Polarized Neutrons

Peter Böni
Physik-Department E21
Technische Universität München
D-85747 Garching, Germany

E-mail: peter.boeni@frm2.tum.de
Web: www.ph.tum.de

School on Pulsed Neutron Sources, Oct. 17-28 2005, The Abdus Salam International Centre for Theoretical Physics

Topics

- Need for polarized neutrons
- Production of polarized neutrons
- Implementation of polarization analysis
- Magnetic scattering cross section: EuS
- Rules for polarization analysis
- Examples: coherent/incoherent: NbD
  background suppression: Fe
  separation of modes: EuS, Cr
  chirality: MnSi, trilayers
- Summary

Need for Polarized Neutrons 1

- nuclear interaction: $\dfrac{2\pi\hbar^2}{m} b\delta(\mathbf{r} - \mathbf{r}_j)$

isotopic incoherence $\Leftrightarrow$ spin incoherence

Need for Polarized Neutrons 1

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

isotopic incoherence $\Leftrightarrow$ spin incoherence

Ni ($I \cong 0$)

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

$$\rightarrow \sigma_{coh} = 4\pi\left(\bar{b}\right)^2$$

does not depend on spin

Need for Polarized Neutrons 1

- nuclear interaction: $\dfrac{2\pi\hbar^2}{m} b\delta(\mathbf{r}-\mathbf{r}_j)$

isotopic incoherence $\Leftrightarrow$ spin incoherence

Ni ($I \cong 0$)

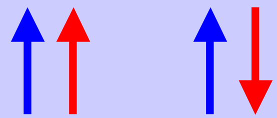
$$\bar{b} = \sum_i f_i b_i$$

$$\rightarrow \sigma_{coh} = 4\pi\left(\bar{b}\right)^2$$

does not depend on spin

hydrogen (I = 1/2)

$$\bar{b} = f^+ b^+ + f^- b^- = \tfrac{3}{4} b^+ + \tfrac{1}{4} b^-$$



spin - dependent

Need for Polarized Neutrons 1

• nuclear interaction: $\dfrac{2\pi\hbar^2}{m} b\delta(\mathbf{r}-\mathbf{r}_j)$

isotopic incoherence $\Leftrightarrow$ spin incoherence

Ni ($I \cong 0$)

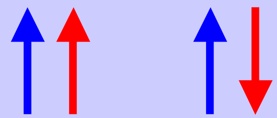
$$\bar{b} = \sum_i f_i b_i$$

$$\rightarrow \sigma_{coh} = 4\pi\left(\bar{b}\right)^2$$

does not depend on spin

hydrogen ($I = 1/2$)

$$\bar{b} = f^+ b^+ + f^- b^- = \tfrac{3}{4} b^+ + \tfrac{1}{4} b^-$$



spin - dependent

Possibility to distinguish between coherent and incoherent scattering

Need for Polarized Neutrons 2

- magnetic moments: $I_{Bragg} \propto b^2 + \frac{2}{3} p^2$

Ni: b = 1.03 ·10^{-12} cm
p = 0.164·10^{-12} cm → 1.7% effect!

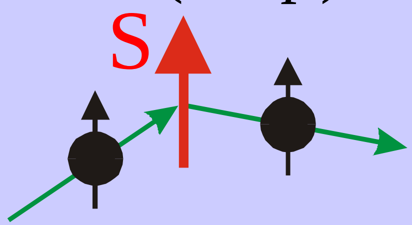
Possibility to measure small magnetic moments

Need for Polarized Neutrons 2

- magnetic moments: $I_{Bragg} \propto b^2 + \frac{2}{3} p^2$

Ni: $b = 1.03 \cdot 10^{-12}$ cm
$p = 0.164 \cdot 10^{-12}$ cm → 1.7% effect!

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



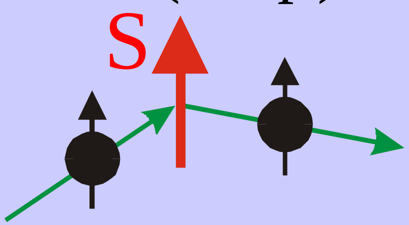
Possibility to measure small magnetic moments

Need for Polarized Neutrons 2

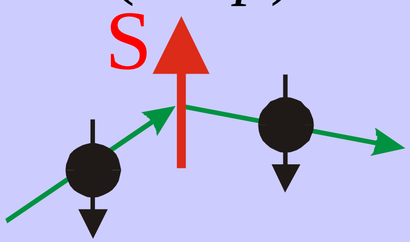
- magnetic moments: $I_{Bragg} \propto b^2 + \frac{2}{3} p^2$

Ni: $b = 1.03 \cdot 10^{-12}$ cm
$p = 0.164 \cdot 10^{-12}$ cm → 1.7% effect!

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



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



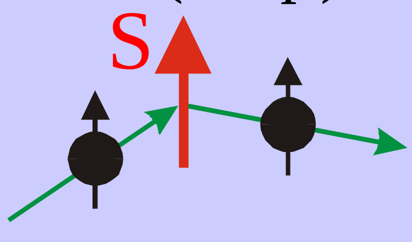
Possibility to measure small magnetic moments

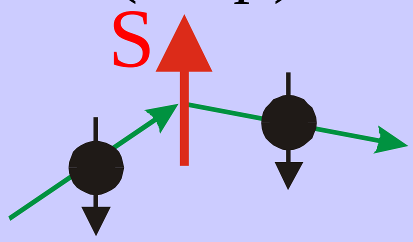
Need for Polarized Neutrons 2

- magnetic moments: $I_{Bragg} \propto b^2 + \frac{2}{3} p^2$

Ni: $b = 1.03 \cdot 10^{-12}$ cm
$p = 0.164 \cdot 10^{-12}$ cm → 1.7% effect!

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





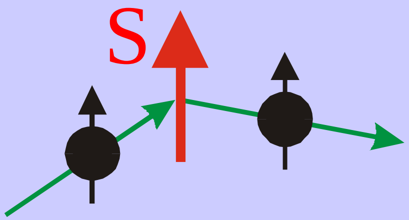
$$\frac{I^{++}}{I^{--}} = \frac{(b+p)^2}{(b-p)^2} = \frac{b^2 + 2bp + p^2}{b^2 - 2bp + p^2} \cong \frac{1 + 2p/b}{1 - 2p/b} \cong 1 + 4\frac{p}{b} \cong 1.64$$

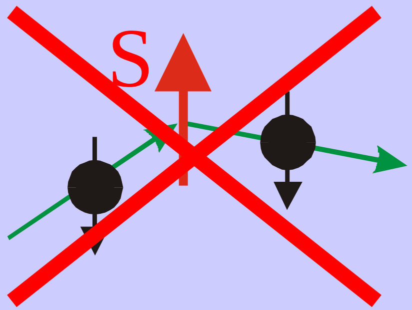
Possibility to measure small magnetic moments

Useful Application

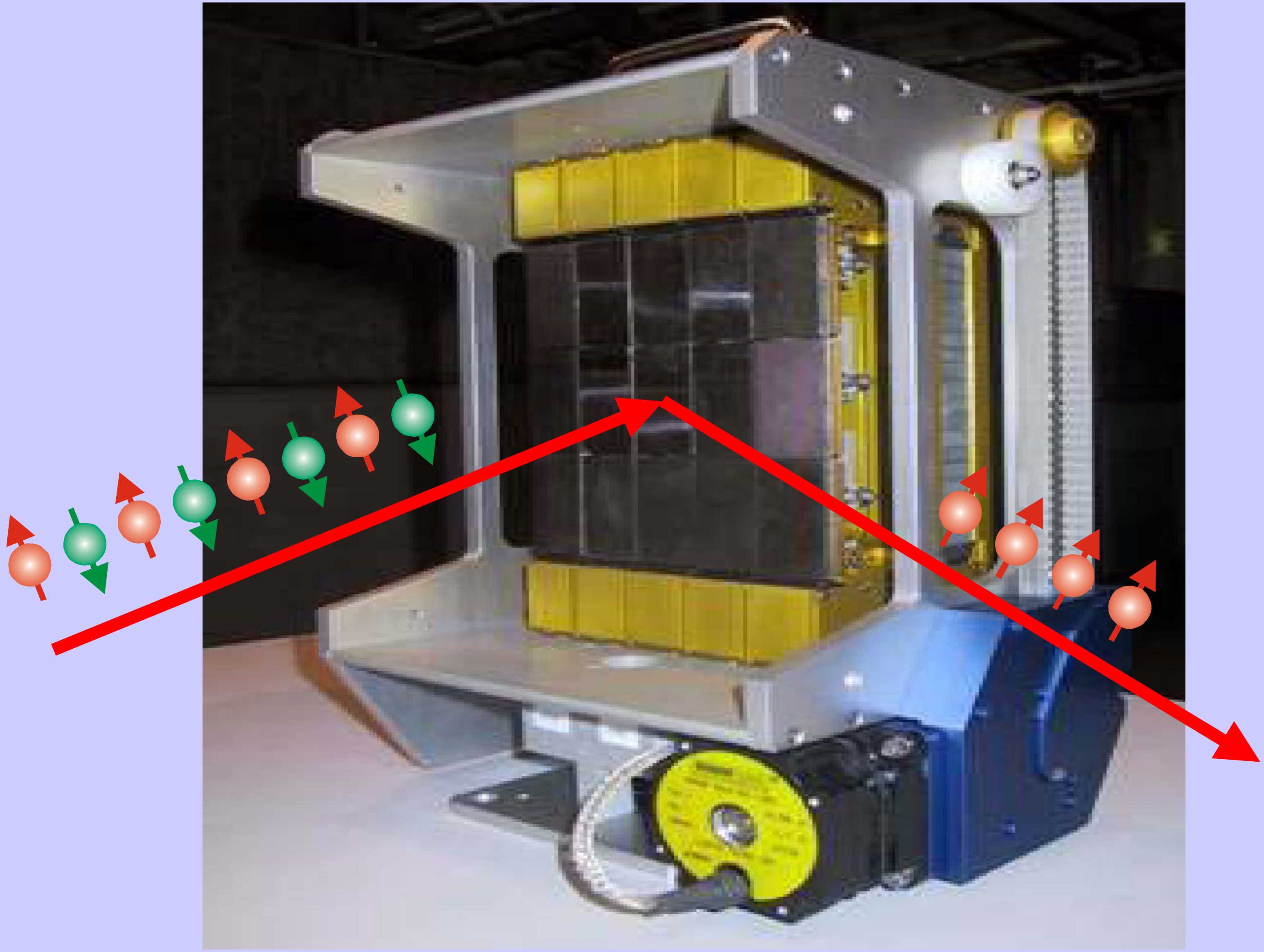
• polarizer with $b = p$:

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





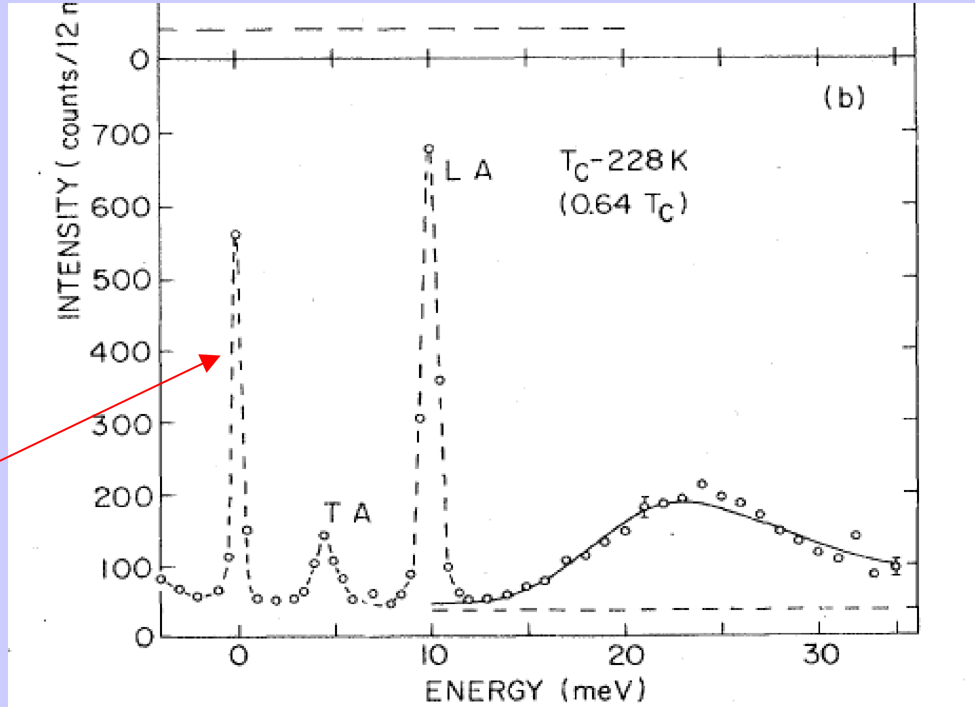
Possibility to produce polarized beams: Heusler alloy Cu_2MnAl



Spectrometer TASP at SINQ (PSI)

Need for Polarized Neutrons 3

- inelastic neutron scattering from Ni: what is what?

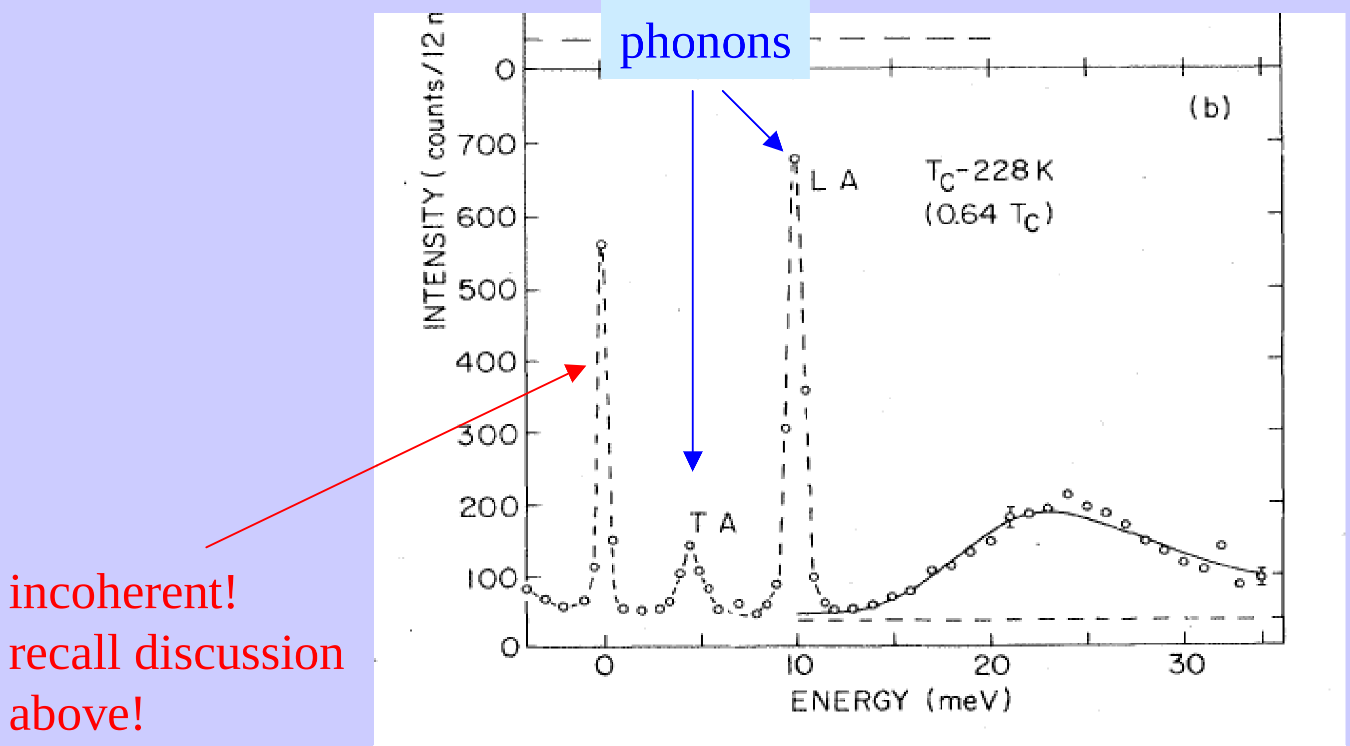


incoherent!
recall discussion
above!

Martínez et al., PRB **32**, 7037 (1985).

Need for Polarized Neutrons 3

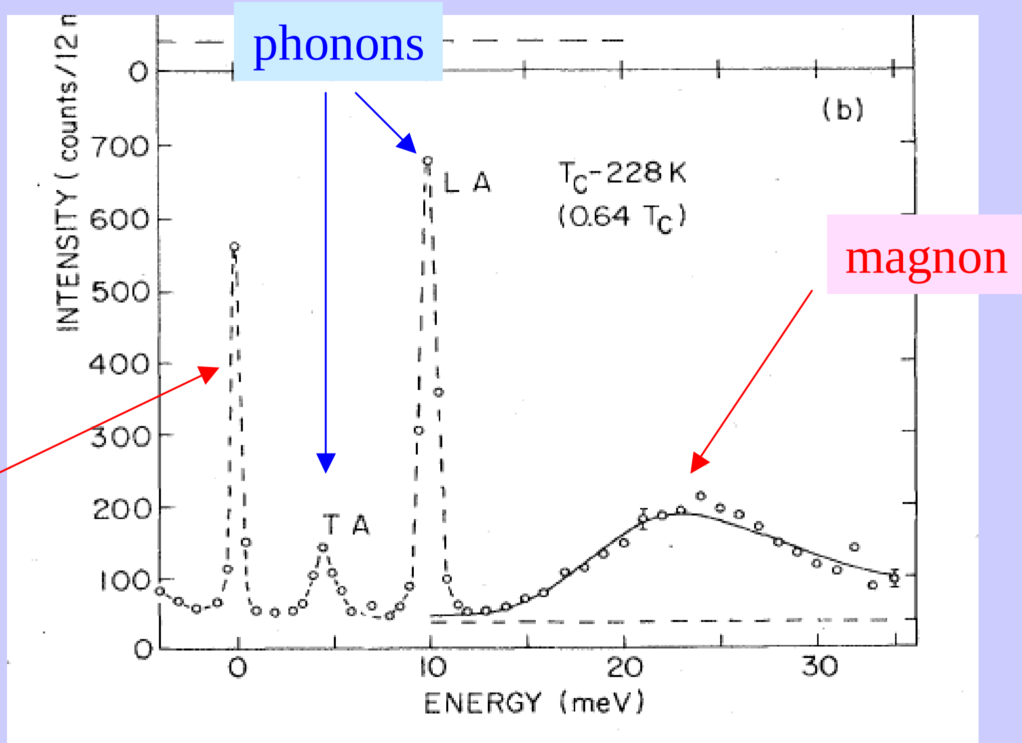
• inelastic neutron scattering from Ni: what is what?



Martínez et al., PRB **32**, 7037 (1985).

Need for Polarized Neutrons 3

- inelastic neutron scattering from Ni: what is what?

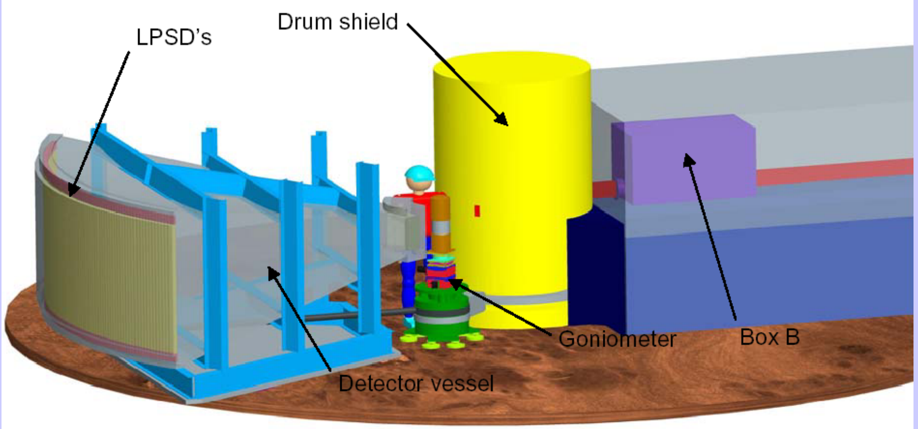


incoherent!
recall discussion
above!

Martínez et al., PRB **32**, 7037 (1985).

What is available?

- Polarized triple axis spectrometers at several reactors (ILL, HMI, NIST, FRM-II, ..) and SINQ (spallation source!)
- TOF at the ILL (D7)
- Neutron Spin Echo: ILL, Jülich, HMI, NIST, LLB, FRM-II
- pulsed sources: OSIRIS at ISIS
- planned: HYSPEC at SNS



How Can Neutrons Be Polarized

- diffraction from Heusler alloys: already discussed

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

- cold and thermal neutrons
- maintenance free
- monochromatic beams!
- however: difficult to grow

How Can Neutrons Be Polarized

- diffraction from Heusler alloys: already discussed

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

- cold and thermal neutrons
- maintenance free
- monochromatic beams!
- however: difficult to grow

- reflection from magnetized multilayers: supermirrors (F. Mezei)

- polarized ^{3}He

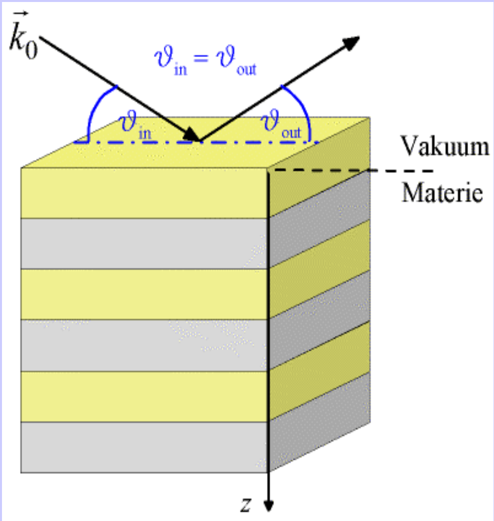
- polarized protons

- Fe-filters, Dy etc.

Supermirrors 1

• diffraction from multilayers: Bragg's law

$\lambda = 4$ Å → $\theta_c = 0.4^0$



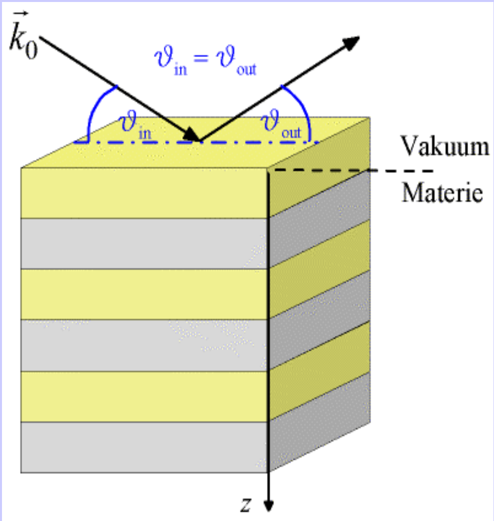
choose: $G_{\_} = G_{nm}$

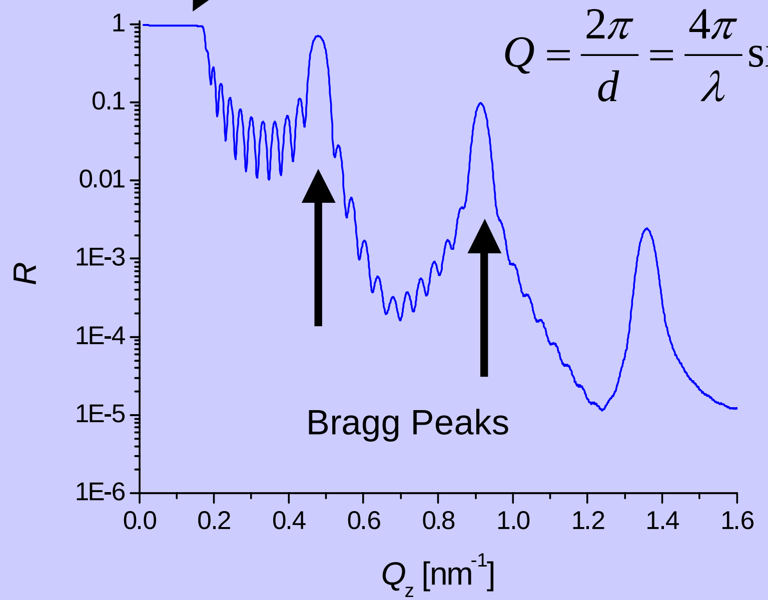
Supermirrors 1

- diffraction from multilayers: Bragg's law

$\lambda = 4$ Å → $\theta_c = 0.4^0$

total reflection: typically 0.1^0Å^{-1}





$$Q = \frac{2\pi}{d} = \frac{4\pi}{\lambda}\sin(\Theta/2)$$

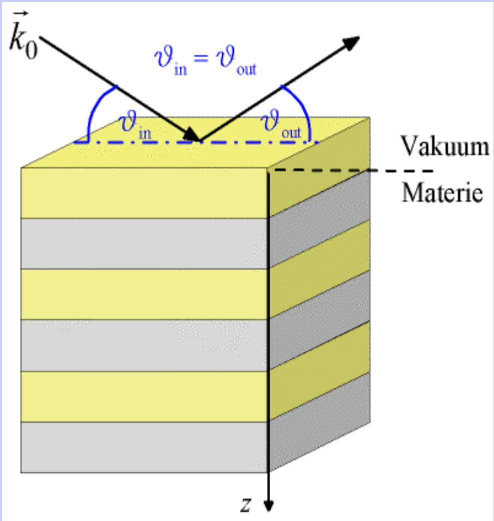
choose: $G\_ = G_{nm}$

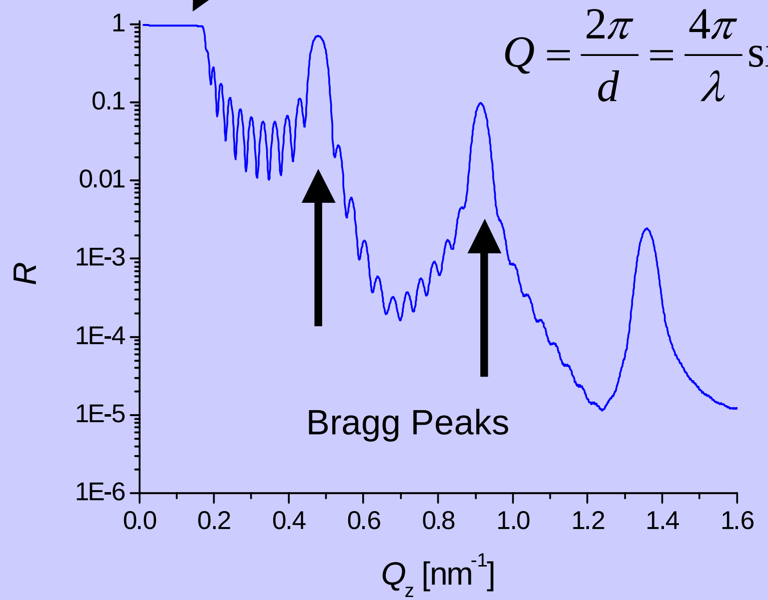
Supermirrors 1

- diffraction from multilayers: Bragg's law

$\lambda = 4$ Å → $\theta_c = 0.4^0$

total reflection: typically 0.1^0Å^{-1}





$$Q = \frac{2\pi}{d} = \frac{4\pi}{\lambda}\sin(\Theta/2)$$

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

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

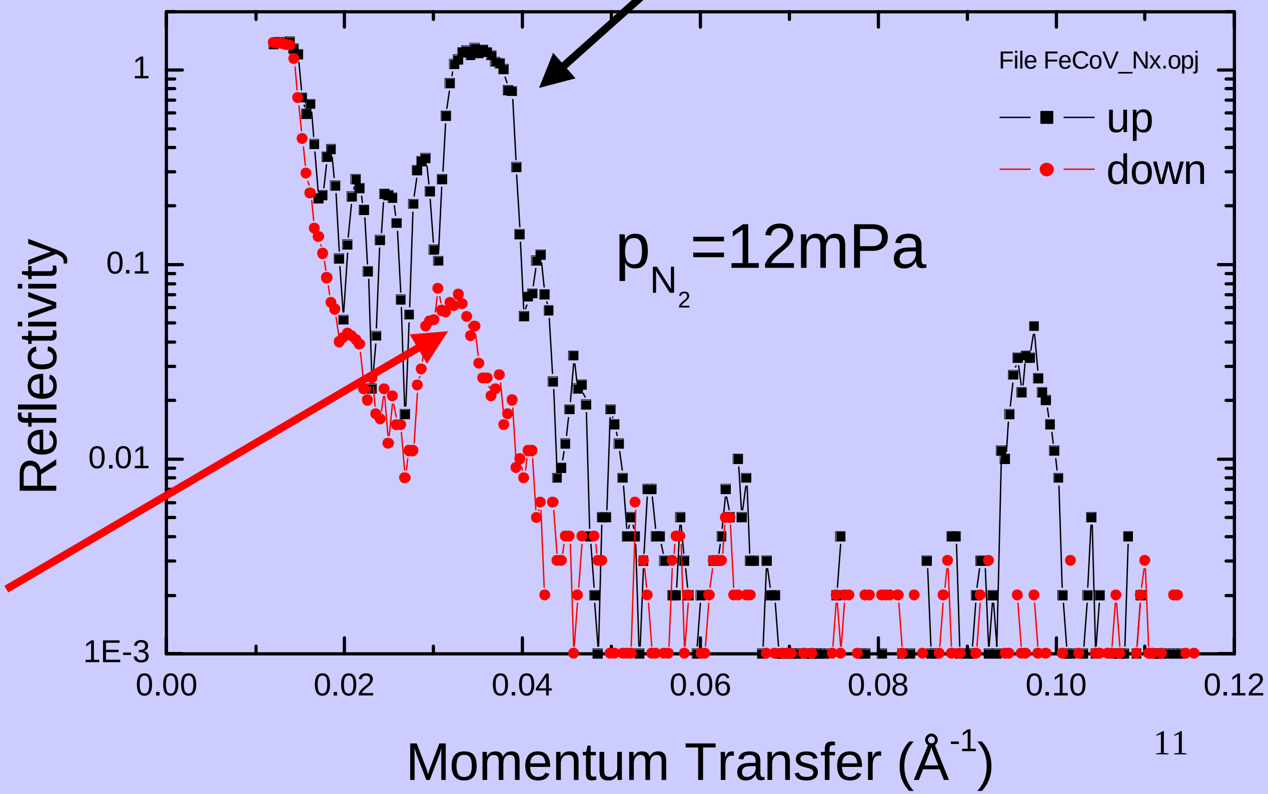
Supermirrors 2

- multilayer $FeCoV/TiN_x$: $G_- = G_{nm} \cong 0$

Supermirrors 2

- multilayer FeCoV/TiN_x: $G_- = G_{nm} \cong 0$

$(b+p)^2$

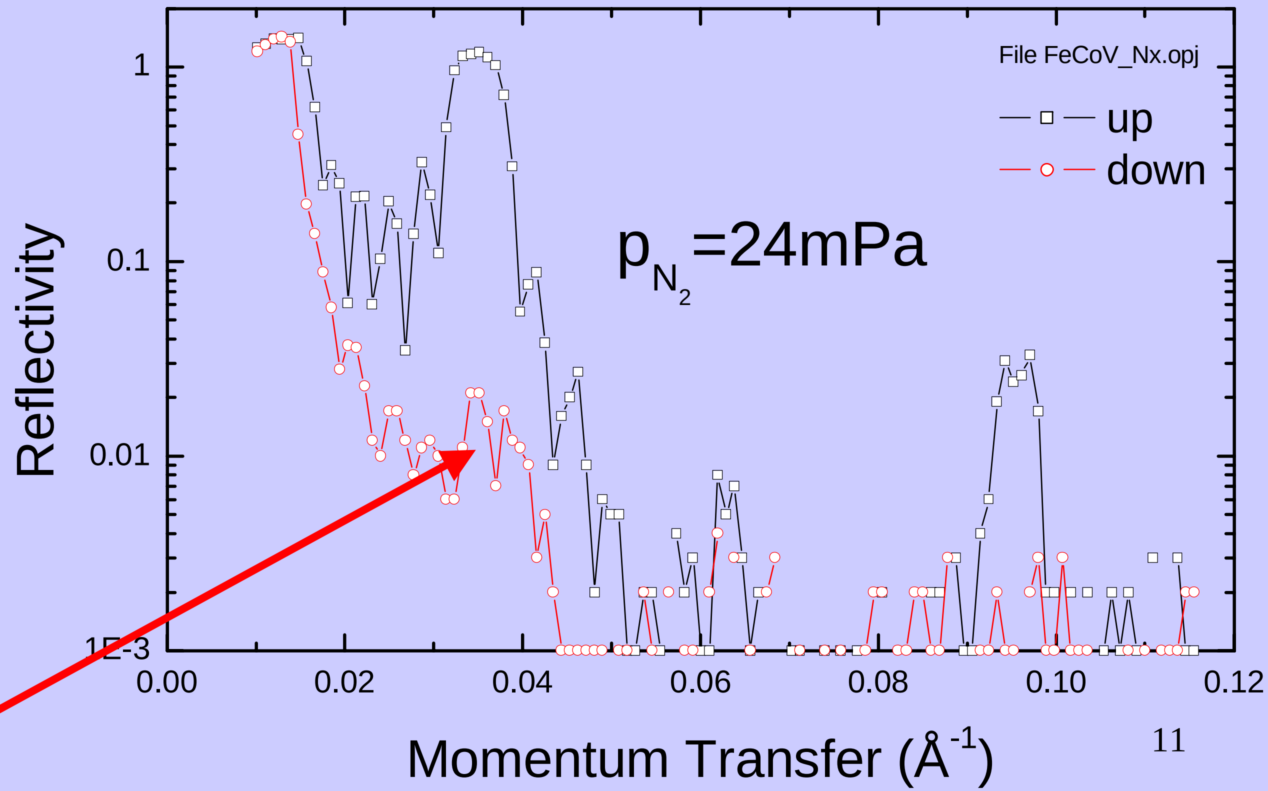


$(b\text{-}p)^2$

$b \neq p$

Supermirrors 2

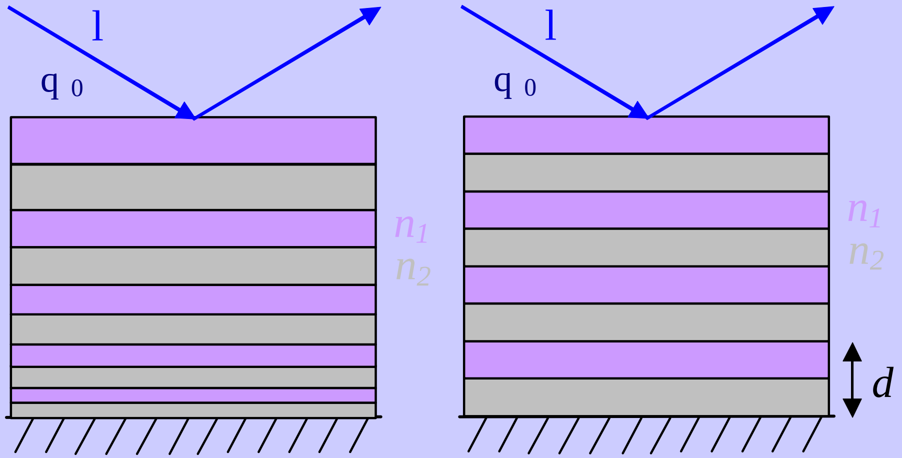
• multilayer FeCoV/TiN$_x$: $G_- = G_{nm} \cong 0$

