POLARIZED NEUTRONS

Contents

Polarized Neutron Beams

Each individual neutron has spin s=½ and an angular momentum of ±½ħ

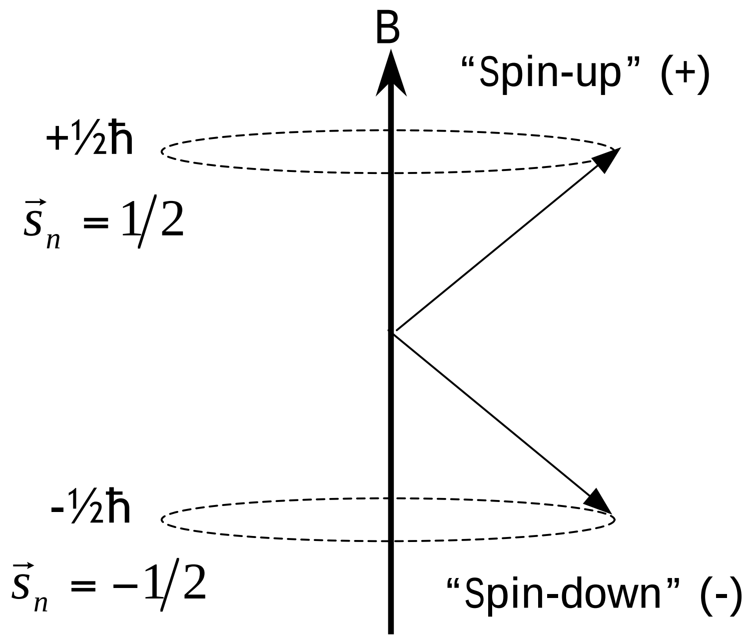
Each neutron has a spin vector $\vec{s}_n$ and we define the polarization of a neutron beam as the ensemble average over all the neutron spin vectors, normalised to their modulus

$$\vec{P} = \langle \vec{s}_n \rangle / \tfrac{1}{2} = 2\langle \vec{s}_n \rangle$$

If we apply an external field (quantisation axis) then there are only two possible orientations of the neutrons: parallel and anti-parallel to the field. The polarization can then be expressed as a scalar:

$$P = \frac{N_+ - N_-}{N_+ + N_-}$$

where there are N_+ neutrons with spin-up and N_- neutrons with spin-down



Polarized Neutron Beams

What we often would like to do in polarized neutron experiments is measure the scalar polarization of the beam.

$$P = \frac{N_+ - N_-}{N_+ - N_-}$$

$$= \frac{(N_+/N_-) - 1}{(N_+/N_-) + 1}$$

$$= \frac{F - 1}{F + 1}$$

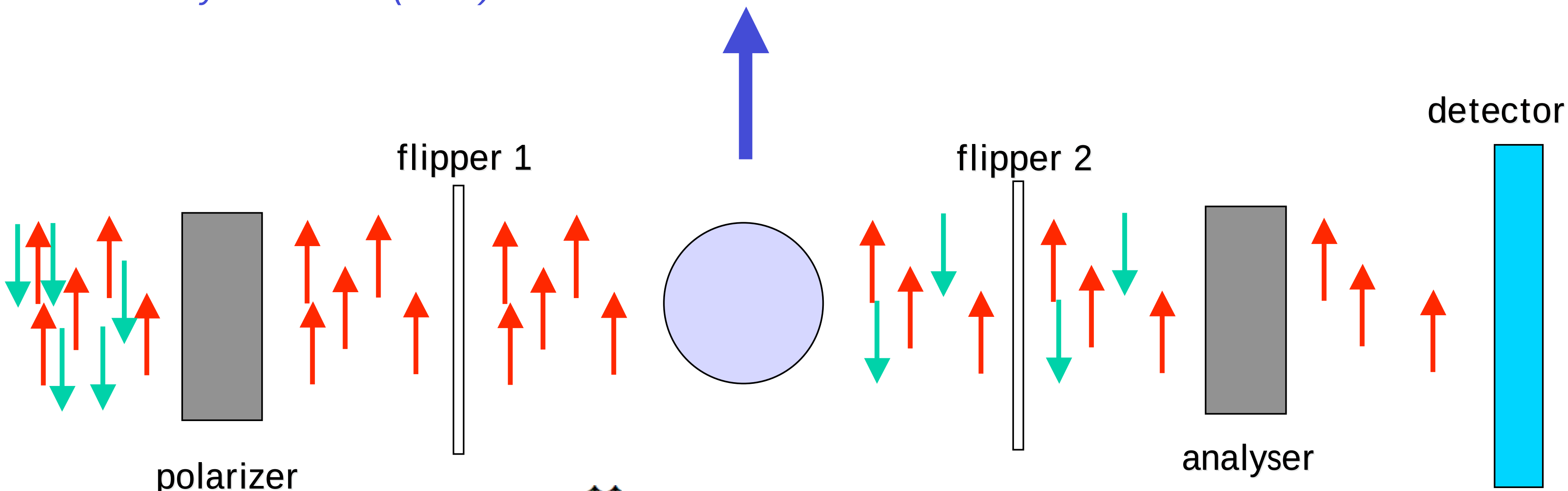
Where $F = \frac{N_+}{N_-}$ is called the Flipping Ratio and is a measurable quantity in a scattering experiment

This description of a polarized beam is OK for experiments in which a single quantisation axis is defined: i.e. *Longitudinal Polarization Analysis*

The technique of 3-dimensional neutron polarimetry, however, uses *Vector (or Spherical) Polarization Analysis*

A Uniaxial PA Experiment

- First attempted by Moon, Riste and Koehler (1969)
  Phys Rev. 181 (1969) 920



$$\left(\frac{d\sigma}{d\Omega}\right)^{\uparrow\uparrow}$$

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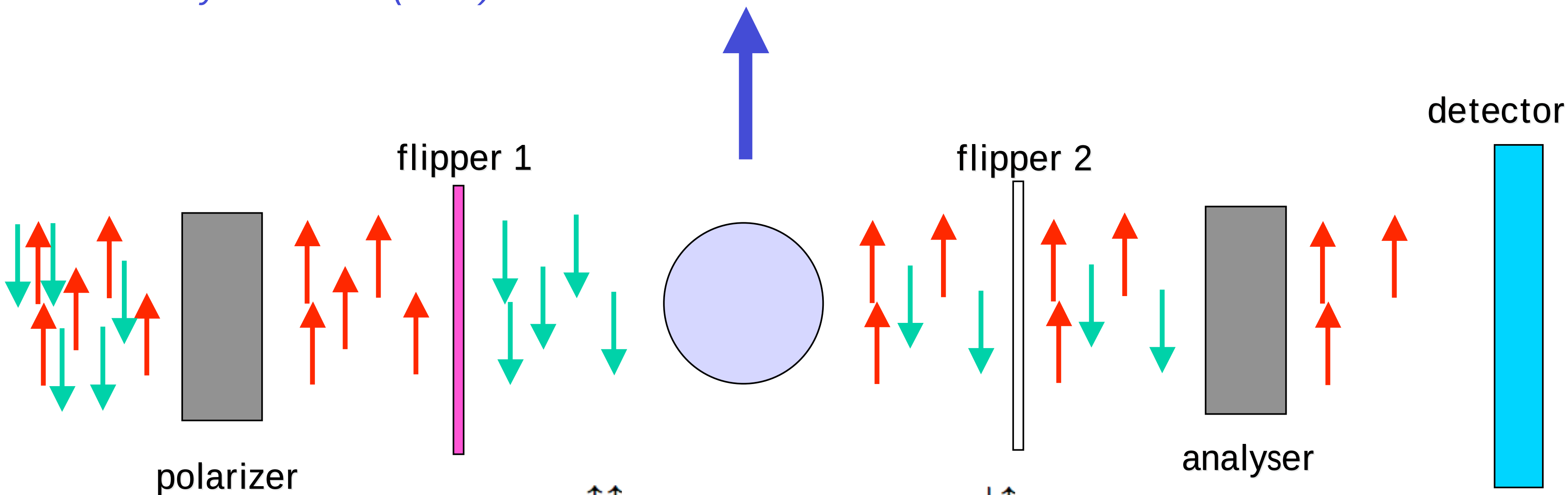

$$\left(\frac{d\sigma}{d\Omega}\right)^{\uparrow\uparrow}$$

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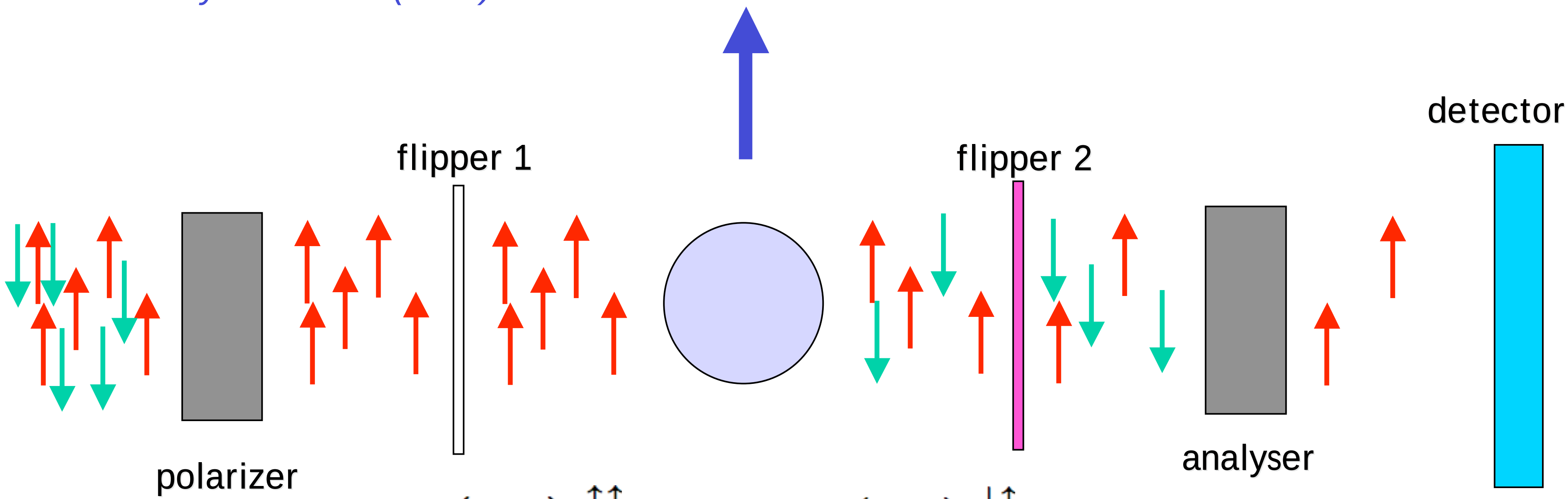

$$\left(\frac{d\sigma}{d\Omega}\right)^{\uparrow\uparrow} \qquad \left(\frac{d\sigma}{d\Omega}\right)^{\downarrow\uparrow}$$

$$\left(\frac{d\sigma}{d\Omega}\right)^{\uparrow\downarrow}$$

A Uniaxial PA Experiment

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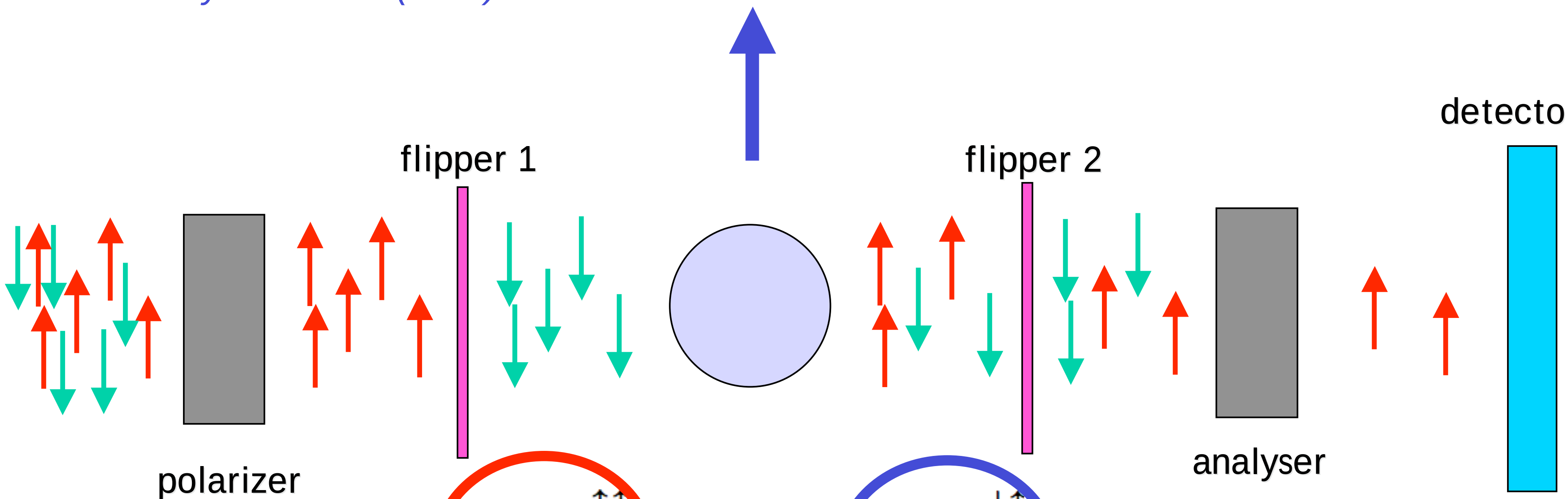


$$\left(\frac{d\sigma}{d\Omega}\right)^{\uparrow\uparrow} \quad \left(\frac{d\sigma}{d\Omega}\right)^{\downarrow\uparrow}$$

"Non-Spin-Flip"

$$\left(\frac{d\sigma}{d\Omega}\right)^{\uparrow\downarrow} \quad \left(\frac{d\sigma}{d\Omega}\right)^{\downarrow\downarrow}$$

"Spin-Flip"

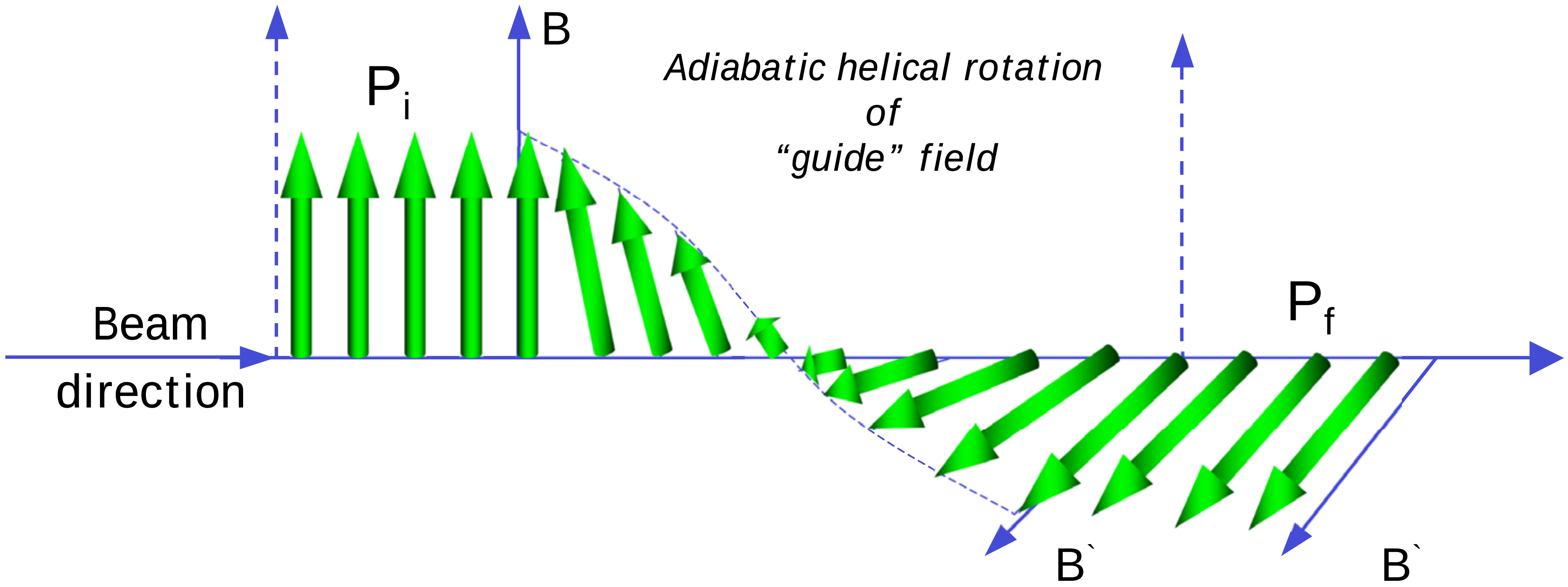
4 cross-sections to measure: big reduction in count rate

Guiding the polarization

If the direction of the magnetic field (quantisation axis) remains constant in the rest frame of the neutrons then the direction of the polarization of the neutron beam will be preserved

However, if the direction of the field B changes sufficiently slowly in the rest frame of the neutrons, then the polarization component parallel to B is conserved - ie there is an adiabatic (or reversible) rotation of the polarization

[rem: An adiabatic process is one in which the system is always "infinitesimally close" to equilibrium. Here the field is changed in such a way that the potential energy of the neutrons is close to its initial value – and returns to this value at the end of the process]



Conditions for adiabatic rotation

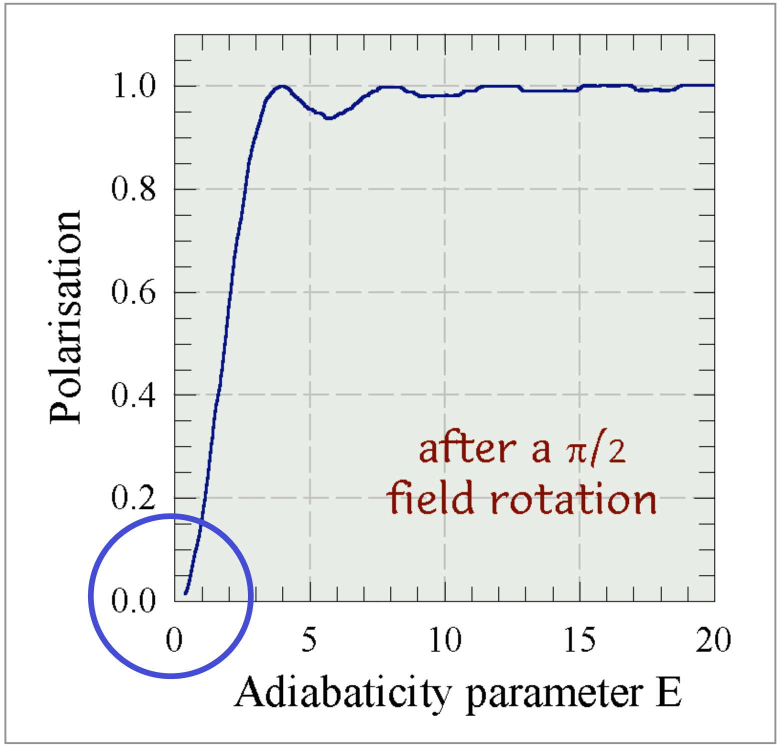
The rate of angular rotation, ω_B, of the field along the y-axis in the rest frame of the neutron is:

$$\omega_B = \frac{d\theta_B}{dt} = \frac{d\theta_B}{dy}.\frac{dy}{dt} = \frac{d\theta_B}{dy}v$$

where v is the neutron velocity

We can therefore define an adiabaticity parameter, E, where

$$E = \frac{\omega_L}{\omega_B} = \frac{|\gamma_n|B}{\frac{d\theta_B}{dy}v}$$



For an adiabatic rotation without loss of polarization we require E>10 (by bitter experience)

This inequality corresponds to

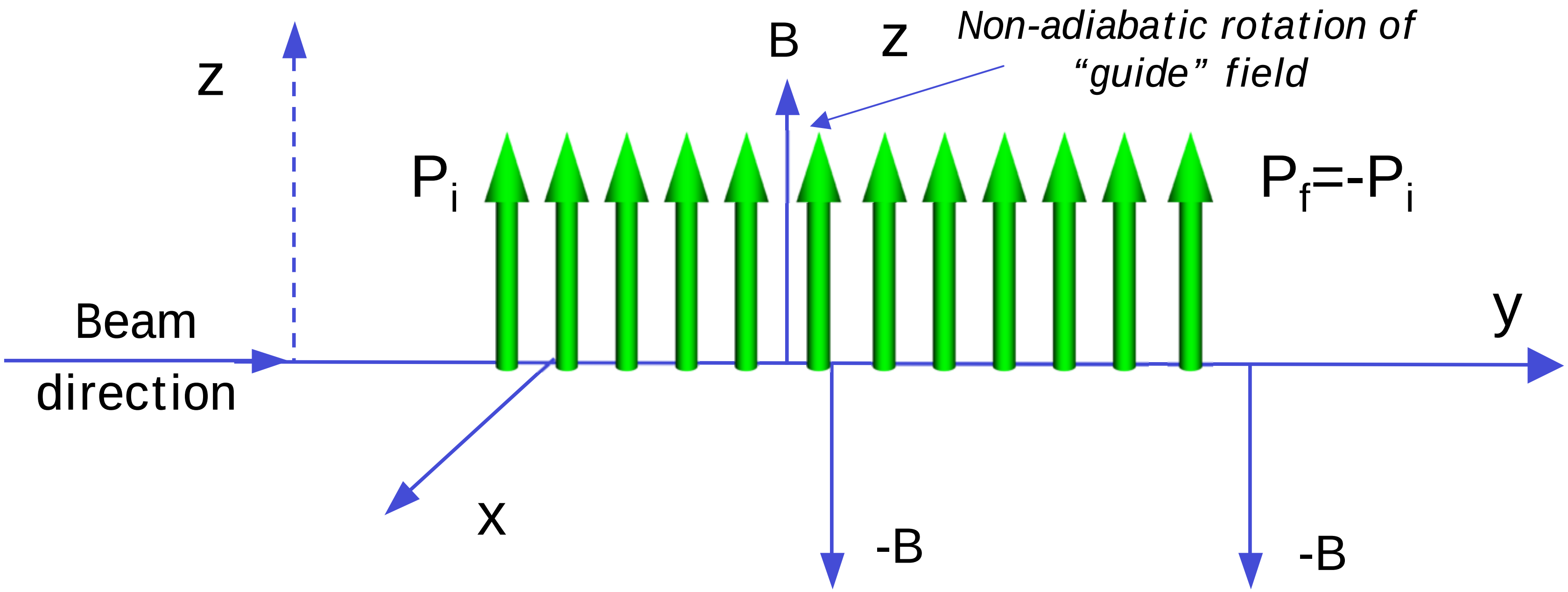
$$\frac{d\theta_B}{dy} < 2.65B\lambda \quad \text{degrees/cm}$$

with B in mT, θ in degrees, distance y in cm and neutron wavelength, λ in Å,

Non-adiabatic transitions

Although we can adiabatically reorient the polarization in the laboratory frame, the polarization of the beam remains constant with respect to the guide field

However, for a non-adiabatic reorientation of the guide field ($\Delta E \neq 0$) the polarization will not re-orient - instead the beam will preserve its initial direction, and begin to precess about the new field direction



Non-adiabatic rotations enable the beam polarization to be effectively "flipped" with respect to the guide field

