))



Measurement of σ^{++}, σ^{--}, σ^{+-}, σ^{-+}







Scattering triangle:

Combine monochromatization with polarization.

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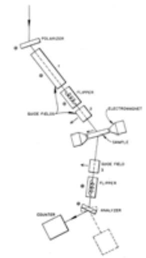


- 1972: Mezei: neutron spin echo spectrometer: high *E*-resolution

- 1976: Mezei: polarizing supermirror (see also Turchin 1967)

  (F. Mezei, Communications on Physics **1**, 81 (1976), V. F. Turchin, Deposited Paper, At. Energy **22** (1967))

- 1980: Ziebeck and Brown: inelastic measurements on 3-d magnets

Polarizers

- Fe in magnetic field:
  neutrons with spin down $(b+p)^2$: large cross section/small transmission
  neutrons with spin up $(b-p)^2$: small cross section/good transmission

- monochromators:
  ^{57}Fe, FeCo
  Heusler Cu_2MnAl (similar *d*-spacing as HOPG)

- Artificial multilayers:
  FeGe multilayers
  supermirrors: Co/Ti, Fe/Si, $Fe_{50}Co_{48}V_2/TiN_x$

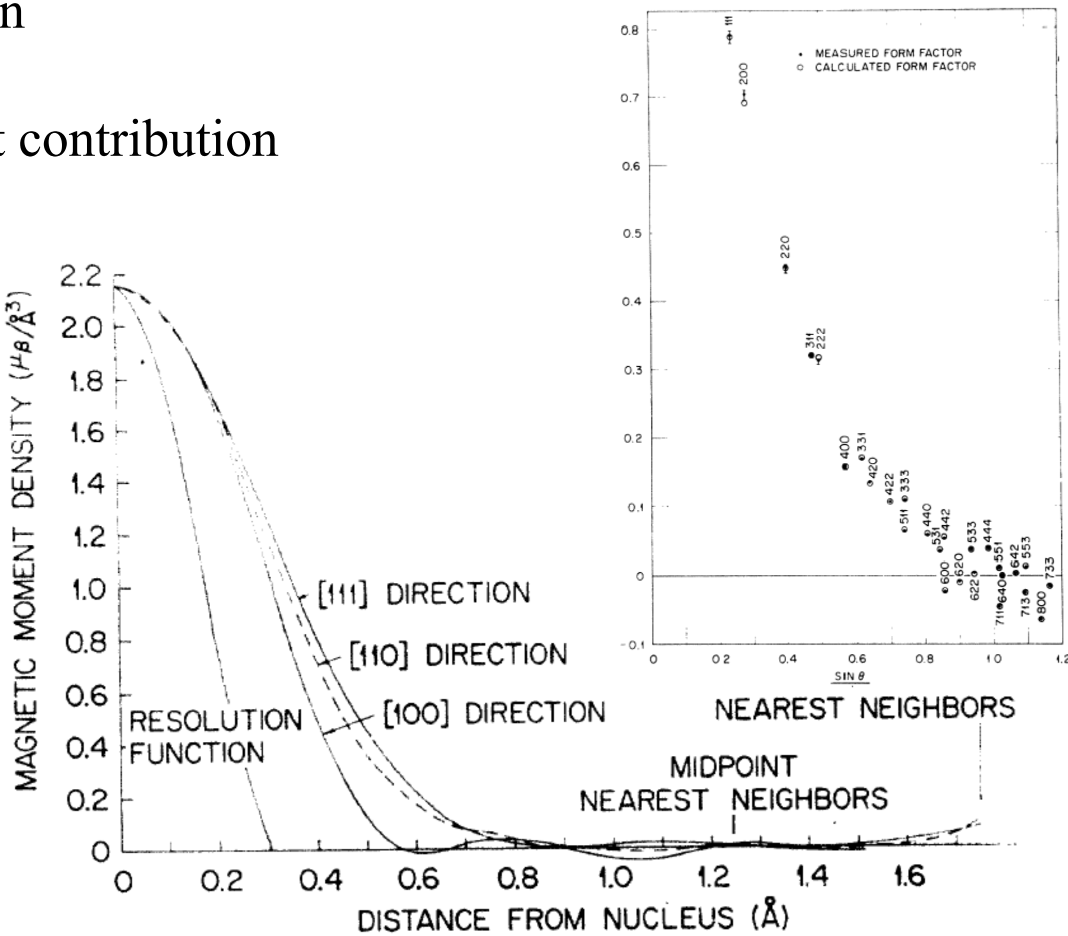
- Spin filters:
  polarized protons
  polarized ^3He
  $SmCo_5$

2. Need for polarized neutrons

Example 1: Measurement of Form Factors

→ information on wave function
→ magnitude of moment
→ magnetic moment: spin/orbit contribution

H. A. Mook, Phys. Rev. **148**, 495 (1966)



Example: ferromagnetic Ni

nuclear scattering length:
• $1.03 \cdot 10^{-12}$ cm
magnetic scattering length:
• $0.164 \cdot 10^{-12}$ cm

$$\frac{I_{mag}}{I_{nuc}} = \frac{\frac{2}{3} p_{mag}^2}{b_{nuc}^2} = 0.0169$$

→ is only a 1.7% percent effect!

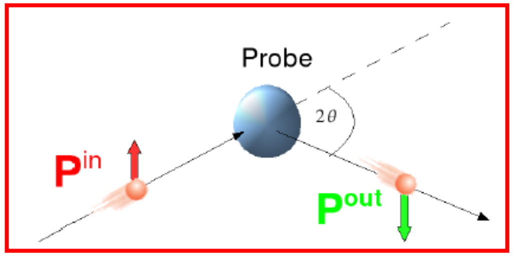
→ with polarisation analysis: $\frac{I^{++}}{I^{--}} \cong 1 + 4\frac{p}{b} \cong 1.64$

Polarization analysis is important to enhance signal:

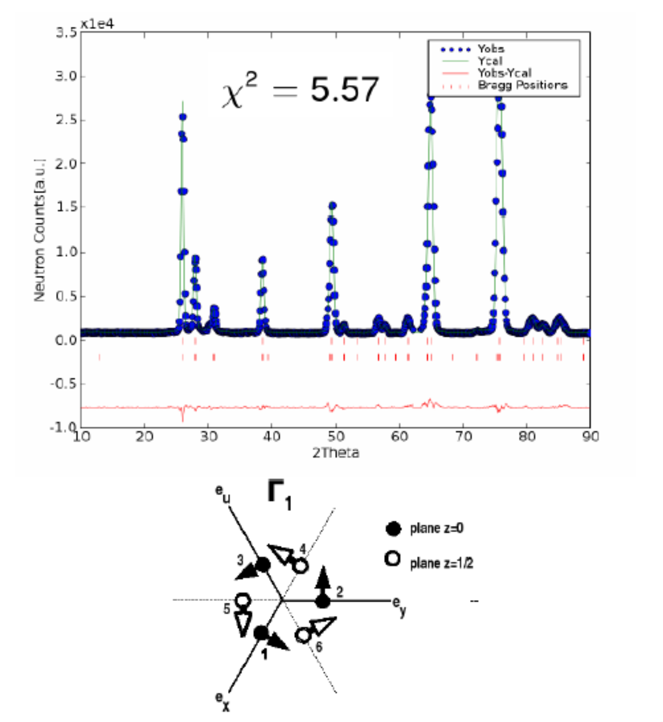
Example 2: Magnetic Structures

Janoschek et al., J. Phys.: Cond. Matter **17**, L425

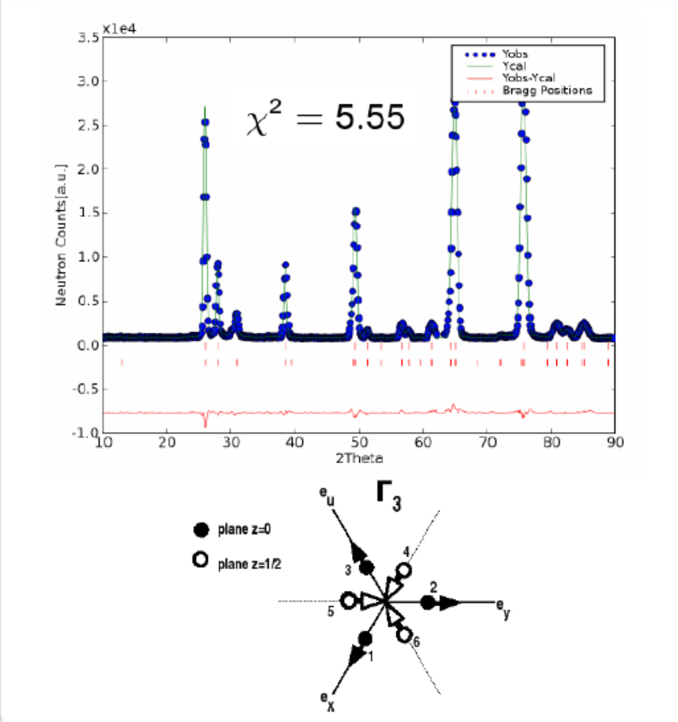
Example:
of $YMnO_3$
multiferroic



Struktur Γ_1



Struktur Γ_3



$$\mathbf{P}_{out} = \begin{pmatrix} \beta & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \beta \end{pmatrix} \mathbf{P}_{in} + \begin{pmatrix} 0 \\ \eta\xi \\ 0 \end{pmatrix}$$

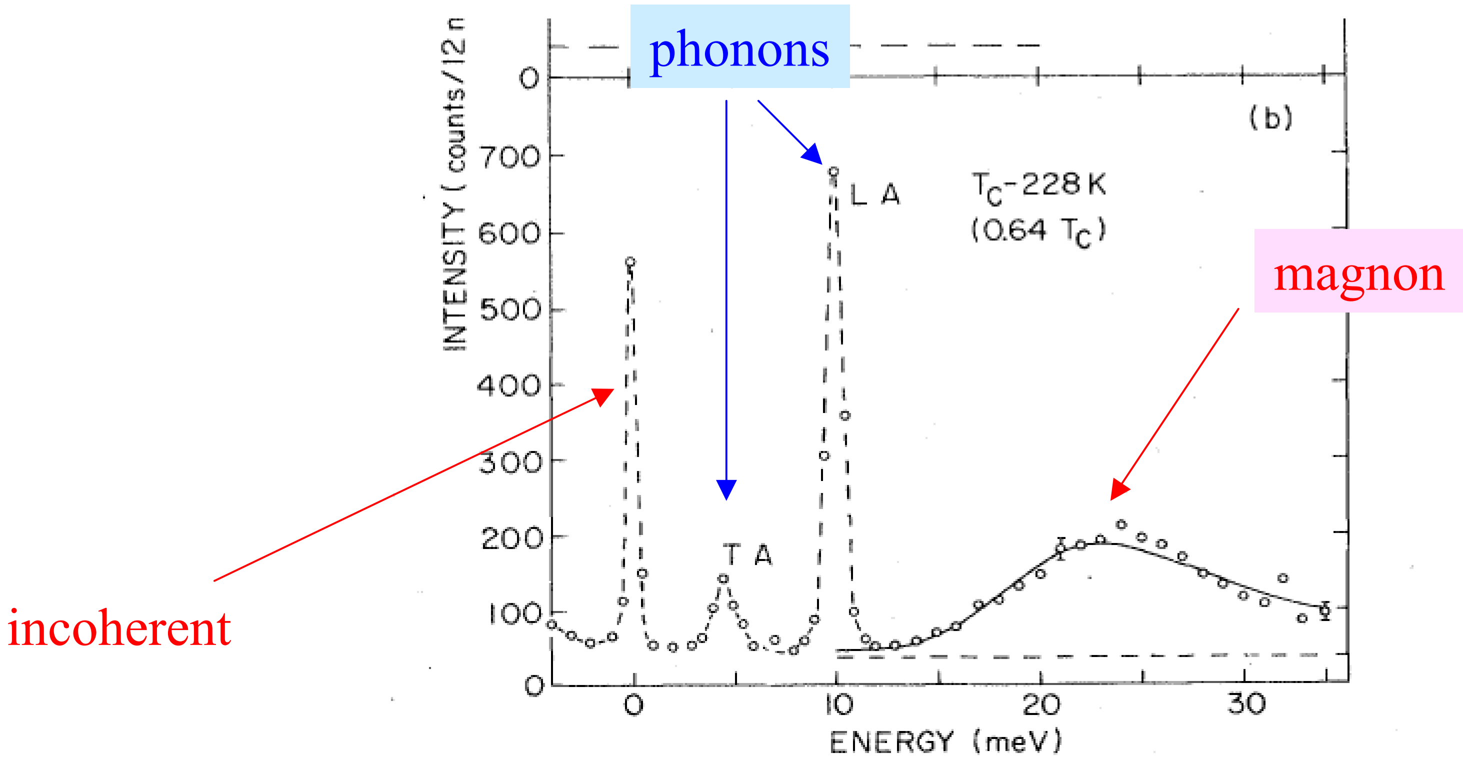
$$\mathbf{P}_{out} = \begin{pmatrix} \beta & 0 & \eta\xi \\ 0 & 1 & 0 \\ -\eta\xi & 0 & \beta \end{pmatrix} \mathbf{P}_{in} + \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

(P. J. Brown *et al.* J. Phys.: Condens. Matter 18 (2006) 10085-10096)

Spherical polarization analysis distinguishes between structures

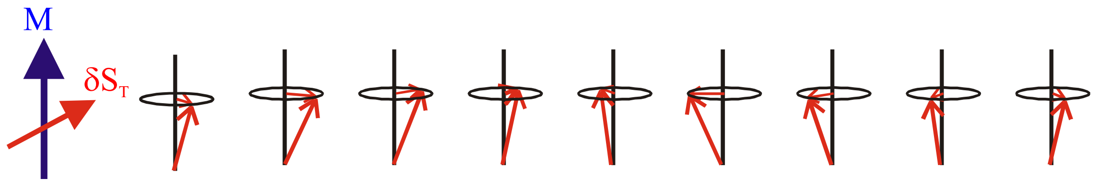
Example 3: Nuclear and Magnetic Excitations

Inelastic neutron scattering from Ni: magnons - phonons?

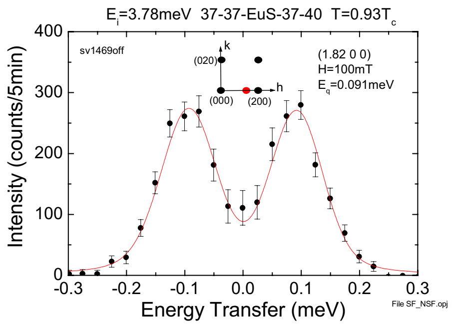


Martínez et al., Phys. Rev. B **32**, 7037 (1985

Example 4: Separation of magnetic modes



2×



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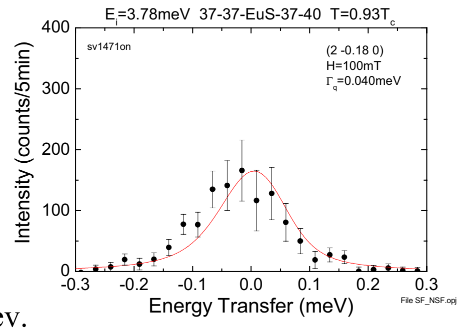

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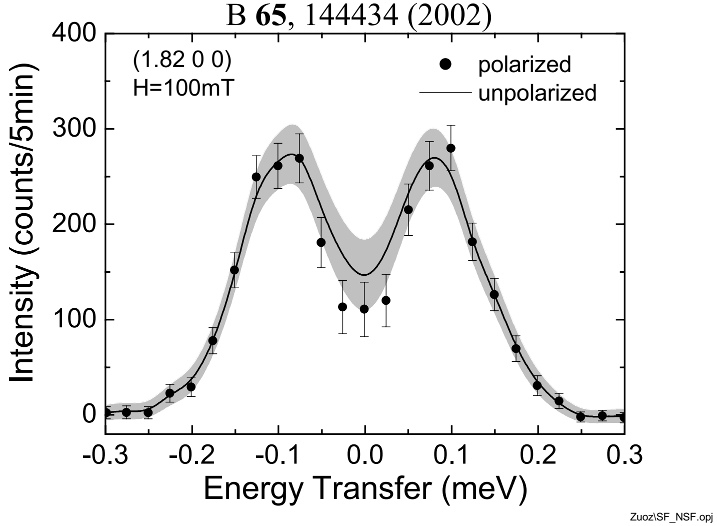
Böni et al., Phys.Rev. B **65**, 144434 (2002)

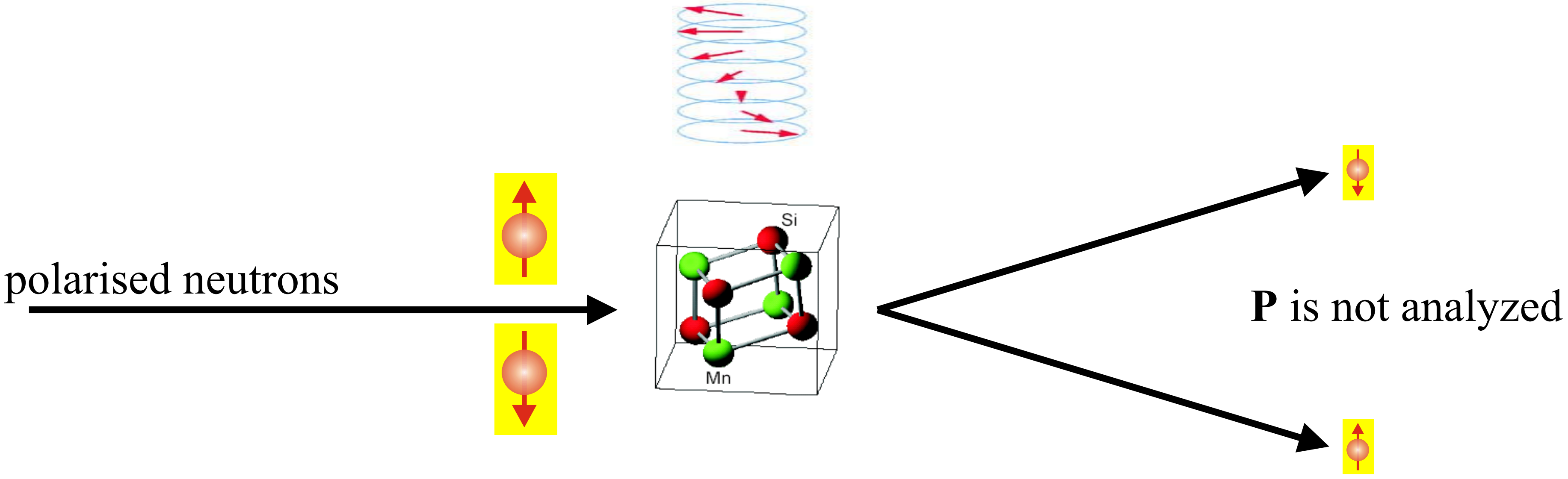
spin waves

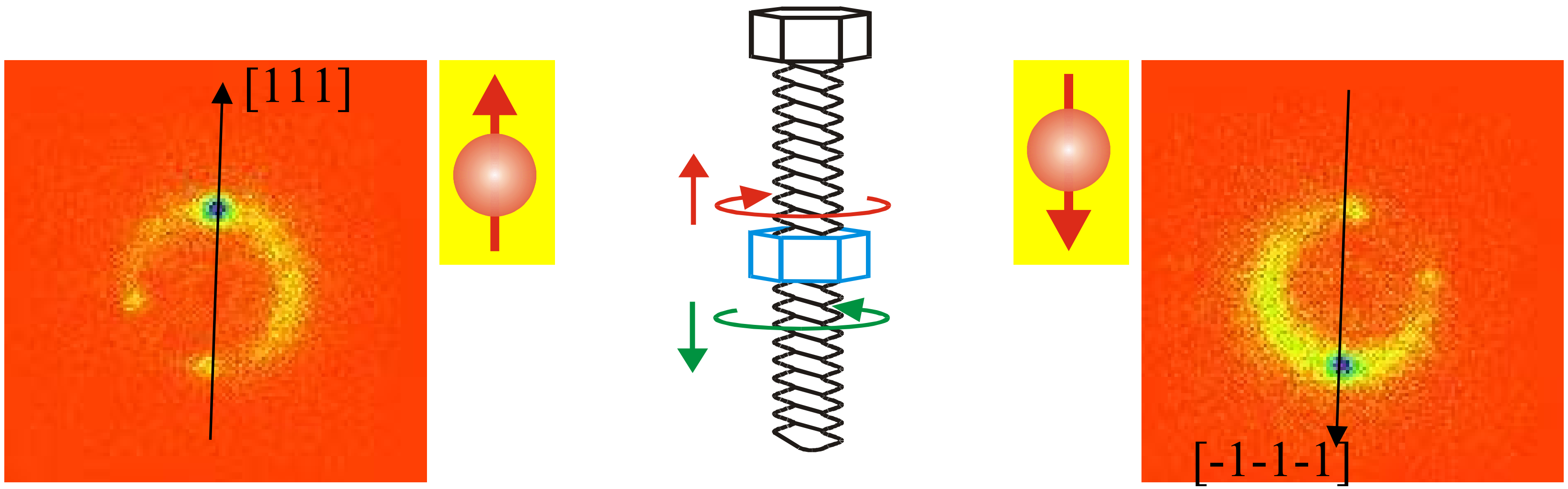


longitudinal fluctuations

Polarization analysis can distinguish between various magnetic modes

Example 5: Chirality





Polarization analysis distinguishes between left- and right-handed spirals

Example 6: Dynamics of Deuterium in Nb

Further examples: polymers, hydrogen storage (→ Zabel)

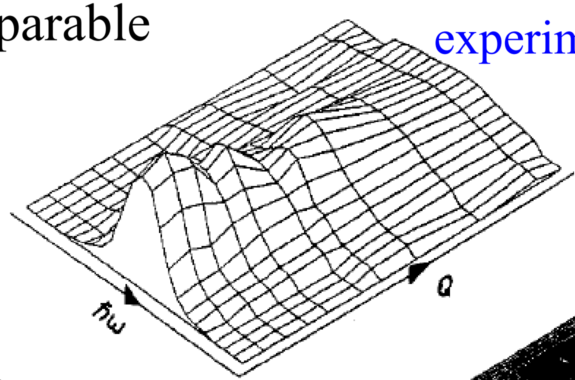
Deuterium:

- $b_{coh} = 5.6$
- $b_{inc} = 2.0$

Scattering lengths comparable

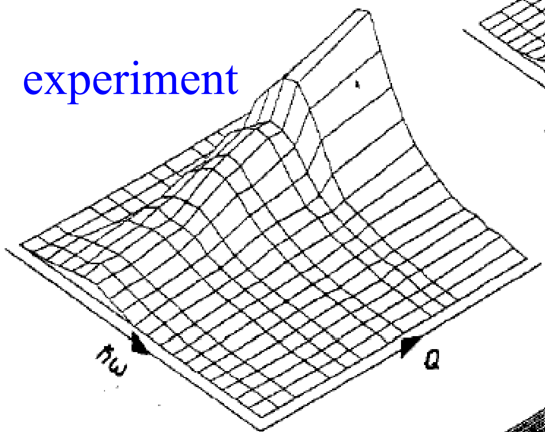
Interstitial concentration of D in Nb: 70%

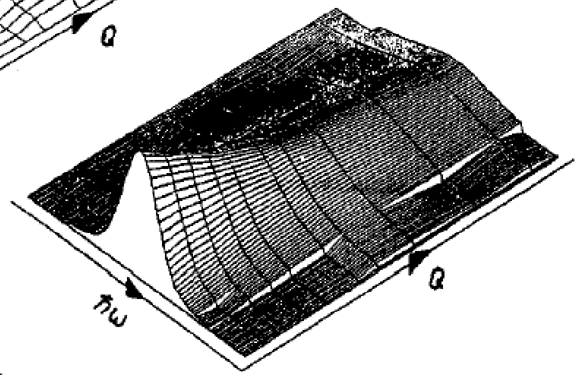
experiment



incoherent scattering:
Diffusion processes

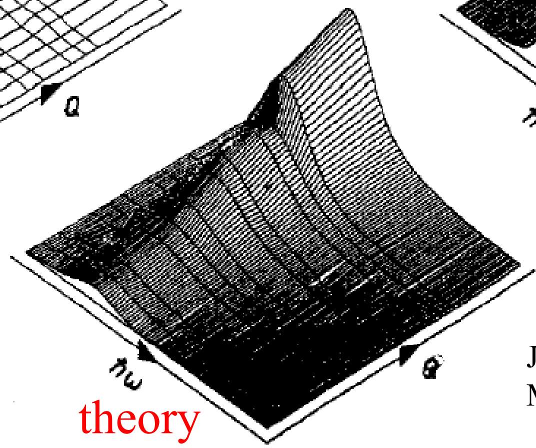
experiment





theory

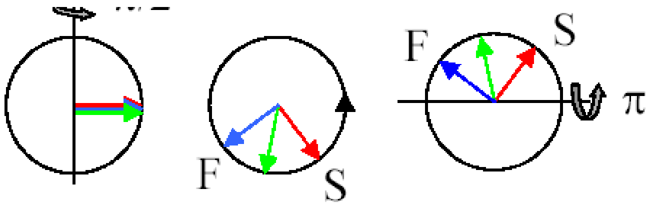
coherent scattering:
lattice dynamics

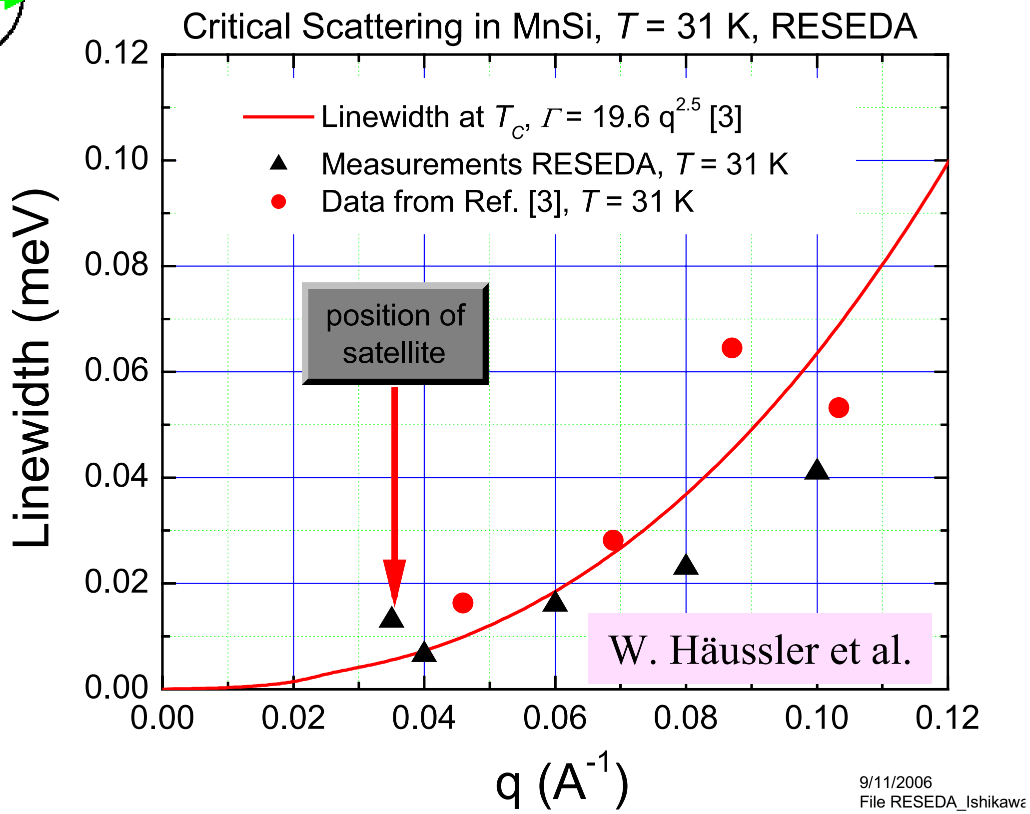


theory

J. C. Cook et al., J. Phys. Condens. Matter **2**, 79 (1990).

Example 7: High-Resolution / Spin Echo



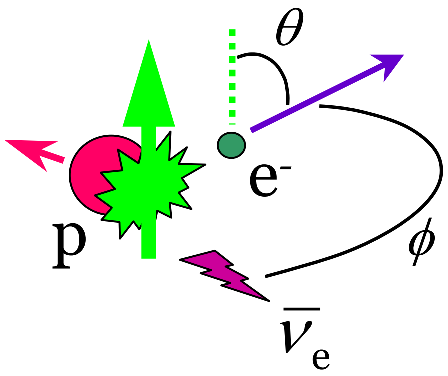


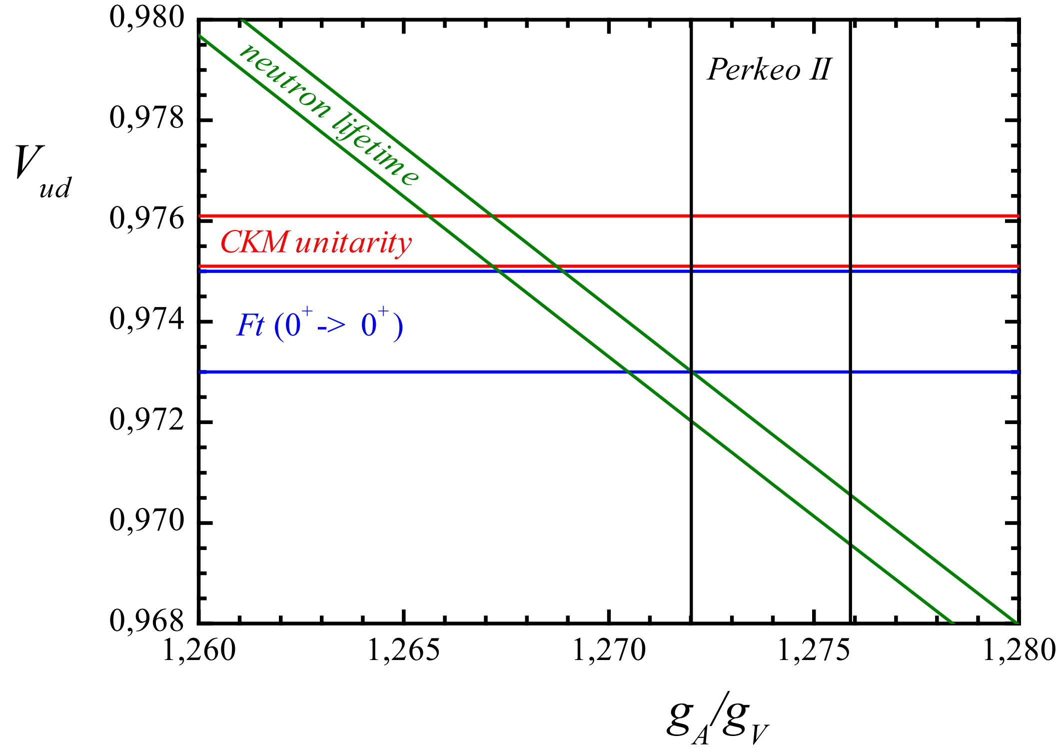
High resolution with polarized neutrons (1μeV)!

Example 8: Polarized Neutrons for Particle Physics

Time inversion invariance experiments:

- $n \rightarrow p + e + \nu + \gamma$ (asymmetry of n-decay)
- electric dipole moment
- neutron lifetime



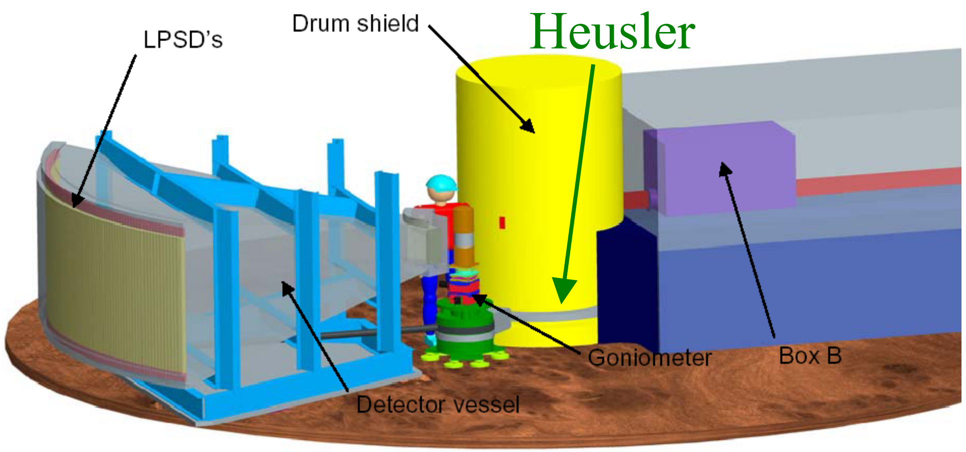


(from O. Zimmer, Techn. Univ. Munich)

Where are polarized beams available?

- Polarized triple axis spectrometers at reactors: ILL, HMI, NIST, FRM-II, …
  and PSI (spallation source)
- Time-of- Flight: ILL (D7), OSIRIS (ISIS), HYSPEC (SNS, planned)
- Neutron Spin Echo: ILL, FRM II, HMI, NIST, LLB, JAEA
- Reflectometers: almost all facilities
- Small angle neutron scattering: HMI, PSI, FRM II, JAEA …
- Particle physics: ILL

polarized neutrons mostly at continuous sources
Urgent need for:
- ToF
- dedicated beam lines



3. Basics of Polarized Beam Technique

Scattering Cross Section

(see also W. Fischer's talk)

- Fermi's golden rule (= 1st Born approximation):

$$\frac{d^2\sigma}{d\Omega dE_f} = \left(\frac{m}{2\pi\hbar^2}\right)^2 \frac{k_f}{k_i} \sum_{\lambda_i} p_{\lambda_i} \sum_{\lambda_f} \left|\left\langle k_f, \lambda_f \middle| \breve{\mathbf{U}} \middle| k_i, \lambda_i \right\rangle\right|^2 \delta\left(E_{\lambda_i} - E_{\lambda_f} + \hbar\omega\right)$$

- $|\lambda_i\rangle$: initial state of sample
- $|\lambda_f\rangle$: final state of sample
- $p_{\lambda i}$: probability that initial state is occupied
- U: interaction potential neutron-sample

- matrix element for nuclear scattering:

$$\frac{2\pi\hbar^2}{m} b\delta(\mathbf{r}-\mathbf{r}_j)$$

$$\left\langle \mathbf{k}_f, \boldsymbol{\lambda}_f \middle| \breve{\mathbf{U}} \middle| \mathbf{k}_i, \boldsymbol{\lambda}_i \right\rangle = \left\langle f \middle| \breve{\mathbf{U}} \middle| i \right\rangle = \left\langle \lambda_f \middle| \int \sum_j \mathrm{e}^{-i\mathbf{k}_f\mathbf{r}} V_j\left(\mathbf{r}-\mathbf{r}_j\right) \mathrm{e}^{i\mathbf{k}_i\mathbf{r}} dr \middle| \lambda_i \right\rangle$$

is essentially proportional to $\sum_j \int b_j e^{i\mathbf{Q}\cdot\mathbf{r}_j}$

Message: scattering given by the square of the Fourier transform of potential

Introducing the Scattering Function

• scattering intensity is proportional to square of scattering amplitude

$$\sum_j \int b_j e^{i\mathbf{Q}\cdot\mathbf{r}_j}$$

• a more detailed treatment yields:

$$\frac{d^2\sigma}{d\Omega dE_f} = \frac{1}{2\pi\hbar}\frac{k_f}{k_i}\sum_{jj'} b_j b_{j'} \int \left\langle \mathrm{e}^{-i\mathbf{Q}\cdot\mathbf{r}_{j'}(0)} \mathrm{e}^{i\mathbf{Q}\cdot\mathbf{r}_j(t)} \right\rangle \mathrm{e}^{-i\omega t} dt$$

• in terms of the scattering function: $\frac{d^2\sigma}{d\Omega dE_f} = \frac{\sigma}{4\pi}\frac{k_f}{k_i} NS(\mathbf{Q},\omega)$

• which is given by $S(\mathbf{Q},\omega) = \frac{1}{2\pi\hbar}\int G(\mathbf{r},t)\mathrm{e}^{i(\mathbf{Q}\cdot\mathbf{r}-\omega t)} d\mathbf{r}dt$

• where the pair correlation function: $G(\mathbf{r},t) = \left(\frac{1}{2\pi}\right)^3 \frac{1}{N}\int\sum_{jj'} \mathrm{e}^{-i\mathbf{Q}\cdot\mathbf{r}} \left\langle b_{j'}\mathrm{e}^{-i\mathbf{Q}\cdot\mathbf{r}_{j'}(0)} b_j \mathrm{e}^{i\mathbf{Q}\cdot\mathbf{r}_j(t)} \right\rangle d\mathbf{Q}$

Magnetic Interaction

- magnetic interaction operator:

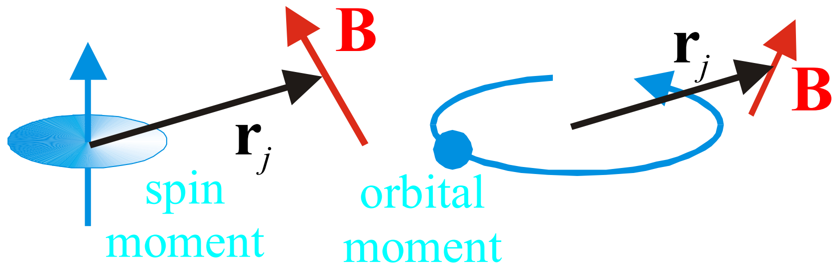
polarization of neutron

$$\breve{\mathbf{U}}_m = -\boldsymbol{\mu}\cdot\mathbf{B} = -\gamma\mu_N\boldsymbol{\sigma}\cdot\mathbf{B}$$

• γ = -1.913:	gyromagnetic ratio
• μ_N:	nuclear magneton
• μ:	magnetic moment of neutron
• σ:	Pauli spin operator
• B:	magnetic field (sample, external field, pseudo)

- field of unpaired electron at position $\mathbf{r}_j$ (dipolar approximation):

$$\mathbf{B}_j = \nabla\times\left\{\frac{\boldsymbol{\mu}_e\times\mathbf{r}_j}{\left|\mathbf{r}_j\right|^3}\right\} + \frac{(-e)}{c}\frac{\mathbf{v}_e\times\mathbf{r}_j}{\left|\mathbf{r}_j\right|^3}$$



Magnetic Scattering Length

- Fourier transform of dipolar interaction yields magnetic scattering length:

$$p = -\gamma r_0 \boldsymbol{\sigma} \cdot \left(\hat{\mathbf{Q}} \times (\mathbf{S} \times \hat{\mathbf{Q}}) + \frac{i}{\hbar |\mathbf{Q}|} \left(\mathbf{p}_e \times \hat{\mathbf{Q}} \right) \right) = -\gamma r_0 \frac{g}{2} \boldsymbol{\sigma} \cdot \left(\hat{\mathbf{Q}} \times (\mathbf{S} \times \hat{\mathbf{Q}}) \right)$$

compare with *b*

- classical radius of electron: $r_0 = 0.2818 \cdot 10^{-12}$ cm
- normalised scattering vector: $\hat{\mathbf{Q}} = \mathbf{Q} / |\mathbf{Q}|$
- Landé factor: $g = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$

- note: *p* depends on vector quantities
  p is comparable to *b*
  σ_{mag}: replace b by p in Fourier transform

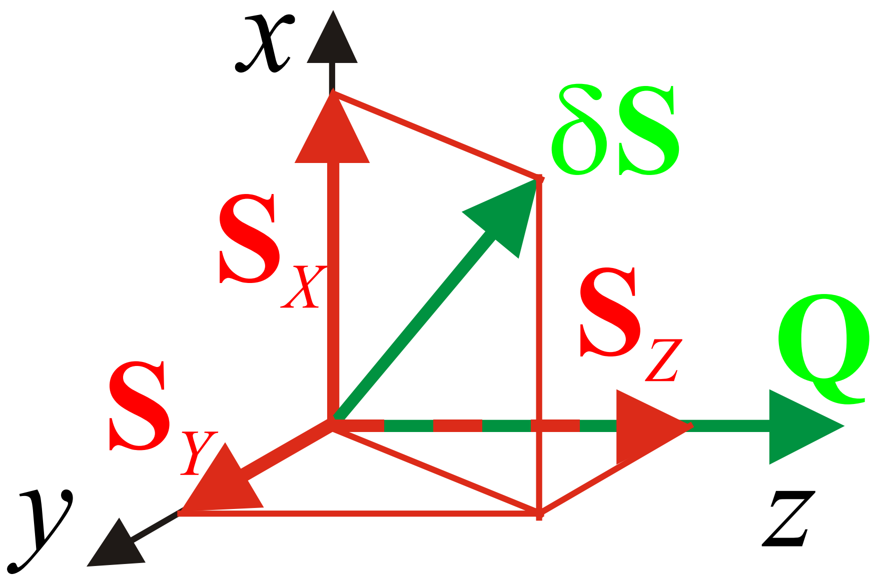
Magnetic Scattering Function

- selection rule for magnetic scattering:

scattering function

$$\left(\frac{d\sigma}{d\Omega dE_f}\right)_{mag} = \frac{k_f}{k_i}\left(\gamma r_0 \frac{g}{2} F(\mathbf{Q})\right)^2 \sum_{\alpha\beta}\left(\delta_{\alpha\beta} - \hat{Q}_\alpha \hat{Q}_\beta\right) S_{\alpha\beta}(\mathbf{Q},\omega)$$

$\left(\hat{\mathbf{Q}} \times (\mathbf{S} \times \hat{\mathbf{Q}})\right)$



→ spin fluctuations along **Q** do not contribute to the scattering

→ the spin components are projected on a plane perpendicular to **Q**

Magnetic Scattering Function

- magnetic scattering function (nuclear scattering not included):
  (non-polarized neutrons)

$$S^{\alpha\beta}(\mathbf{Q},\omega) = \frac{1}{2\pi\hbar}\int\sum_{jj'}\left\langle S_{j'\alpha}(0)S_{j\beta}(t)\right\rangle e^{i\mathbf{Q}\cdot(\mathbf{r}_j-\mathbf{r}_{j'})}\mathrm{e}^{-i\omega t}\,dt$$

$S^{\alpha\beta}(\mathbf{Q},\omega)$ corresponds to the **Fourier transform** of the magnetic pair correlation function that gives the probability to find a magnetic moment at position $\mathbf{r}_j$ at time t with a spin component $S_{j\beta}(t)$ and the same or another moment at position $\mathbf{r}_{j'} = 0$ at time $t = 0$ with a component $S_{j'\alpha}(0)$.

- note: projection operator $\sum_{\alpha\beta}\left(\delta_{\alpha\beta} - \hat{Q}_\alpha\hat{Q}_\beta\right)$ is included in the scattering cross section

Imaginary Part of the Magnetic Susceptibility

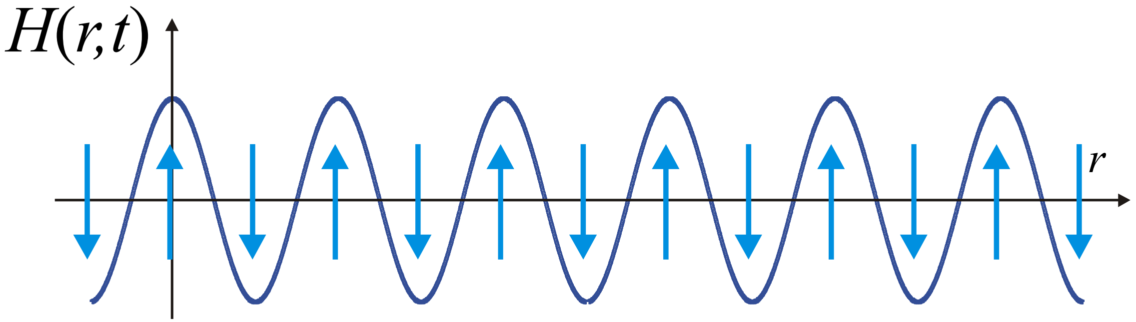
- fluctuation-dissipation theorem (→ W. Fischer's talk):

$$S^{\alpha\beta}(\mathbf{Q},\omega) = \frac{\hbar}{\pi} \frac{1}{1-\mathrm{e}^{-\hbar\omega/k_B T}} \Im\chi^{\alpha\beta}(\mathbf{Q},\omega)$$

imaginary part of the generalised susceptibility

Interpretation: The magnetic moment of the neutron acts on the sample like a frequency and wavevector dependent magnetic field **B(Q**,ω).

$$\mathbf{M}_\alpha(\mathbf{Q},\omega) = \sum_\beta \chi^{\alpha\beta}(\mathbf{Q},\omega)\mathbf{B}_\beta(\mathbf{Q},\omega)$$



- $S^{\alpha\beta}(\mathbf{Q},\omega)$ is directly related to the susceptibility

Magnetic Susceptibility

The magnetic properties of a material (bulk, thin films etc.) can be determined by means of various techniques:

- bulk measurements: $\chi(0,\omega)$ (susceptometer, ESR, etc.)
- nuclear techniques: $\int \chi(\mathbf{Q},\omega)d\mathbf{Q}$ (NMR, μSR)
- neutron scattering: $\chi(\mathbf{Q},\omega)$

→ Information of magnetic properties on various scales in time and space

Magnetic properties "understood" if all measurements are consistent with each other

Polarization Analysis

We have seen, it is difficult to:

• separate magnetic from nuclear scattering

• distinguish between magnetic modes

• coherent from incoherent scattering

So far neglected:

• spin of the neutron

→ polarization analysis

Polarization analysis: Nuclear Scattering

• nuclear scattering $$I(Q) \propto \left(\sum_i b_i e^{i\mathbf{Q}\cdot\mathbf{r}_i} \right)^2$$ sum amplitudes first!

