Polarized neutrons: calling names

F. Mezei
Hungarian Academy of Sciences, SzFKI, Budapest, H-1121
Los Alamos National Laboratory, Lujan Center, Los Alamos, NM 87544

Current address: ESS AB, 22100 Lund, Sweden

What do neutrons see?

Bloch (July 9, 1936)

A neutron inside condensed matter is influenced by

"(1)…interaction of the neutron with atomic nucleus….
(2)…inhomogeneous magnetic field in its surrounding acting on the magnetic moment of the neutron."

(2) is much weaker but *"acts on distances so much larger"*

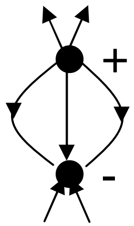
$$V(\mathbf{R},t) = 2\pi\hbar^2 m^{-1} \sum b_i(1 + c_i \mathbf{I}_i \sigma)\, \delta(\mathbf{R} - \mathbf{r}_i(t)) + mgh + \\ + \left(-\mu \mathbf{B}(\mathbf{R},t) \text{ or } -\mu \mathbf{H}(\mathbf{R},t) \right)$$

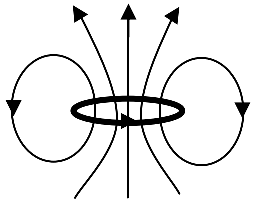
The neutron sees nuclear spins, but does not see magnetic moments!!

B or H? Electromagnetism theory had no answer to the new problem posed by the neutron and quantum mechanics: it can overlap with the source of magnetic fields (electrons or current in wires).

What do neutrons see?

The choices are quite different:

H: 

or **B:**  **???** ($\mathbf{B} = \mathbf{H} + 4\pi\mathbf{M}$)

What do neutrons see?

Shull, Wollan and Strauser (1951)

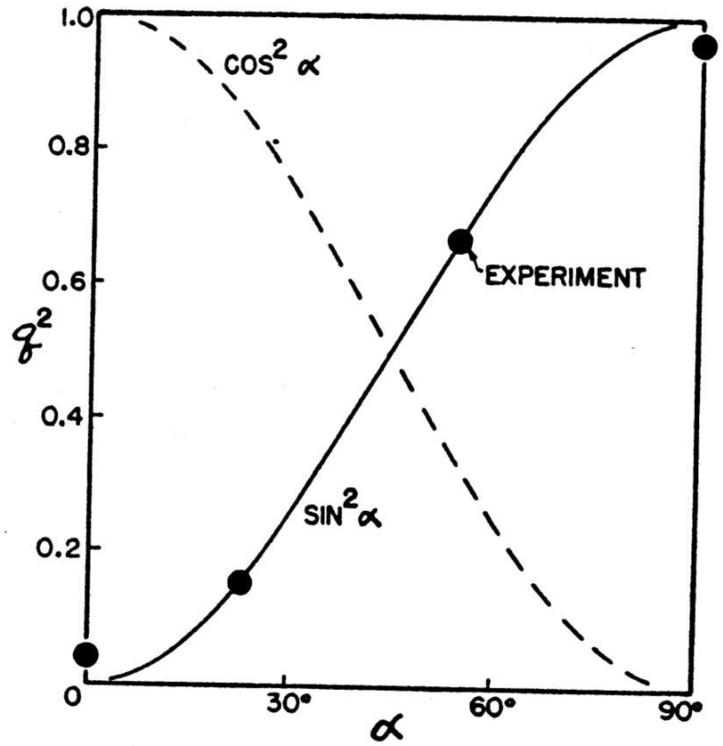


FIG. 2. Variation of q^2 with the angle α between the scattering and magnetization vectors. The experimental points have been normalized to the unmagnetized value of $q^2=2/3$.

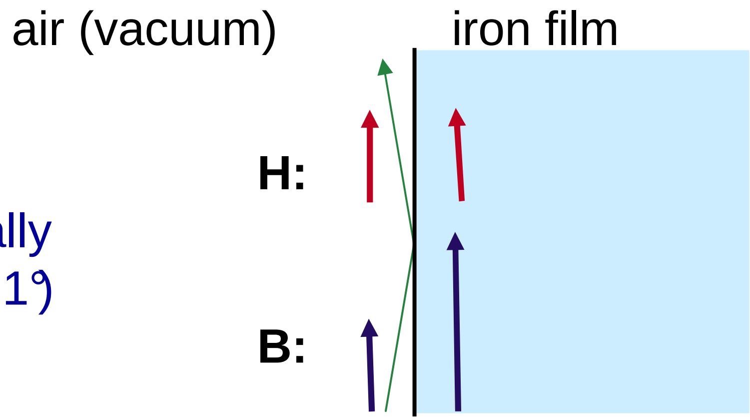
Magnetic Bragg peak intensity in magnetite observed as a function of the angle between $\mathbf{H}_{ext}$ and $\mathbf{Q}_{111}$

De Gennes: the $\sin^2\alpha$ factor can be taken into account by considering $\mathbf{M}_{\perp}$ and $\mathbf{j}$ = c curl $\mathbf{M}$ ($H = -\mu\mathbf{B}$)

If $\cos^2\alpha$ would hold, we would have $\mathbf{M}_{||}$ and $H = -\mu\mathbf{H}$.