Non-adiabatic transitions

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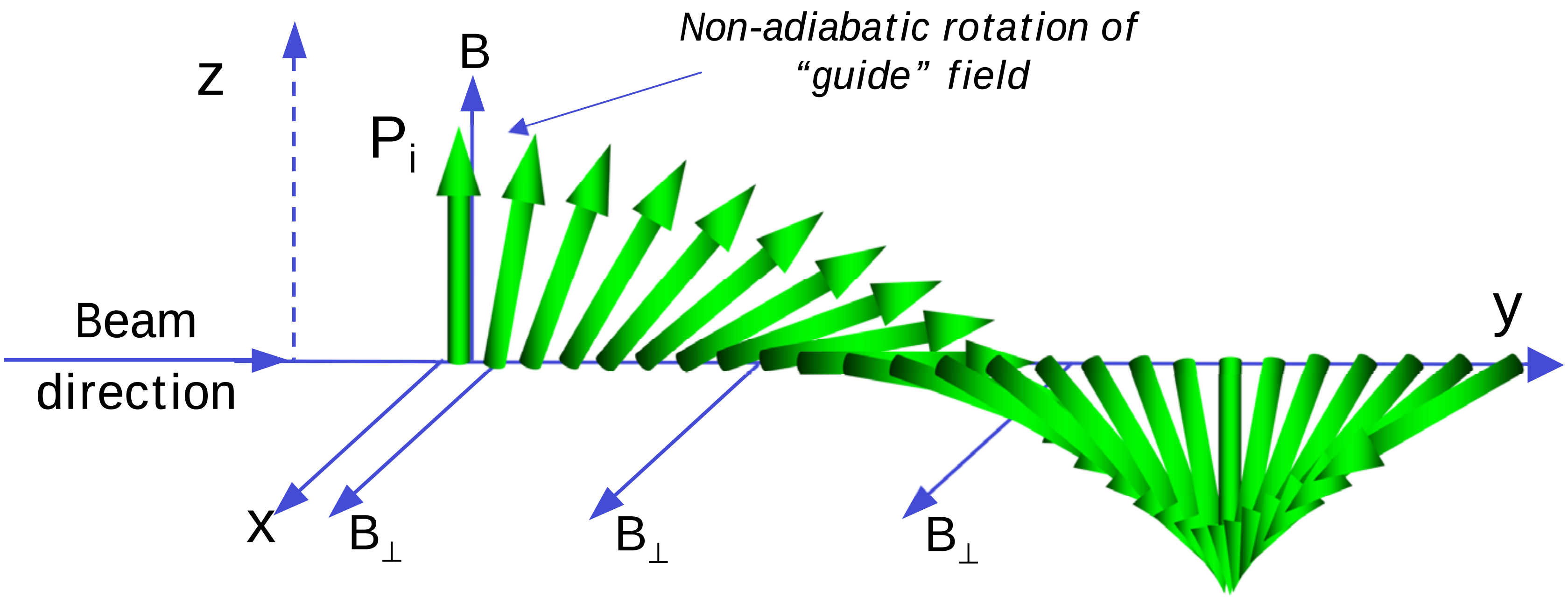
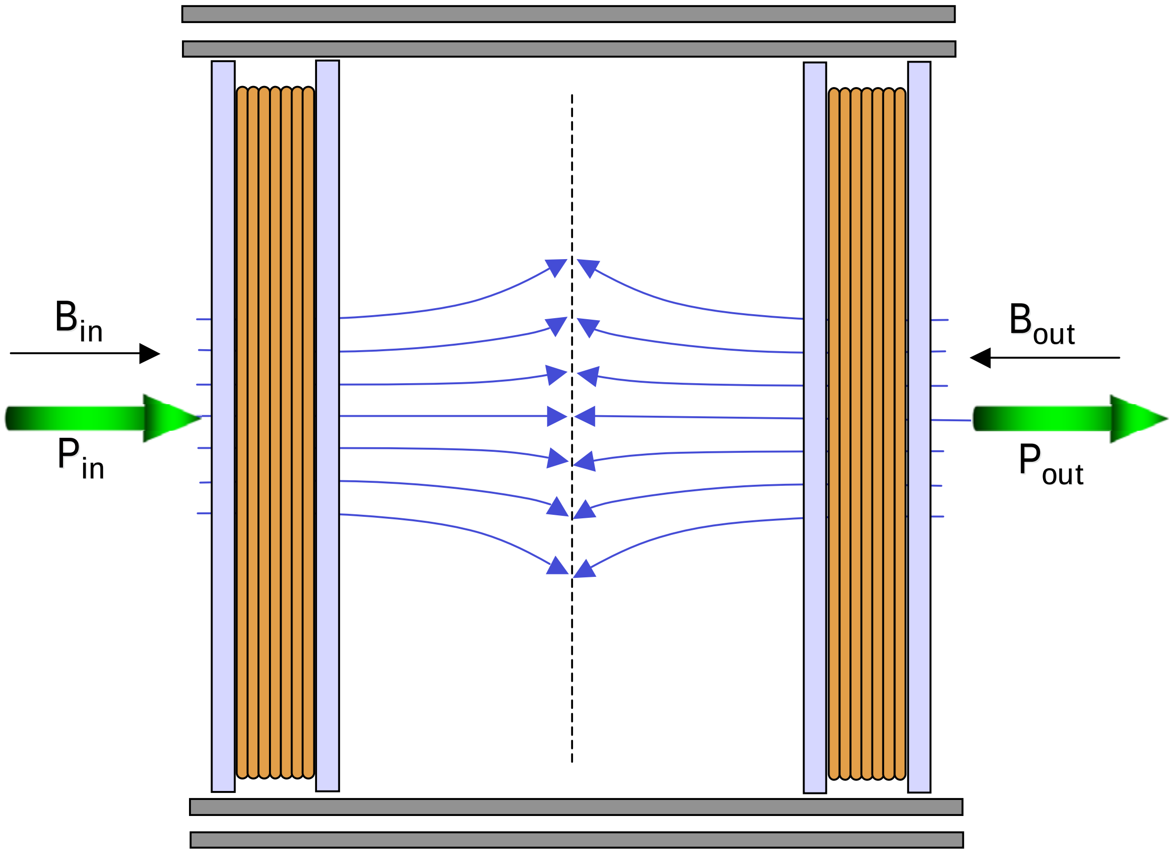


Non-adiabatic rotations enable the beam polarization to be effectively "flipped" with respect to the guide field

Non-adiabatic spin flippers

A wide variety of devices have been employed as effective non-adiabatic "spin-flippers":

Drabkin flipper: useful for white beams of limited size
- used on the reflectometers CRISP and SURF at ISIS



Radial magnetic field off-axis
Result in low flipping ratios

Useful for thin beams only

BUT
No material in beam

Non-adiabatic spin flippers

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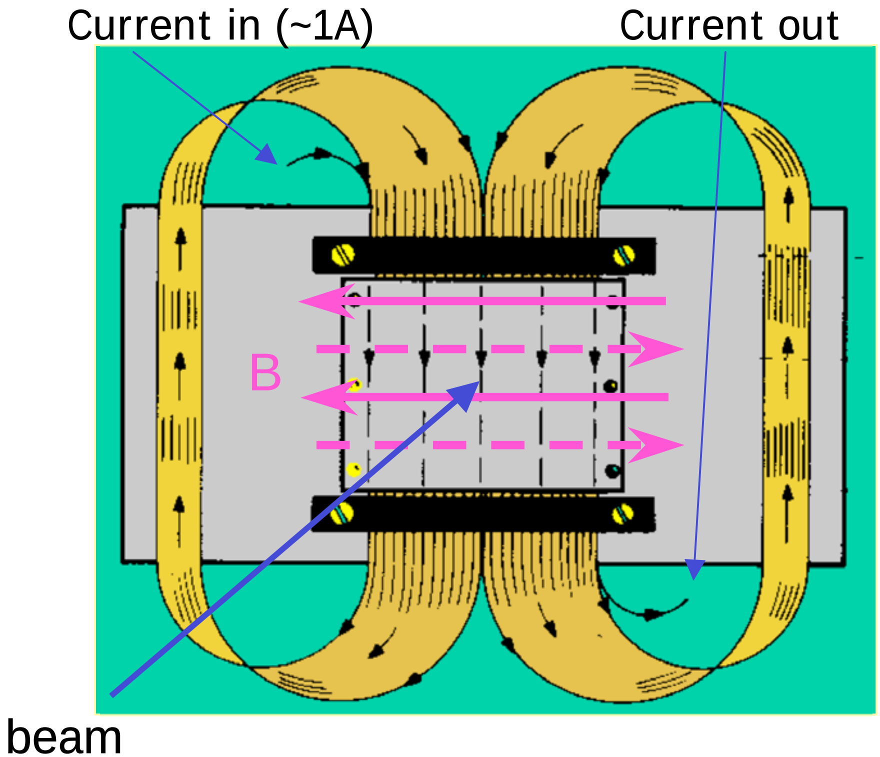
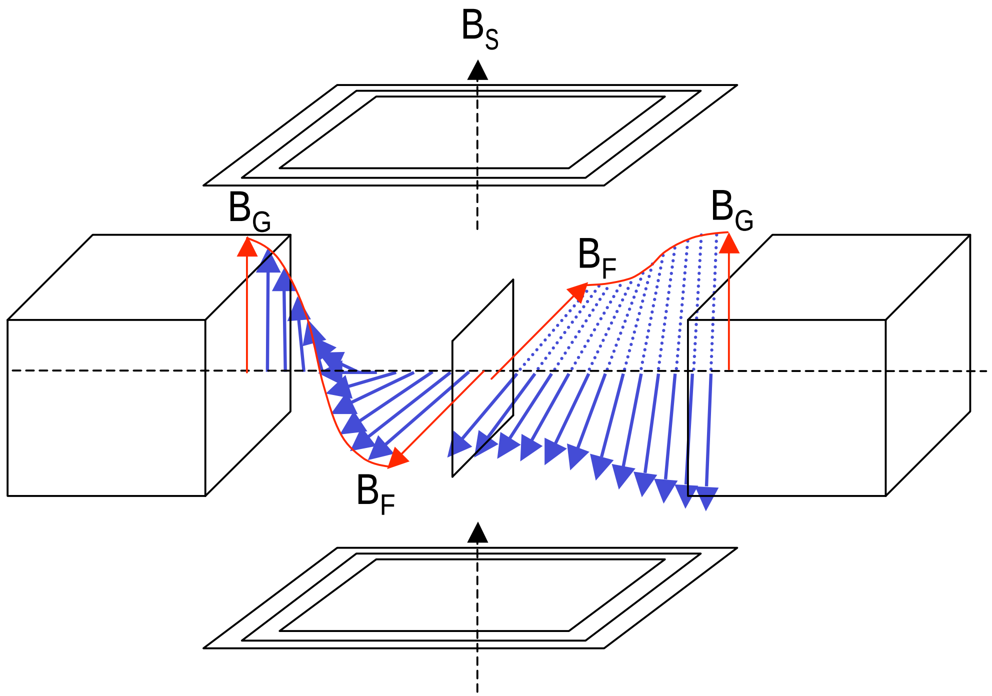


Dabbs foil current sheet
or Kjeller '8'

see eg, Jones and Williams
NIM 152, 463 (1978)

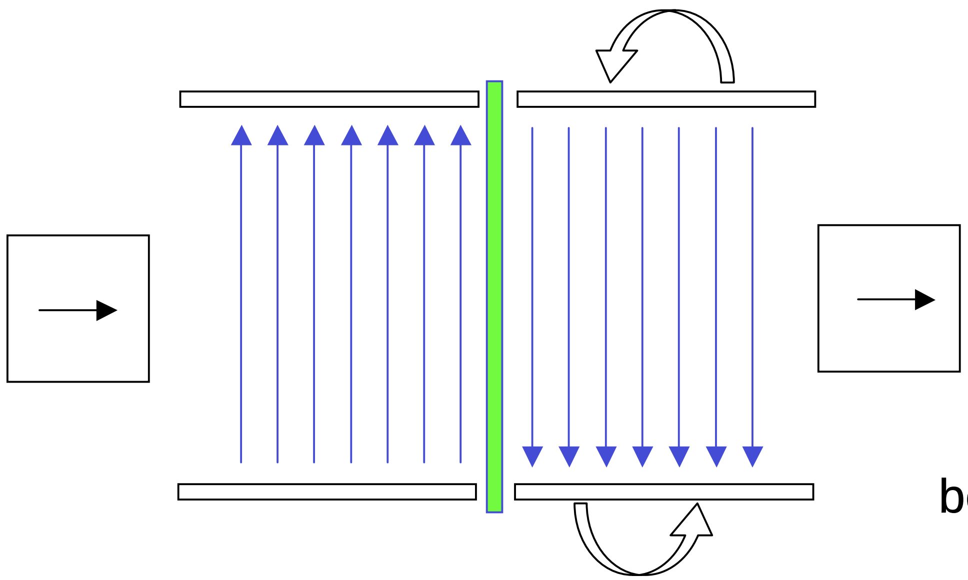


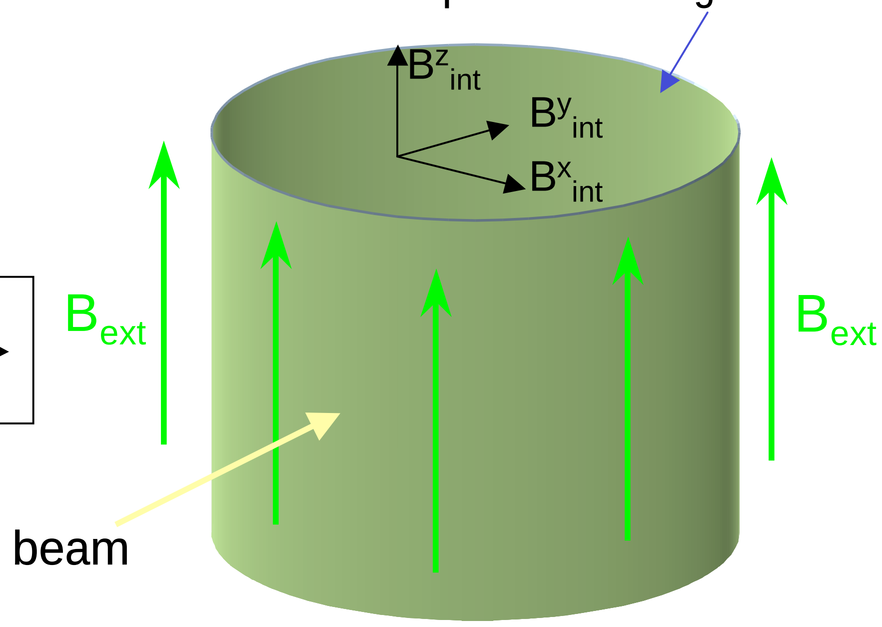
B_G = Fixed guide field
B_F = Flipper Field
B_s = Solenoidal field (flipper off)

Non-adiabatic spin flippers

A wide variety of devices have been employed as effective non-adiabatic “spin-flippers”:

Meissner shields





Single Meissner shield Nb foil with rotatable guide field sections

see e.g., Tasset et al
Physica B 156-157 627 (1989)

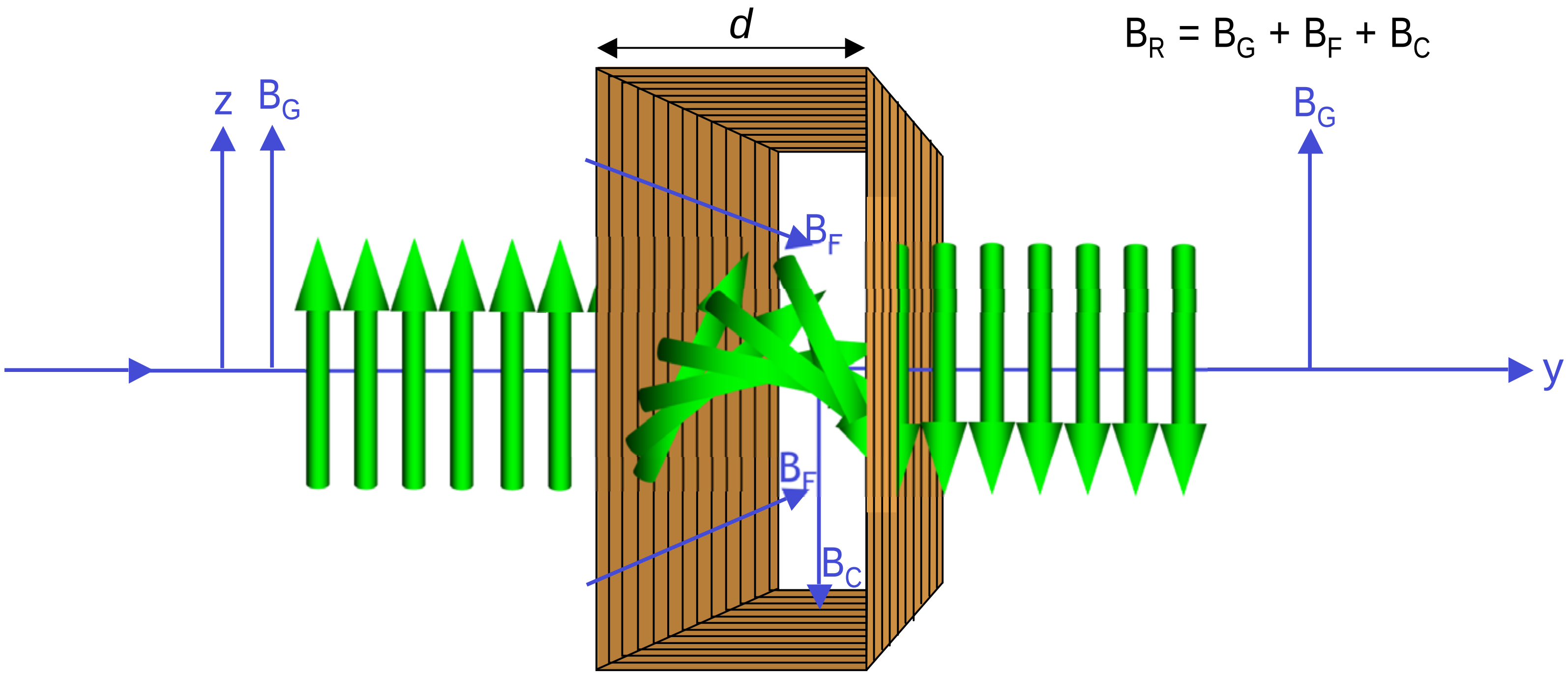
Concentric Meissner shields surround the sample on CRYOPAD

see e.g., Tasset et al
Physica B 267-268 69 (1999)

The Mezei spin flipper

The Mezei coil uses a non-adiabatic process to project the polarization direction of the beam onto any arbitrary field axis:

A π-flip with respect to the guide field can be achieved if the resultant field within the coil, $\mathbf{B}_R$, is perpendicular to $\mathbf{B}_G$ and $d = \pi v / |\gamma B_R|$

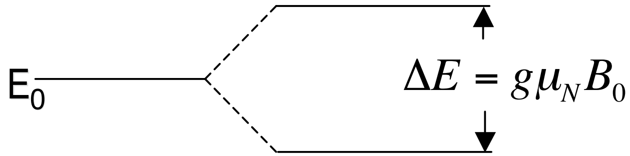


(a 1Å neutron will be spin flipped by π radians in a distance of 1cm if B_R=7mT)

For further details see, e.g. *Hayter Z Physik B 31, 117 (1978)*

Radio-frequency flippers

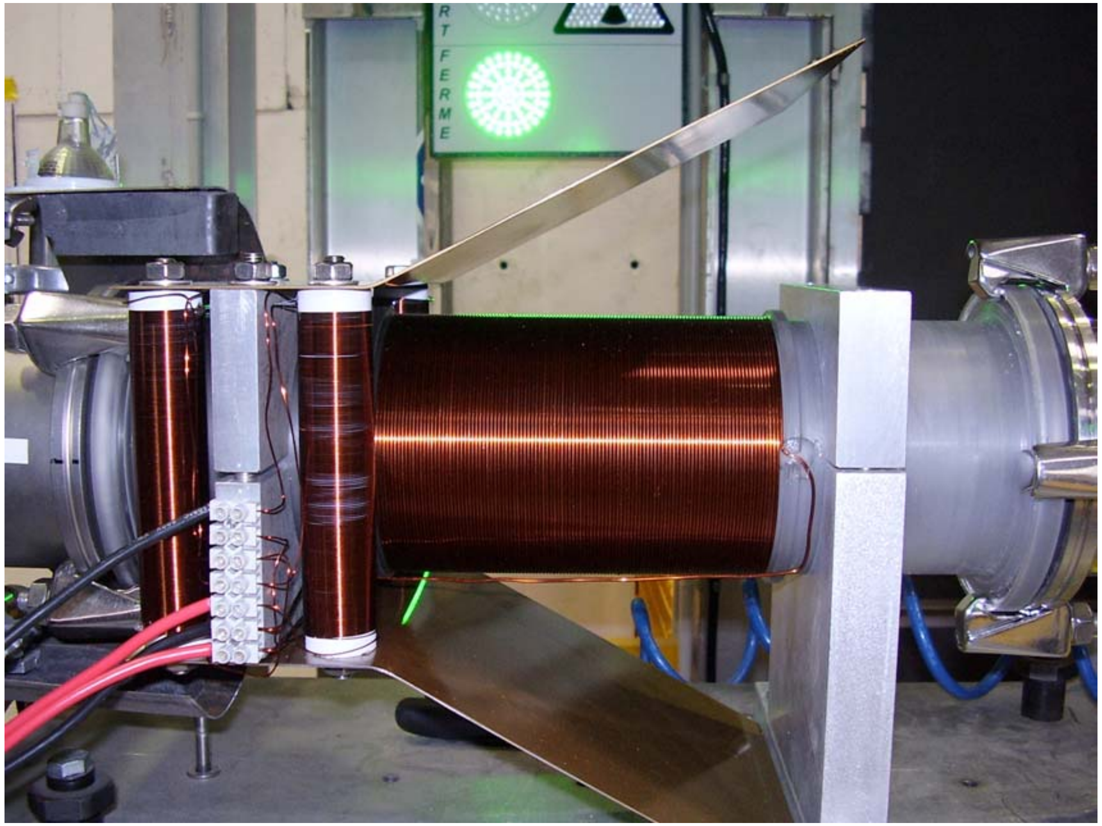
Zeeman splitting in field B_0



Resonance frequency of transitions between "up" and "down" states is therefore

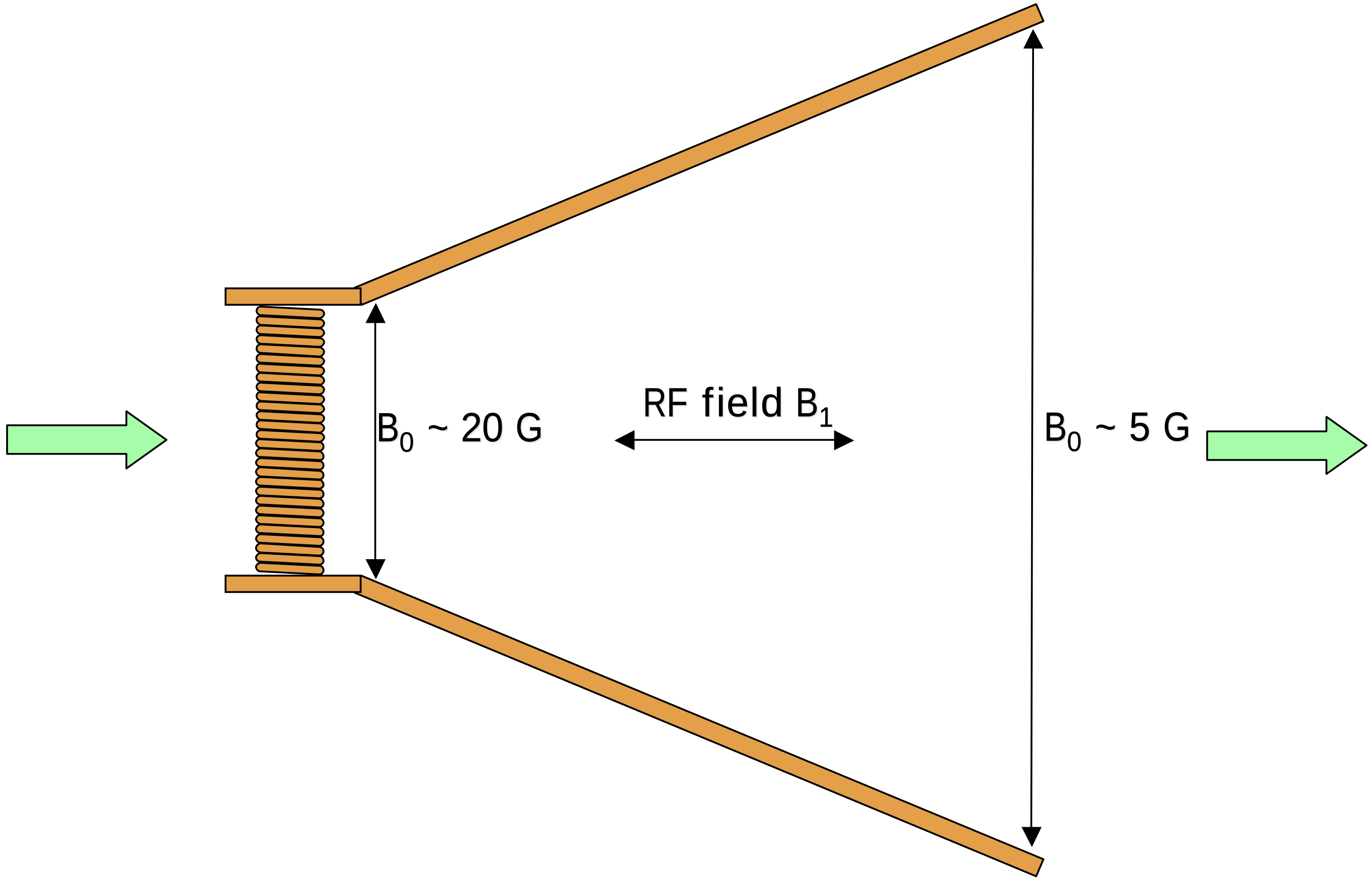
$$\omega = \frac{g\mu_N B_0}{\hbar} = \gamma B_0$$