• different isotopes: $$b_i = \bar{b} \pm \Delta b_i$$

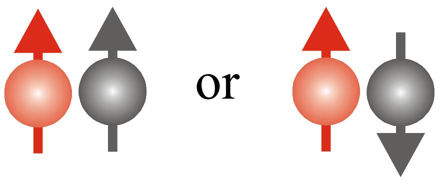
$$\to \bar{b} = \sum_i f_i b_i$$

$$\to \sum_i \Delta b_i = 0$$

coherent scattering: waves from different sites interfere with each other
→ correlations between nuclei
(diffraction, phonons, magnons etc.)

incoherent scattering: only waves from same site interfere with each other
→ self correlations
(diffusion processes)

• spin t of nuclei ≠ 0: scattering from nucleus depends on $\boldsymbol{\sigma}$



$$b_i = \bar{b} \pm \boldsymbol{\sigma}\cdot\mathbf{I}$$

→ b^+

→ b^-

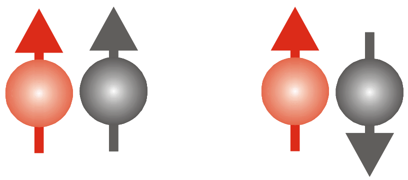
Incoherent cross section is polarization dependent

Polarization analysis: Magnetic Scattering

• magnetic scattering: $$p = -\gamma r_0 \frac{g}{2} \boldsymbol{\sigma} \cdot \left(\hat{\mathbf{Q}} \times (\mathbf{S} \times \hat{\mathbf{Q}}) \right) \propto \boldsymbol{\sigma} \cdot \mathbf{M}_{\perp}$$

→ true magnetic interaction!
→ $\mathbf{M}_{\perp}$ depends on $\mathbf{Q}$

• spin incoherent scattering: depends on polarization of neutrons



$$b_i = \overline{b} \pm \boldsymbol{\sigma} \cdot \mathbf{I}$$

→ is **not** a magnetic (dipolar) interaction → no projection operator

→ spin-incoherence can be detected with polarized neutrons!

Pauli Spin Matrices

• general structure of interactions: $\boldsymbol{\sigma} \cdot \mathbf{A} = \sigma_x A_x + \sigma_y A_y + \sigma_z A_z$

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

$$\sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\sigma_x|\uparrow\rangle = |\downarrow\rangle \quad \sigma_x|\downarrow\rangle = |\uparrow\rangle$$

$$\sigma_y|\uparrow\rangle = i|\downarrow\rangle \quad \sigma_y|\downarrow\rangle = -i|\uparrow\rangle$$

$$\sigma_z|\uparrow\rangle = |\uparrow\rangle \quad \sigma_z|\downarrow\rangle = -|\downarrow\rangle$$

σ_z is already diagonal

eigenfunctions:

$$|\uparrow\rangle = \begin{vmatrix} 1 \\ 0 \end{vmatrix}\rangle \text{ and } |\downarrow\rangle = \begin{vmatrix} 0 \\ 1 \end{vmatrix}\rangle$$

Magnetic Interaction

$$p \propto \boldsymbol{\sigma} \cdot \mathbf{M}_\perp = \sigma_x M_{\perp,x} + \sigma_y M_{\perp,y} + \sigma_z M_{\perp,z}$$

only spin-flip scattering possible

$$\sigma_x|\uparrow\rangle = |\downarrow\rangle \quad \sigma_x|\downarrow\rangle = |\uparrow\rangle$$

$$\sigma_y|\uparrow\rangle = i|\downarrow\rangle \quad \sigma_y|\downarrow\rangle = -i|\uparrow\rangle$$

$$\langle\uparrow|\sigma_x|\uparrow\rangle = \langle\uparrow|\downarrow\rangle = 0 \quad \langle\downarrow|\sigma_x|\downarrow\rangle = \langle\downarrow|\uparrow\rangle = 0$$

$$\langle\uparrow|\sigma_y|\uparrow\rangle = i\langle\uparrow|\downarrow\rangle = 0 \quad \langle\downarrow|\sigma_y|\downarrow\rangle = -i\langle\downarrow|\uparrow\rangle = 0$$

$$\sigma_z|\uparrow\rangle = |\uparrow\rangle \quad \sigma_z|\downarrow\rangle = -|\downarrow\rangle$$

$$\langle\downarrow|\sigma_z|\uparrow\rangle = \langle\downarrow|\uparrow\rangle = 0 \quad \langle\downarrow|\sigma_z|\uparrow\rangle = -\langle\downarrow|\uparrow\rangle = 0$$

only non-spin-flip scattering possible for $M_{\perp,z}$

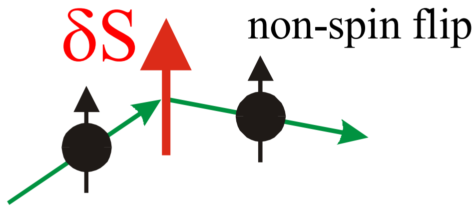
(same is true for incoherent scattering: $A+BI_z$)

Selection Rules for Polarization Analysis

Note: The polarization of the neutron defines the *z*-axis
(so called longitudinal polarization analysis)

$$\left\langle \uparrow \left| \sigma \cdot \breve{\mathbf{M}}_{\perp} \right| \uparrow \right\rangle = \breve{M}_{\perp,z}$$

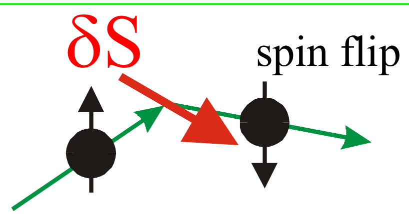
$$\left\langle \downarrow \left| \sigma \cdot \breve{\mathbf{M}}_{\perp} \right| \downarrow \right\rangle = -\breve{M}_{\perp,z}$$



$<\uparrow|\sigma\cdot\mathbf{M}_\perp|\uparrow> = M_{\perp z}$

$$\left\langle \downarrow \left| \sigma \cdot \breve{\mathbf{M}}_{\perp} \right| \uparrow \right\rangle = \breve{M}_{\perp,x} + i\breve{M}_{\perp,y} = \breve{M}^{+}$$

$$\left\langle \uparrow \left| \sigma \cdot \breve{\mathbf{M}}_{\perp} \right| \downarrow \right\rangle = \breve{M}_{\perp,x} - i\breve{M}_{\perp,y} = \breve{M}^{-}$$



$<\uparrow|\sigma\cdot\mathbf{M}_\perp|\downarrow> = M_{\perp x} + i\, M_{\perp y}$

„Half-Polarized“ Beam Technique

see M. Blume, Phys. Rev. 130, 1670 (1963):

$$\sigma = N \cdot N^* + \mathbf{M} \cdot \mathbf{M}^* + \mathbf{P}_i \cdot (N \cdot \mathbf{M}^* + N^* \cdot \mathbf{M}) + i\mathbf{P}_i \cdot (\mathbf{M} \times \mathbf{M}^*)$$

$$N = \sum b_i e^{i\mathbf{Q}\cdot\mathbf{r}_i}$$

nuclear scattering

$$\mathbf{M}_\perp = \hat{\mathbf{Q}} \times \left(\mathbf{M}(\mathbf{Q}) \times \hat{\mathbf{Q}}\right)$$

$$\mathbf{M}(\mathbf{Q}) = \int \mathbf{M}(\mathbf{r}) e^{i\mathbf{Q}\cdot\mathbf{r}} d\mathbf{r}$$

magnetic scattering operator

chiral term

Special case: ferromagnet with |**M**| = N:

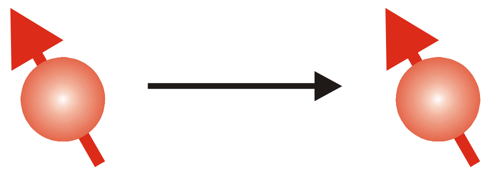
- chiral term is 0
- P_i = -1: σ = 0 → useful for polarizing neutrons
- P_i = +1: σ finite

Rules for Polarization Analysis 1

• **nuclear scattering** (excluding nuclear spin incoherence):

no Pauli spin matrices involved

→ all scattering is non-spin-flip



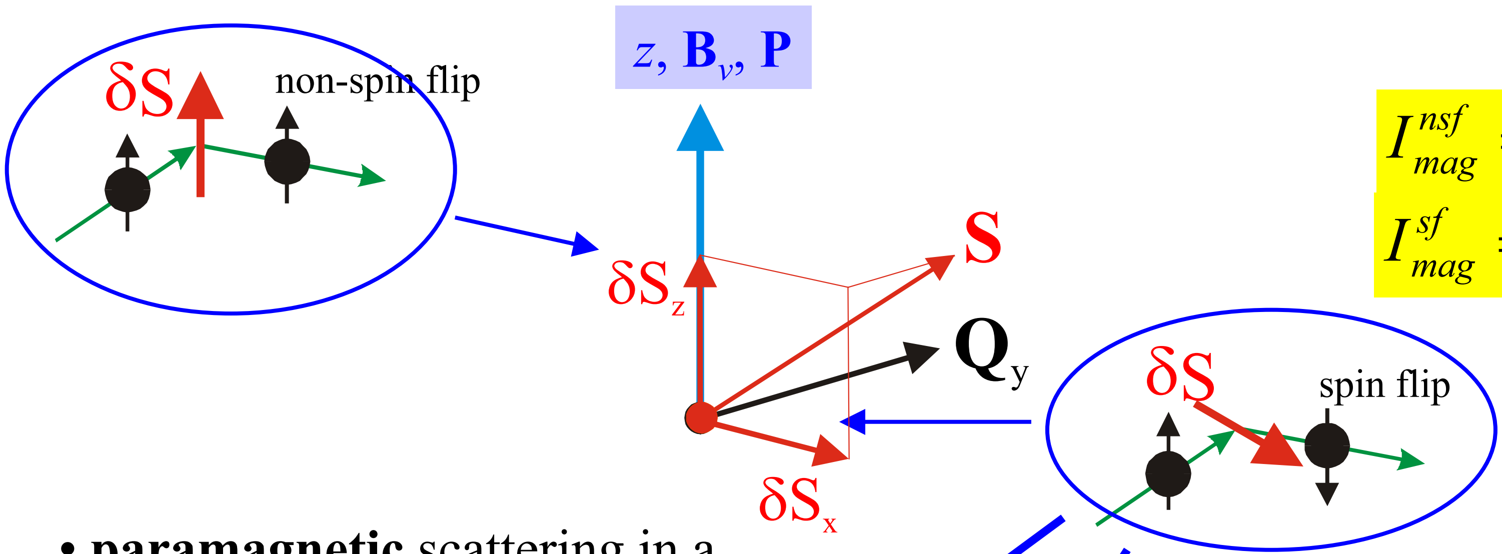
• (room) **background**:

→ contributes to all scattering channels

Rules for Polarization Analysis 2

(special case: isotropic ferromagnet!)

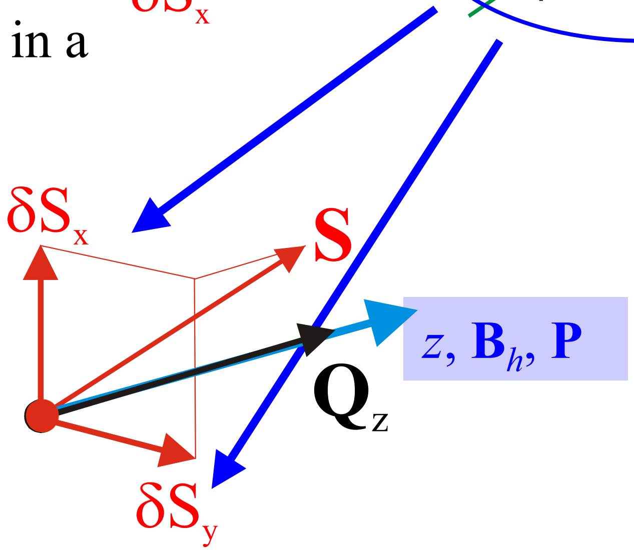
• **paramagnetic** scattering in a vertical field: **Q** ⊥ **B**



$$I^{nsf}_{mag} = \tfrac{1}{2}\sigma_{mag}$$

$$I^{sf}_{mag} = \tfrac{1}{2}\sigma_{mag}$$

• **paramagnetic** scattering in a horizontal field: **Q** // **B**



$$I^{nsf}_{mag} = 0$$

$$I^{sf}_{mag} = \sigma_{mag}$$

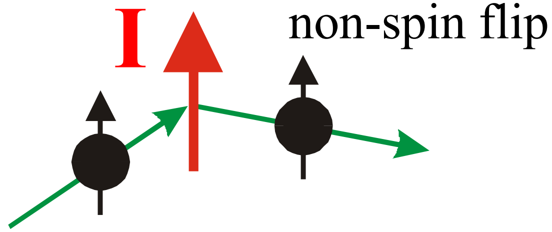
Rules for Polarization Analysis 3

- **spin incoherent** scattering:

coherent nuclear scattering

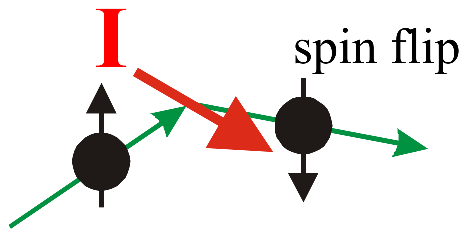
$$\langle \uparrow | A + B\boldsymbol{\sigma}\cdot\mathbf{I} | \uparrow \rangle = A + BI_z$$

$$\langle \downarrow | A + B\boldsymbol{\sigma}\cdot\mathbf{I} | \downarrow \rangle = A - BI_z$$



$$\langle \downarrow | A + B\boldsymbol{\sigma}\cdot\mathbf{I} | \uparrow \rangle = B(I_x + iI_y)$$

$$\langle \uparrow | A + B\boldsymbol{\sigma}\cdot\mathbf{I} | \downarrow \rangle = B(I_x - iI_y)$$



- at reasonable temperatures:
  (nuclear spins disordered)

$$\langle I_x^2 \rangle = \langle I_y^2 \rangle = \langle I_z^2 \rangle = \frac{1}{3} I(I+1)$$

- contribution of spin-incoherent:

$$I_{NSI}^{nsf} = \tfrac{1}{3}\sigma_{NSI} \qquad I_{NSI}^{sf} = \tfrac{2}{3}\sigma_{NSI}$$

Summary: Polarization Analysis

	non-spin-flip	spin-flip
Q // B	$\sigma_N + 0\sigma_m + \frac{1}{3}\sigma_{NSI} + \sigma_{bg}$	$\sigma_m + \frac{2}{3}\sigma_{NSI} + \sigma_{bg}$
Q ⊥ B	$\sigma_N + \frac{1}{2}\sigma_m + \frac{1}{3}\sigma_{NSI} + \sigma_{bg}$	$\frac{1}{2}\sigma_m + \frac{2}{3}\sigma_{NSI} + \sigma_{bg}$

Measurement of all cross sections allows the determination of individual scattering contributions.

Example: Paramagnetic scattering from ferromagnetic material:

$$\frac{1}{2}\sigma_{mag} = I^{nsf}_{Q\perp B} - I^{nsf}_{Q//B}$$

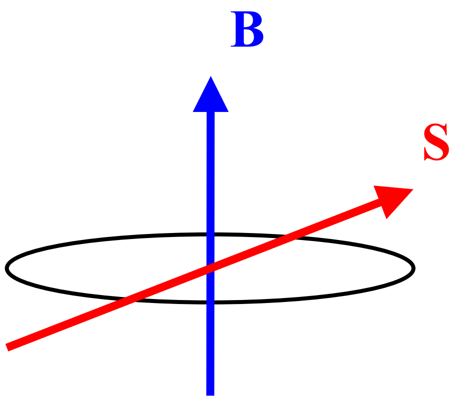
$$\frac{1}{2}\sigma_{mag} = I^{sf}_{Q//B} - I^{sf}_{Q\perp B}$$

4. Ancillary equipment for polarization analysis

Guiding the Polarization of Neutrons

- **Larmor precession:** $$\hbar\frac{d\mathbf{S}}{dt} = \mathbf{M}_{mec} = \gamma\hbar\mathbf{S}\times\mathbf{B}$$

gyromagnetic ratio: $\gamma_l = -2\pi\cdot 2916\frac{\text{rad}}{\text{Gs}} = -183.2461\frac{\text{rad}}{\text{Ts}}$



- spin precession in **B**-field: $\mathbf{S}(t) = S\begin{pmatrix}\cos\omega_L t\\ \sin\omega_L t\\ 0\end{pmatrix}$
- Larmor frequency: $\omega_L = -\gamma B$
- change of phase: $\varphi = (\varphi(t)-\varphi(0) = \omega_L t = -\gamma_l B t = -\gamma_l B\frac{s}{v}$

- **example:**
  - B = 100 Gauss
  - s = 100 mm
  - v = 1000 m/s

→ φ = -183 rad ≅ 29 revolutions

Neutron beam quickly depolarises!

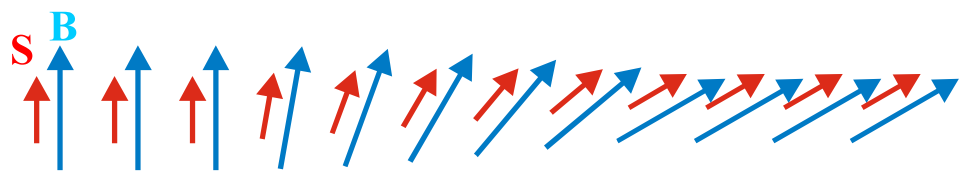
Adiabatic – Sudden Transitions

• **maintain direction of polarization:**

→ guide fields: define quantization axis, **B** (2 mT) >> $\mathbf{B}_{earth}$ (0.1 mT)

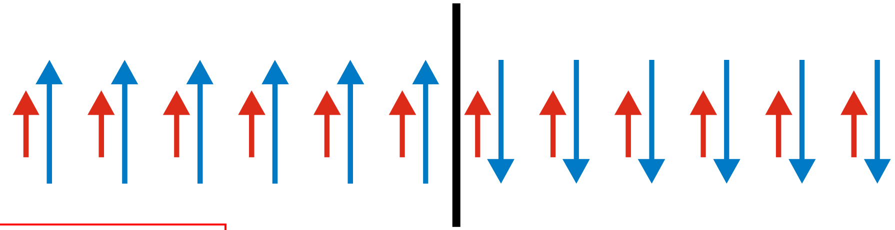
adiabatic transition:

rotation of **B** << ω_L: **P** follows **B**



sudden transition:

B changes abruptly,
→ **P** does not follow **B**



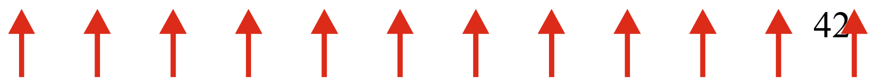
(Nb-shield, current sheet)

• B = 10 Gauss
• s = 1 mm
• v = 1000 m/s

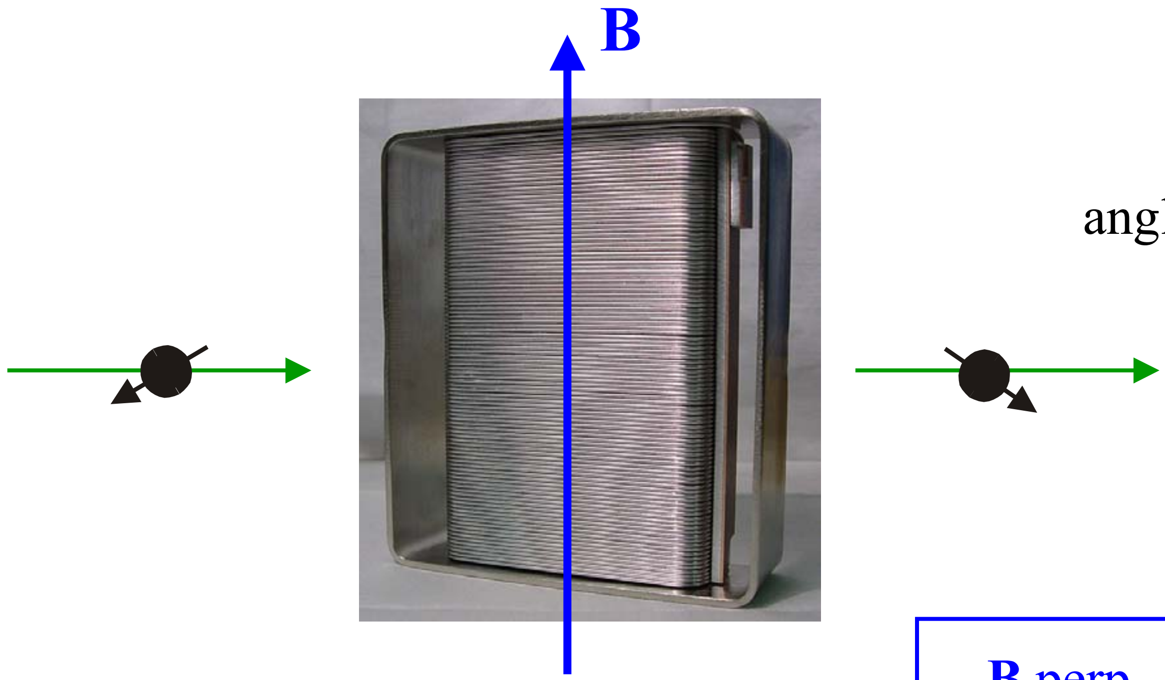
→ 0.029 revolutions!

→ Choose **B** = 0 → no precession → no depolarisation

$B = 0$:

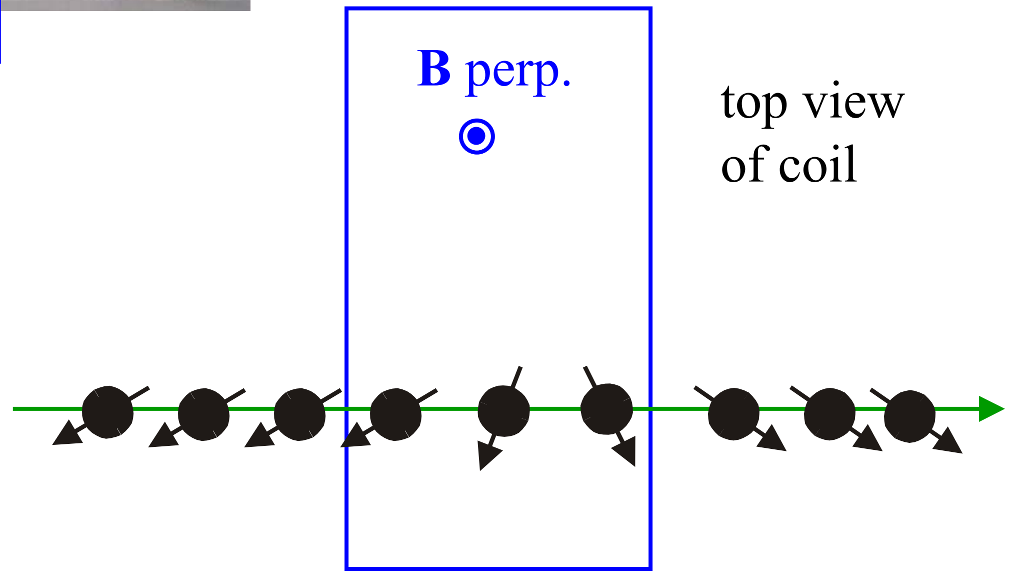


Spin Rotators



angle of rotation given by:

$$\varphi = \omega_L t = -\gamma B \frac{d}{v}$$

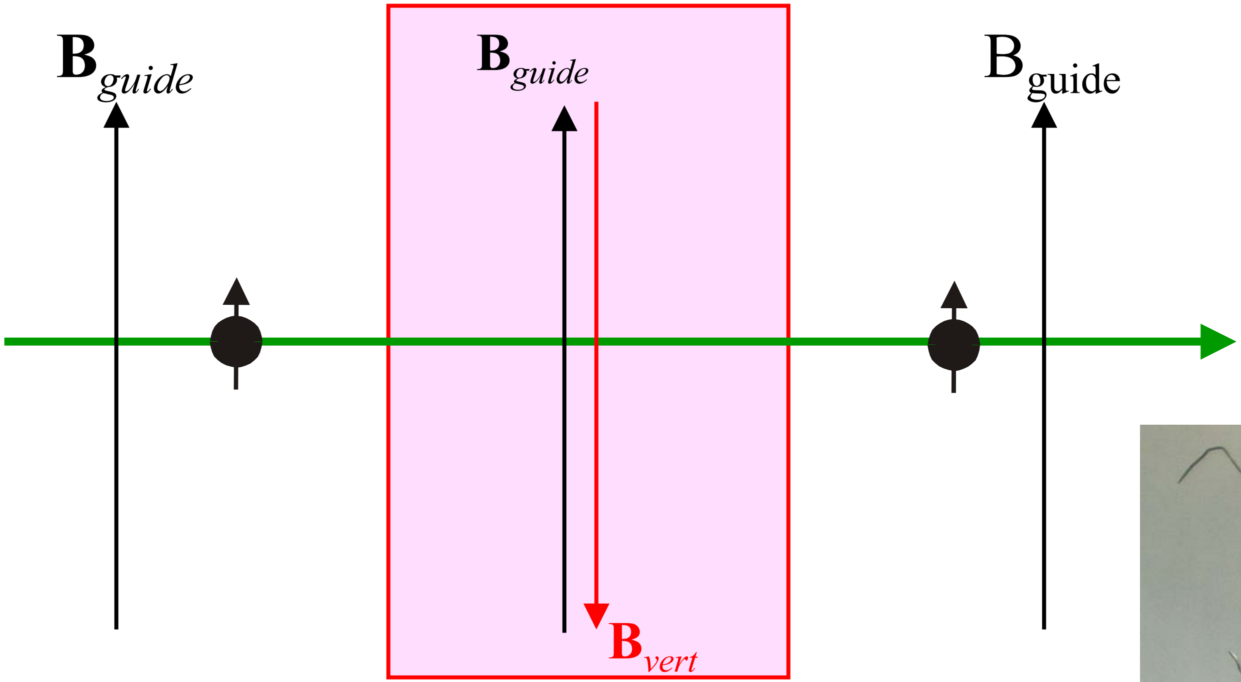


top view
of coil

Sudden transition at the boundary of the wires

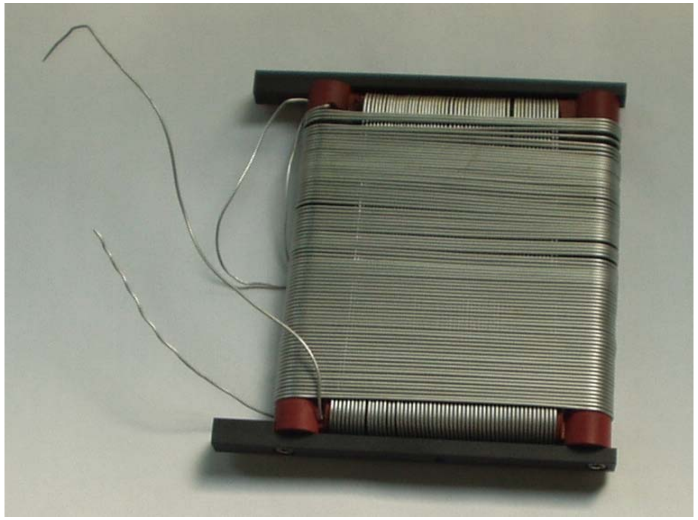
(current sheet)

Changing Polarisation: Flat Coil Spin Flipper



vertical guide field is cancelled by negative compensation field:

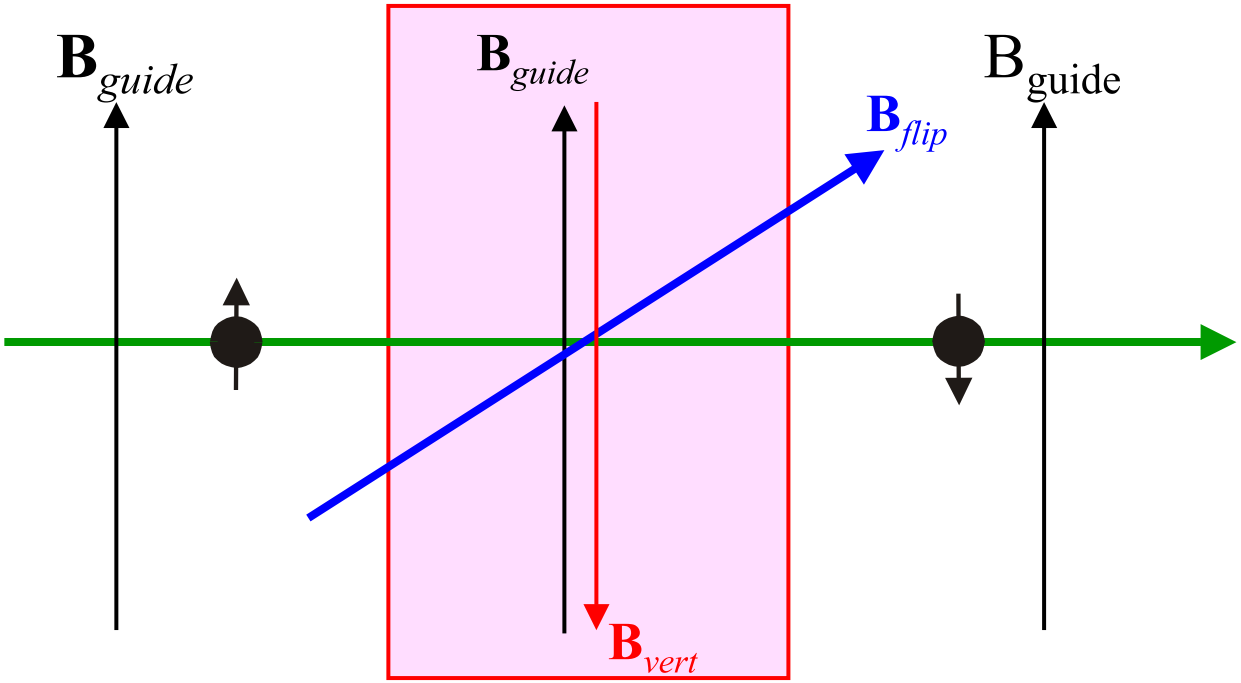
$\mathbf{B}_{vert} = -\mathbf{B}_{guide}$



Principle of the Flat Coil Spin Flipper

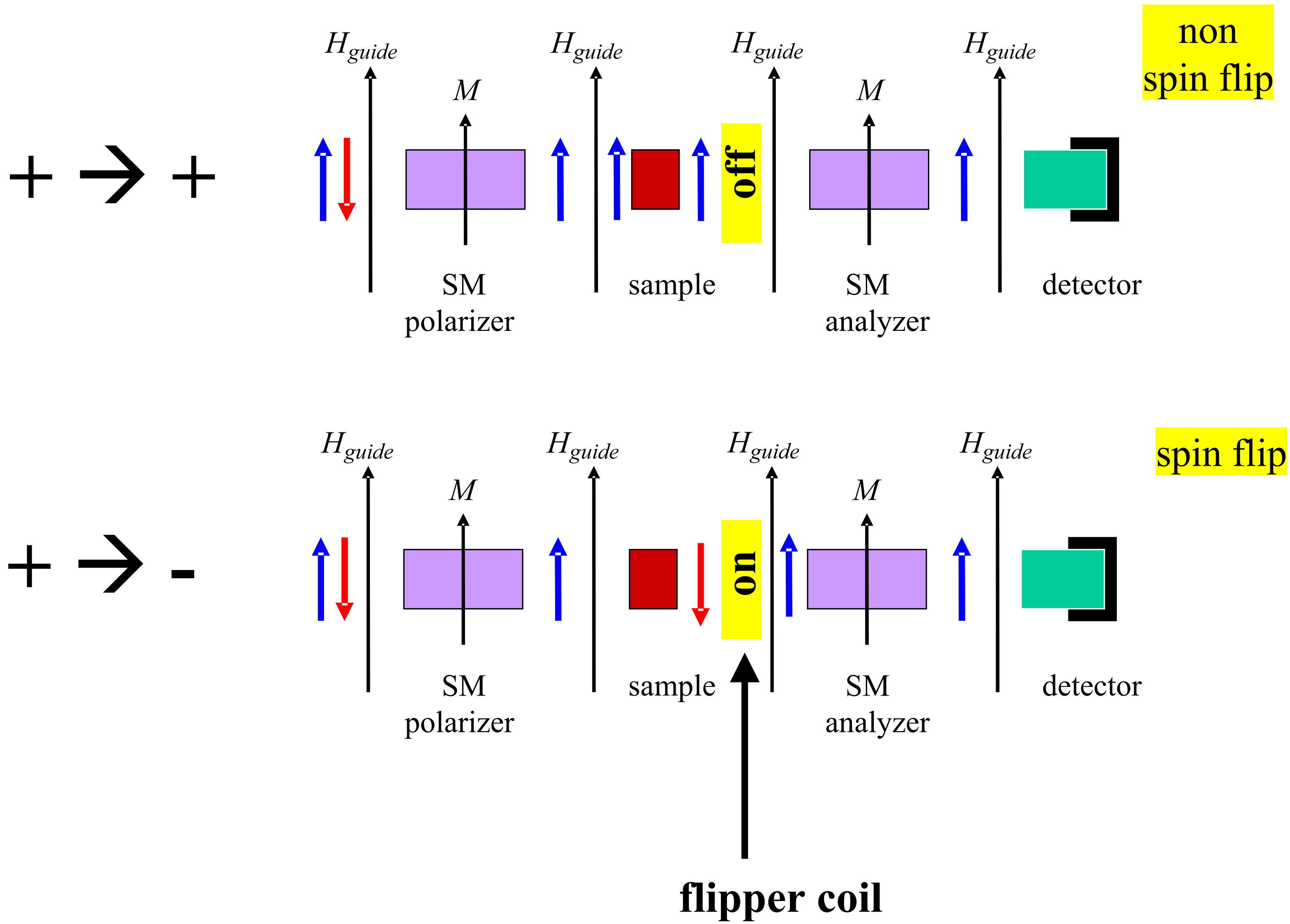
$\mathbf{B}_{flip}$ is chosen such that neutron makes a π-rotation, when passing the flipper coil

$$\varphi = \boxed{-\gamma_l B \frac{s}{v} = \pi}$$



vertical guide field is cancelled by negative compensation field: $\mathbf{B}_{vert} = -\mathbf{B}_{guide}$

Polarized Beam Experiment



Classical Polarization Analysis

- polarization precesses around magnetic field
- guide field parallel to incident polarization
  will prevent depolarization!

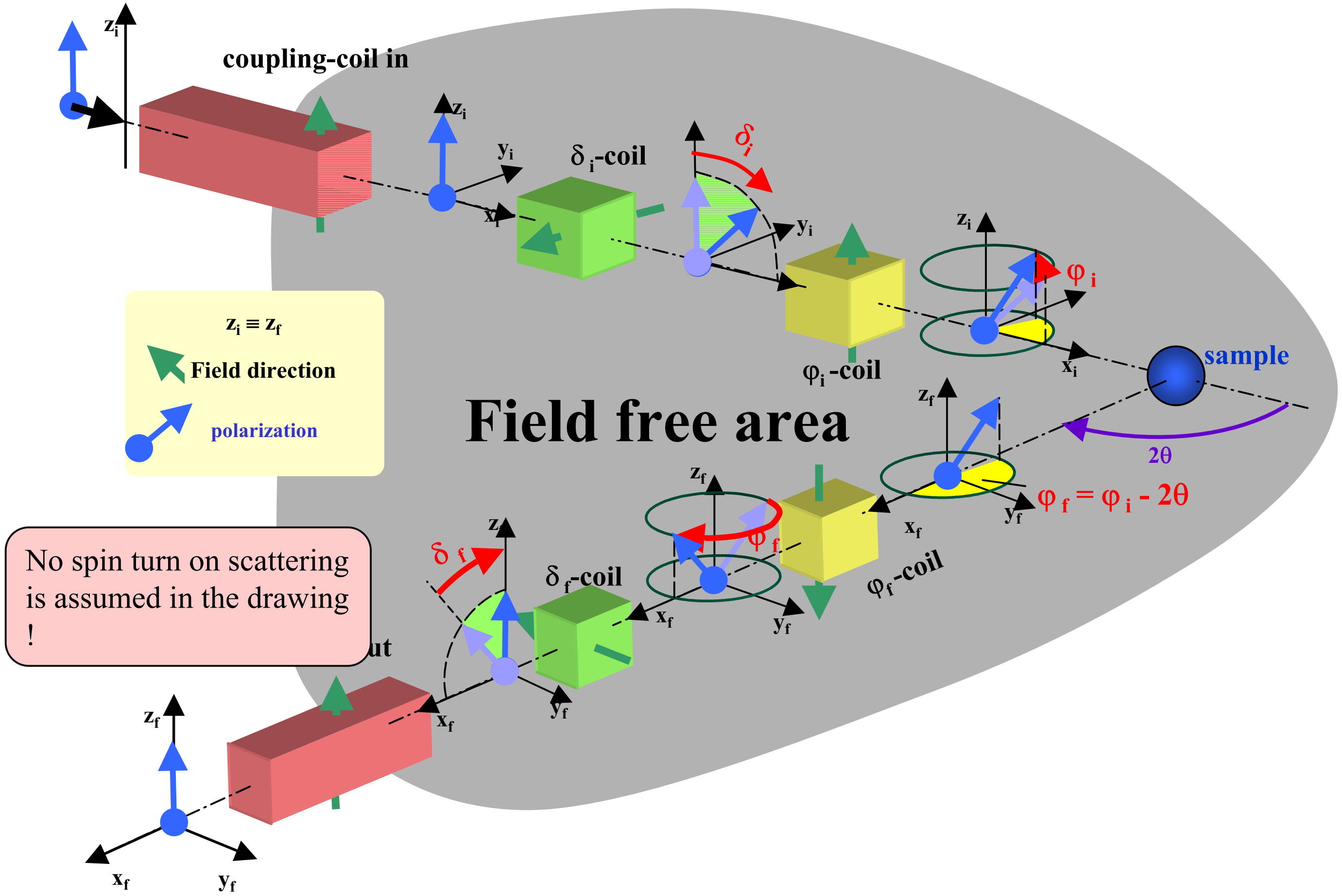
However:

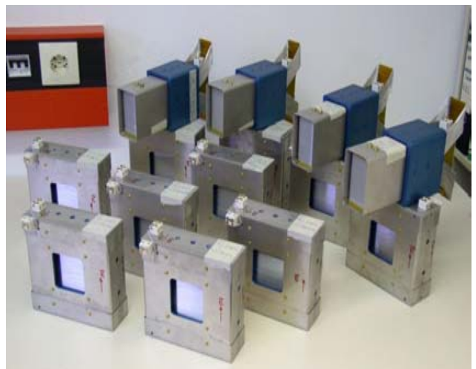
- Depolarization of components of scattered polarization perpendicular to guide field
- only component parallel to initial polarisation can be measured
  → longitudinal polarisation analysis
- Loss of information: diagonal elements P_{ij} $(i \neq j)$ are lost

$$\overrightarrow{P'} = \begin{pmatrix} P^{x\prime} \\ P^{y\prime} \\ P^{z\prime} \end{pmatrix} = \begin{pmatrix} P_{xx} & P_{yx} & P_{zx} \\ P_{xy} & P_{yy} & P_{zy} \\ P_{xz} & P_{yz} & P_{zz} \end{pmatrix} \begin{pmatrix} P^{x} \\ P^{y} \\ P^{z} \end{pmatrix} + \begin{pmatrix} \hat{P}^{x} \\ \hat{P}^{y} \\ \hat{P}^{z} \end{pmatrix}$$

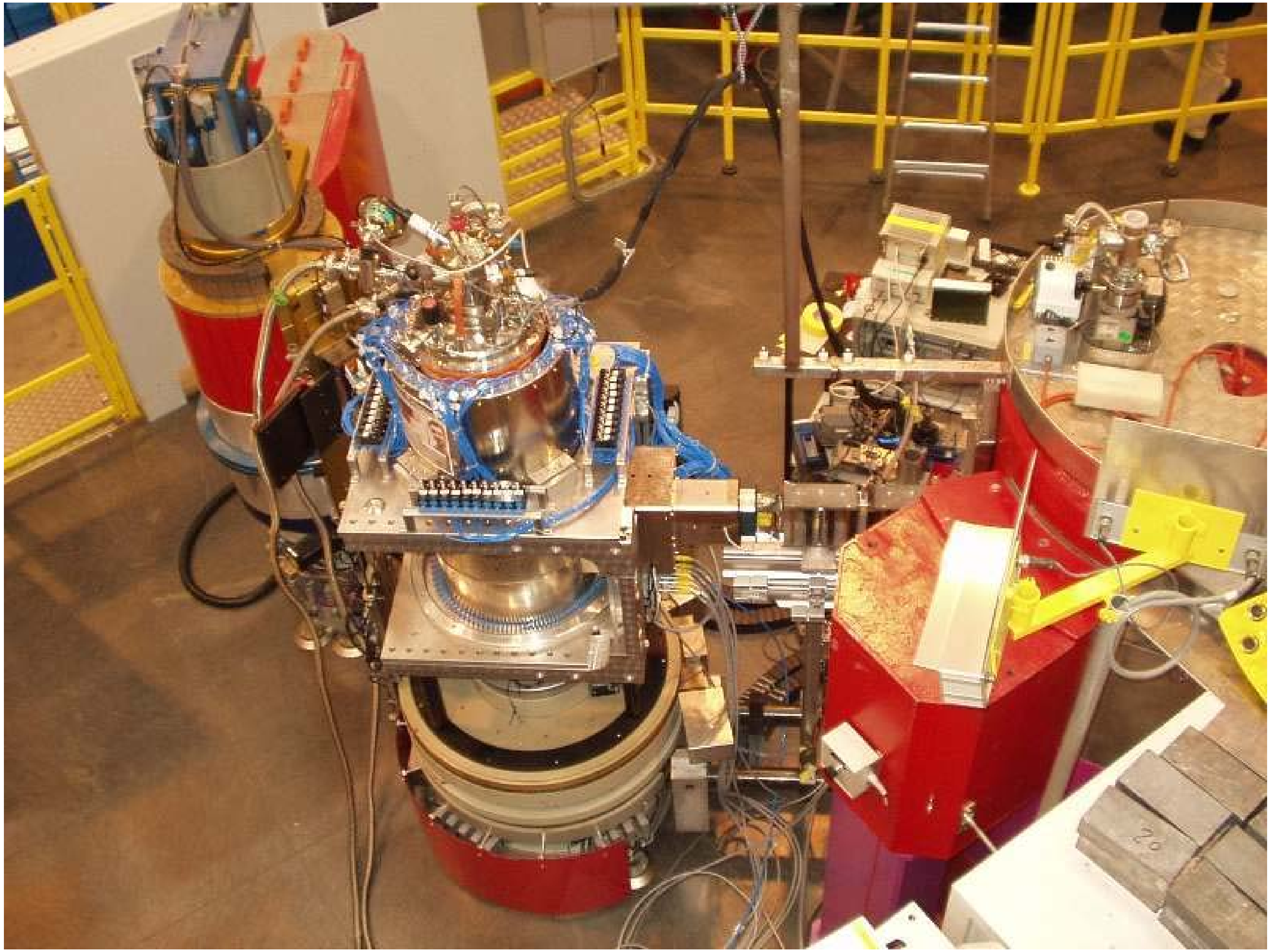
Spherical Polarization Analysis

Solution:
- **P** is conserved in ZERO magnetic field
- complete polarization tensor can be measured





MuPAD installed on TASP @ SINQ

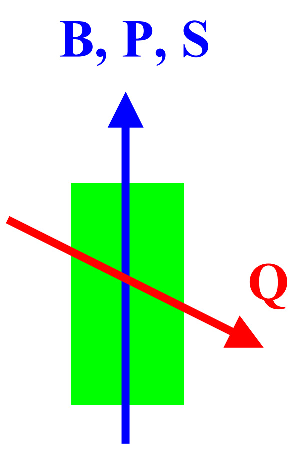


5. Heusler Monochromators

Polarizing Single-Crystals

Ferromagnet in saturating field **B**:

- all moments parallel to **B**
- note: **S** is antiparallel to μ



$$p = -\gamma r_0 \frac{g}{2} \boldsymbol{\sigma} \cdot \left(\hat{\mathbf{Q}} \times (\mathbf{S} \times \hat{\mathbf{Q}}) \right)$$

$$\downarrow$$

$$p \propto \pm \gamma r_0 \frac{g}{2} S$$

Bragg intensity of magnetic crystal:

- given by adding or subtracting p

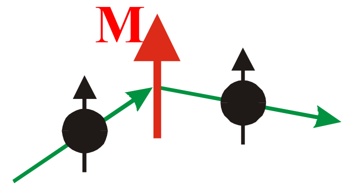
$$I(Q) \propto \left(\sum_i (b_i \pm p_i) e^{i\mathbf{Q}\cdot\mathbf{r}_i} \right)^2$$

- Bragg peaks appear at reciprocal lattice points G_{hkl}

$$\longrightarrow \quad I_{hkl} \propto \delta(Q - G_{hkl})$$

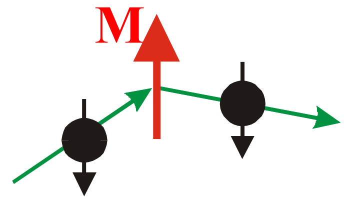
Polarizing Heusler

$$I^{++} \propto (b+p)^2$$



$$I(Q) \propto \left(\sum_i (b_i \pm p_i) e^{i\mathbf{Q}\cdot\mathbf{r}_i} \right)^2$$

$$I^{--} \propto (b-p)^2$$



Heusler (Cu_2MnAl): $\mu = 4.12\ \mu_B$

- flipping ratio R:

$$R = \frac{I_{111}^{++}}{I_{111}^{--}} = \frac{(b+p)^2}{(b-p)^2} = \frac{4b^2}{0} = \infty$$