What do neutrons see?

Hughes & Burgy (1951):



neutron total reflection on optically flat iron surface (critical angle < 1°)

Since the component of **H** parallel to the surface between two materials must be continuous across the surface, there **should be no magnetic contribution** in neutron reflection for layers polarized in the plane of the mirror.

What do neutrons see?

Hughes & Burgy (1951):

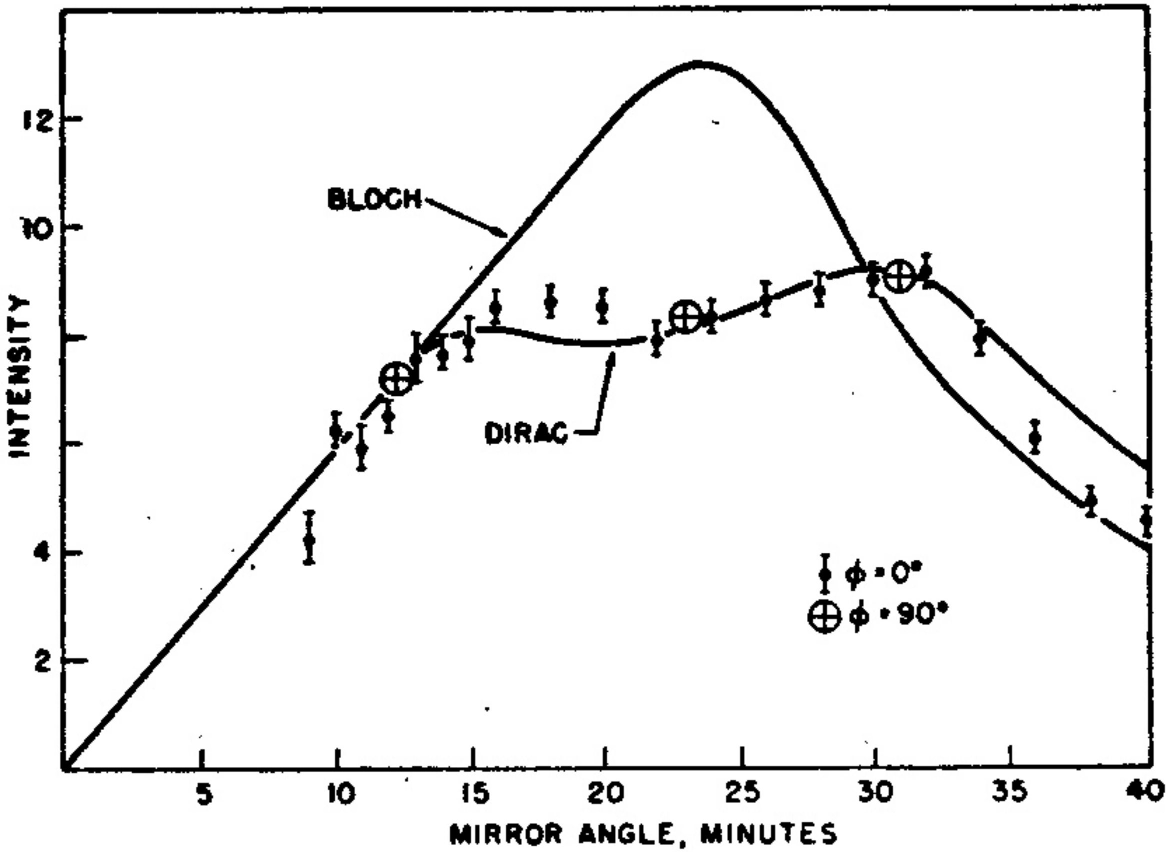
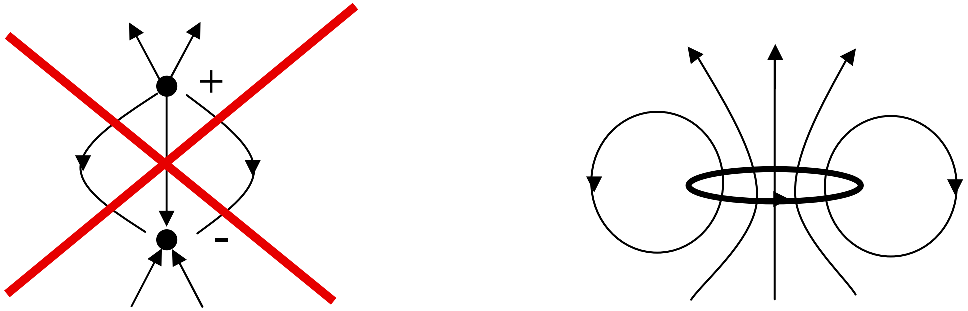


Fig. 4. Intensity of filtered neutrons reflected from a magnetized iron mirror. The theoretical curve labeled "Bloch" corresponds to Bloch's constant, C equal to zero, while "Dirac" corresponds to $C = 1$. Experimental points for two directions of magnetization, $\phi = 0°$ and $90°$, are shown.