Which is just the Larmor precession frequency. Transitions between up and down states occur on applying an RF field at ω_L perpendicular to the main field



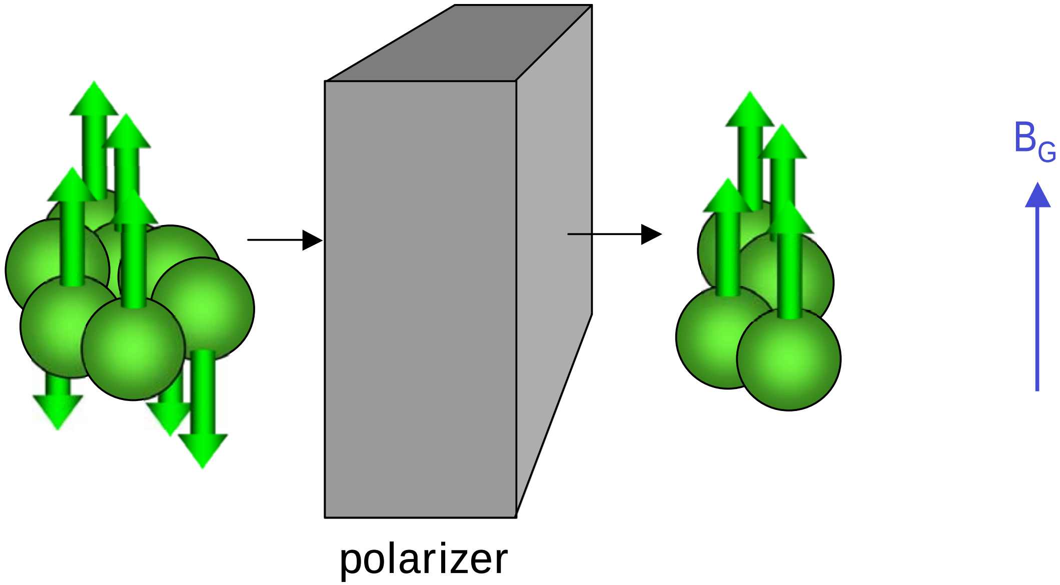
RF flipper installed on the small-angle instrument D22 at the ILL

Radio-frequency flippers



- RF frequency is kept constant while B_0 decreases
- So for all neutron wavelengths, resonance will occur at appropriate value of B_0
- Depends crucially on length of time spent in resonance region - hence thermal/hot flippers must be very long - BUT - no material is in the beam

The production of polarized beams



There are three principal (passive) methods of beam polarization, each with specific advantages in particular experimental situations

(a) polarizing filters (e.g. preferential absorption by polarized ^{3}He nuclei)

(b) polarizing mirrors and supermirrors (using preferential reflection)

(c) polarizing crystals (e.g. $Co_{92}Fe_8$, Heusler crystals (Cu_2MnAl)) using preferential Bragg reflection)

See, e.g. Williams in Polarized Neutrons, Oxford University Press, 1988

Neutron polarization - filters

The polarizing efficiency of a filter, P, is defined in terms of the transmission of the two spin states, T_+ and T_-

$$P = \frac{T_+ - T_-}{T_+ + T_-}$$

where the total transmission of the filter is $T = (T_+ + T_-) / 2$

The filter performance depends upon both P and T - P can be increased by making the filter thicker, but only at the expense of total transmission, T. As a compromise it is the quality factor $P\sqrt{T}$ that is usually optimised
(but see *Cussen, J Neutron Res., 7, 15, 1998*)

For a generalised polarizing filter with total spin cross sections given in terms of the spin-independent absorption cross section, σ_o and a spin-dependent absorption cross section σ_p we have

$$\sigma_\pm = \sigma_0 \pm \sigma_p$$

From which it can (easily) be shown that

$$P = -\tanh(N\sigma_p t) \quad \text{and} \quad T = \exp(-N\sigma_0 t)\cosh(N\sigma_p t)$$

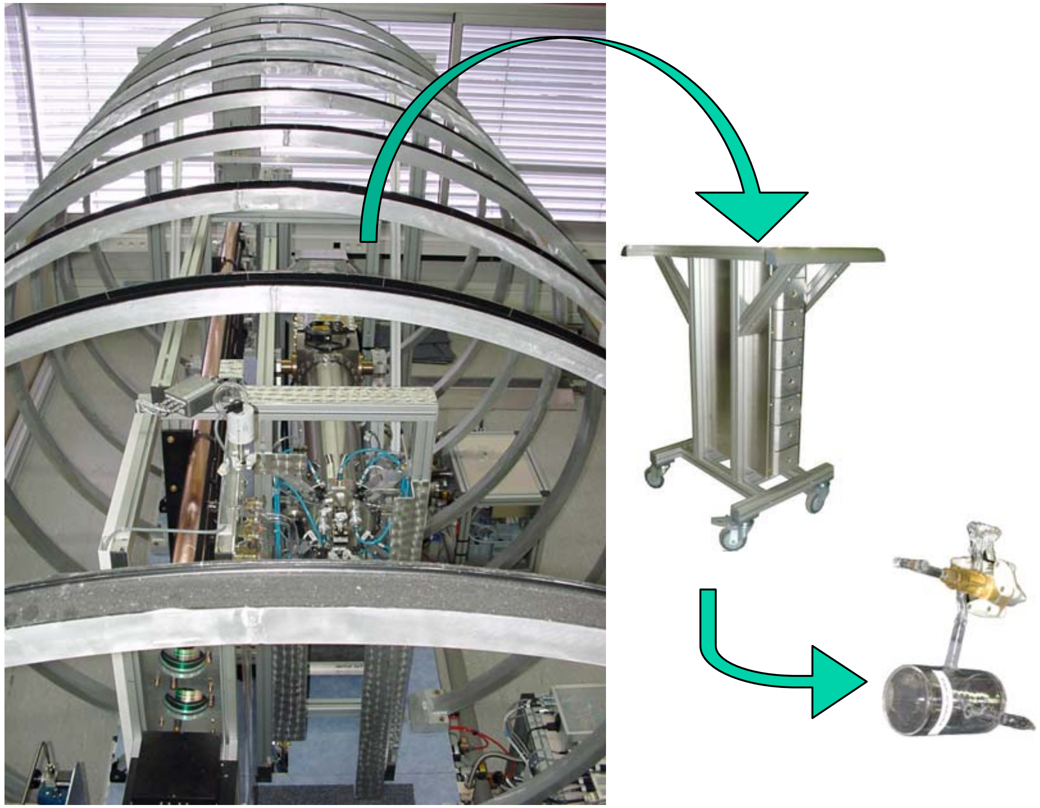
Where N is the number density of atoms/nuclei responsible for spin selection and t is the filter thickness

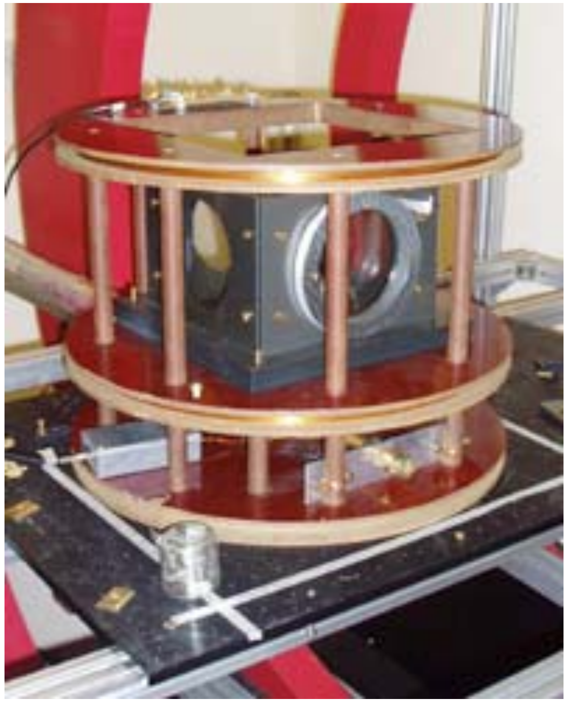
See, e.g. Williams in Polarized Neutrons, Oxford University Press, 1988

^3He polarizing filters

^3He is, an ideal material for a neutron polarizer - σ_0 equals σ_P and hence transmission only occurs for one spin-state

It is now possible to produce large quantities of highly spin polarized (80%) ^3He gas -at room temperature- by optical pumping methods:





MEOP - Metastable Exchange Optical Pumping

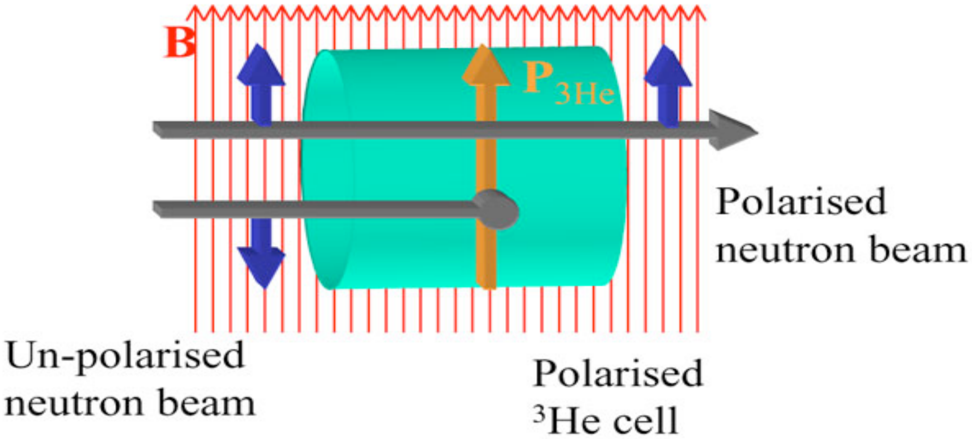
*Andersen et. al., Physica B **356** (2005) 103-108*

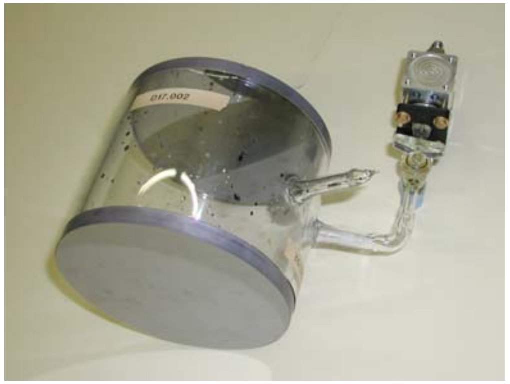
SEOP - Spin Exchange Optical Pumping

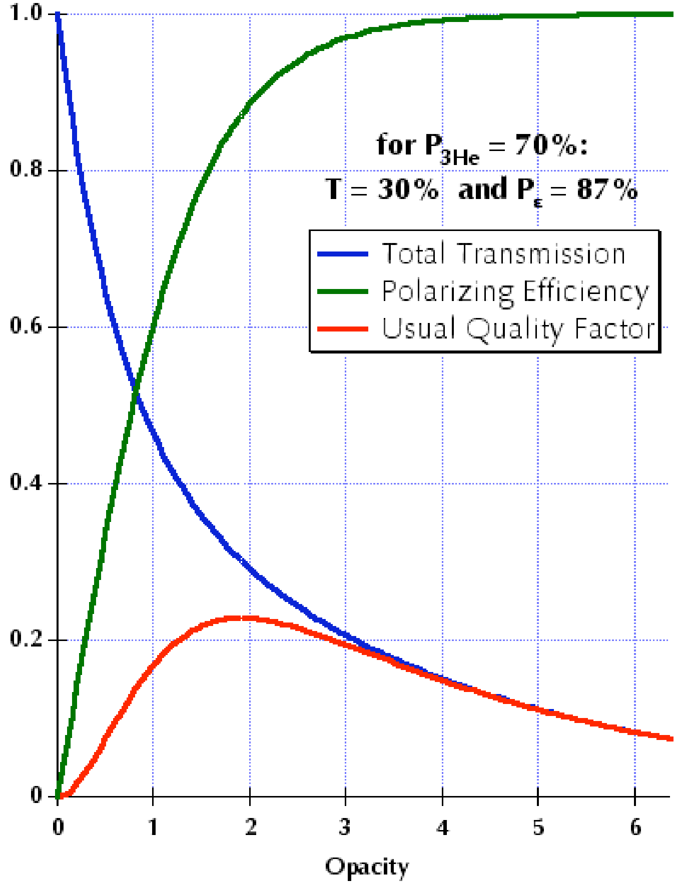
*Babcock et. al., Phys. Rev. Lett. **96** (2006) 083003*

^3He polarizing filters in operation

^3He polarizing filters have been developed at ILL and used in real experiments as either a polarizer or analyser







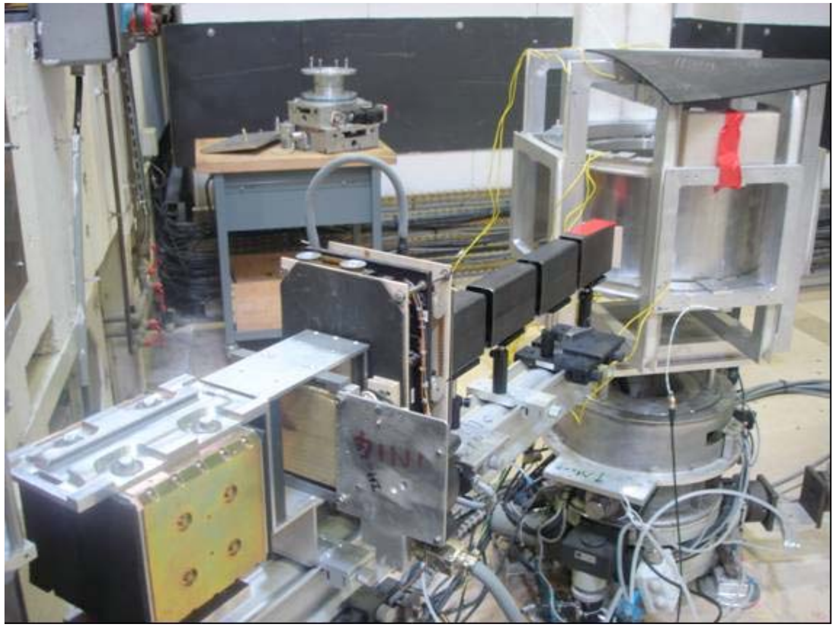
Typical values: 75% initial ^3He nuclear polarization with a relaxation time of 100 hours

Relaxation of the ^3He polarization arises from collisions with the container walls, from dipole-dipole interactions, and from stray magnetic fields.

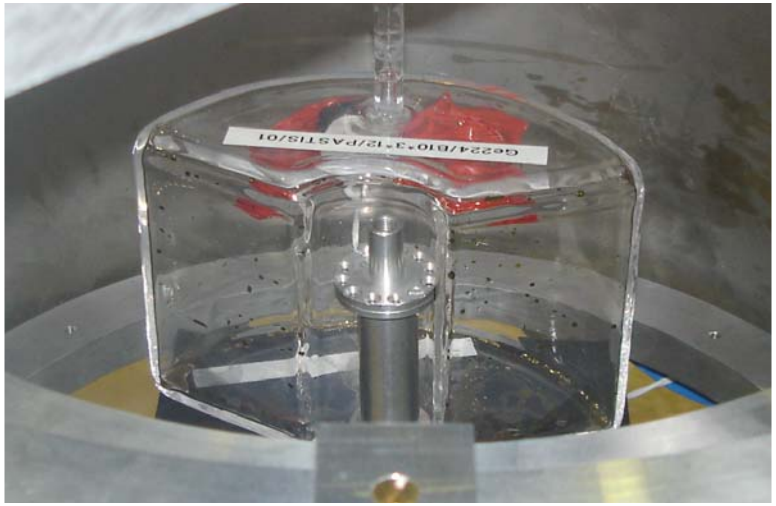
^{3}He polarizing filters in operation

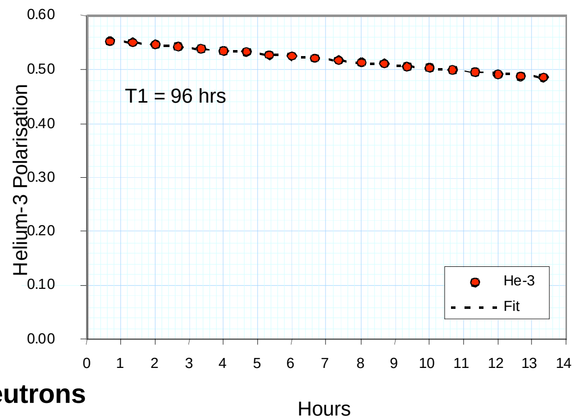
PASTIS Polarization Analysis Studies on a Thermal Inelastic Spectrometer

Time-of-flight inelastic spectrometers require a neutron analyser that covers a wide solid angle and is efficient at thermal energies - ^{3}He spin filter is ideal for this



PASTIS test setup on IN3 at the ILL



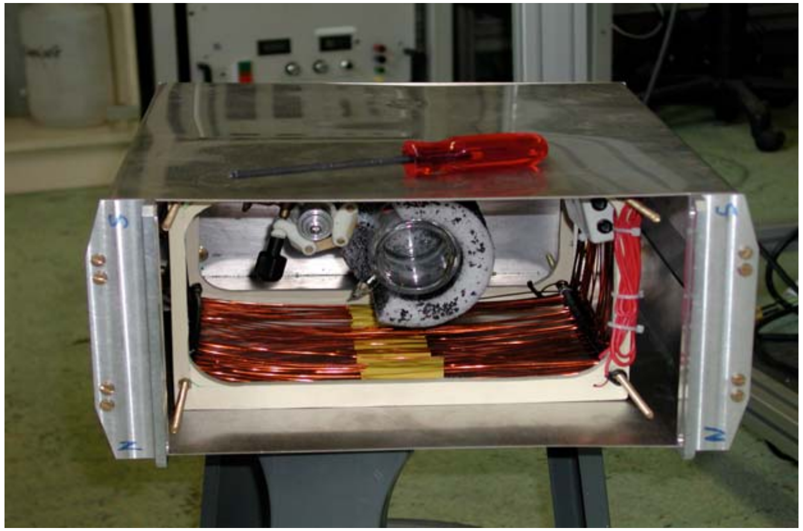


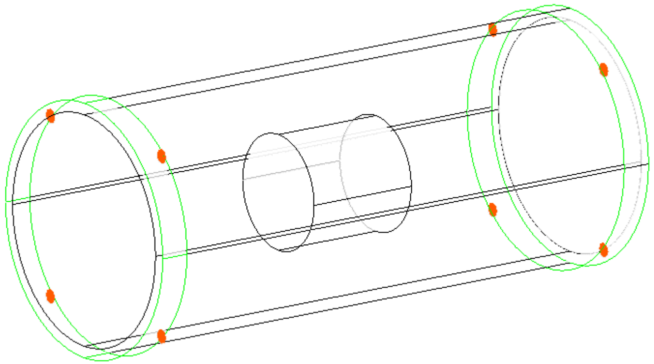
*Stewart et.al. Physica B **385-86** (2006) 1142-1145*

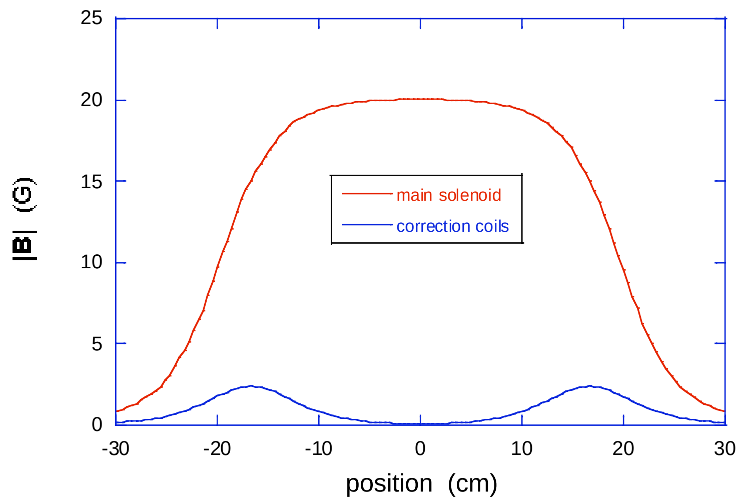
Magic boxes and flipperizers

On-beam magnetic environments for moderate stray field and small(ish) solid angles:

“Magic box”, shielded solenoid:







- Including ^{3}He flipper

Petoukhov, et. al., Nucl. Inst. Methods A ***560*** *(2006) 480-48*

Neutron Optics

All optical phenomena have their neutron counterparts: eg refractive index

Optical

$$n = \frac{c}{v}$$

Neutron

$$n = \frac{\lambda_1}{\lambda_2} = \frac{k_2}{k_1}$$

If we assume that the neutron experiences a change of energy equivalent to <V> when it enters medium 2, we can write

$$n = \frac{k_2}{k_1} = \left[\frac{E_1 - \langle V \rangle}{E_1}\right]^{\frac{1}{2}} \approx 1 - \frac{\langle V \rangle}{2E_1}$$

assuming that $\langle V \rangle << E_1$

The potential <V> will in general consist of a nuclear and magnetic part (Fermi pseudopotential)

$$\langle V \rangle_N = \frac{2\pi\hbar^2}{m} N\overline{b} \qquad \langle V \rangle_M = \frac{2\pi\hbar^2}{m} N\overline{p} = \pm \mu_n B$$

Neutron polarization - mirrors

Therefore, the spin dependent refractive index of magnetised mirrors for neutrons of wavelength λ is .

$$n_{\pm} = 1 - \left(\frac{N\lambda^2}{2\pi}\right)\left(\bar{b} \pm \bar{p}\right)$$

where b is mean coherent nuclear scattering length, N is the number density of scattering nuclei, and B is the flux density applied in the plane of the surface

Snell's law for refraction states $n_{1,2} = \cos\theta_1 / \cos\theta_2$

And the critical angle of reflection when $\theta_2 = 0$ is $n_{1,2} = \cos\theta_c \approx 1 - \frac{\theta_c^2}{2}$

There are therefore two critical glancing angles $\theta_{c\pm}$ for total (external) reflection:

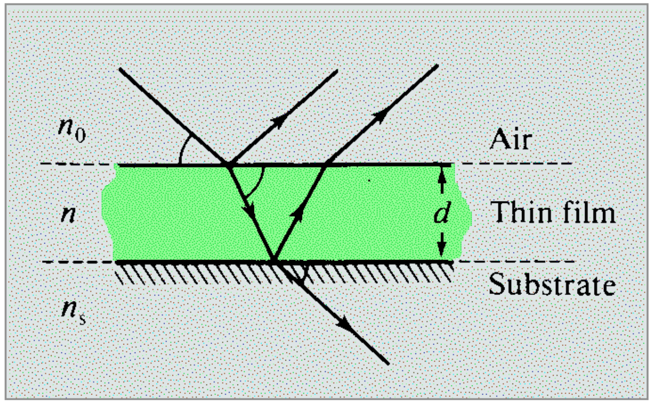
$$\theta_{c\pm} = \lambda\left[\frac{N}{\pi}\left(\bar{b} \pm \bar{p}\right)\right]^{\frac{1}{2}}$$

Between these two critical angles the reflected beam is effectively fully polarized, and in some circumstances the critical angle for one spin state can be made zero

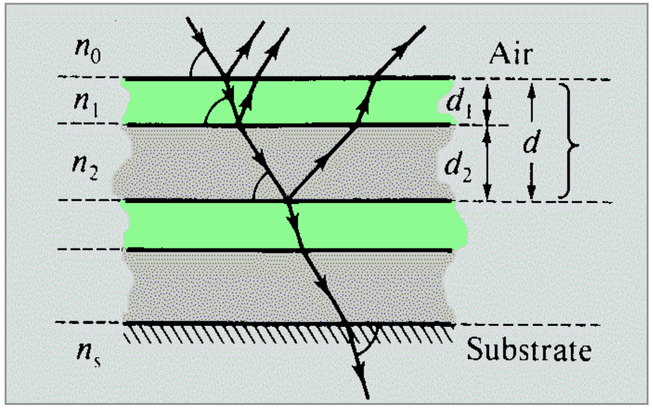
However, the critical angles are very small (typically 10 arc minutes)

Hughes and Burgy, Phys. Rev. ***81*** *(1951) 498*

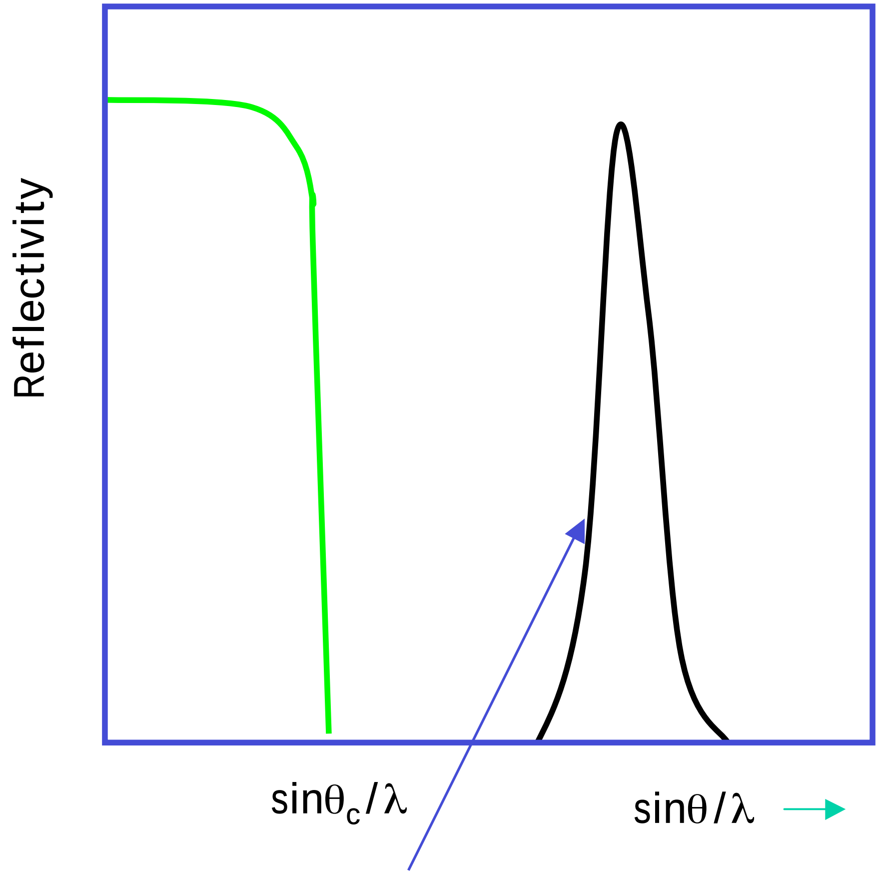
Neutron Polarization - supermirrors



Thin film (eg CoFe)

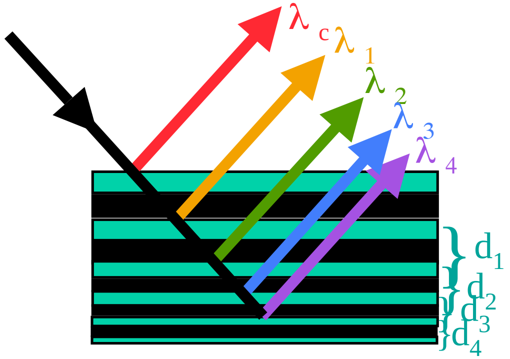


Bi-layers (eg Fe/Ge)

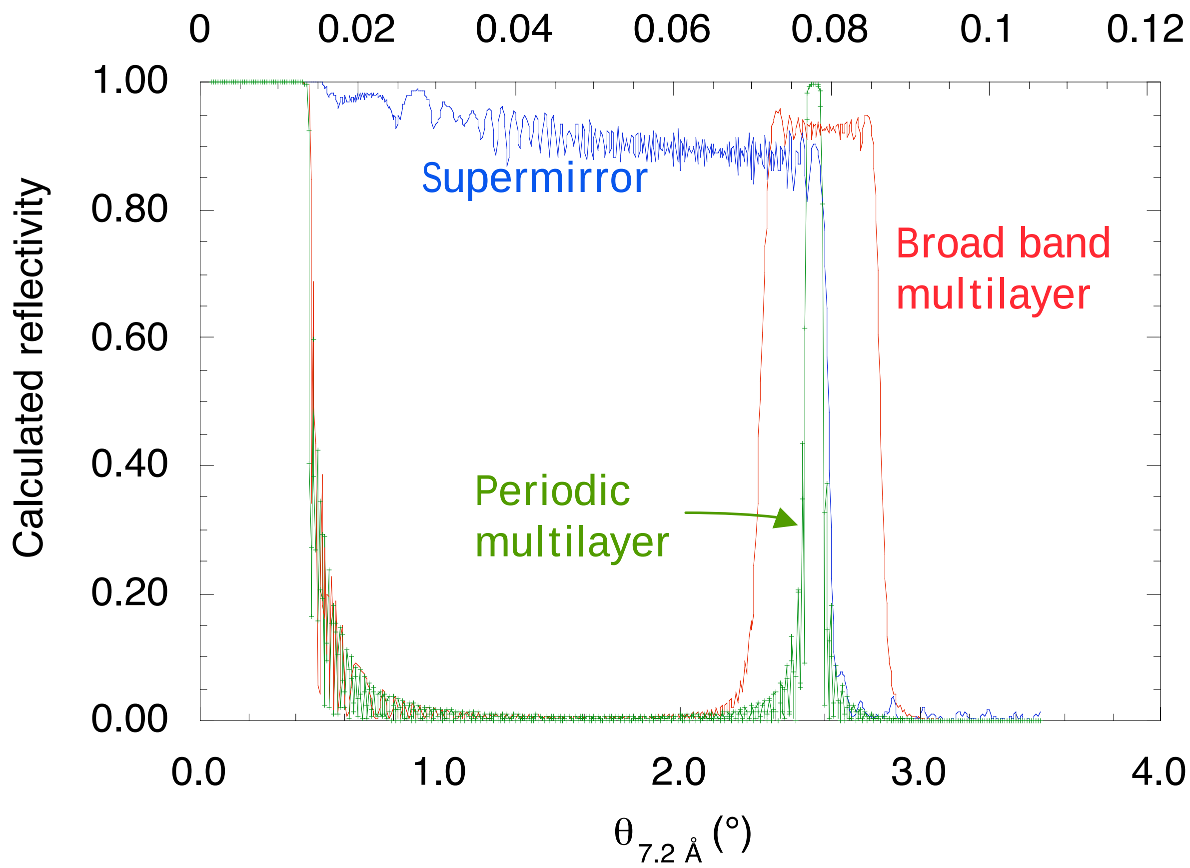


The multi-bilayer system introduces an additional Bragg peak at $\sin\theta/\lambda = 1/2d$

Neutron Polarization - supermirrors



Supermirror systems
(eg Co/Ti, Fe/Si etc)



A gradient in the lattice spacing of the bilayers results in a range of effective Bragg angles, and therefore a reflectivity which extends from m=2 to m=4 times the θ/λ values expected for normal mirror reflections

Mezei, Commun. Phys. ***1*** *(1976) 81*

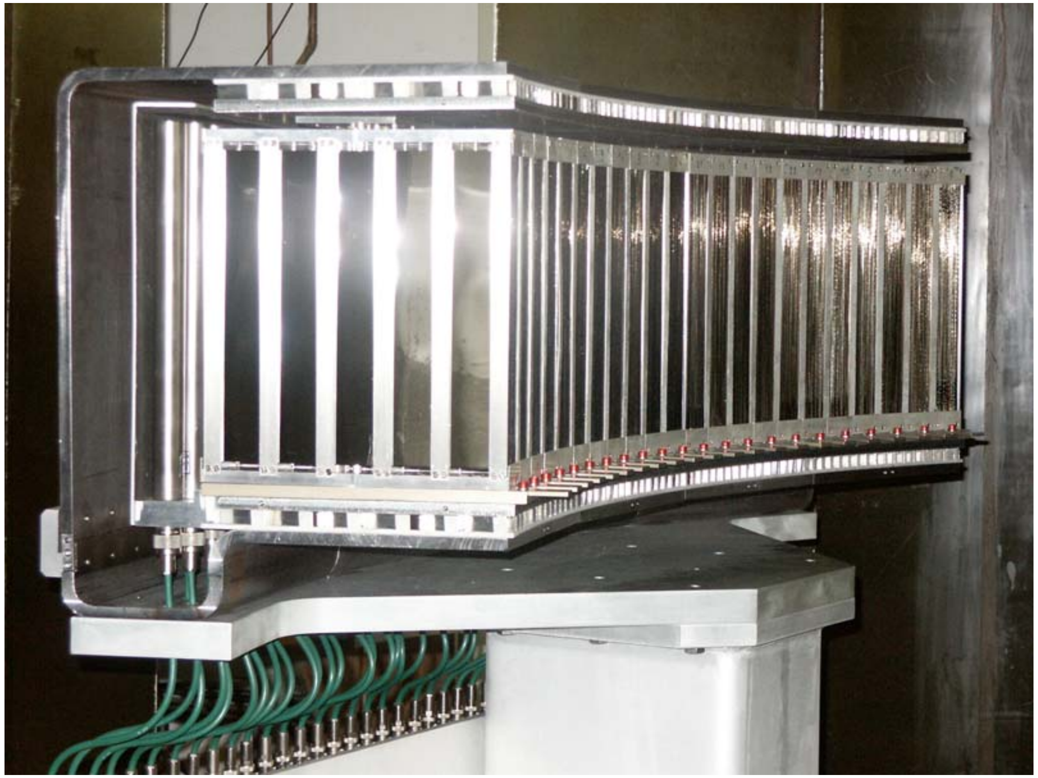
Supermirror production

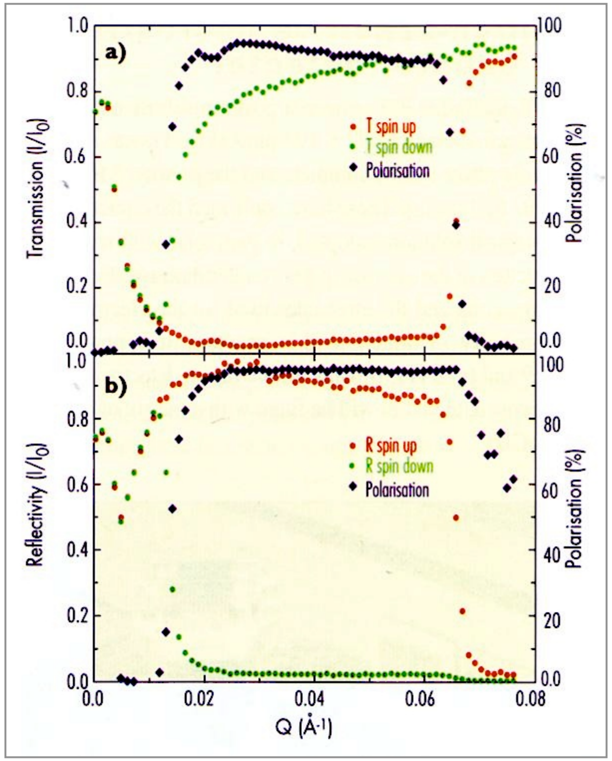
The PI sputtering machine at the ILL (2005)

Alternate Co and Ti layers are sputtered onto glass substrates - around 500 bilayers are required for an m=3 supermirror

Supermirrors

Approximately ten instruments at ILL currently use supermirror bender assemblies as broad band polarization at cold neutron wavelengths (λ>2.5 Å)





On the right are recent reflection and transmission results from a 590 layer m=3 Fe/Si supermirror on a 0.5mm Si wafer *(Hoghoj et al, Physica B **267-8** (1999) 355)*

See also *Boni et al, (Physica B **267-8**(1999) 320)* for the development of remnant supermirrors

Supermirrors

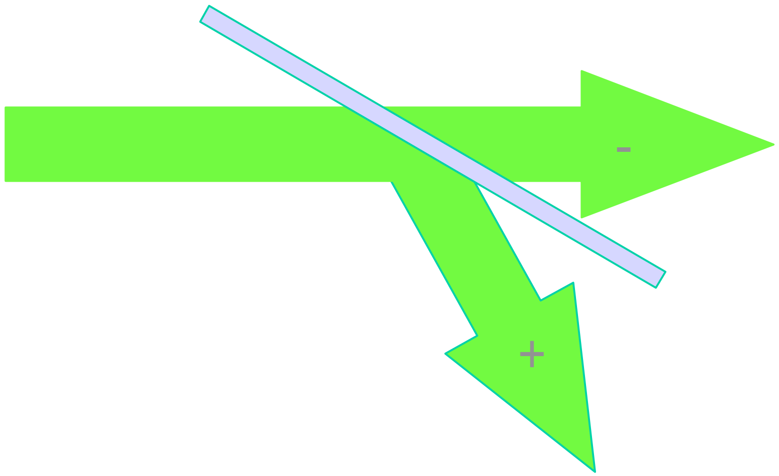
In a supermirror, the basic unit is a non-magnetic/magnetic (A/B) bilayer, which has a reflectivity of the form

$$R_{\pm} \propto \left[N_A b_A - N_B \left(b_B \pm p_B \right) \right]^2$$

Therefore, with a judicious choice of N and b, it can be arranged that R_{-} = 0 implying perfect beam polarization at all angles of incidence

In practice this is very difficult to achieve, since the spin-down neutrons have to go somewhere. They are either transmitted or absorbed in an absorbing layer (often Gd, which has a non-zero reflectivity at very low angles)

Transmission polarizer



Very good polarization since clean separation of polarization states is achieved. Can only accept limited divergence and one wavelength

Hughes and Burgy, Phys. Rev. ***81*** *(1951) 498*

Supermirrors

In a supermirror, the basic unit is a non-magnetic/magnetic (A/B) bilayer, which has a reflectivity of the form

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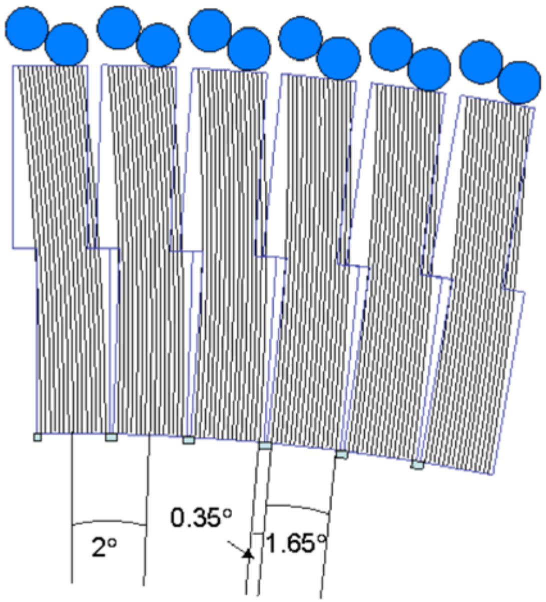
In practice this is very difficult to achieve, since the spin-down neutrons have to go somewhere. They are either transmitted or absorbed in an absorbing layer (often Gd, which has a non-zero reflectivity at very low angles)

Bender polarizers (D7, ILL)



Supermirrors are bent to ensure at least one reflection of the neutrons. Polarization less good due to finite reflectivity of absorbing layer. But able to accept large divergence of angles (stacked device)

O Schärpf, Physica B ***174*** *(1991) 514-527*

Supermirrors

In a supermirror, the basic unit is a non-magnetic/magnetic (A/B) bilayer, which has a reflectivity of the form

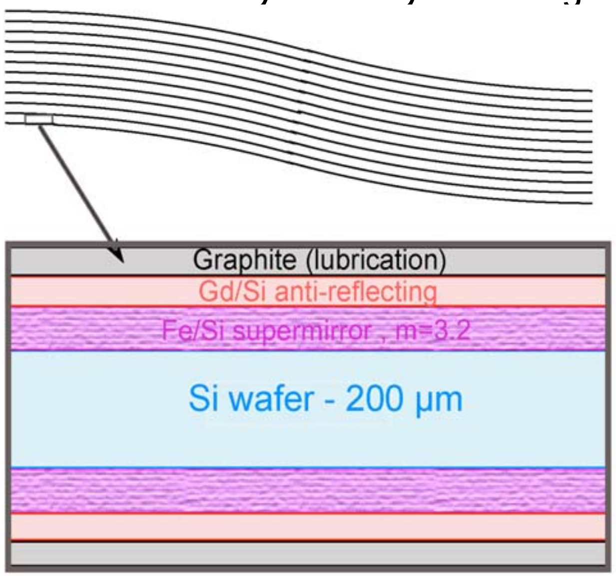
$$R_{\pm} \propto \left[N_A b_A - N_B \left(b_B \pm p_B \right) \right]^2$$

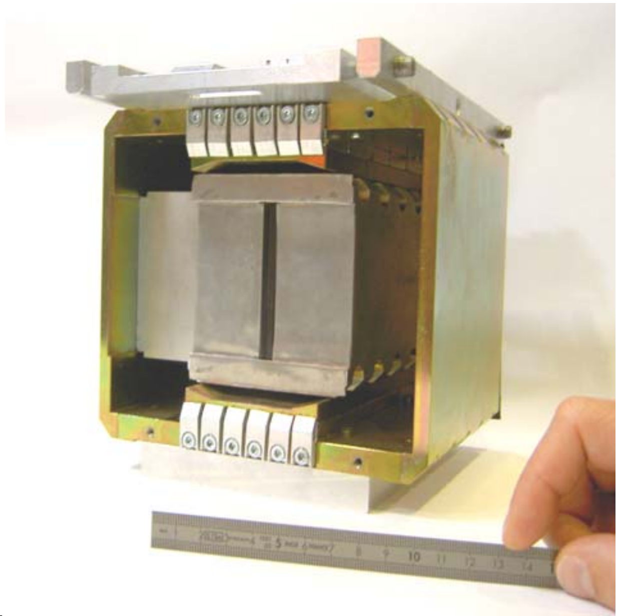
Therefore, with a judicious choice of N and b, it can be arranged that $R_{-} = 0$ implying perfect beam polarization at all angles of incidence

In practice this is very difficult to achieve, since the spin-down neutrons have to go somewhere. They are either transmitted or absorbed in an absorbing layer (often Gd, which has a non-zero reflectivity at very low angles)

S-Bender polarizers (IN14, ILL)

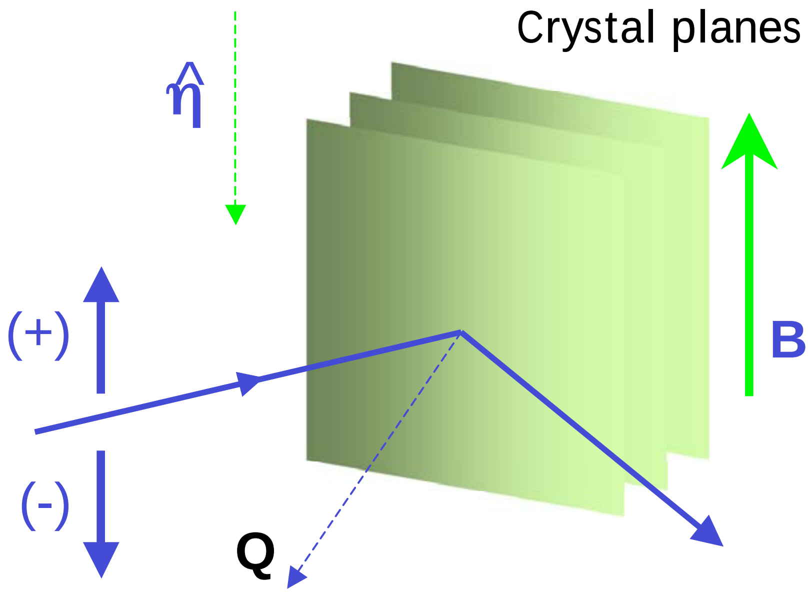
No deviation of neutrons





*Stunault et. al., Physica B **385-86** (2006) 1152-1154*

Neutron polarization - crystals



The cross section for Bragg reflection in the geometry shown left, in which the incident beam is considered as a superposition of P=1 and P=-1 states, is

$$d\sigma / d\Omega = F_N^2(\mathbf{Q}) + 2F_N(\mathbf{Q})F_M(\mathbf{Q})(\mathbf{P}\cdot\hat{\boldsymbol{\eta}}) + F_M^2(\mathbf{Q})$$

where $F_{N,M}(\mathbf{Q})$ are the nuclear and magnetic structure factors for the reflection

For $\mathbf{P}\cdot\hat{\boldsymbol{\eta}} = -1$: $\quad d\sigma / d\Omega = \left[F_N(\mathbf{Q}) + F_M(\mathbf{Q})\right]^2$ $\qquad$ For $\mathbf{P}\cdot\hat{\boldsymbol{\eta}} = 1$: $\quad d\sigma / d\Omega = \left[F_N(\mathbf{Q}) - F_M(\mathbf{Q})\right]^2$

If $|F_N(\mathbf{Q})| = |F_M(\mathbf{Q})|$ the reflected beam will be polarized.