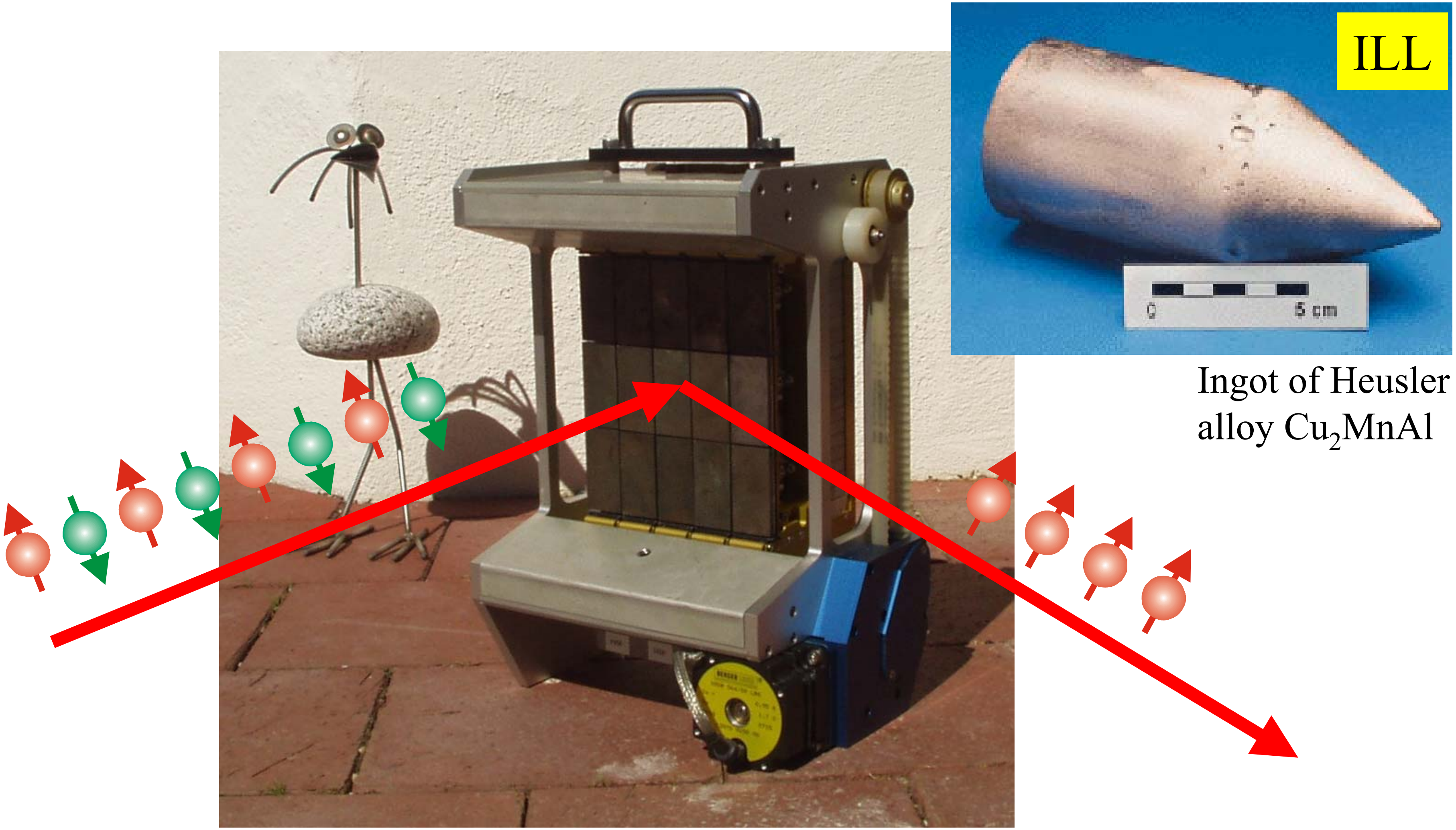
- polarisation P:

$$P = \frac{R-1}{R+1} = 1$$

Experiment: P ≅ 90% – 95%

Compare with expression for half-polarized set-up with $N = M$:

$$\sigma = N \cdot N^* + \mathbf{M} \cdot \mathbf{M}^* + \mathbf{P}_i \cdot (N \cdot \mathbf{M}^* + N^* \cdot \mathbf{M})$$

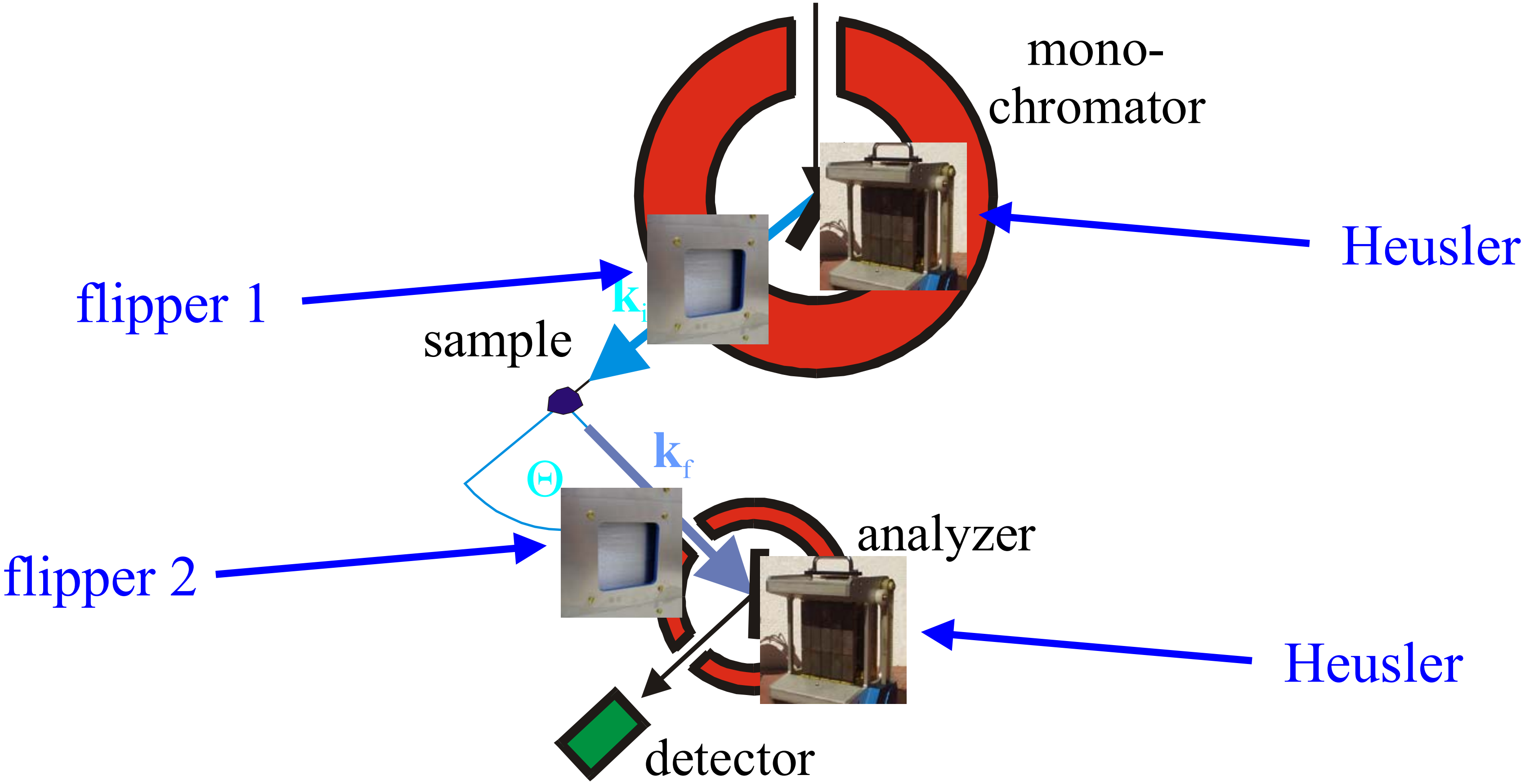


Ingot of Heusler alloy Cu_2MnAl

TASP analyzer at SINQ (PSI, Roessli/Böni)

Selection of wavelength and polarization

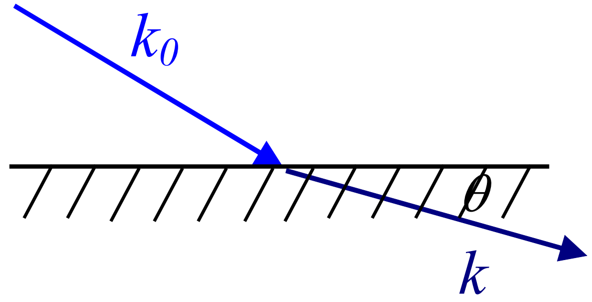
Implementation: Triple-Axis Spectrometer



Combine monochromatization with polarization.

6. Polarizing supermirrors

Total Reflection from Surfaces



Schrödinger equation: $\frac{\hbar^2}{2m}\nabla^2\Psi + V\Psi = E\Psi$

- in vacuum: $V = 0 \longrightarrow E = \frac{\hbar^2 k_0^2}{2m_n}$
- in material: $V = \frac{2\pi\hbar}{m}\rho(b \pm p) \longrightarrow E - V = \frac{\hbar^2 k^2}{2m_n}$
- refractive index: $n^2 = \frac{k^2}{k_0^2} = 1 - \frac{V}{E}$

ρ: number density
b: coherent scattering length
m: mass of neutron

$\Rightarrow$ $n \approx 1 - \frac{1}{2\pi}\lambda^2\rho(b \pm p)$ $\Rightarrow$ $\theta_c = \lambda\sqrt{\frac{\rho(b \pm p)}{\pi}}$

Example: Ni

$\theta_{C,Ni}$ (^{0})= 0.1$m\lambda$ (Å)

"m = 1"

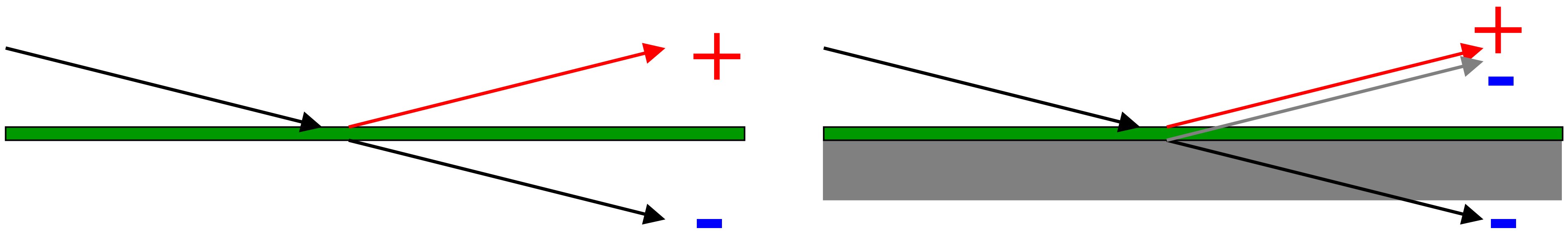
Total Reflection from $Fe_{50}Co_{48}V_2$

(O. Schärpf, J. Penfold, 1970'ies)

$$b \cong p \longrightarrow \theta_c = \lambda\sqrt{\frac{\rho(b \pm p)}{\pi}}$$

- no reflection for one spin state
- Strong reflection for opposite spin state

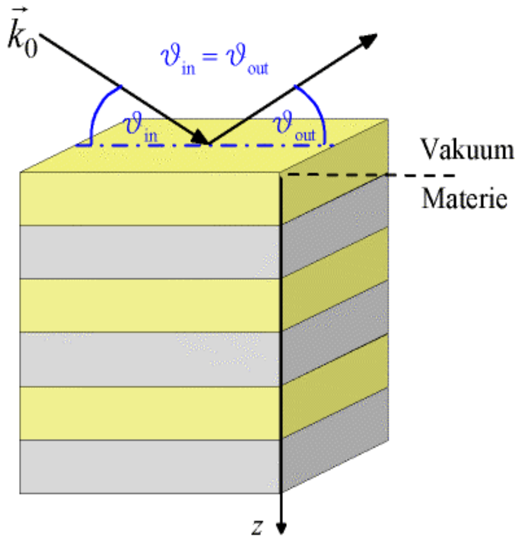
Film transparent for one spin state:



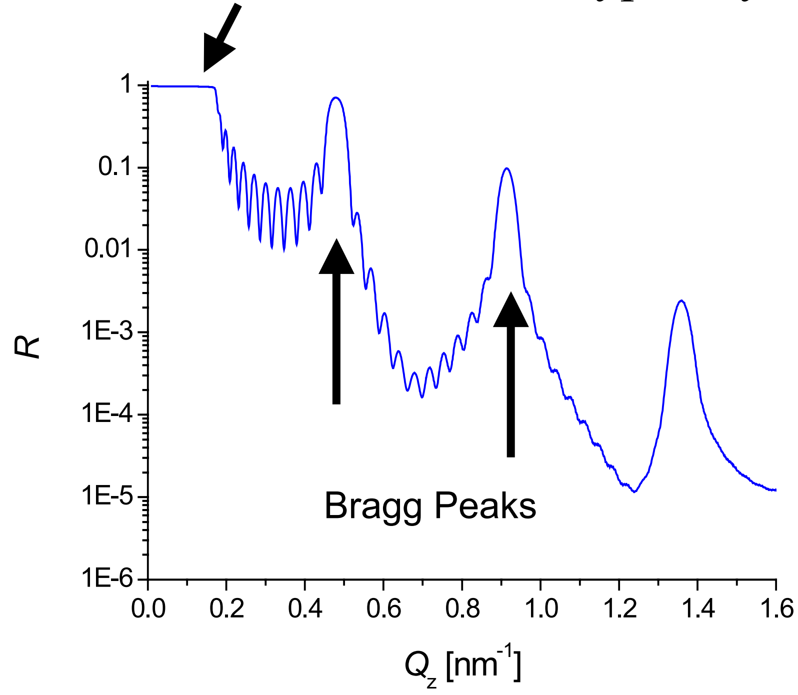
- free standing: transmission polarizer
- reflection angles **too small** → (Mezei, Turchin) → supermirrors

Diffraction from Multilayers

Bragg's law: $Q = \frac{2\pi}{d} = \frac{4\pi}{\lambda}\sin(\Theta/2)$ → $\vartheta_{in} \cong \Theta/2 = \frac{\lambda}{2d}$



total reflection: typically 0.1⁰Å⁻¹



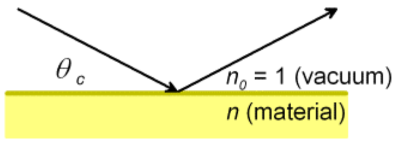
- magnetic layer: $G_{\pm} = n(b \pm p)$
- non-magnetic layer: $G_{nm} = n_{nm} b_{nm}$

choose: $G_{-} = G_{nm}$

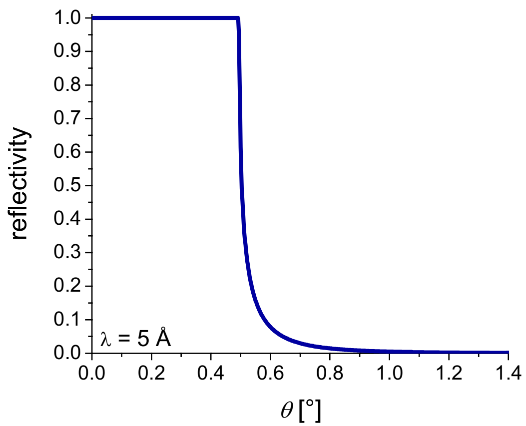
How Does a Supermirror Work

(Turchin, Mezei 1976)

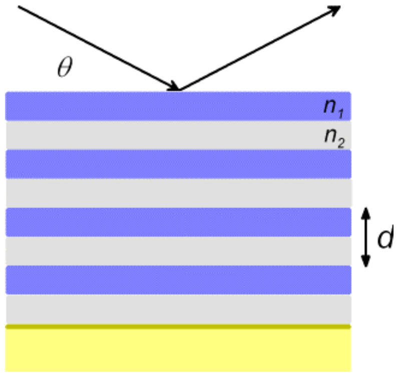
smooth surfaces



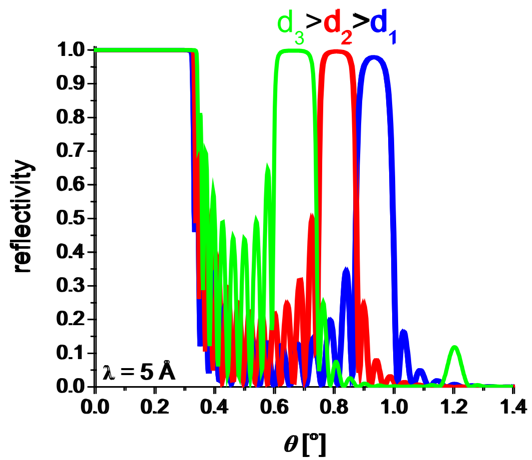
- refractive index $n < 1$
- total external reflection
  e.g. Ni: $q_c = 0.1$ °/Å



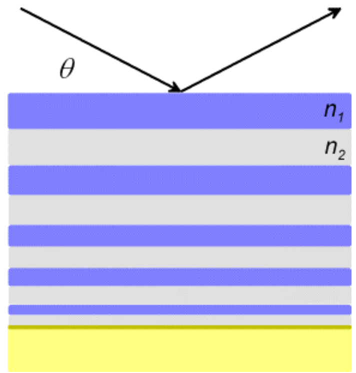
multilayer

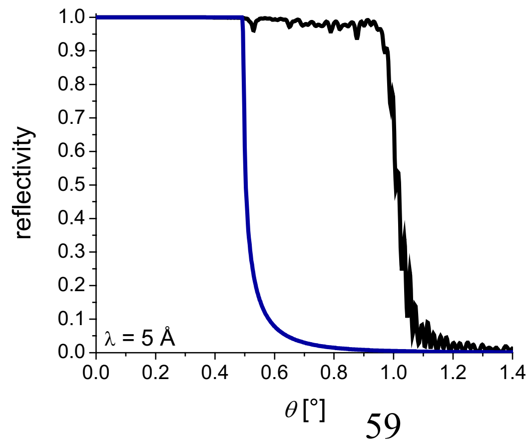


$$\lambda = 2d\sin\theta$$



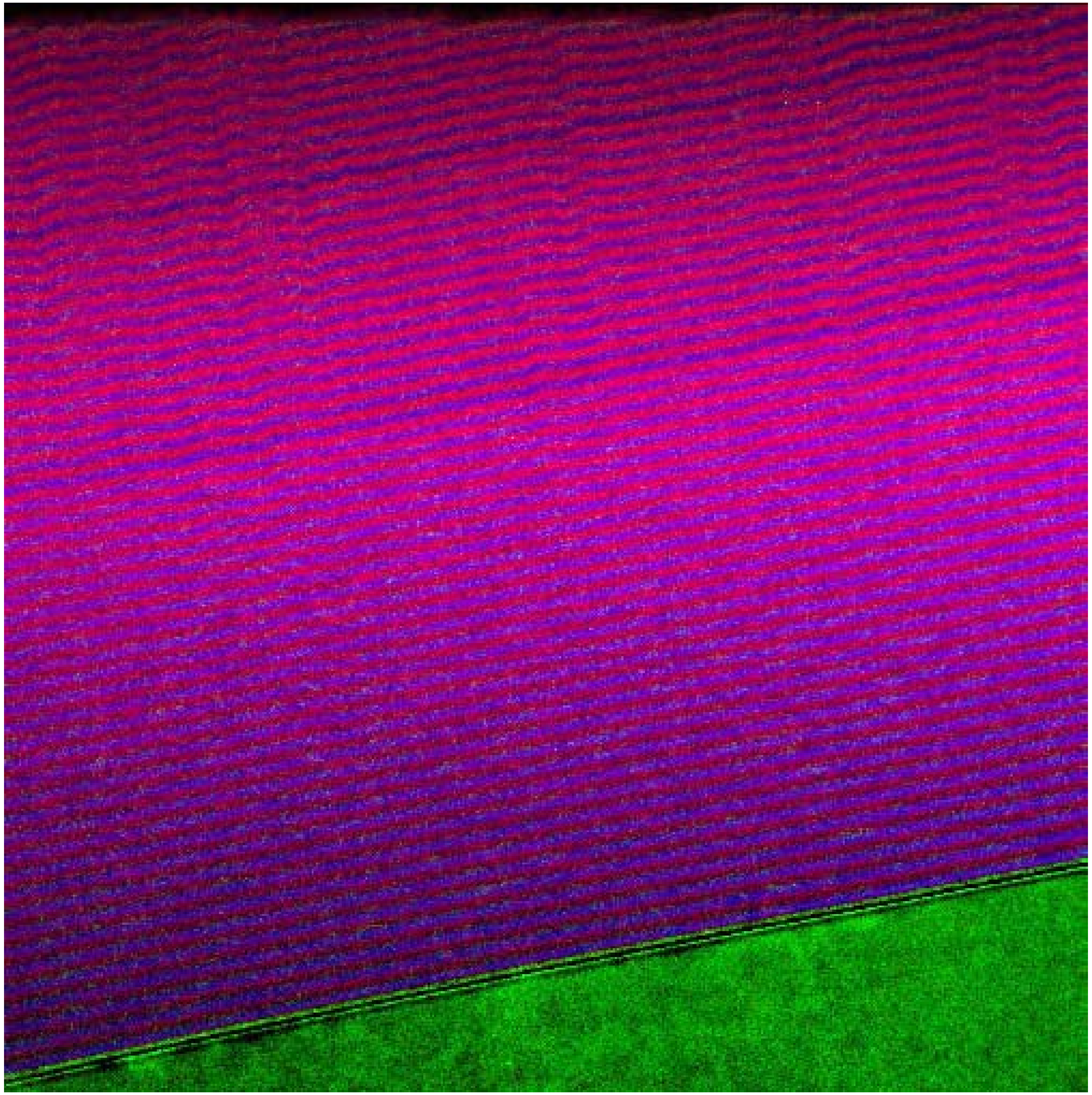
supermirror





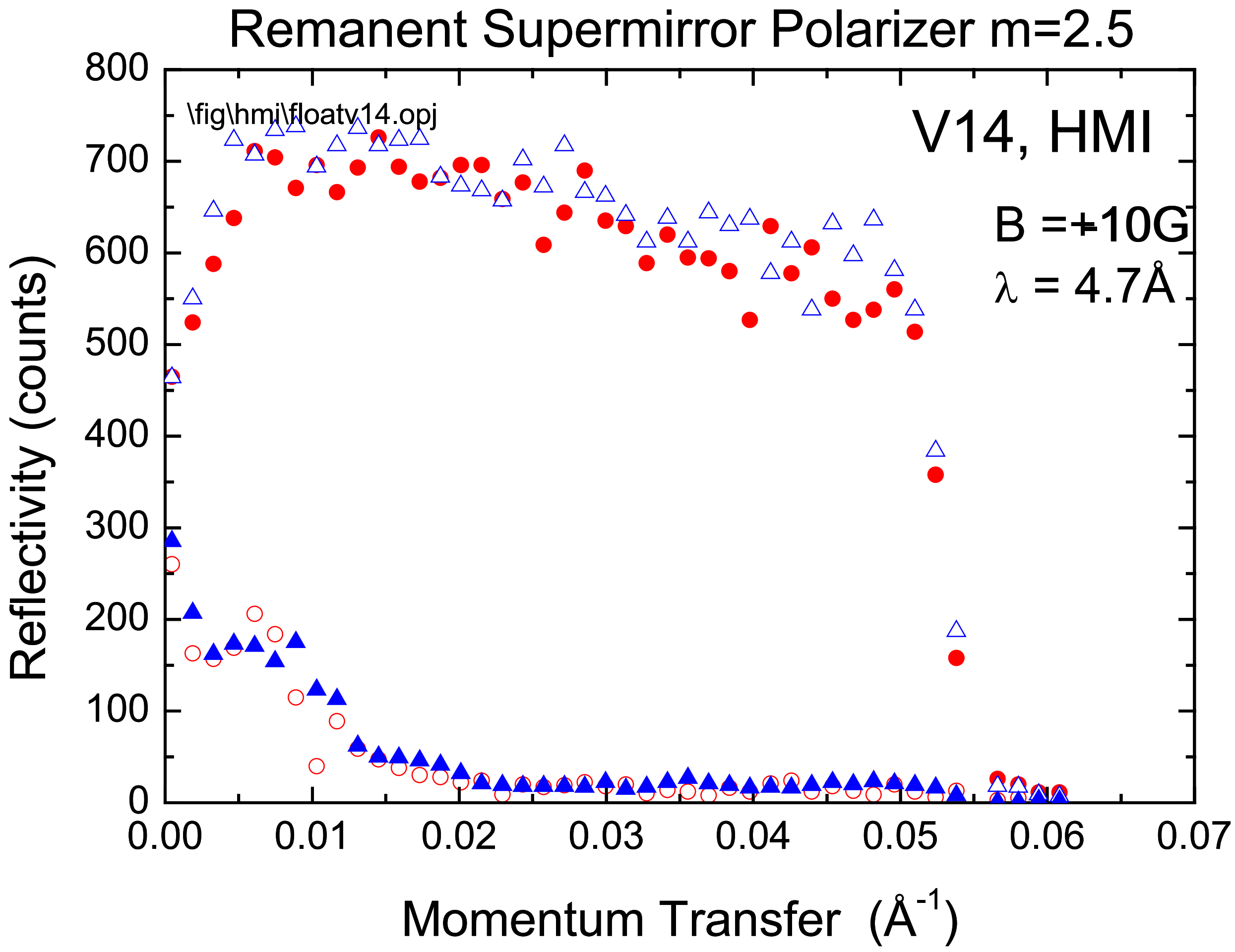
TEM of a Polarizing Supermirror

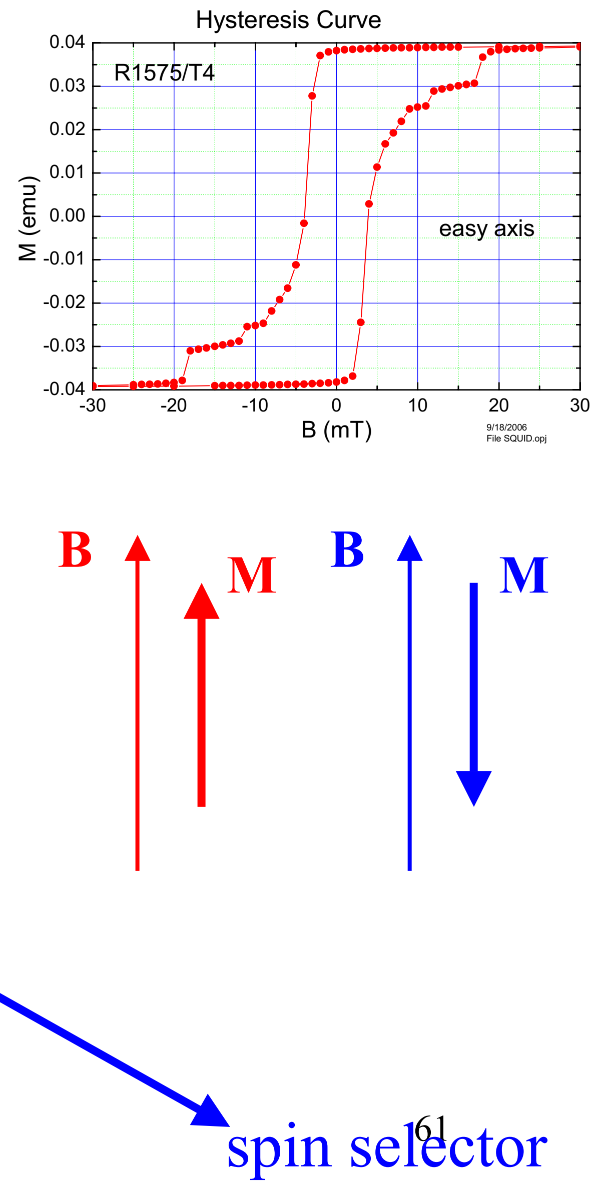
produced at PSI:



Remanent Supermirrors

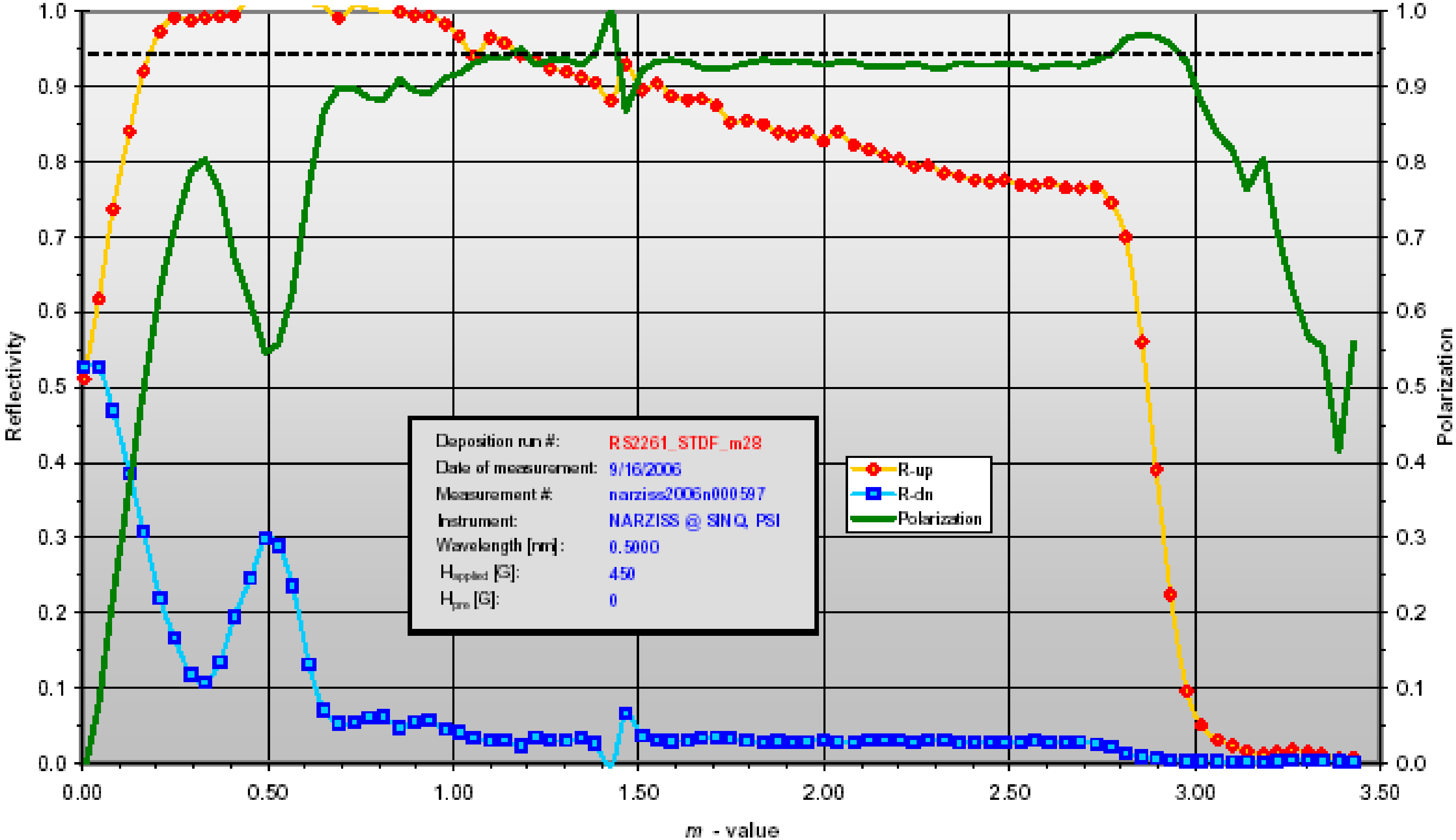
$$\breve{\mathbf{U}}_m = -\boldsymbol{\mu} \cdot \mathbf{B}$$





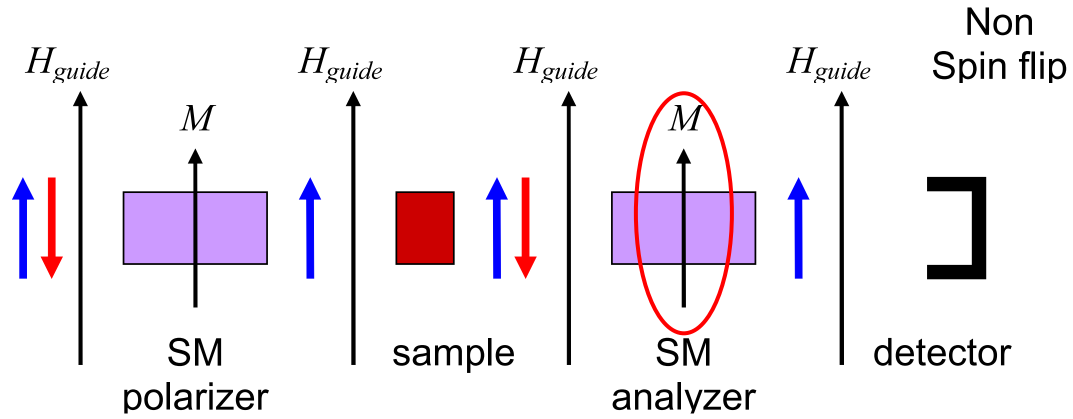
(measured by: K. Pappas, HMI)

Towards Large m

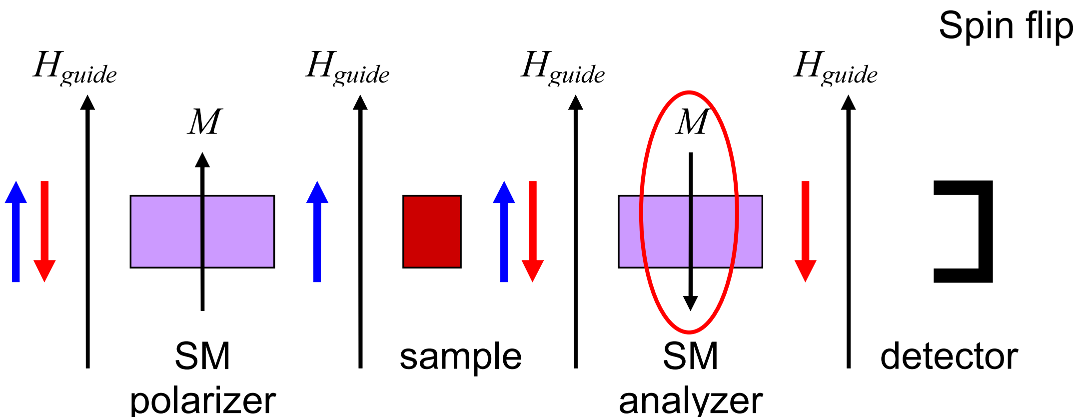


Spin Selection - Supermirror

Remanent polarizing supermirrors



⇓ short field pulse of 200 G



Advantages:

+ high polarization: > 95 %
+ white beam polarization
+ remanent polarizing supermirror

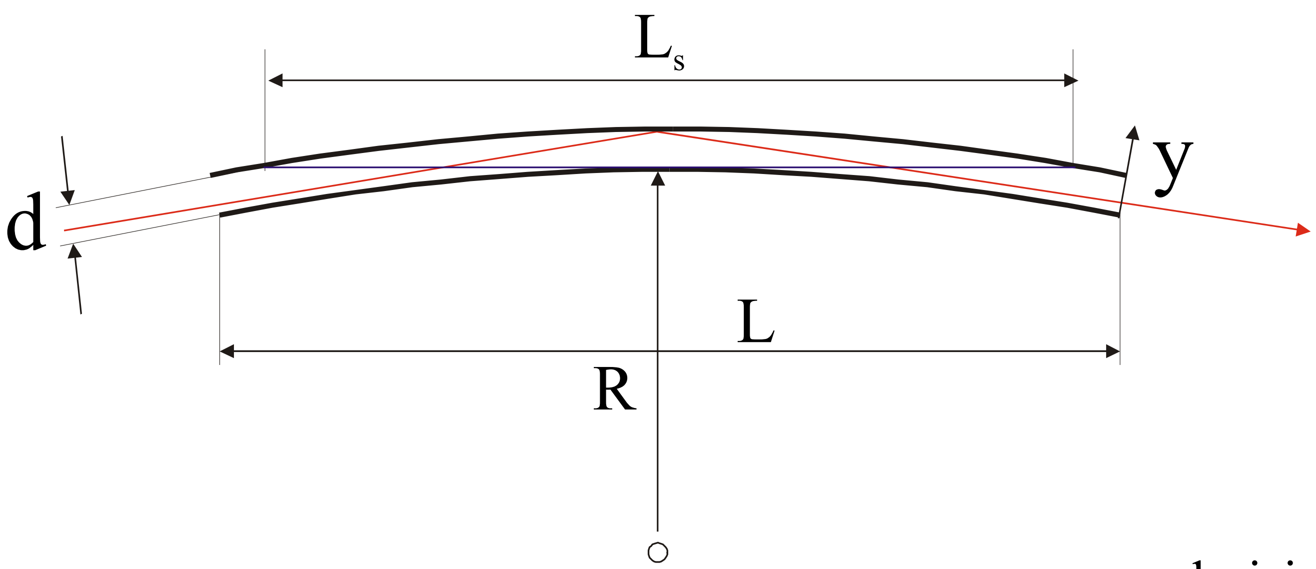
  ⇔ no spin flipper necessary
+ compact devices
+ polarizing neutron guide

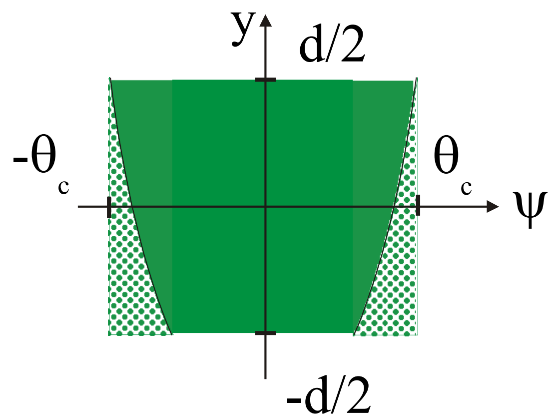
Disadvantages:

- diffuse scattering
- precise alignment necessary
- limited divergence
- cobalt!!

Polarizing Guide / Bender

Idea: each neutron is reflected at least once:



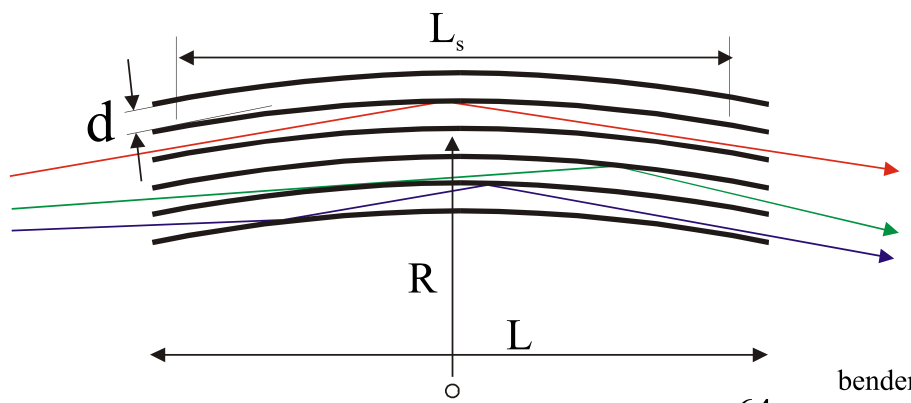


phase space diagram

useful equations: $c = 0.099^0/\text{Å}$

- critical angle: $\theta_c = mc\lambda$
- charact. wavelength: $\lambda^* = \frac{1}{mc}\sqrt{\frac{2d}{R}}$
- line of sight: $L_s = \sqrt{8dR}$

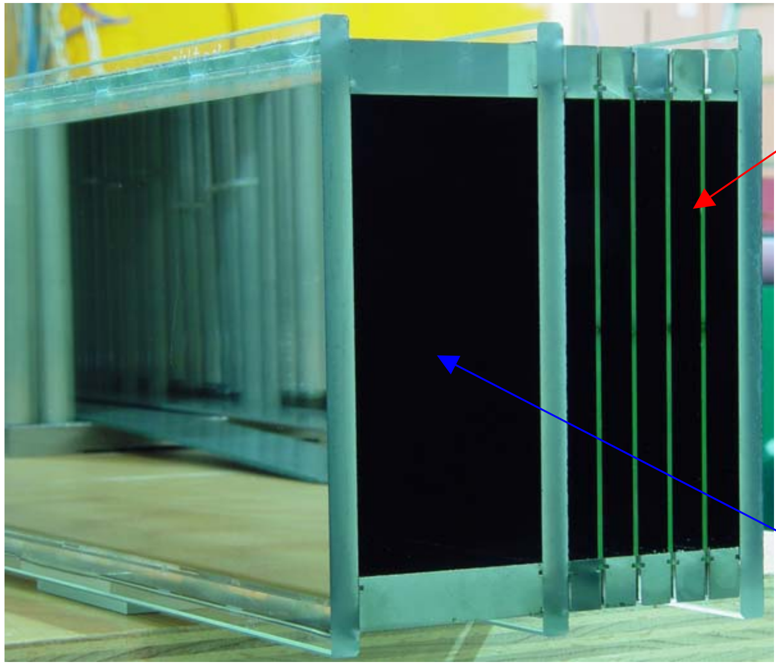
polarising bender: shorter device



bender

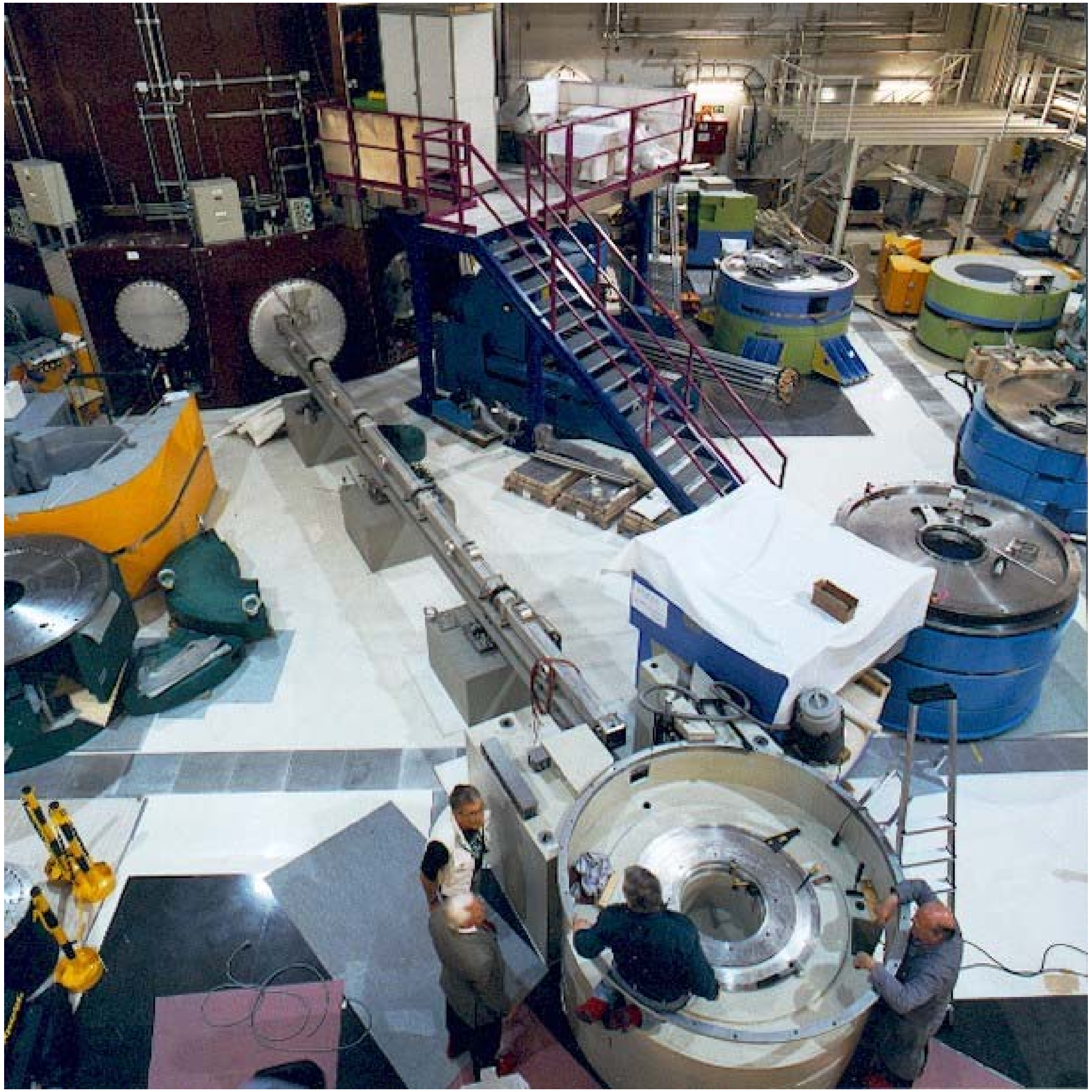
Implementation: TRISP @ FRM II

(T. Keller, B. Keimer @ MPI Stuttgart)



polarizing section:
- 5 channels 8 x 97 mm²
- length: 10m
- polarizing supermirrors
- m=2.5 (critical angle: 0.25°/Å)

non-polarizing section:
- non polarizing supermirrors
- m=2.5



• Loss: typically factor of two due to polarization
→ most powerful thermal beam at FRM-II