What the neutrons see:



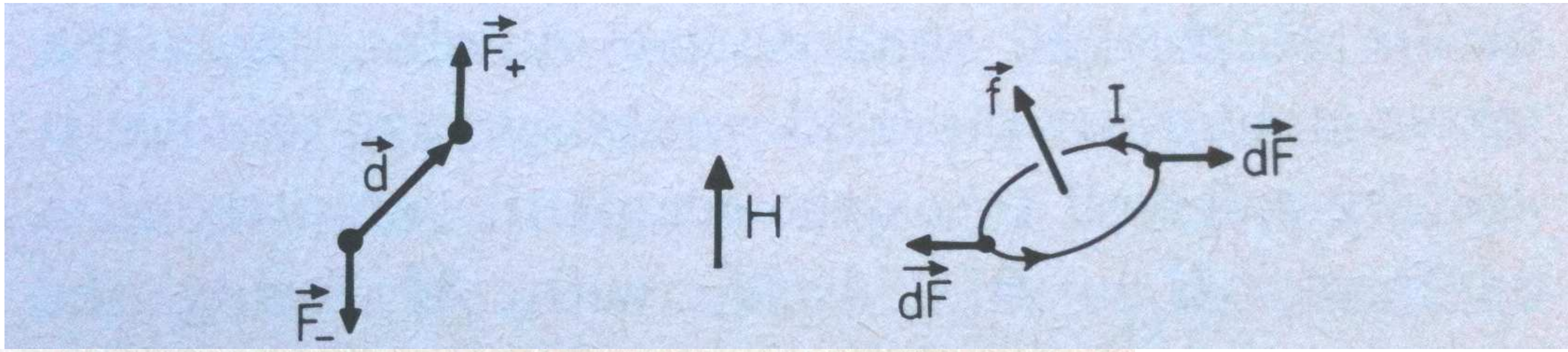
Conclusion:

Neutrons have shown that currents are the only physical origin of magnetism, H is not a physical quantity (nor are magnetic moments!!!)

The conceptual error of using H can be mathematically corrected for by introducing a fictitious new interaction: the so called Fermi contact interaction

The other side of the issue: **how do the neutrons see?**

Magnetic forces are not the same for the two models of neutron magnetic moment!



$$\boldsymbol{F}_\mathrm{d} = \boldsymbol{F}^+ + \boldsymbol{F}^- = (\boldsymbol{\mu} \cdot \mathrm{grad})\,\boldsymbol{H}$$

$$= \mathrm{grad}(\boldsymbol{\mu} \cdot \boldsymbol{H}) - \boldsymbol{\mu} \times \mathrm{curl}\ \boldsymbol{H},$$

$$\boldsymbol{F}_\mathrm{c} = \oint \mathrm{d}\boldsymbol{F} = \frac{I}{c} \oint \mathrm{d}\boldsymbol{l} \times \boldsymbol{H}$$

$$= \frac{I}{c} \int \mathrm{grad}(\boldsymbol{H} \cdot \mathrm{d}\boldsymbol{f}) - \frac{I}{c} \int (\mathrm{div}\ \boldsymbol{H})\ \mathrm{d}\boldsymbol{f}$$

$$= \mathrm{grad}(\boldsymbol{\mu} \cdot \boldsymbol{H}).$$

Outside magnetic media H = B

If j ≠ 0, there is a difference!

In current loop model only is -μ**B** (or -μ**H**) a usable potential!

