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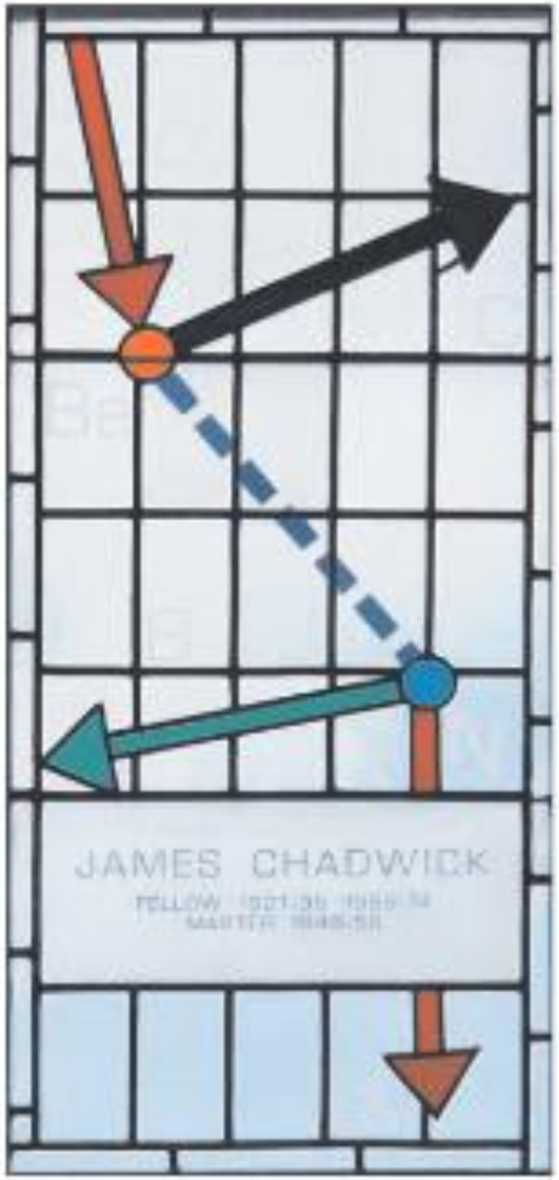
Applications of SANS I

ELIZABETH BLACKBURN, 2021-06-01

Outline

- Diffraction at small angles
- Using a field to control the signal from a magnetic material.
- Exploring the role of anisotropy and other factors in the diffuse SANS signal

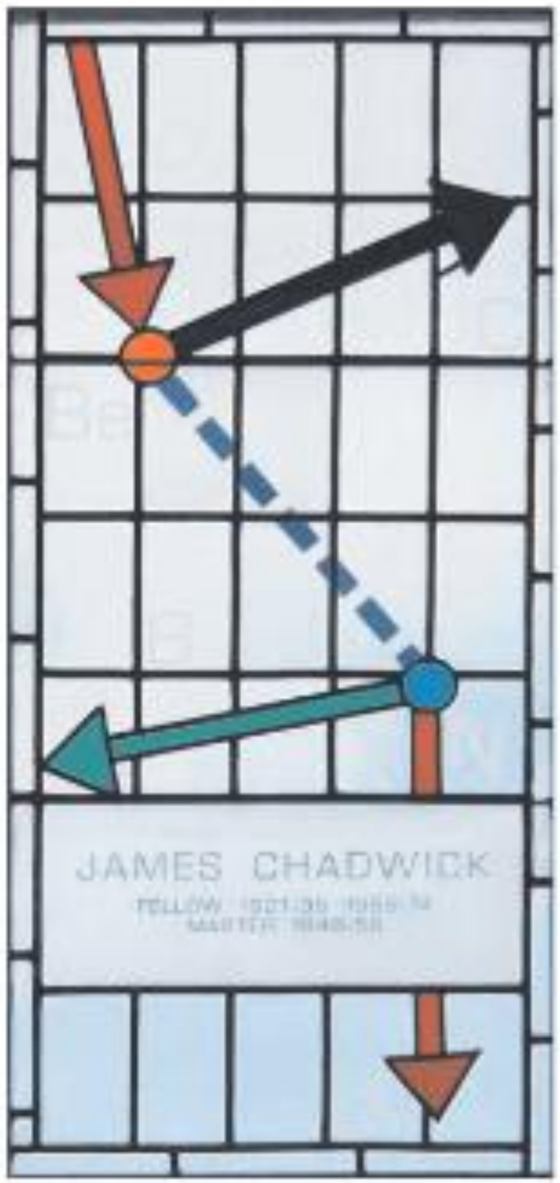
$${}^{4}_{2}\alpha + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{0}\mathrm{n}$$