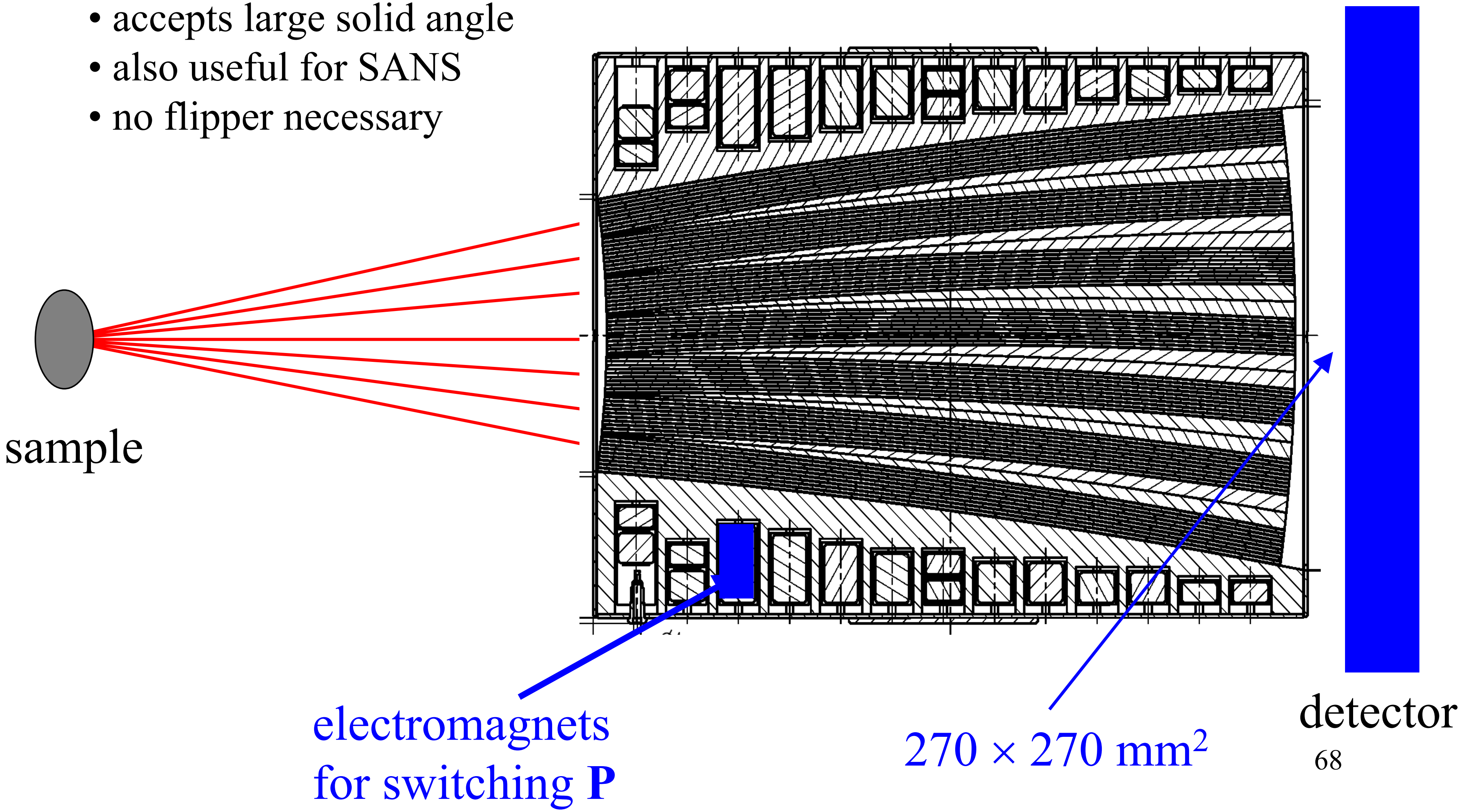
Polarizing Guide: iNSE (JAEA)

(M. Nagao)

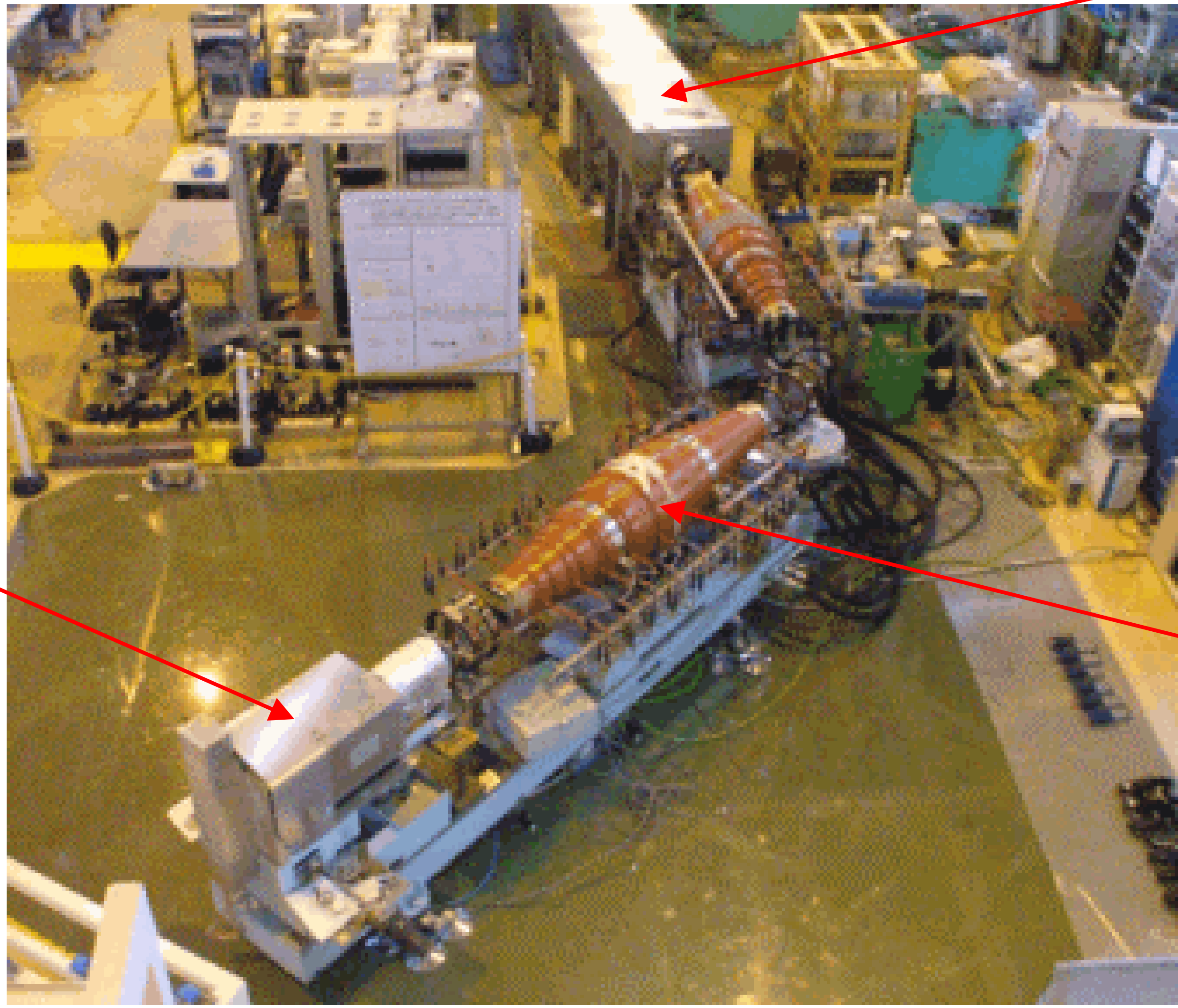
$P = 93\%$

Focusing Spin Selector: iNSE (JAEA)

- accepts large solid angle
- also useful for SANS
- no flipper necessary

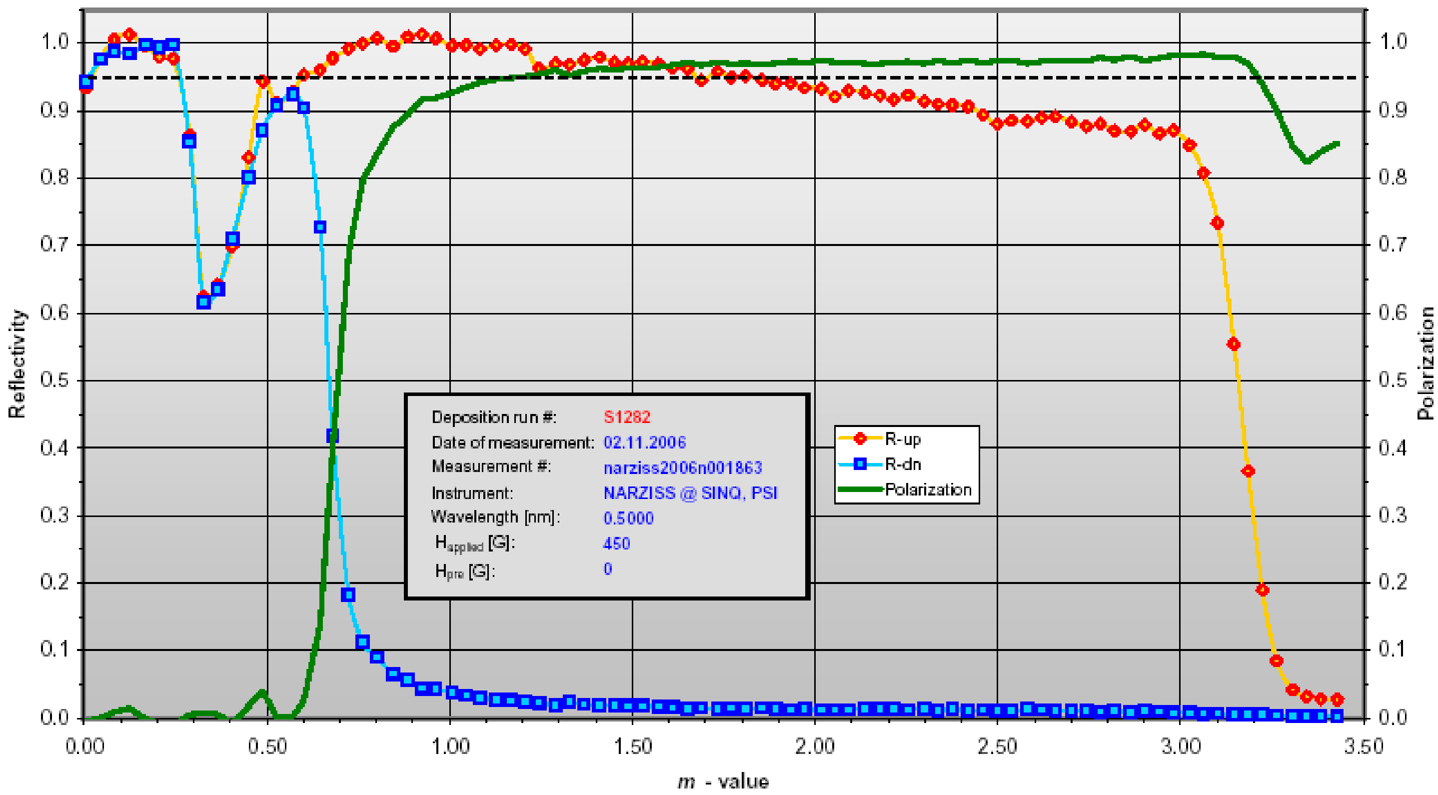


Neutron Spectrometer iNSE (JAEA)



Small Activation → Supermirror Fe/Si

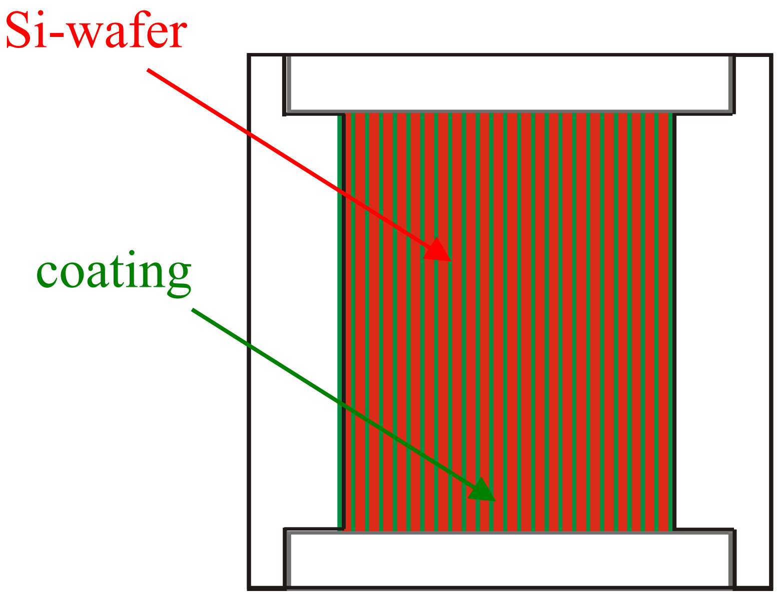
$$G_{-} = G_{nm} > 0$$

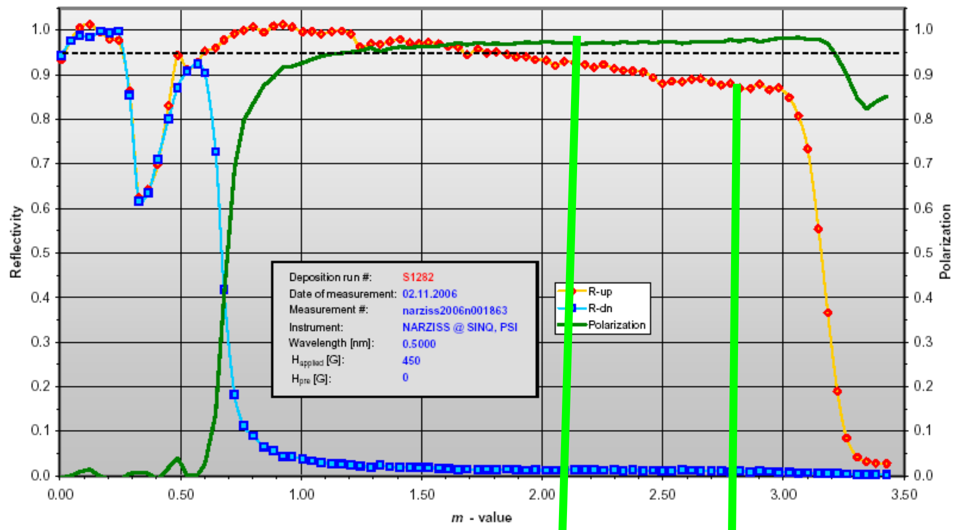


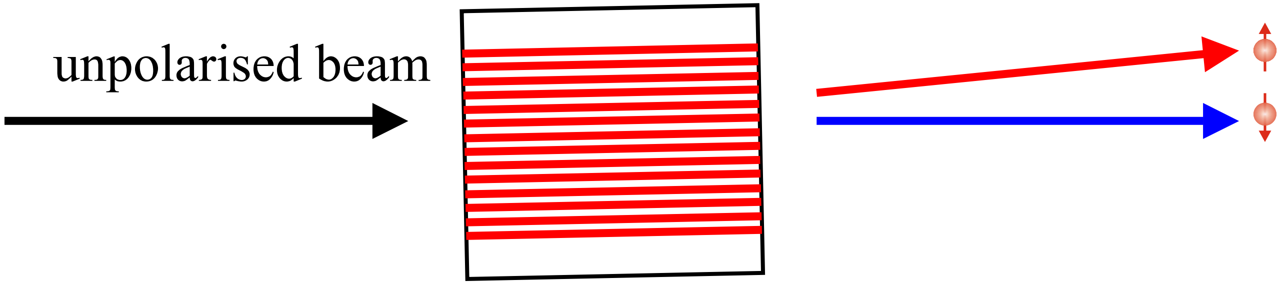
- high reflectivity
- high polarization
- no Co → no activation

Transmission Polarizer: $G_- = G_{nm} > 0$

stacked Si-wafers coated with polarizing supermirror





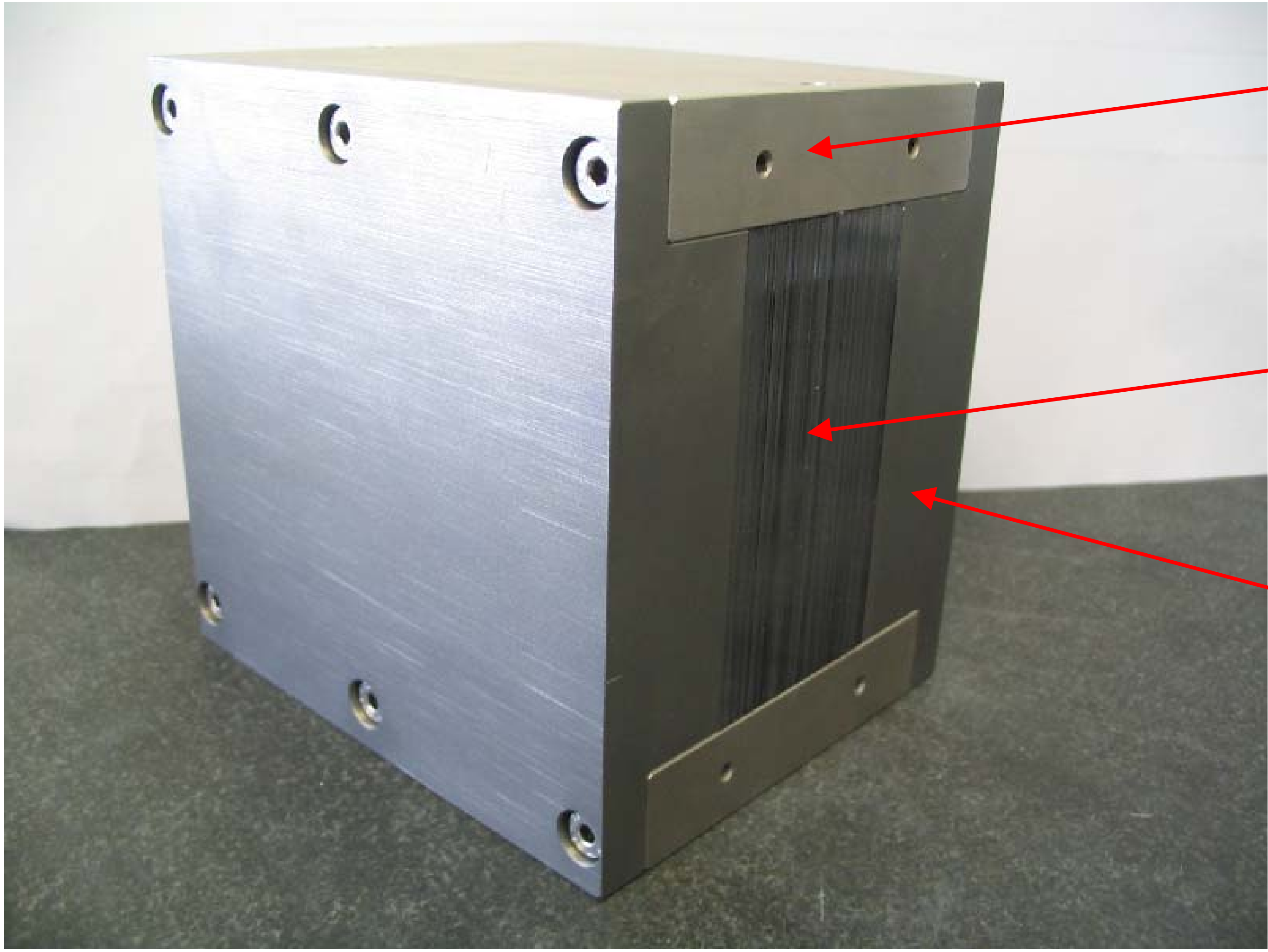


- spin up: **P** given by polarization of supermirror

- spin down: **P** given by reflectivity of reflection curve

watch out: neutrons are absorbed while transmitting the stack of Si-wafers

Polarizer for NSE @ SNS



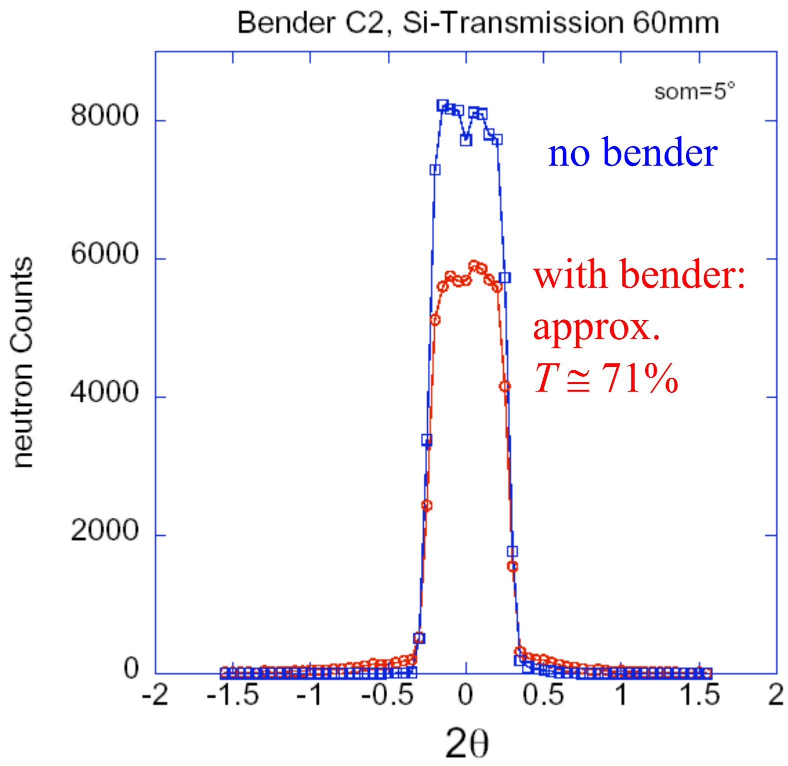
soft iron

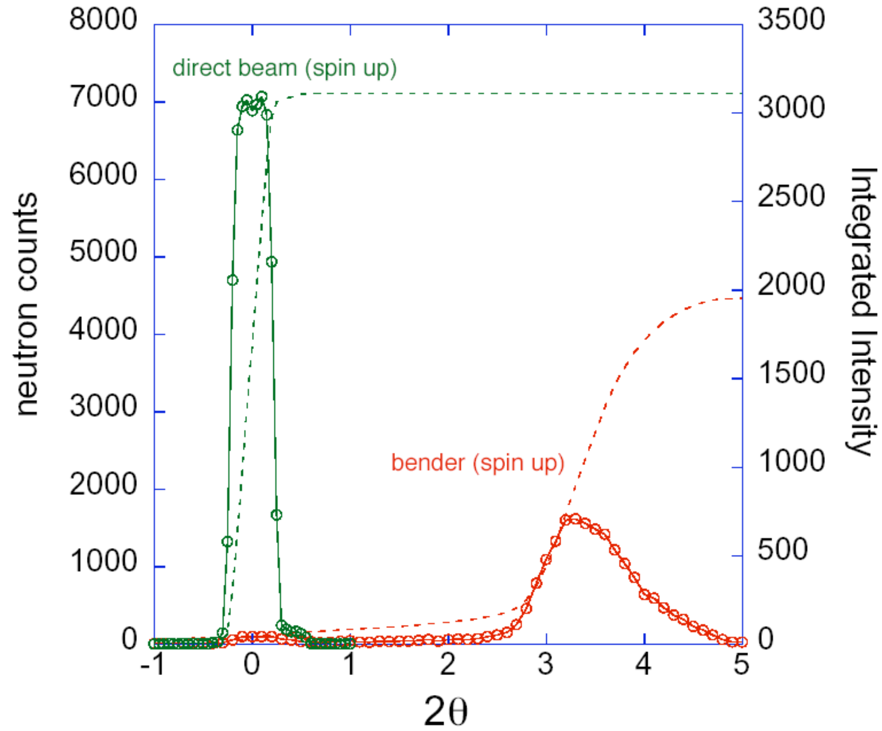
Si-wafers

Sides:
- made of Ti
- including magnets

Transmission/Reflection of Bender

$\lambda = 4.7$ Å

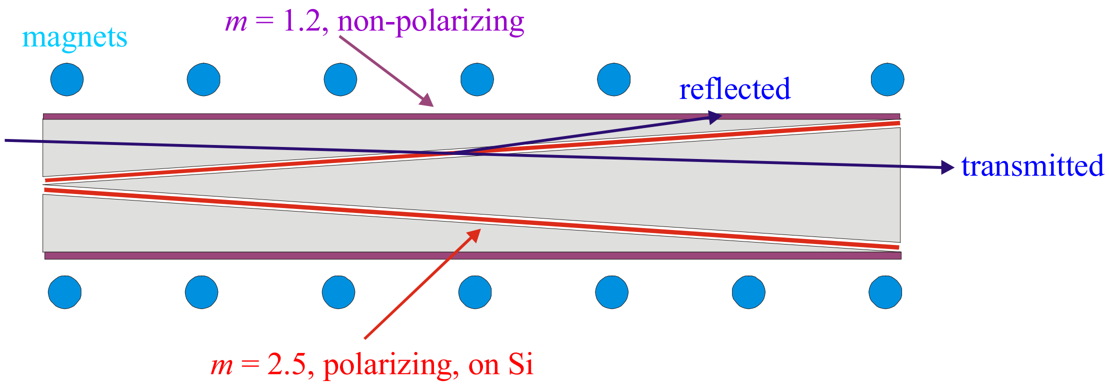


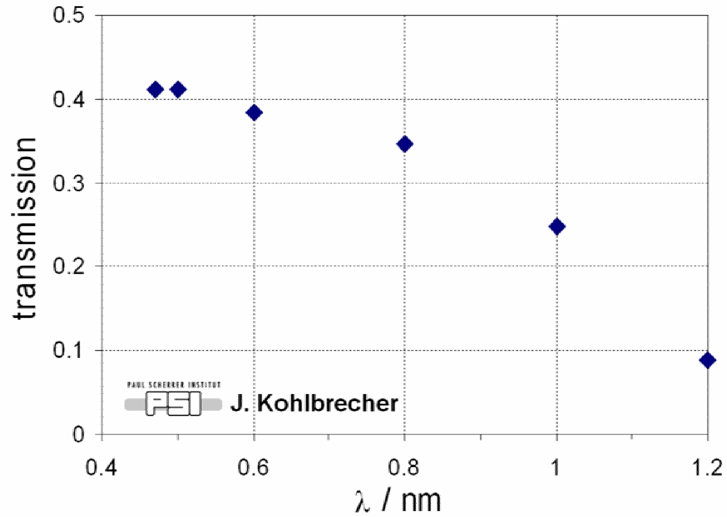


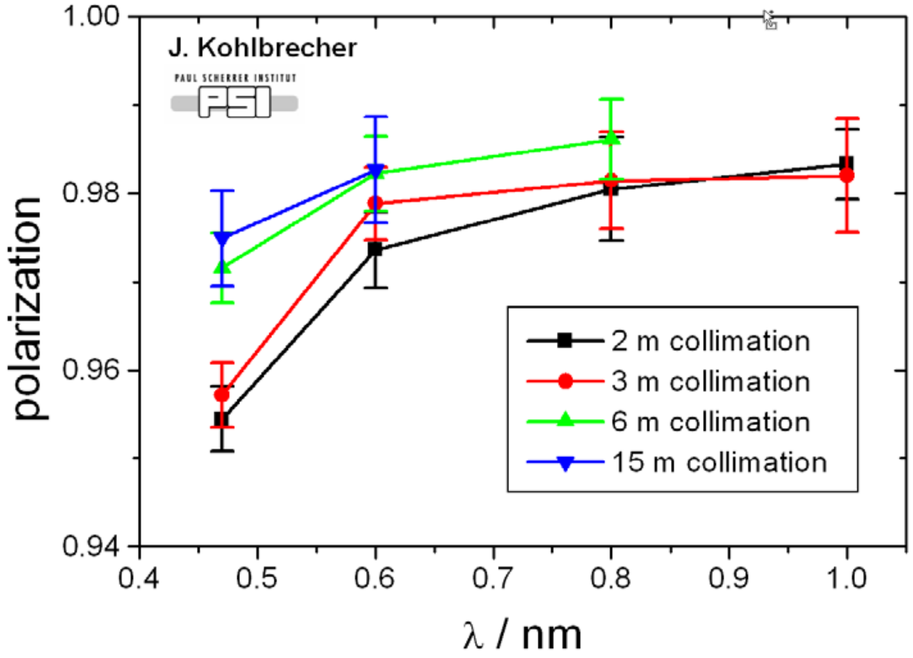
- transmitted beam: small divergence
- reflected beam broadened
- excellent: polarization

Neutron Beam Polarization: Cavity

(Idea: F. Mezei, HMI)







o instrument SANS-I @ PSI

o cavity transmission polarizer

+ high polarization

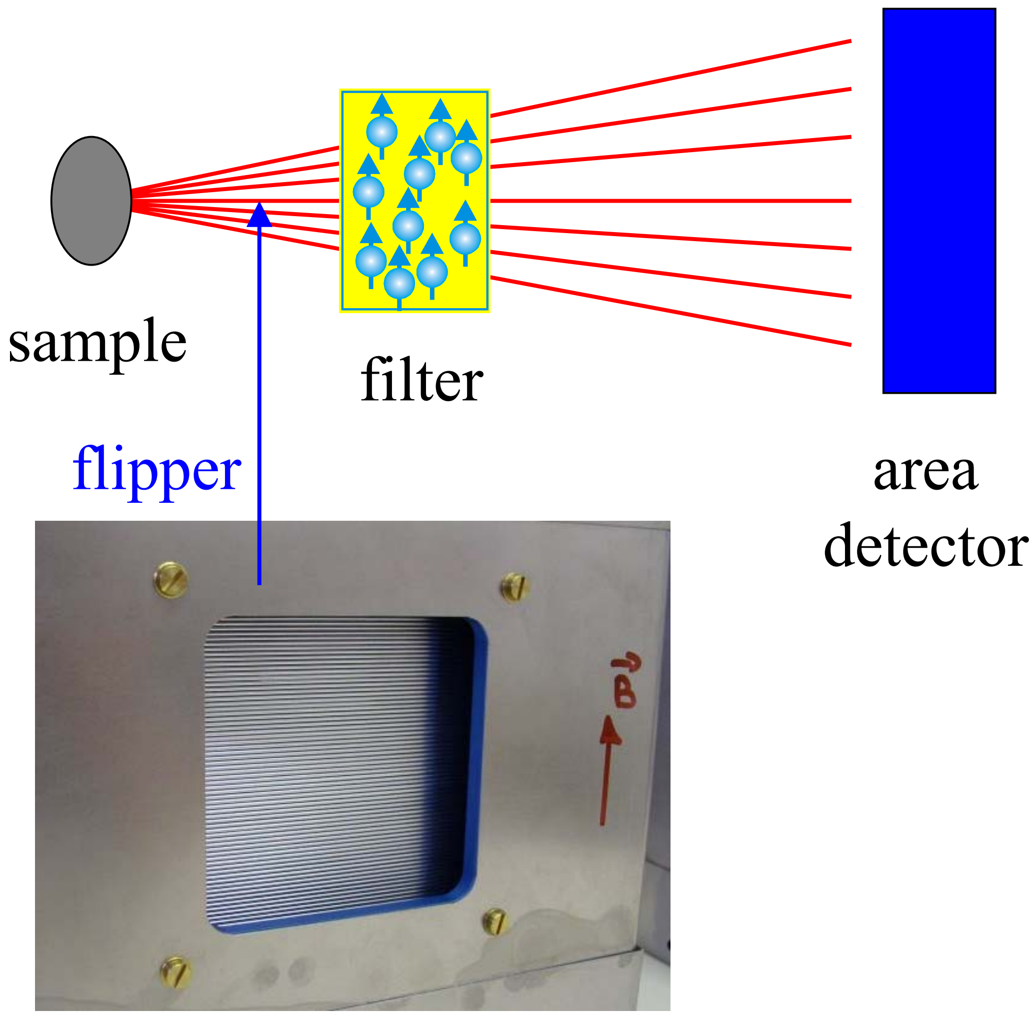
+ high transmission

+ no deflection of neutron beam

- limited wavelength band

7. Spin Filters: Protons, ^3He

Properties of Spin Filter



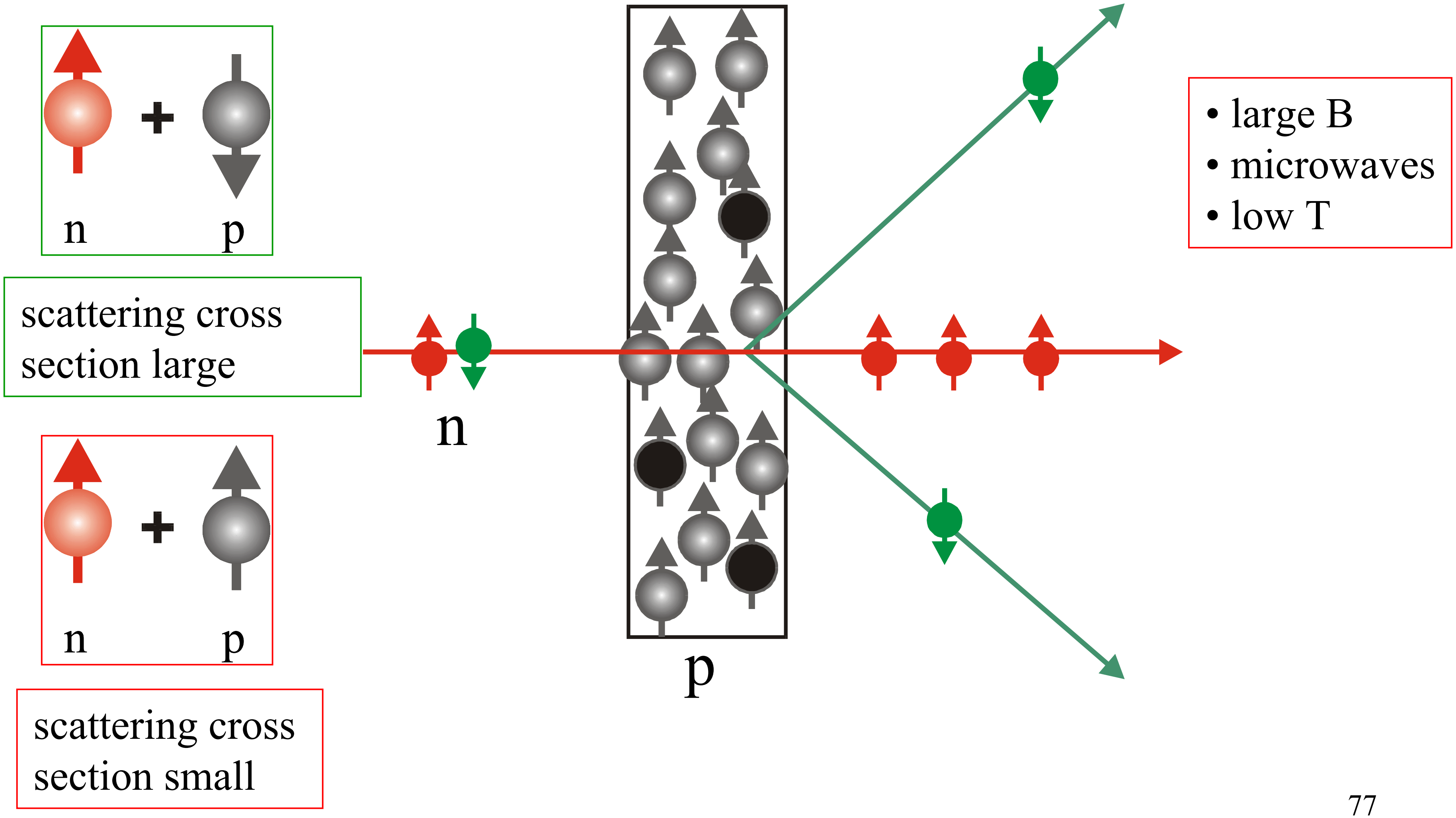
properties of filter:

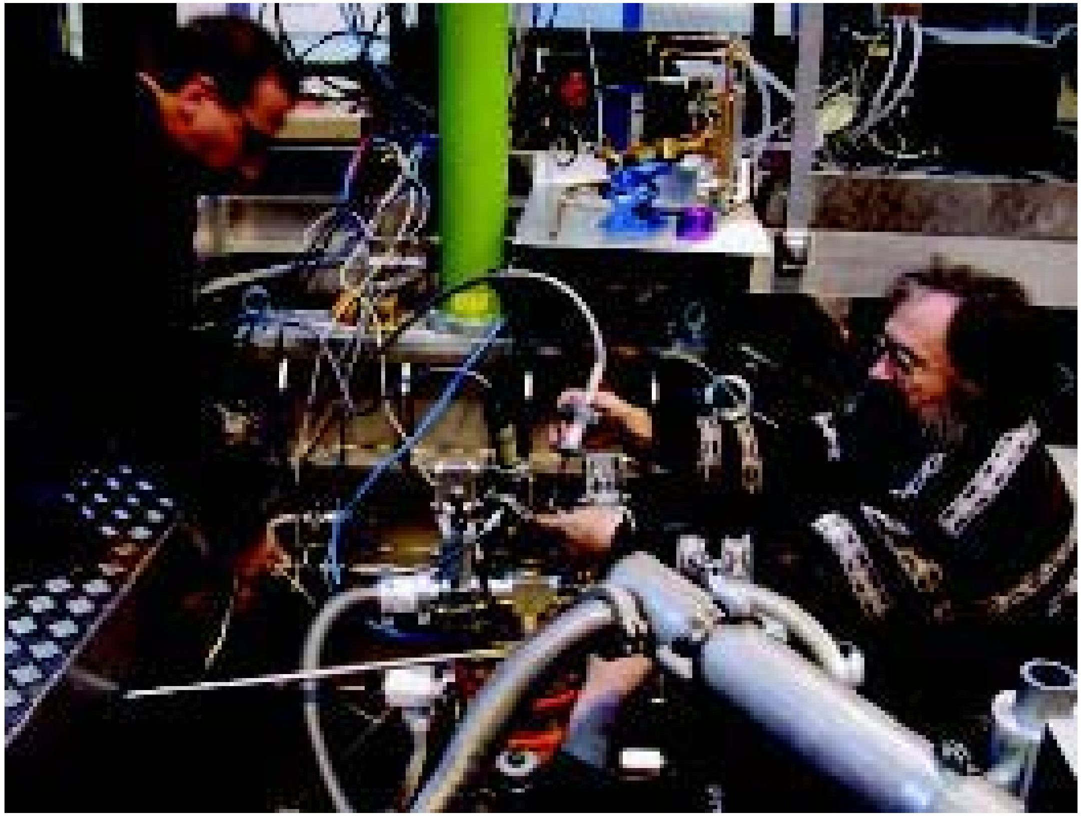
- high transmission for one spin state
- zero transmission for other spin state
- does not change phase space of neutrons

Polarized Proton Target

(Van den Brandt, Hautle, Konter: PSI)

• **scattering** is strongly spin dependent

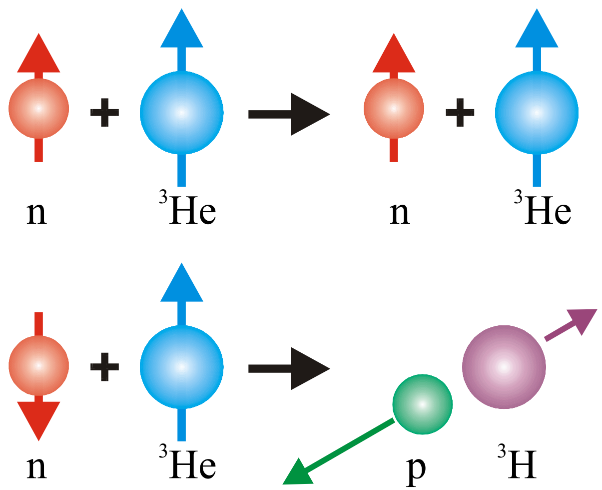




+ homogeneous: area detectors
+ no change of phase space
+ "*E*-independent": ideal for TOF
- complicated technique

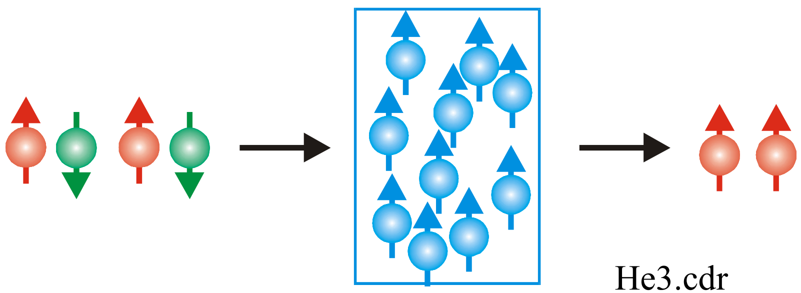
^{3}He-Polarizers

- **absorption** is strongly spin dependent



$\sigma \cong 0$ (5 barns)

σ large (5925 barns Å/λ)



He3.cdr

+ homogeneous: area detectors
+ no change of phase space
+ "*E*-independent": TOF
- complicated technique

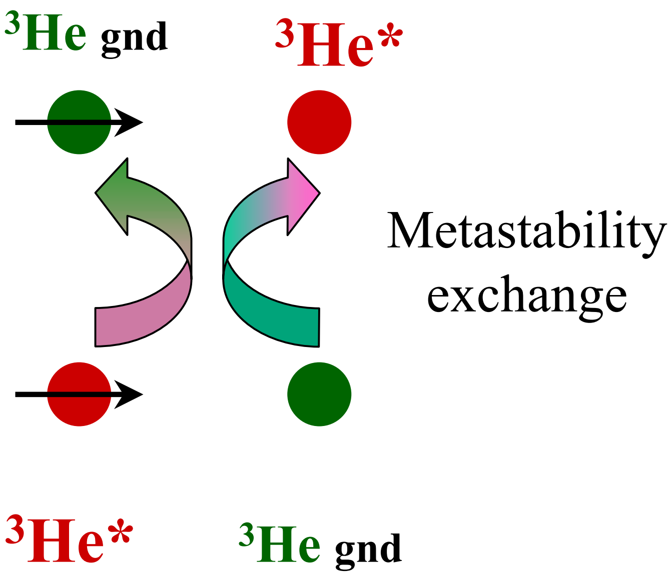
Production of Polarized ^{3}He

Metastability Exchange Optical Pumping

Nuclear polarization of ^{3}He*

↓

Nuclear polarization of ^{3}He (gnd)