Within the coil walls **curl H ≠ 0**: **spurious acceleration for dipole!**

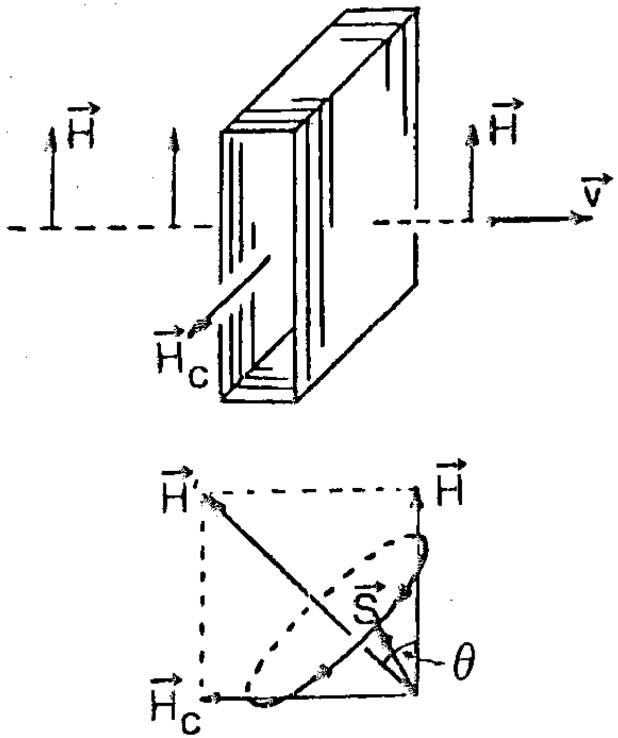
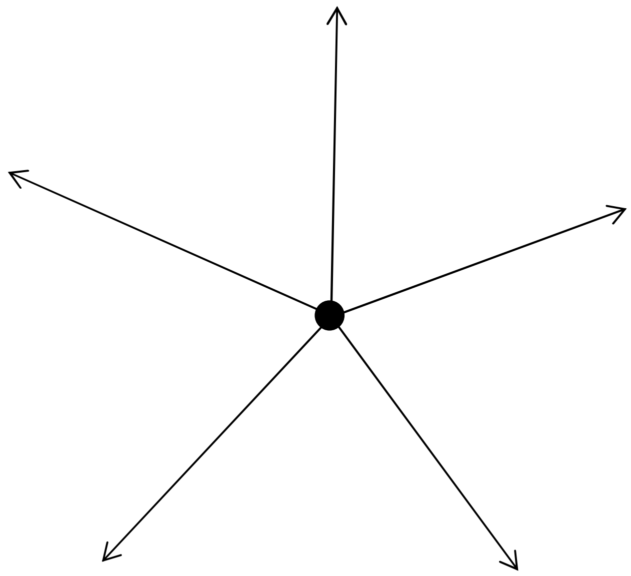


Fig. 3. The flat coil 3D spin flipper device used in NSE spectroscopy and an example of spin turn by Larmor precession inside the coil.

Magnetic dipoles do not exist.
Can monopoles exist?

Interaction with neutrons is not like monopoles would be!



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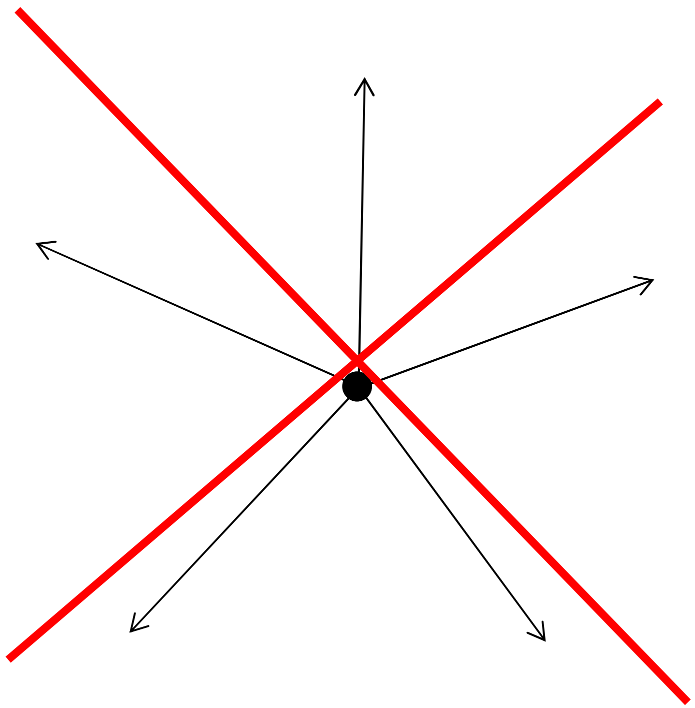
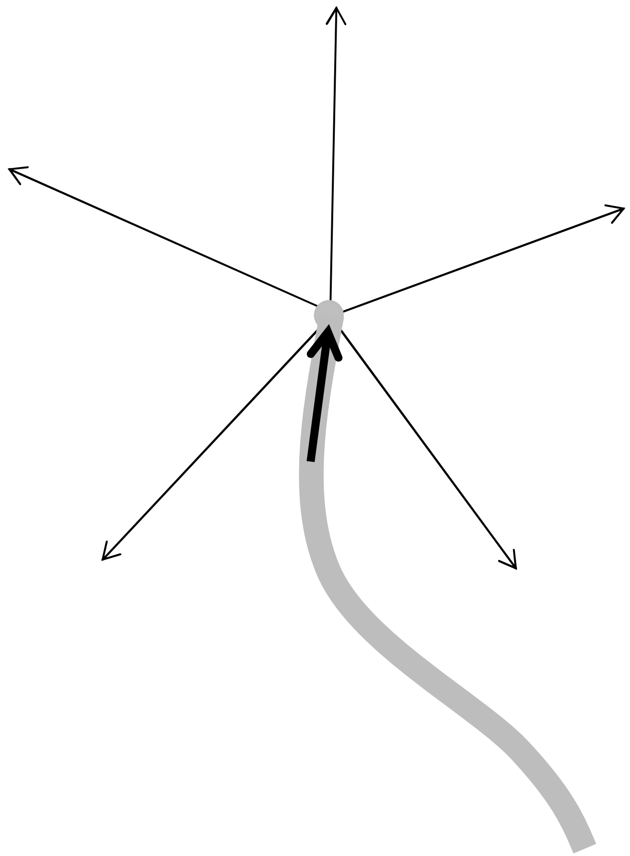