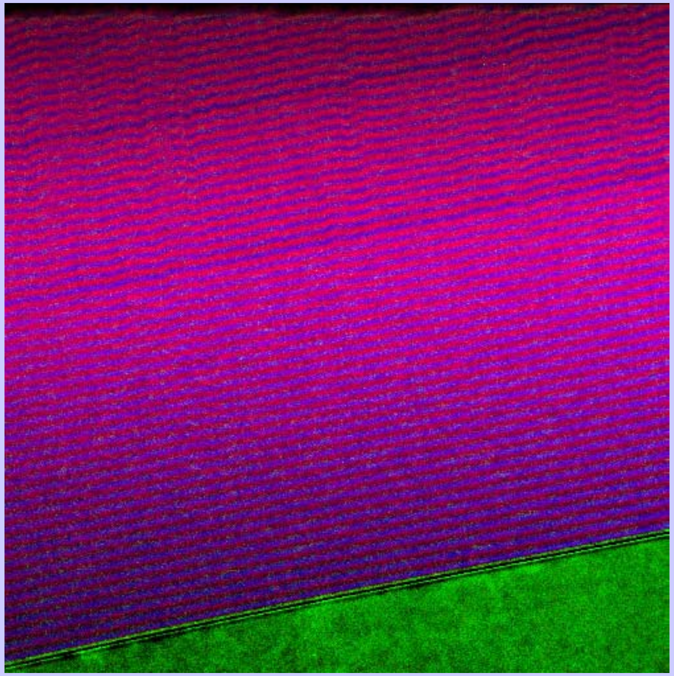


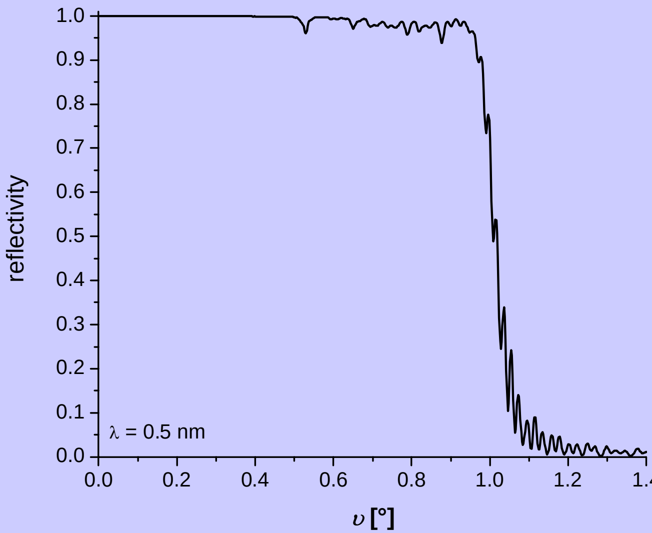
$b \cong p$

Supermirrors 3

Idea: F. Mezei

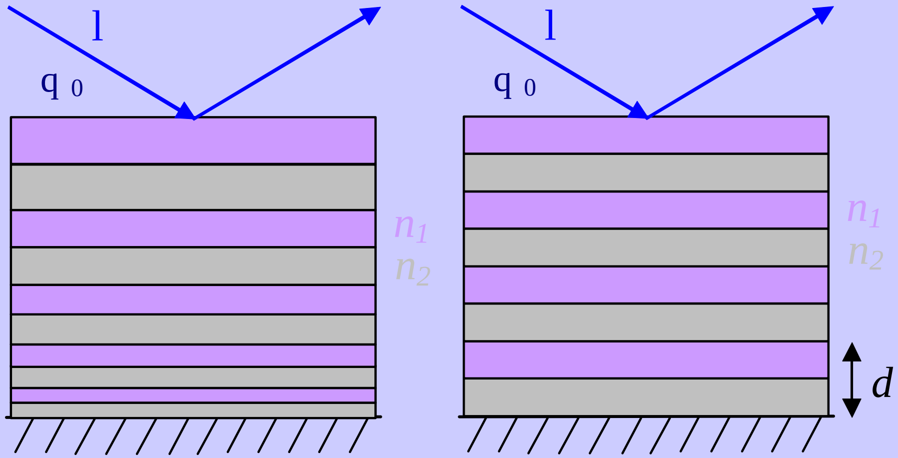


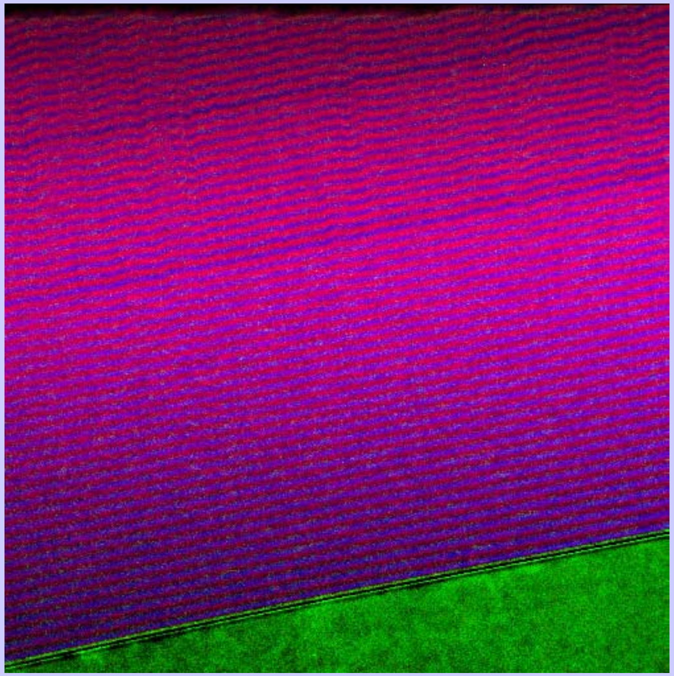


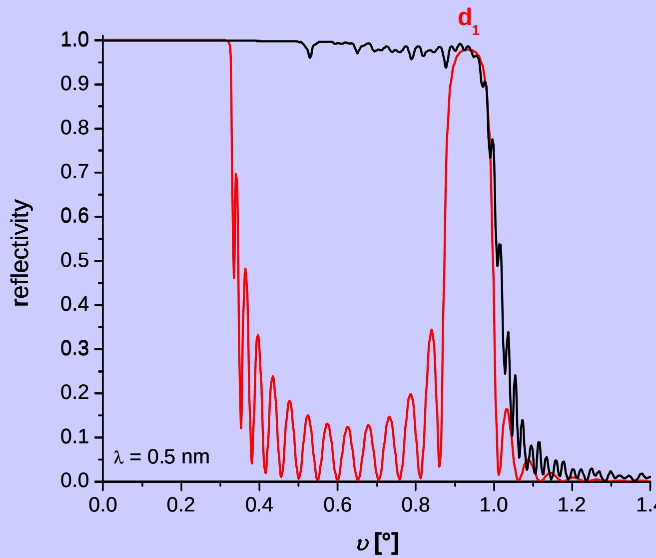


Supermirrors 3

Idea: F. Mezei

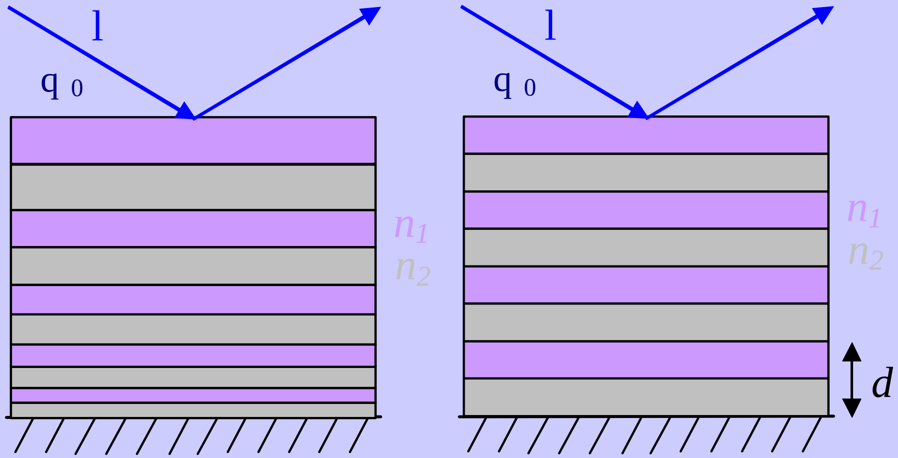


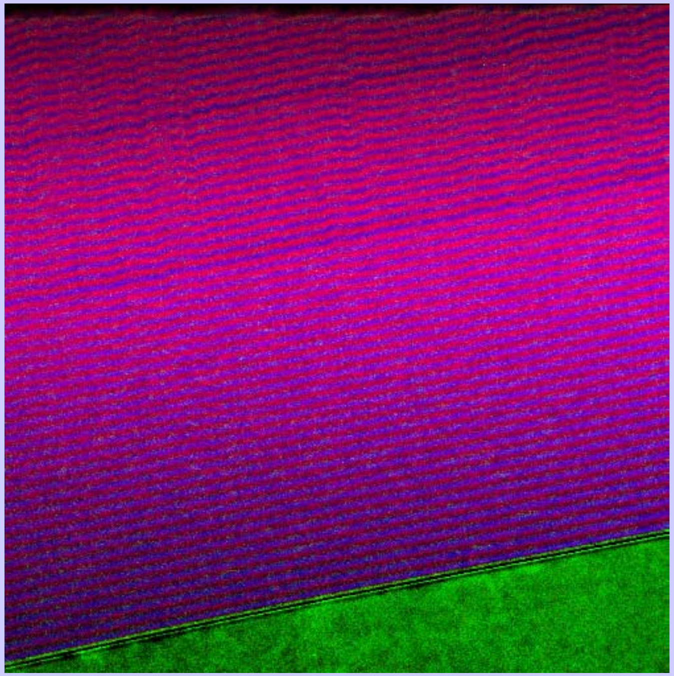


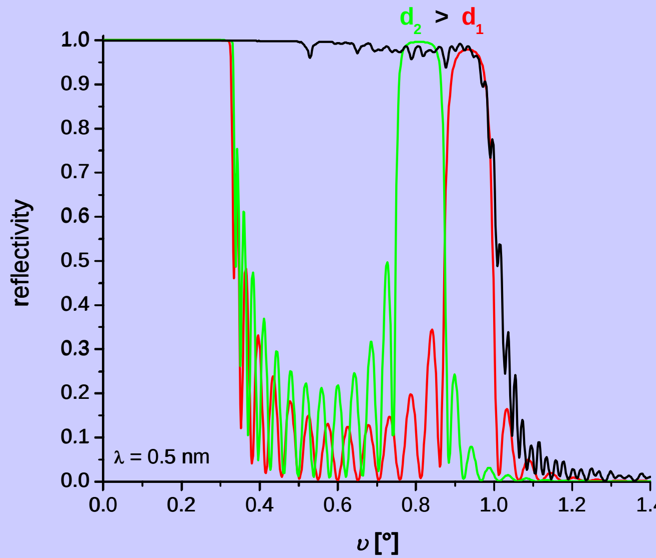


Supermirrors 3

Idea: F. Mezei

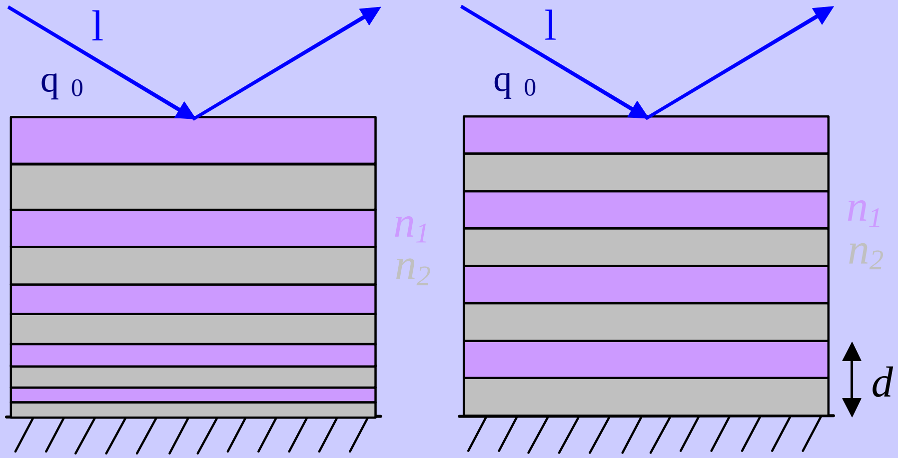


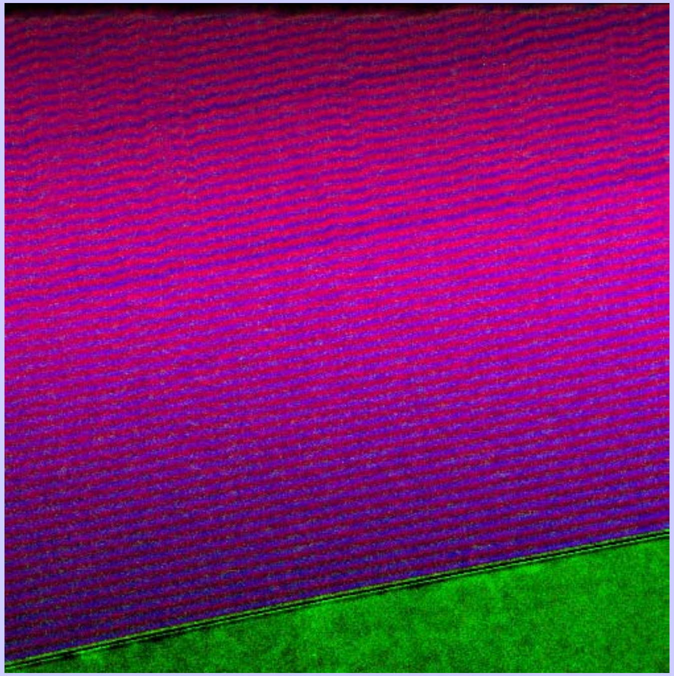


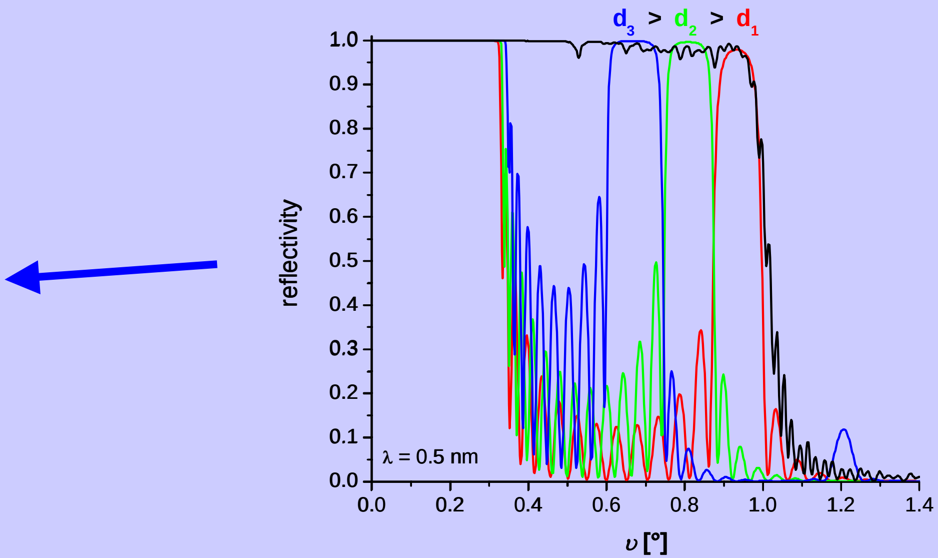


Supermirrors 3

Idea: F. Mezei



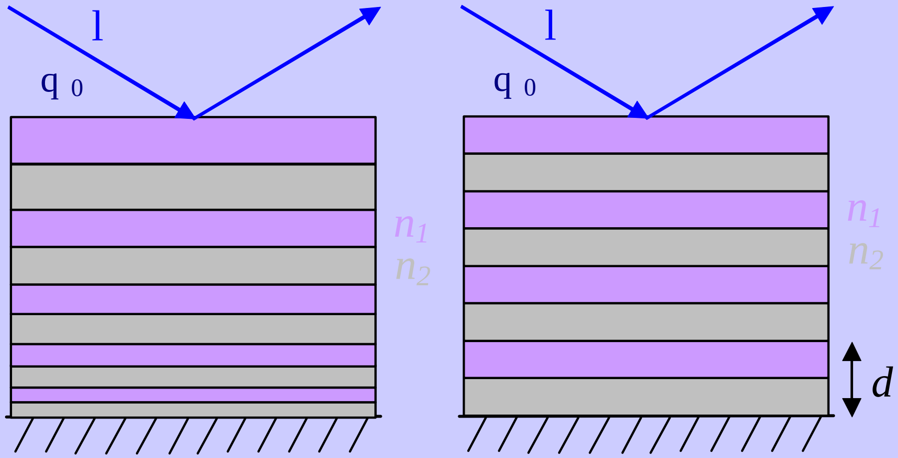


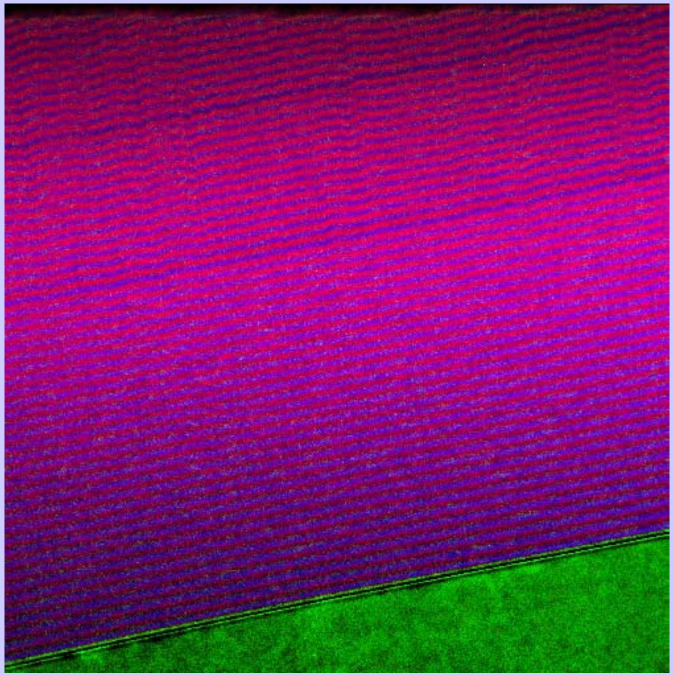


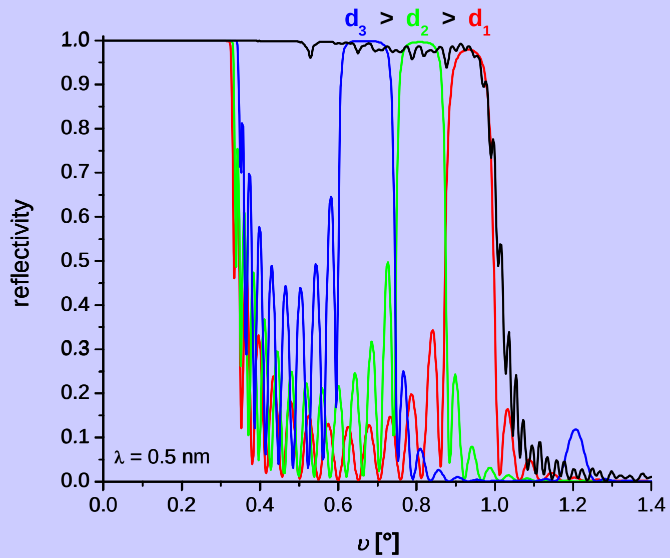
Supermirrors 3

Idea: F. Mezei

Slow variation of the thickness of the bilayers.

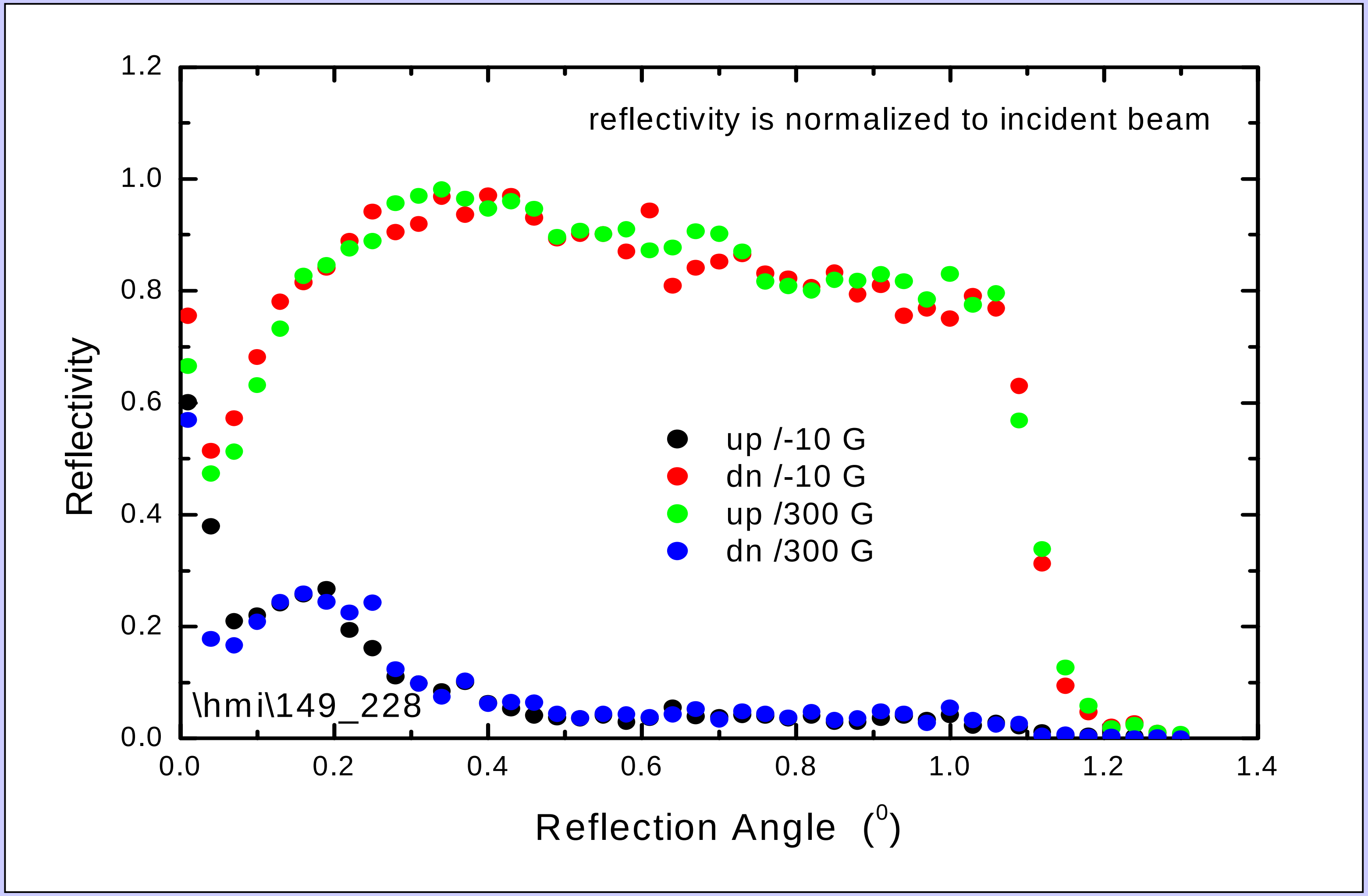






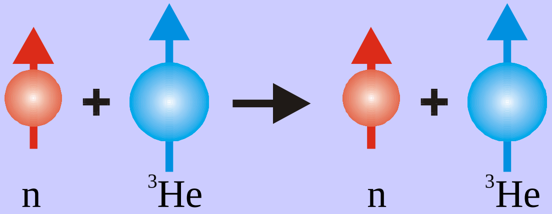
Supermirrors 4

- cold and thermal neutrons
- maintenance free
- not so good for area detectors

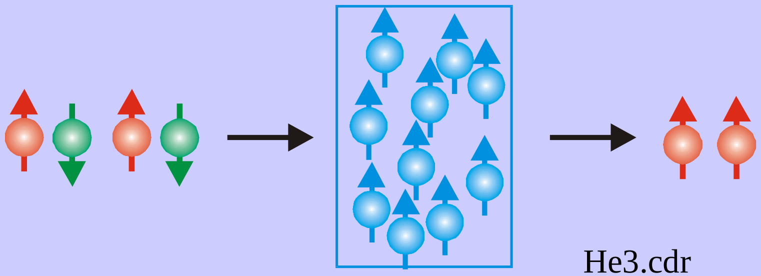


^{3}He-Polarizers

- **absorption** is strongly spin dependent



$\sigma \cong 0$

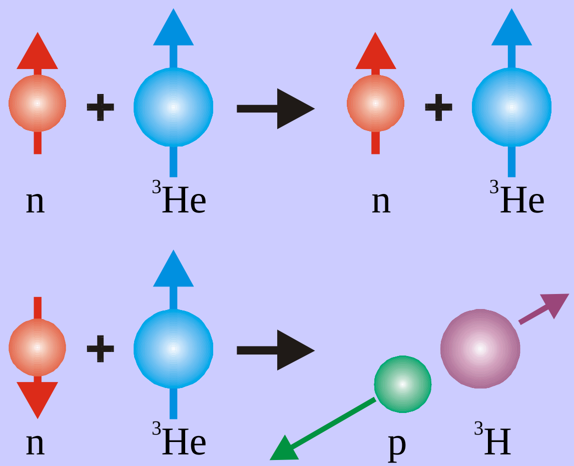


He3.cdr

- homogeneous: SANS
- no change of phase space
- “*E*-independent”: TOF
- complicated technique

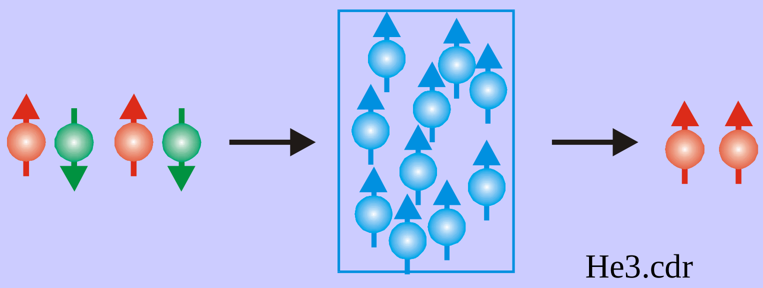
^{3}He-Polarizers

- **absorption** is strongly spin dependent



$\sigma \cong 0$

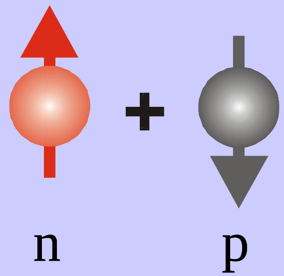
σ large



- homogeneous: SANS
- no change of phase space
- "*E*-independent": TOF
- complicated technique

Polarized Proton Target

• **scattering** is strongly spin dependent

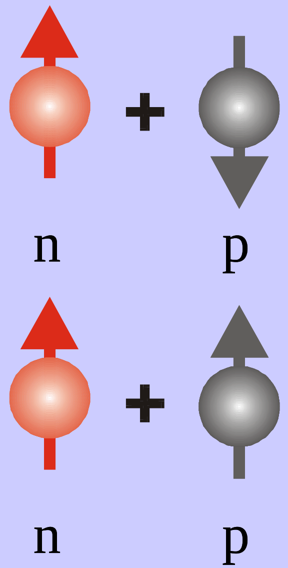


scattering cross section σ large

• homogeneous: SANS
• no change of phase space
• "*E*-independent": TOF
• complicated technique

Polarized Proton Target

- **scattering** is strongly spin dependent



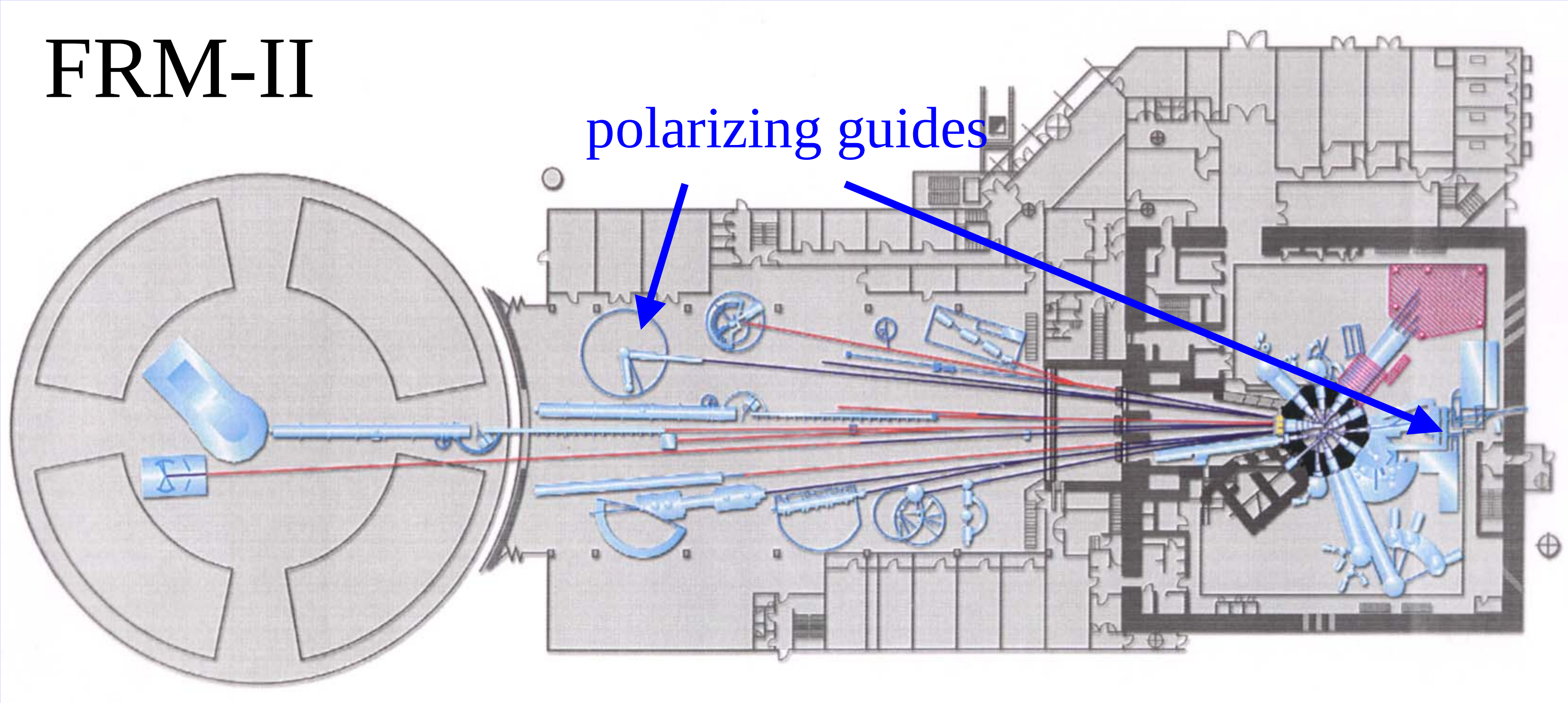
scattering cross section σ large

scattering cross section σ small

- homogeneous: SANS
- no change of phase space
- "*E*-independent": TOF
- complicated technique

Implementation: Primary Spectrometer

- transport of neutron by means of neutron guides



Implementation: Primary Spectrometer

Implementation straight forward!