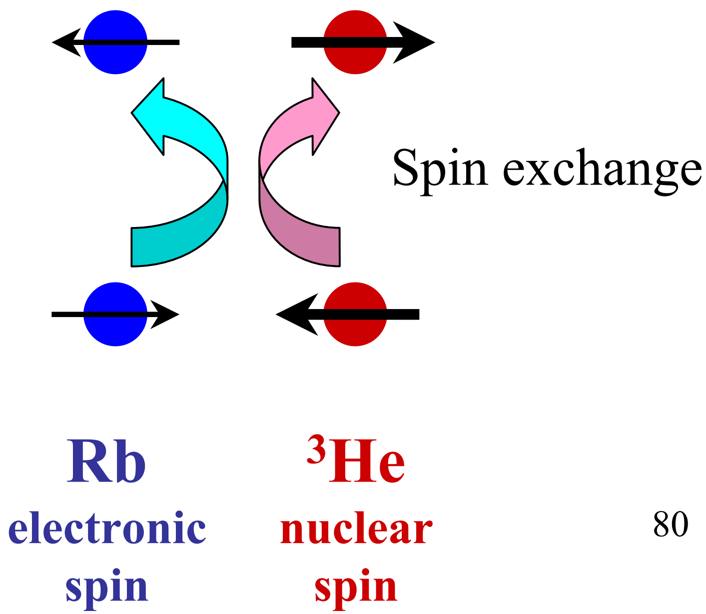


Spin Exchange Optical Pumping

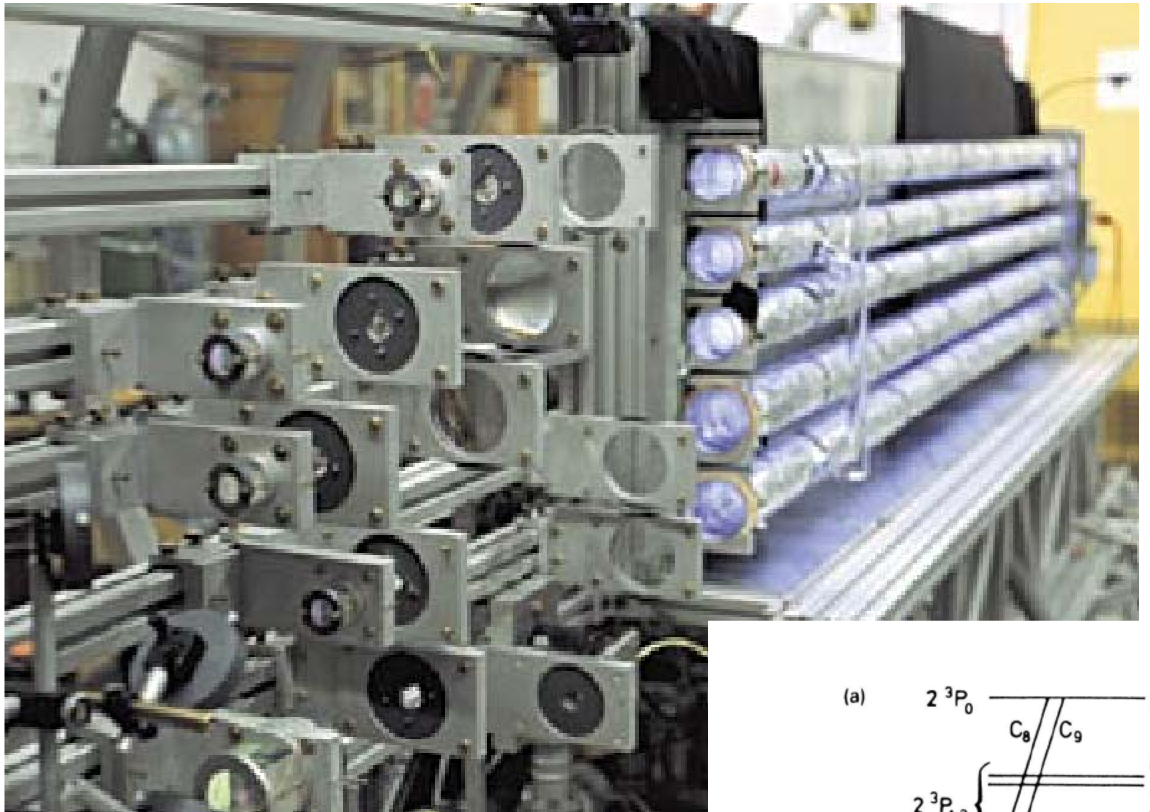
Electronic polarization of **Rb**

↓

Nuclear polarization of ^{3}He



^{3}He-Polarizers: MEOP



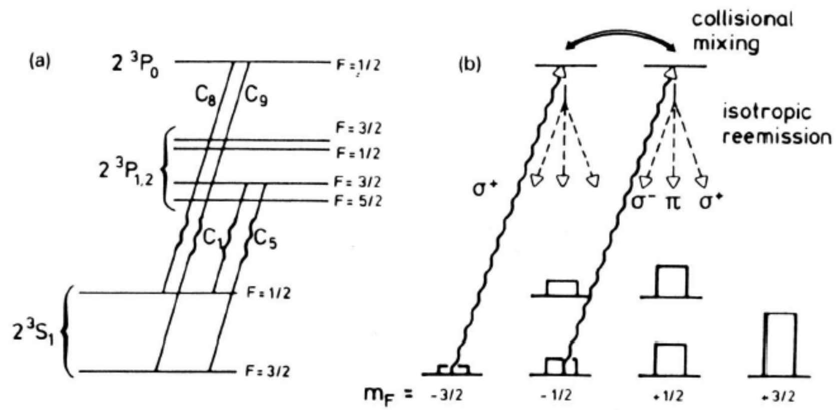
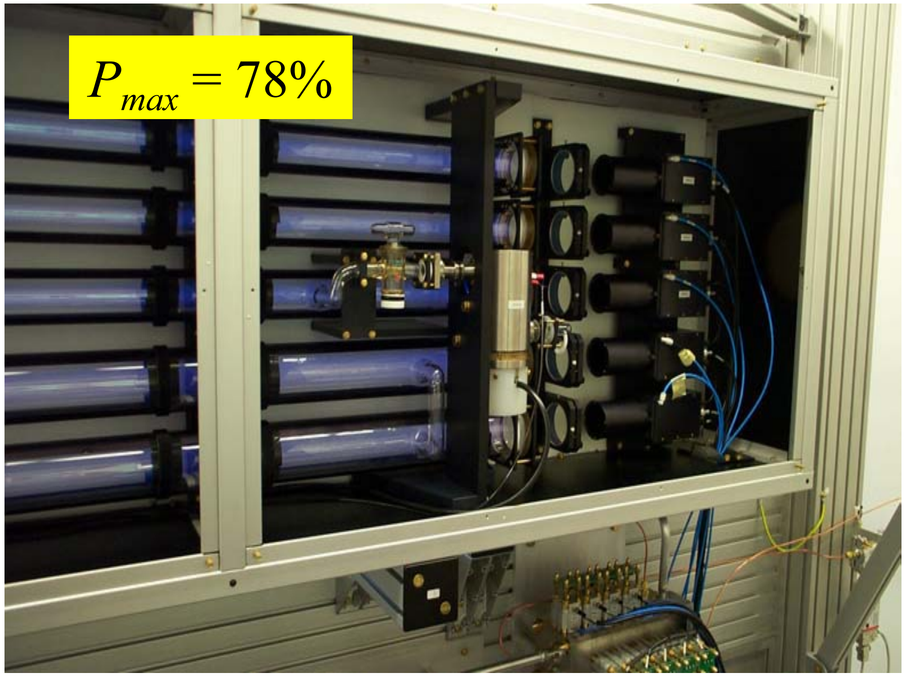


Abbildung 2: Der metastabile Zustand von ^{3}He ($1s2s^3S_1, F = \frac{1}{2}$), bzw. ($1s2s^3S_1, F = \frac{3}{2}$) wird über die C_8- oder C_9-Linie auf den Zustand ($1s1p^3P_0$, $F = \frac{1}{2}$) gehoben und polarisiert. Die Absorption von rechtszirkular-polarisierten Photonen führt letztlich zu einer Zunahme der magnetischen Sublevel mit hoher magnetischer Quantenzahl. [2]

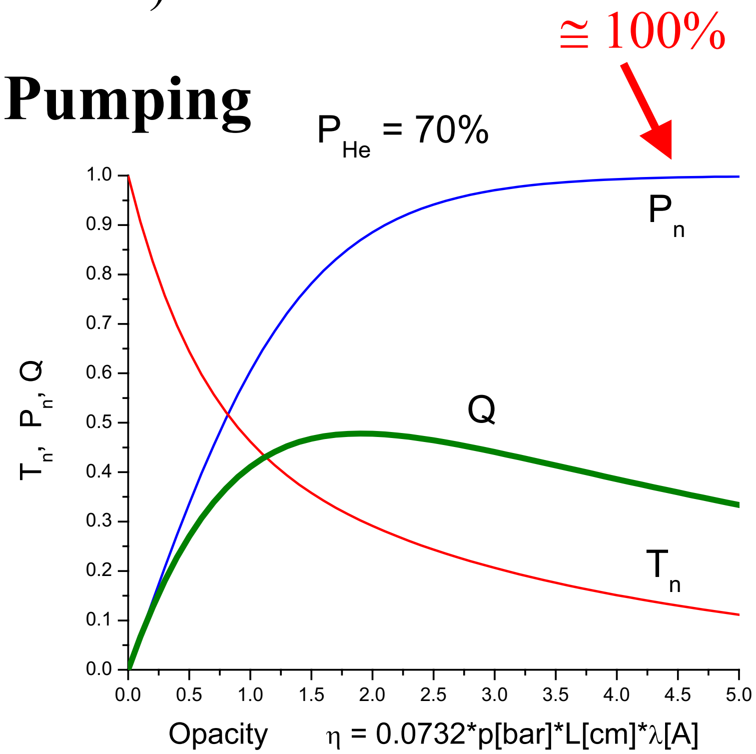
Production of Polarized ^{3}He: MEOP

(Mainz, ILL, HMI, FRM II)

Metastability Exchange Optical Pumping



from: S. Masalovich, FRM II, TUM



quality factor: $Q = P \cdot \sqrt{T}$

$$P_n = \tanh(\eta P_{He}) \qquad T_n = e^{-\eta} \cdot \cosh(\eta P_{He})$$

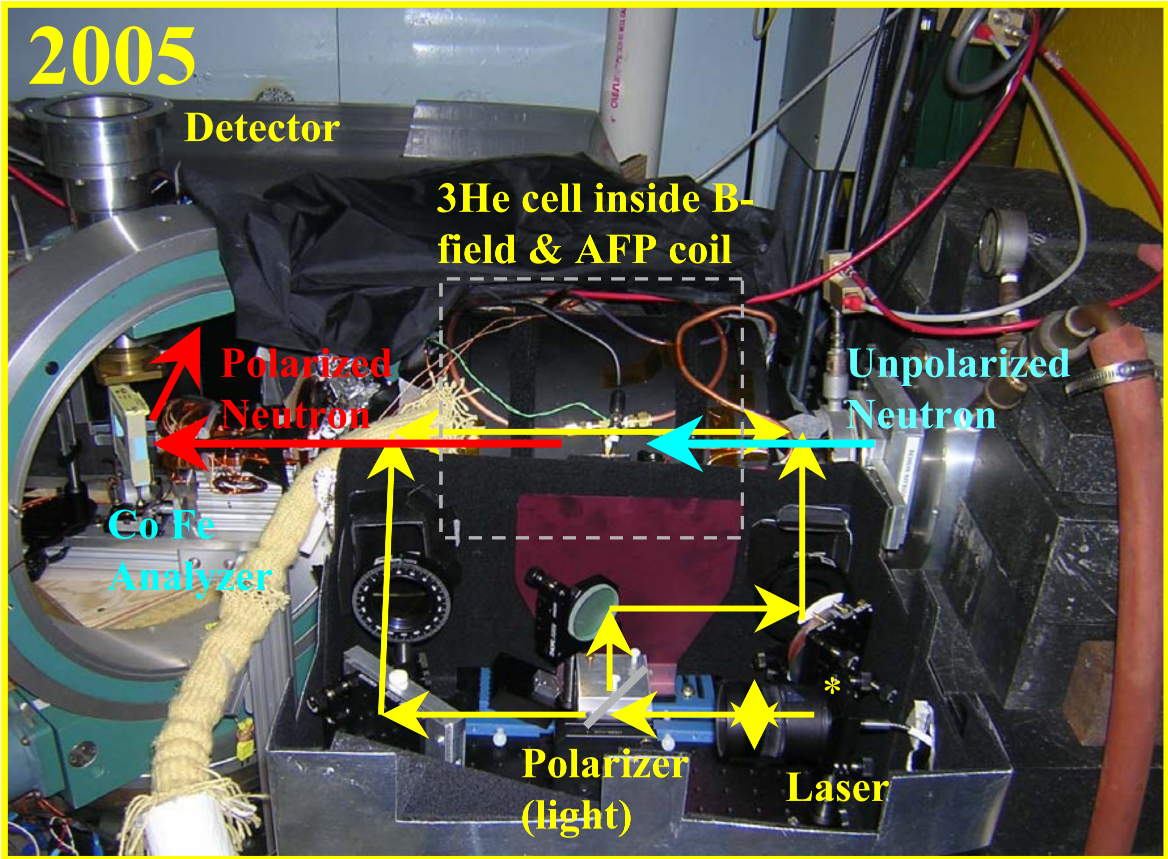
opacity: $\eta = 0.0732 \cdot pL\lambda$

- not continuous: filters have to be exchanged
- compression necessary

Production of Polarized ^3He: SEOP

(NIST, Jülich, Argonne, Oak Ridge)

Spin Exchange Optical Pumping: Experiment in March 06 at IPNS



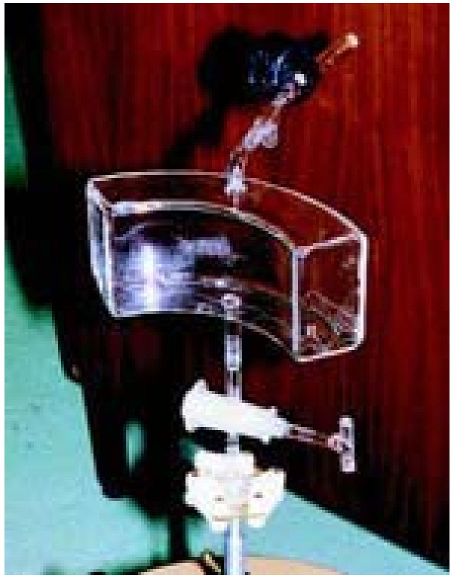
V.O. Garlea, G.L. Jones, B. Collett, W.C. Chen, T.R. Gentile, P.M.B. Piccoli, M.E. Miller, A.J. Schultz, H.Y. Yan, X. Tong, M. Snow, B.C. Sales, S.E. Nagler, W.T. Lee, C. Hoffmann

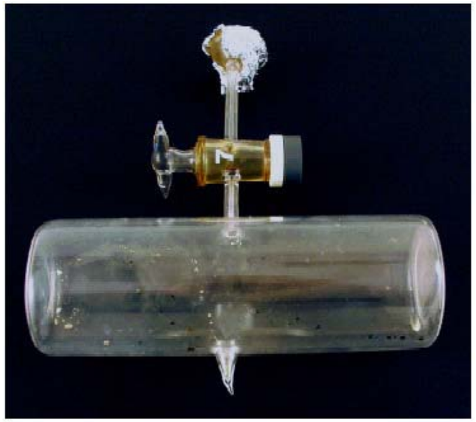
^{3}He polarization: 60%

In 2007: 70%

- continuous
- high pressure

^{3}He-Polarizers: Discussion





Quartz / single crystal silicon cells coated with cesium

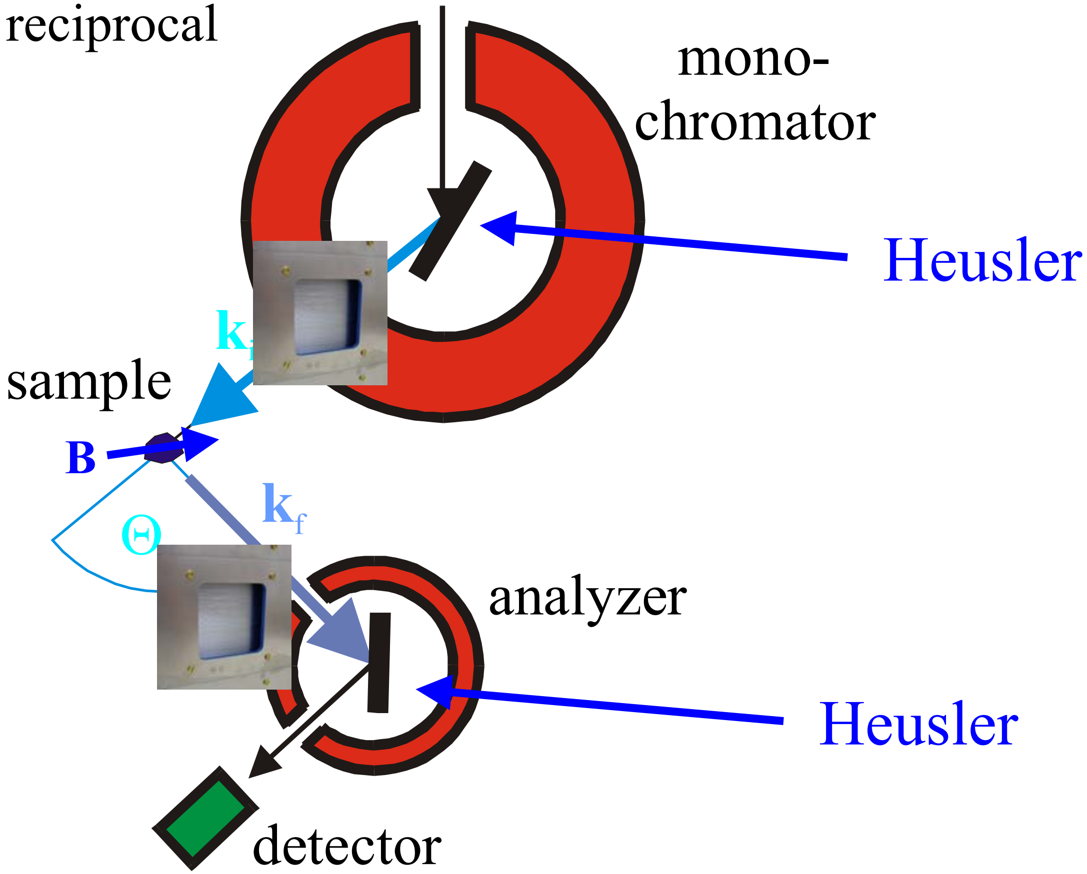
+ white beam polarizaton
+ good efficiency for $\lambda < 1$ Å
+ wide angle analysis
  - off specular reflectometry
  - SANS
+ transmission geometry ⇔ straight beam path
+ no precise alignment necessary
+ decoupling of divergence and polarization
+ calibration of polarization

- decay of efficiency with time (MEOP)
- neutron beam absorption
- complicated (manpower, etc.)

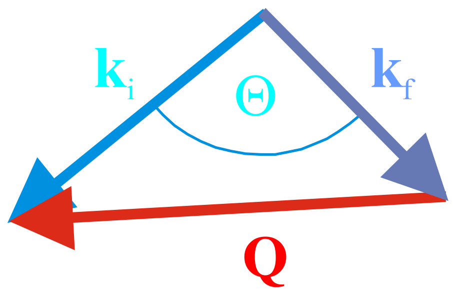
8. Instruments

Polarized Triple-Axis Spectrometer

- **controlled** access to predetermined points in reciprocal space

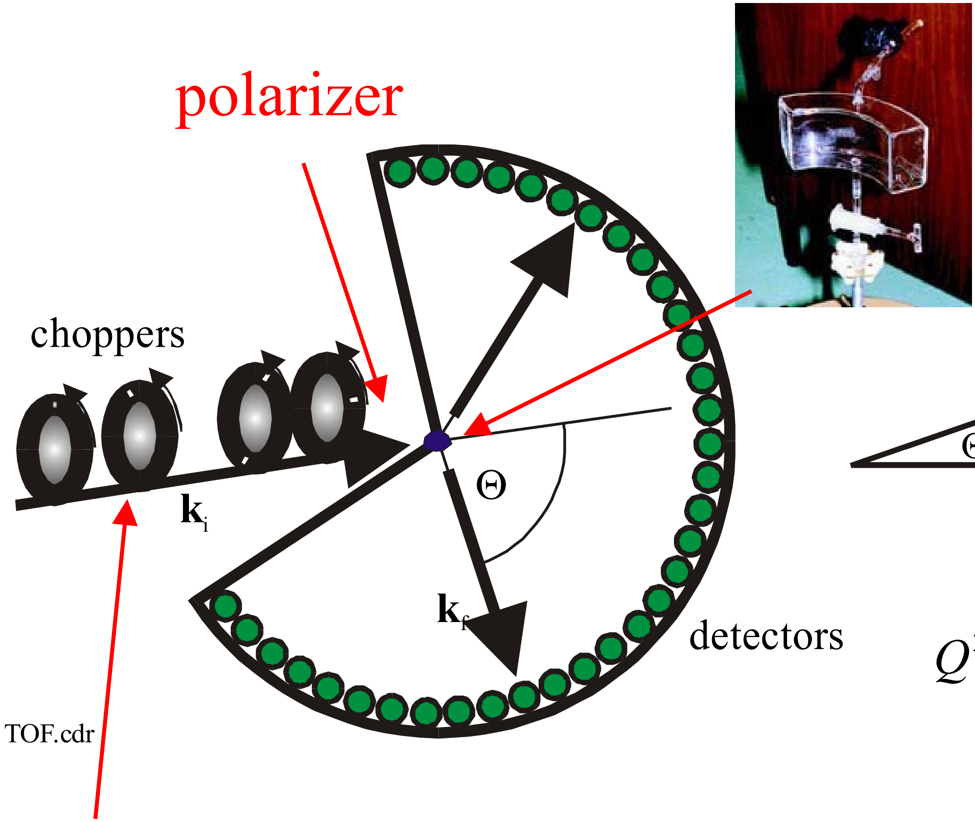


Scattering triangle:

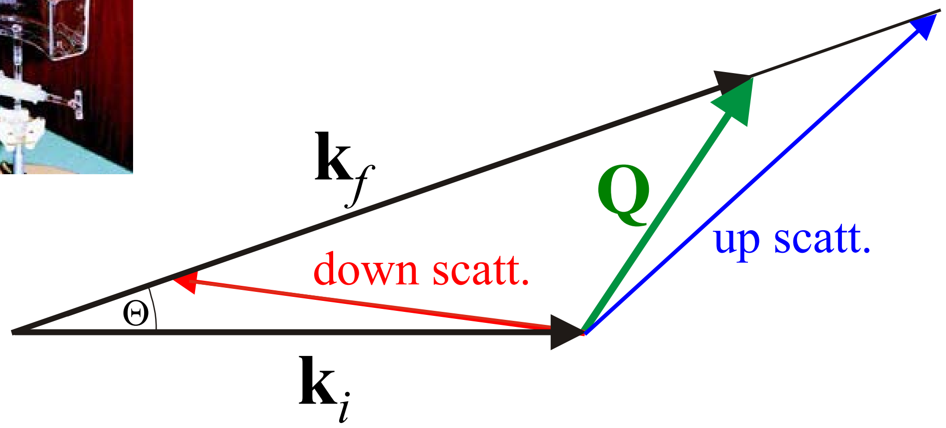


Combine monochromatization with polarization.

Polarized ToF-Spectrometer



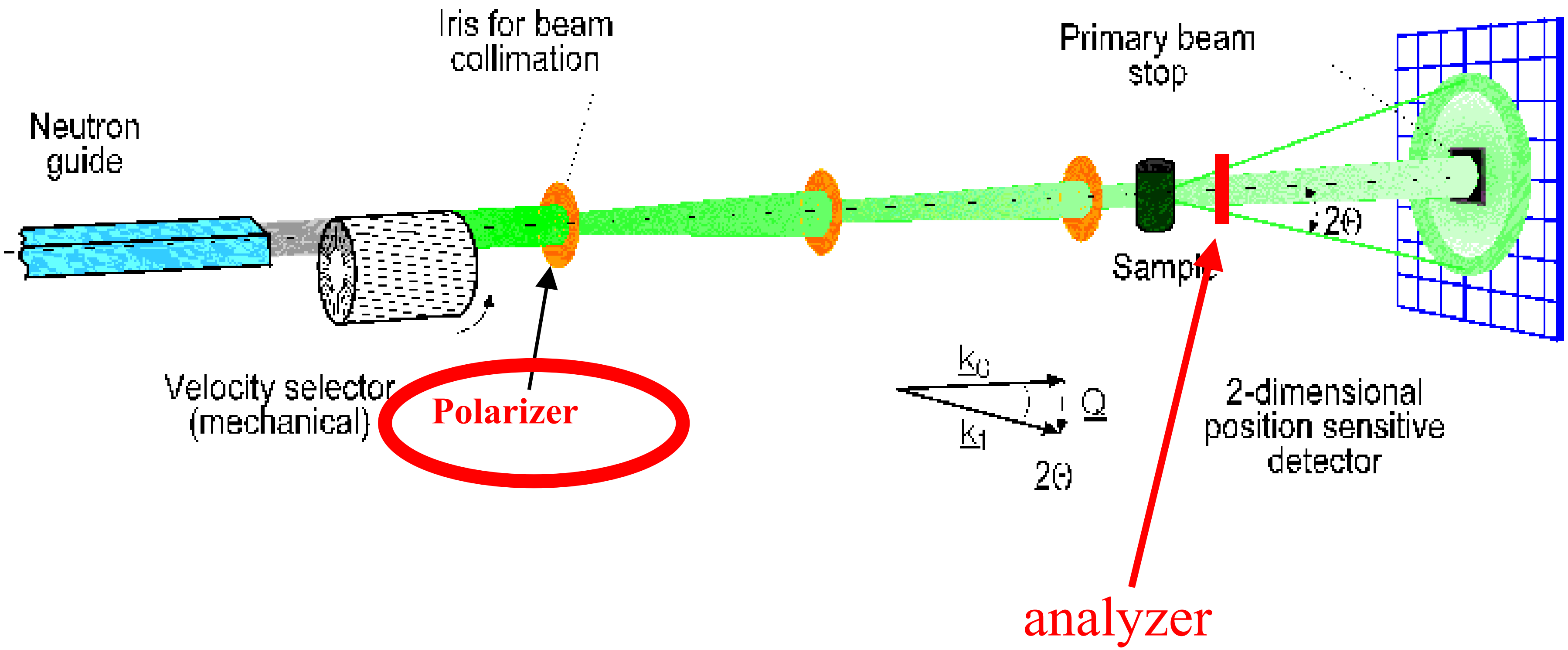
incident beam is polarized: guide, cavity



$$Q^2 = \frac{2m}{\hbar^2}\left(2E_i - \hbar\omega - 2\sqrt{E_i(E_i - \hbar\omega)}\cos\Theta\right)$$

Analyzer for white beam, high energy, large area.

Polarized SANS Diffractometer



Area detector necessary → analyzer should not disturb phase space
→ ^{3}He-polarizer is well suited

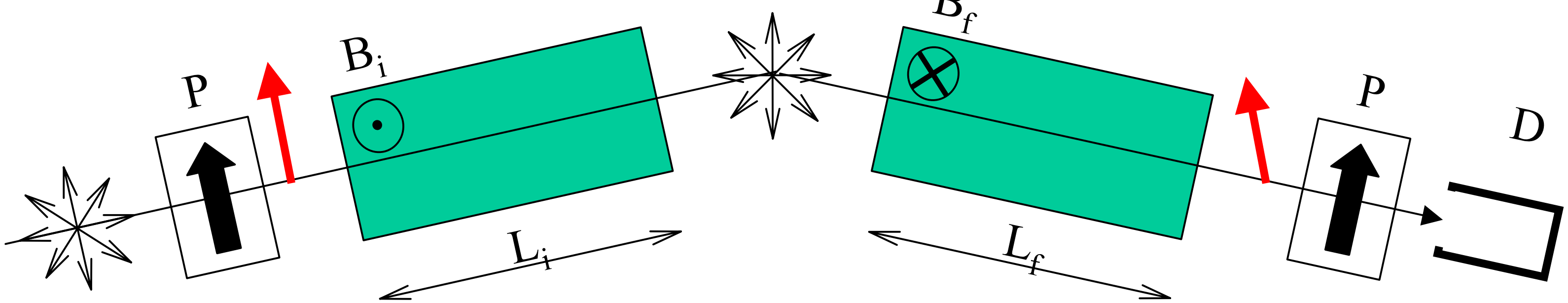
Neutron Spin Echo

Goal: improve the *E*-resolution of a spectrometer:

• Triple axis spectrometer: insert collimations, decrease neutron energy
→ decrease of intensity, dynamic range restricted

• ToF spectrometer: shorten the neutron pulses → decrease in intensity

• Idea: use spin degree of freedom of neutron as a clock



$$\varphi_i = \omega_L t_i = \gamma B_i \frac{L_i}{v}$$

$$\varphi_f = \omega_L t_f = -\gamma B_f \frac{L_f}{v}$$

$$\varphi_{ges}(v) = 0 \quad \text{if} \quad B_i L_i = B_f L_f$$

Energy resolution decoupled from momentum resolution

Neutron Spin Echo – Neutron Resonance SE

sample exchanges energy with sample:

• quasielastic scattering (diffusion)

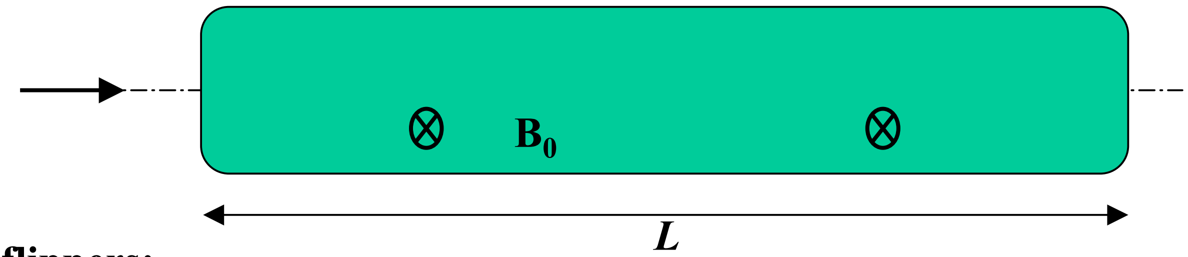
• inelastic scattering: phonons, spin waves

→ $\varphi_{ges}(v) \neq 0$

→ degree of polarization is a measure of energy transfer to neutron

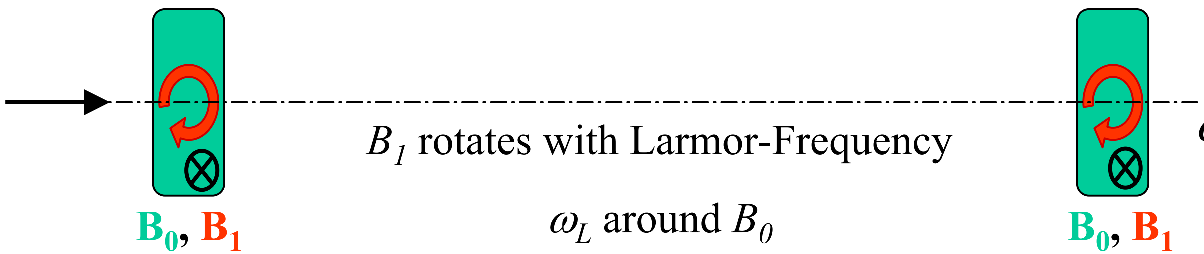
Technical realisation: Resonance spin flippers

Static precession field:



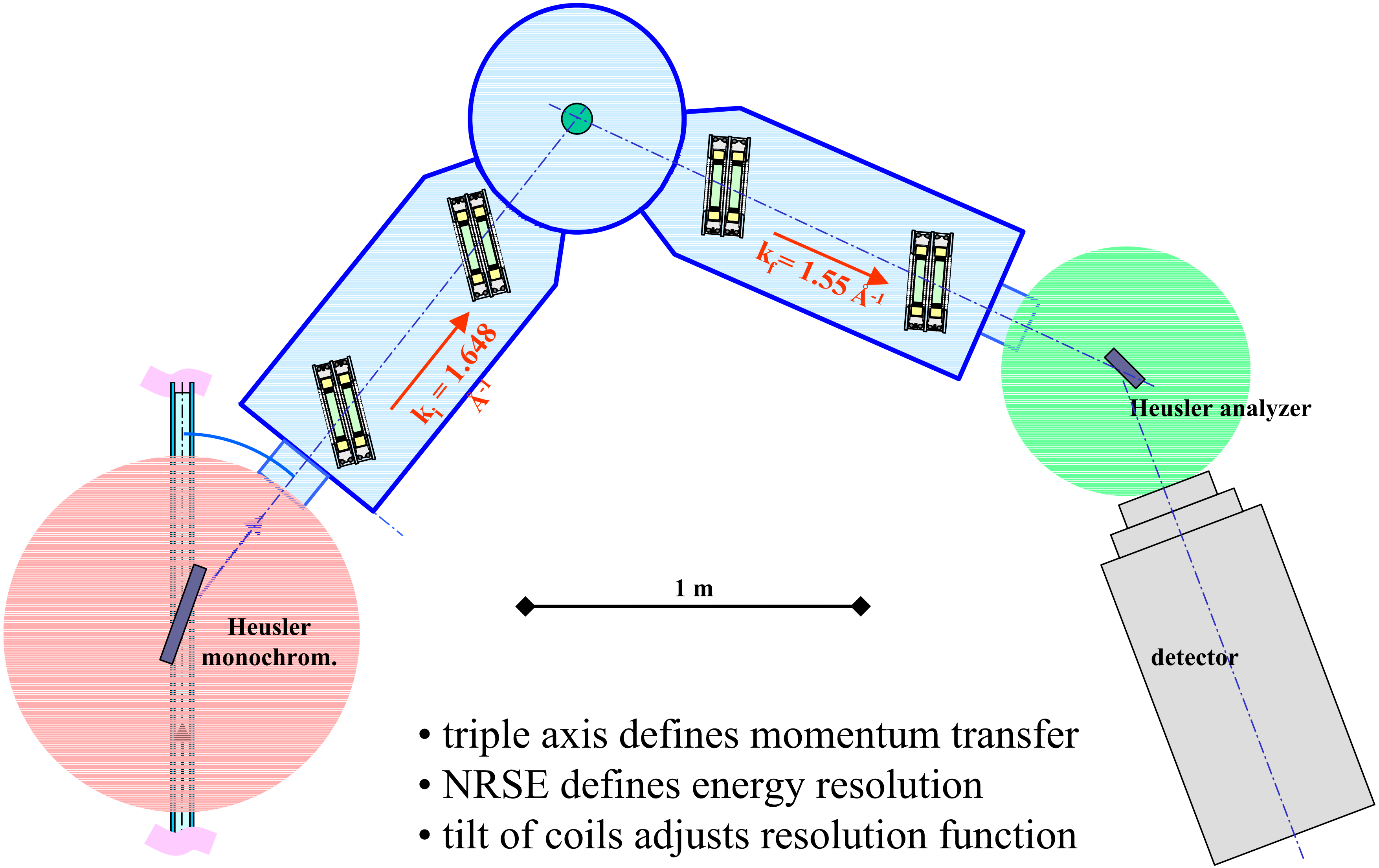
$\varphi = \omega_L \cdot t = \gamma \cdot B_0 L/v$

RF – flippers:



$\varphi = -2\ \omega_L \cdot t = -2\ \gamma \cdot B_0 L/v$

Technical Realisation: NSE + TAS



• triple axis defines momentum transfer
• NRSE defines energy resolution
• tilt of coils adjusts resolution function to dispersion

Technical Realisation: NSE + TAS

Spectrometer
TRISP @ FRM II
Keimer, MPI
Stuttgart

9. Applications for Polarized Neutrons

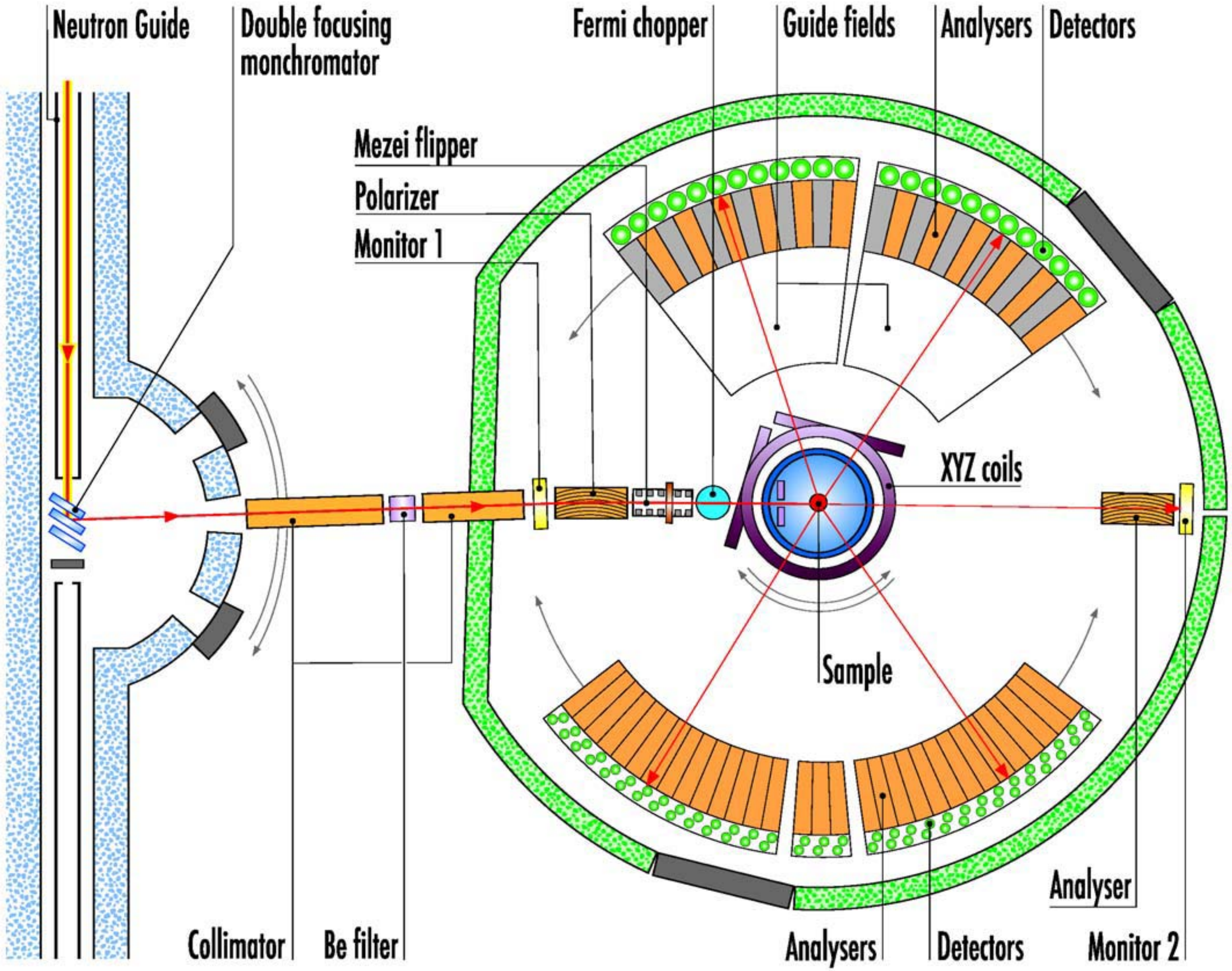
Example 1: Deuterium in Nb

- investigation of the interstitial diffusion process
- interesting for superionic conductors (like AgI)
- deuterium: σ_{coh}= 5.6 barns, σ_{inc}= 2.0 barns

- 1st approach: theoretical separation, high quality data necessary
- 2nd approach: polarization analysis

→ spectrometer: D7 at Institute Laue-Langevin, E_i = 3.52 meV
(TOF at a continuous source!)

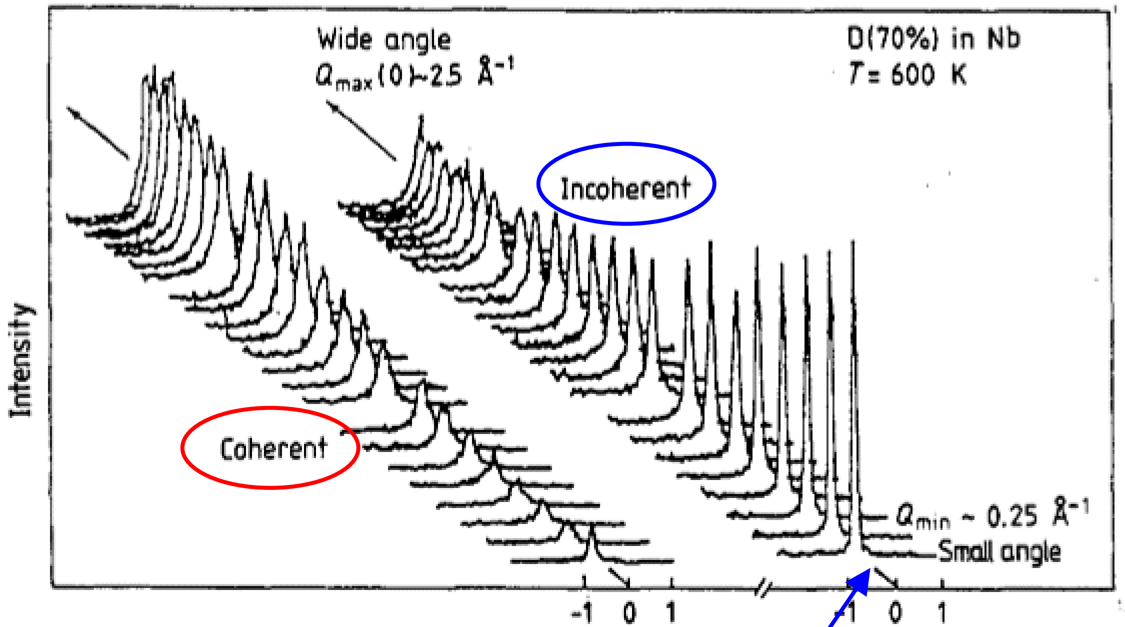
D7: From Yellow Book @ ILL



Deuterium in Nb

$$I_{NSI}^{nsf} = \tfrac{1}{3}\sigma_{NSI} \qquad I_{NSI}^{sf} = \tfrac{2}{3}\sigma_{NSI}$$

J. C. Cook et al., J. Phys. Condens. Matter **2**, 79 (1990).



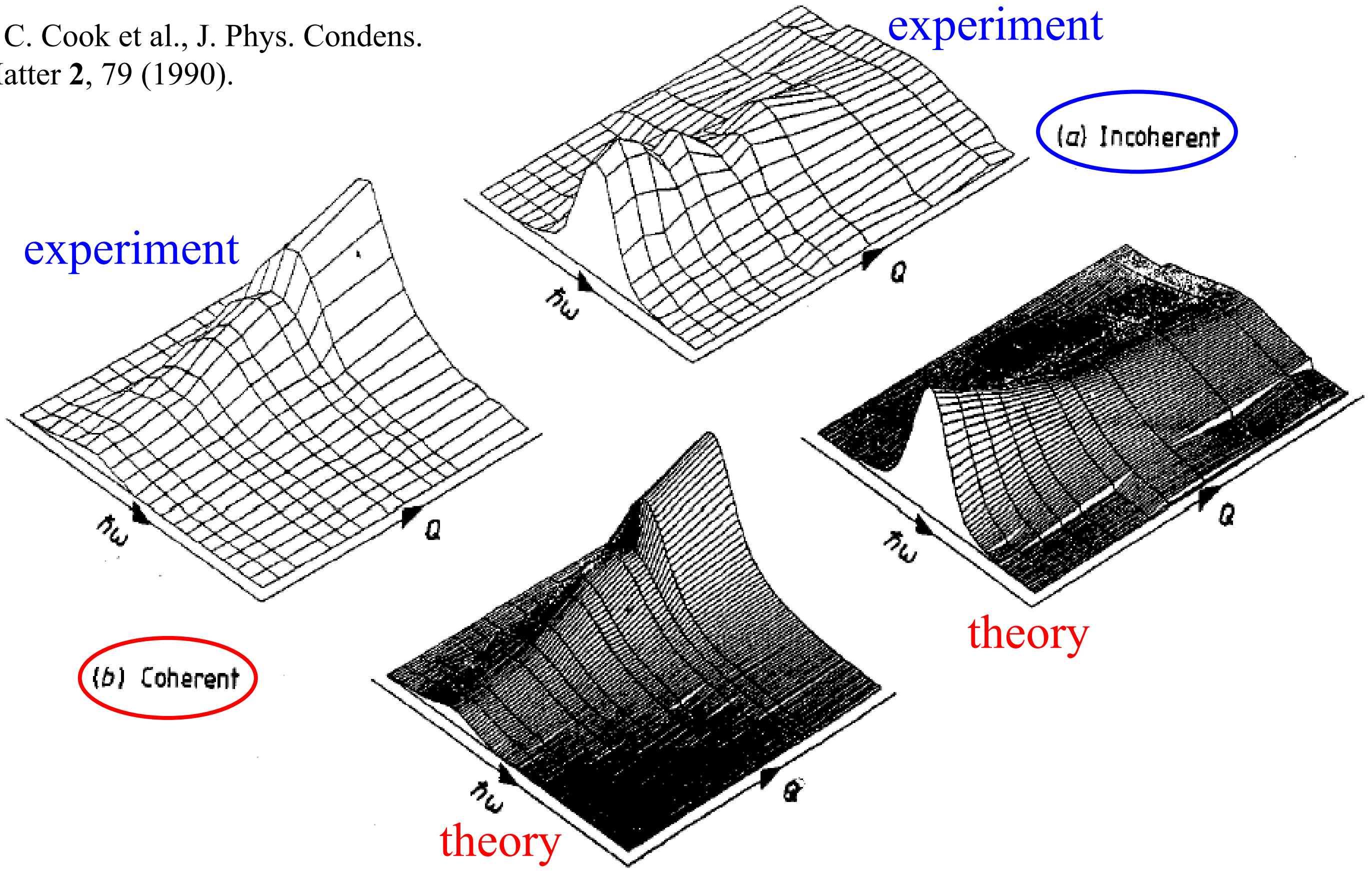
Energy Transfer (meV)

Figure 2. The separated coherent and incoherent parts of the total scattering around the elastic position as a function of detector angle.