Bragg diffraction in the small angle regime

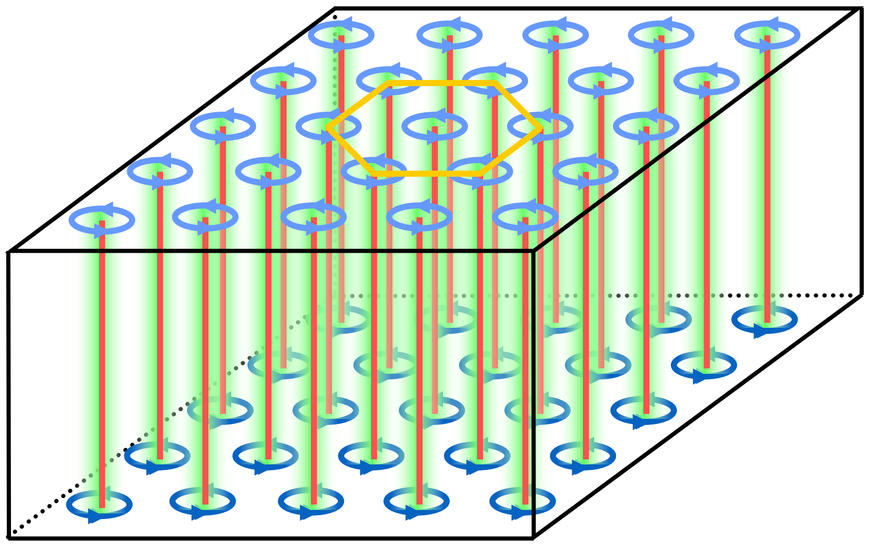
- Illustration using vortex lattices in superconductors.
- Other examples, including non-magnetic ones!
- The differences between pulsed and continuous sources.
- Problems that may arise.

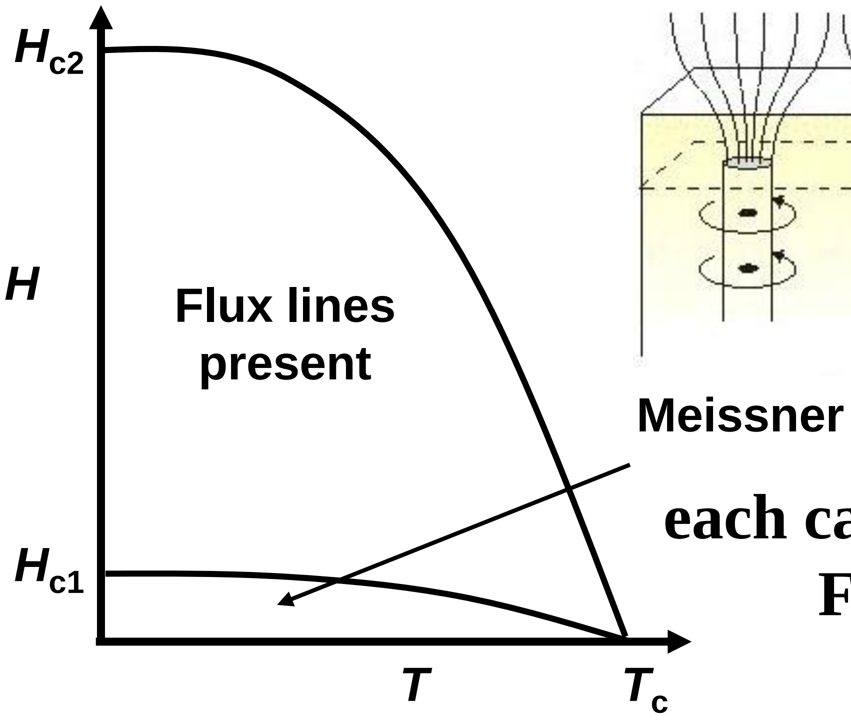
$${}^4_2\alpha + {}^9_4\mathrm{Be} \rightarrow {}^{12}_6\mathrm{C} + {}^1_0\mathrm{n}$$