The nuclear and magnetic structure factors can be either positive or negative, so beam polarization, $\mathbf{P}_f$, could be either "up" or "down" with respect to **B** .

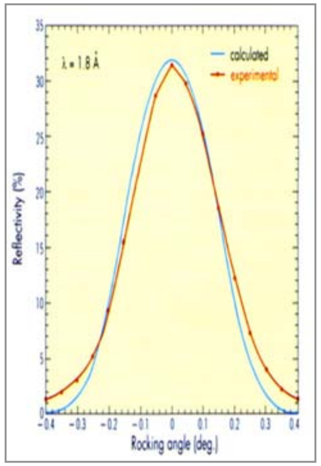
In general the polarizing efficiency of a crystal reflection is given by

$$P_f = \frac{2F_N(\mathbf{Q})F_M(\mathbf{Q})}{\left[F_N^2(\mathbf{Q}) + F_M^2(\mathbf{Q})\right]}$$

Crystal polarizers/monochromators

	$Co_{92}Fe_8$	Cu_2MnAl	Fe_3Si
Matched reflection	(200)	(111)	(111)
d-spacing (Å)	1.76	3.43	3.27
2θ at λ=1Å	33.1	16.7	17.6
Maximum λ (Å)	3.5	6.9	6.5

Cu_2MnAl has a higher reflectivity and lower absorption than $Co_{92}Fe_8$, also $F_N=-F_M$ so the beam is negatively polarized with respect to $\underline{B}$



Cu_2MnAl (Heusler) crystal grown at ILL, with associated reflectivity curve.

Neutron Polarization and Scattering

We start with the (elastic - $|k_i| = |k_f|$) scattering cross-section

$$\frac{d\sigma}{d\Omega} = \left(\frac{m_n}{2\pi\hbar^2}\right)\left|\langle \mathbf{k}'\mathbf{S}'|V|\mathbf{k}\mathbf{S}\rangle\right|^2$$

Where the spin-state of the neutron **S** is either spin-up $|\uparrow\rangle = \begin{pmatrix}1\\0\end{pmatrix}$ or spin down $|\downarrow\rangle = \begin{pmatrix}0\\1\end{pmatrix}$

1) <u>Nuclear (I = 0) scattering</u>

V is the Fermi pseudopotential, and the matrix element is

$$\langle \mathbf{S}'|b|\mathbf{S}\rangle = b\langle \mathbf{S}'|\mathbf{S}\rangle = \begin{cases} b & \left\{\begin{matrix} |\uparrow\rangle \rightarrow |\uparrow\rangle \\ |\downarrow\rangle \rightarrow |\downarrow\rangle \end{matrix}\right\} \text{Non-spin-flip} \\ 0 & \left\{\begin{matrix} |\uparrow\rangle \rightarrow |\downarrow\rangle \\ |\downarrow\rangle \rightarrow |\uparrow\rangle \end{matrix}\right\} \text{Spin-flip} \end{cases}$$

where we have used the fact that the spin states are orthogonal and normalised

$$\langle\uparrow|\downarrow\rangle = \langle\downarrow|\uparrow\rangle = 0, \quad \langle\uparrow|\uparrow\rangle = \langle\downarrow|\downarrow\rangle = 1$$

Neutron Polarization and Scattering

2) <u>Magnetic scattering</u>

V is the magnetic scattering potential given by

$$V_m(\mathbf{Q}) = -\frac{\gamma_n r_0}{2\mu_B}\boldsymbol{\sigma}\cdot\mathbf{M}_\perp(\mathbf{Q}) = -\frac{\gamma_n r_0}{2\mu_B}\sum_\zeta \sigma_\zeta \cdot M_{\perp\zeta}(\mathbf{Q}) \text{ (see e.g. Squires)}$$

where ζ = x, y, z. Here $M_\perp(\mathbf{Q})$ represents the component of the Fourier transform of the magnetisation of the sample, which is perpendicular to the scattering vector **Q** - i.e. the neutron sensitive part. σ_ζ are the Pauli spin matrices

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Substitution of these into the magnetic potential gives us the matrix elements

$$\langle \mathbf{S}' | V_m(\mathbf{Q}) | \mathbf{S} \rangle = -\frac{\gamma_n r_0}{2\mu_B}\begin{cases} M_{\perp z}(\mathbf{Q}) & |\uparrow\rangle \to |\uparrow\rangle \\ -M_{\perp z}(\mathbf{Q}) & |\downarrow\rangle \to |\downarrow\rangle \\ M_{\perp x}(\mathbf{Q}) - iM_{\perp y}(\mathbf{Q}) & |\uparrow\rangle \to |\downarrow\rangle \\ M_{\perp x}(\mathbf{Q}) + iM_{\perp y}(\mathbf{Q}) & |\downarrow\rangle \to |\uparrow\rangle \end{cases}$$

Non-spin-flip (first two)

Spin-flip (last two)

1st RULE OF THUMB

Neutron Polarization and Magnetic Scattering

The non-spin-flip scattering is sensitive only to those components of the magnetisation parallel to the neutron spin

The spin-flip scattering is sensitive only to those components of the magnetisation perpendicular to the neutron spin

NB This is one of those points that you should take away with you. It is the basis of all magnetic polarization analysis techniques

Neutron Polarization and Scattering

3) Nuclear spin-dependent scattering

In general a bound state is formed between the nucleus and the neutron during scattering with either spins antiparallel (spin-singlet) or spins parallel (spin-triplet). The scattering lengths for these situations are different and are termed b_- and b_+. We define the scattering length operator

$$\hat{\mathbf{b}} = A + B\boldsymbol{\sigma}\cdot\mathbf{I}$$

$$A = \frac{(I+1)b_+ + Ib_-}{2I+1}, \quad B = \frac{b_+ - b_-}{2I+1}$$

(see e.g. Squires, p173)

The calculation of the matrix elements now proceeds analogously to the case of magnetic scattering

$$\langle \mathbf{S}'|\hat{\mathbf{b}}|\mathbf{S}\rangle = \begin{cases} A + BI_z & |\uparrow\rangle \to |\uparrow\rangle \\ A - BI_z & |\downarrow\rangle \to |\downarrow\rangle \\ B(I_x - iI_y) & |\uparrow\rangle \to |\downarrow\rangle \\ B(I_x + iI_y) & |\downarrow\rangle \to |\uparrow\rangle \end{cases}$$

Non-spin-flip

Spin-flip

Since the nuclear spins are (normally) random $\langle I_x\rangle = \langle I_y\rangle = \langle I_z\rangle = 0$

Therefore, with the coherent scattering amplitude proportional to $\bar{b}$, we can write

$\bar{b} = A$ i.e. the coherent scattering is entirely non-spin-flip

Neutron Polarization and Scattering

Bringing all this together, we get

$$|\uparrow\rangle \rightarrow |\uparrow\rangle = \overline{b} - \frac{\gamma_n r_0}{2\mu_B} M_{\perp z} + BI_z$$

$$|\downarrow\rangle \rightarrow |\downarrow\rangle = \overline{b} + \frac{\gamma_n r_0}{2\mu_B} M_{\perp z} - BI_z$$

Moon, Riste and Koehler (*Phys Rev* ***181*** *(1969) 920*)

$$|\uparrow\rangle \rightarrow |\downarrow\rangle = -\frac{\gamma_n r_0}{2\mu_B}\left(M_{\perp x} - iM_{\perp y}\right) + B\left(I_x - iI_y\right)$$

$$|\downarrow\rangle \rightarrow |\uparrow\rangle = -\frac{\gamma_n r_0}{2\mu_B}\left(M_{\perp x} + iM_{\perp y}\right) + B\left(I_x + iI_y\right)$$

Remember that: $\mathbf{M}_\perp = -2\mu_B\left[\hat{\boldsymbol{\eta}} - (\hat{\boldsymbol{\eta}}\cdot\hat{\mathbf{Q}})\hat{\mathbf{Q}}\right]$ (see e.g. Squires)

These lead to the:

2nd RULE OF THUMB

If the polarization is parallel to the scattering vector, then the magnetisation in the direction of the polarization will not be observed since the magnetic interaction vector is zero. i.e. all magnetic scattering will be spin-flip

Incoherent Scattering

Now, let's take another look at the nuclear incoherent scattering. We know that this is given by $\overline{b^2} - \left(\overline{b}\right)^2$

Applying this to the $|\uparrow\rangle \rightarrow |\uparrow\rangle$ transition, and neglecting magnetic scattering, we get

$$\overline{b^2} = \left\langle \left(\overline{b} + BI_z\right)^2 \right\rangle$$

$$= \left\langle \left(\overline{b}\right)^2 \right\rangle + \left\langle B^2 I_z^2 \right\rangle + 2\left\langle \overline{b} B I_z \right\rangle$$

Now, for a randomly oriented distribution of nuclei of spin I, we have

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

$$\Rightarrow I_x^2 = I_y^2 = I_z^2 = \frac{1}{3} I(I+1)$$ since the distribution is isotropic

Therefore we can write

$$\overline{b^2} - \left(\overline{b}\right)^2 = \left\langle \left(\overline{b}\right)^2 \right\rangle - \left(\overline{b}\right)^2 + \frac{1}{3} B^2 I(I+1)$$

Isotope incoherent scattering

spin incoherent scattering

The other transitions are dealt with in a similar way

Neutron Polarization and Scattering

Finally, we get

$$\left|\uparrow\right\rangle \rightarrow \left|\uparrow\right\rangle = \bar{b} - \frac{\gamma_n r_0}{2\mu_B} M_{\perp z} + b_{II} + \frac{1}{3} b_{SI}$$

$$\left|\downarrow\right\rangle \rightarrow \left|\downarrow\right\rangle = \bar{b} + \frac{\gamma_n r_0}{2\mu_B} M_{\perp z} + b_{II} + \frac{1}{3} b_{SI}$$

$$\left|\uparrow\right\rangle \rightarrow \left|\downarrow\right\rangle = -\frac{\gamma_n r_0}{2\mu_B}\left(M_{\perp x} - iM_{\perp y}\right) + \frac{2}{3} b_{SI}$$

$$\left|\downarrow\right\rangle \rightarrow \left|\uparrow\right\rangle = -\frac{\gamma_n r_0}{2\mu_B}\left(M_{\perp x} + iM_{\perp y}\right) + \frac{2}{3} b_{SI}$$

where

$$b_{II} = \sqrt{\left\langle\left(\bar{b}\right)^2\right\rangle - \left(\bar{b}\right)^2}$$

$$b_{SI} = \sqrt{B^2 I(I+1)}$$

The details of the magnetic scattering will in general depend on the direction of the neutron polarization with respect to the scattering vector, and also on the nature of the orientation of the magnetic moments

Science…

Uni-directional polarized neutron scattering

"Flipping ratio" measurements without spin analysers to determine magnetic form factors and spin density distributions in magnetically aligned samples and magnetic defects in disordered ferromagnets

eg D3

Three directional polarized neutron scattering

Spin flip and non-spin flip scattering measured in X-, Y- and Z-directions (sometimes with energy analysis) to separate the magnetic and nuclear scattering in antiferromagnets and paramagnets

eg D7

Three dimensional polarization analysis or spherical polarimetry

Measurement of final polarization of scattered beam independently of spin state of incident beam (by working in zero field), giving transverse components of scattered polarization in both elastic and inelastic scattering.

eg CRYOPAD

Also…reflectometry, depolarization measurements, fundamental physics etc…

Magnetic diffraction

For a ferromagnet the cross section for unpolarized neutrons is

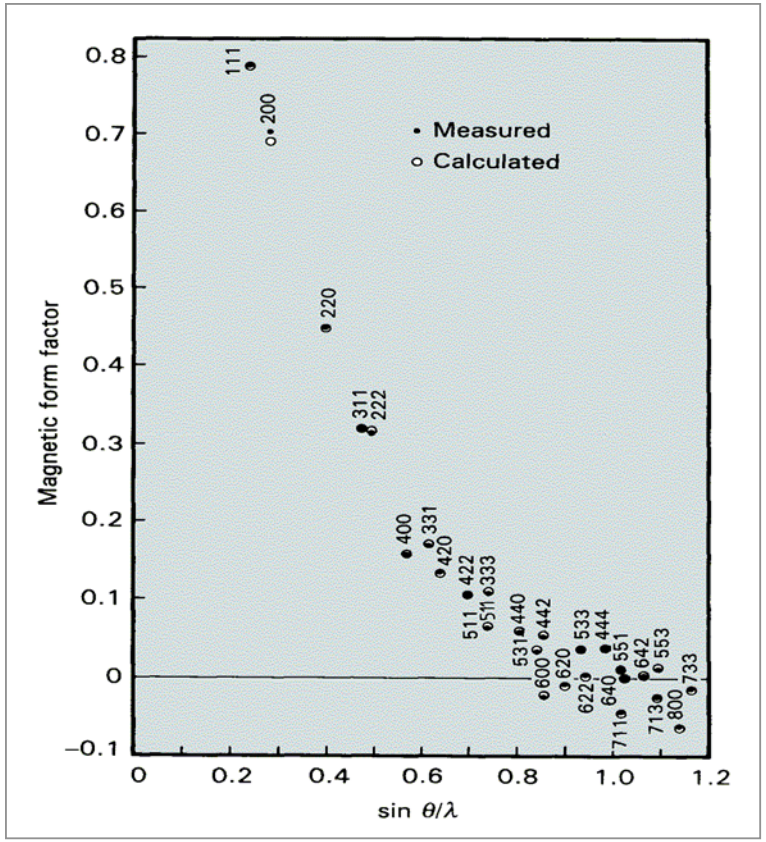
$$\frac{d\sigma}{d\Omega} = F_N^2(\mathbf{Q}) + F_M^2(\mathbf{Q})$$

If we take a simple ferromagnet such as Ni (b_{Ni}=1.03×10^{-12}cm, μ_{Ni}= 0.6μ_B) aligned such that the magnetisation is perpendicular to **Q** (i.e. magnetic interaction vector = 1) the ratio of the magnetic to the nuclear contribution to the intensity of even the lowest angle (111) reflection is only

$$F_M^2(\mathbf{Q}) \big/ F_N^2(\mathbf{Q}) = 0.017$$

By the (400) reflection this ratio has fallen as a consequence of the magnetic form factor to

$$F_M^2(\mathbf{Q}) \big/ F_N^2(\mathbf{Q}) = 6 \times 10^{-4}$$



Polarized magnetic diffraction

For a ferromagnetic sample aligned in a field perpendicular to the scattering vector we have

$$\mathbf{M}_\perp = -2\mu_B\left[\hat{\boldsymbol{\eta}} - (\hat{\boldsymbol{\eta}}\cdot\hat{\mathbf{Q}})\hat{\mathbf{Q}}\right] = -2\mu_B\hat{\boldsymbol{\eta}}$$

and $M_\perp$ has no component in the xy-plane, so that the spin-flip scattering is zero. This implies that we don't need to analyse the neutron spin, it will always end up in the same direction it started in. Therefore

$d\sigma/d\Omega = \left[F_N(\mathbf{Q}) - F_M(\mathbf{Q})\right]^2$ for neutrons polarized parallel to the field

$d\sigma/d\Omega = \left[F_N(\mathbf{Q}) + F_M(\mathbf{Q})\right]^2$ for neutrons polarized antiparallel to the field

where

$$F_N(\mathbf{Q}) = \sum_i b_i \exp(i\mathbf{Q}\cdot\mathbf{r}_i)$$

$$F_M(\mathbf{Q}) = \gamma_n r_0 \sum_i g_{J_i} J_i f_i(\mathbf{Q}) \exp(i\mathbf{Q}\cdot\mathbf{r}_i)$$

Notice that to simulate an unpolarized measurement, we simply average the two polarized cross sections

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left[\left(F_N(\mathbf{Q}) - F_M(\mathbf{Q})\right)^2 + \left(F_N(\mathbf{Q}) + F_M(\mathbf{Q})\right)^2\right]$$
$$= F_N^2(\mathbf{Q}) + F_M^2(\mathbf{Q})$$

NB we have neglected incoherent scattering here

Flipping ratios

Using a spin flipper to access these two polarized cross sections we can determine the "flipping ratio", R, of a particular Bragg reflection:

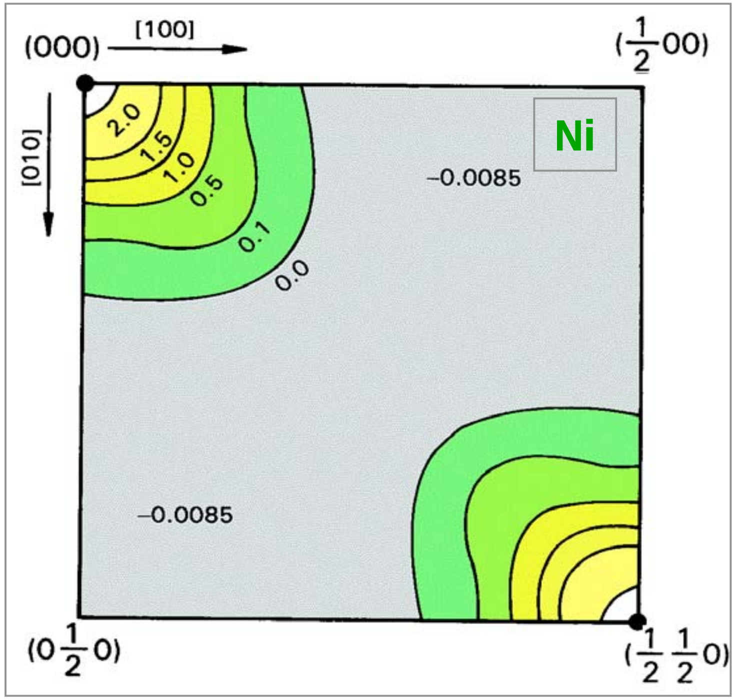
$$R = \frac{(d\sigma/d\Omega)_{\Downarrow}}{(d\sigma/d\Omega)_{\Uparrow}} = \frac{[F_N(\mathbf{Q}) + F_M(\mathbf{Q})]^2}{[F_N(\mathbf{Q}) - F_M(\mathbf{Q})]^2} = \left(\frac{1+\gamma}{1-\gamma}\right)^2$$

$$\text{with} \quad \gamma = \frac{F_M(\mathbf{Q})}{F_N(\mathbf{Q})}$$

(but only for a centrosymmetric structure!
See Forsyth, Atomic Energy Review 17,345,1979)

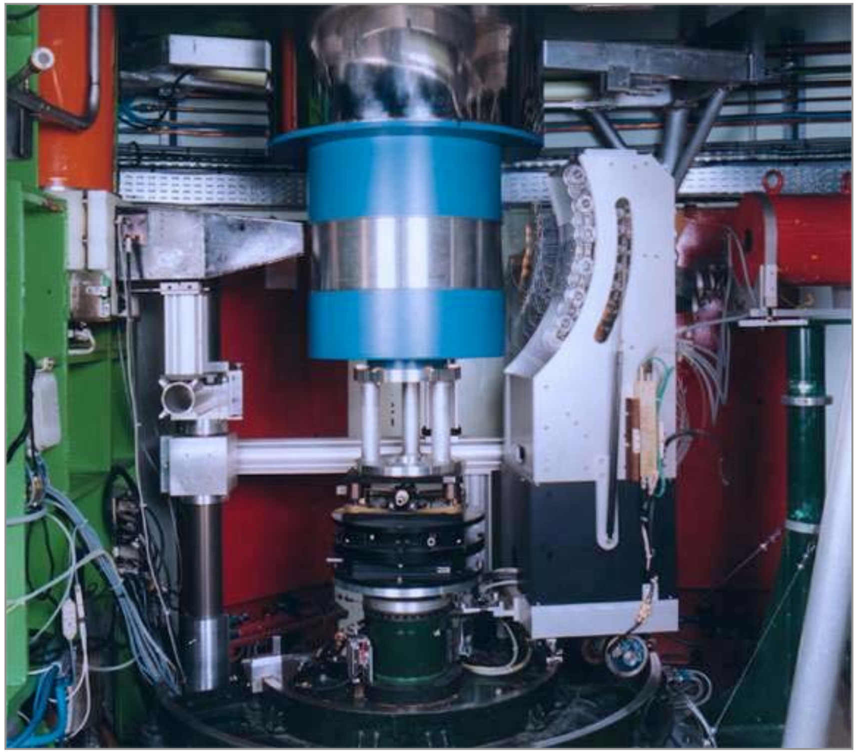
So, for example, in the case of Ni we measure a flipping ratio of 1.7 at the (111) reflection and 1.1 at the (400) reflection

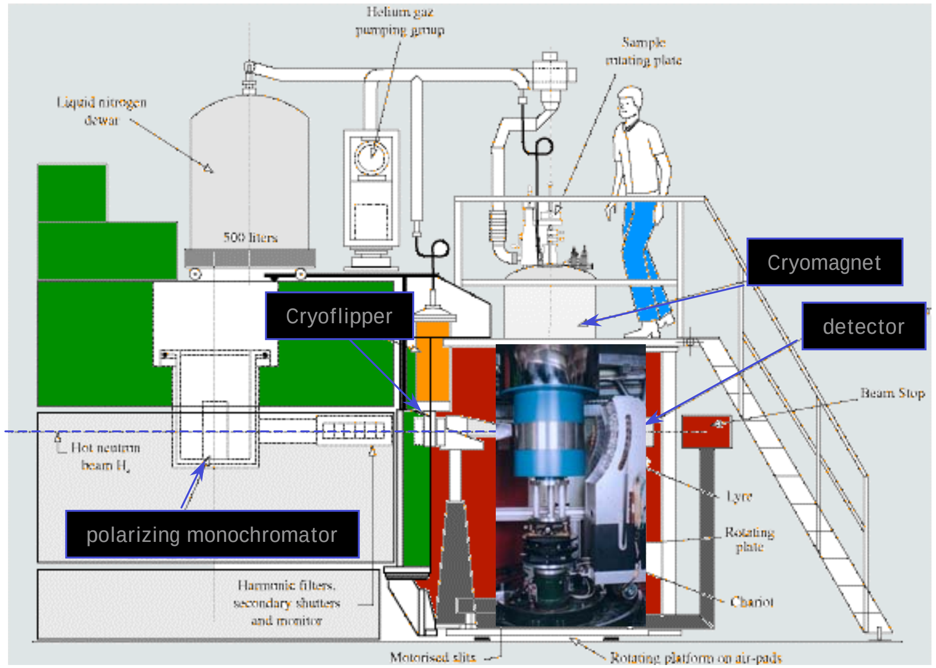
The goal is, of course, to determine $F_M(\mathbf{Q})$ which can then be Fourier transformed to give a full 3-dimensional spin density distribution



Instrumentation

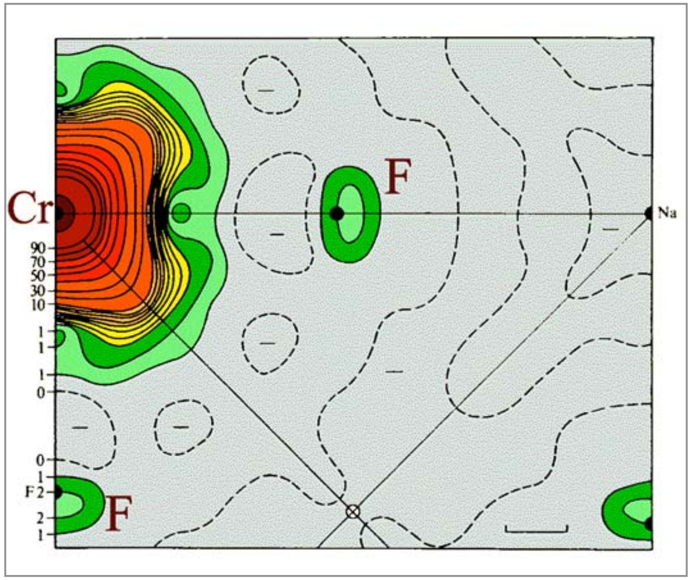
The D3 diffractometer, ILL





Spin Density Distributions

K_2NaCrF_6

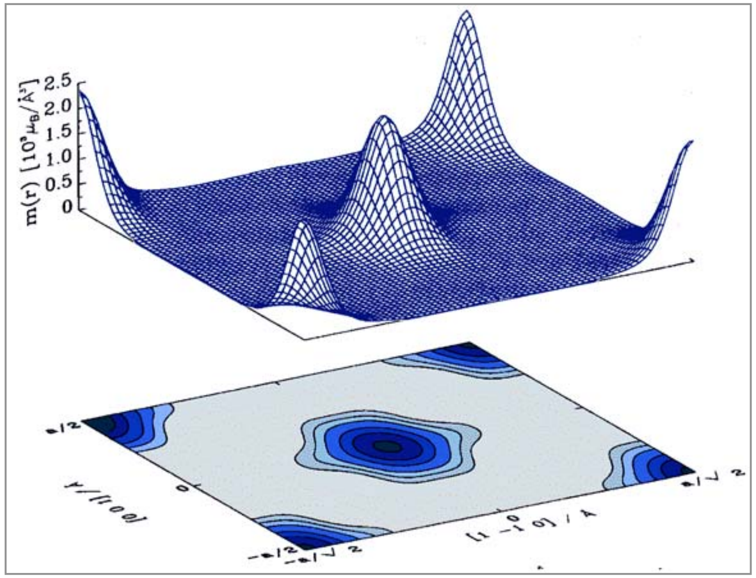


K_2NaCrF_6 is a cubic insulator in which Cr^{3+} ions are at the centre of an octahedron of F^-

T_{2g} symmetry around Cr and islands of spin density around F indicative of spin transfer through covalent bonding

Wedgwood, Proc Roy Soc A349, 447 (1976)

Antiferromagnetic Cr metal



Pure Cr is an itinerant electron spin density wave antiferromagnet.