D gives rise to incoherent and incoherent scattering

Deuterium in Nb

J. C. Cook et al., J. Phys. Condens. Matter **2**, 79 (1990).

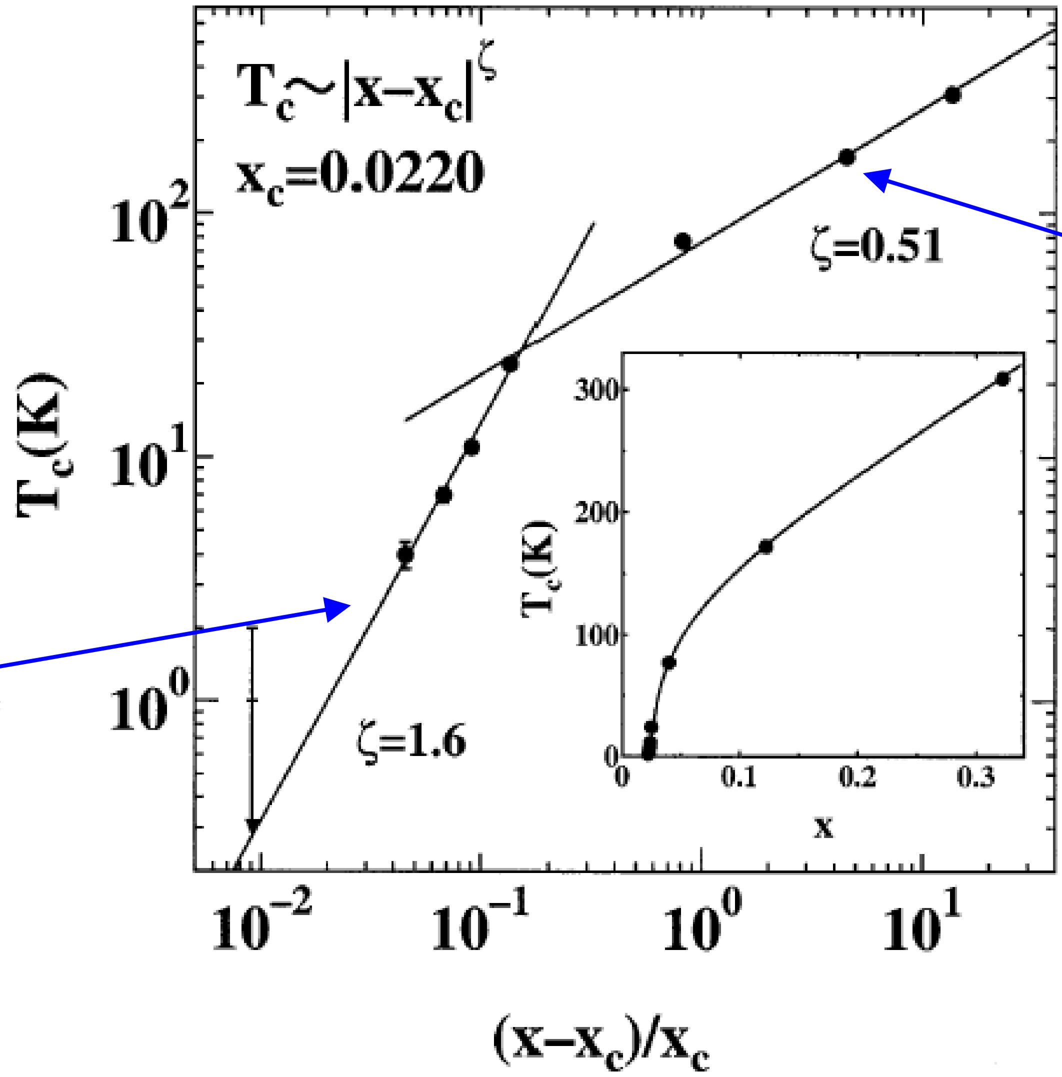


- separation successful
- good agreement with theory
- incoherent-coherent residence times: $\tau_{coh} = 0.49\,\tau_{inc}$

Ex. 2: Quantum Phase Transition in $PdNi_x$

- Pd: enhanced paramagnet
- doping with Ni → ferromagnetic

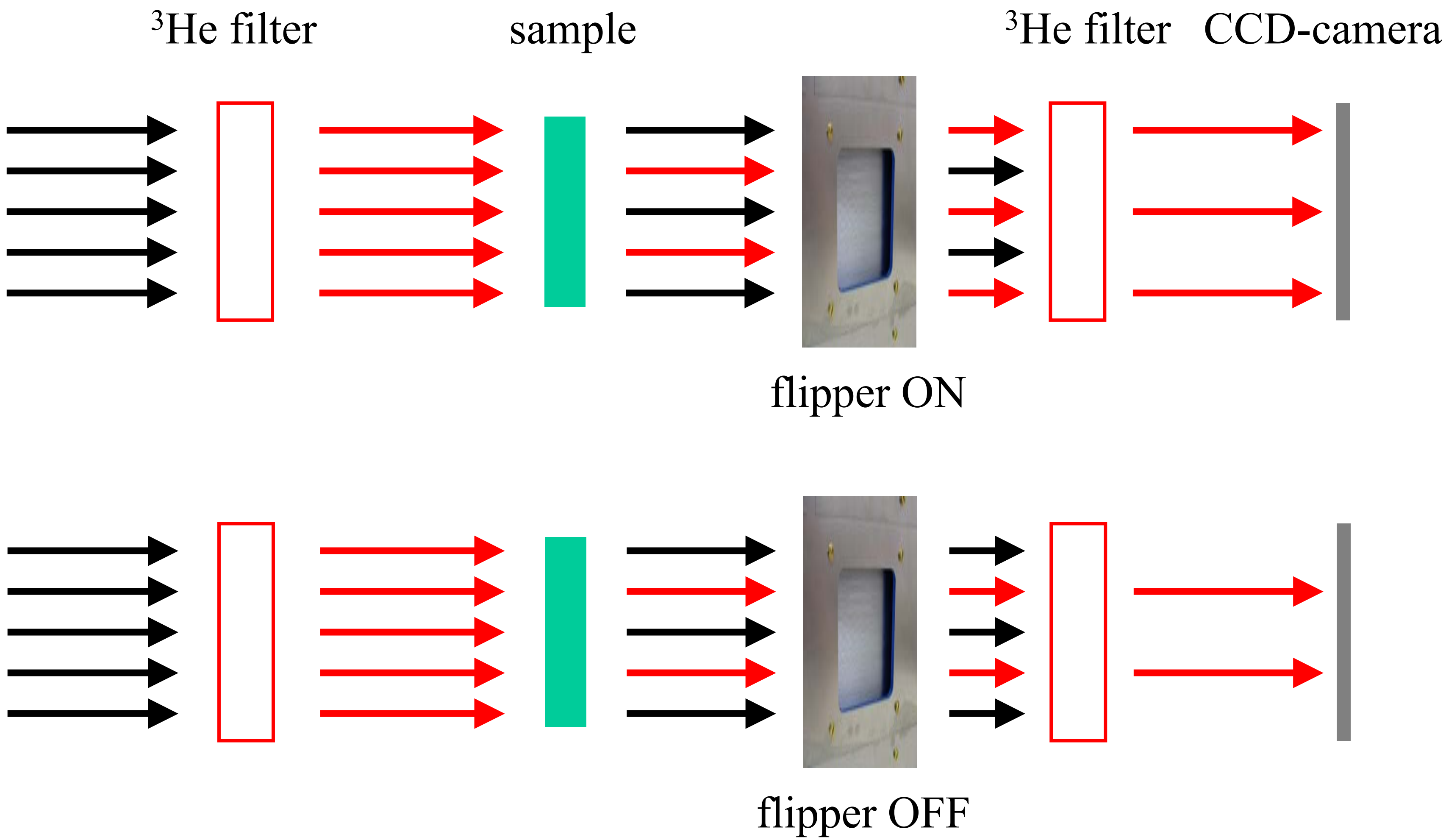
M. Yamada and S. Tanda, Physica B **284-288**, 1305 (2000)



Problem: homogeneity of sample

Experiment: Radiography

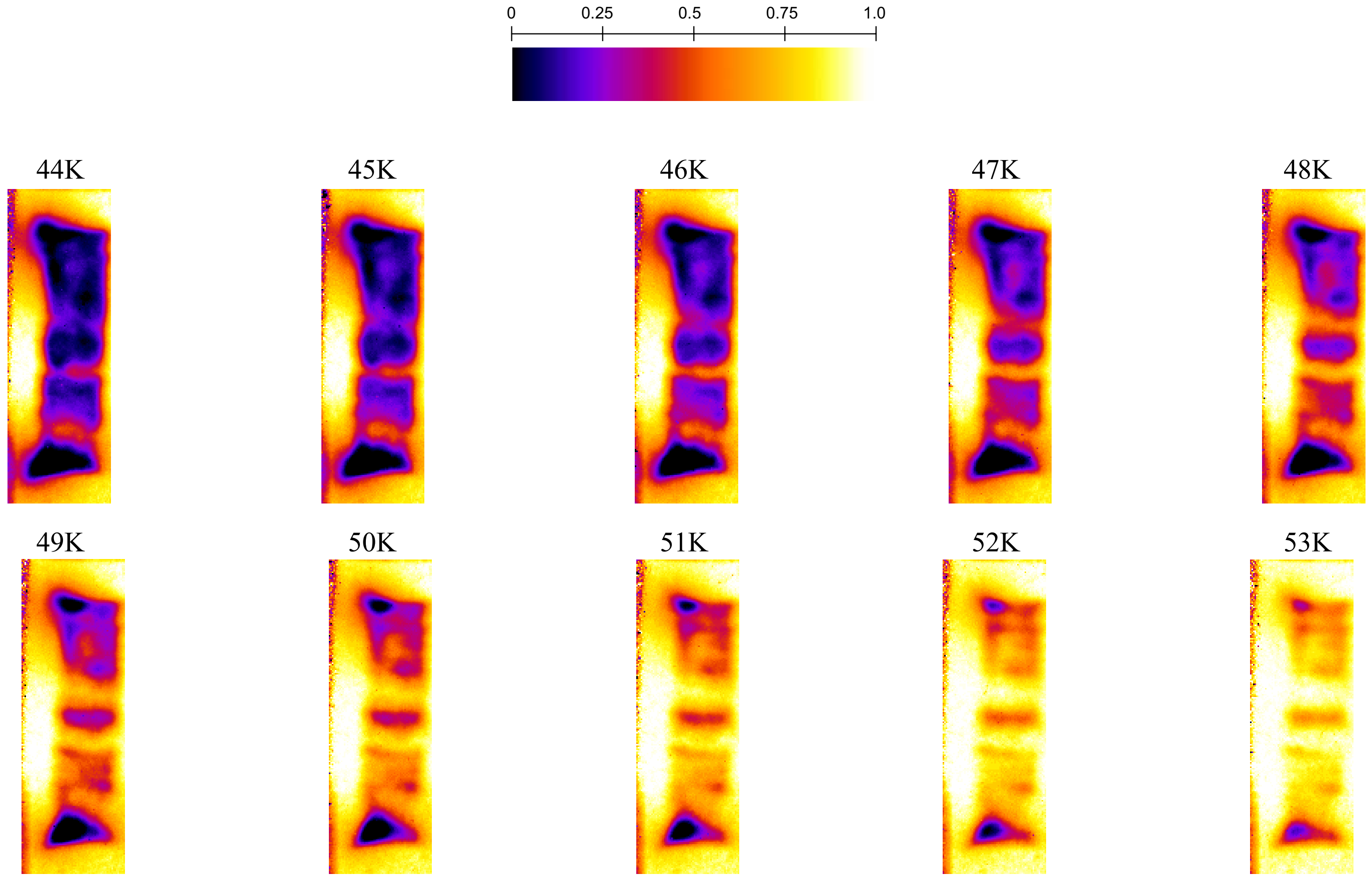
Idea: neutrons are depolarized by ferromagnetic domains



Experimental Results

Probe 1 3.24% Ni - Polarization

M. Schulz, E21, TUM



Neutrons are depolarized by ferromagnetic domains → blue regions

Short Introduction into Spin Waves

$$\mathrm{H} = -\sum_{jj'} J_{jj'} \mathbf{S}_j \cdot \mathbf{S}_{j'}$$

Fourier transform (compare with diffraction!)

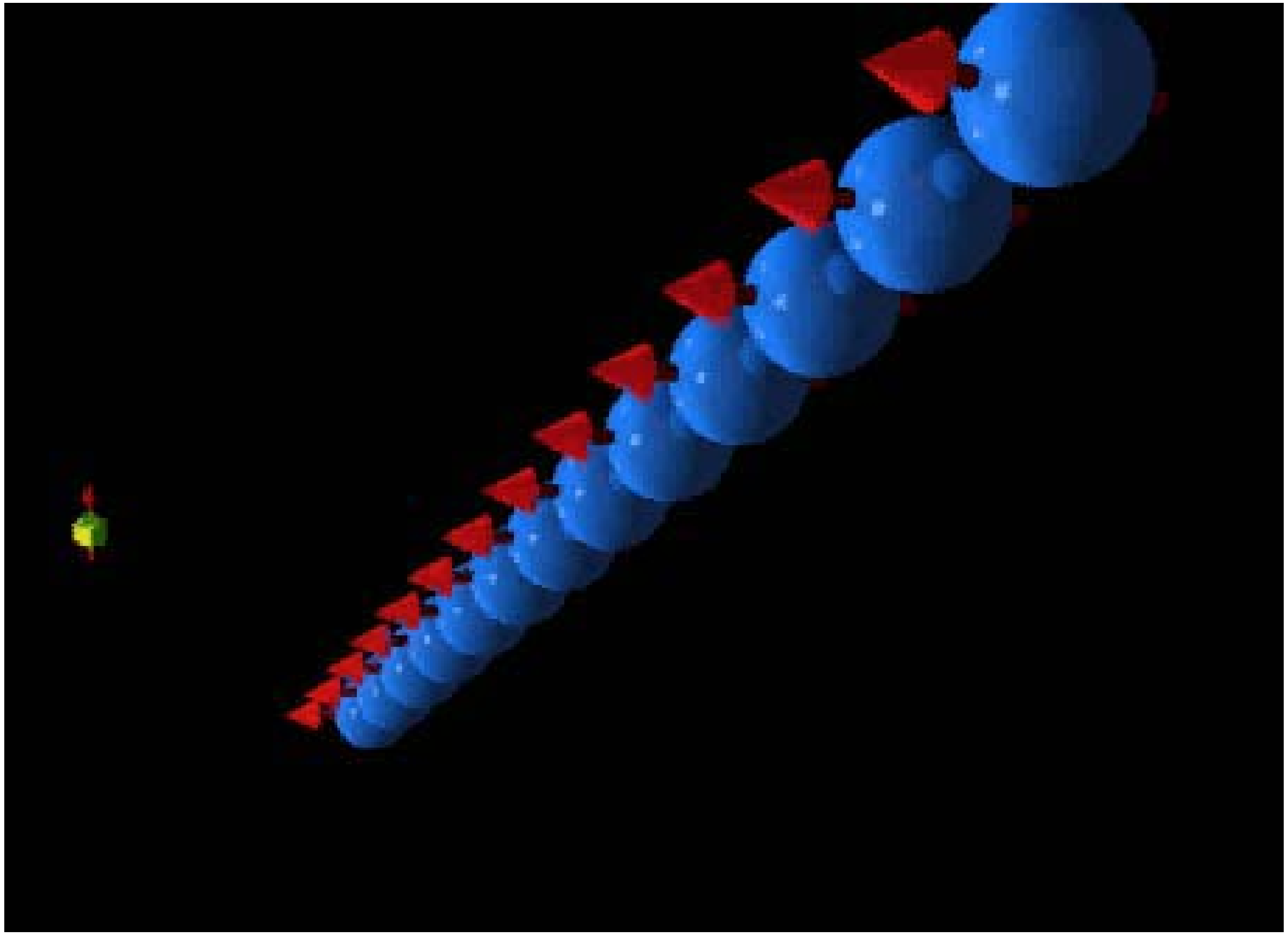
• linear spin wave theory: $\hbar\omega_q = 2S\left(J(0) - J(\mathbf{q})\right)$

where: $J(\mathbf{q}) = \sum_{jj'} J_{jj'} e^{i\mathbf{q}\cdot(\mathbf{r}_j - \mathbf{r}_{j'})}$

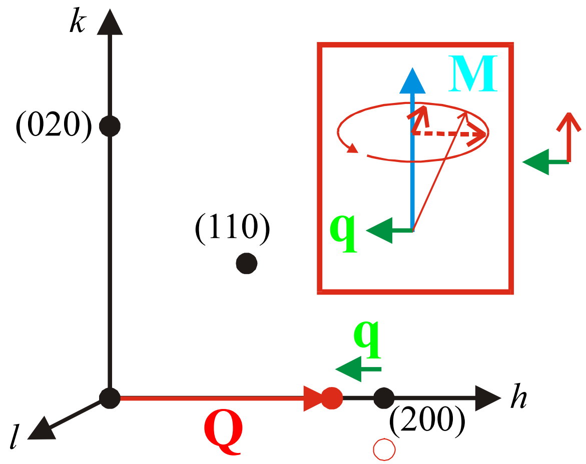
• most simple case: $J_{ij} = J$ (see Charles Kittel: Solid State Physics)

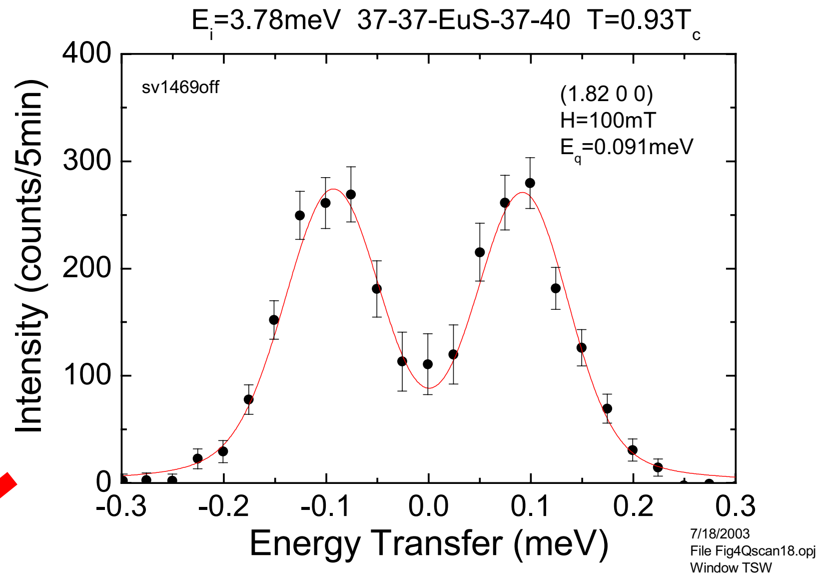
$$E_q = 4JS(1-\cos qa) \xrightarrow{\text{small } q} E_q = Dq^2$$

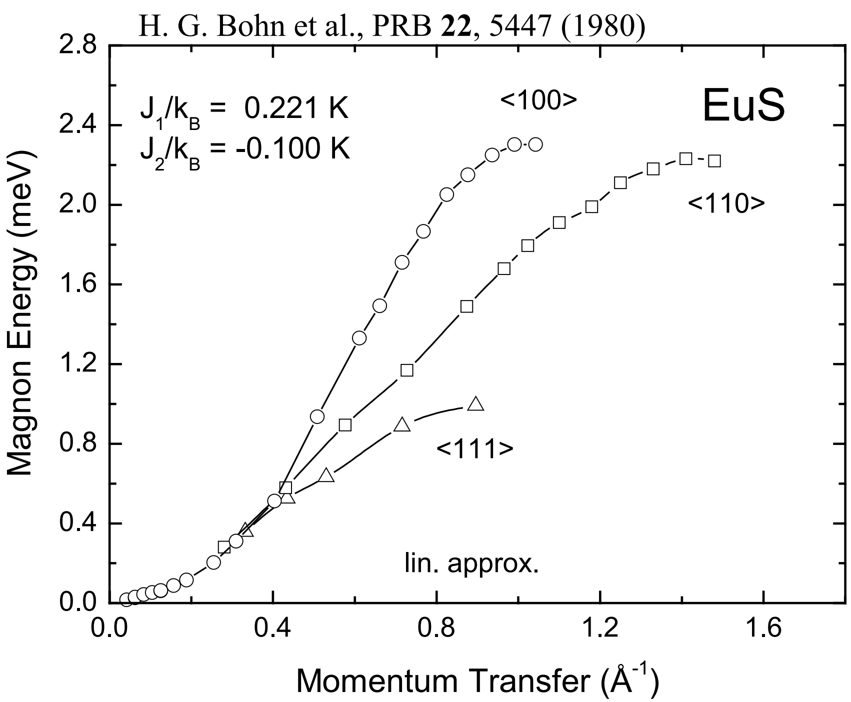
Spin Waves

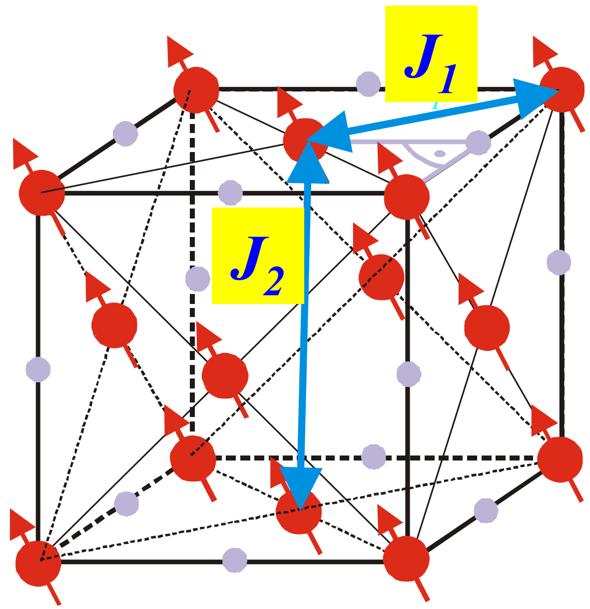


EuS: The ideal FM









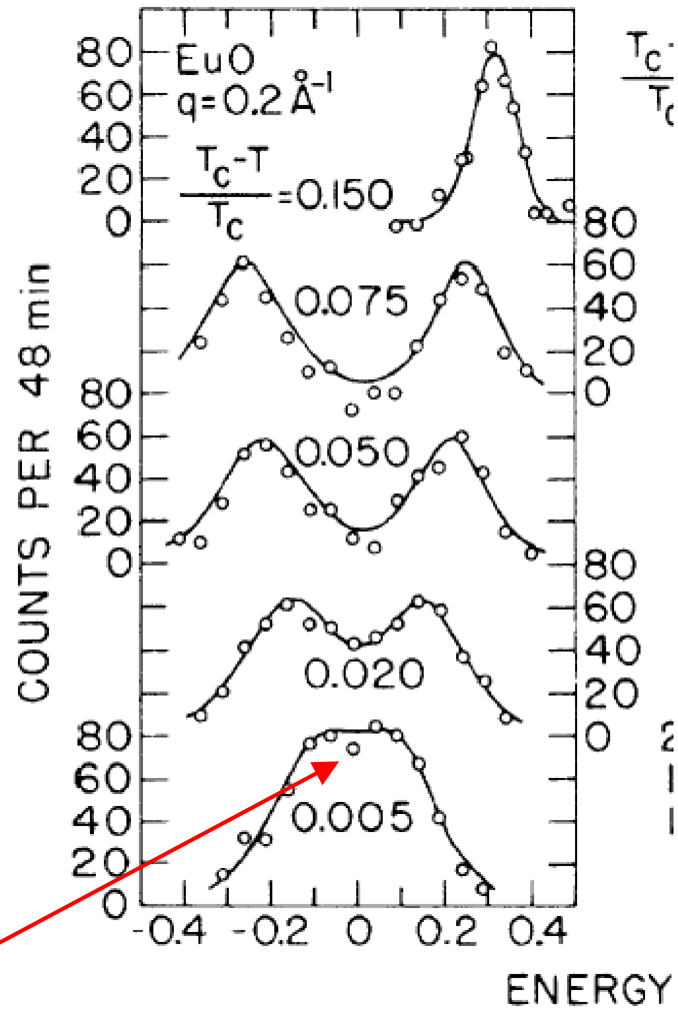
Determination of J_1 and J_2

What can we learn?

- exchange interactions: information on electronic structure

- phase transitions: critical exponents, universality

- importance of additional terms of magnetic interaction: anisotropies (xy-like, Ising)



O. W. Dietrich et al., PRB **14**, 4923 (1976)

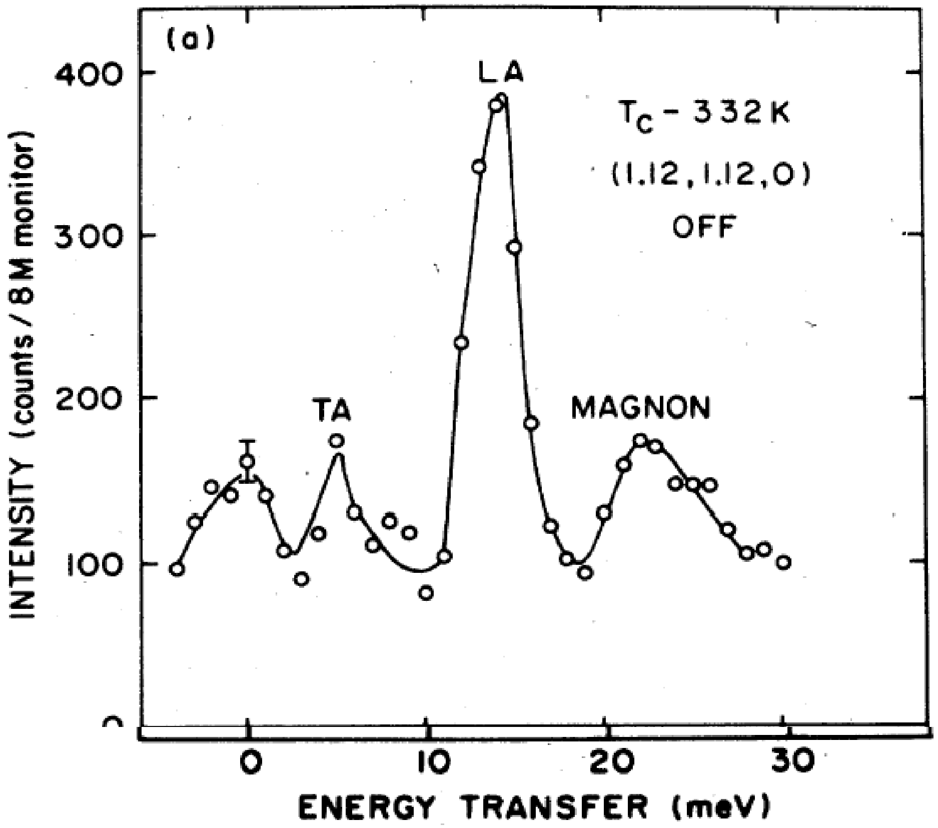
evolves into critical scattering close to and above T_C

Example 3: Paramagnetic Scattering in Fe

- Fe is an itinerant ferromagnet: how does the magnetism vanish at T_C?
  - disordering due to thermal fluctuations?
  - vanishing of exchange splitting?

→ experiment with unpolarized neutrons

Wicksted et al., PRB 30, 3655 (1984)

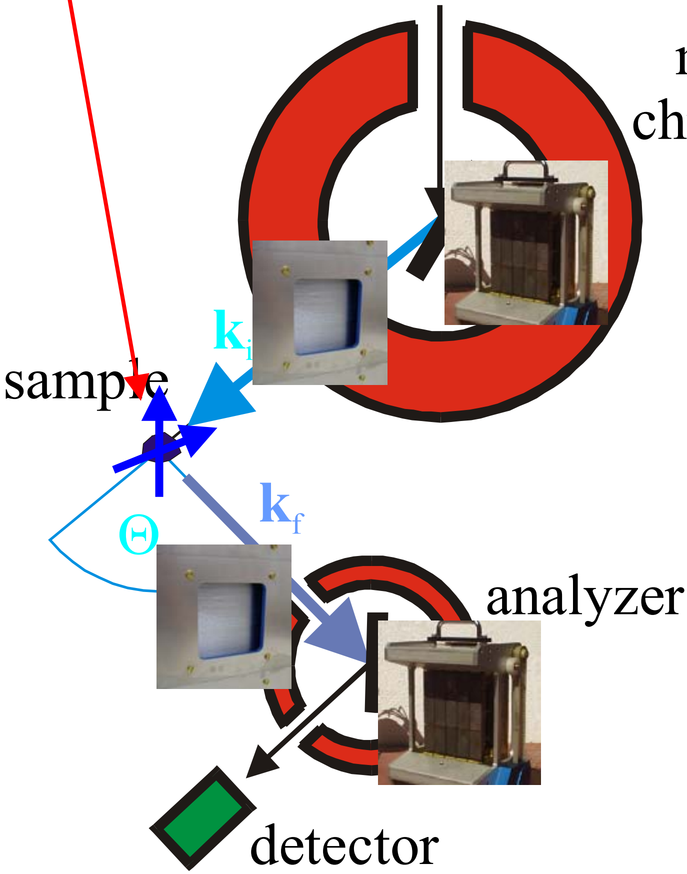


Distinction of magnetic from nuclear scattering (phonons, incoherent) difficult

Experiment: TAS with Pol. Analyzis

Application of:

- vertical field $\mathbf{B}_v$
- horizontal field $\mathbf{B}_h$



Extract magnetic scattering by measuring four spin-dependent cross sections:

Momentum transfer: $\mathbf{Q} = \mathbf{k}_i - \mathbf{k}_f$

	non-spin-flip	spin-flip
Q // B	$\sigma_N + 0\sigma_m + \frac{1}{3}\sigma_{NSI} + \sigma_{bg}$	$\sigma_m + \frac{2}{3}\sigma_{NSI} + \sigma_{bg}$
Q ⊥ B	$\sigma_N + \frac{1}{2}\sigma_m + \frac{1}{3}\sigma_{NSI} + \sigma_{bg}$	$\frac{1}{2}\sigma_m + \frac{2}{3}\sigma_{NSI} + \sigma_{bg}$

$$\tfrac{1}{2}\sigma_{mag} = I^{nsf}_{Q\perp B} - I^{nsf}_{Q//B}$$

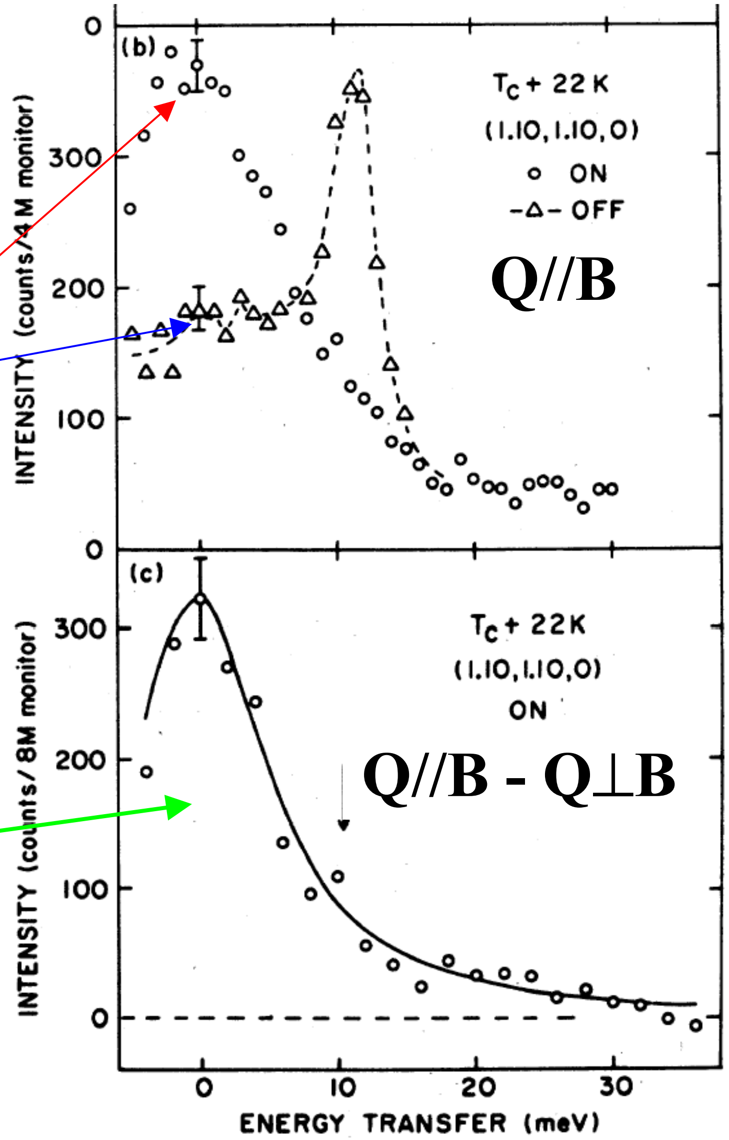
$$\tfrac{1}{2}\sigma_{mag} = I^{sf}_{Q//B} - I^{sf}_{Q\perp B}$$

Experimental Result

Wicksted et al., PRB 30, 3655 (1984)

	non-spin-flip	spin-flip
Q // B	$\sigma_N + 0\sigma_m + \frac{1}{3}\sigma_{NSI} + \sigma_{bg}$	$\sigma_m + \frac{2}{3}\sigma_{NSI} + \sigma_{bg}$
Q ⊥ B	$\sigma_N + \frac{1}{2}\sigma_m + \frac{1}{3}\sigma_{NSI} + \sigma_{bg}$	$\frac{1}{2}\sigma_m + \frac{2}{3}\sigma_{NSI} + \sigma_{bg}$

$$\frac{1}{2}\sigma_{mag} = I^{sf}_{Q//B} - I^{sf}_{Q\perp B}$$



Interpretation of Paramagnetic Scattering

→ no spin waves above T_C

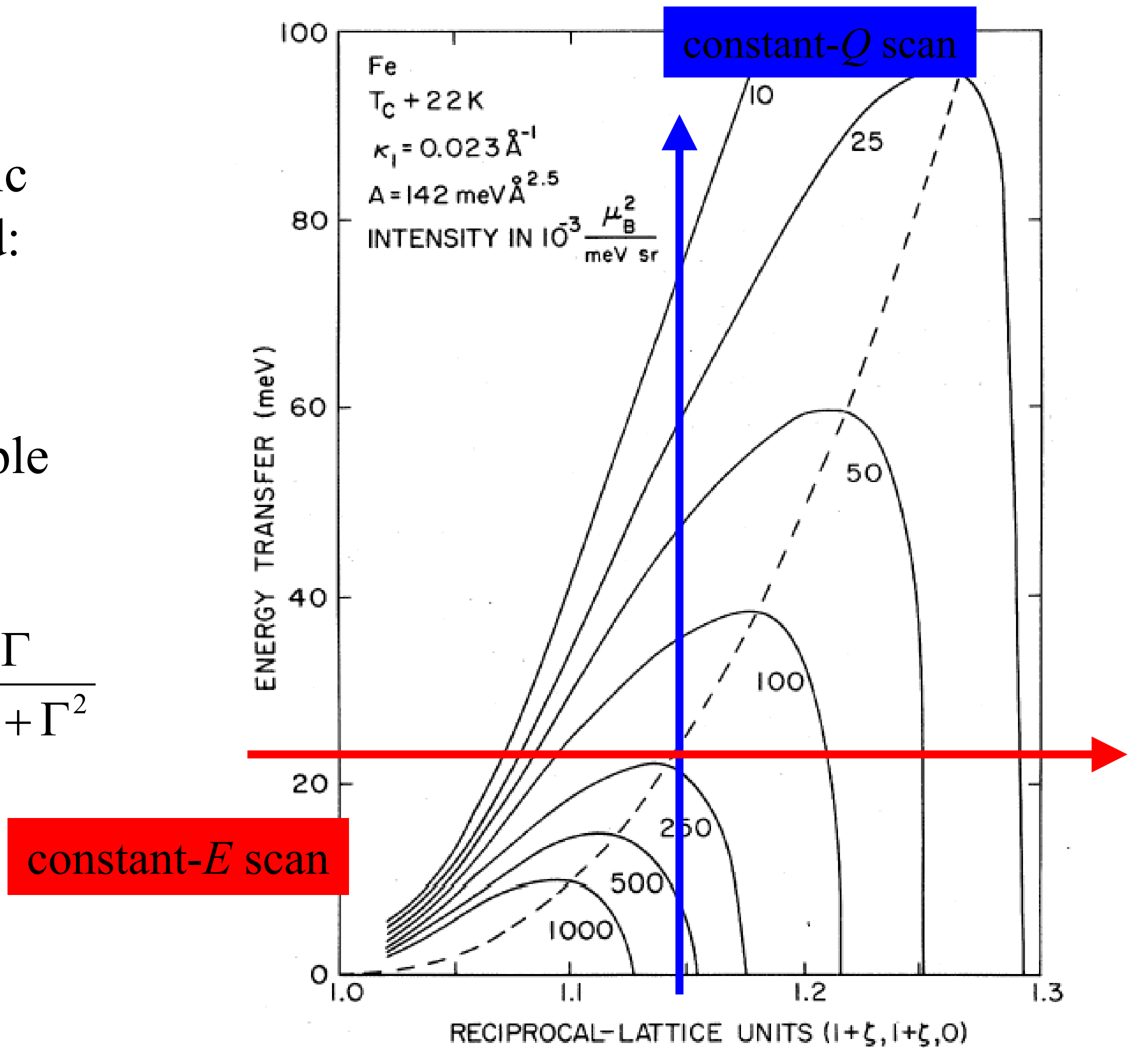
→ time evolution of magnetic fluctuations can be measured:

→ $\Gamma = Aq^{2.5}$

→ behavior similar as a simple Heisenberg ferromagnet

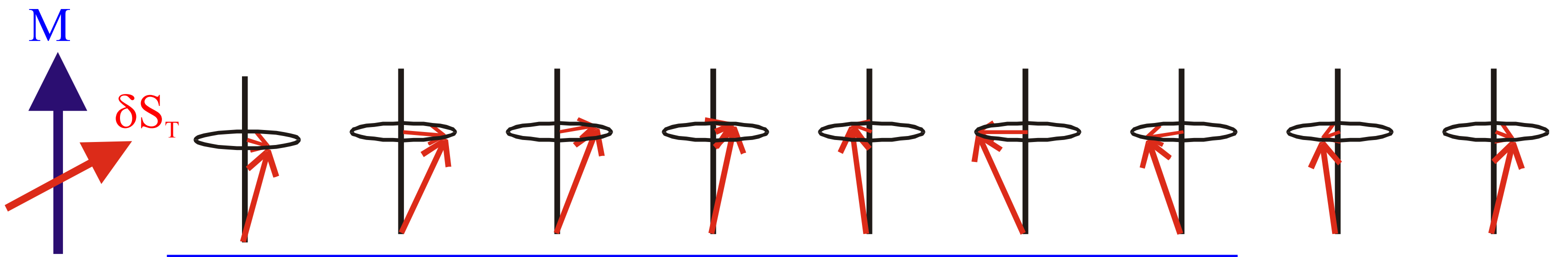
$$S(\mathbf{Q},\omega) = \chi(0,0)\frac{\kappa^2}{\kappa^2+q^2}\frac{1}{\pi}\frac{\Gamma}{\omega^2+\Gamma^2}$$

Wicksted et al., PRB 30, 3655 (1984)



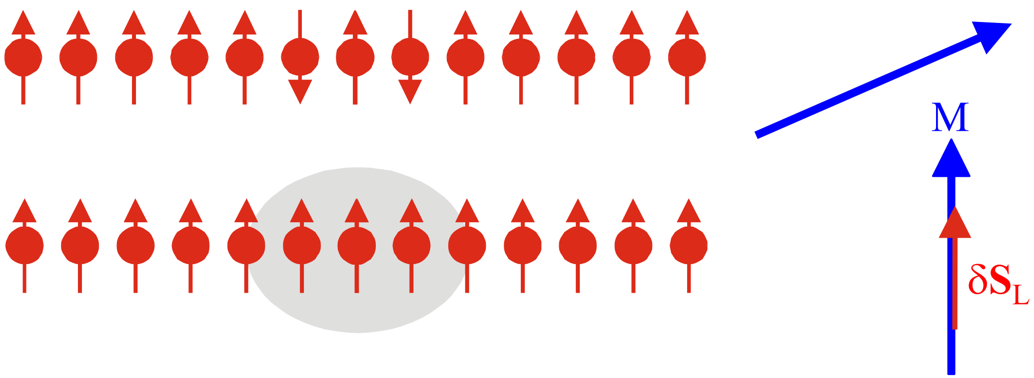
Example 4: Longitudinal Fluctuations

• visualisation of spin waves (magnons) at low temperature:



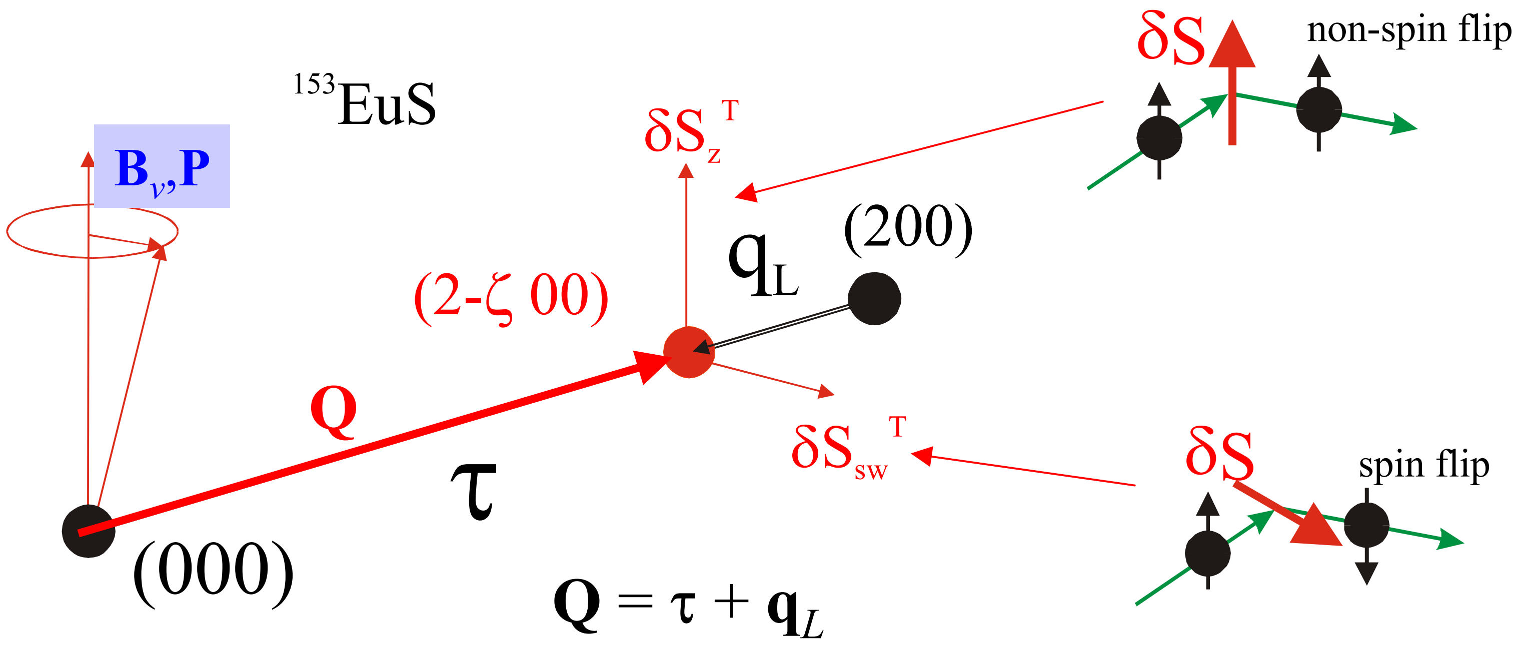
spin deviation is perpendicular to magnetization

• close to T_C: magnon-magnon interaction



magnetization changes
→ spin fluctuation is along magnetization

Experiment: Polarized TAS



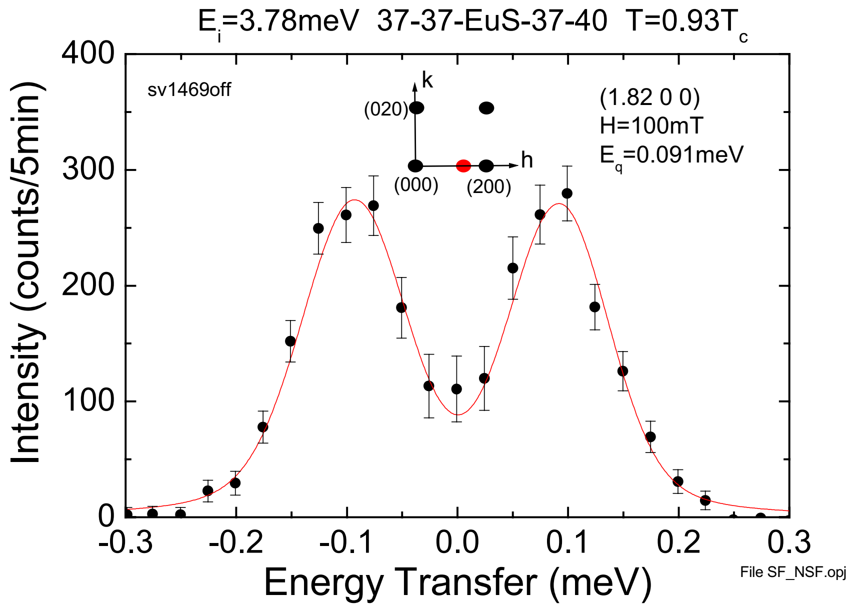
Experimental realisation:

- **Q** along [200] direction → fluctuations perpendicular to **Q** contribute to scattering cross section: $\delta \mathbf{S}_z^T$, $\delta \mathbf{S}_{sw}^T$
- magnetic field **B** is applied vertical to scattering plane
- **P** does not change ("non spin flip scattering"): longitudinal fluctuations $\delta \mathbf{S}_z^T$
- **P** is inverted ("spin flip scattering"): scattering by spin waves $\delta \mathbf{S}_{sw}^T$

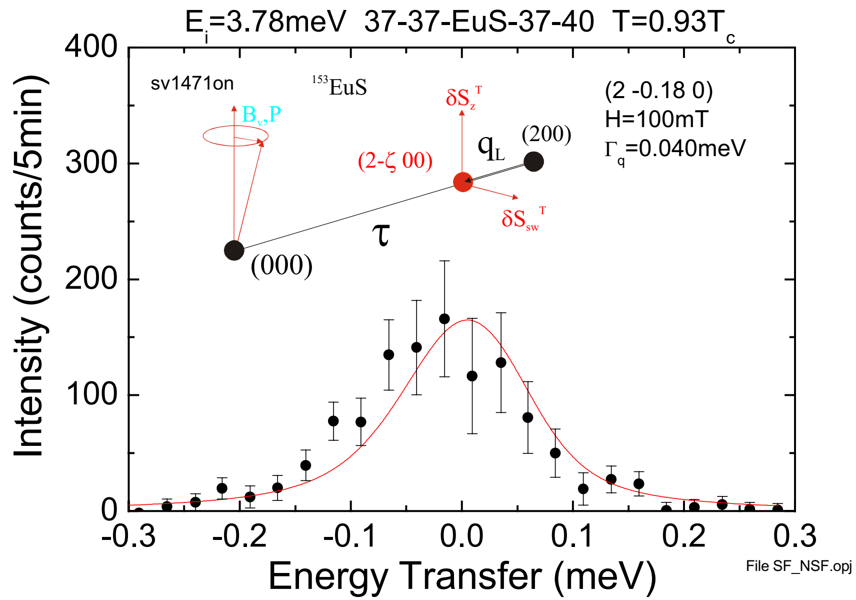
→ measure spin flip and non spin flip scattering to distinguish the modes

Experimental Result

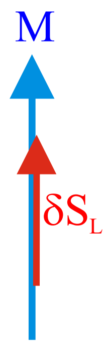
Spin waves:



Longitudinal fluctuations:



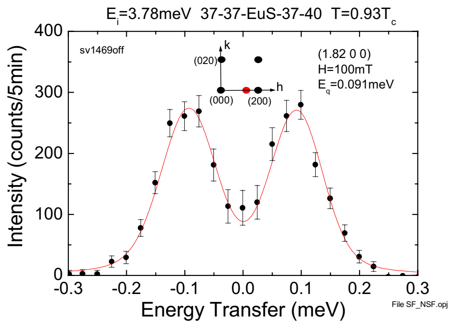
Longitudinal fluctuations exist and are important near T_C