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

Spallation Neutron Source in Oak Ridge (USA)

New concepts:

- translation of guides (POWGEN at SNS, TRISP at FRM-II)
- Elliptic guides (not yet implemented as polarizer)

Implementation: Secondary Spectrometer 1

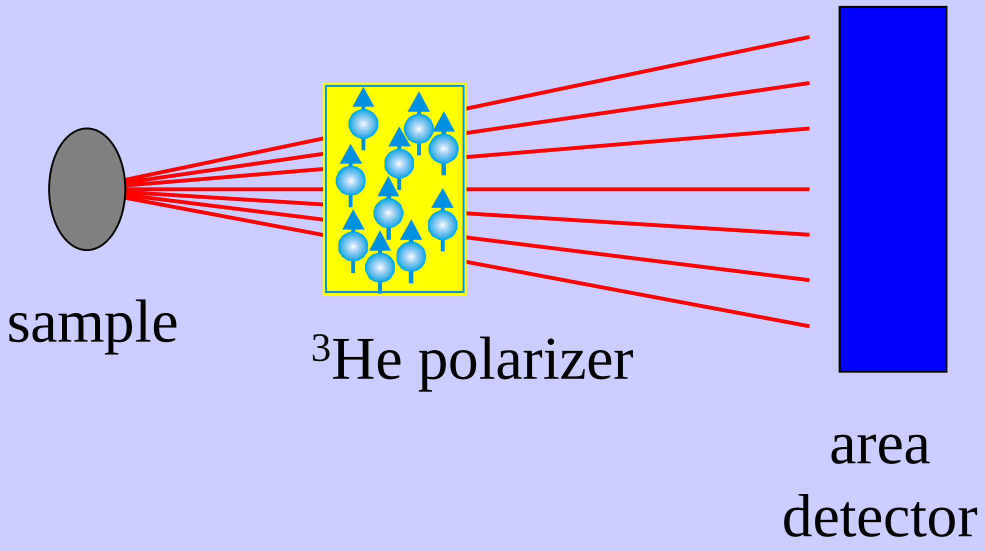
- monochromatic – energy band
- low – high energy
- single detector– area detector (dimension of detector!)
- trade-off of polarization vs. intensity

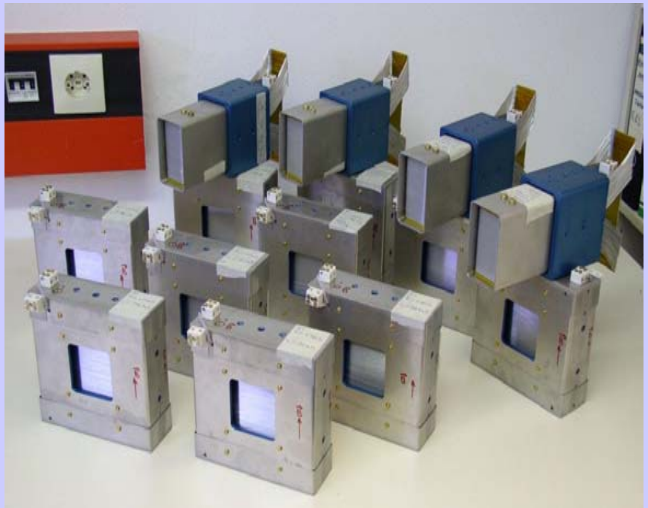
Implementation: Secondary Spectrometer 1

- monochromatic – energy band
- low – high energy
- single detector– area detector (dimension of detector!)
- trade-off of polarization vs. intensity

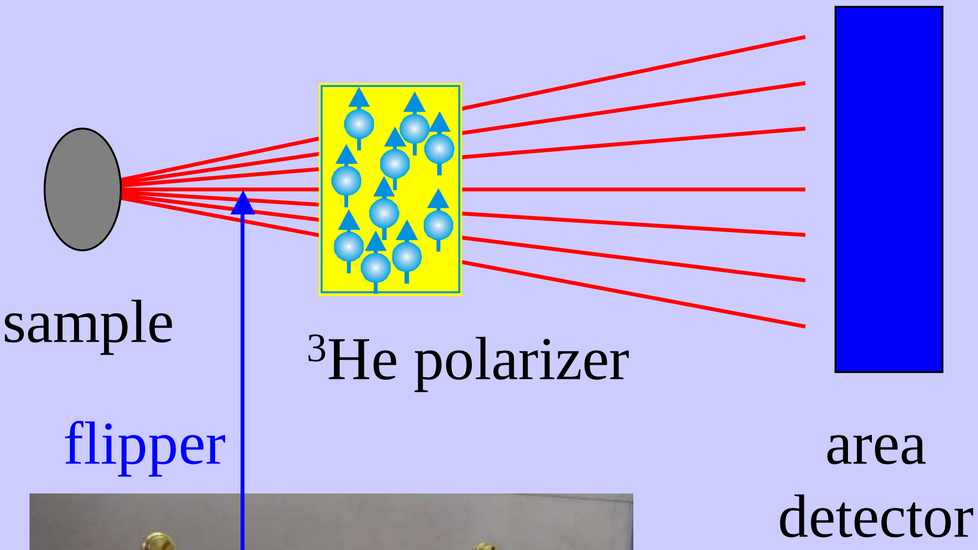
- space
- price
- maintenance
- personal opinions (my opinion: the simpler the better)

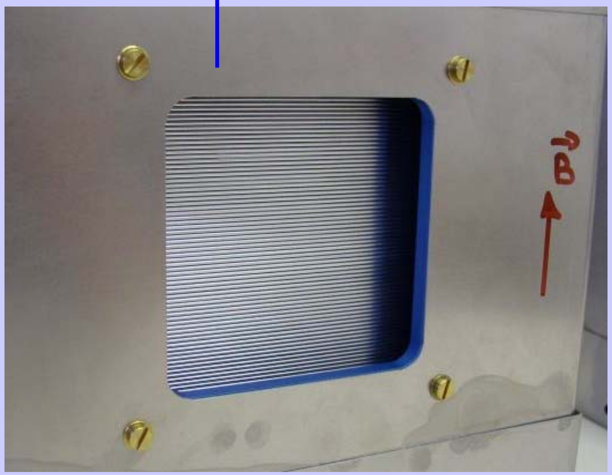
Implementation: Secondary Spectrometer 2

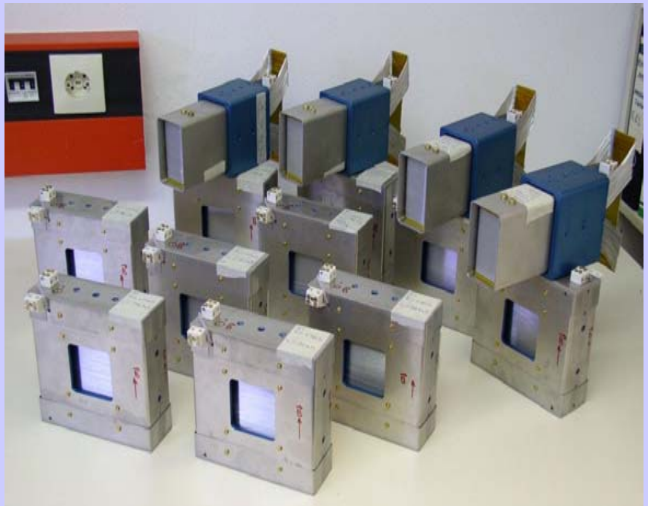




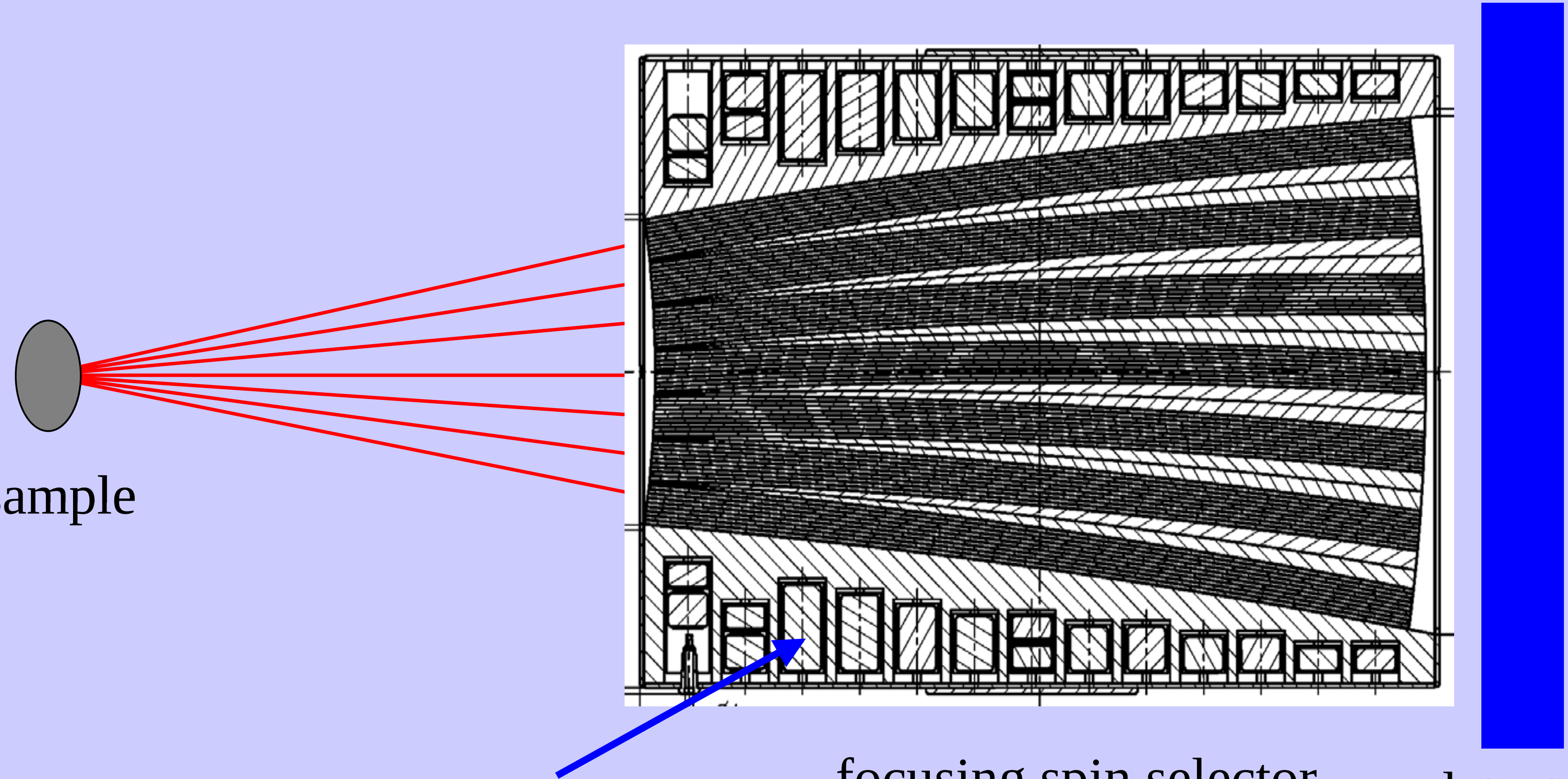
Implementation: Secondary Spectrometer 2







Implementation: Secondary Spectrometer 3



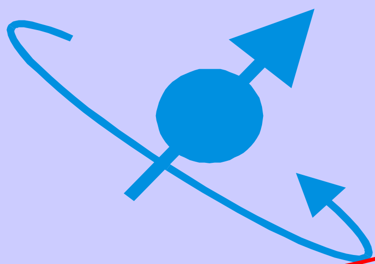
Magnetic Moment of Neutrons

• nuclear interaction:

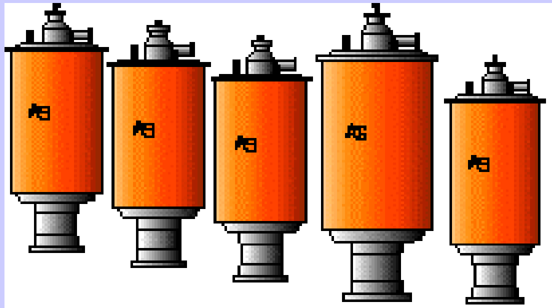
- form factor = 1: large **Q** accessible
- coherent - incoherent scattering
- no charge → large penetration depth

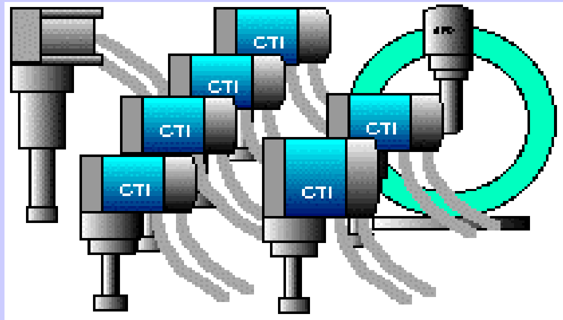
• spin = 1/2 → magnetic moment

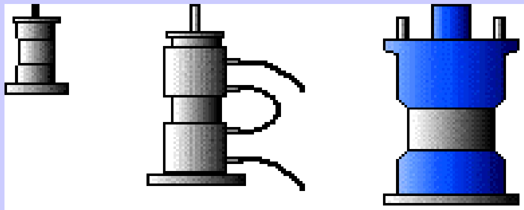
$$\mu_n = 1.913\mu_N$$

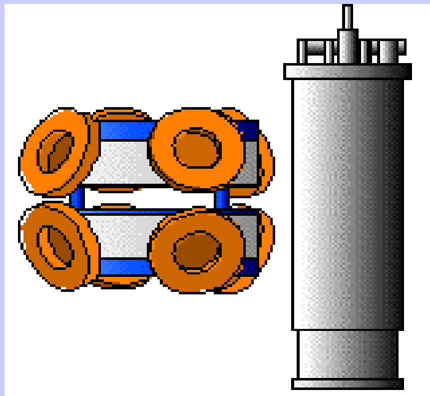


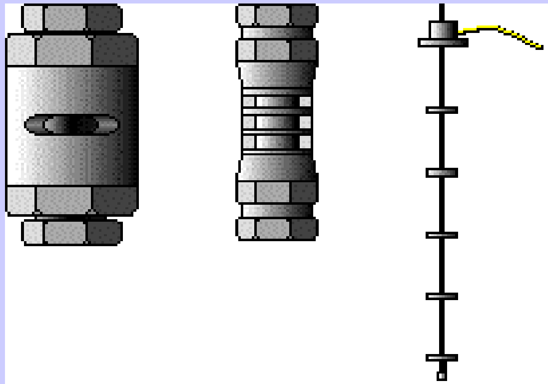
Properties of Neutrons











Sample environment is essential (not only the neutrons)!

Scattering Cross Section

(hear 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

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

Message: → scattering given by Fourier transform of potential

Scattering Cross Section

(hear W. Fischer's talk!)

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

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

- $|\lambda_i\rangle$: 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:

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

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

Message: → scattering given by Fourier transform of potential

Magnetic Interaction

- magnetic interaction operator:

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

γ = -1.913:	gyromagnetic ratio
μ_N:	nuclear magneton
$\boldsymbol{\mu}$:	magnetic moment of neutron
$\boldsymbol{\sigma}$:	Pauli spin operator

spin

Magnetic Interaction

- magnetic interaction operator:

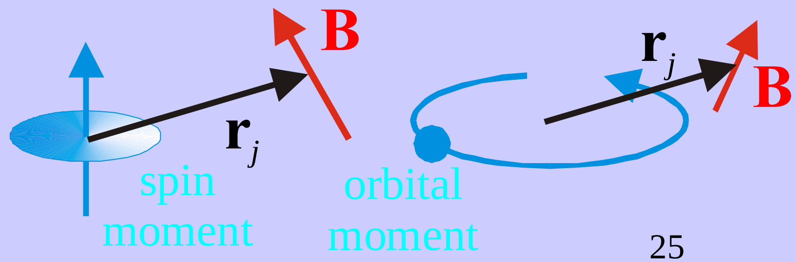
$$\breve{\mathbf{U}}_m = -\boldsymbol{\mu}\cdot\mathbf{B} = -\gamma\mu_N\boldsymbol{\sigma}\cdot\mathbf{B}$$

spin

γ = -1.913:	gyromagnetic ratio
μ_N:	nuclear magneton
$\boldsymbol{\mu}$:	magnetic moment of neutron
$\boldsymbol{\sigma}$:	Pauli spin operator

- field of unpaired electron at position $\mathbf{r}_i$:

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



Magnetic Scattering Length

- Fourier transform yields magnetic scattering length:

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

b

$r_0 = 0.2818 \cdot 10^{-12}$ cm: classical radius of electron

$\hat{\mathbf{Q}} = \mathbf{Q} / |\mathbf{Q}|$

- important: *p* depends on vector quantities
  p is comparable to *b*

Magnetic Scattering Length

- Fourier transform yields magnetic scattering length:

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

$r_0 = 0.2818 \cdot 10^{-12}$ cm: classical radius of electron

b

$$\hat{\mathbf{Q}} = \mathbf{Q} / |\mathbf{Q}|$$

$$g = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$$

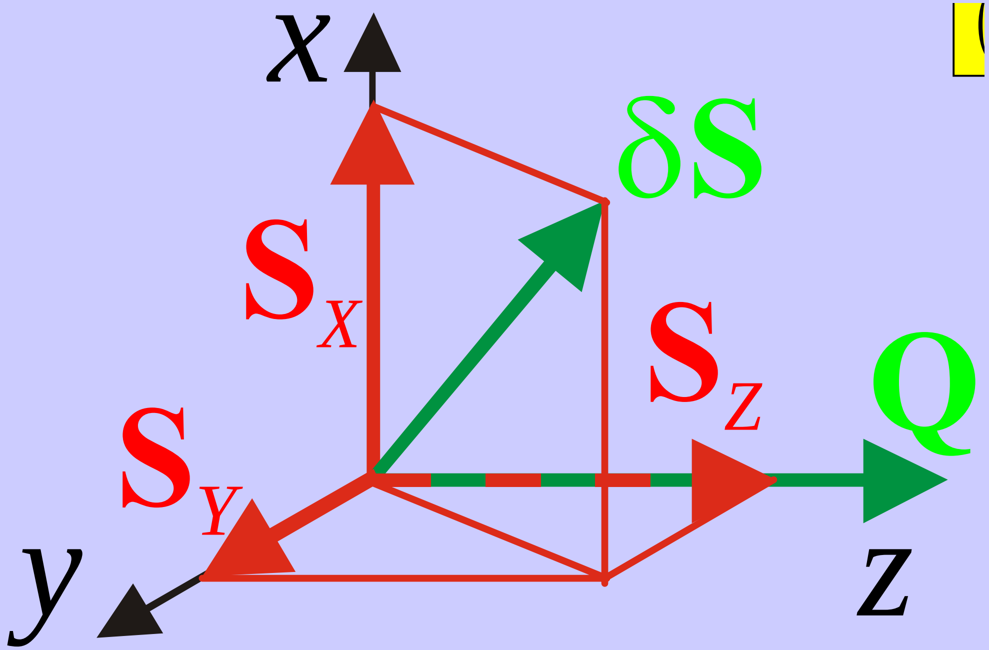
- important: *p* depends on vector quantities
  p is comparable to *b*

Magnetic Scattering Function

- selection rule for magnetic scattering:

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

scattering function



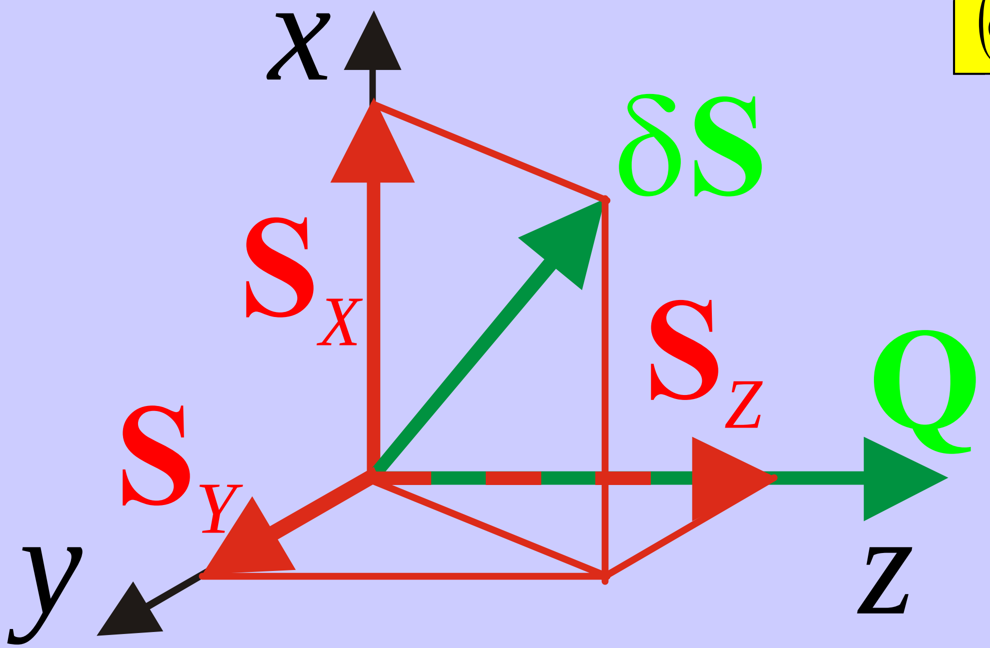
Magnetic Scattering Function

- selection rule for magnetic scattering:

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

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

scattering function



Magnetic Scattering Function

- magnetic scattering function (phonons neglected!):

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

(hear W. Fischer’s talk!)

Magnetic Scattering Function

- magnetic scattering function (phonons neglected!):

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

$S^{\alpha\beta}(\mathbf{Q},\omega)$ 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 $S_{j'\alpha}(0)$.

(hear W. Fischer's talk!)

Imaginary Part of the Magnetic Susceptibility

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

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

imaginary part

Imaginary Part of the Magnetic Susceptibility

- from the 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

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

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

Imaginary Part of the Magnetic Susceptibility

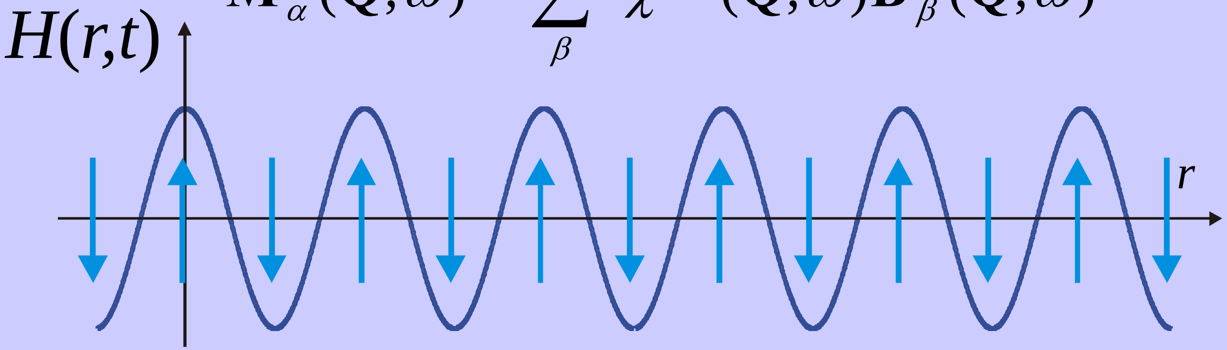
- from the fluctuation-dissipation theorem (→ W. Fischer's talk):

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

imaginary part

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

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



Imaginary Part of the Magnetic Susceptibility

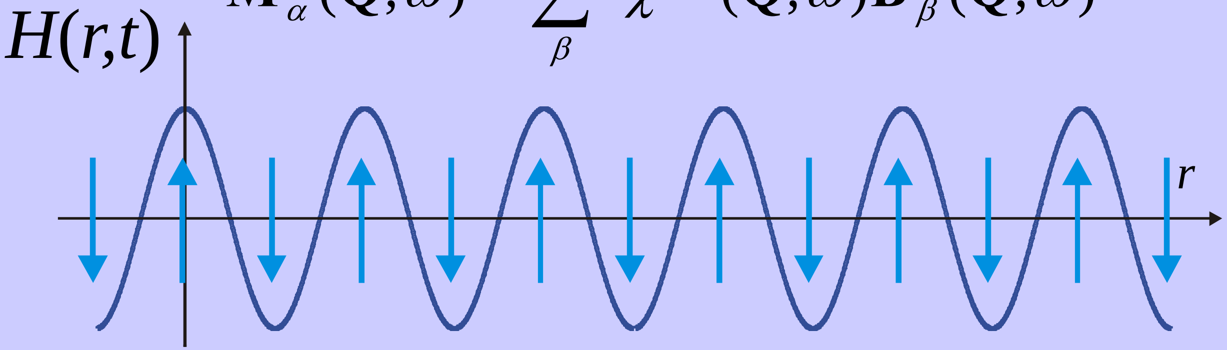
- from the fluctuation-dissipation theorem (→ W. Fischer's talk):

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

imaginary part

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

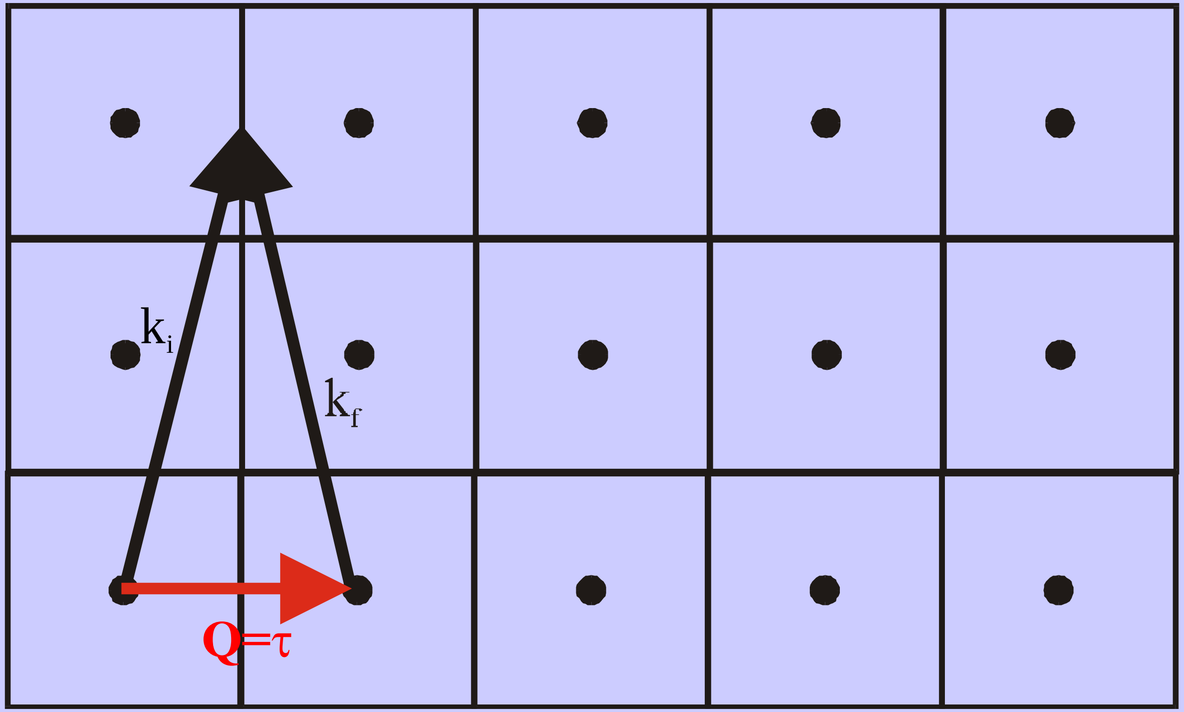
$$\mathbf{M}_{\alpha}(\mathbf{Q},\omega)=\sum_{\beta}\chi^{\alpha\beta}(\mathbf{Q},\omega)\mathbf{B}_{\beta}(\mathbf{Q},\omega)$$



- comparison with bulk susceptibility $\chi(0,\omega)$, μSR, etc.

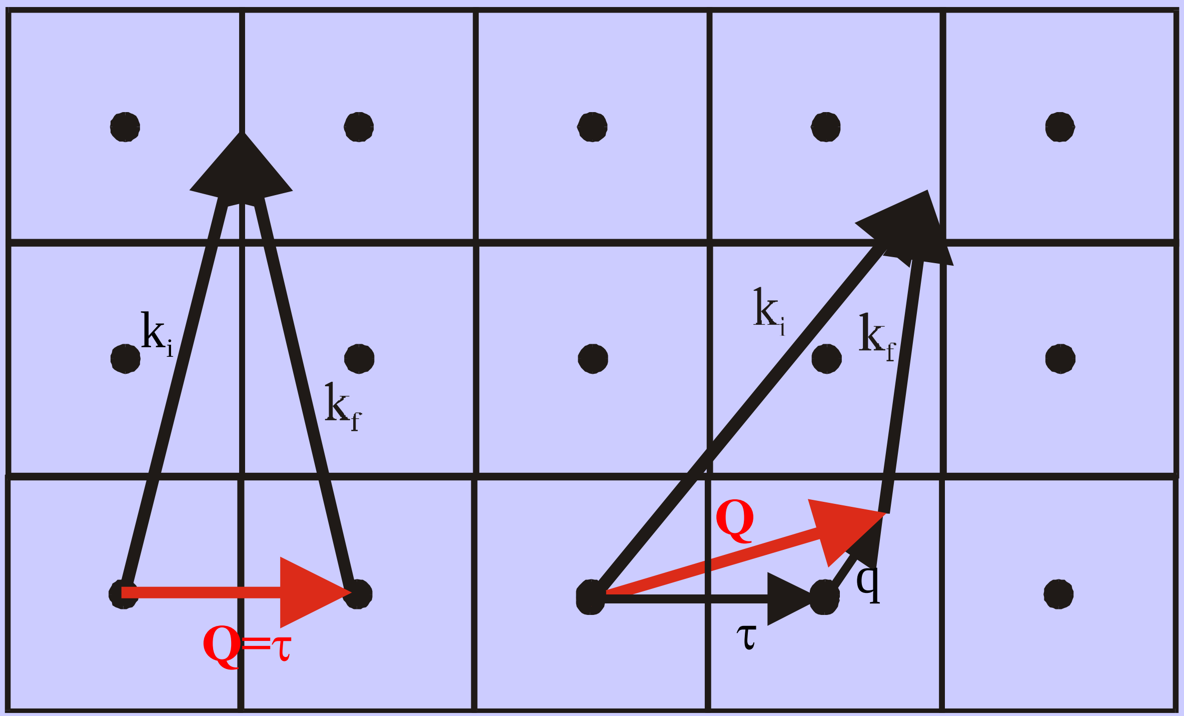
Reciprocal Space - Scattering Triangle

- energy and momentum conservation:



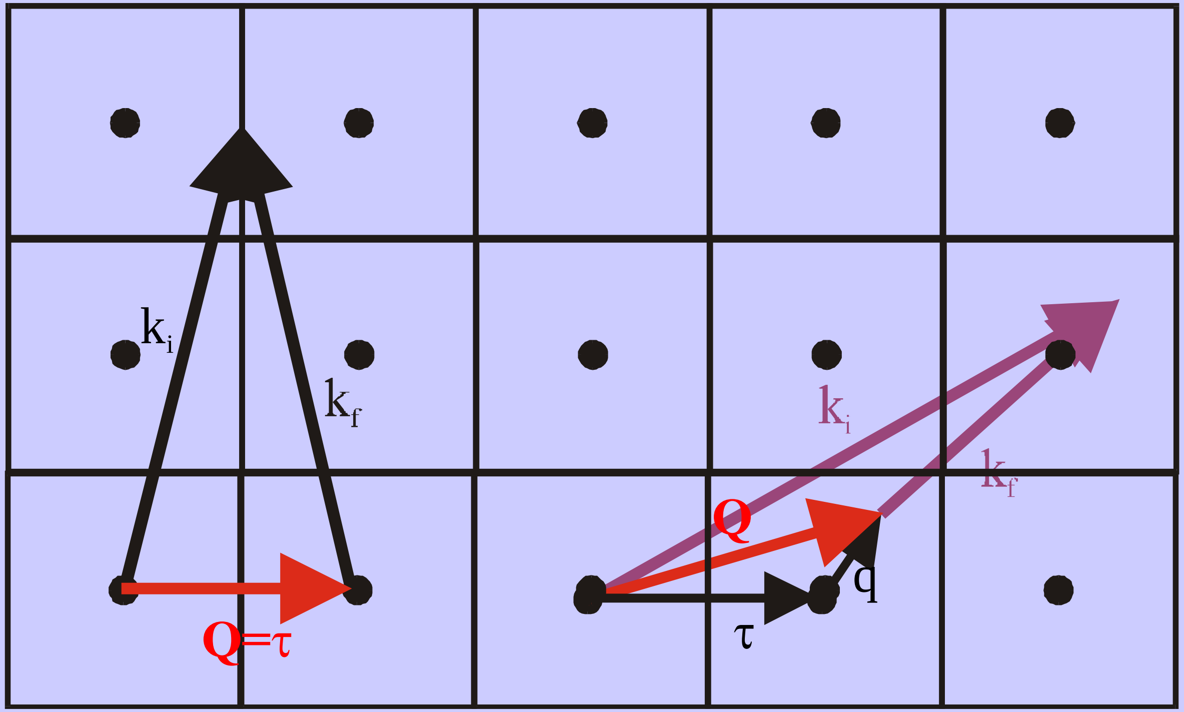
Reciprocal Space - Scattering Triangle

- energy and momentum conservation:



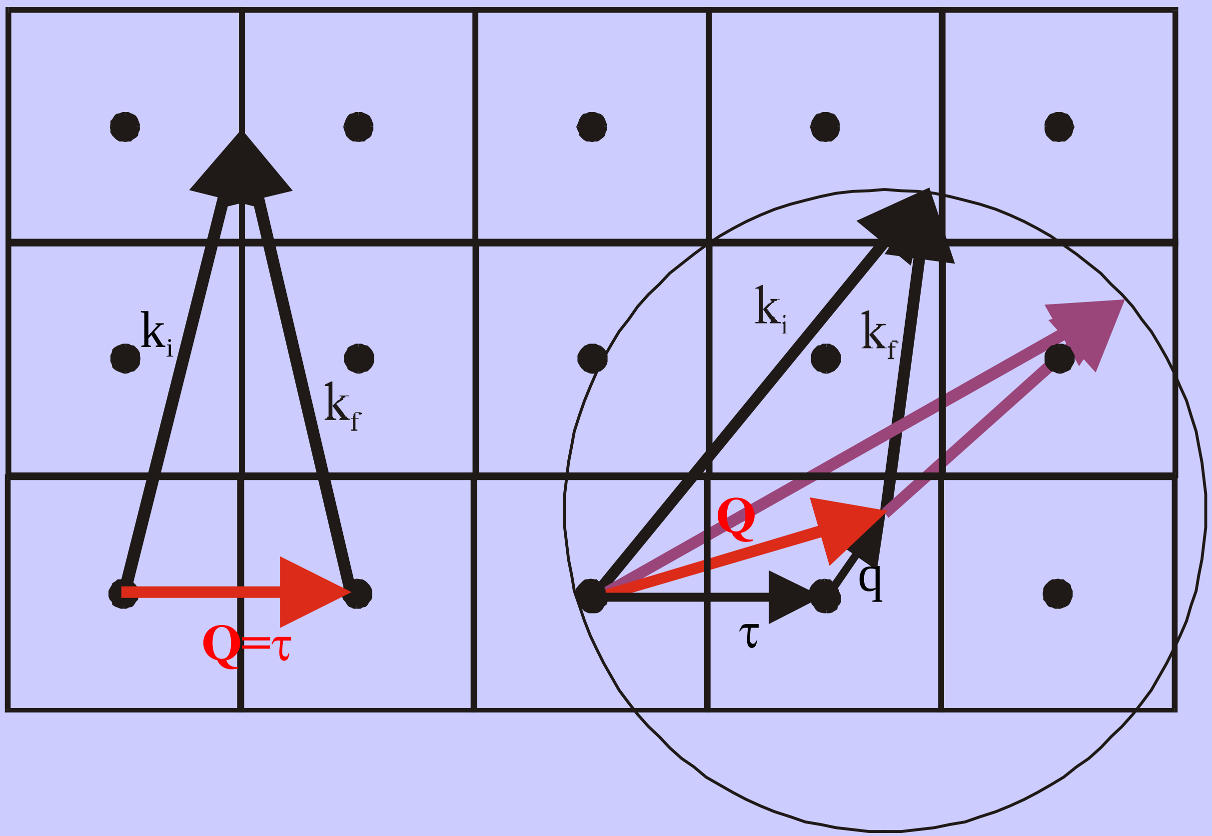
Reciprocal Space - Scattering Triangle

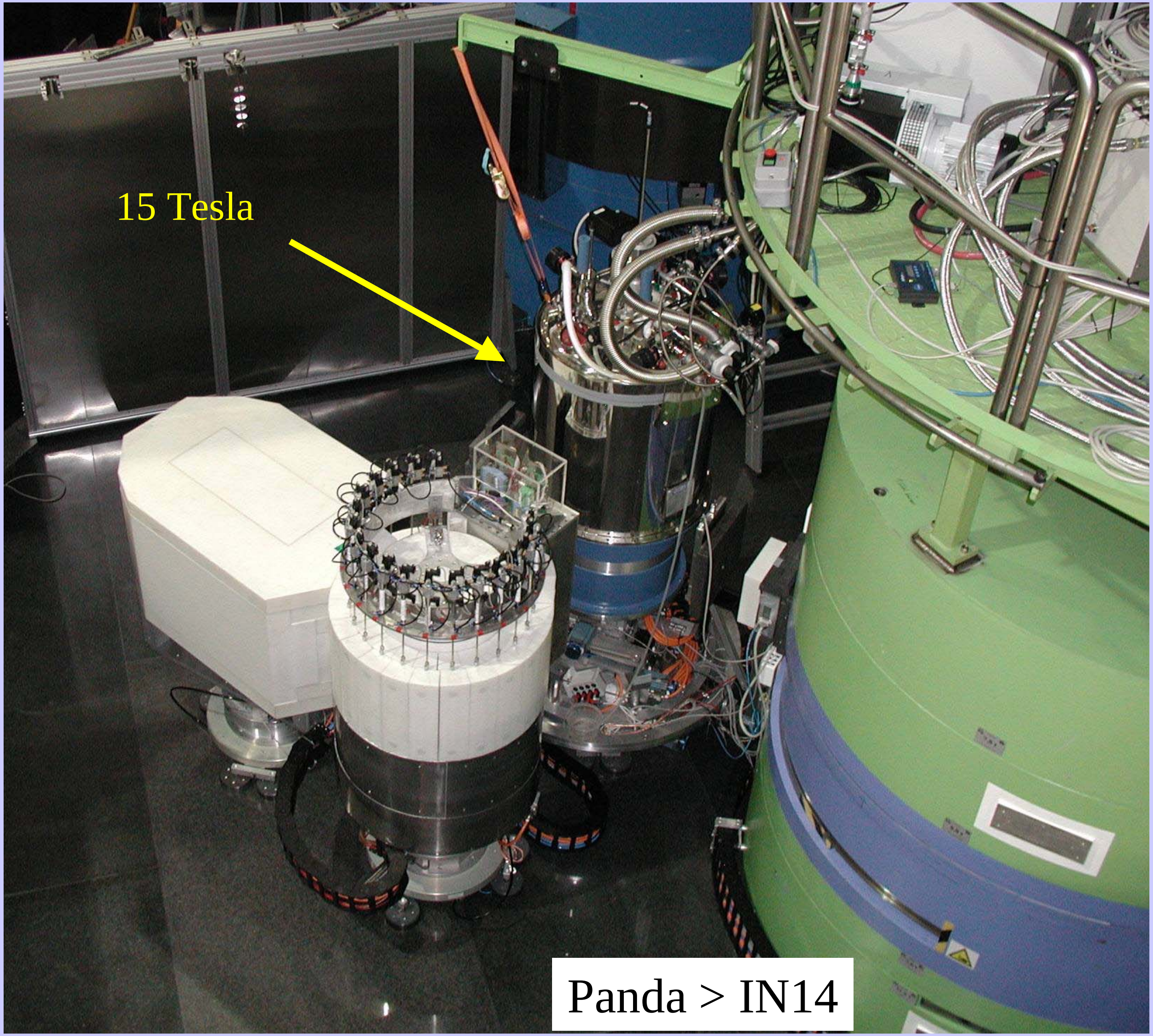
- energy and momentum conservation:



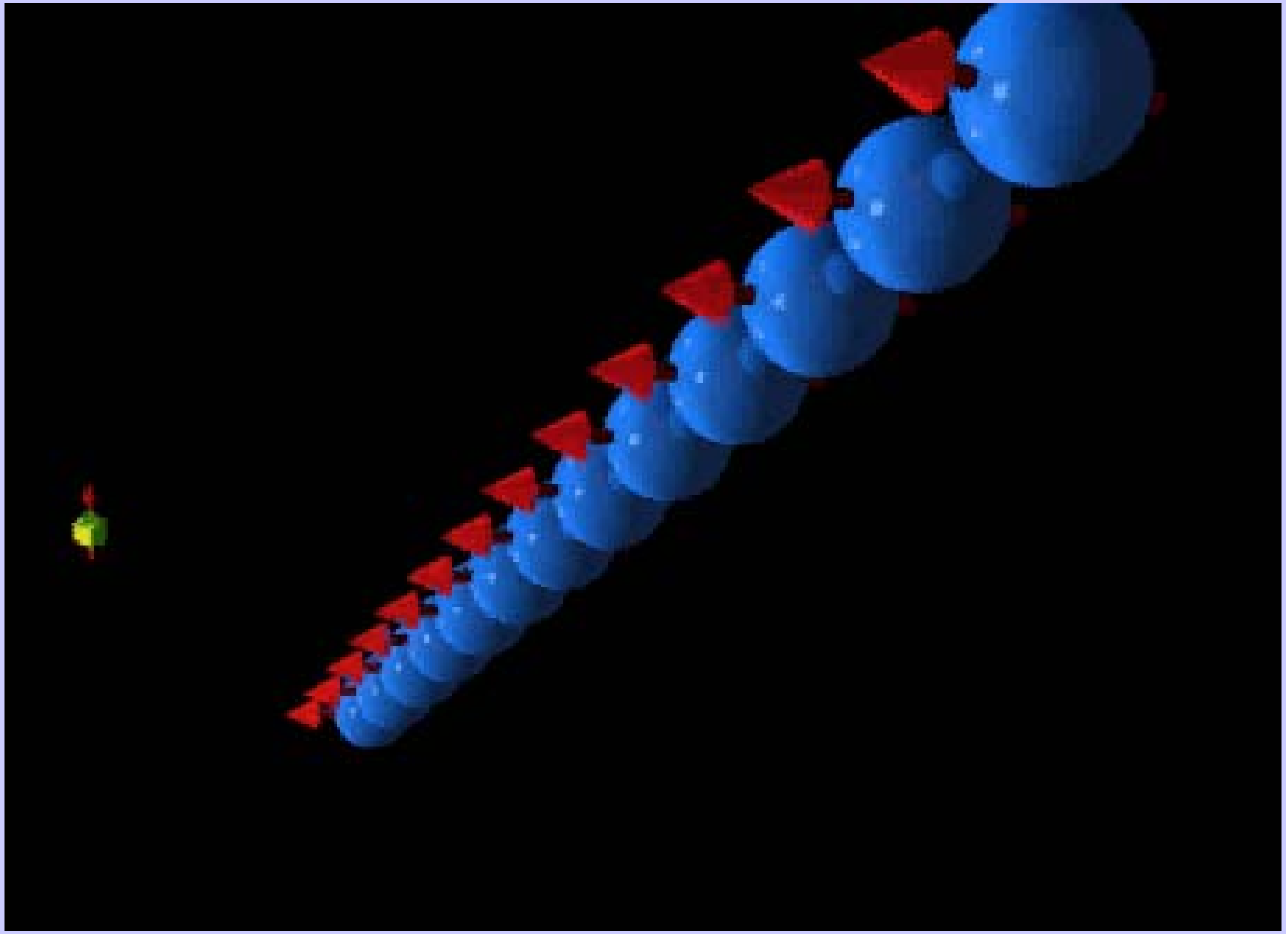
Reciprocal Space - Scattering Triangle

- energy and momentum conservation:

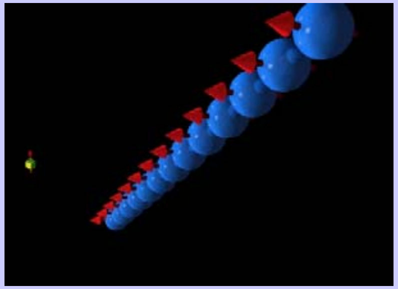



15 Tesla
Panda > IN14

Spin Waves



Local Moment System



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

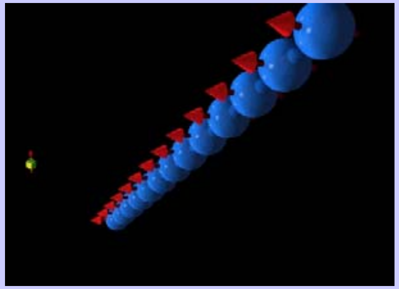
• linear spin wave theory: $\hbar\omega_q = 2S\big(J(0) - J(\mathbf{q})\big)$

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

Fourier transform (compare with diffraction!)

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

Local Moment System



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

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

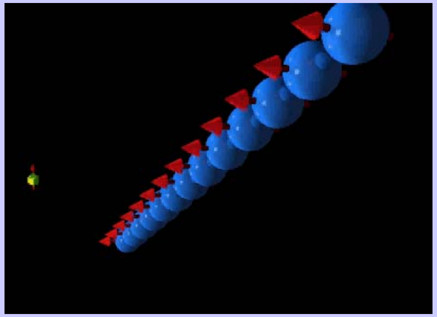
  where: $J(\mathbf{q}) = \sum_{jj'} J_{jj'} e^{i\mathbf{q}\cdot(\mathbf{r}_j - \mathbf{r}_{j'})}$

- most simple case: $J_{ij} = J$ (see Kittel)

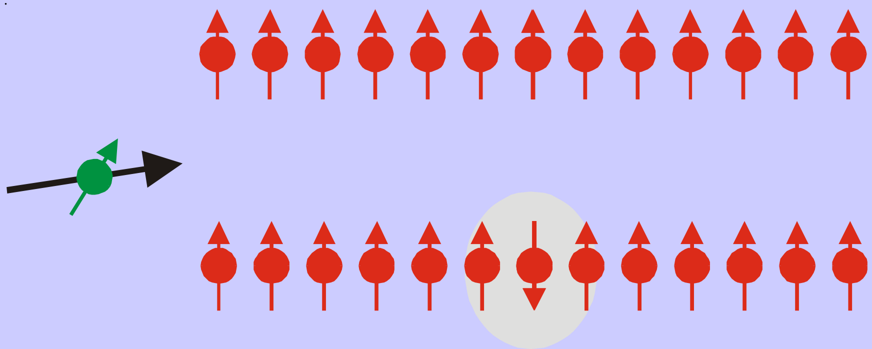
Fourier transform (compare with diffraction!)

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

Visualization: Spin Waves

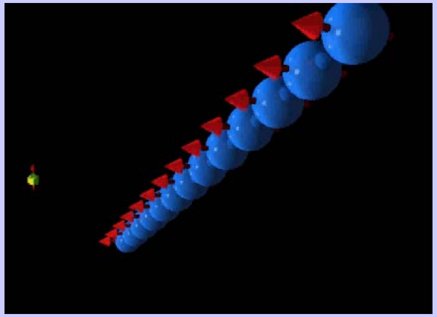


• Quantum mechanical picture:

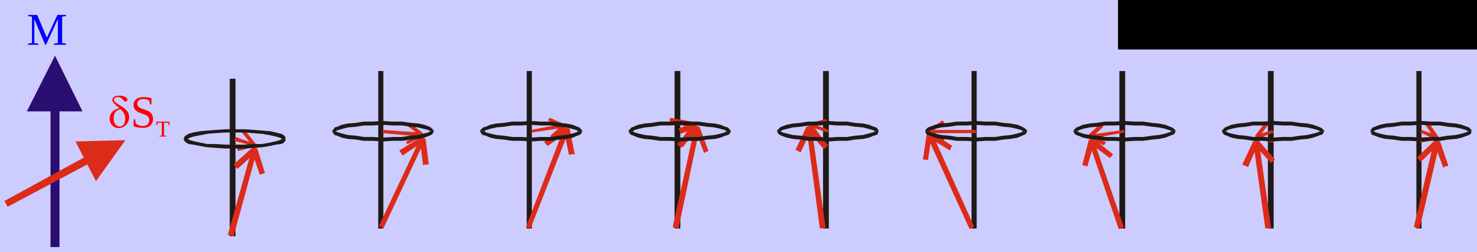


coherent superposition of spin flips → spin wave

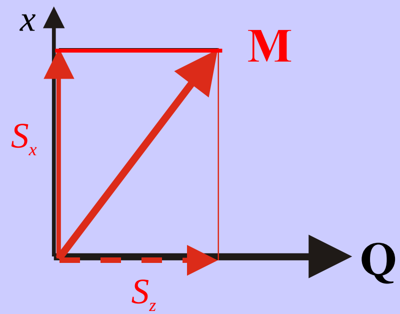
Application: Spin Waves

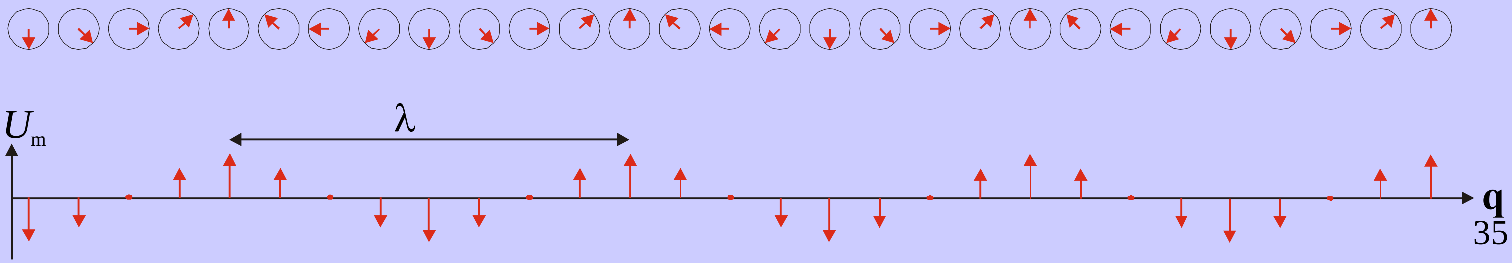


- Classical picture:

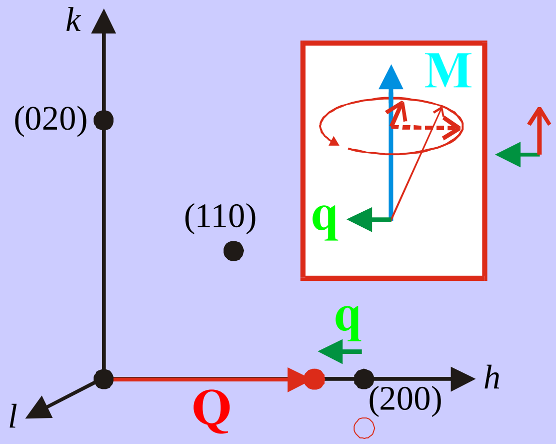


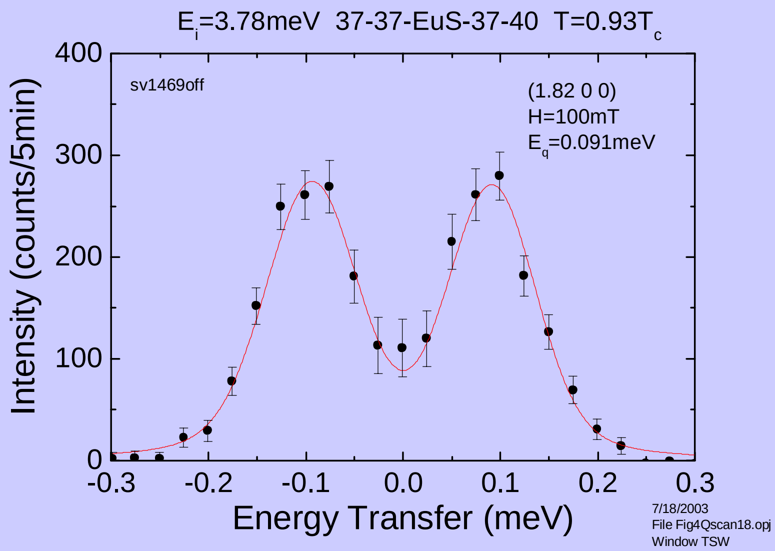
- Why do neutrons see spin waves?



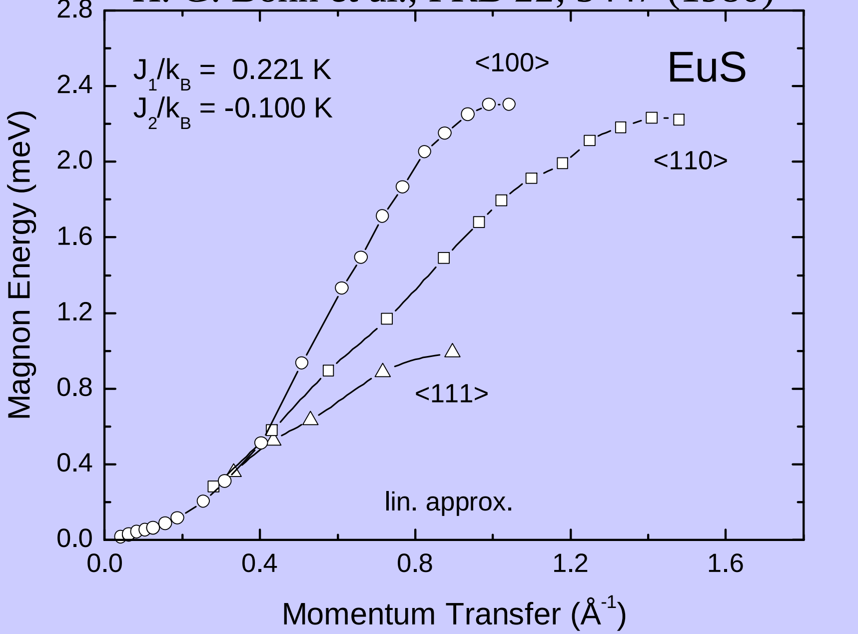


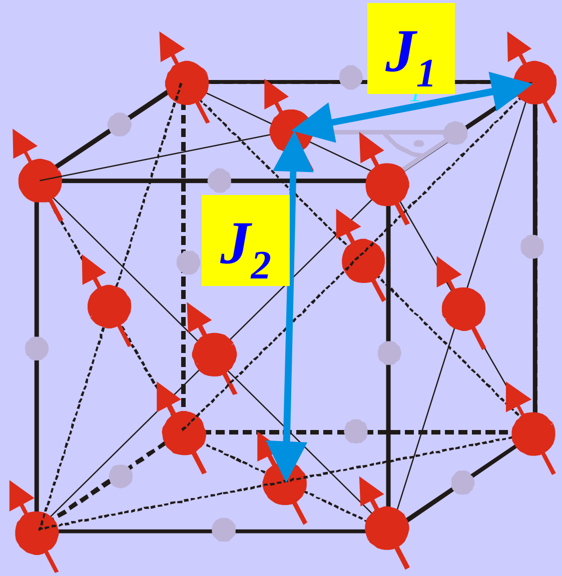
EuS: The ideal FM





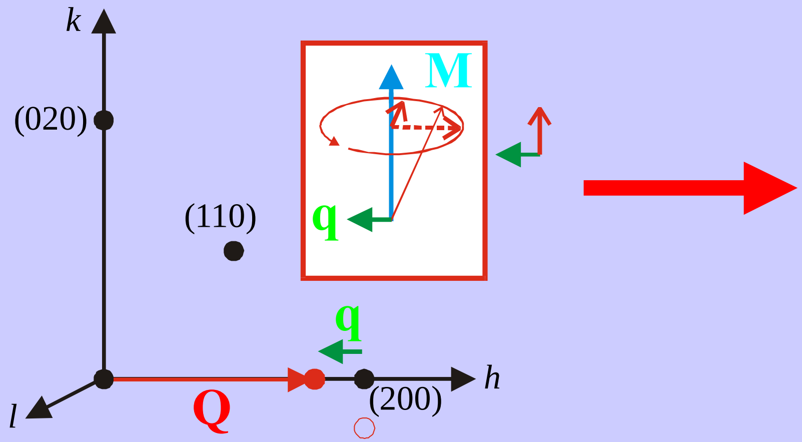
H. G. Bohn et al., PRB **22**, 5447 (1980)

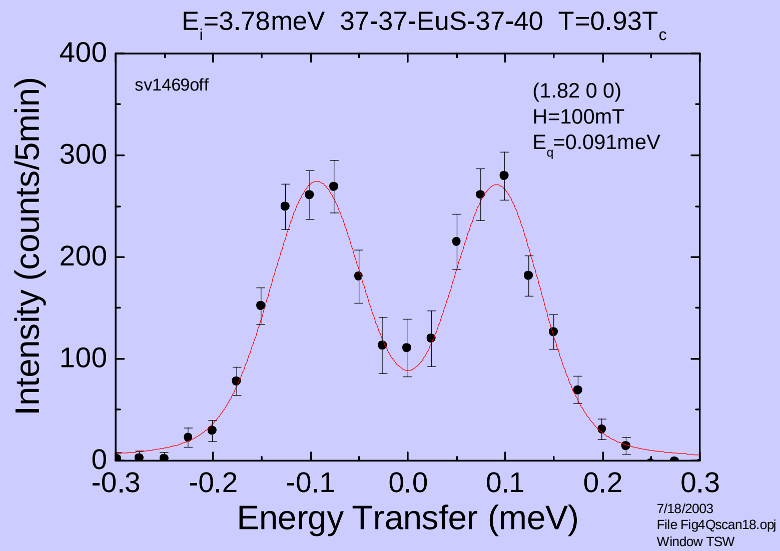


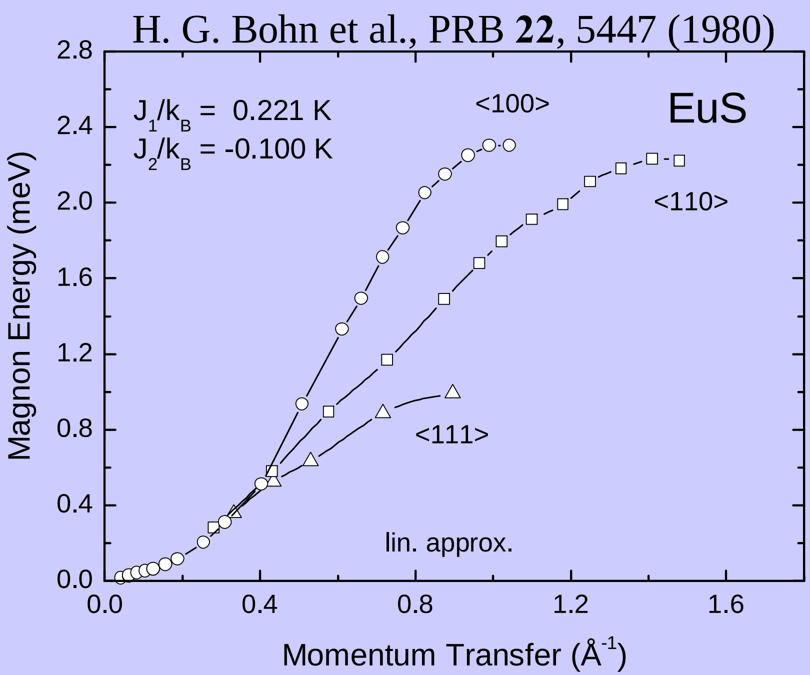


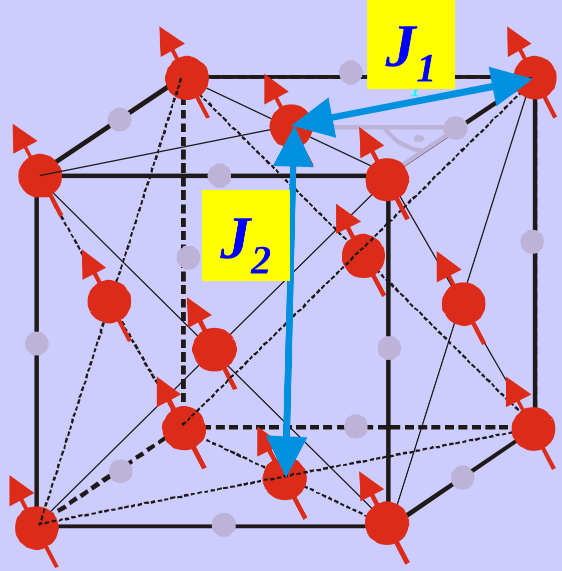
Determination of J_1 and J_2

EuS: The ideal FM



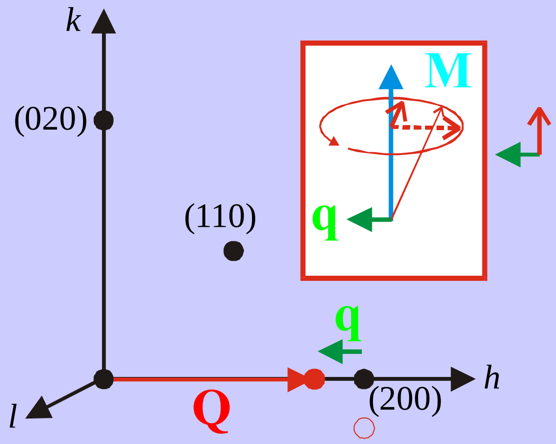


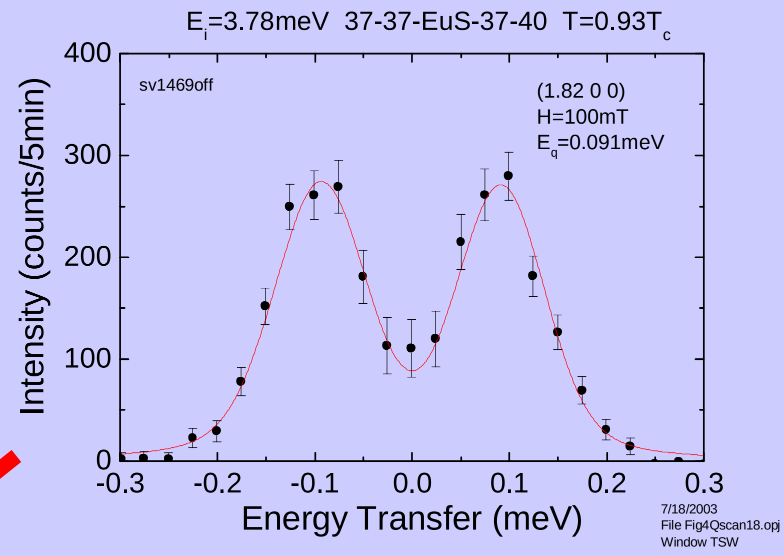


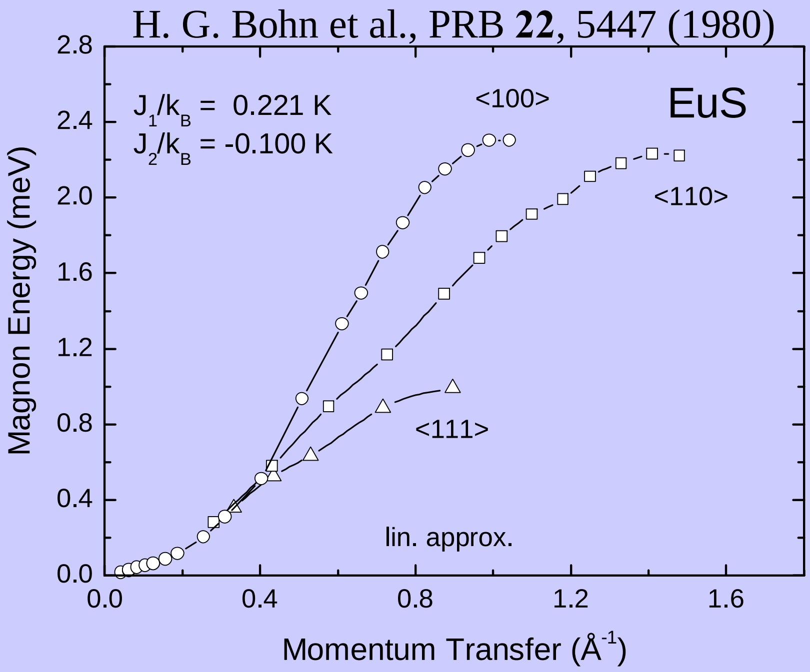


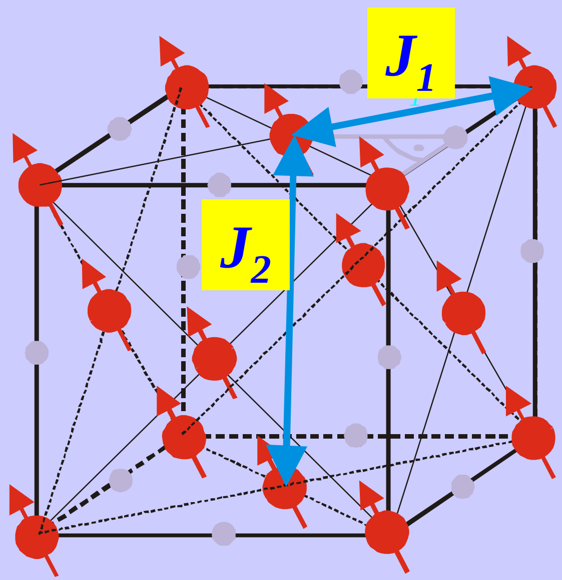
Determination of J_1 and J_2

EuS: The ideal FM



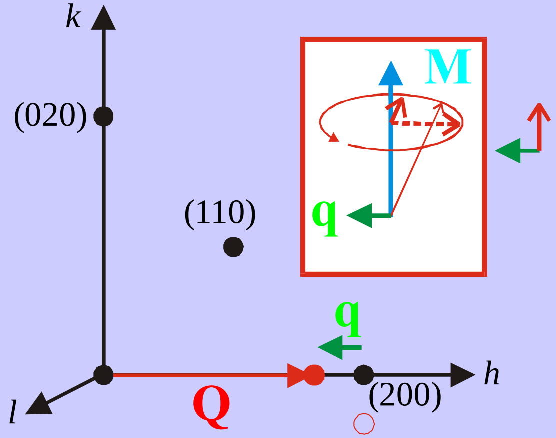


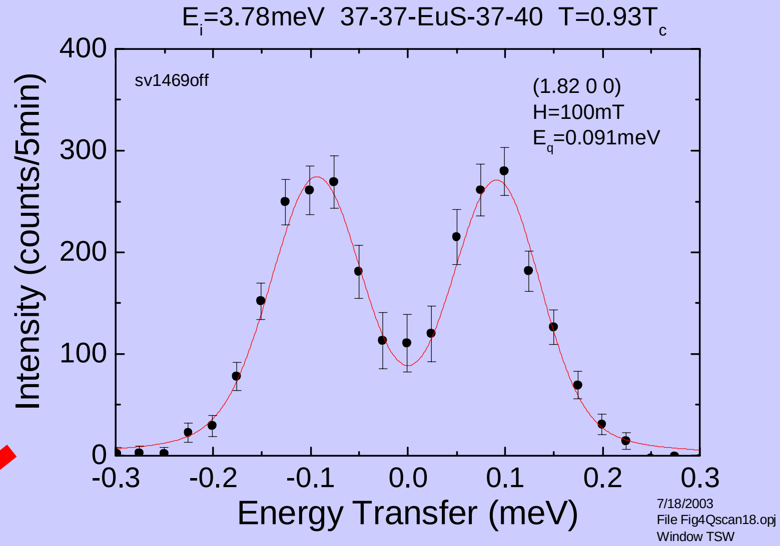


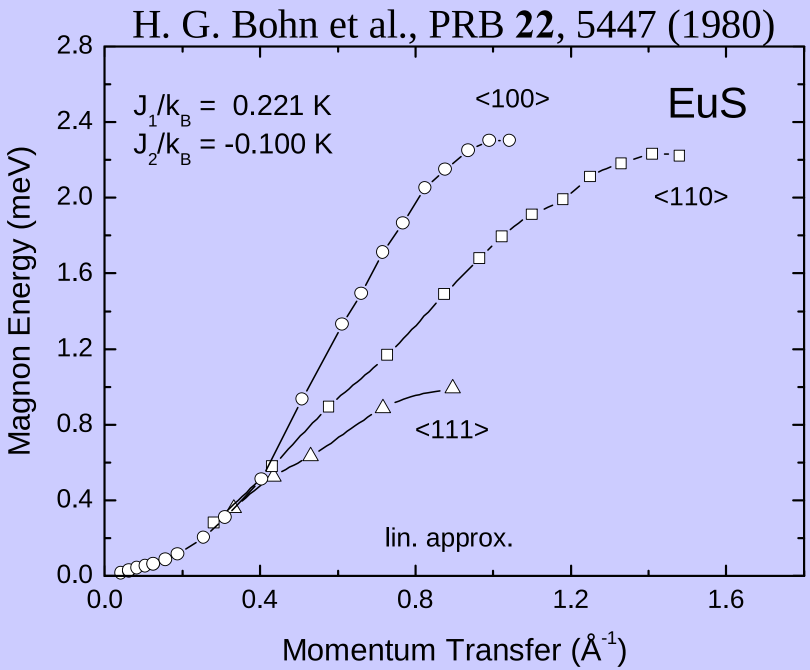


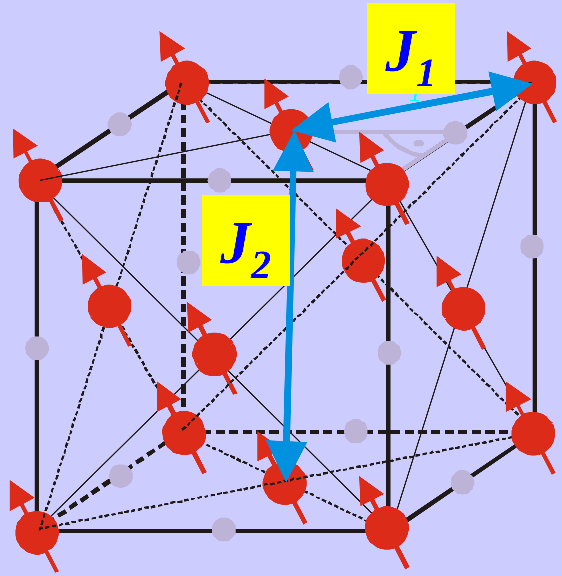
Determination of J_1 and J_2

EuS: The ideal FM









Determination of J_1 and J_2

What can we learn?