"Dirac string": solenoid

Degrees of freedom in scattering experiments

Goal: measurement of transition probabilities between well defined initial and final states

neutron spin wave function

$$|\chi\rangle\, e^{i\mathbf{kr}} \longrightarrow |\chi'\rangle\, e^{i\mathbf{k'r}}$$

Note: there is a confusion on beam coherence between different **k** states. It is irrelevant for scattering. Each initial state has infinite extension in space and time, can probe as far as the sample shows correlations (e.g. in perfect crystals)

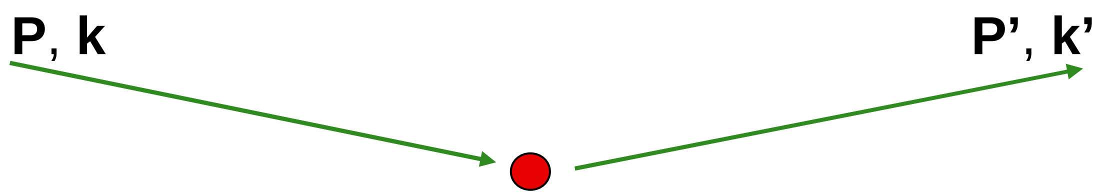
With finite resolution this transforms into measuring initial and final distributions

beam polarization (vector)

$$\mathbf{P},\, f(\mathbf{k}) \longrightarrow \mathbf{P'},\, f(\mathbf{k'})$$

1)Preparation of initial beam 2)Analysis of scattered beam

(direction, velocity or wavelength, polarisation: 2x6 dimensional parameter space)



Degrees of freedom in scattering experiments

Only one instrument has all these degrees of freedom: D3 -Cryopad at ILL. **Usual reduced combinations are**: (essentially any combination of choices from the groups A, B, and C possible)

A.

1) **Transmission experiment**
   observe straight beam after the sample **k** = **k'**,(e.g. reveals Bragg peaks)
2) **"Elastic scattering"** = fundamentally inexact assumption |**k**| = |**k'**|
   only direction of **k'** analyzed, OK if inelastic scattering negligible
   (strong Bragg scattering, small angle scattering, reflectometry)
3) **Inelastic scattering**
   both direction and absolute value **k** analyzed at the expense of large reduction of beam intensity at detector

Degrees of freedom in scattering experiments

B.

1) **Unpolarized neutrons**

   P = 0, **P’** is not observed

2) **Scattering of polarized neutrons**

   effect of **P** on scattering probability in samples magnetized in a field **B**||**P**

   P’ is not analyzed (moderate loss of intensity)

3) **Polarization analysis**

   a direction is selected for **P,** and only (**PP’**)/ |**P**| projection is analyzed

   (additional substantial loss of intensity)

4) **3 directions polarization analysis**

   (**PP’**)/ |**P**| projection analyzed for 3 perpendicular directions (x, y, z) of a **P**

   $\cos^2\alpha_x + \cos^2\alpha_y + \cos^2\alpha_z = 1$, macroscopically isotropic samples $\mathbf{P'} = -\mathbf{q}(\mathbf{Pq})/q^2$

5) **3 dimensional (or vectorial or generalized) polarization analysis, polarimetry**

   the full **P’** = T(**P**) tensor is observed

   Number of degrees of freedom?

C.