However a field induced magnetic form factor can be measured

Results (analysed using Max. Ent. methods) are consistent with 60% orbital and 40% spin contributions

Strempfer et al Physica B 267-8 56 (1999)

3-directional polarization analysis

With 3-directional polarization analysis (X-Y-Z difference method) we employ a multi-detector at various scattering angles. Therefore we cannot arrange for **P||Q** for all detectors, and must use an alternative method for magnetic separation.

In addition, it is difficult to get a wide angle spin-flipper, so we make do with one flipper before the sample. Therefore we see the following transitions

$$\left|\uparrow\right\rangle \rightarrow \left|\uparrow\right\rangle = b - \frac{\gamma_n r_0}{2\mu_B} M_{\perp z} + b_{II} + \frac{1}{3} b_{SI}$$

$$\left|\downarrow\right\rangle \rightarrow \left|\uparrow\right\rangle = -\frac{\gamma_n r_0}{2\mu_B}\left(M_{\perp x} + iM_{\perp y}\right) + \frac{2}{3} b_{SI}$$

The cross-sections (considering magnetic part only) are therefore

$$\left(\frac{d\sigma}{d\Omega}\right)_{NSF} = \left(\frac{\gamma_n r_0}{2\mu_B}\right)^2 \left\langle M^*_{\perp z} M_{\perp z} \right\rangle$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{SF} = \left(\frac{\gamma_n r_0}{2\mu_B}\right)^2 \left\langle \left(M_{\perp x} + iM_{\perp y}\right)^* \left(M_{\perp x} + iM_{\perp y}\right) \right\rangle$$

$$= \left(\frac{\gamma_n r_0}{2\mu_B}\right)^2 \left\langle M^*_{\perp x} M_{\perp x} + M^*_{\perp y} M_{\perp y} \right\rangle$$

3-directional polarization analysis

It can be shown (see Squires p 179) that in the case of a fully disordered paramagnet these expressions reduce to

$$\left(\frac{d\sigma}{d\Omega}\right)_{NSF}^{\xi} = \frac{1}{3}\left(\frac{\gamma r_0}{2}\right)^2 g^2 f^2(\mathbf{Q}) J(J+1)\left[1-\left(\hat{\mathbf{P}}\cdot\hat{\mathbf{Q}}\right)^2\right]$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{SF}^{\xi} = \frac{1}{3}\left(\frac{\gamma r_0}{2}\right)^2 g^2 f^2(\mathbf{Q}) J(J+1)\left[1+\left(\hat{\mathbf{P}}\cdot\hat{\mathbf{Q}}\right)^2\right]$$

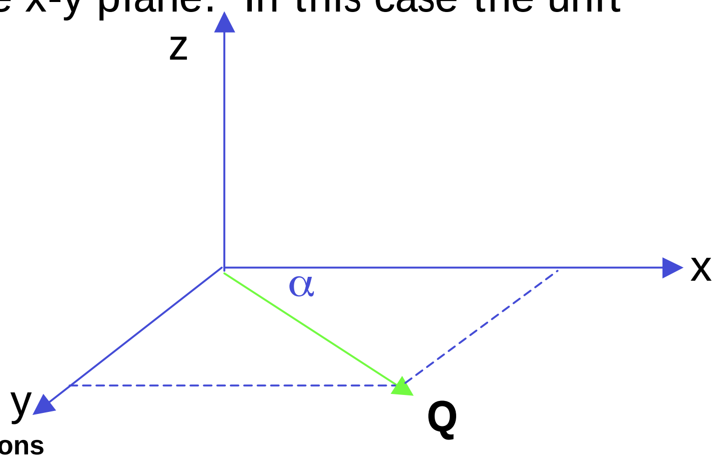
where we have replaced the z-direction with the general direction ζ = x, y, or z

We can immediately see that setting the polarization (ζ) direction along the scattering vector has the desired effect of rendering all the magnetic scattering in the spin-flip cross-section.

Now we suppose that we have a multi-detector in the x-y plane. In this case the unit scattering vector is

$$\hat{\mathbf{Q}} = \begin{pmatrix} \cos\alpha \\ \sin\alpha \\ 0 \end{pmatrix}$$

where α is the angle between **Q** and an arbitrary x-axis - the “Schärpf angle”



The six partial cross sections

Substituting this unit scattering vector into the NSF and SF cross sections leads then to 6 equations (including now the nuclear coherent, isotope incoherent and spin-incoherent terms)

$$\left(\frac{d\sigma}{d\Omega}\right)_X^{NSF} = \frac{1}{2}\sin^2\alpha\left(\frac{d\sigma}{d\Omega}\right)_{mag} + \frac{1}{3}\left(\frac{d\sigma}{d\Omega}\right)_{SI} + \left(\frac{d\sigma}{d\Omega}\right)_{nuc+II}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_X^{SF} = \frac{1}{2}\left(\cos^2\alpha + 1\right)\left(\frac{d\sigma}{d\Omega}\right)_{mag} + \frac{2}{3}\left(\frac{d\sigma}{d\Omega}\right)_{SI}$$

x-direction

$$\left(\frac{d\sigma}{d\Omega}\right)_Y^{NSF} = \frac{1}{2}\cos^2\alpha\left(\frac{d\sigma}{d\Omega}\right)_{mag} + \frac{1}{3}\left(\frac{d\sigma}{d\Omega}\right)_{SI} + \left(\frac{d\sigma}{d\Omega}\right)_{nuc+II}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_Y^{SF} = \frac{1}{2}\left(\sin^2\alpha + 1\right)\left(\frac{d\sigma}{d\Omega}\right)_{mag} + \frac{2}{3}\left(\frac{d\sigma}{d\Omega}\right)_{SI}$$

y-direction

$$\left(\frac{d\sigma}{d\Omega}\right)_Z^{NSF} = \frac{1}{2}\left(\frac{d\sigma}{d\Omega}\right)_{mag} + \frac{1}{3}\left(\frac{d\sigma}{d\Omega}\right)_{SI} + \left(\frac{d\sigma}{d\Omega}\right)_{nuc+II}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_Z^{SF} = \frac{1}{2}\left(\frac{d\sigma}{d\Omega}\right)_{mag} + \frac{2}{3}\left(\frac{d\sigma}{d\Omega}\right)_{SI}$$

z-direction

Schärpf and Capellmann Phys Stat Sol a135 (1993) 359

Separation of the cross sections

The principal cross sections can be extracted by combining the six partials:

The magnetic cross-section is independently calculated in 2 ways

$$\left.\begin{aligned}\left(\frac{d\sigma}{d\Omega}\right)_{mag} &= 2\left[\left(\frac{d\sigma}{d\Omega}\right)_{SF}^{X} + \left(\frac{d\sigma}{d\Omega}\right)_{SF}^{Y} - 2\left(\frac{d\sigma}{d\Omega}\right)_{SF}^{Z}\right] \\ \left(\frac{d\sigma}{d\Omega}\right)_{mag} &= 2\left[2\left(\frac{d\sigma}{d\Omega}\right)_{NSF}^{Z} - \left(\frac{d\sigma}{d\Omega}\right)_{NSF}^{X} - \left(\frac{d\sigma}{d\Omega}\right)_{NSF}^{Y}\right]\end{aligned}\right\} = \frac{2}{3}\left(\frac{\gamma_n r_0}{2}\right)^2 g_J^2 f^2(Q) J(J+1)$$

For the other cross-sections, we have

$$\left(\frac{d\sigma}{d\Omega}\right)_{SI} = \frac{1}{2}\left(\frac{d\sigma}{d\Omega}\right)_{TSF} - \left(\frac{d\sigma}{d\Omega}\right)_{mag} = B^2 I(I+1)$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{nuc+II} = \frac{1}{6}\left[2\left(\frac{d\sigma}{d\Omega}\right)_{TNSF} - \left(\frac{d\sigma}{d\Omega}\right)_{TSF}\right] = b^2 S(Q) + \overline{b^2} - \left(\overline{b}\right)^2$$

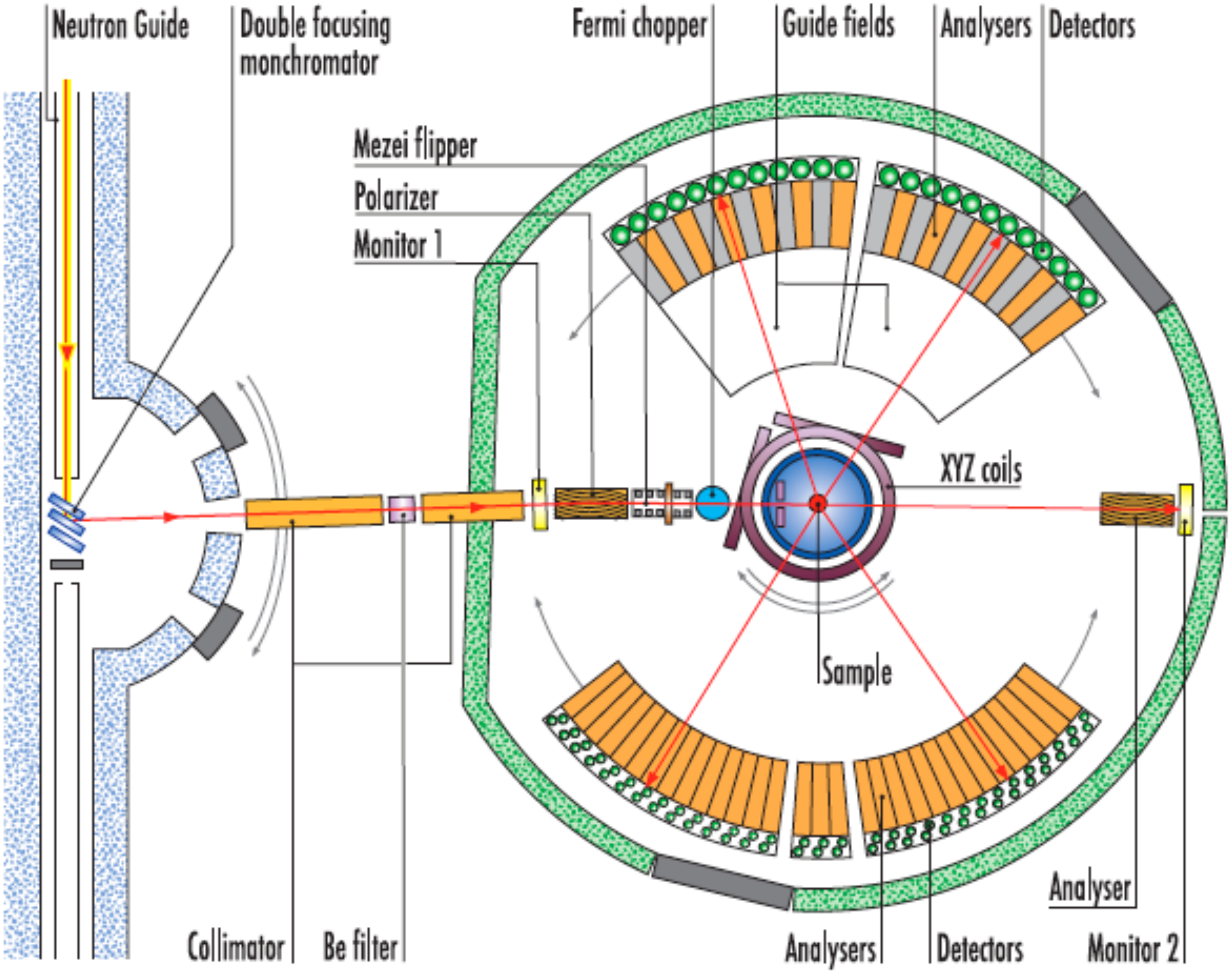
where the subscript, TNSF or TSF refers to the total (x + y + z) NSF or SF scattering cross sections

The 3-directional, or xyz- difference method is most widely used for diffuse scattering studies of magnetic correlations in spin glasses, antiferromagnets and frustrated systems – the general requirement being that these equations only work if there are no collinear (or chiral) components to the magnetisation

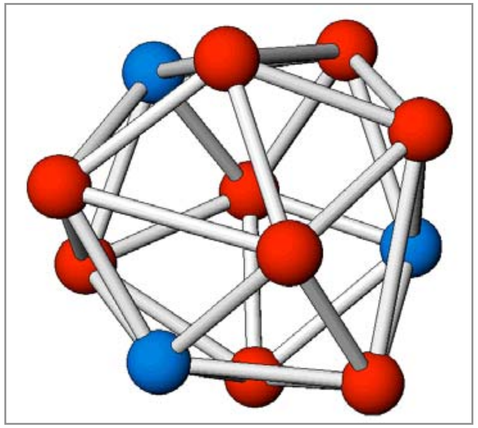
Stewart, et. al. J. Applied Phys. ***87*** *(2000)*

Instrumentation

D7 - Diffuse scattering spectrometer (with time-of-flight time-focusing option)

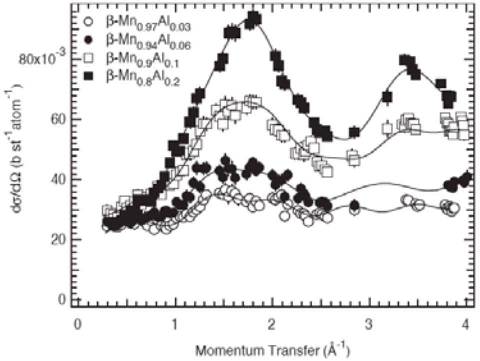


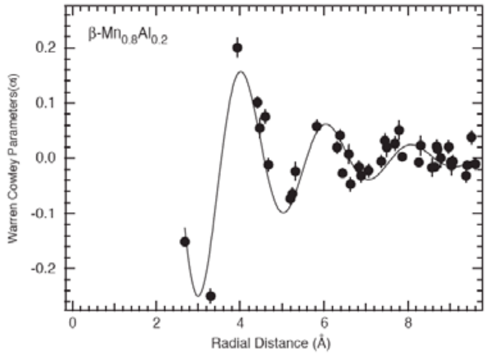
Diffuse scattering - β-MnAl

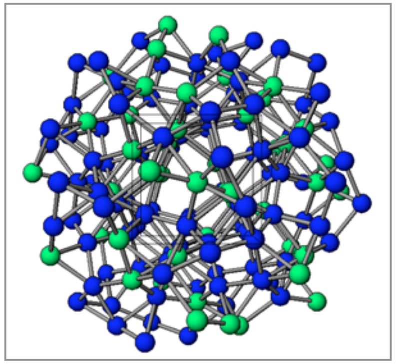


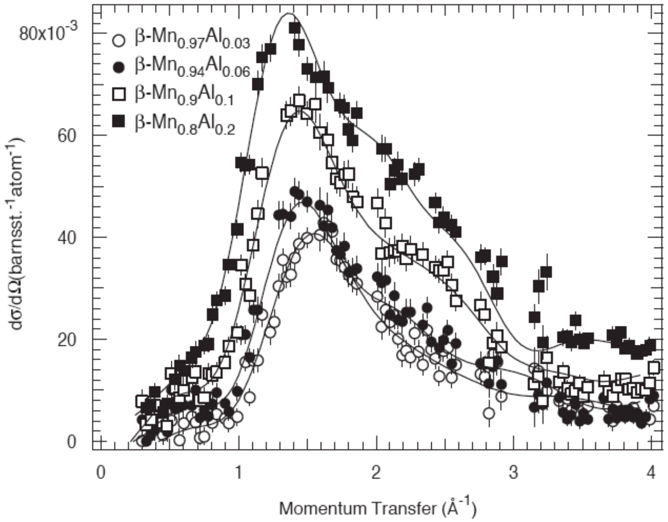
β-$Mn_{1-x}Al_x$ (0<x<0.2) is a topologically frustrated spin glass-like itinerant magnet.

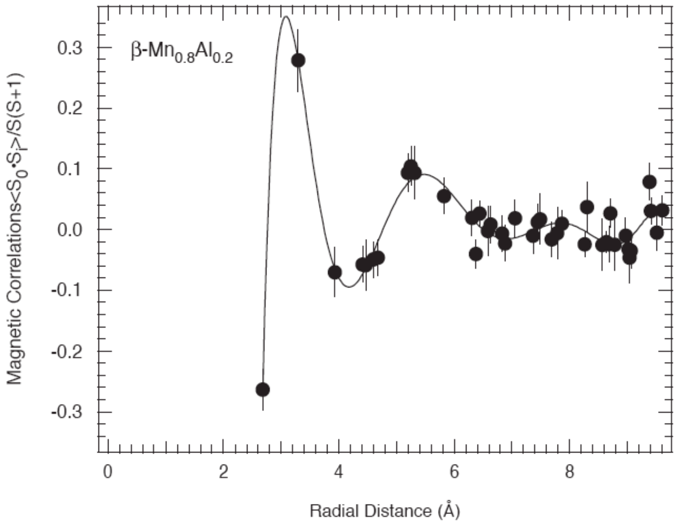
3-directional PA has enabled magnetic and nuclear correlations to be measured and modelled using reverse Monte Carlo methods