• exchange interactions: information on electronic structure

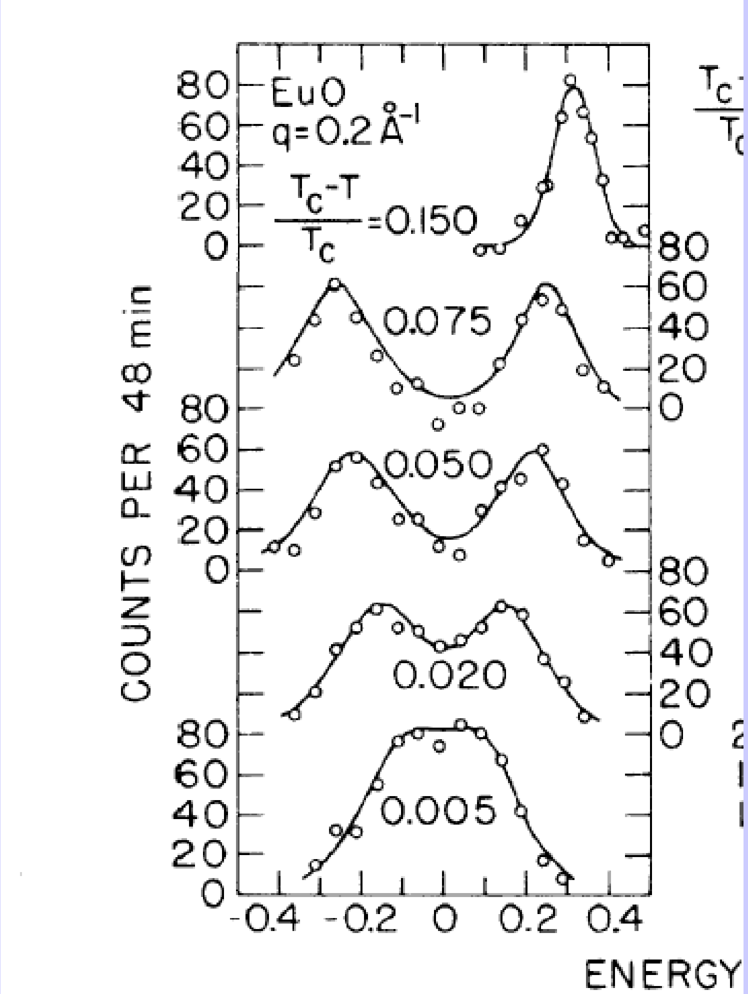
• phase transitions: critical exponents, universality

Selection rules help to distinguish spin waves from phonons.

What can we learn?

• exchange interactions: information on electronic structure

• phase transitions: critical exponents, universality



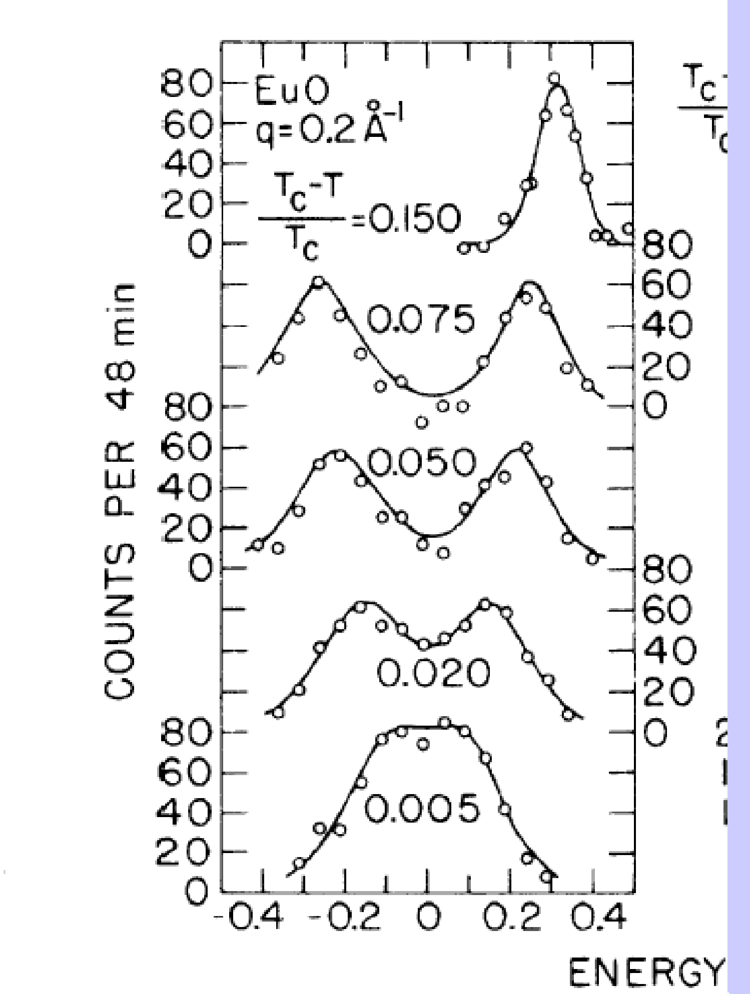
O. W. Dietrich et al., PRB 14, 4923 (1976)

Selection rules help to distinguish spin waves from phonons.

What can we learn?

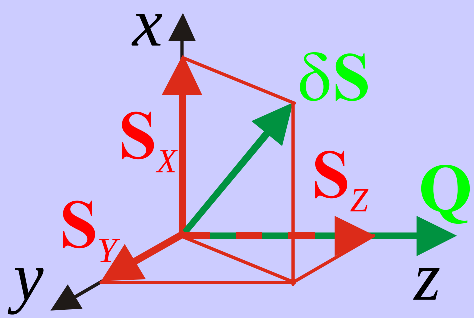
- exchange interactions: information on electronic structure
- phase transitions: critical exponents, universality
- additional terms in interaction: anisotropies (xy-like, Ising)

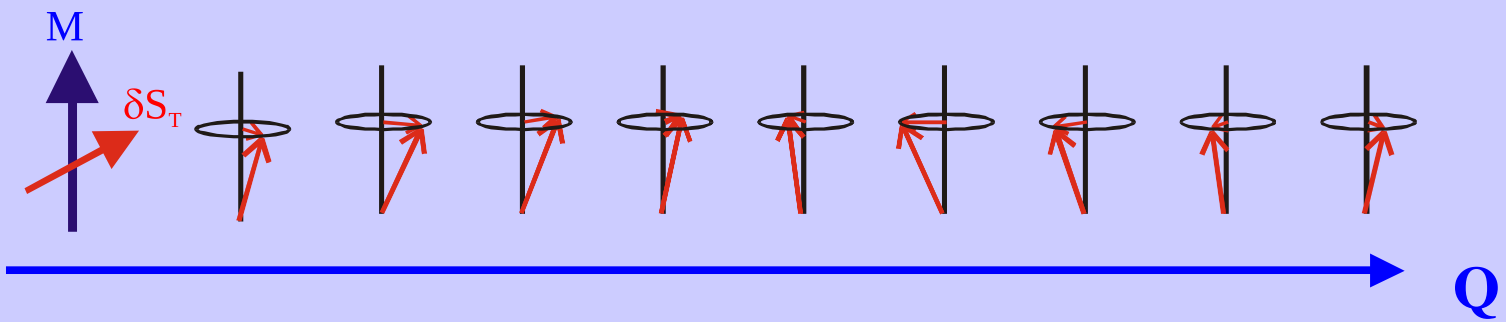
Selection rules help to distinguish spin waves from phonons.



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

What did we really measure?



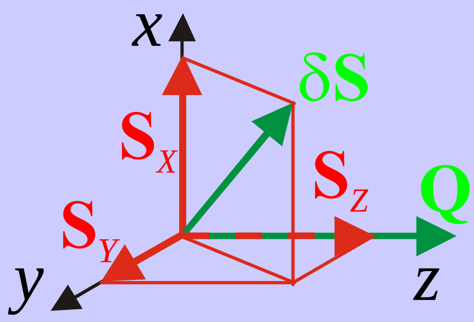


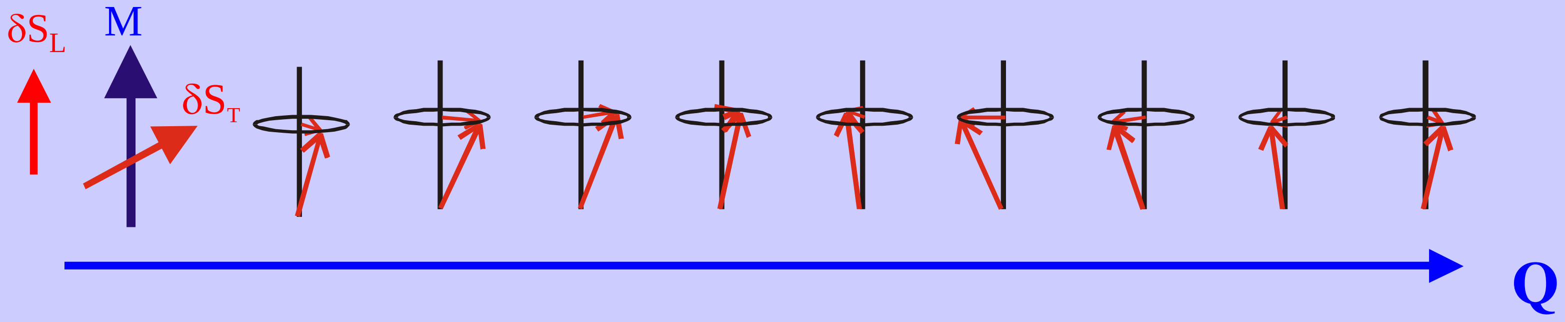
• sum of transverse and longitudinal fluctuations

"do not exist" in normal text books
(extremely important in itinerant antiferromagnets!)

• distinction only possible by means of **polarized neutrons!**

What did we really measure?





• sum of transverse and longitudinal fluctuations

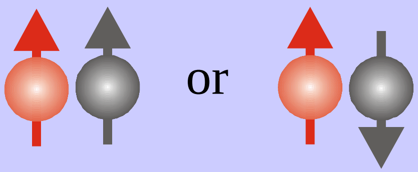
"do not exist" in normal text books
(extremely important in itinerant antiferromagnets!)

• distinction only possible by means of **polarized neutrons!**

Polarization analysis: Nuclear Scattering

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

- different isotopes: $\quad b_i = \overline{b} \pm \Delta b_i$



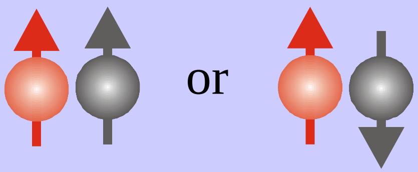
$$b_i = \overline{b} \pm \boldsymbol{\sigma} \cdot \mathbf{I}$$

b^+

b^-

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: $$b_i = \bar{b} \pm \Delta b_i$$ → $\bar{b} = \sum_i f_i b_i$; → $\sum_i \Delta b_i = 0$



→ $$b_i = \bar{b} \pm \boldsymbol{\sigma}\cdot\mathbf{I}$$ → b^+ ; → b^-

Polarization analysis: Nuclear Scattering

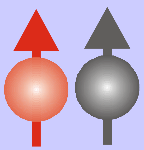
- nuclear scattering $$I(Q) \propto \left(\sum_i b_i e^{i\mathbf{Q}\cdot\mathbf{r}_i} \right)^2$$ sum amplitudes first!

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

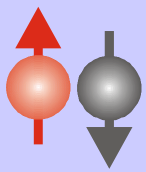
$$\bar{b} = \sum_i f_i b_i$$

$$\sum_i \Delta b_i = 0$$

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



or



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

b^+

b^-

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!

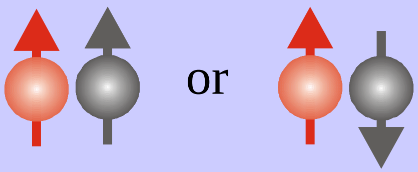
- different isotopes: $$b_i = \bar{b} \pm \Delta b_i$$

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

$\rightarrow \sum_i \Delta b_i = 0$

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)



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

$\rightarrow$ b^+

$\rightarrow$ b^-

Polarization analysis: Nuclear Scattering

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

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

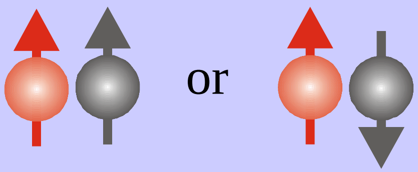
$$\bar{b} = \sum_i f_i b_i$$

$$\sum_i \Delta b_i = 0$$

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 σ



or

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

b^+

b^-

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 $\mathbf{Q}$

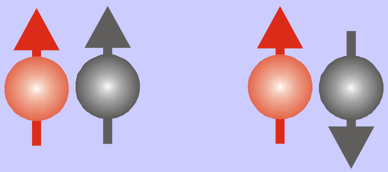
→ is **not** a magnetic interaction!
→ spin-incoherence can be detected with polarized neutrons!

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



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

→ is **not** a magnetic interaction!
→ spin-incoherence can be detected with polarized neutrons!

Pauli Spin Matrices 1

- Let us play with the matrices: $\boldsymbol{\sigma} \cdot \mathbf{A} = \sigma_x A_x + \sigma_y A_y + \sigma_z A_z$

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

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

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

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

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

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

Pauli Spin Matrices 1

- Let us play with the matrices: $\boldsymbol{\sigma} \cdot \mathbf{A} = \sigma_x A_x + \sigma_y A_y + \sigma_z A_z$

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

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

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

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

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

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

σ_z is already diagonal with eigenfunctions:

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

Pauli Spin Matrices 2

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

only spin-flip scattering possible

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

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

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

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

$$\rangle$$

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

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

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

Pauli Spin Matrices 2

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

only spin-flip scattering possible

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

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

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

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

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

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

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

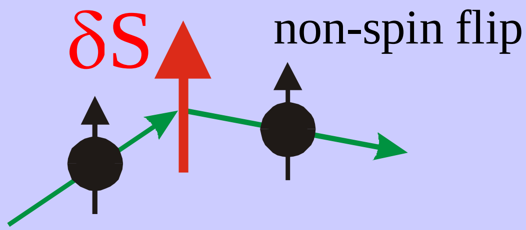
same is true for incoherent scattering: $A + BI_z$

Selection Rules for Polarization Analysis

Note: The polarization of the neutron defines the *z*-axis!

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

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



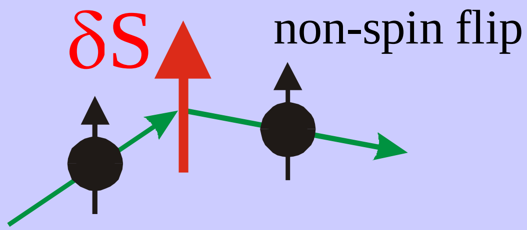
$\langle \uparrow | \sigma \cdot \mathbf{M}_{\perp} | \uparrow \rangle = M_{\perp z}$

Selection Rules for Polarization Analysis

Note: The polarization of the neutron defines the *z*-axis!

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

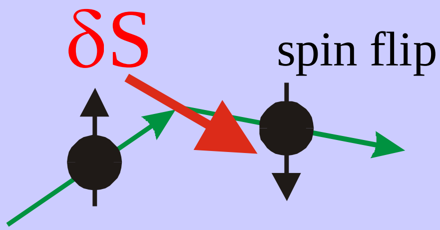
$$\left\langle \downarrow \middle| \sigma \cdot \breve{\mathbf{M}}_{\perp} \middle| \downarrow \right\rangle = -\breve{M}_{\perp,z}$$



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

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

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



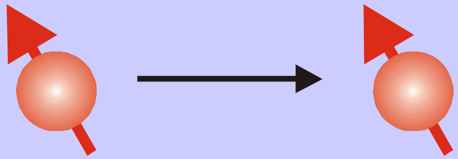
$<\uparrow|\sigma\cdot\mathbf{M}_{\perp}|\downarrow> = M_{\perp x} + i\, M_{\perp y}$

Rules for Polarization Analysis 1

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

no Pauli spin matrices involved

→ all scattering is non-spin-flip

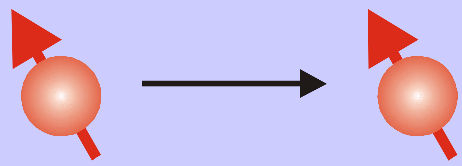


Rules for Polarization Analysis 1

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

no Pauli spin matrices involved

→ all scattering is non-spin-flip



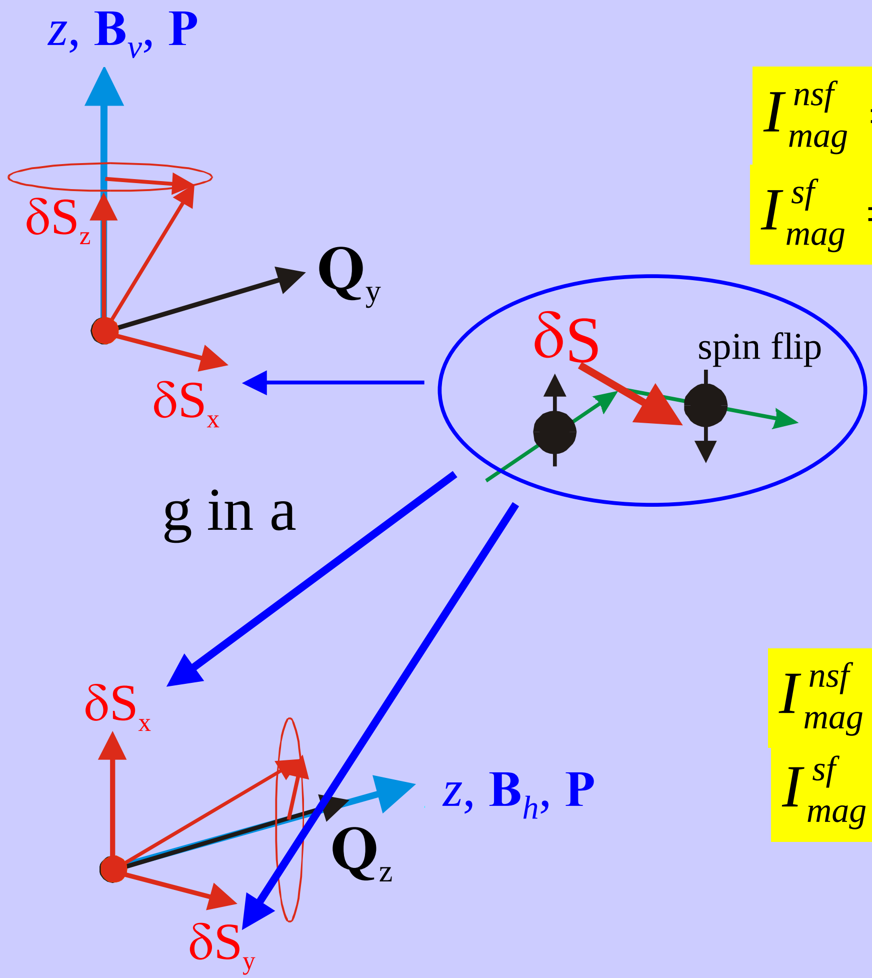
• (room) **background**:

→ contributes to all scattering channels

Rules for Polarization Analysis 2

(special case: isotropic ferromagnet!)

- **paramagnetic** scattering in a vertical field: $\mathbf{Q} \perp \mathbf{B}$



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

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

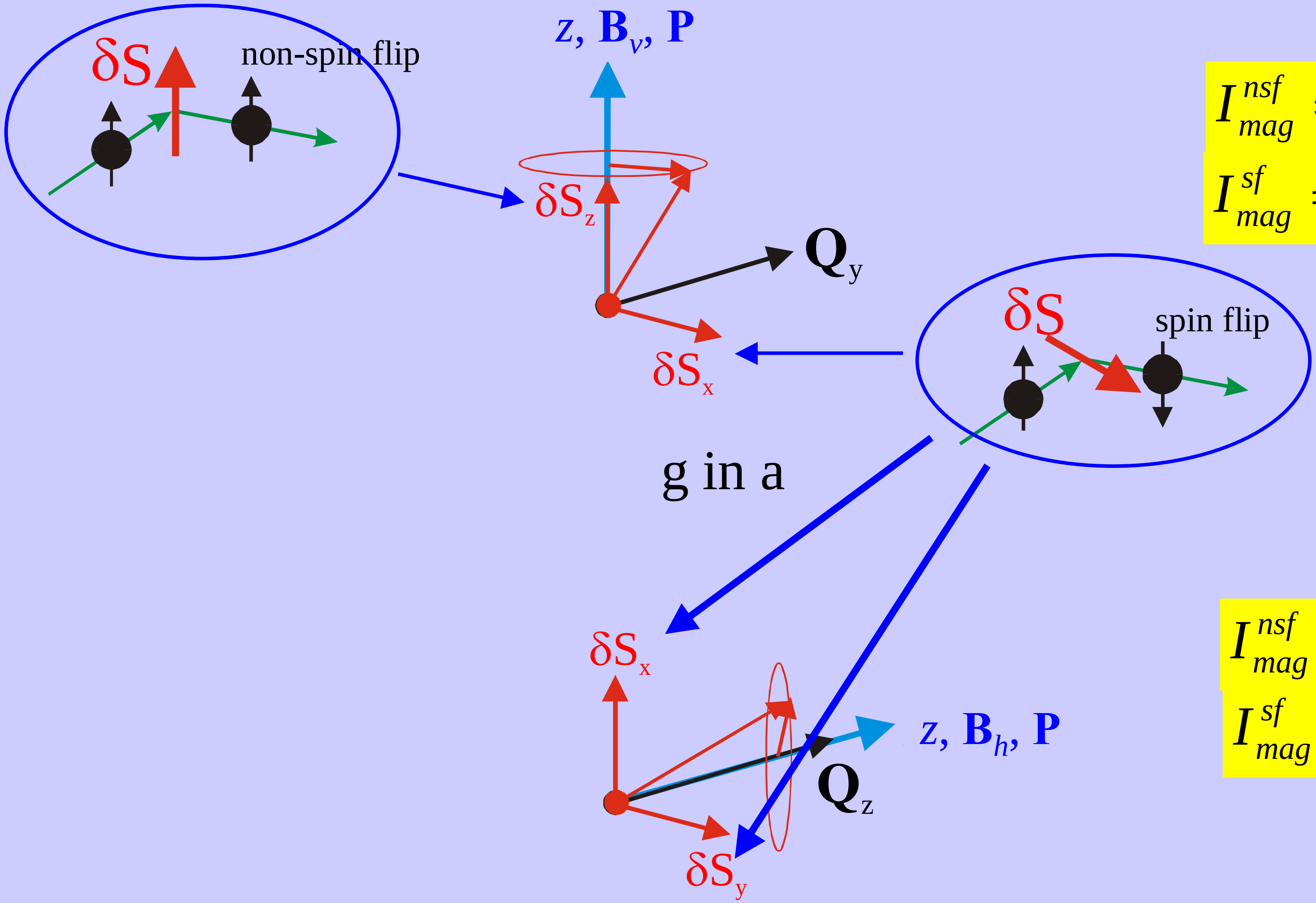
$$I_{mag}^{nsf} = 0$$

$$I_{mag}^{sf} = \sigma_{mag}$$

Rules for Polarization Analysis 2

(special case: isotropic ferromagnet!)

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



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

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

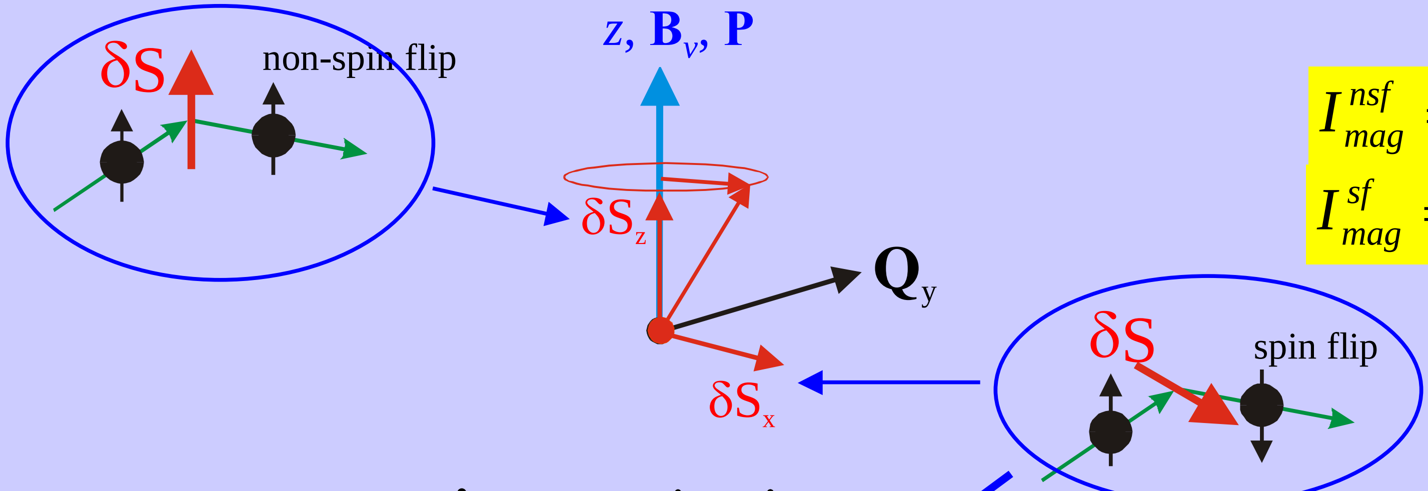
$$I^{nsf}_{mag} = 0$$

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

Rules for Polarization Analysis 2

(special case: isotropic ferromagnet!)

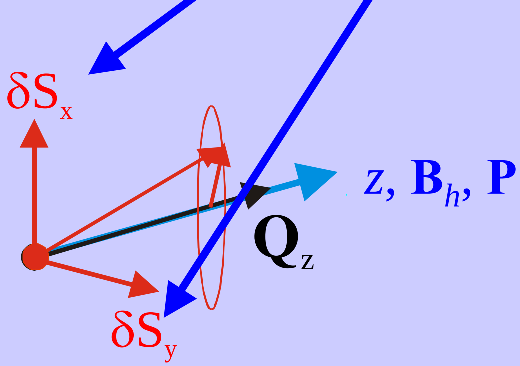
• **paramagnetic** scattering in a vertical field: **Q ⊥ B**



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

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

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



$$I_{mag}^{nsf} = 0$$

$$I_{mag}^{sf} = \sigma_{mag}$$

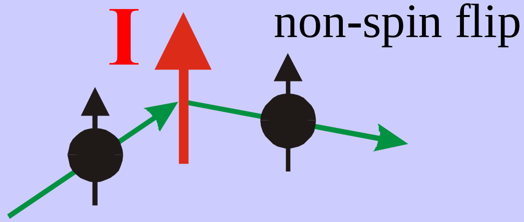
Rules for Polarization Analysis 3

- **spin incoherent** scattering:

discussed before: nuclear scattering

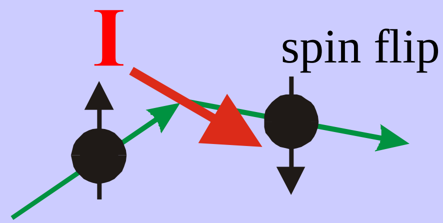
$$\left\langle \uparrow \left| A + B\boldsymbol{\sigma}\cdot\mathbf{I} \right| \uparrow \right\rangle = A + BI_z$$

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



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

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



- at reasonable temperatures: $\left\langle I_x^2 \right\rangle = \left\langle I_y^2 \right\rangle = \left\langle I_z^2 \right\rangle = \frac{1}{3} I(I+1)$

- contribution of spin-incoherent: $I_{NSI}^{nsf} = \frac{1}{3}\sigma_{NSI}$ $\quad I_{NSI}^{sf} = \frac{2}{3}\sigma_{NSI}$

Rules for Polarization Analysis 4

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

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

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

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

Rules for Polarization Analysis 4

	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.

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

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

Rules for Polarization Analysis 4

	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:

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

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

Rules for Polarization Analysis 4

	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.

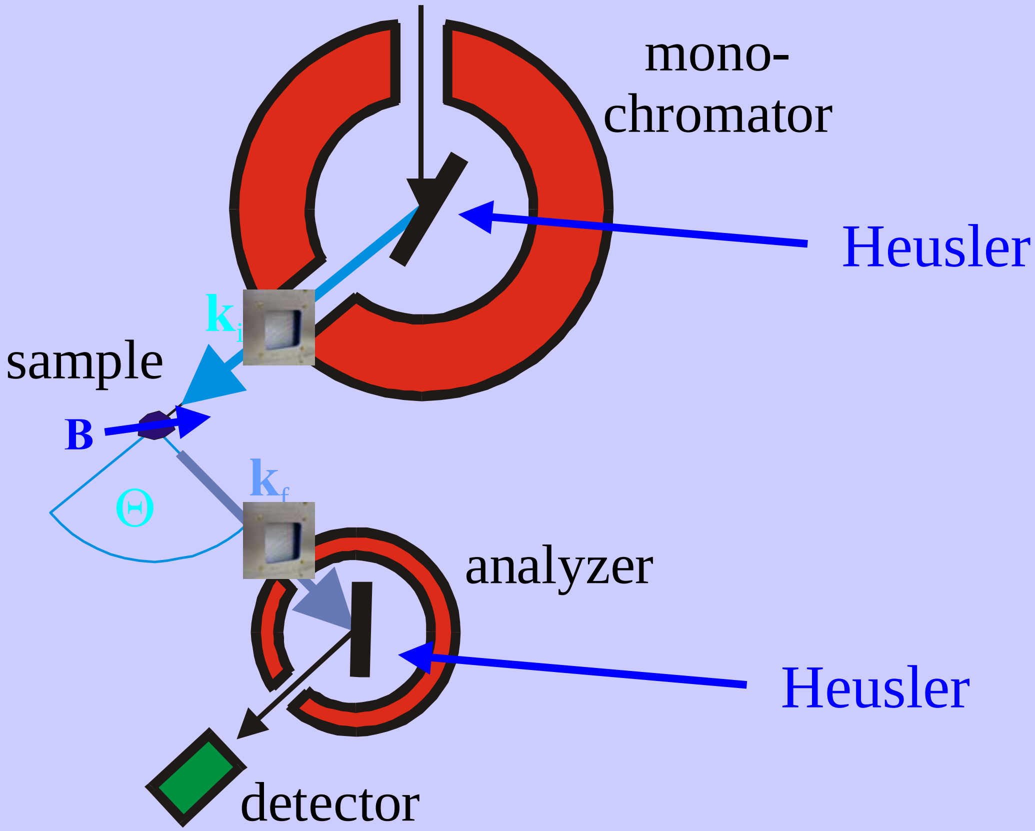
Example: Paramagnetic scattering from ferromagnetic material:

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

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

Polarized Triple-Axis Spectrometer

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



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

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

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!)