Neutron Spin Echo (NSE)

polarization encodes information on **k** and **k’** for highest resolution inelastic spectroscopy

Degrees of freedom in scattering experiments

Polarized neutron options (B.1- 5) allow us to distinguish the various contributions:

i) nuclear scattering: b_i
ii) nuclear spin scattering (nuclear magnetism): $c_i\mathbf{I}_i$
iii) magnetic scattering: **B** produced by spin and orbital magnetism **M** inside the sample, with magnetization defined by the equation **j** = c.curl **M** at the boundary condition **M** = 0 in free space (**j** is the current density)

Less common examples:

- Depolarization experiments: A.1 - B.3 (or B.5) for the study of ferro-(or ferri-) magnetic domains
- Generalized NSE: A.3 - C to study elementary excitations with high resolution
- Standard, Paramagnetic, Ferromagnetic NSE,…: A.2 – C: the sample behaves differently
- Polarometric Spin Echo: A.2 - B.5 – C: NSE study of 3D polarization channels

Degrees of freedom in scattering experiments

3D polarization analysis

Possibly independent neutron counts: 36

No. of independent parameters: s=½ Hilbert space of 2D

$$|\chi'\rangle = \hat{S}\,|\chi\rangle$$

$$\hat{S} = b\hat{I} + \boldsymbol{a}\cdot\hat{\boldsymbol{\sigma}},$$

b = complex scalar , $\boldsymbol{a}$ = complex vector

$$\langle\chi'|\chi'\rangle = b^*b + \boldsymbol{a}^*\cdot\boldsymbol{a} + \boldsymbol{S}\cdot(b^*\boldsymbol{a} + \boldsymbol{a}^*b) + \mathrm{i}\boldsymbol{S}\cdot(\boldsymbol{a}^*\times\boldsymbol{a}) \qquad (16)$$

and

$$\boldsymbol{S}'\langle\chi'|\chi'\rangle = b^*\boldsymbol{a} + \boldsymbol{a}^*b - \mathrm{i}(\boldsymbol{a}^*\times\boldsymbol{a}) + \boldsymbol{S}b^*b + \mathrm{i}b^*(\boldsymbol{a}\times\boldsymbol{S}) + \mathrm{i}(\boldsymbol{S}\times\boldsymbol{a}^*)b + (\boldsymbol{a}^*\cdot\boldsymbol{S})\boldsymbol{a} + \boldsymbol{a}^*(\boldsymbol{S}\cdot\boldsymbol{a}) - \boldsymbol{S}(\boldsymbol{a}^*\cdot\boldsymbol{a}). \qquad (17)$$

$\boldsymbol{S}, \boldsymbol{S}'$ = spin vectors

Degrees of freedom in scattering experiments

Scattering: average over many samples / sample states

$$\boldsymbol{S} \rightarrow \boldsymbol{P}$$

$$\overline{\langle \chi' | \chi' \rangle} = A + \boldsymbol{B} \cdot \boldsymbol{P}, \qquad \boldsymbol{P}' \overline{\langle \chi' | \chi' \rangle} = \boldsymbol{C} + \mathsf{T}\boldsymbol{P},$$

A = real number, $\boldsymbol{B}, \boldsymbol{C}$ = real vectors, T = real tensor $\rightarrow$ 16 parameters

$$\overline{b^*b},\ \overline{a^*_\alpha a_\alpha},\ \mathrm{Re}(\overline{a^*_\alpha a_\beta}),\ \mathrm{Im}(\overline{a^*_\alpha a_\beta}),\ \mathrm{Re}(\overline{b^* a_\alpha}),\ \mathrm{Im}(\overline{b^* a_\alpha})$$