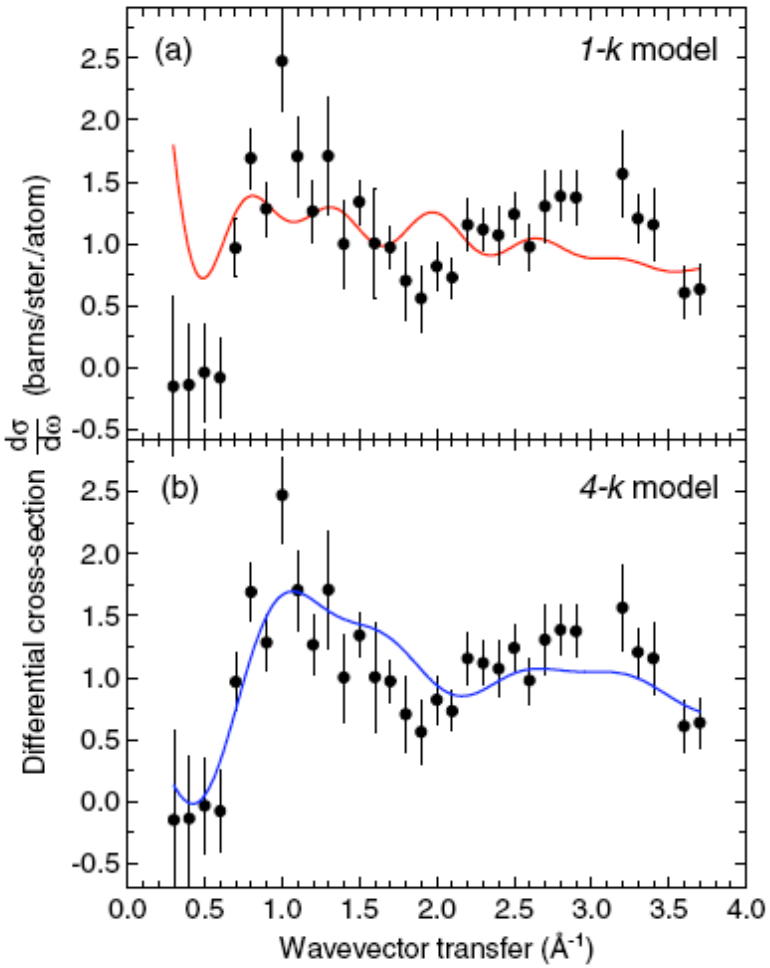


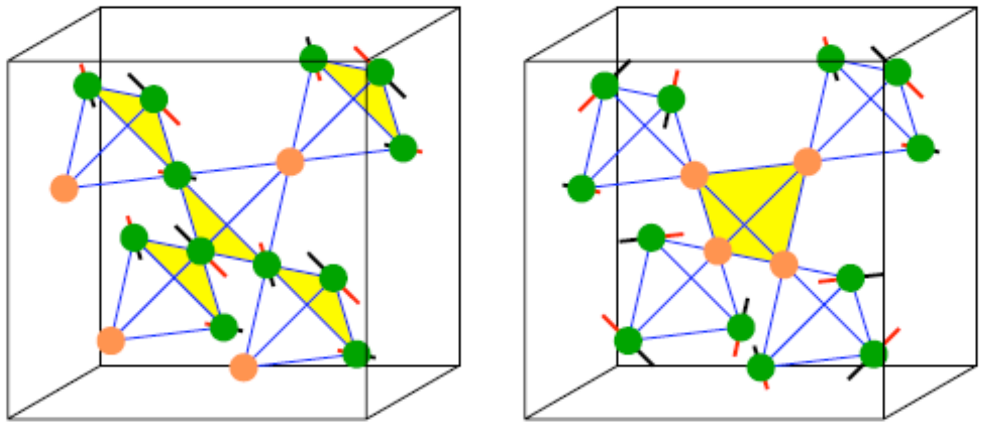




Stewart, et. al. J. Mag. Magn. Mater. ***272*** *676(2004)*

Diffuse scattering - Magnetic frustration

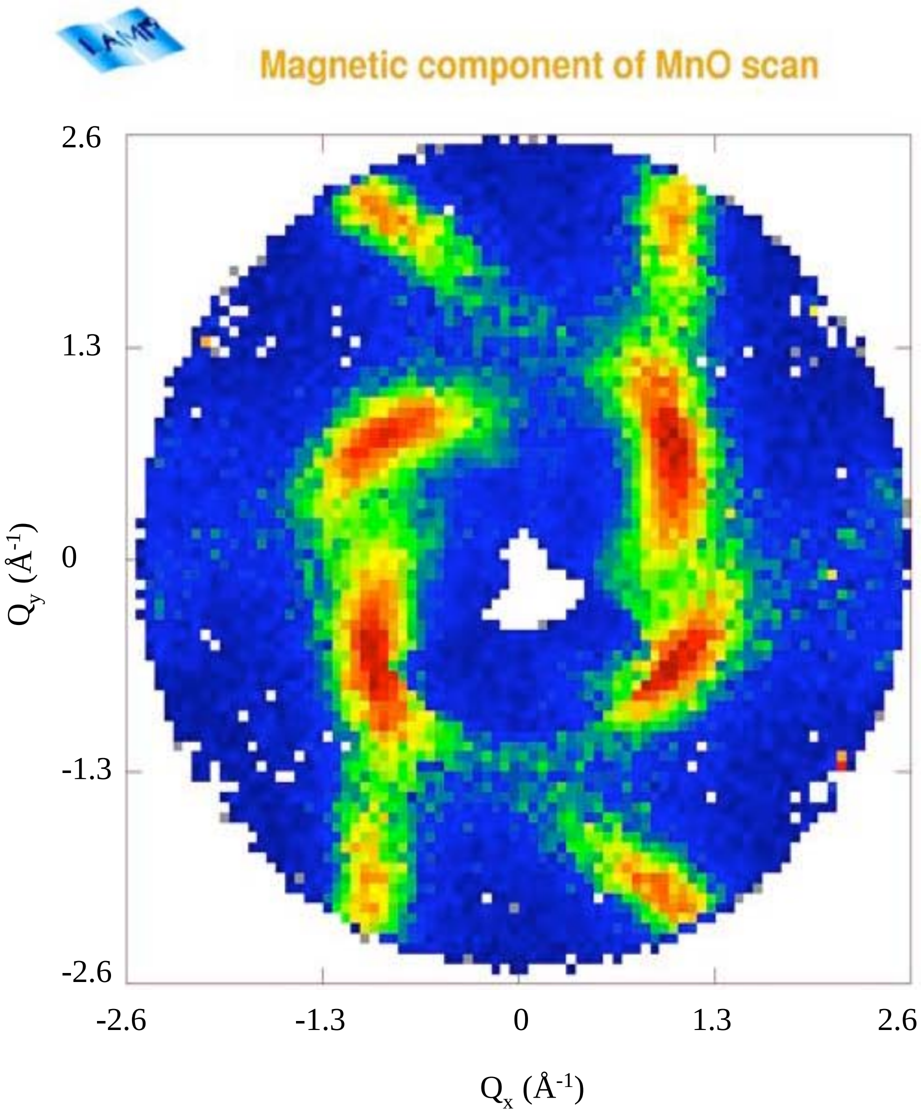




Magnetic short-range order in $Gd_2Ti_2O_7$ - due to geometrical frustration of anti-ferromagnetic exchange interactions

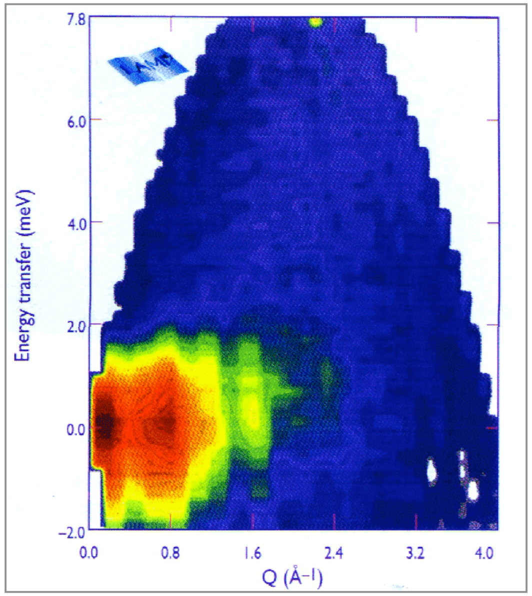
Stewart et al, J Phys: Condensed Matter 16, L321 (2004)

Strongly correlated systems

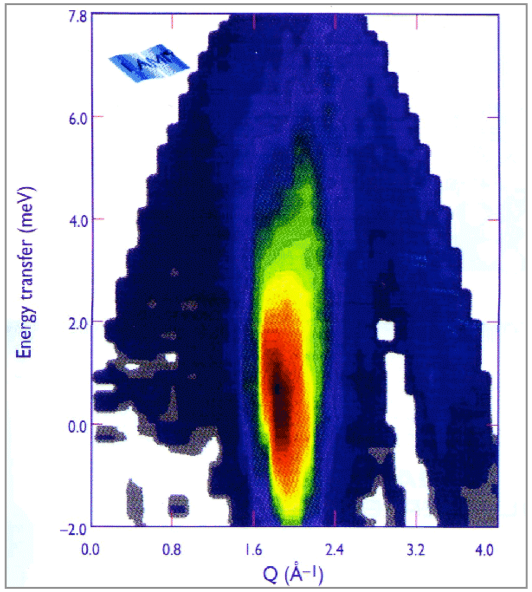


NEUTRONS FOR SCIENCE

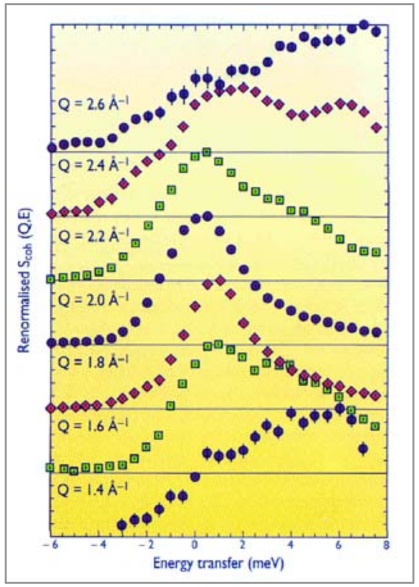
Non-magnetic inelastic scattering



Spin Incoherent scattering (single particle excitations)



Nuclear coherent scattering (collective excitations)



S(Q,E) for the coherent scattering

Time-of-flight analysis of the scattering from para-hydrogen at 16K

Again The X-, Y-, Z- difference technique has been used on D7 to separate the spin incoherent and nuclear coherent scattering

Neutron Polarimetry

To this point we have only been concerned with applying uniaxial polarization analysis - i.e. with measuring the scattered intensity associated with a scalar change of polarization along a particular axis.

This is “longitudinal polarization analysis”

For a full description of the scattering processes we must perform “polarization analysis” in its true sense, i.e. we must measure all components of the polarization vector

This is “neutron polarimetry”

The general equations are (and I’m just going to quote them!) are found by repeating our previous uniaxial analysis in three dimensions

$$\sigma = \begin{cases} NN^* & \text{Nuclear} \\ \mathbf{M}_\perp \cdot \mathbf{M}_\perp{}^* + i\mathbf{P}_i \cdot \left(\mathbf{M}_\perp{}^* \times \mathbf{M}_\perp\right) & \text{Magnetic} \\ \mathbf{P}_i \cdot \left(\mathbf{M}_\perp N^* + \mathbf{M}_\perp{}^* N\right) & \text{NM Interference} \end{cases}$$

and

$$\mathbf{P}_f \sigma = \begin{cases} \mathbf{P}_i NN^* & \text{Nuclear} \\ -\mathbf{P}_i\left(\mathbf{M}_\perp \cdot \mathbf{M}_\perp{}^*\right) + \mathbf{M}_\perp\left(\mathbf{P}_i \cdot \mathbf{M}_\perp{}^*\right) + \mathbf{M}_\perp{}^*\left(\mathbf{P}_i \cdot \mathbf{M}_\perp\right) - i\left(\mathbf{M}_\perp{}^* \times \mathbf{M}_\perp\right) & \text{Magnetic} \\ \mathbf{M}_\perp N^* + \mathbf{M}_\perp{}^* N - i\left(N\mathbf{M}_\perp{}^* - N^*\mathbf{M}_\perp\right) \times \mathbf{P}_i & \text{NM Interference} \end{cases}$$

Blume (*Phys Rev* <u>*130*</u>*, 1670, 1963, Physica B* <u>*267-268*</u>*, 211, 1999*)

or: Hicks (*Advances in physics,* <u>*45*</u>*, 243, 1996*)

Neutron Polarimetry

$$\sigma = \begin{cases} NN^* & \text{Nuclear} \\ \mathbf{M}_\perp \cdot \mathbf{M}_\perp^* + i\mathbf{P}_i \cdot \left(\mathbf{M}_\perp^* \times \mathbf{M}_\perp\right) & \text{Magnetic} \\ \mathbf{P}_i \cdot \left(\mathbf{M}_\perp N^* + \mathbf{M}_\perp^* N\right) & \text{NM Interference} \end{cases}$$

$$\mathbf{P}_f \sigma = \begin{cases} \mathbf{P}_i NN^* & \text{Nuclear} \\ -\mathbf{P}_i\left(\mathbf{M}_\perp \cdot \mathbf{M}_\perp^*\right) + \mathbf{M}_\perp\left(\mathbf{P}_i \cdot \mathbf{M}_\perp^*\right) + \mathbf{M}_\perp^*\left(\mathbf{P}_i \cdot \mathbf{M}_\perp\right) - i\left(\mathbf{M}_\perp^* \times \mathbf{M}_\perp\right) & \text{Magnetic} \\ \mathbf{M}_\perp N^* + \mathbf{M}_\perp^* N - i\left(N\mathbf{M}_\perp^* - N^*\mathbf{M}_\perp\right) \times \mathbf{P}_i & \text{NM Interference} \end{cases}$$

Points to note are:

1) Pure nuclear scattering does not effect the neutron polarization
2) The cross-terms are non zero only for non-collinear (e.g. spiral) structures where $M_\perp^*$ and $M_\perp$ are not parallel.
3) Scattering by NM interference will only occur when the nuclear and magnetic contributions occur with the same wavevector.

Where there is no NM interference and no chiral terms (which is generally true for paramagnets and glassy systems) the above equations reduce to the uniaxial equations.

Flipping ratios revisited....

$$\sigma = \begin{cases} NN^* & \text{Nuclear} \\ \mathbf{M}_\perp \cdot \mathbf{M}_\perp^* + \cancel{i\mathbf{P}_i \cdot \left(\mathbf{M}_\perp^* \times \mathbf{M}_\perp\right)} & \text{Magnetic} \\ \mathbf{P}_i \cdot \left(\mathbf{M}_\perp N^* + \mathbf{M}_\perp^* N\right) & \text{NM Interference} \end{cases}$$

$$\mathbf{P}_f \sigma = \begin{cases} \mathbf{P}_i NN^* & \text{Nuclear} \\ -\mathbf{P}_i\left(\mathbf{M}_\perp \cdot \mathbf{M}_\perp^*\right) + \mathbf{M}_\perp\left(\mathbf{P}_i \cdot \mathbf{M}_\perp^*\right) + \mathbf{M}_\perp^*\left(\mathbf{P}_i \cdot \mathbf{M}_\perp\right) \cancel{- i\left(\mathbf{M}_\perp^* \times \mathbf{M}_\perp\right)} & \text{Magnetic} \\ \mathbf{M}_\perp N^* + \mathbf{M}_\perp^* N \cancel{- i\left(N\mathbf{M}_\perp^* - N^*\mathbf{M}_\perp\right) \times \mathbf{P}_i} & \text{NM Interference} \end{cases}$$

The imaginary part of $M_\perp$ contains the phase information on the magnetic order. For non-chiral structures,

$$\mathbf{M}_\perp = \mathbf{M}_\perp^*$$

$$\Rightarrow \mathbf{M}_\perp^* \times \mathbf{M}_\perp = 0$$

Interaction vector

$$\left.\begin{matrix} \mathbf{M}_\perp \propto \mathbf{Q} \times \mathbf{M} \times \mathbf{Q} \\ \mathbf{M} \perp \mathbf{Q} \end{matrix}\right\} \Rightarrow \mathbf{M}_\perp \| \mathbf{M} \Rightarrow \mathbf{M}_\perp \| \mathbf{P}_i$$

Sample is magnetised

$$\Rightarrow \mathbf{P}_i = \mathbf{P}_f$$

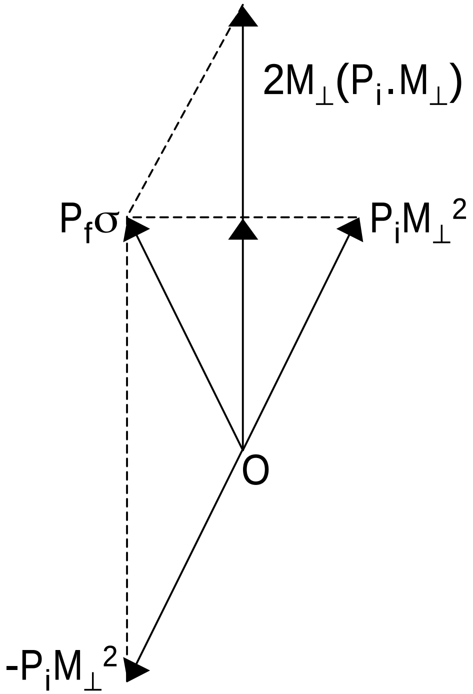
So we recover the form of the cross-section for magnetic diffraction - and the observation that there is no spin-flip scattering

Polarimetry examples

$$\mathbf{P}_f\sigma = \left\{ \begin{array}{c} \mathbf{P}_i N N^* \\ -\mathbf{P}_i\left(\mathbf{M}_\perp \cdot \mathbf{M}_\perp{}^*\right) + \mathbf{M}_\perp\left(\mathbf{P}_i \cdot \mathbf{M}_\perp{}^*\right) + \mathbf{M}_\perp{}^*\left(\mathbf{P}_i \cdot \mathbf{M}_\perp\right) - i\left(\mathbf{M}_\perp{}^* \times \mathbf{M}_\perp\right) \\ \mathbf{M}_\perp N^* + \mathbf{M}_\perp{}^* N - i\left(N\mathbf{M}_\perp{}^* - N^*\mathbf{M}_\perp\right) \times \mathbf{P}_i \end{array} \right.$$

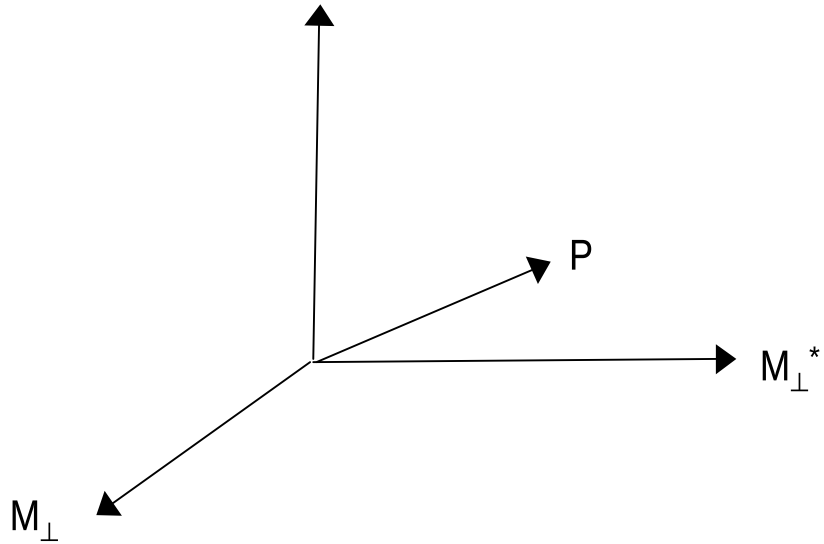
- e.g. $M_\perp$ and $M_\perp^*$ are parallel –
- no nuclear scattering

$$\mathbf{P}_f\sigma = -\mathbf{P}_i\mathbf{M}_\perp^2 + 2\mathbf{M}_\perp\left(\mathbf{P}_i \cdot \mathbf{M}_\perp\right)$$



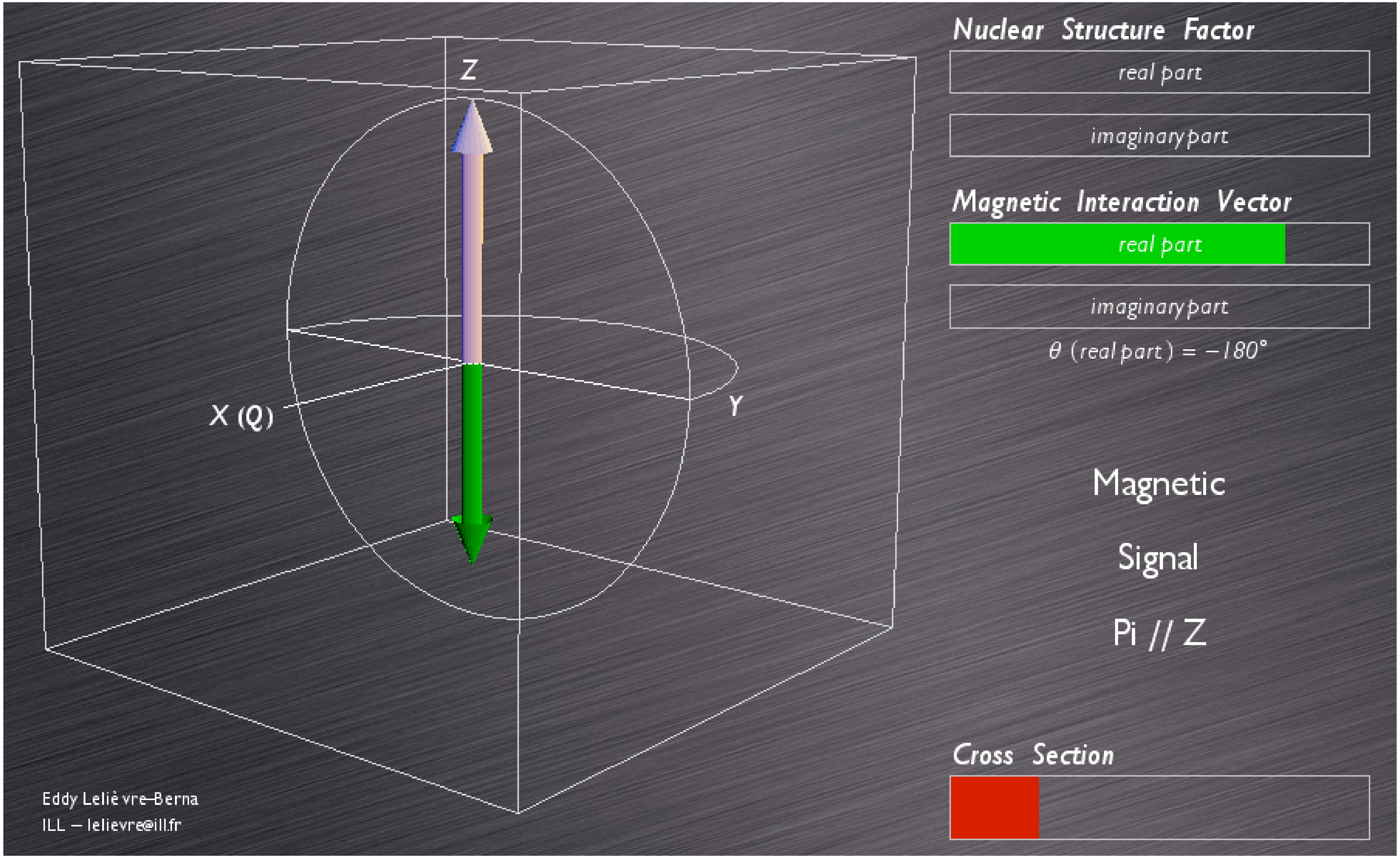
- e.g. $M_\perp$ and $M_\perp^*$ are perpendicular –
- no nuclear scattering - *chiral systems*