Deuterium in Nb

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

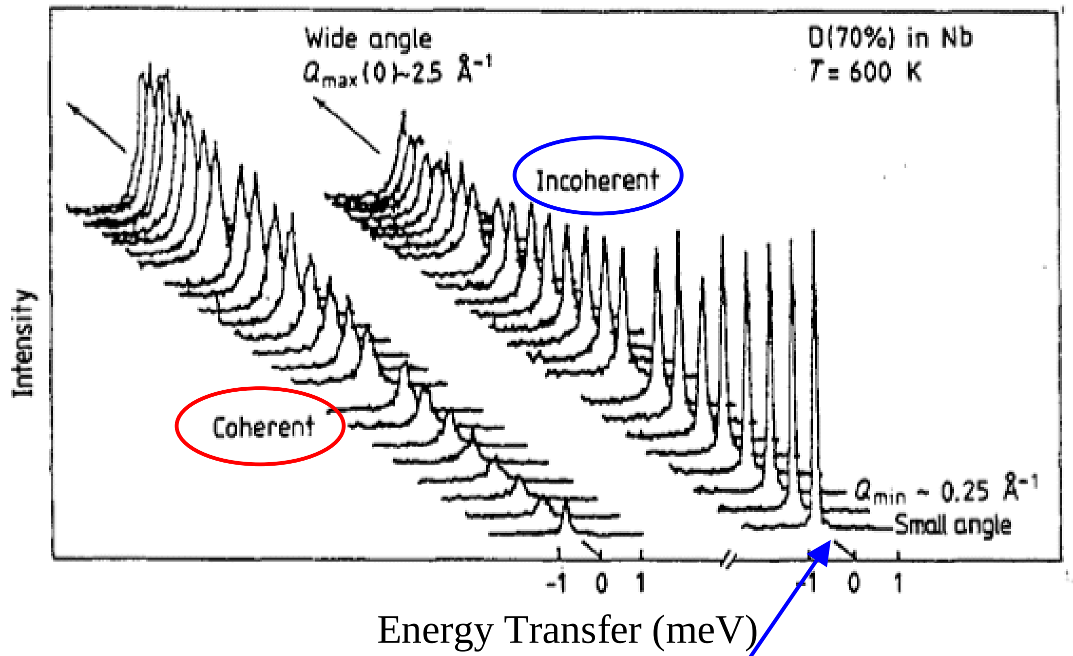
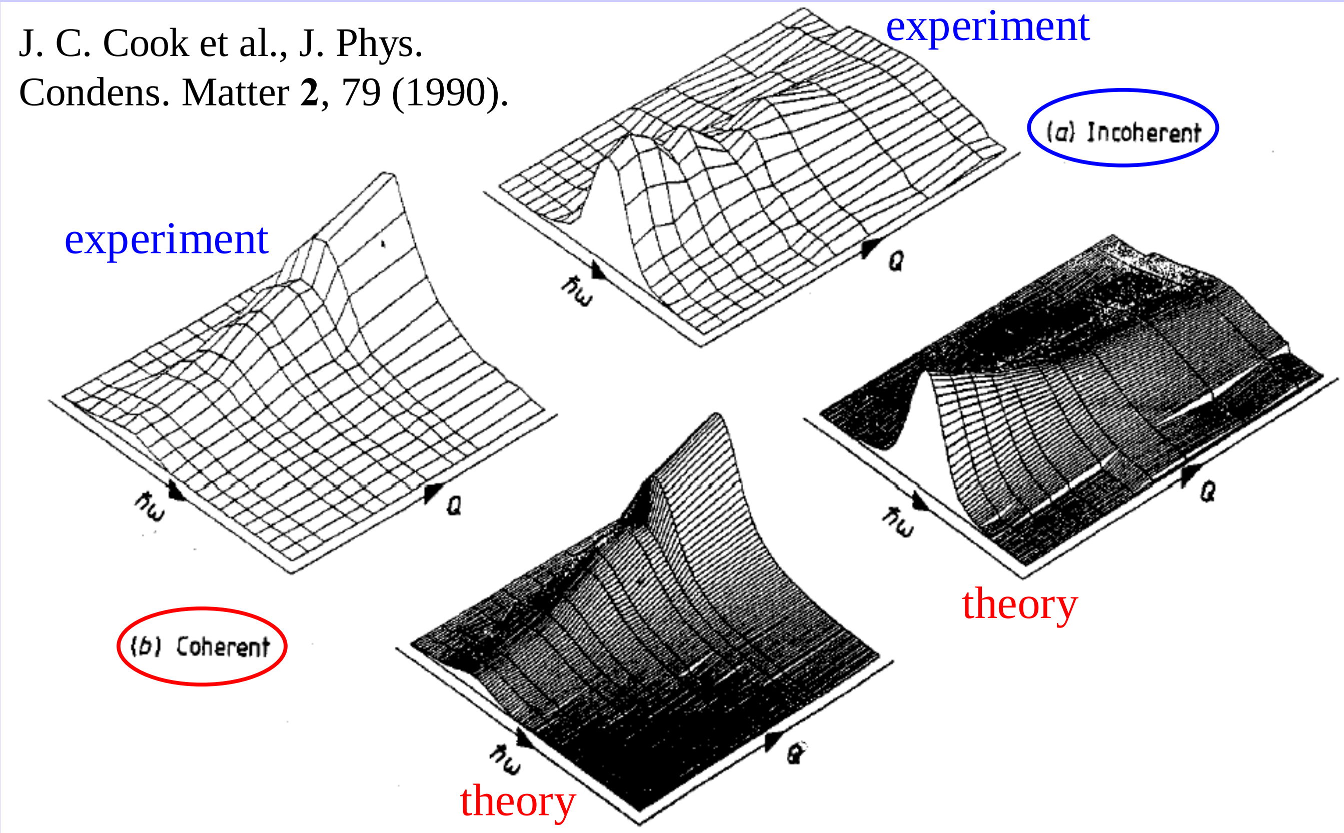


Figure 2. The separated coherent and incoherent parts of the total scattering around the elastic position as a function of detector angle.

H provides mostly incoherent scattering i.e. the self-correlations!

Deuterium in Nb

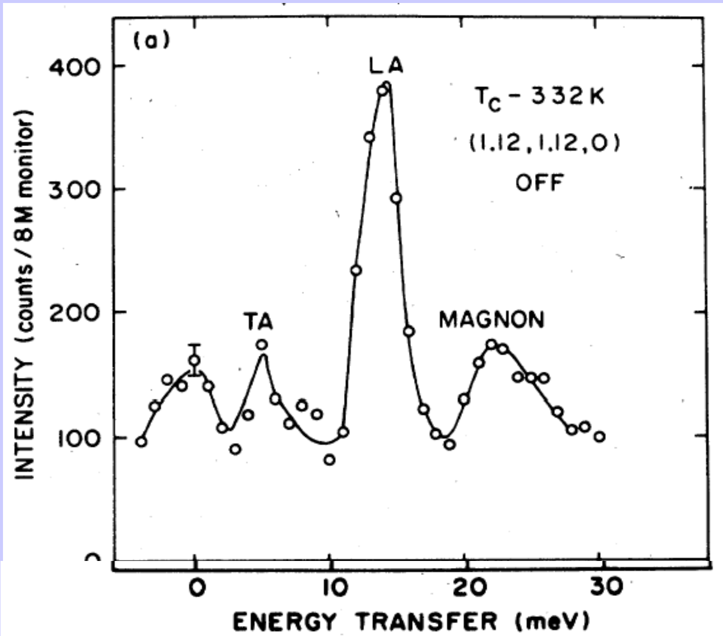


- separation successful
- good agreement with theory
- incoherent-coherent residence times: $\tau_{coh} = 0.49\,\tau_{inc}$

Example 2: Paramagnetic Scattering in Fe

- Fe in ferromagnetic phase

unpolarised beam:



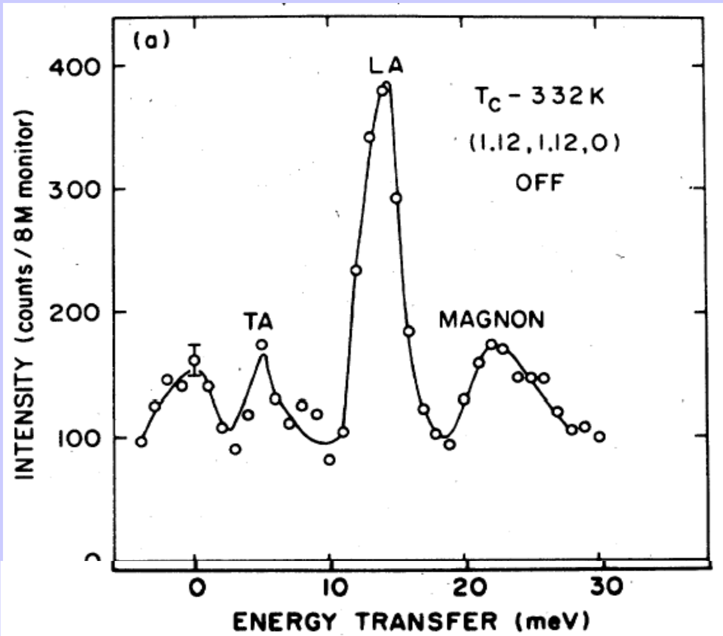
Wicksted et al., PRB 30, 3655 (1984)

$$\sigma_m + \tfrac{2}{3}\sigma_{NSI} + \sigma_{bg} - (\tfrac{1}{2}\sigma_m + \tfrac{2}{3}\sigma_{NSI} + \sigma_{bg})$$

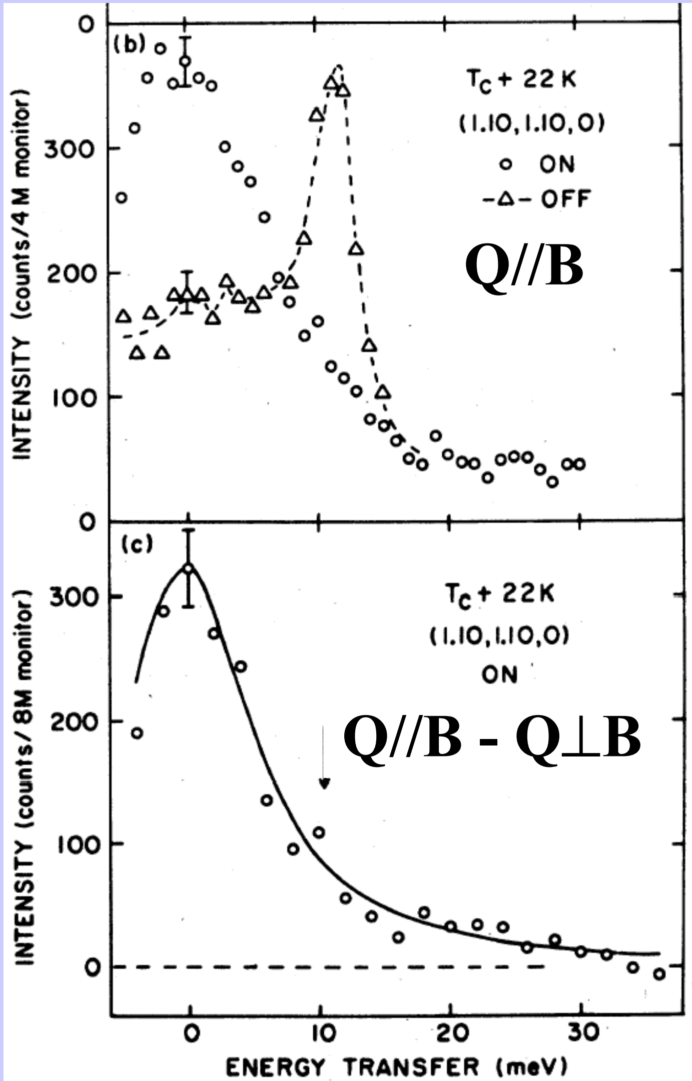
Example 2: Paramagnetic Scattering in Fe

- Fe in ferromagnetic phase

unpolarised beam:



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



$$\sigma_m + \tfrac{2}{3}\sigma_{NSI} + \sigma_{bg} - (\tfrac{1}{2}\sigma_m + \tfrac{2}{3}\sigma_{NSI} + \sigma_{bg})$$

Paramagnetic Scattering in Fe

→ 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

constant-*E* scan

Overview with TOF at a pulsed source?

Paramagnetic Scattering in Fe

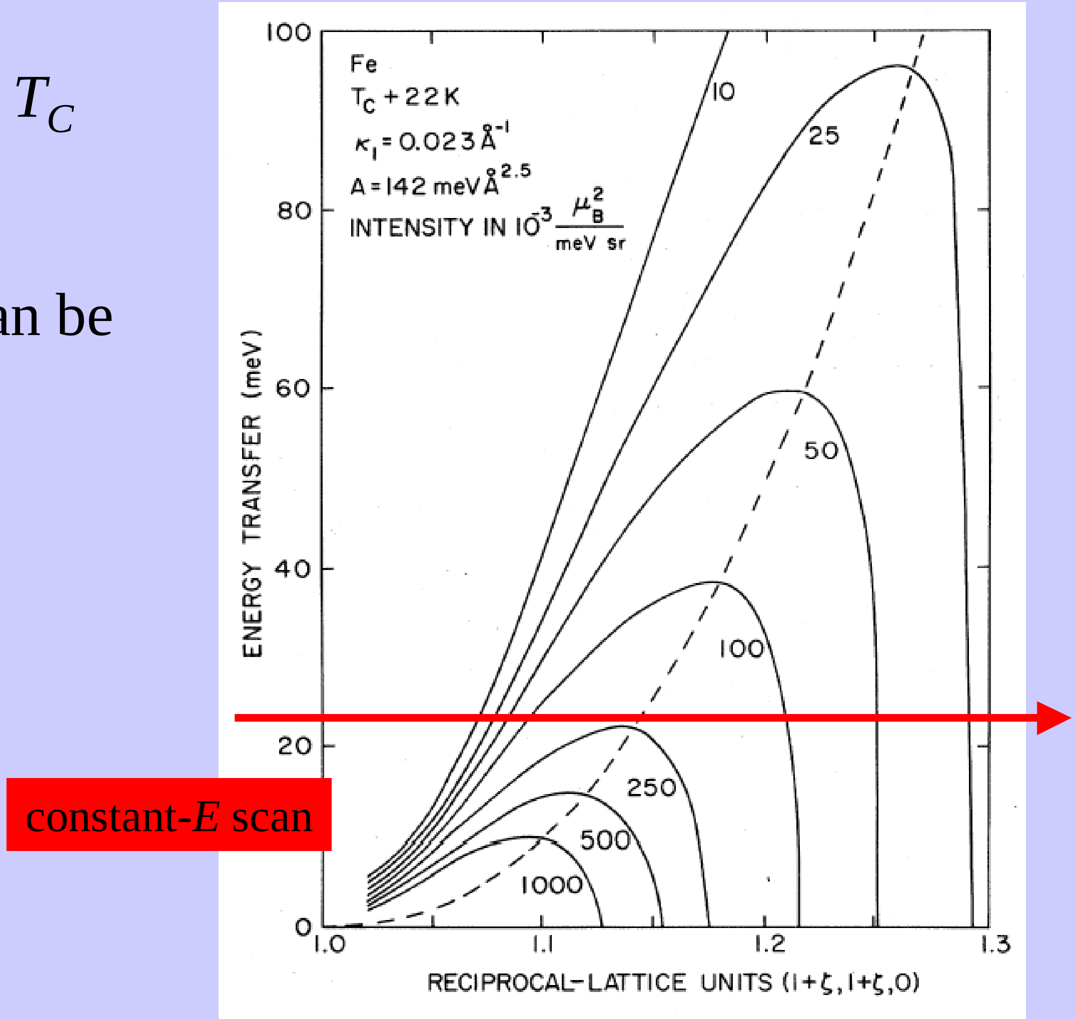
→ no spin waves above T_C

→ time evolution of magnetic fluctuations can be measured:

→ $\Gamma = Aq^{2.5}$

→ behavior similar as a simple Heisenberg ferromagnet

Overview with TOF at a pulsed source?



Paramagnetic Scattering in Fe

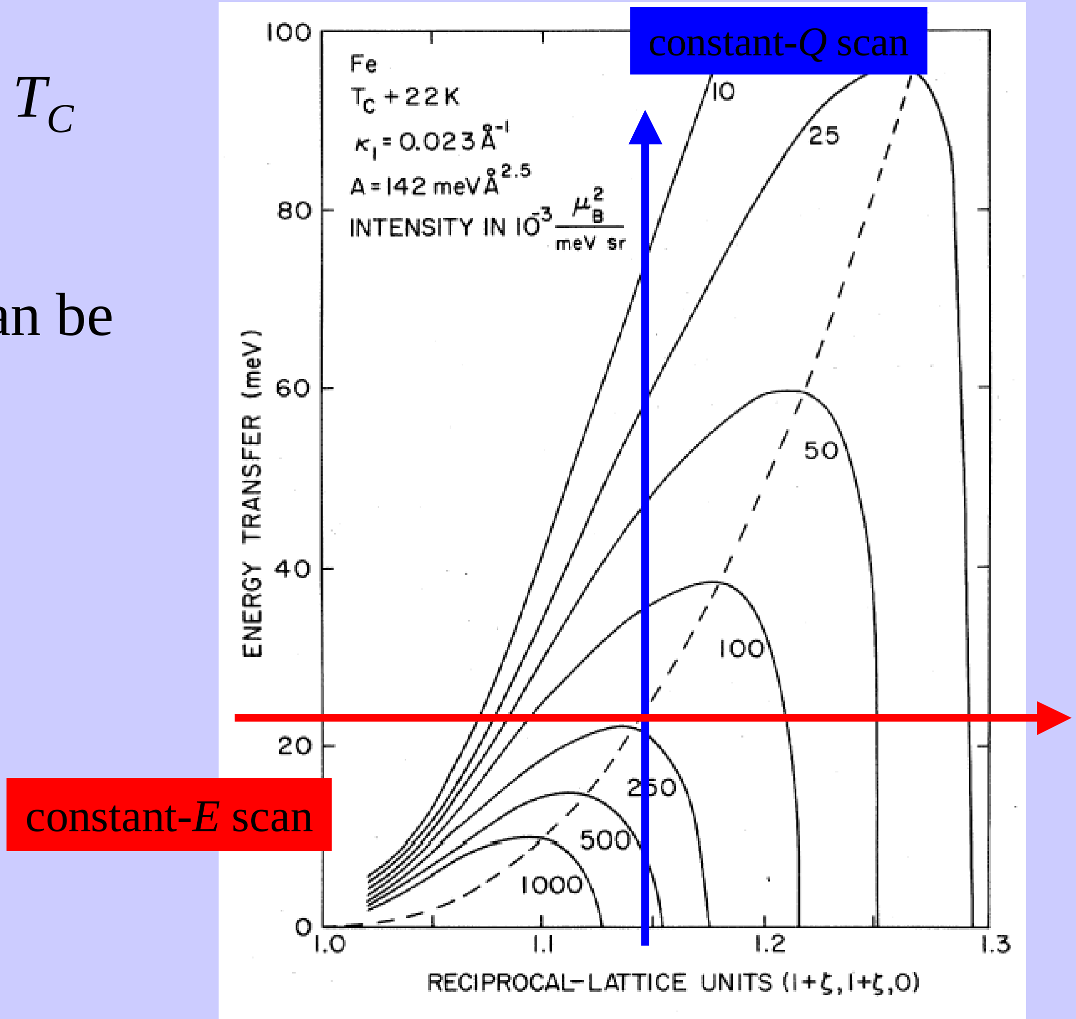
→ no spin waves above T_C

→ time evolution of magnetic fluctuations can be measured:

→ $\Gamma = Aq^{2.5}$

→ behavior similar as a simple Heisenberg ferromagnet

Overview with TOF at a pulsed source?



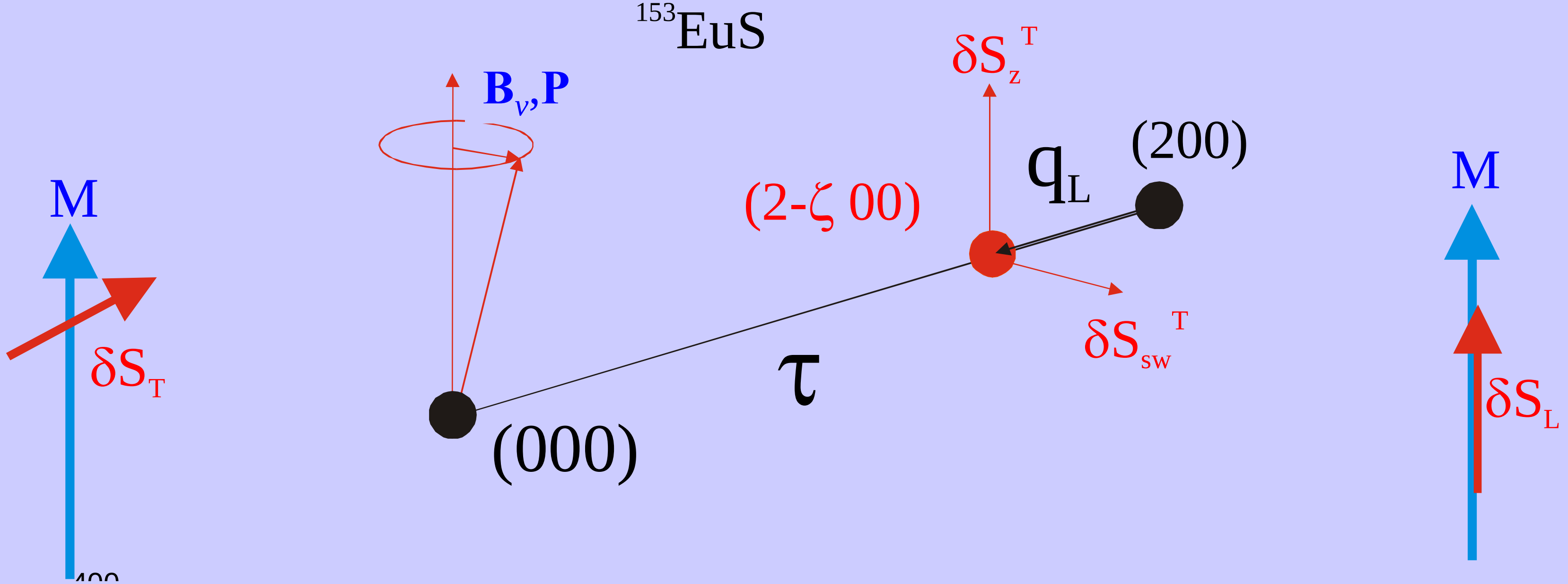
So far:

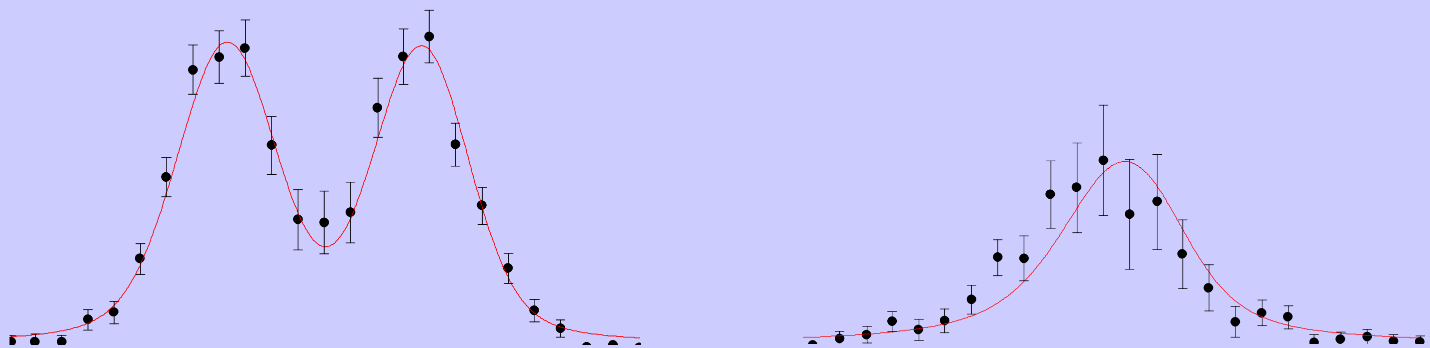
- Incoherent – coherent scattering
- Supression of nuclear scattering

Next:

- distinction between magnetic modes

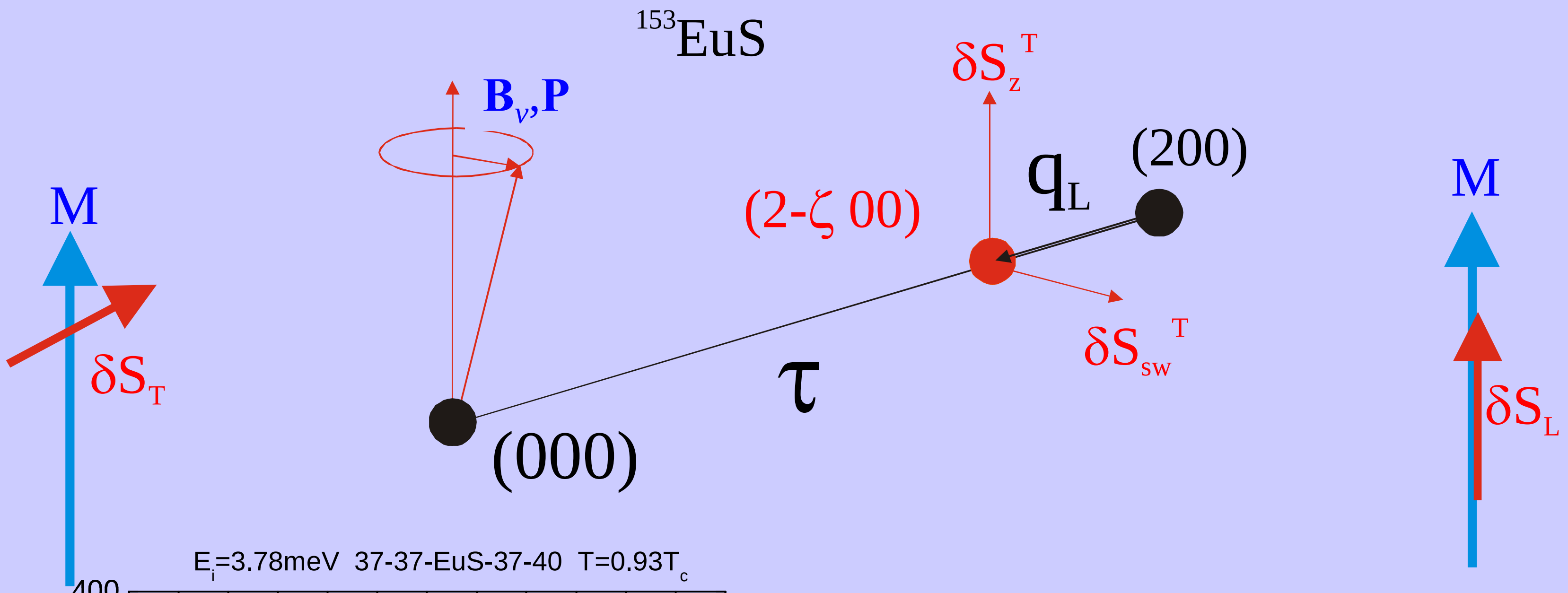
Example 3: Longitudinal Fluctuations in EuS

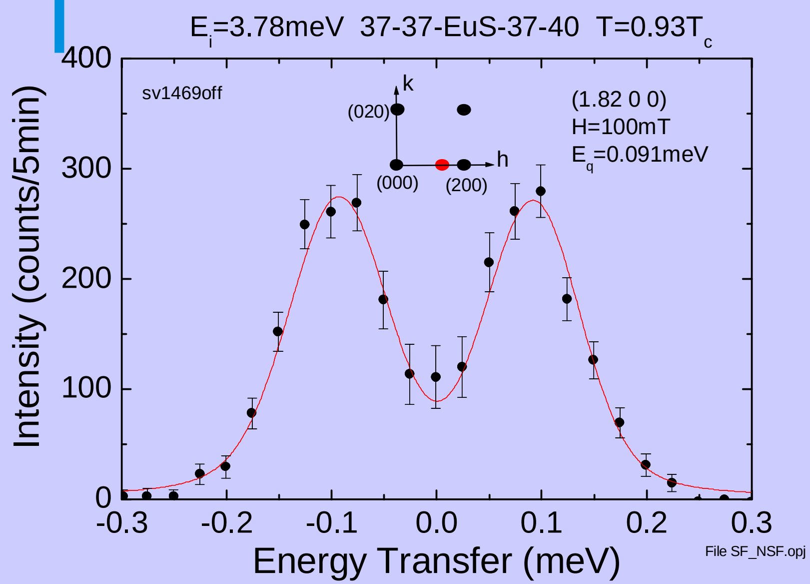


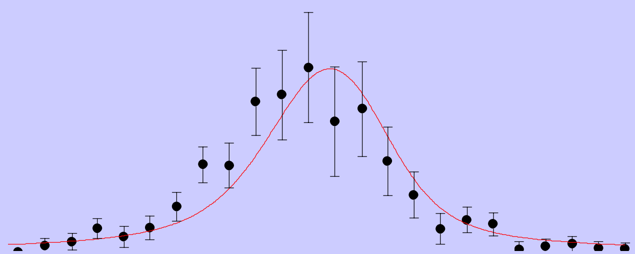


Böni et al., PRB **65**, 144434 (2002)

Example 3: Longitudinal Fluctuations in EuS

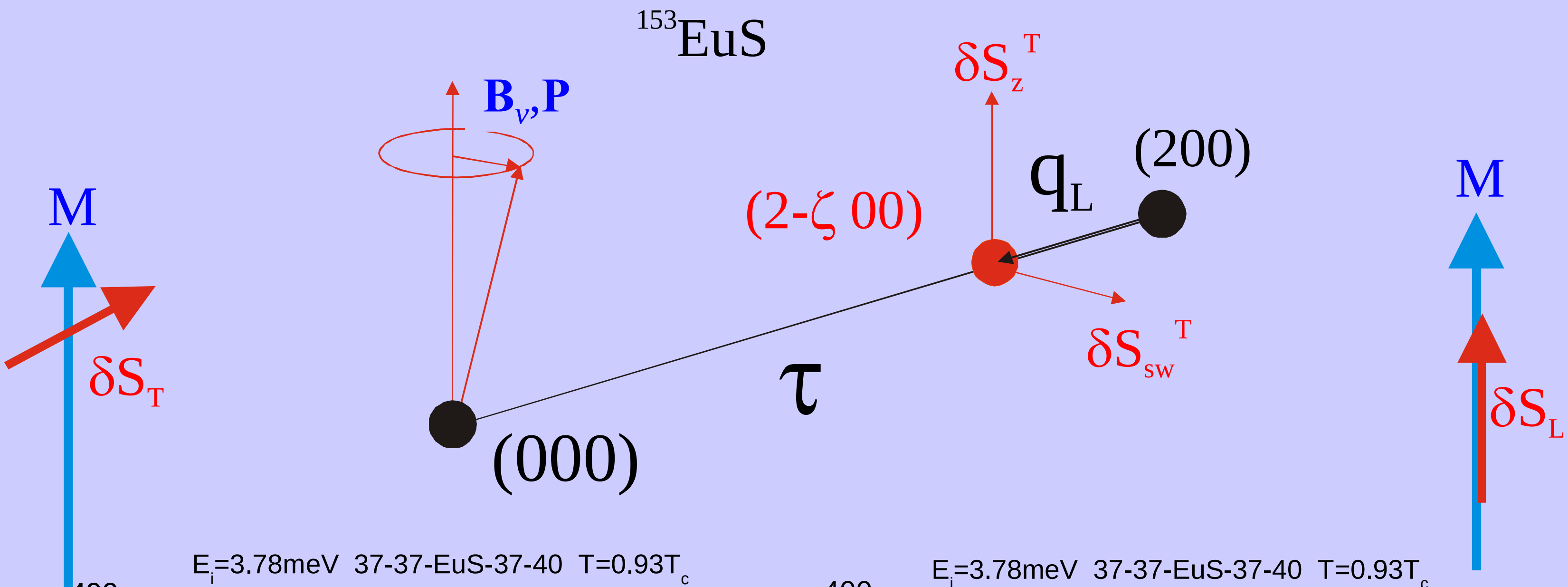


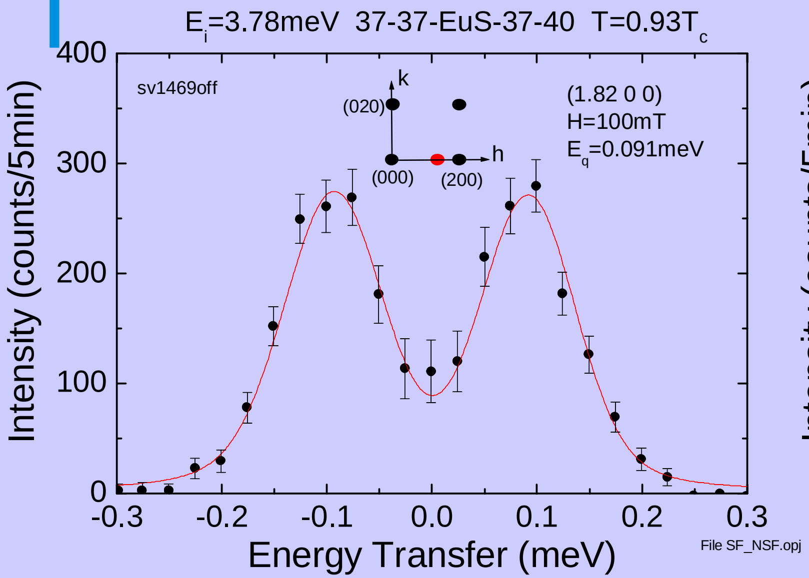


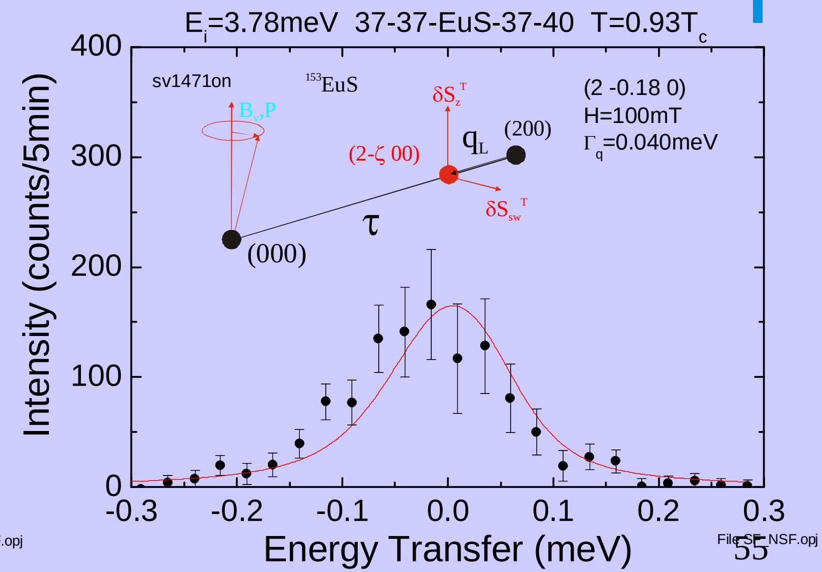


Böni et al., PRB **65**, 144434 (2002)

Example 3: Longitudinal Fluctuations in EuS



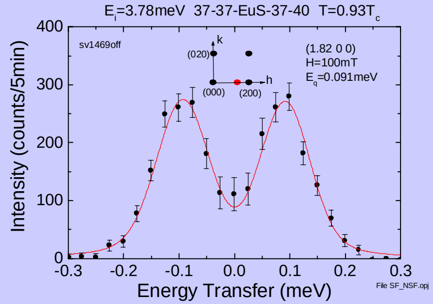




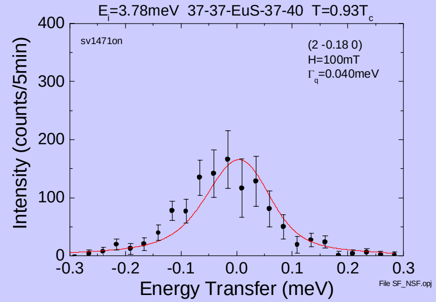
Böni et al., PRB **65**, 144434 (2002)

Polarized Neutrons Necessary?