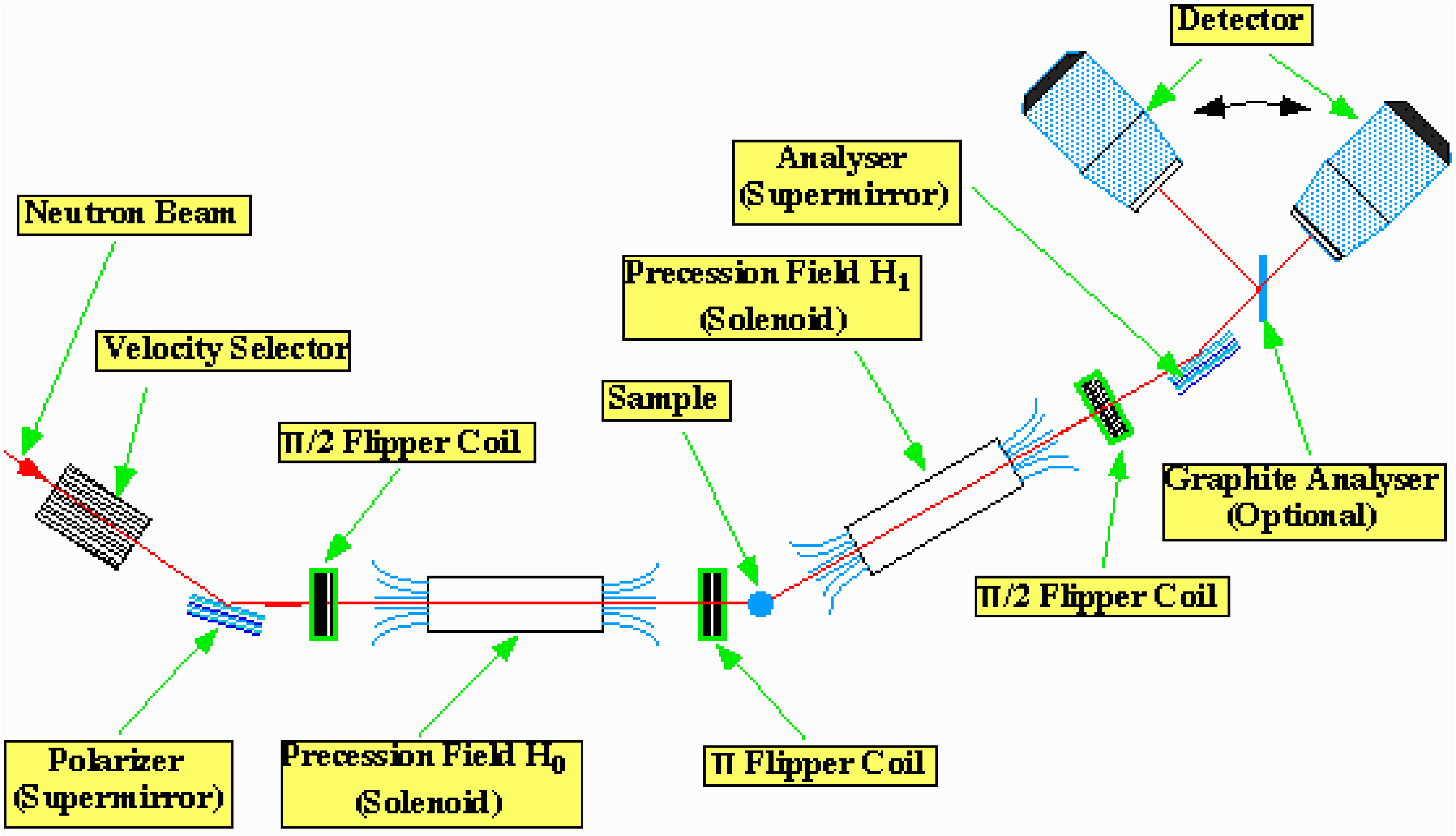
16 independent averages = 16 cross sections for each (**q**,ω) or (**k**,**k'**)

Equations to calculate cross sections from measured A, $\boldsymbol{B}$, $\boldsymbol{C}$ and T: solvable. E.g.

$$B_\alpha = 2\,\mathrm{Re}(\overline{b^* a_\alpha}) + 2\,\mathrm{Im}(\overline{a^*_\beta a_\gamma}).$$

$$C_\alpha = 2\,\mathrm{Re}(\overline{b^* a_\alpha}) - 2\,\mathrm{Im}(\overline{a^*_\beta a_\gamma}),$$