$P_f\sigma = -iM_\perp \wedge M_\perp^*$

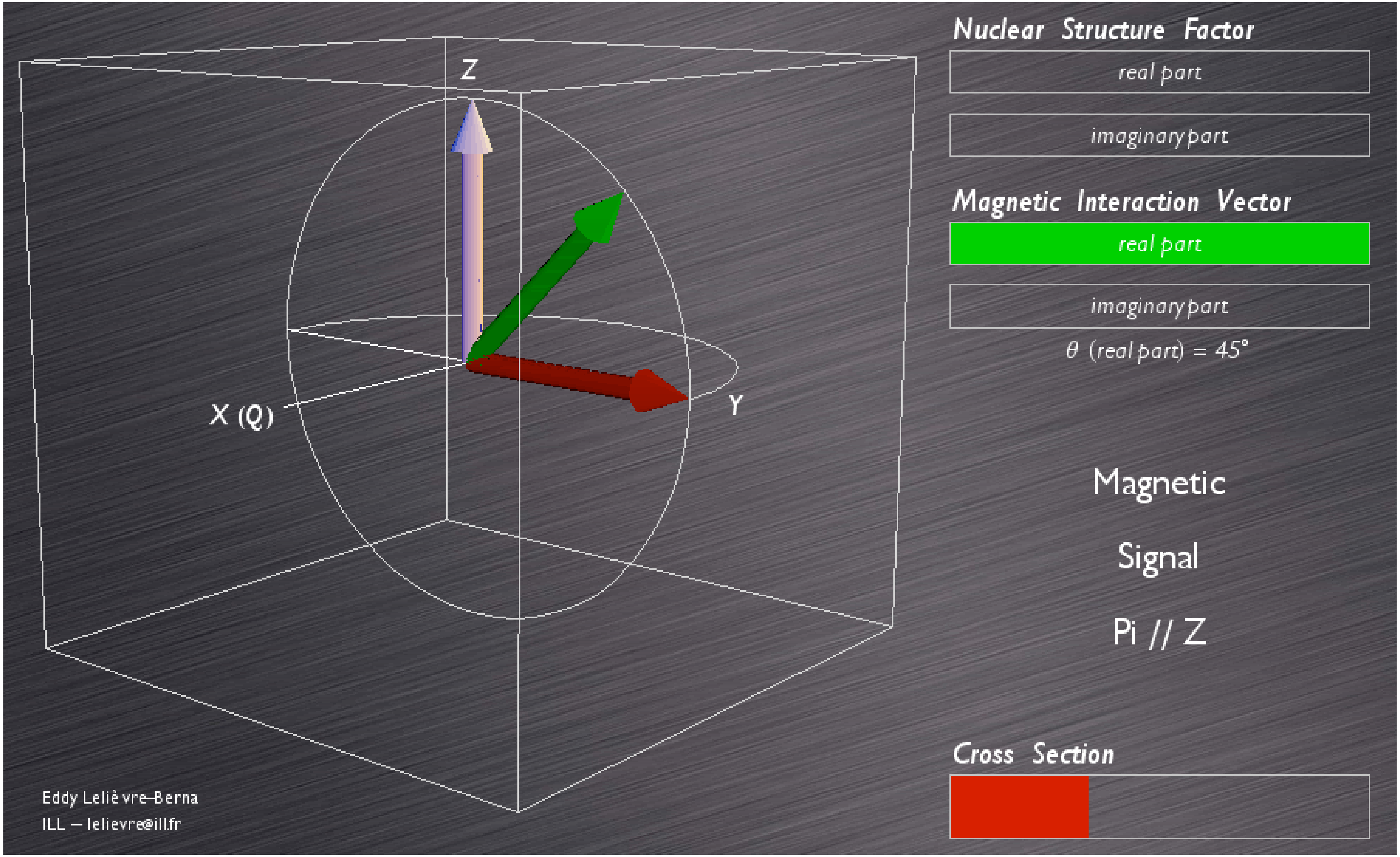


Creation of polarization - independent of incident $\mathbf{P}_i$

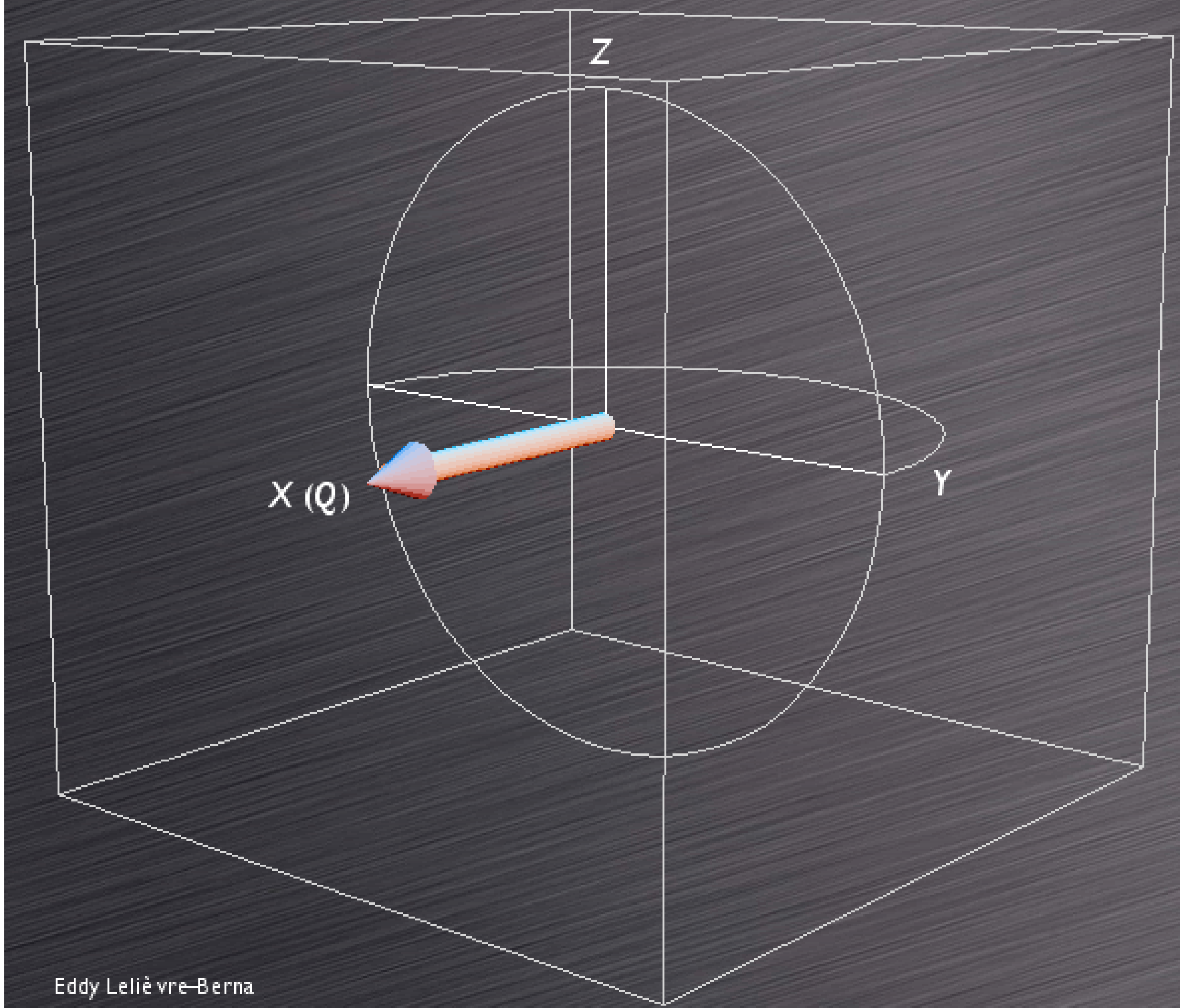
Polarimetry - M real



Polarimetry - M complex



Polarimetry - NM (real/real)



Nuclear Structure Factor

real part

imaginary part

Magnetic Interaction Vector

real part

imaginary part

θ (real part) = 90°

Nuclear & Magnetic

Signal

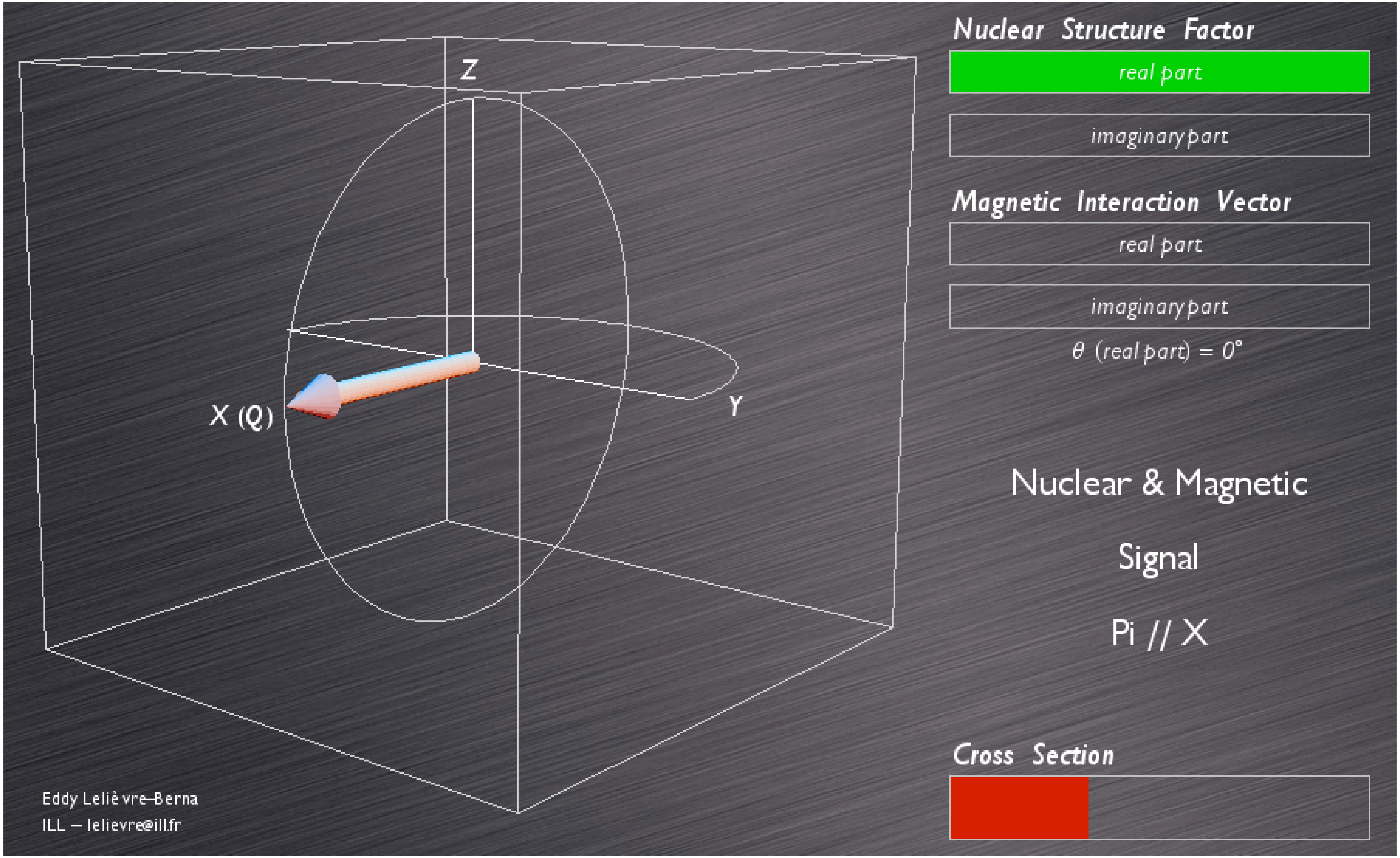
Pi // X

Cross Section

Eddy Lelièvre-Berna

ILL – lelievre@ill.fr

Polarimetry - NM (real/imag))



The Polarization Tensor

The goal is to determine complex magnetic structures. In practice this is done by measuring the polarization tensor **P** which is unambiguously defines all the terms in the Blume equations

$$\mathbf{P}_f = \boldsymbol{P}\mathbf{P}_i \qquad \text{where} \qquad \boldsymbol{P} = \begin{bmatrix} P_{xx} & P_{xy} & P_{xz} \\ P_{yx} & P_{yy} & P_{yz} \\ P_{zx} & P_{zy} & P_{zz} \end{bmatrix}$$

In practice, this is what is measured in a neutron polarimetry measurement

As an illustrative example, in the case of collinear antiferromagnet - aligned in the z-direction, the polarization tensor would be

$$\boldsymbol{P} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

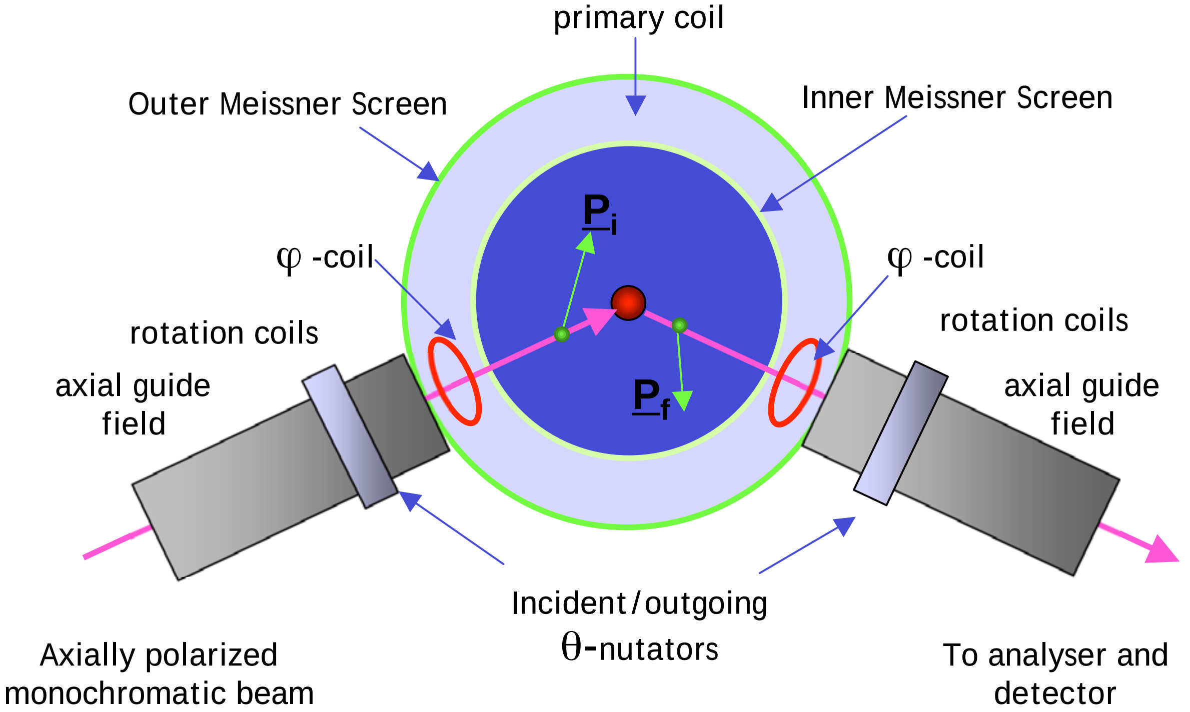
The appearance of any non-collinear magnetism would feed through into the off-diagonal components

NB The 3-directional PA method (D7) only measures the diagonal components of this matrix and would therefore miss this information

CRYOPAD

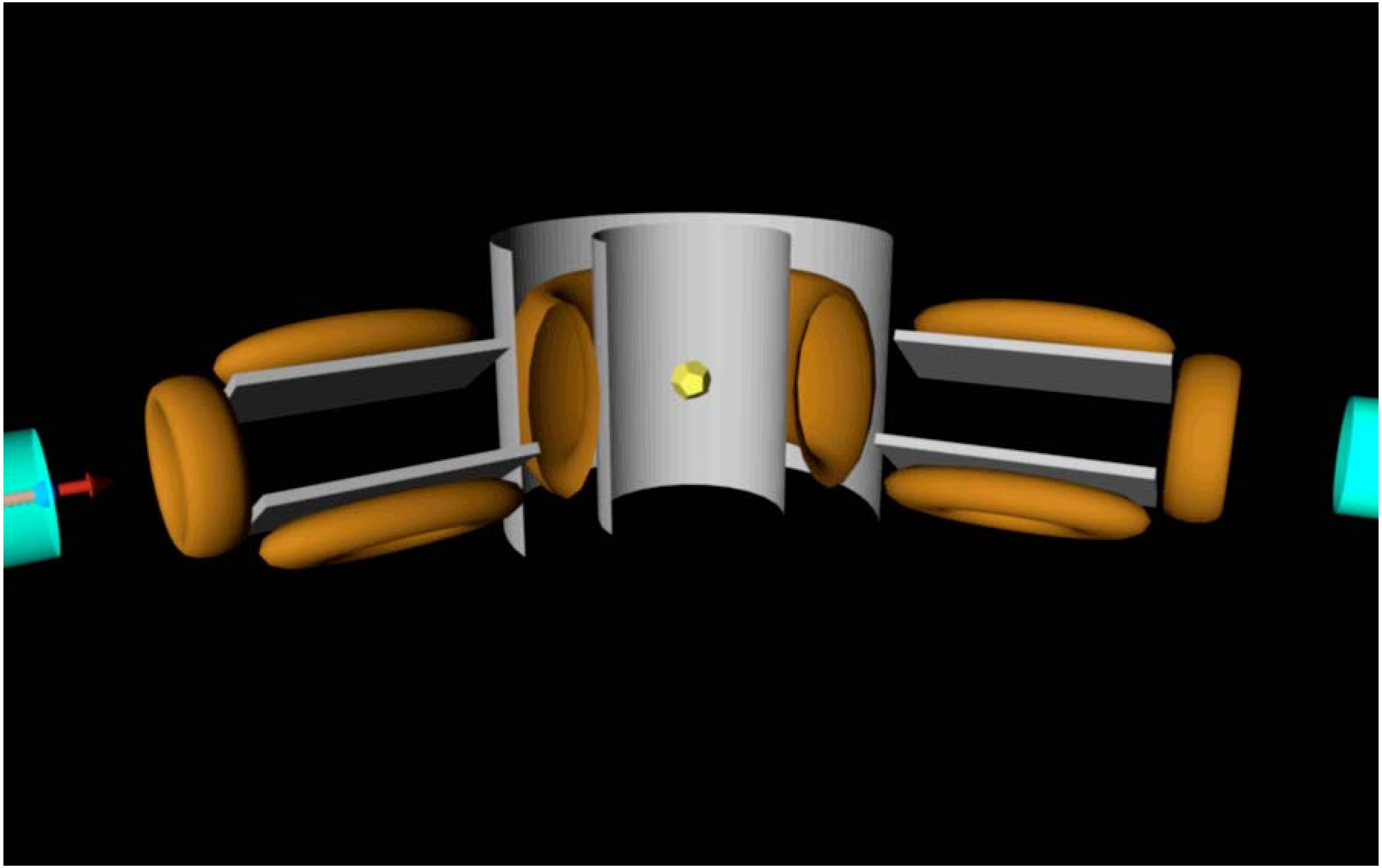
CRYOPAD has been developed by Tasset and co-workers at ILL in order to determine the vector polarization of the scattered beam for any predetermined direction of the vector polarization of the incident beam (i.e. measurement of the polarization tensor)

The field along the whole of the neutron beam is perfectly defined with the help of spin nutators, precession coils, Meissner screens, in order to align and analyse the polarization in any direction in space.

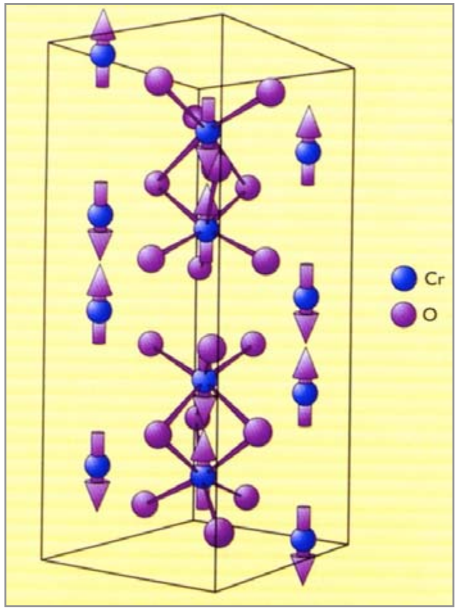


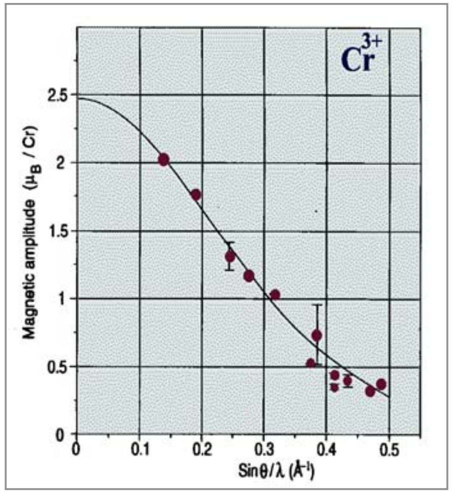
Tasset et al, Physica B 267-8, 69, (1999)

CRYOPAD



Some results from CRYOPAD





Cr_2O_3 *Brown et al, Physica B 267-268, 215, 1999)*

Cr_2O_3 is a collinear antiferromagnet with zero propagation vector for which the magnetic and nuclear scattering are phase shifted by °90

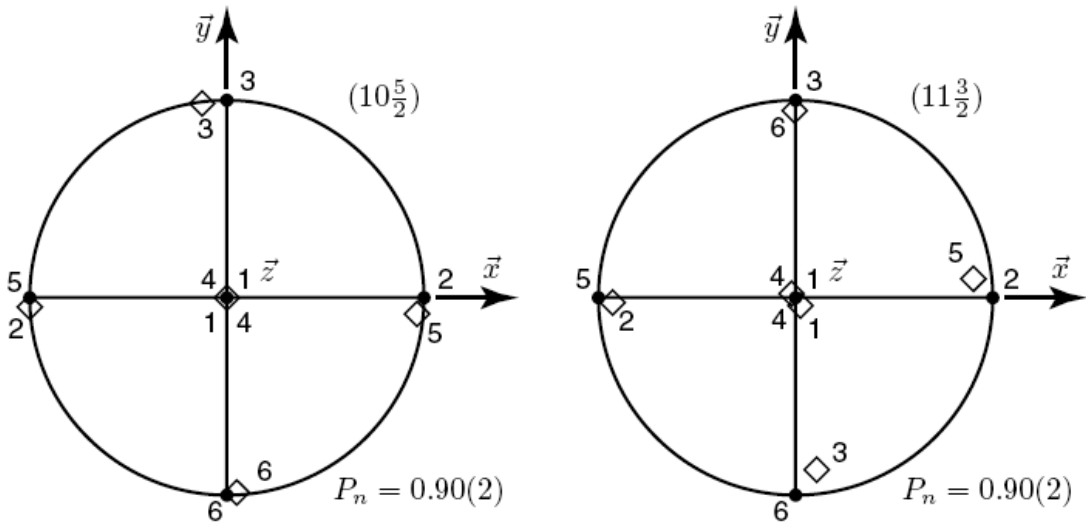
It is anti-centrosymmetric and therefore information about 180º antiferromagnetic domains cannot be obtained by measuring just the cross section or with uniaxial polarized neutron measurements

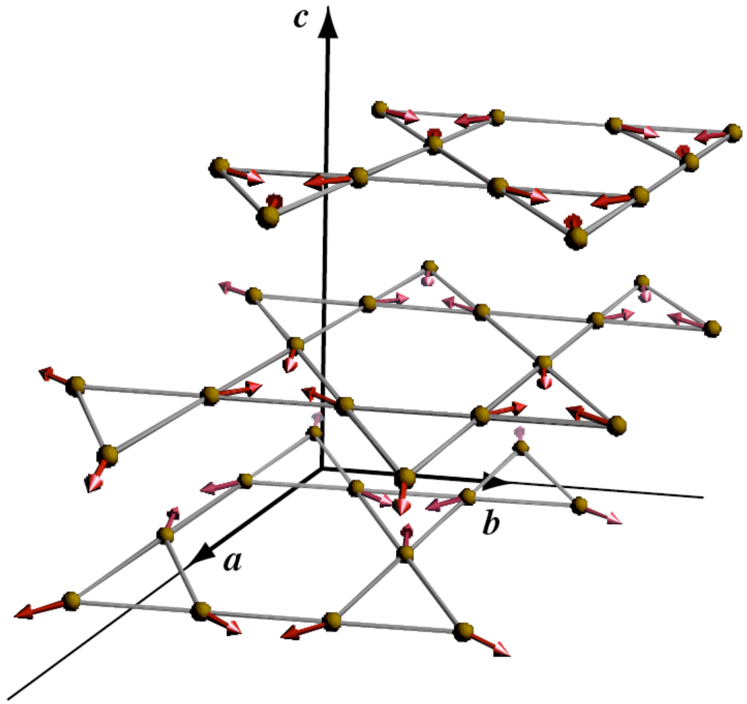
By cooling under various conditions of electric and magnetic fields an imbalance in domain populations is achieved - the crystal is then measured in zero field

Not only are the magnetic structures for the cooling conditions obtained - but for the first time the zero field magnetic form factor of an antiferromagnet is determined

Other studies include inelastic scattering measurements of, for example, $CuGeO_3$ *(Regnault et al, Physica B 267-268, 227, 1999)* and structural studies of complex magnetic phases e.g. Nd *(Roberts et al, Ibid 243)*

Magnetic order in kagomé lattices





Stereograms showing the directions of incident and scattered polarizations for the 1 0 5/2 and 1 1 3/2 reflections. The symbols • and ◊ represent respectively the incident and scattered polarization directions. The numbers are used to identify the corresponding pairs.

Harrison et. al. Submitted to J. Phys: Cond. Matter, 2005