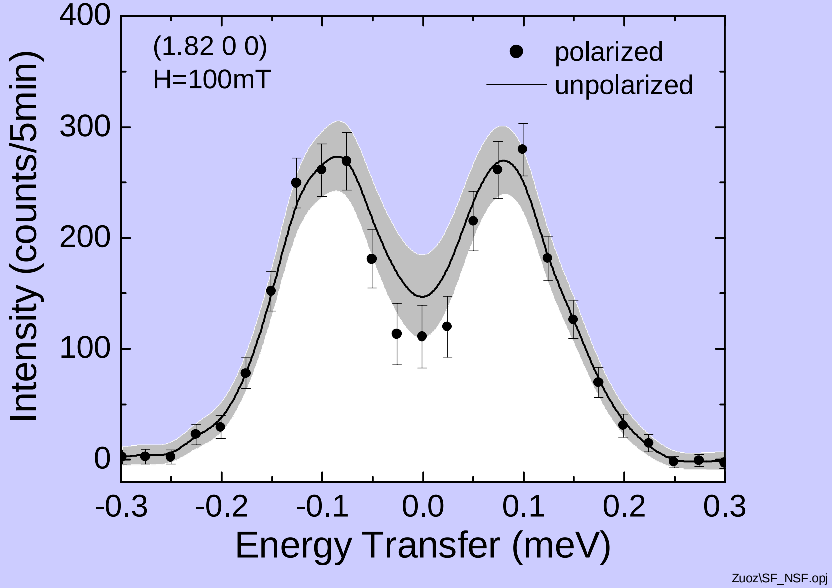
2×



+

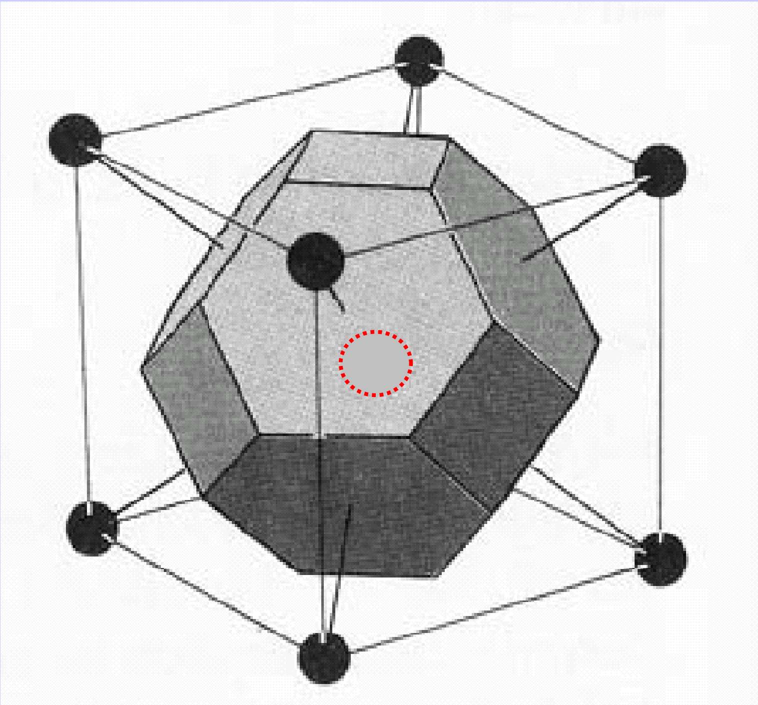


=



Polarization analysis important for measurements near T_C

Example 4: Cr, an Itinerant Antiferromagnet



Very simple material?

complicated topology of Fermi surface

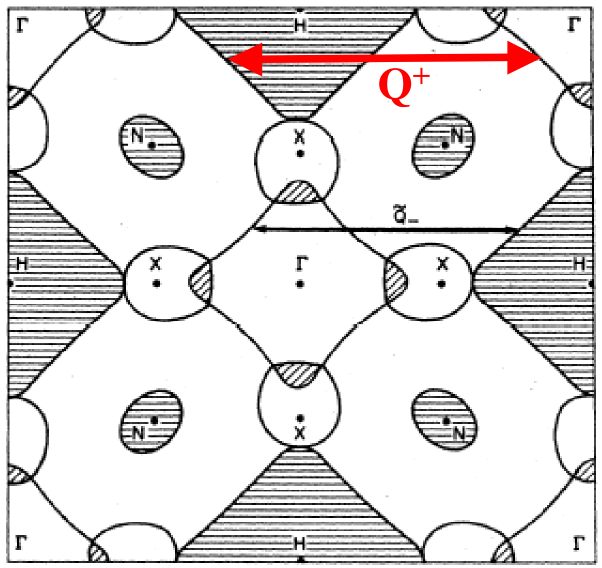
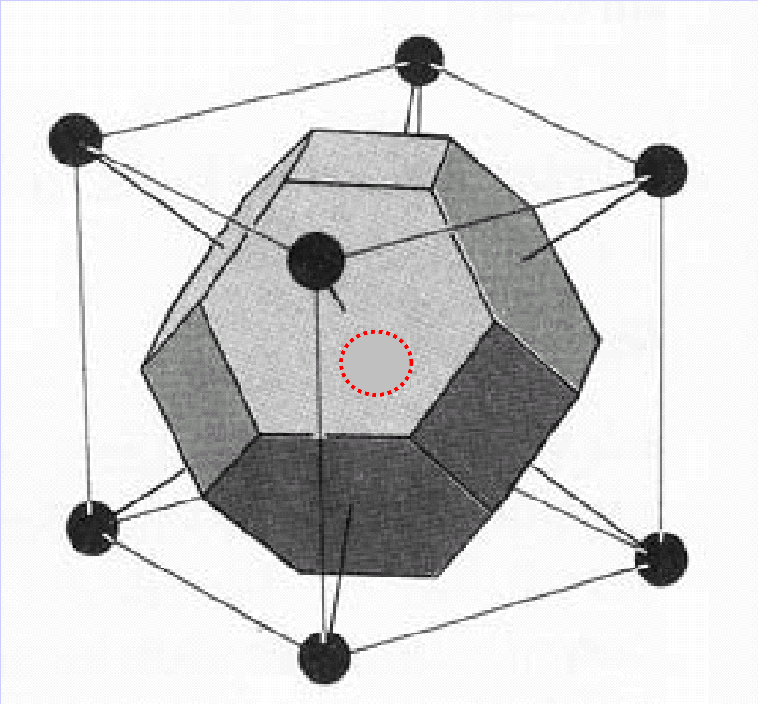


FIG. 59. Fermi-surface cross section: (100) plane (after Laurent *et al.*, 1981). Typical nesting vectors, $\tilde{Q}_{\pm}=(0,0,1\pm\delta)$, between the Γ and H surfaces are shown.

Example 4: Cr, an Itinerant Antiferromagnet



Very simple material?

complicated topology of Fermi surface

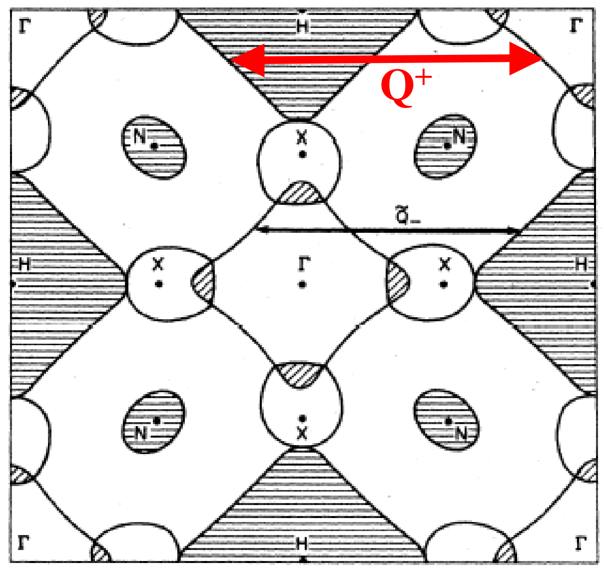
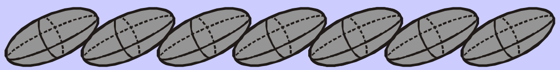
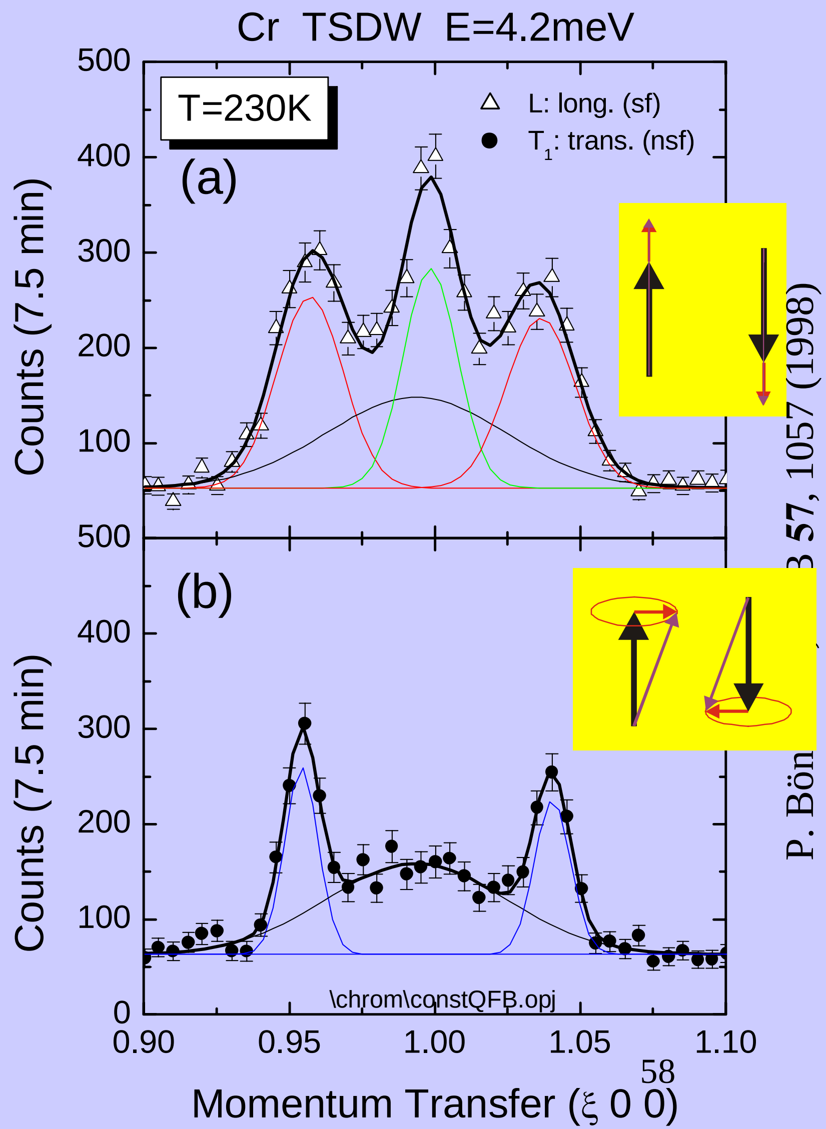


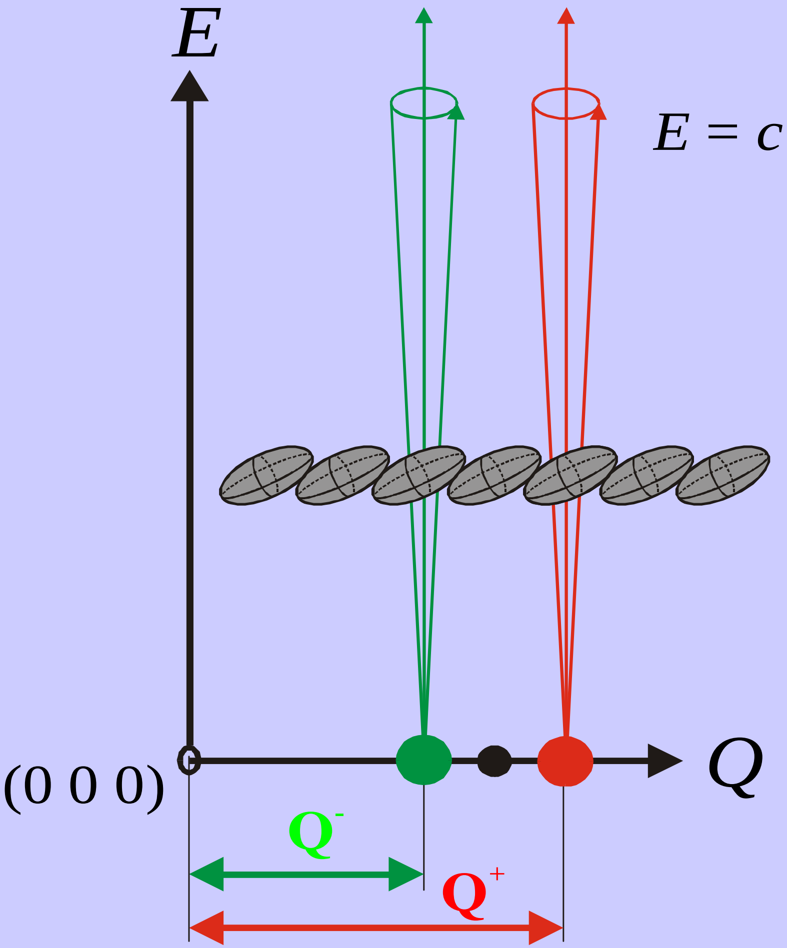
FIG. 59. Fermi-surface cross section: (100) plane (after Laurent *et al.*, 1981). Typical nesting vectors, $\tilde{Q}_{\pm}=(0,0,1\pm\delta)$, between the Γ and *H* surfaces are shown.

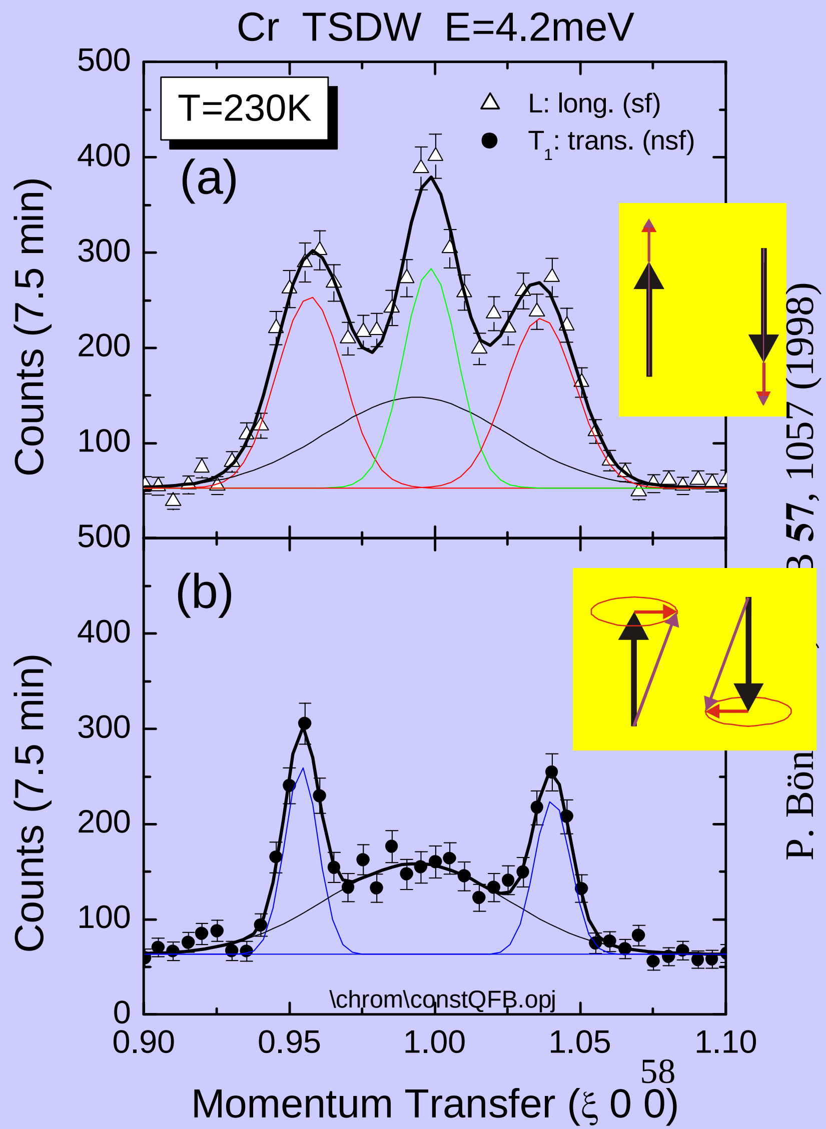
Measurement of *c* with Polarization Analysis



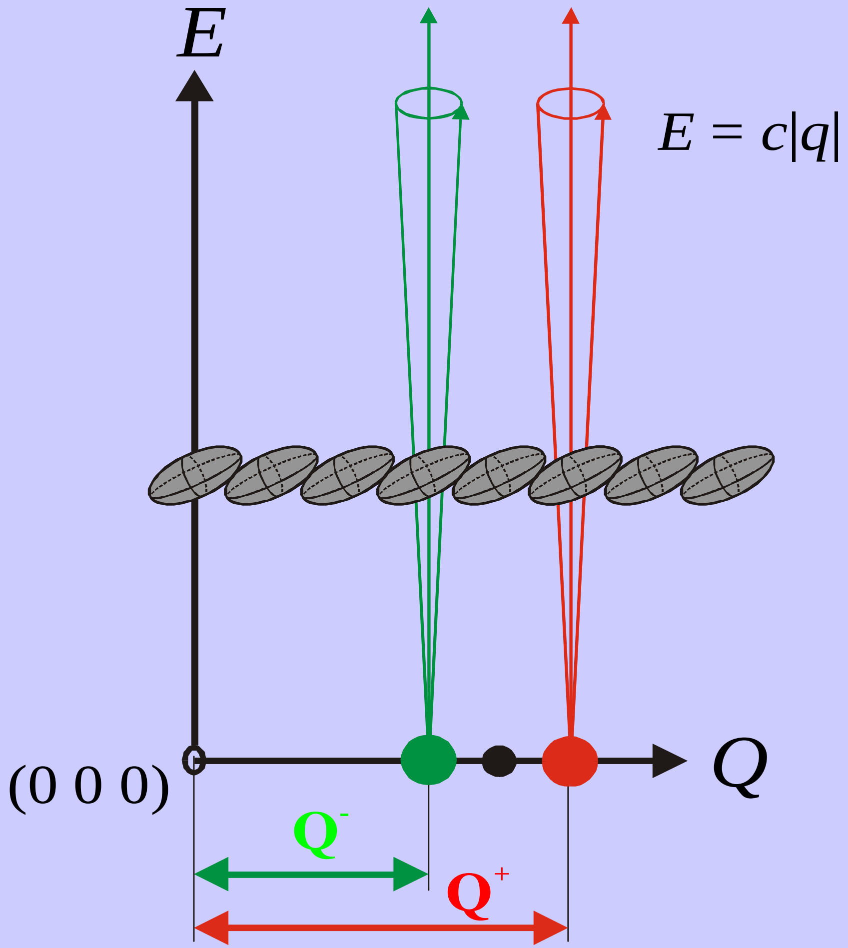


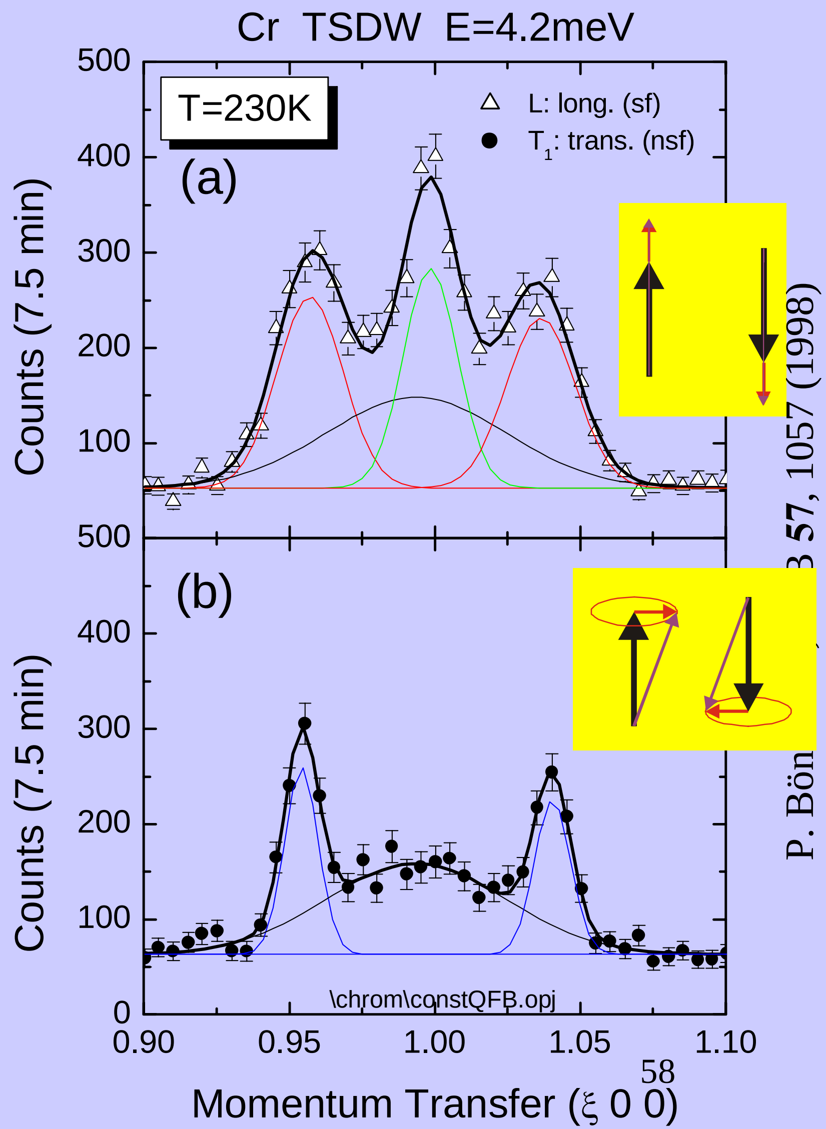
Measurement of *c* with Polarization Analysis



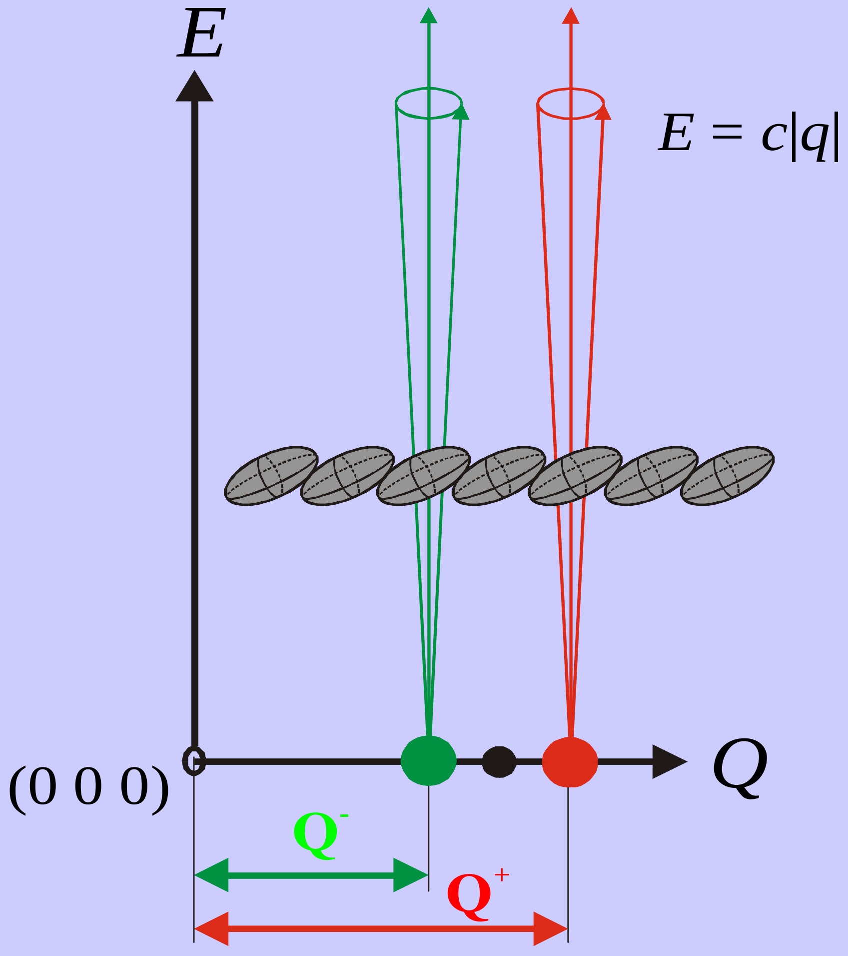


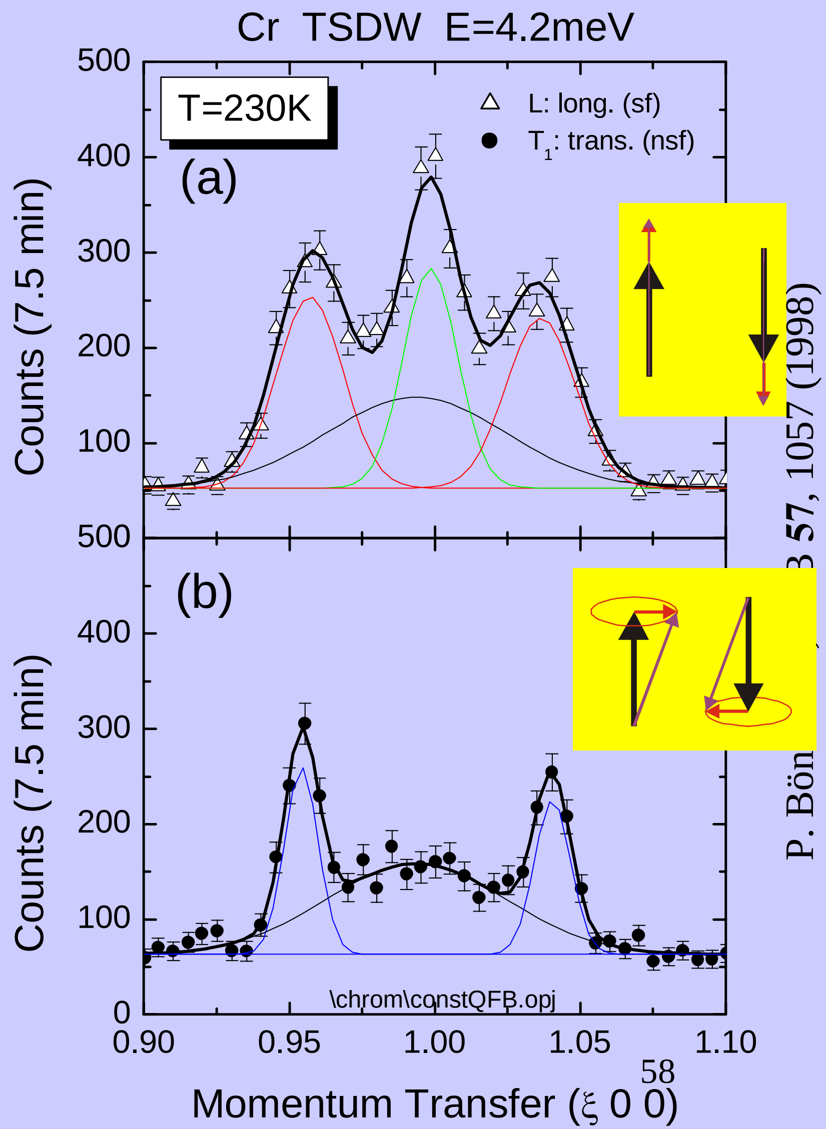
Measurement of *c* with Polarization Analysis





Measurement of *c* with Polarization Analysis





Strong longitudinal fluctuations far below T_N is unexpected!