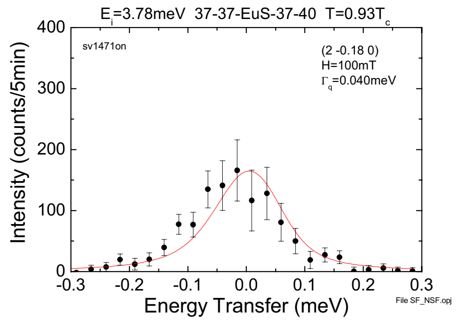
after: Böni et al., Phys.Rev. B **65**, 144434 (2002)

Polarized Neutrons Necessary? YES

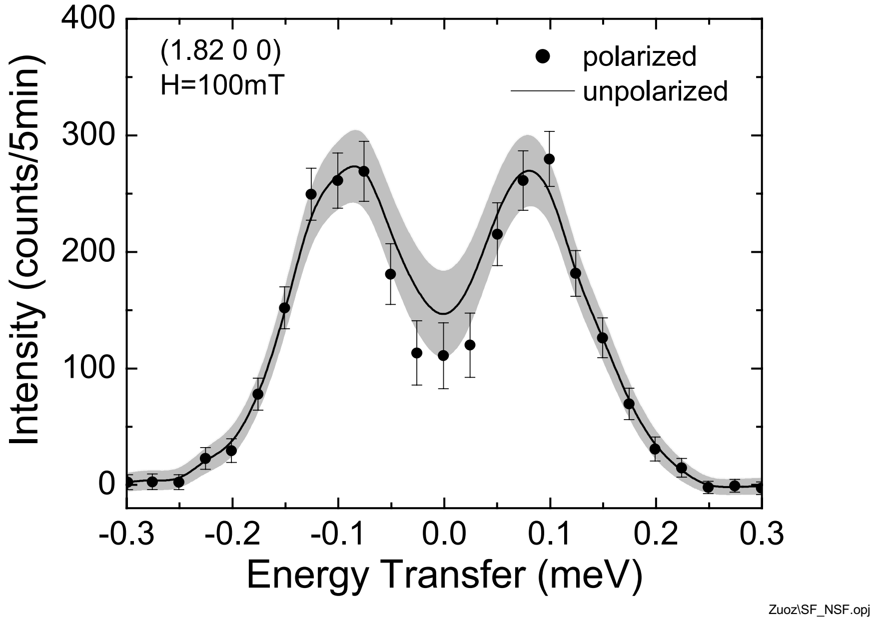
2×



+



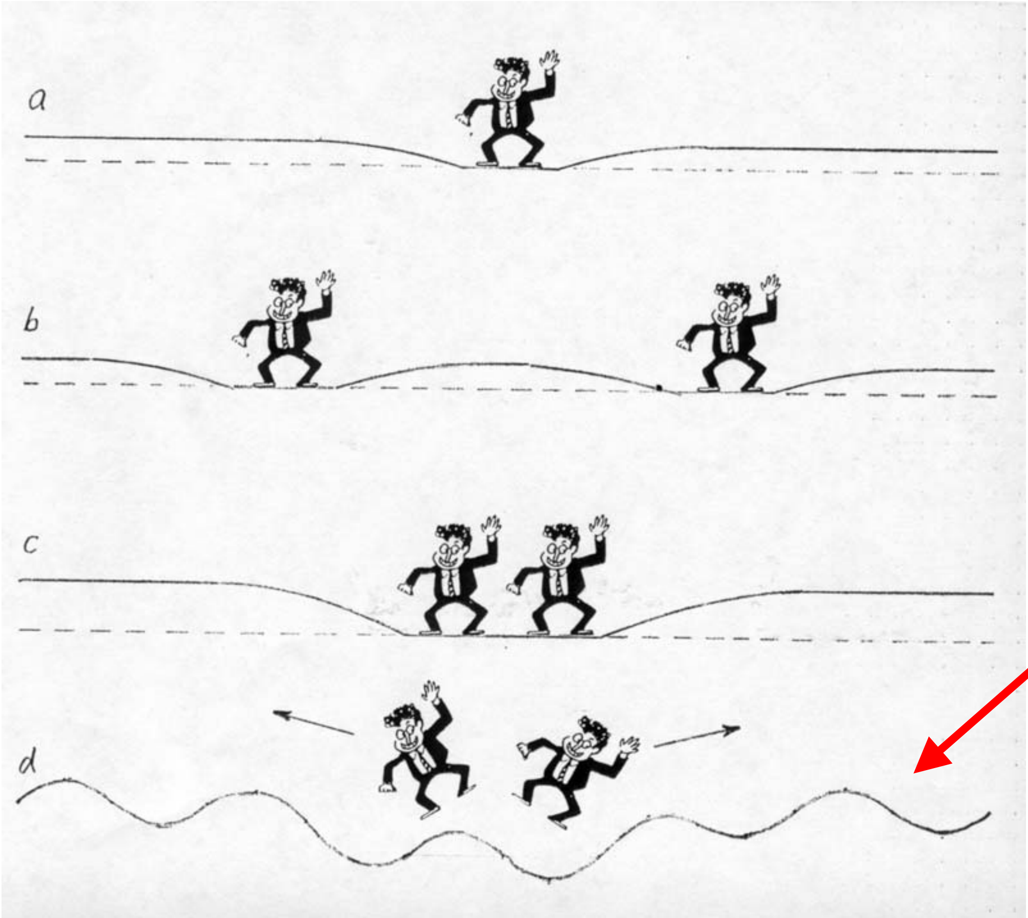
=



Polarization analysis: Method to distinguish magnetic modes

Ex. 5: Conventional Superconductivity (BCS)

BCS-theory: The electron-phonon interaction couples to electrons and produces a Cooper-Pair: $\{\mathbf{p}_{\uparrow}, -\mathbf{p}_{\downarrow}\}$



direct verification of electron-phonon coupling:

measure damping of phonons

1st Experiment:
in Pb
Furrer und Hälg

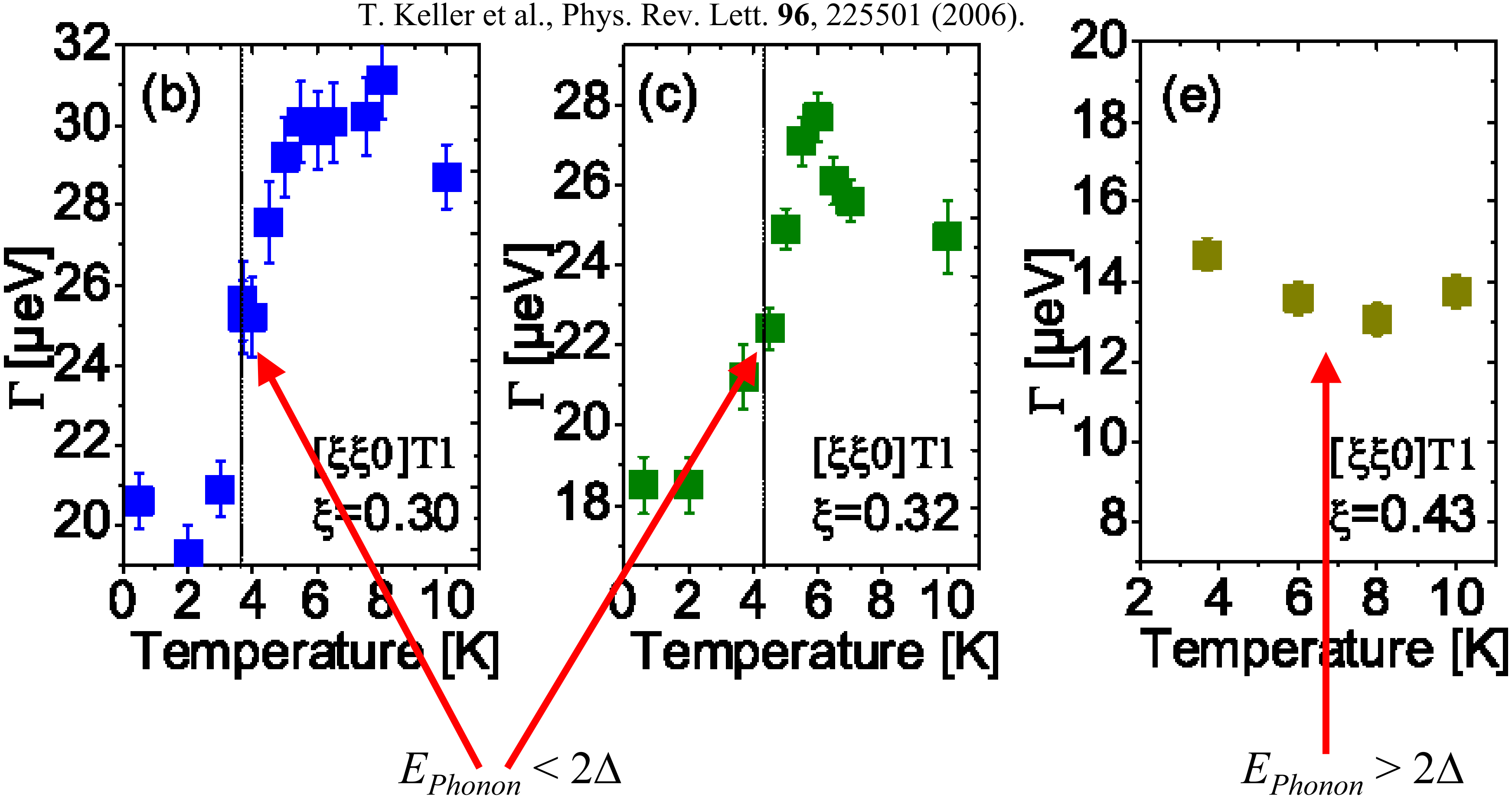
Triple-Axis with Spin-Echo: TRISP

spin-echo
coils

Damping of Phonons in Pb

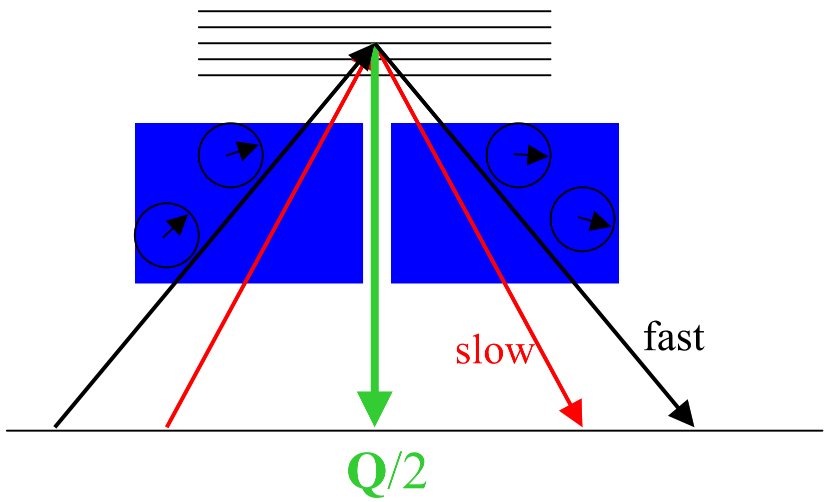
Method: Triple axis spectrometer combined with neutron spin echo

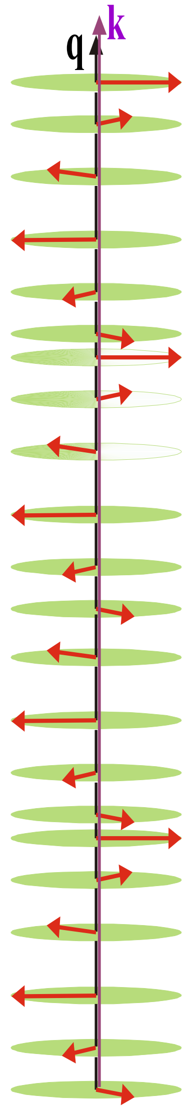
T. Keller et al., Phys. Rev. Lett. **96**, 225501 (2006).



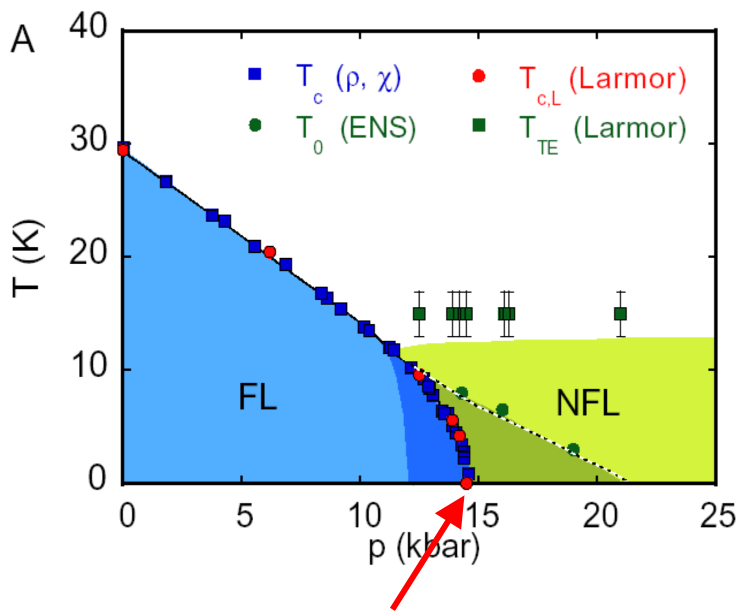
Open question: Mechanism in high-T_C compounds?

Example 6: Larmor Precession in MnSi





• magnetic phase diagram:



Idea of experiment:

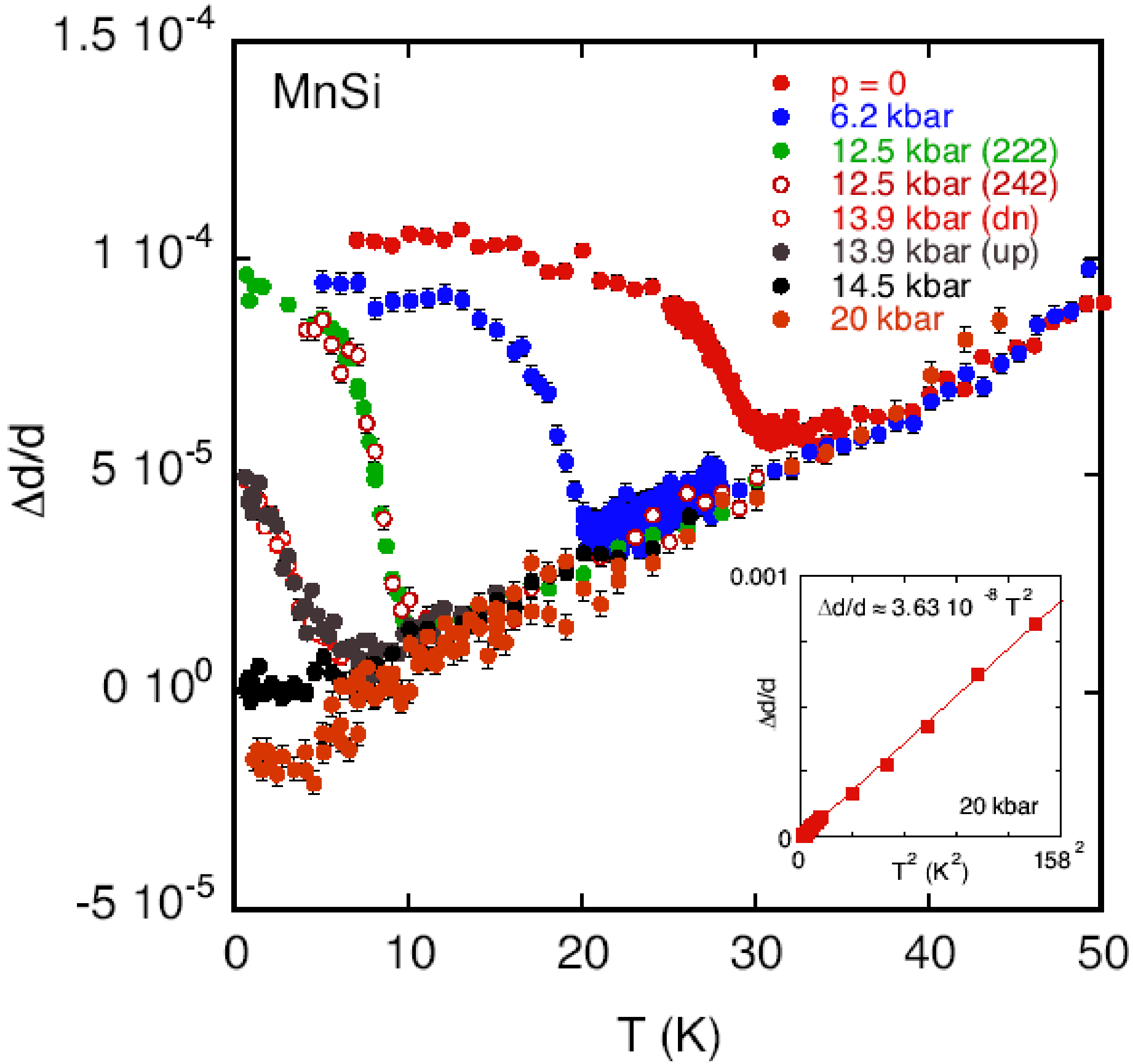
- measure precession of polarization in **B**-field before and after sample
- reciprocal lattice vector determines flight path of neutron through field
- time spent in magnetic field independent of wavelength of neutron
  → number of precession for all diffracted neutrons identical

Questions:

- change of lattice constant near T_C
- is there a quantum critical point at 14.6 kbar?

Thermal Expansion in MnSi

C. Pfleiderer, P. Böni, T. Keller, U. K. Rössler, and A. Rosch, Science **316**, 1871 (2007)



Interpretation:
- no quantum critical point
- it is not a melting of helical order near the QCP

Very extreme conditions:
- $p = 20$ kbar
- $T = 300$ mK

Neutrons indeed unique:
1 part in 10^{-6}!

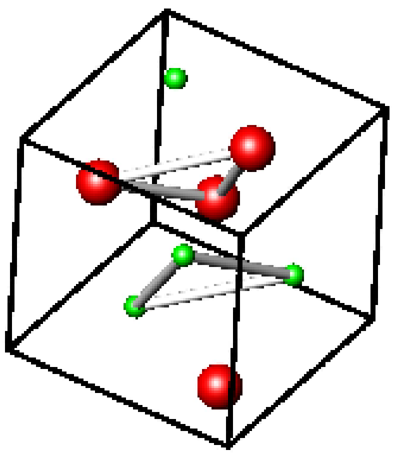
Example 6: Chiral Fluctuations

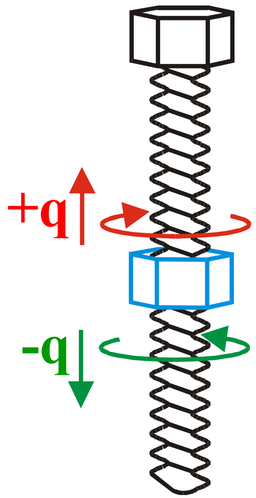
Recall: half polarized beam setup:

$$\sigma = N \cdot N^* + \mathbf{M} \cdot \mathbf{M}^* + \mathbf{P}_i \cdot (N \cdot \mathbf{M}^* + N^* \cdot \mathbf{M}) + i\mathbf{P}_i \cdot (\mathbf{M} \times \mathbf{M}^*)$$

nuclear Bragg peaks

chiral term





right handed screw

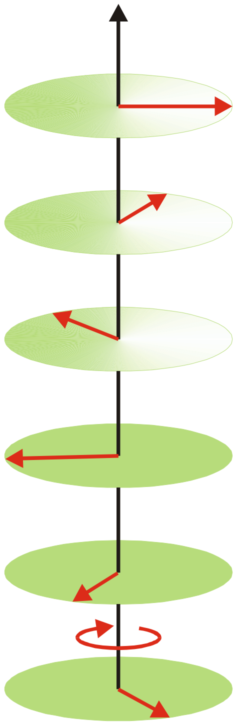
Exchange + Dzyaloshinskii-Moriya:

$$J \cdot \mathbf{S}_1 \cdot \mathbf{S}_2 + D \cdot \mathbf{S}_1 \times \mathbf{S}_2$$

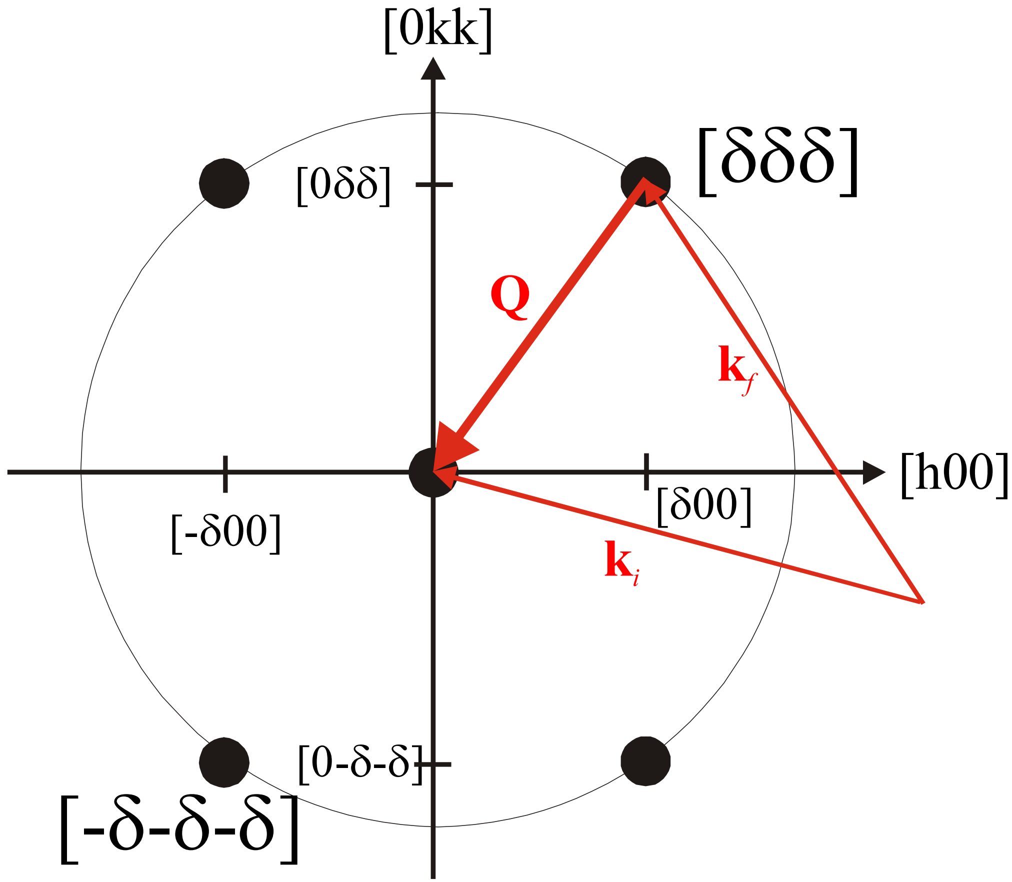
$$\tan \phi = \frac{D}{J}$$

Magnetic Spiral in MnSi

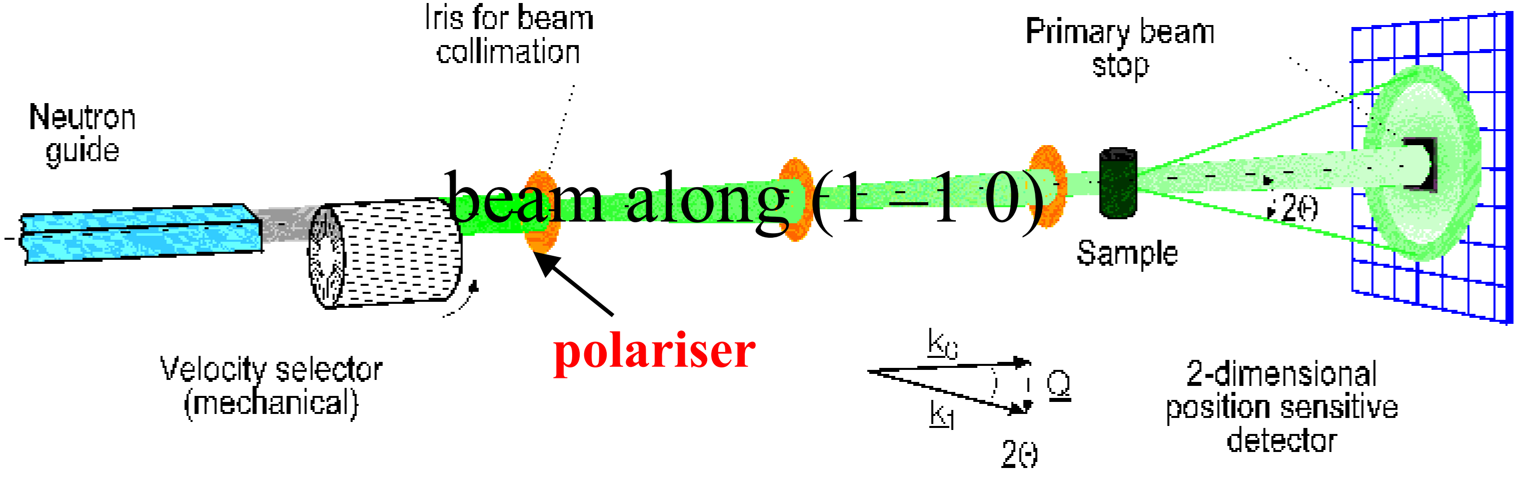
- Ishida et al. (1985): left handed spiral



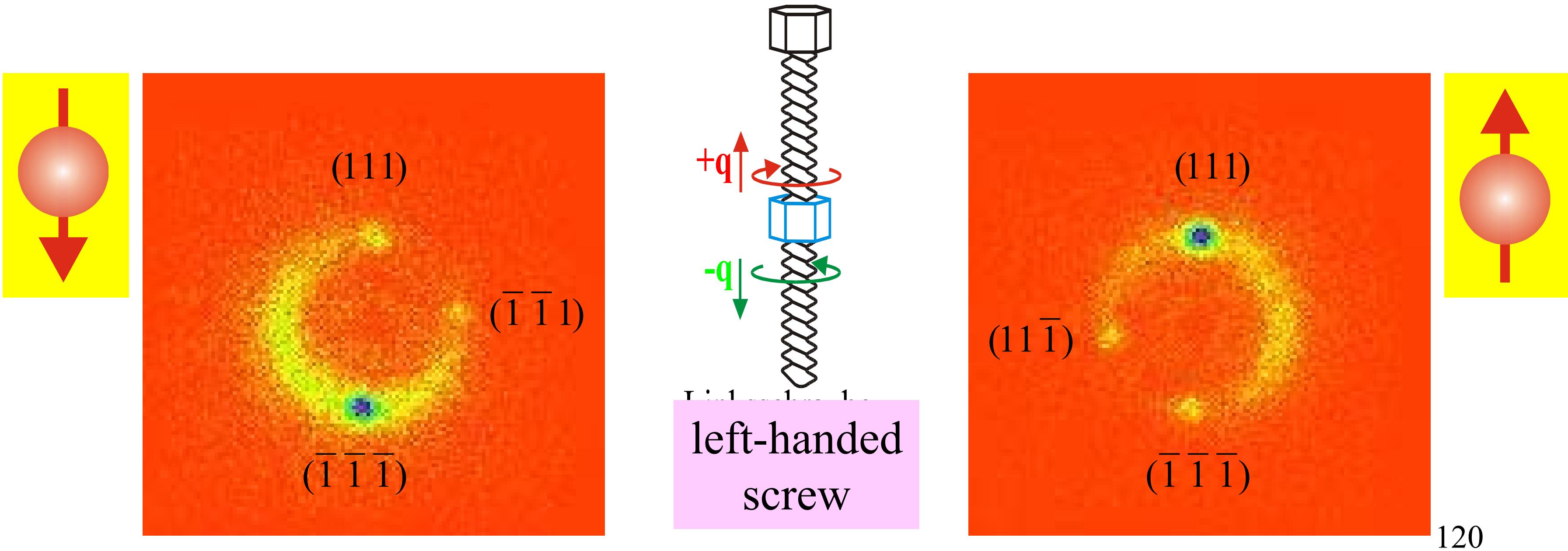
period: 180 Å



Small q → SANS



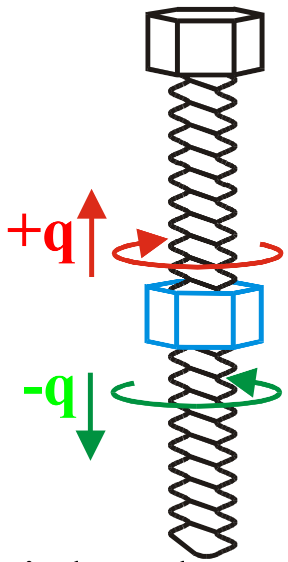
Iris for beam collimation
Primary beam stop
Neutron guide
beam along $(1\ \bar{1}\ 0)$
Sample
2Θ
Velocity selector (mechanical)
polariser
k_0
Q
k_1
2Θ
2-dimensional position sensitive detector



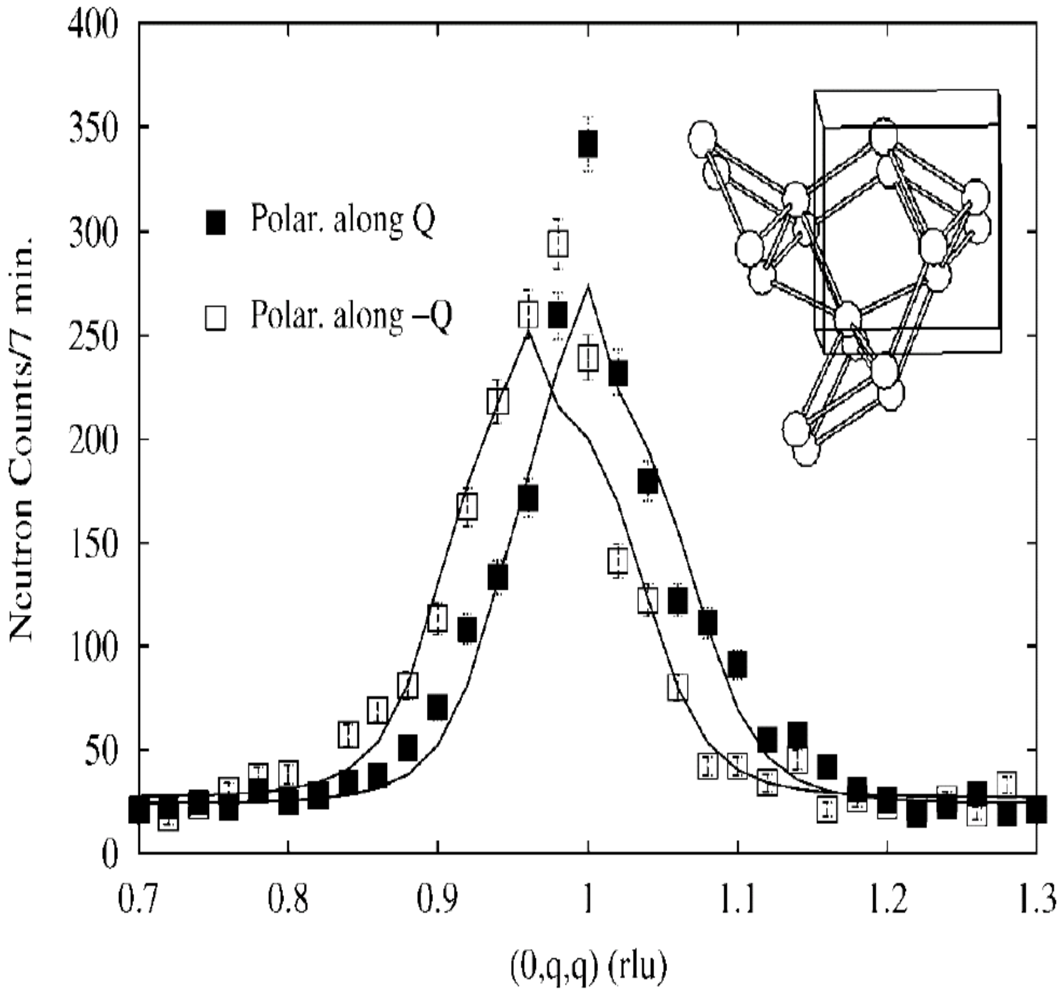
(1 1 1)
$(\bar{1}\ \bar{1}\ 1)$
$(\bar{1}\ \bar{1}\ \bar{1})$
+q
-q
left-handed screw
(1 1 1)
$(1\ 1\ \bar{1})$
$(\bar{1}\ \bar{1}\ \bar{1})$

Paramagnetische Phase

Kopplung zwischen Chiralität und Wellenvektor



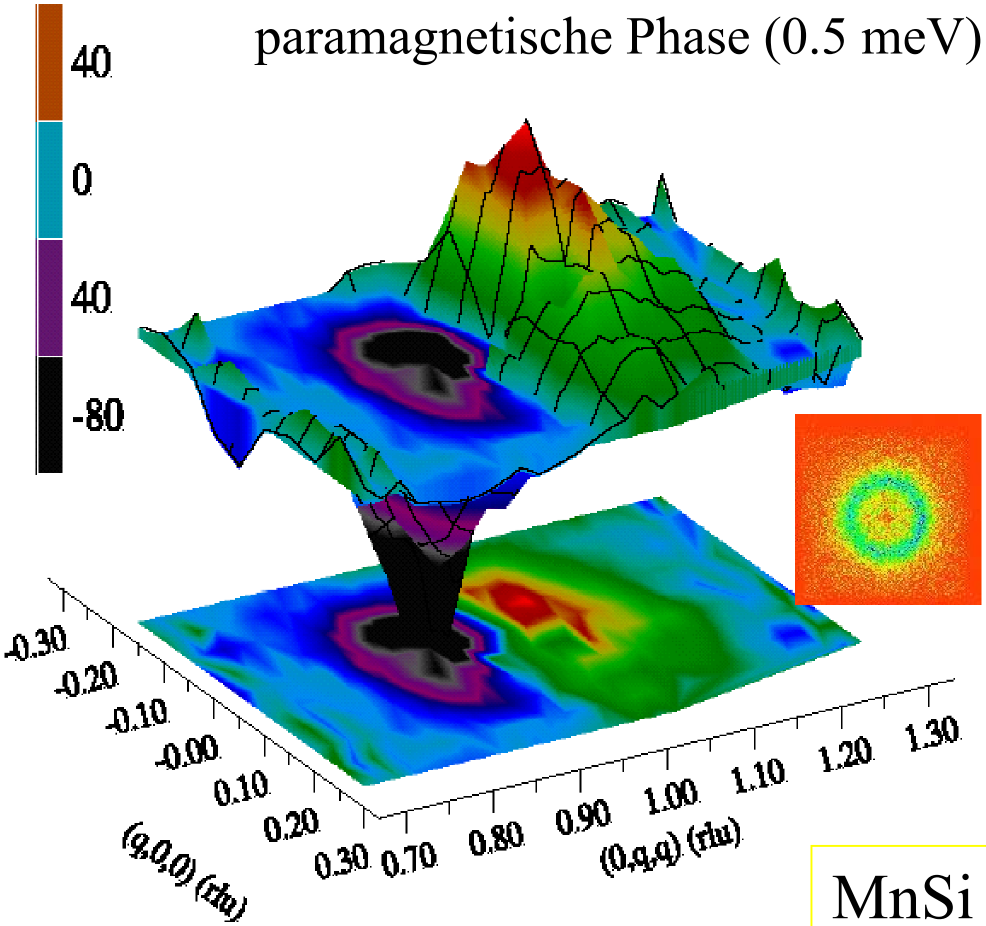
Linksschraube



Fluktuationen zeigen ebenfalls Chiralität!

Roessli, Böni, Fischer and Endoh, PRL 88, 237204 (2002).

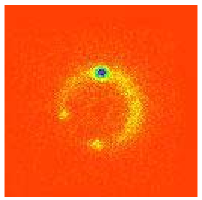
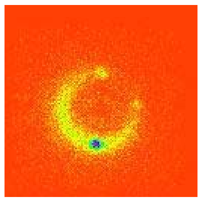
Paramagnetische Phase



MnSi

$$I^{\pm} \approx \mathbf{S}_i \cdot \mathbf{S}_j \pm i\mathbf{P}(\mathbf{S}_i \times \mathbf{S}_j)$$

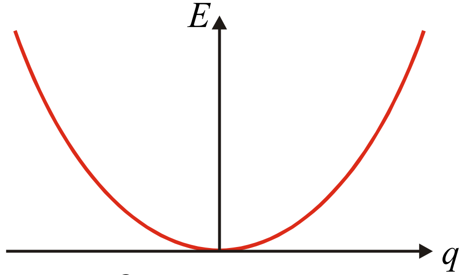
$$I^{+} - I^{-} = 2i\mathbf{P}(\mathbf{S}_i \times \mathbf{S}_j)$$

 –  $= 2i\mathbf{P}(\mathbf{S}_i \times \mathbf{S}_j)$

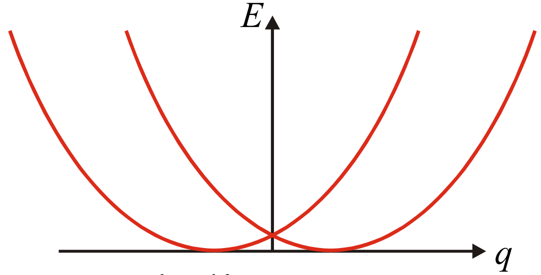
Fluktuationen zeigen ebenfalls Chiralität!

Magnons in MnSi

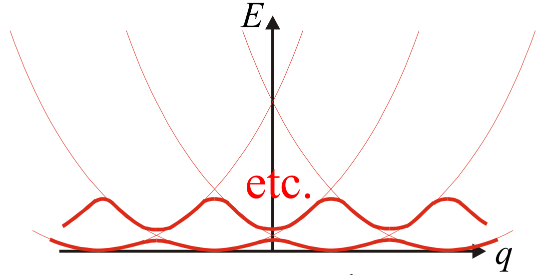
spin waves in incommensurate structures:



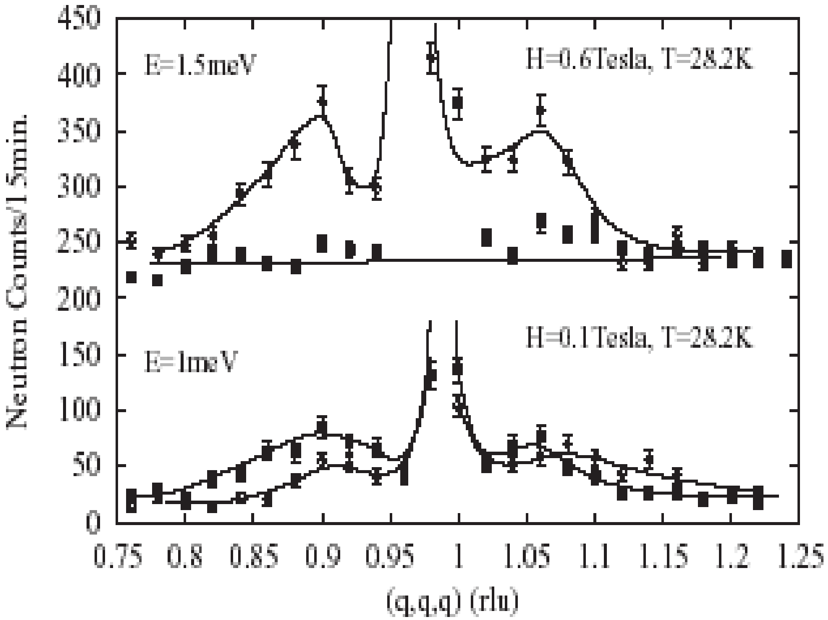
ferromagnet



helimagnet



Izyumov and Laptev



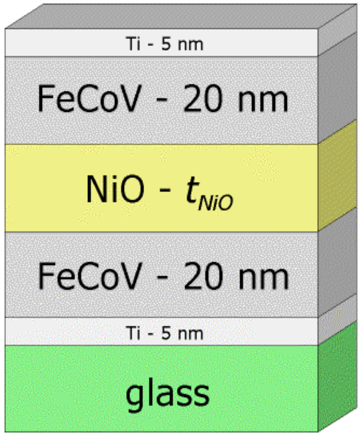
B. Roessli et al., Physica B **345**, 124 (2004)

Example 6: 3-*d* Polarisation Analysis

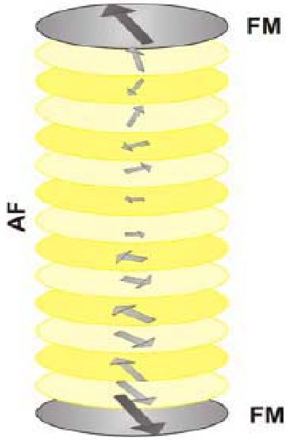
k = (0.017 0.017 0.017)

Example 7: Chirality in Multilayers

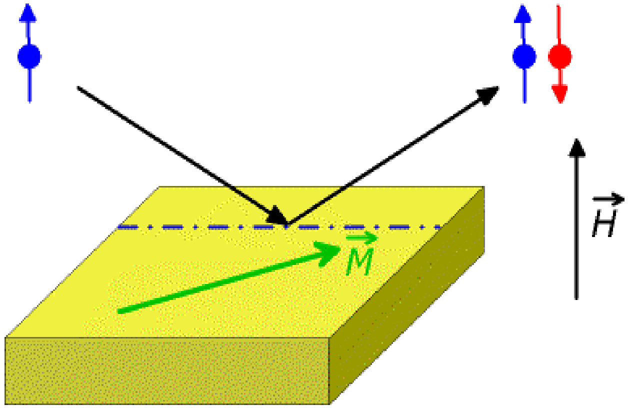
sample



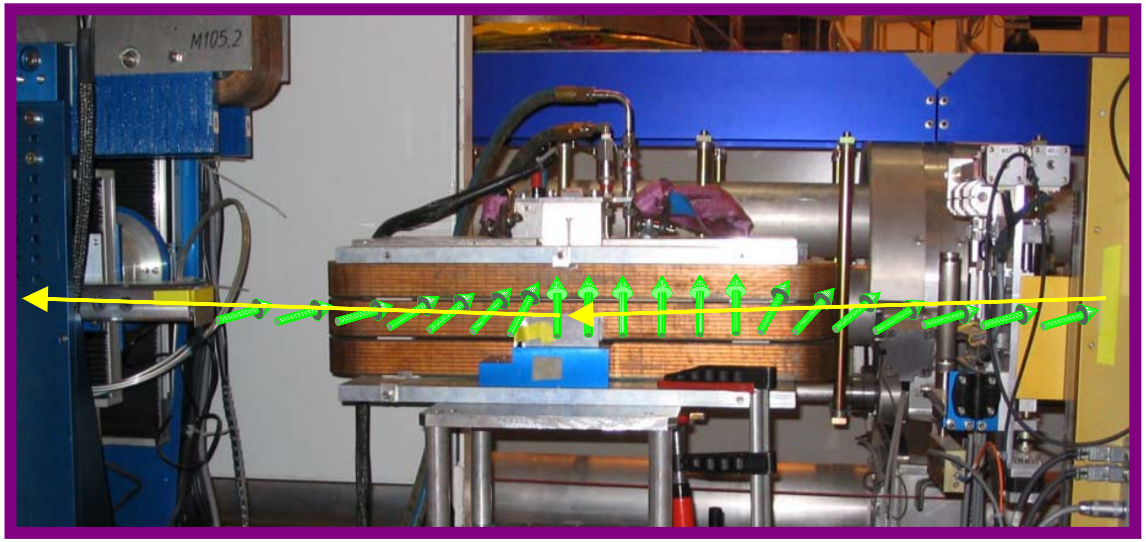
af screw



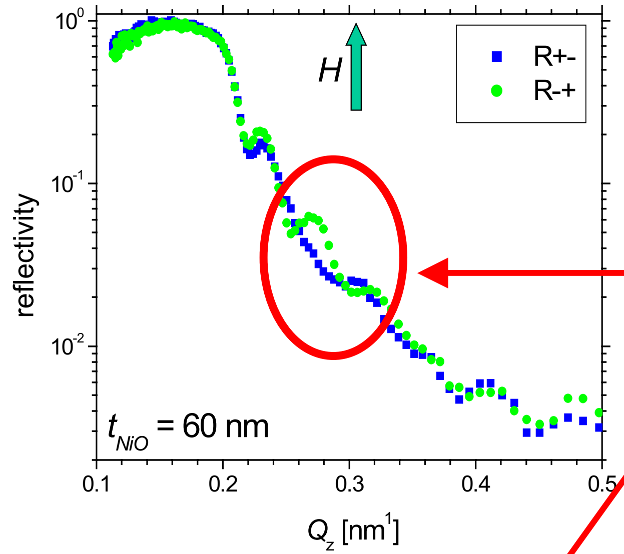
scattering geometry



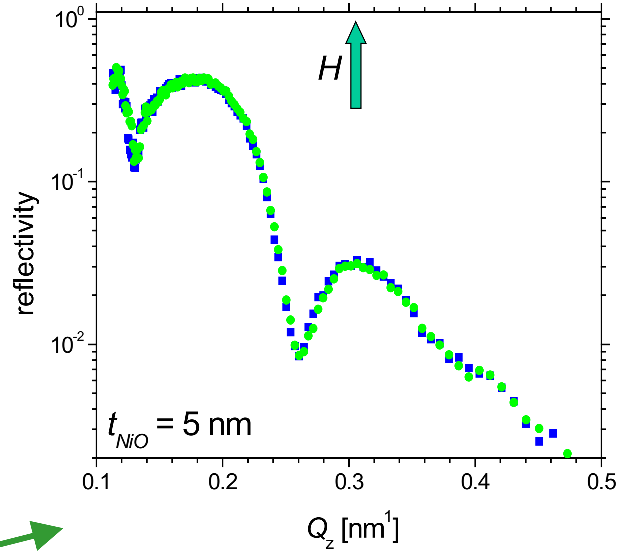
$$\sigma_c = i\mathbf{P}_0 \cdot \left(\mathbf{S}_{bot} \times \mathbf{S}_{top}\right)$$