NSE and polarization anlysis

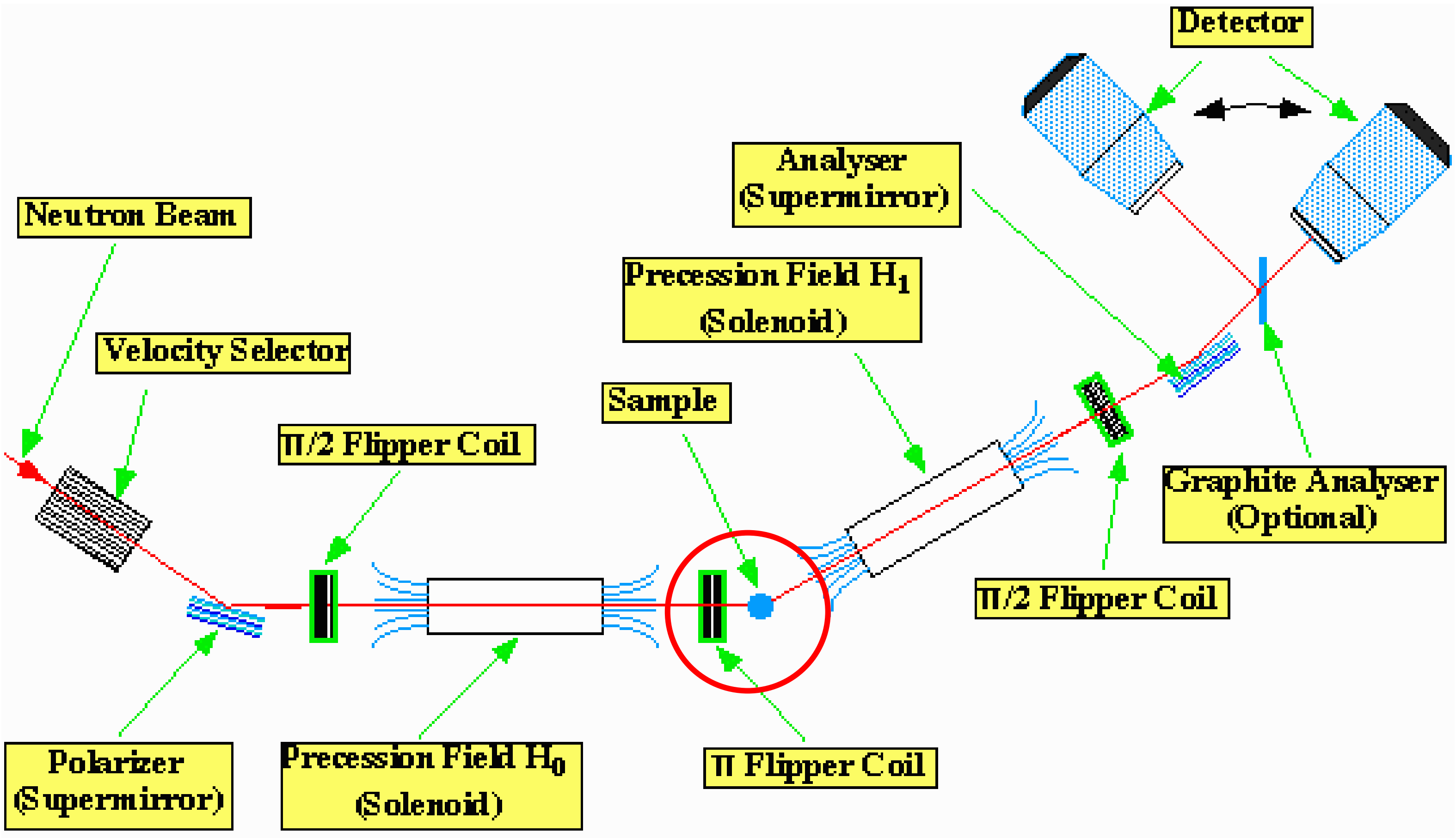


With NSE switched off:

identify scattering contributions: 1D, 3 directional, 3D (possible, not often useful for NSE)

In standard echo: all contributions added up with specific factors

NSE and polarization anlysis



Standard: π	Intensity mod. **π/2 analyzer polarizer π/2**
Paramagnetic: -	Polarimetric: **π/2 Cryopad π/2**
Ferromagnetic: **π/2 H π/2**	

The complexity is not only in finding the names (which mean the same thing for everybody)

Assumptions about sample behavior are always involved: they have to be right!

The most general case [determination of 16 cross sections for one (q,ω)] is rarely practical.

Early milestones

Scattering of polarized neutrons:

effect of **P** on scattering probability in samples magnetized in a field **B**||**P**
P' is not analyzed (moderate loss of intensity)

Shull (1951): highly polarized Bragg reflections in magnetite

Polarization analysis:

a direction is selected for **P,** and only
(**PP'**)/ |**P**| projection is analyzed
(additional substantial loss of intensity)

Moon, Riste and Koehler (1969):
all 6 parameters for **P || P'**

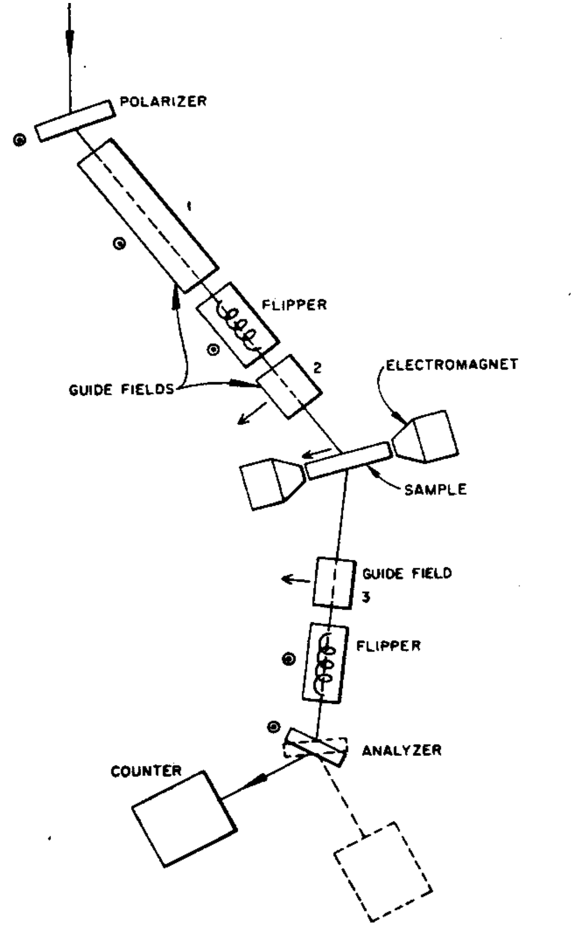


FIG. 1. Experimental arrangement. Arrows adjacent to the guide fields show the direction of the magnetic field sensed by the neutrons.