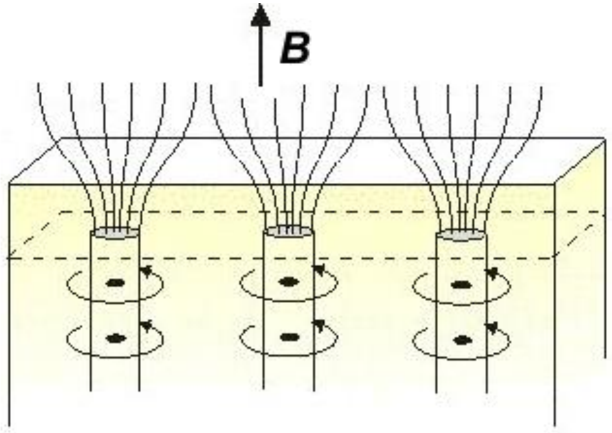


Bragg diffraction in the small angle regime

- Illustration using vortex lattices in superconductors.



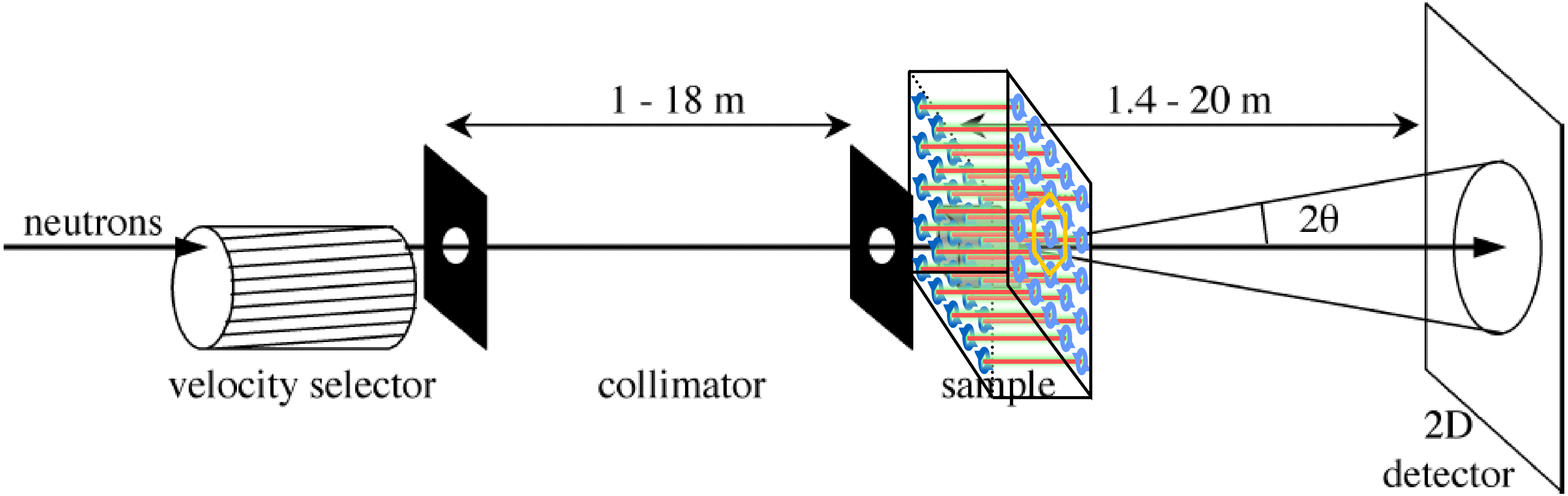