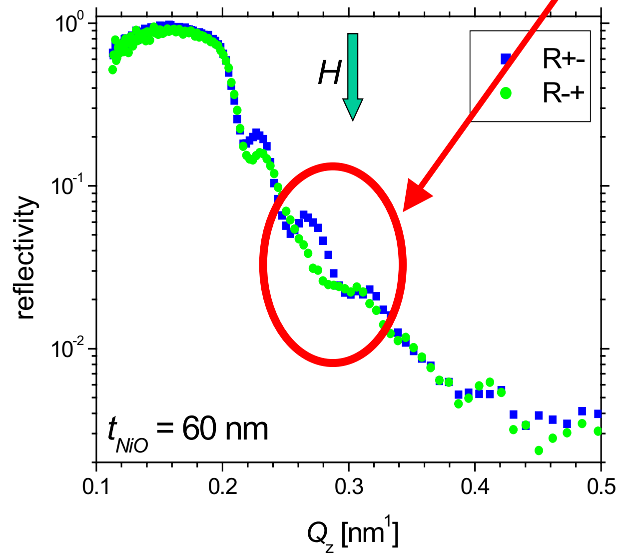


Chirality in Multilayers



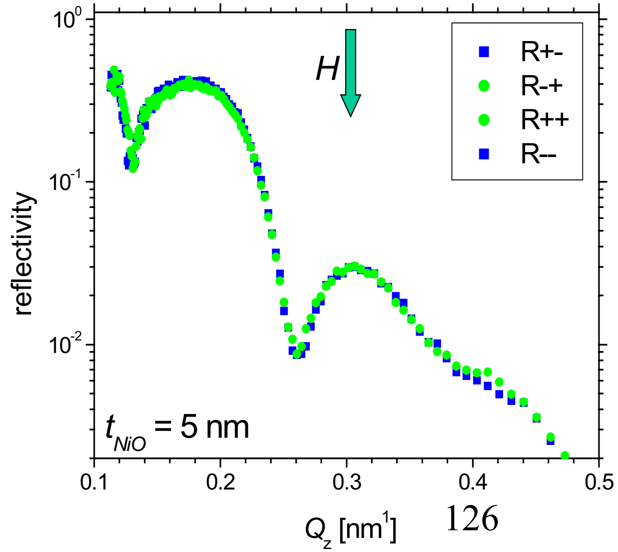
asymmetry in SF-signal





SF-signal is symmetric
⇔ magnetization rotates together

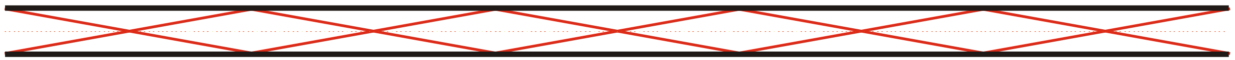
GMR sensors for angular measurements



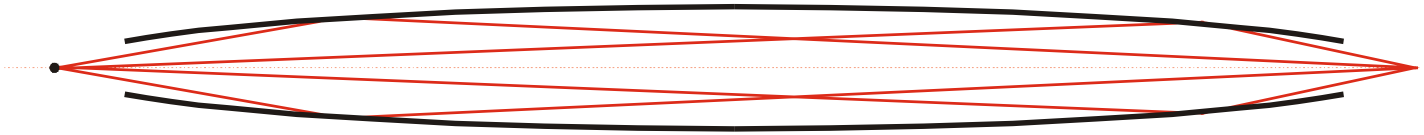
10. Focusing Techniques

Elliptic Guides - Large Critical Angles

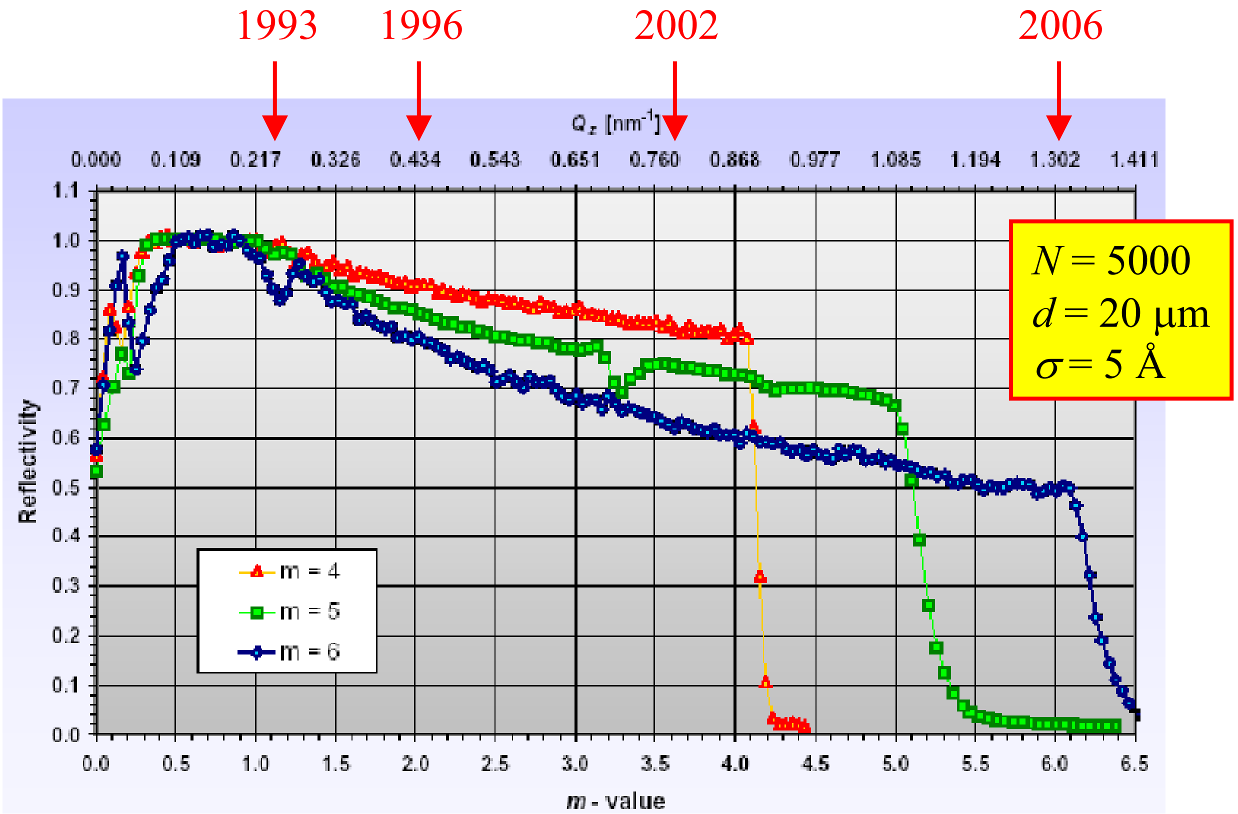
Past - present:



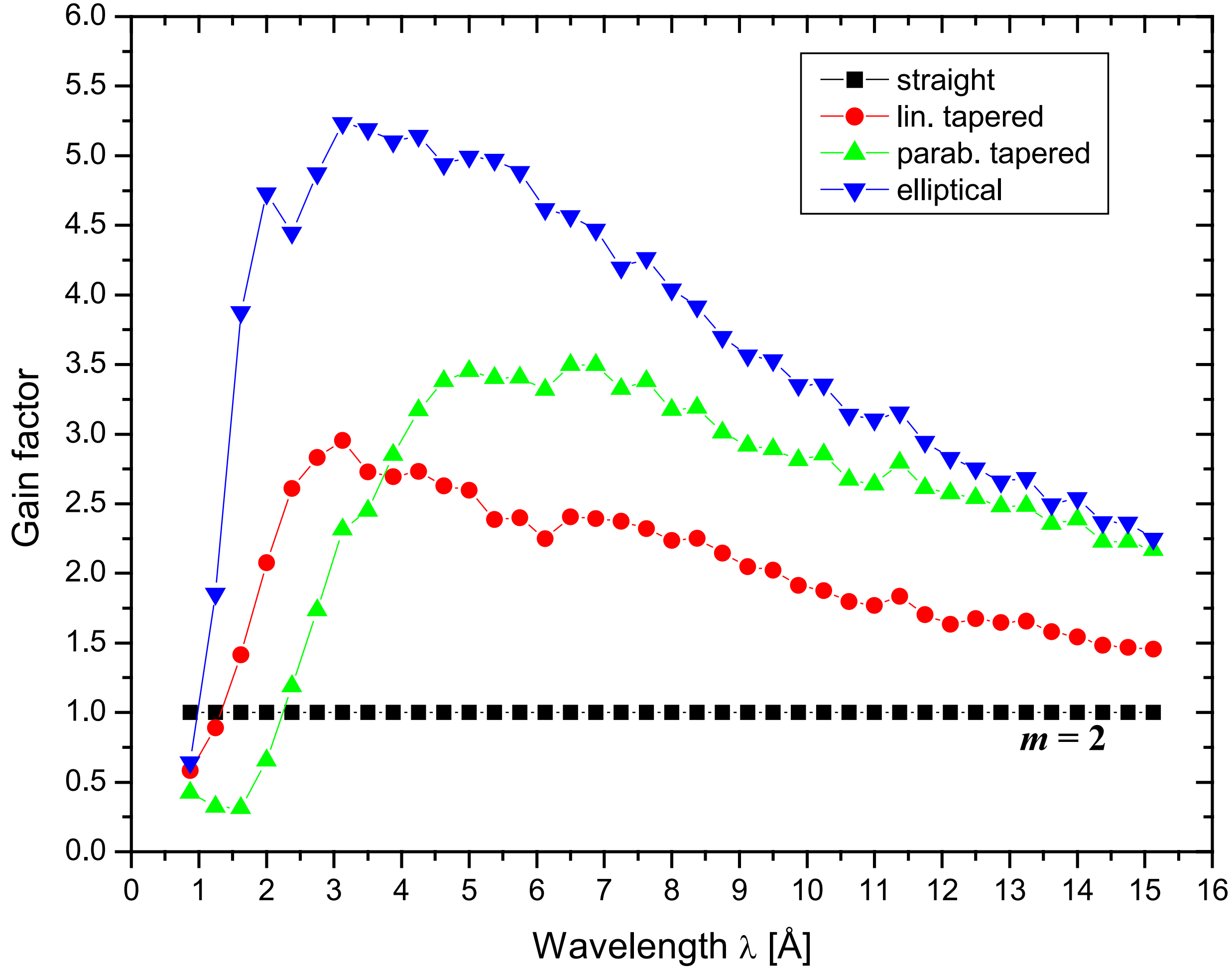
Present – future:



Coatings:



Intensity Gain with Elliptic Guides

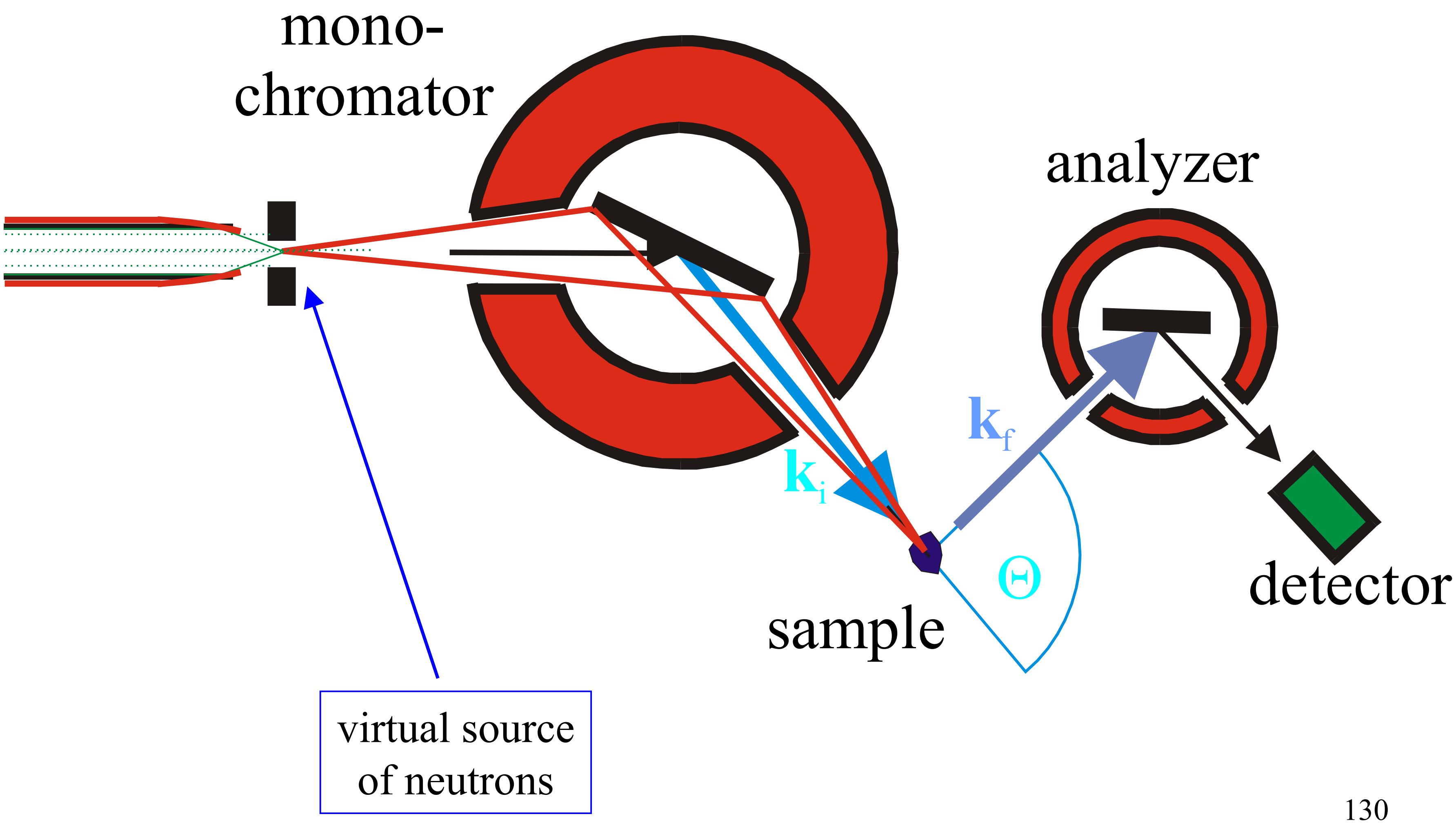


Gain: > 5
with $m = 3$

Now: $m = 6$

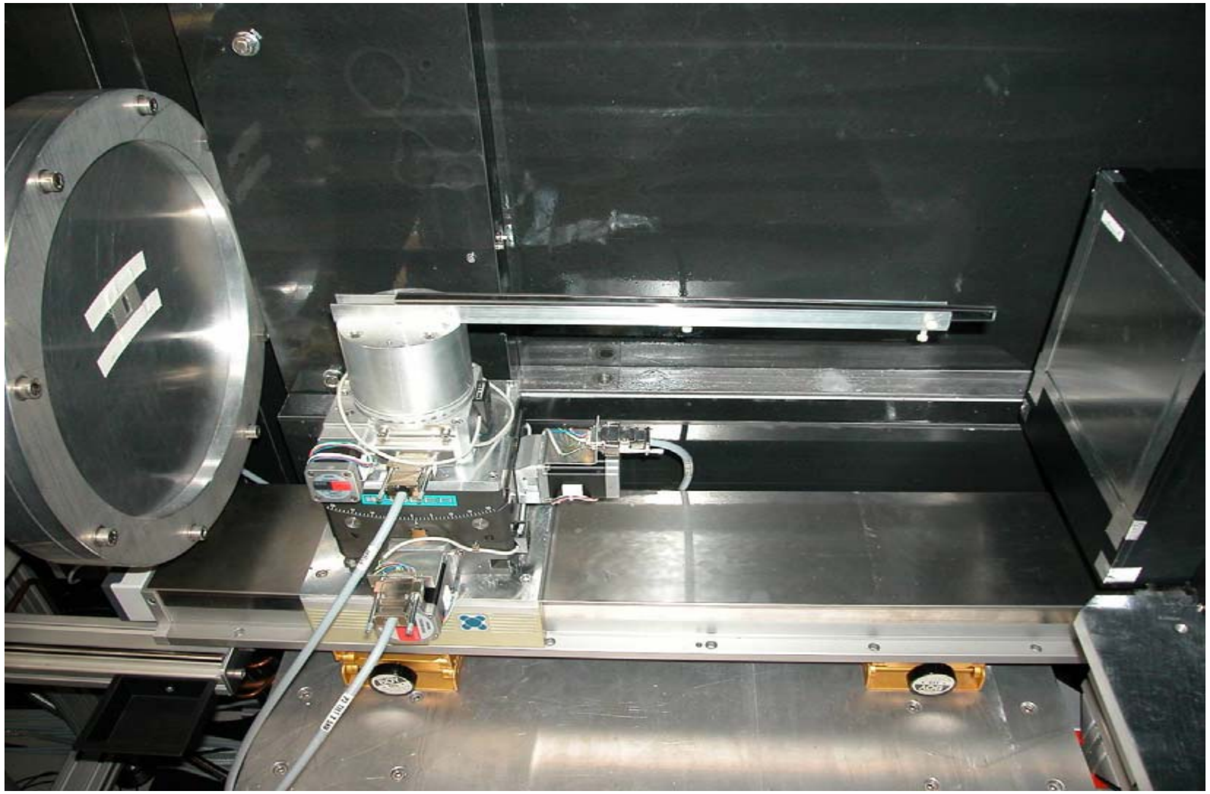
(C. Schanzer, P. Böni, and U. Filges, Nucl. Inst. and Meth. A **529**, 63-68 **(2004)**)

Guides - Monochromators



Elliptic Focusing: Set up

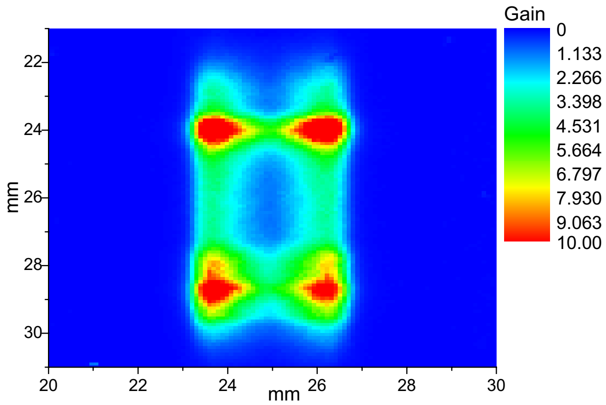
- exit: 4 x 8 mm²
- largest cross-section: 10.59 x 21.17 mm²
- focal point: 80 mm



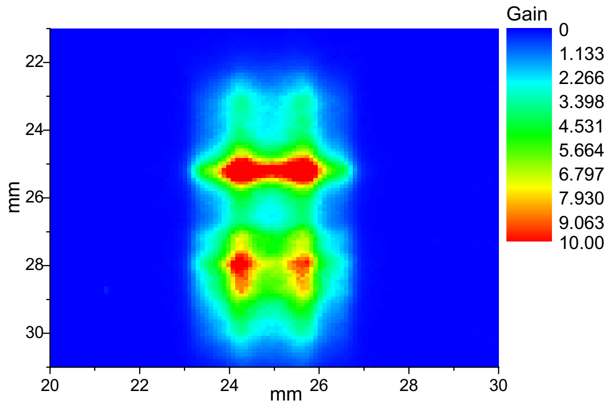
N. Kardjilov et al., NIMA **542** (2005) 248.

Experimental Results: Elliptic Focusing

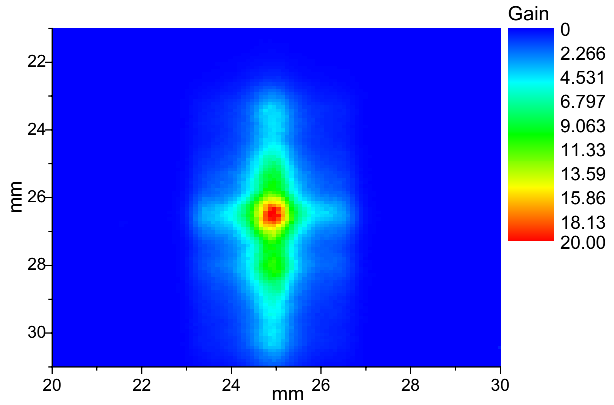
$\lambda = 3$ Å



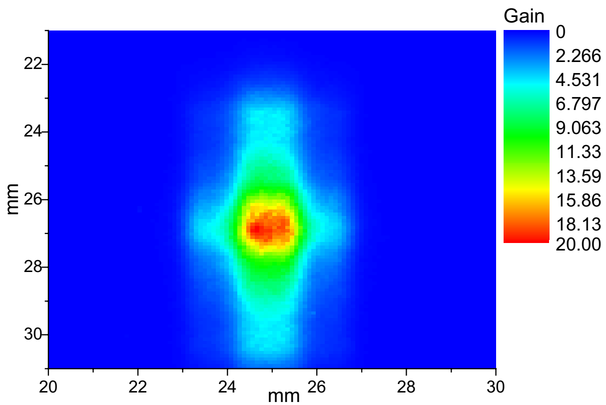
Distance: 0 mm



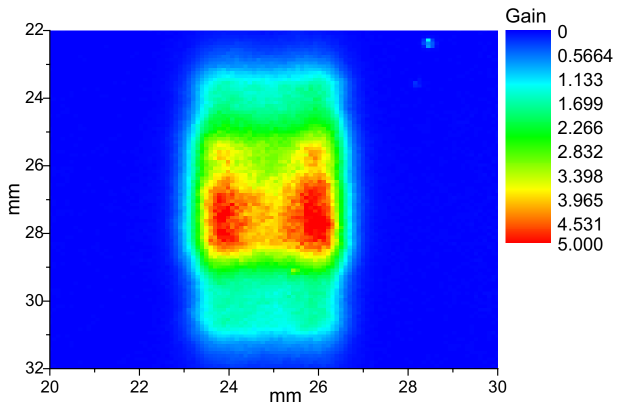
40 mm



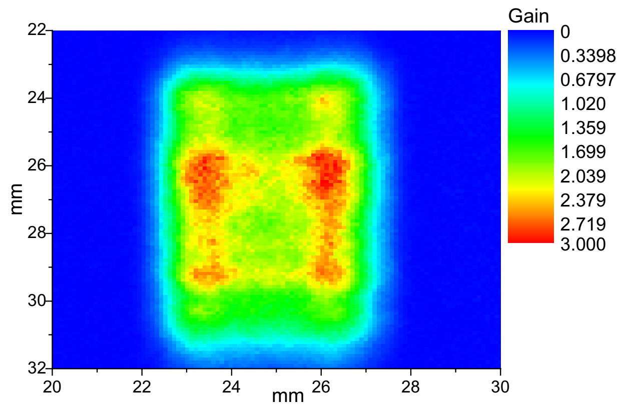
80 mm



Distance: 100 mm



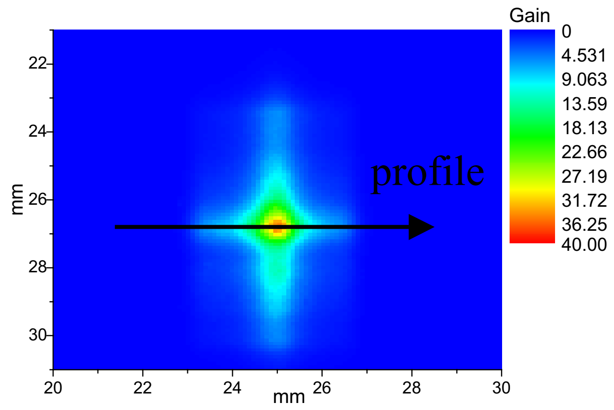
150 mm

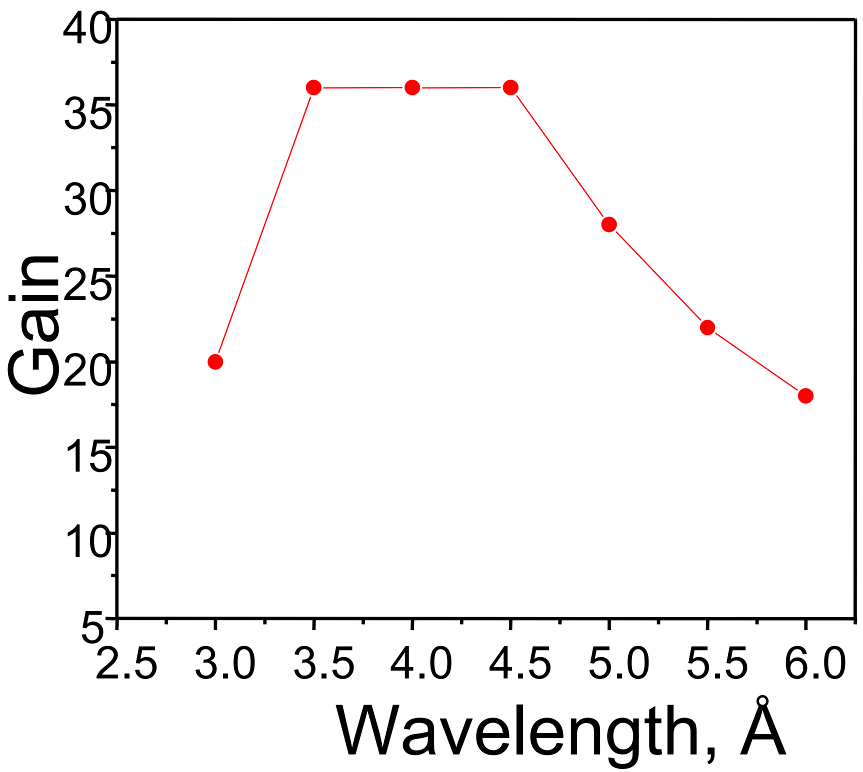


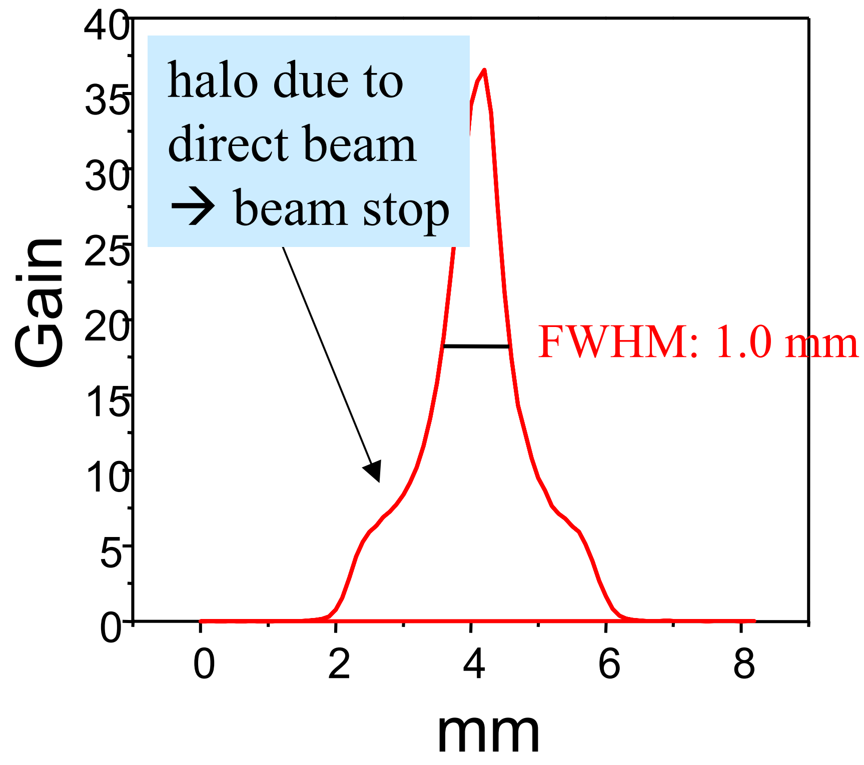
200 mm

collaboration with N. Kardjilov, HMI

Performance of Elliptic Focusing



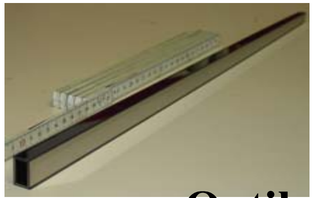




Next step: *m* = 3 → 6, use polarizing coatings

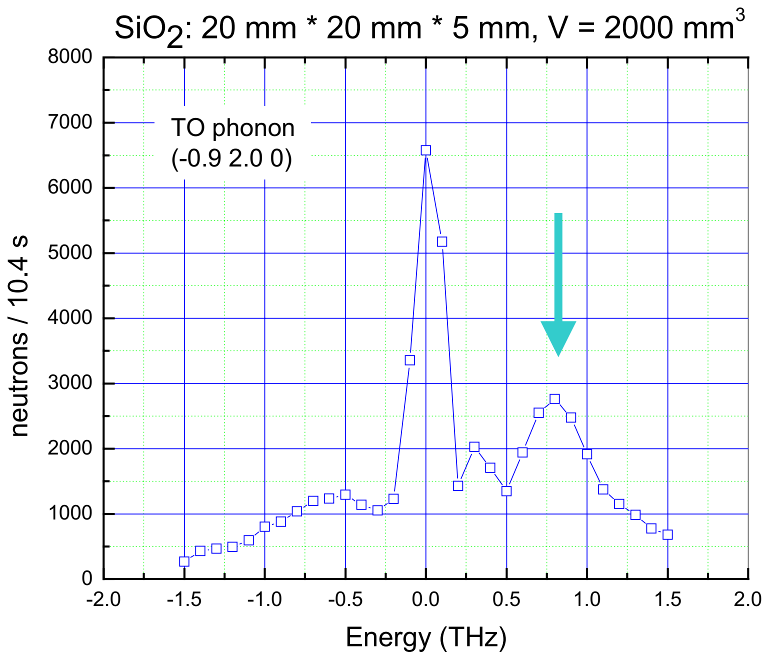
Inelastic Scattering and Focusing

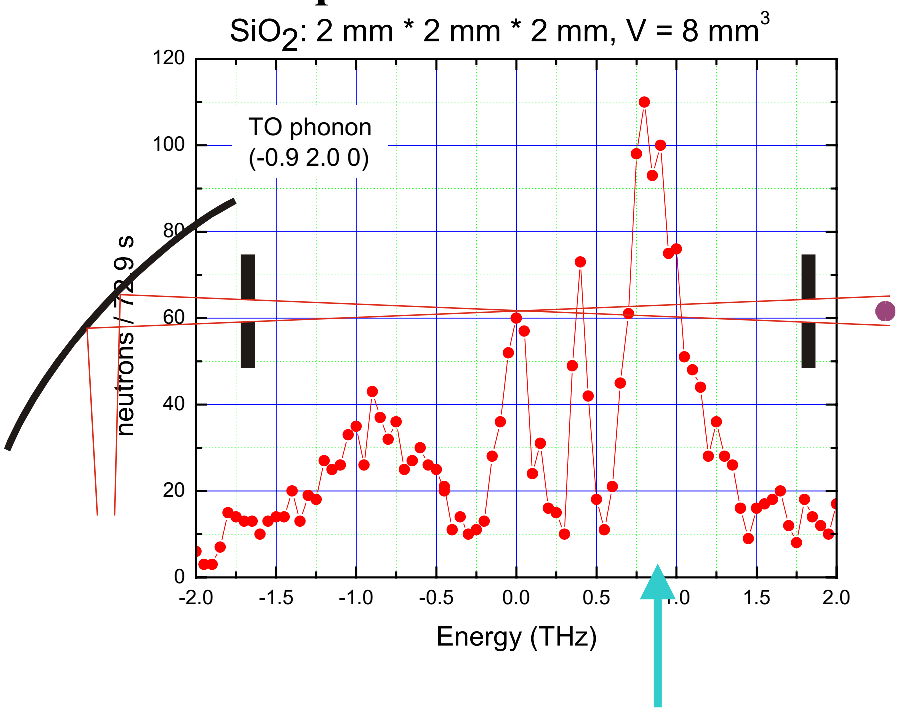
+



+

Optik





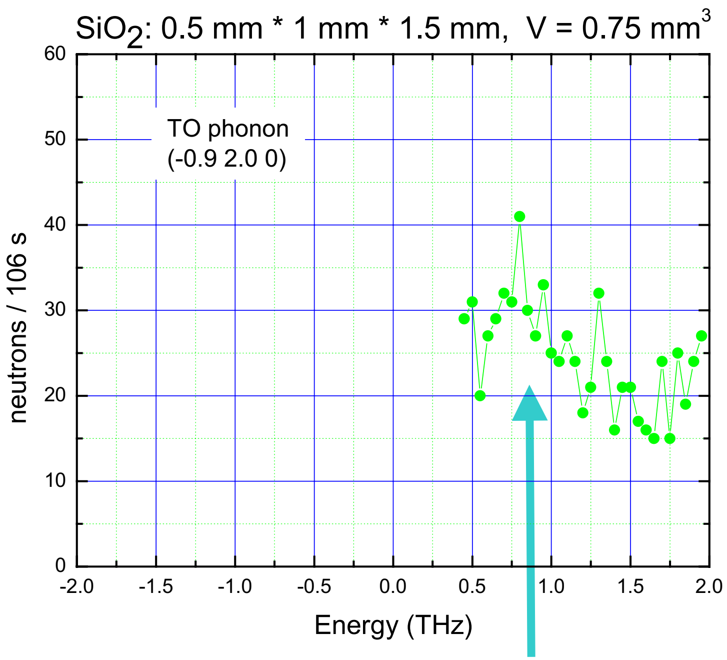
- volume of sampe: **250 times smaller**
- low background
- better resolution

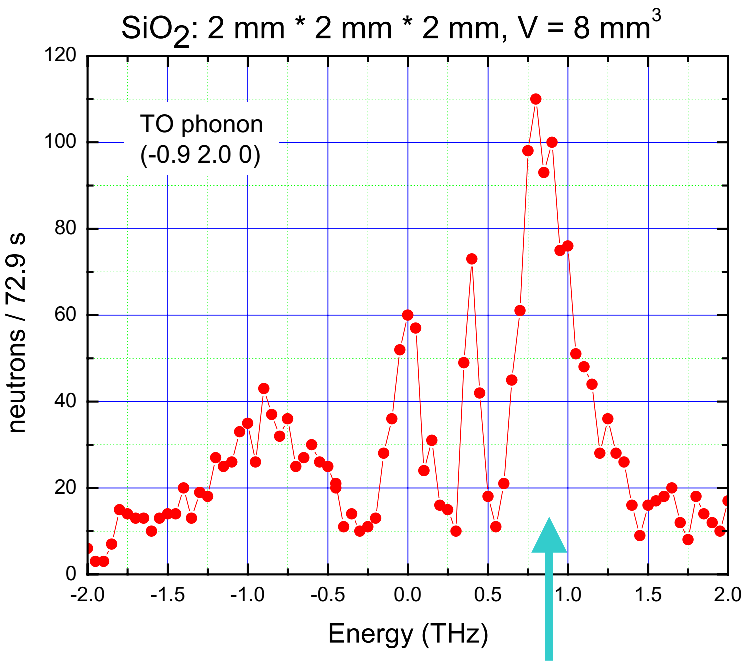
Hradil, Mühlbauer, Böni
4. Oktober 2007

Going to the limits

+

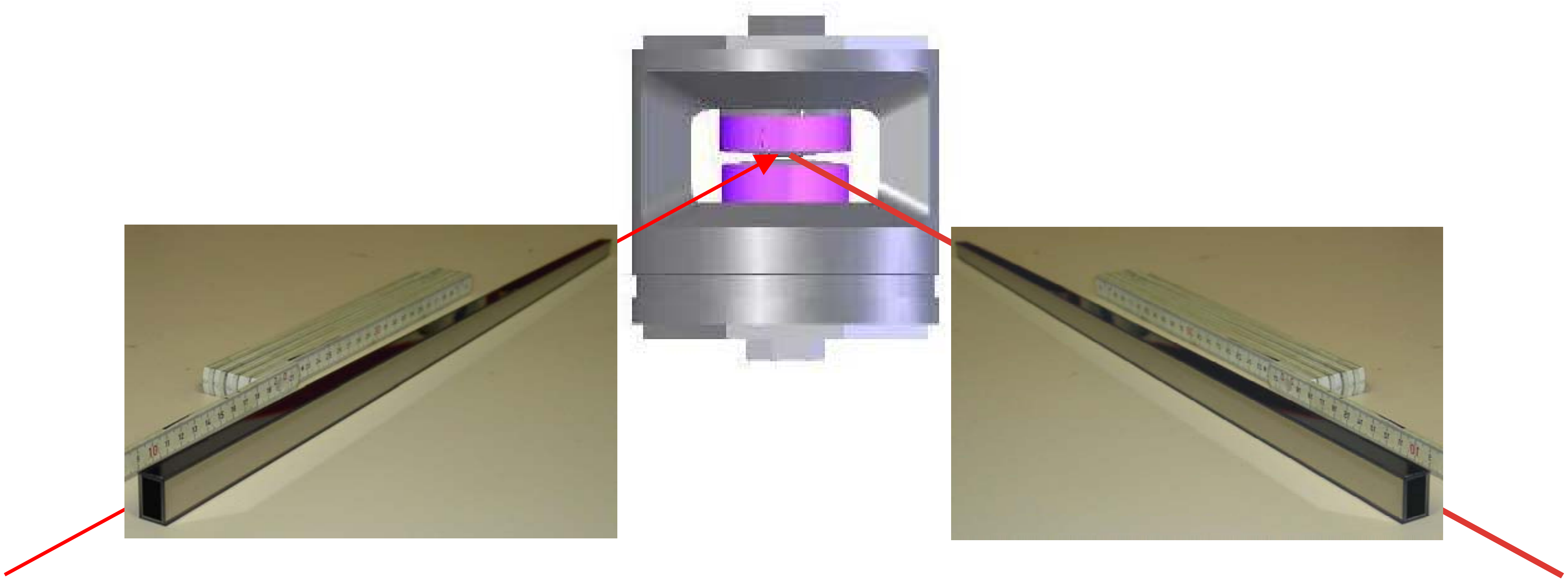
+





- volume of sampe: > **2000 times smaller**
- low background
- better resolution

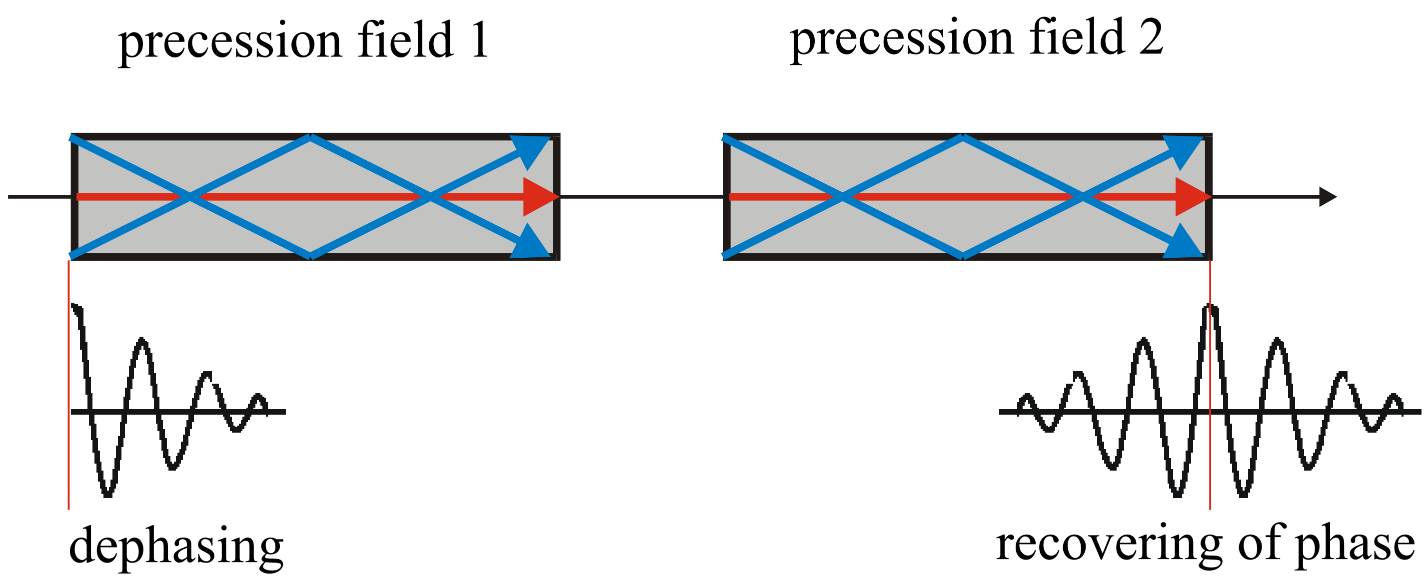
Future Applications



Experiments are possible with very small samples (comp. synchrotron radiation):

→ extreme environment (p, **B**)
→ quantum phase transitions
→ combine with polarization of neutrons

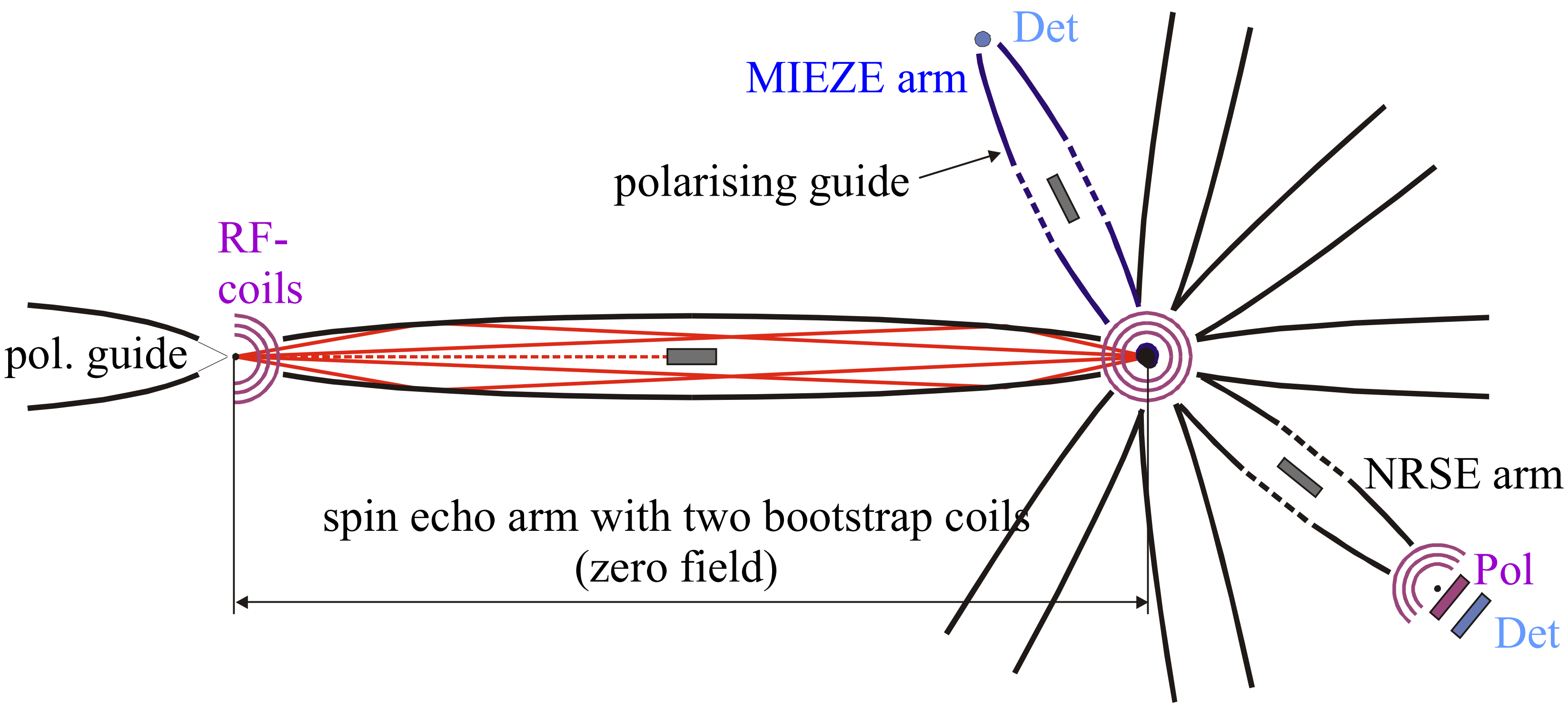
Elliptic Guides - NSE



• large beams → low intensity

• large beams → large divergence → various $\int \mathbf{H} d\mathbf{s}$
→ decrease of resolution

Solution with Elliptic Guides



- same flight paths
- good resolution
- multi angle
- compact design

- low RF-power
- low heat production
- compact design
- simple detector for MIEZE

11. Conclusions

Conlusions

• extraction of magnetic cross sections

• separation of magnetic modes

• itinerant antiferromagnets: Fermi surface topology

• chirality in itinerant magnets and multilayers

• next: 3-*d* polarization analysis of magnetic excitations

• high energy resolution with neutron spin echo

• extreme spatial resolution with Larmor diffraction

• large intensity gains possible by combining polarization analysis and focusing techniques

Missing: Polarized beam instruments at pulsed sources

How to polarize neutrons:

• most efficient for polarizing neutrons: polarizing guides
→ consider activation problems (Co)

• (linear) position sensitive detectors:
- cold/thermal neutrons: supermirrors
- hot/epithermal neutrons: ^{3}He or supermirrors with very large *m*

• area detectors: ^{3}He most convenient

→ Urgent need for polarized beam lines
in particular for time of flight instruments

Acknowledgments

- C. Schanzer
- M. Janoschek
- S. Mühlbauer
- R. Gähler
- B. Roessli
- C. Pfleiderer
- and many others …

Literature

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