Is it all? Is I^{+-} always equal to I^{-+}

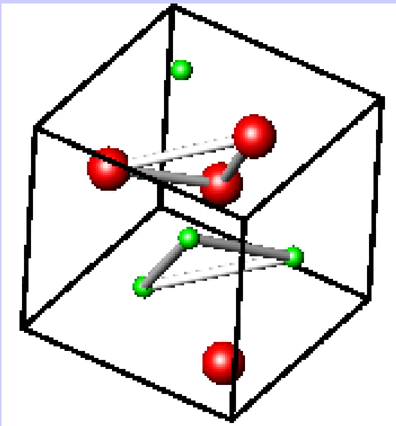
- of course not!
- non-centrosymmetric materials: I^{+-} may be $\neq I^{-+}$

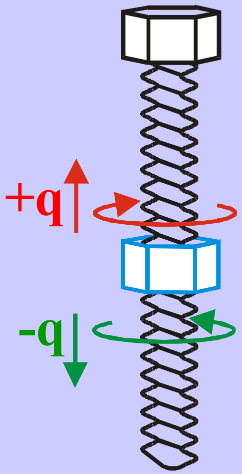
$$\tan\phi = \frac{D}{J}$$

Is it all? Is I^{+-} always equal to I^{-+}

- of course not!
- non-centrosymmetric materials: I^{+-} may be $\neq I^{-+}$

Example 5: MnSi





right handed screw

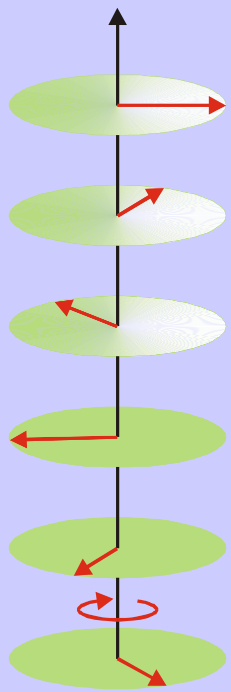
Exchange + Dzyaloshinskii-Moriya:

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

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

Magnetic Spiral in MnSi

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

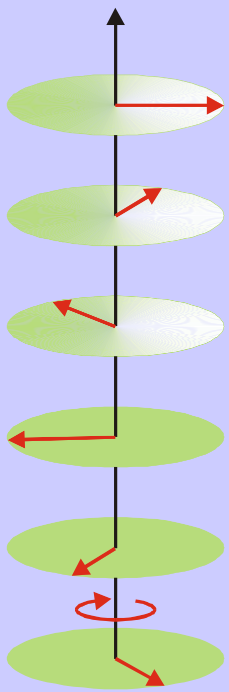


period: 180 Å

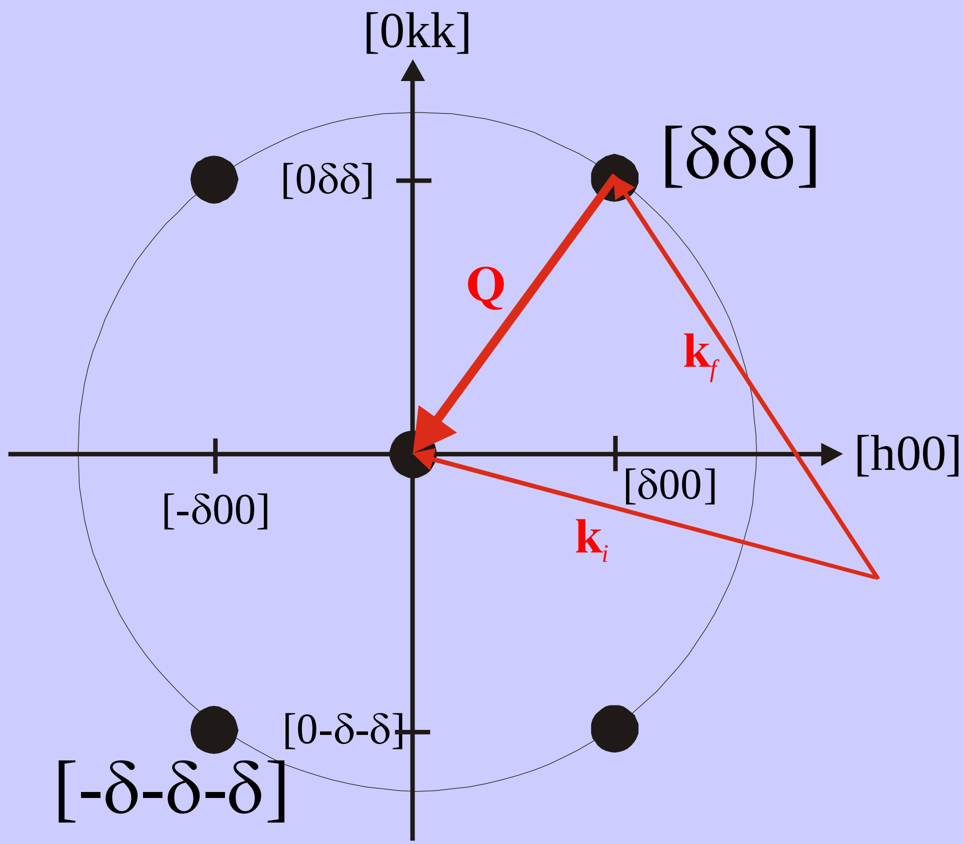
→ **SANS**

Magnetic Spiral in MnSi

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

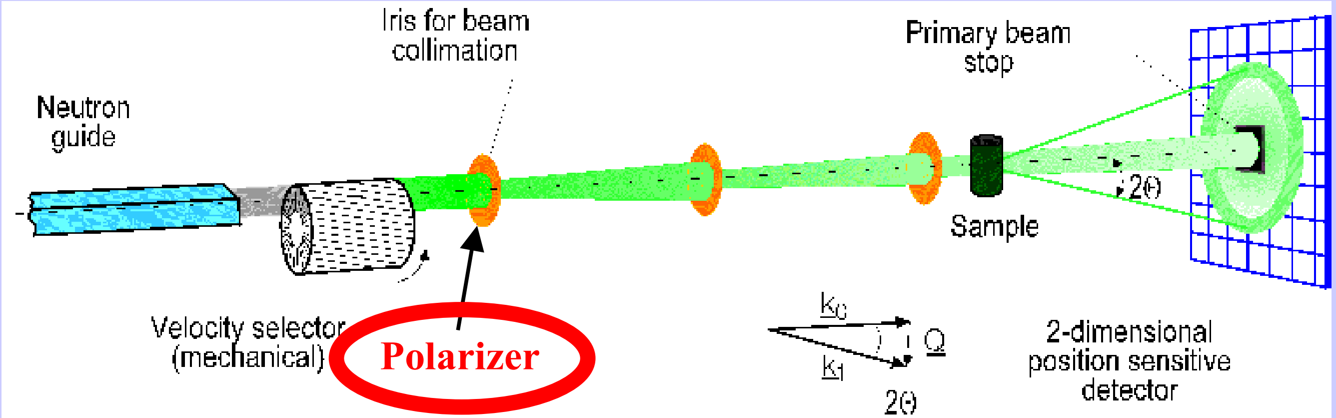


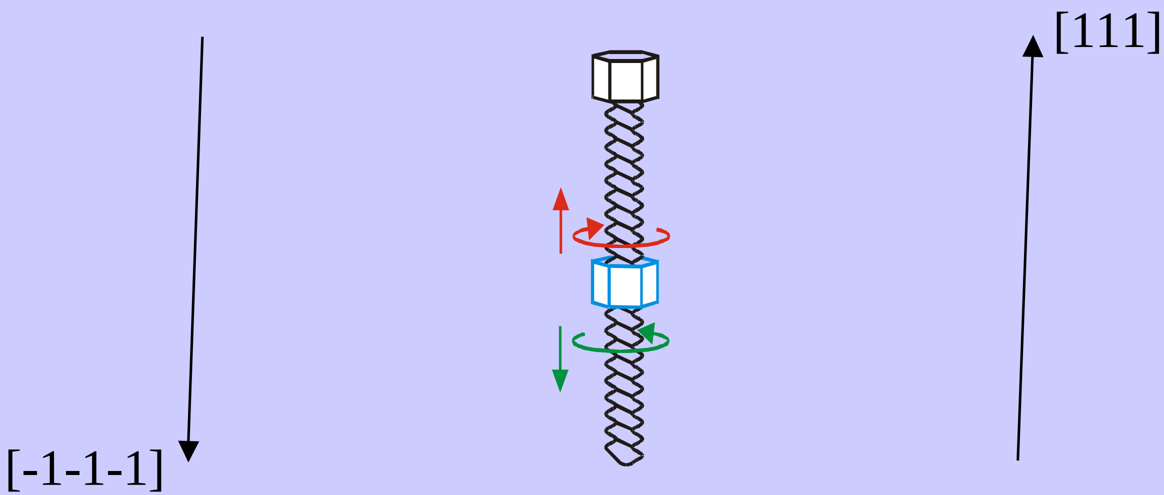
period: 180 Å



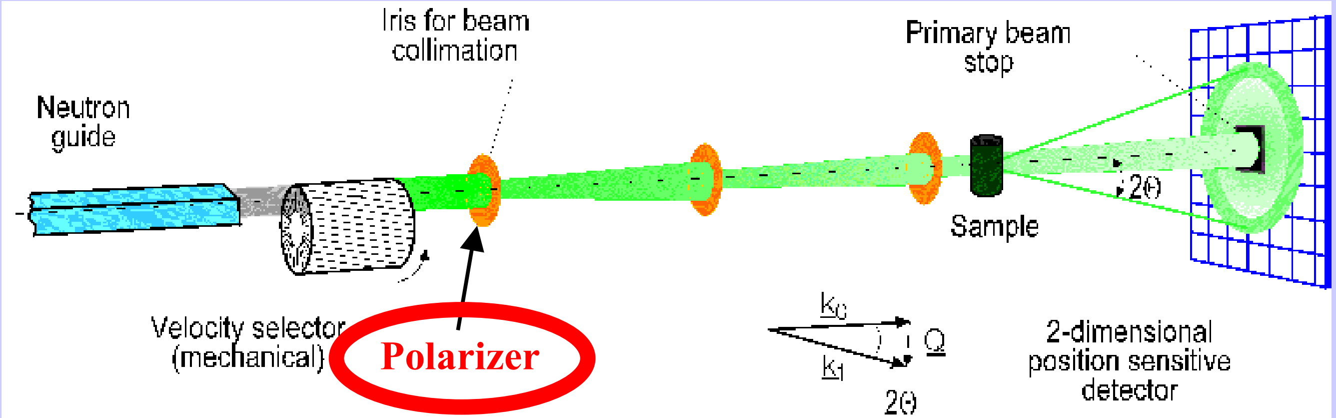
→ **SANS**

SANS-Results: Screw is indeed left-handed

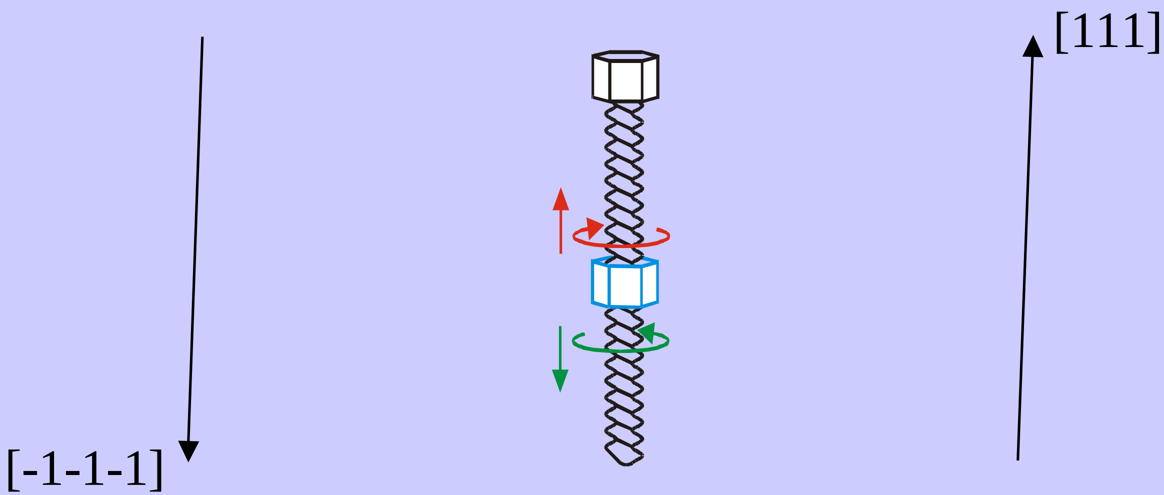




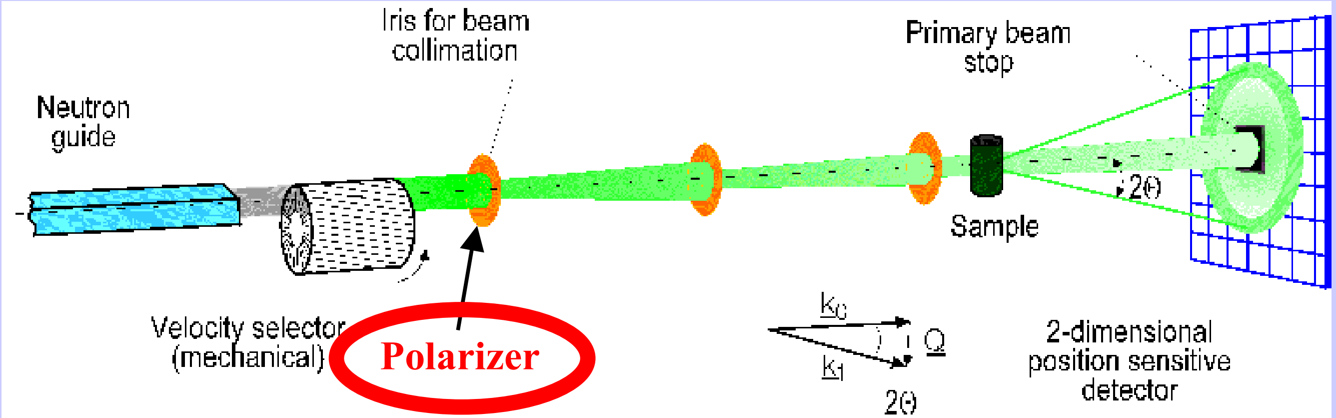
SANS-Results: Screw is indeed left-handed



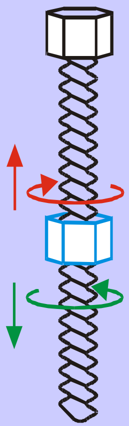
$I^{\pm} \approx \mathbf{S}_i \cdot \mathbf{S}_j \pm i\mathbf{P}(\mathbf{S}_i \times \mathbf{S}_j)$ no spin analysis necessary: only spin flip scattering

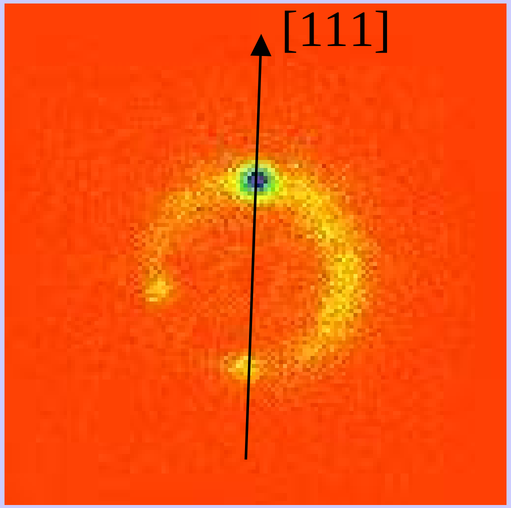


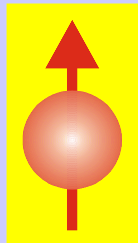
SANS-Results: Screw is indeed left-handed



$I^{\pm} \approx \mathbf{S}_i \cdot \mathbf{S}_j \pm i\mathbf{P}(\mathbf{S}_i \times \mathbf{S}_j)$ no spin analysis necessary: only spin flip scattering

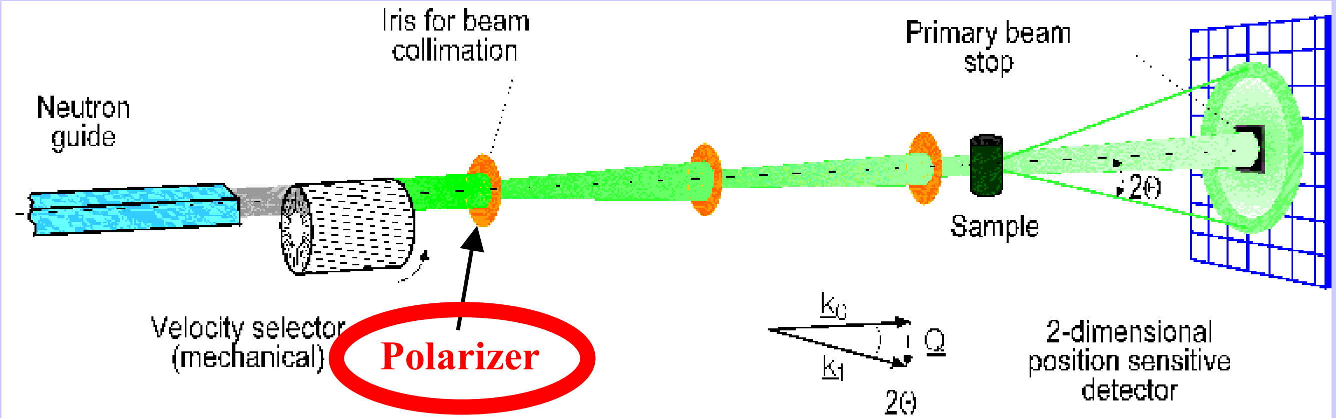




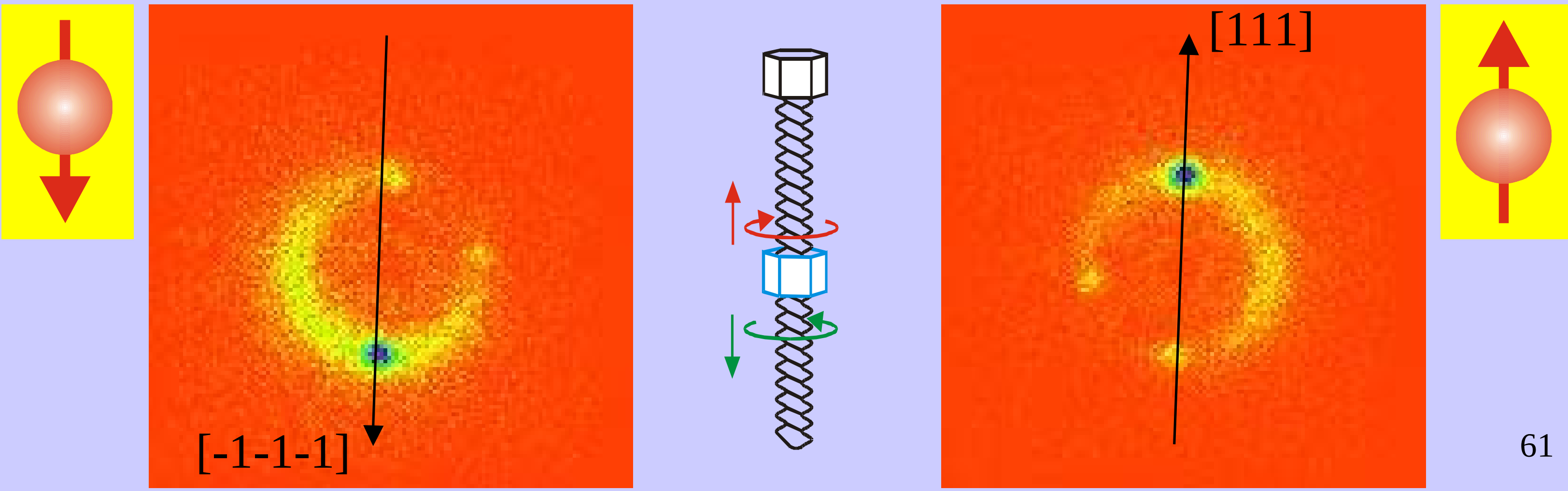


[-1-1-1]

SANS-Results: Screw is indeed left-handed

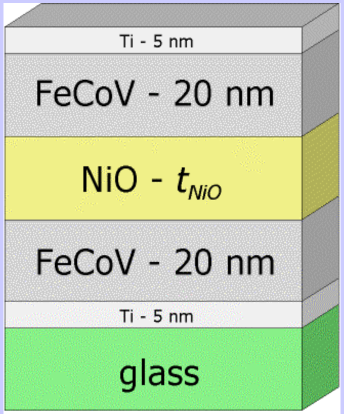


$I^{\pm} \approx \mathbf{S}_i \cdot \mathbf{S}_j \pm i\mathbf{P}(\mathbf{S}_i \times \mathbf{S}_j)$ no spin analysis necessary: only spin flip scattering

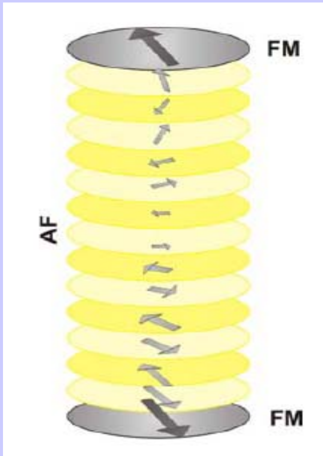


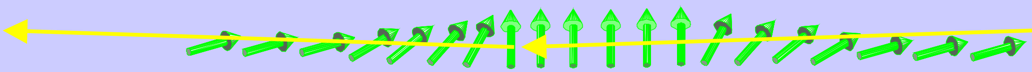
Example 6: Chirality in Multilayers

sample



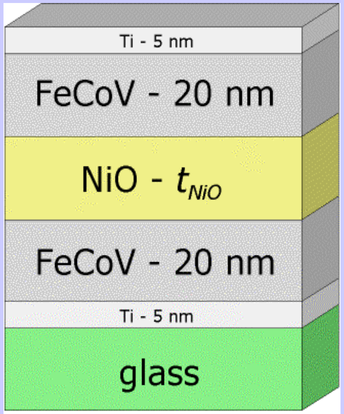
af screw



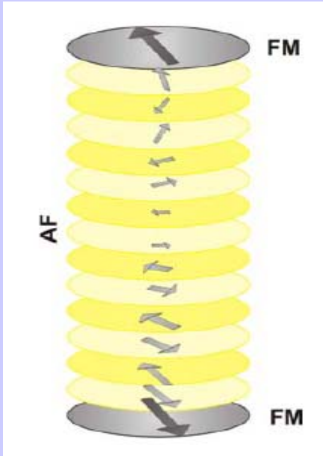


Example 6: Chirality in Multilayers

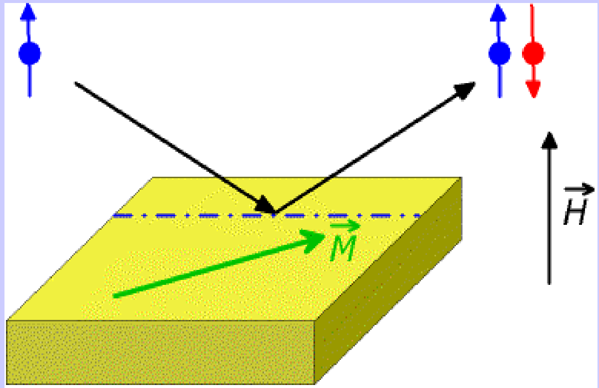
sample



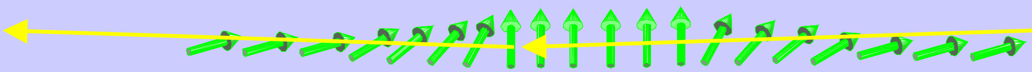
af screw



scattering geometry

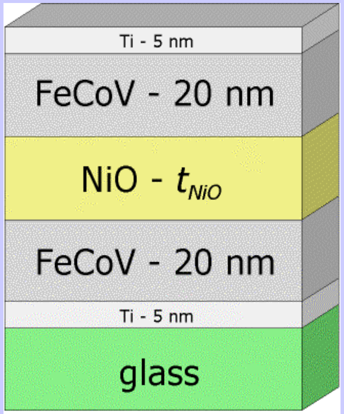


$$\sigma_c = i\mathbf{P}_0 \cdot \left(\mathbf{S}_{bot} \times \mathbf{S}_{top}\right)$$

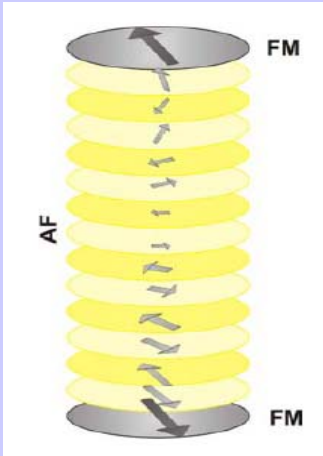


Example 6: Chirality in Multilayers

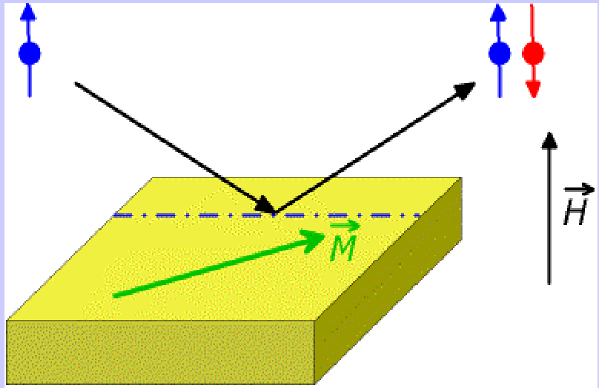
sample



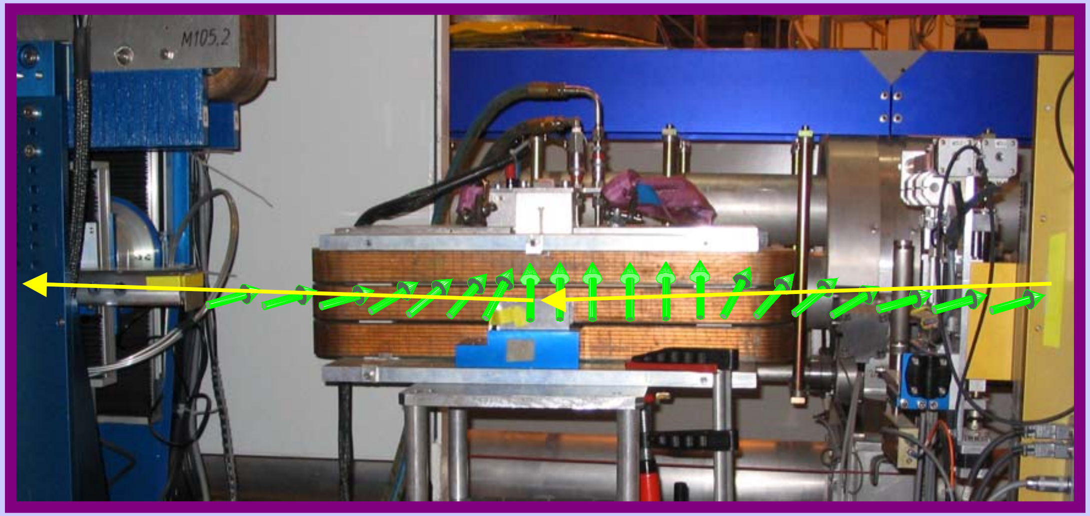
af screw



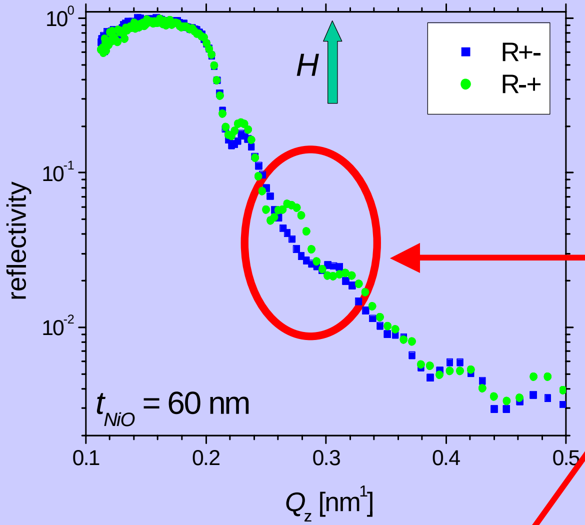
scattering geometry



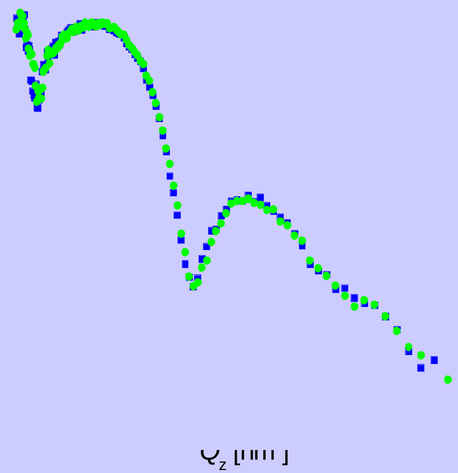
$$\sigma_c = i\mathbf{P}_0 \cdot \left(\mathbf{S}_{bot} \times \mathbf{S}_{top}\right)$$

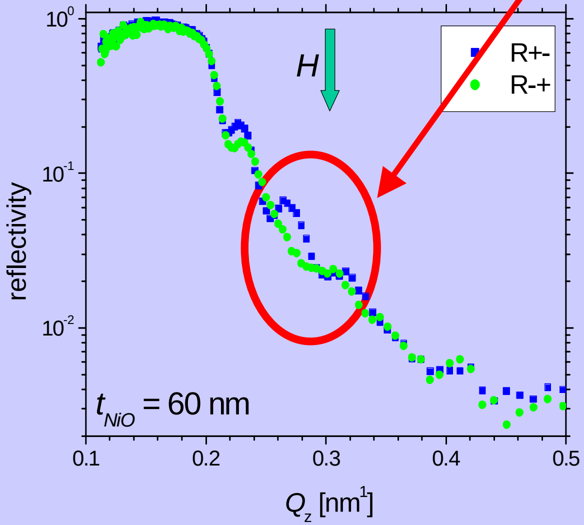


Chirality in Multilayers

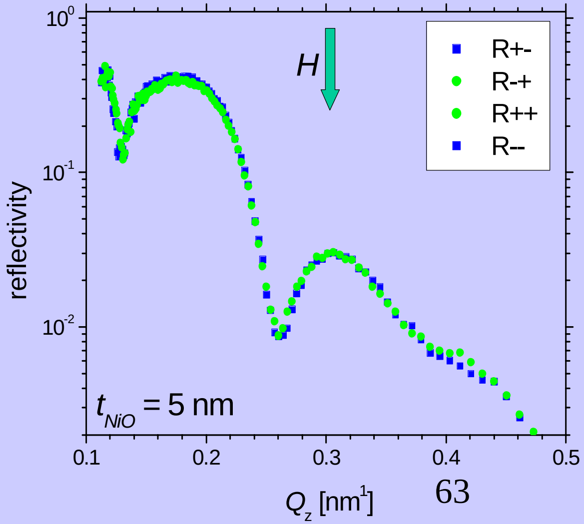


asymmetry in
SF-signal



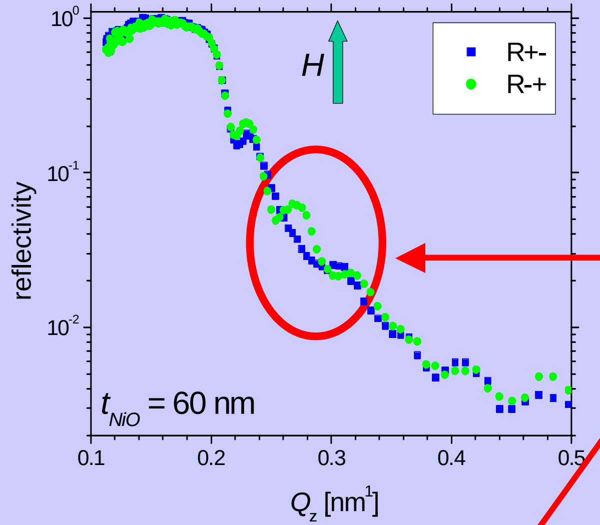


SF-signal is symmetric
⇔ magnetization rotates
together

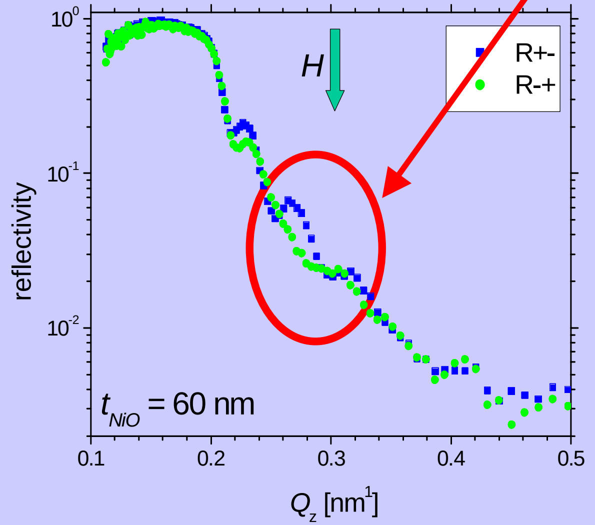


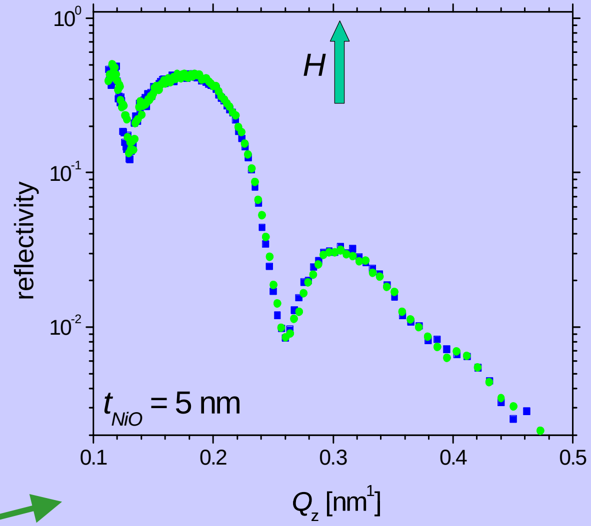
GMR sensors for
angular
measurements

Chirality in Multilayers

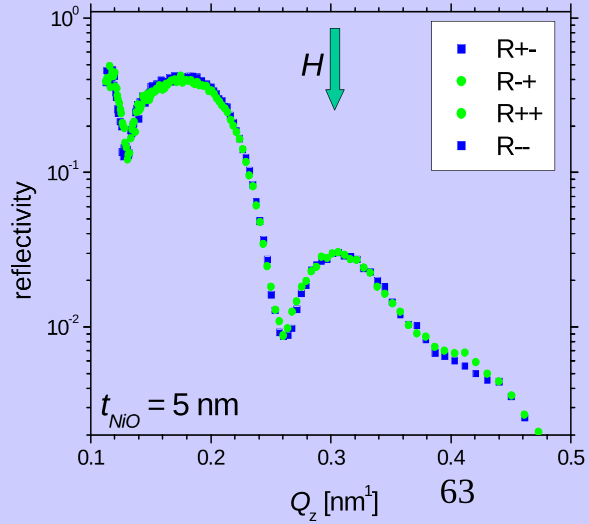


asymmetry in
SF-signal





SF-signal is symmetric
⇔ magnetization rotates together



GMR sensors for angular measurements

Summary

• extraction of magnetic cross sections

• separation of magnetic modes

Missing: Polarized beam instruments
at pulsed sources

Summary

• 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

Missing: Polarized beam instruments
at pulsed sources

Summary

- 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
- not mentioned: high resolution with neutron spin echo
  application in particle physics

Missing: Polarized beam instruments
at pulsed sources

I am sorry for the tough finish of my presentation!