each carries a flux of

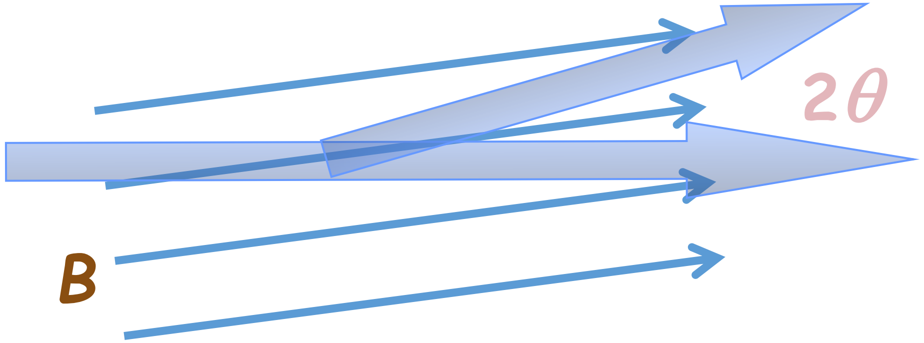
$$\Phi_o = h/2e$$

Scattering from vortex lattices



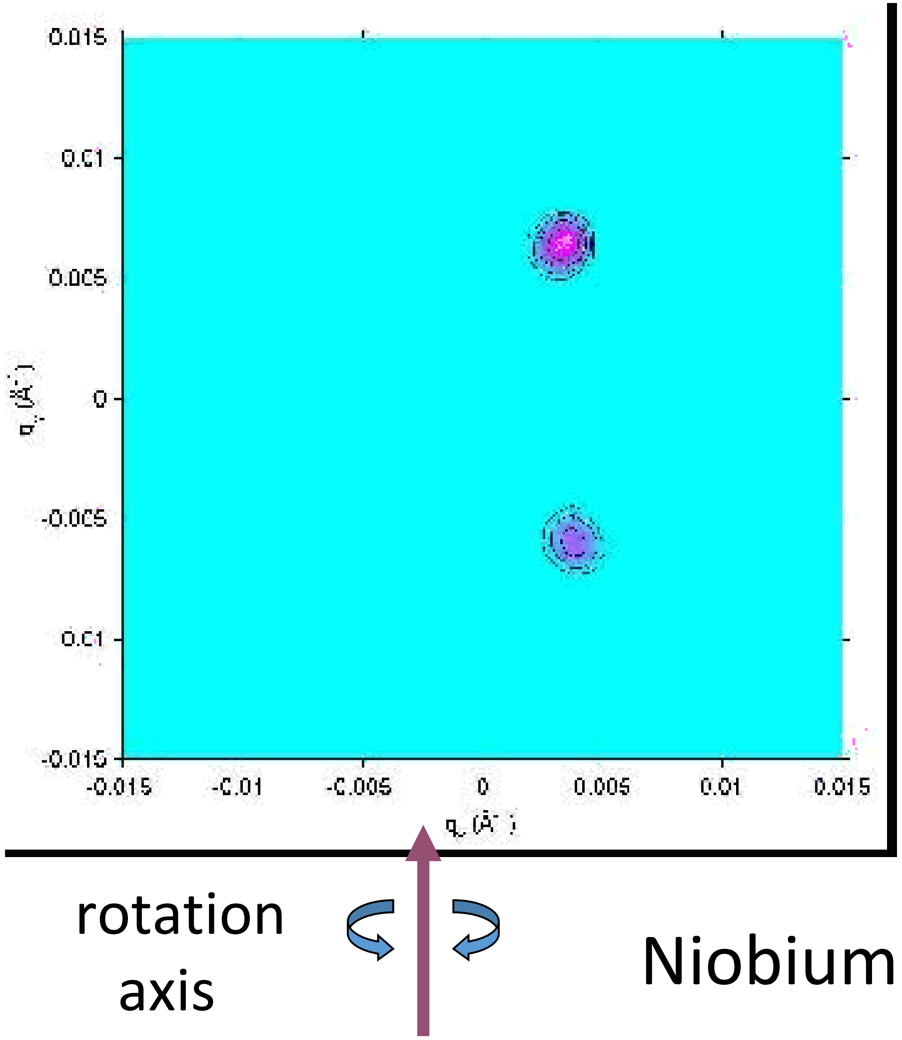
Usual geometry for vortex lattices (and skyrmions):

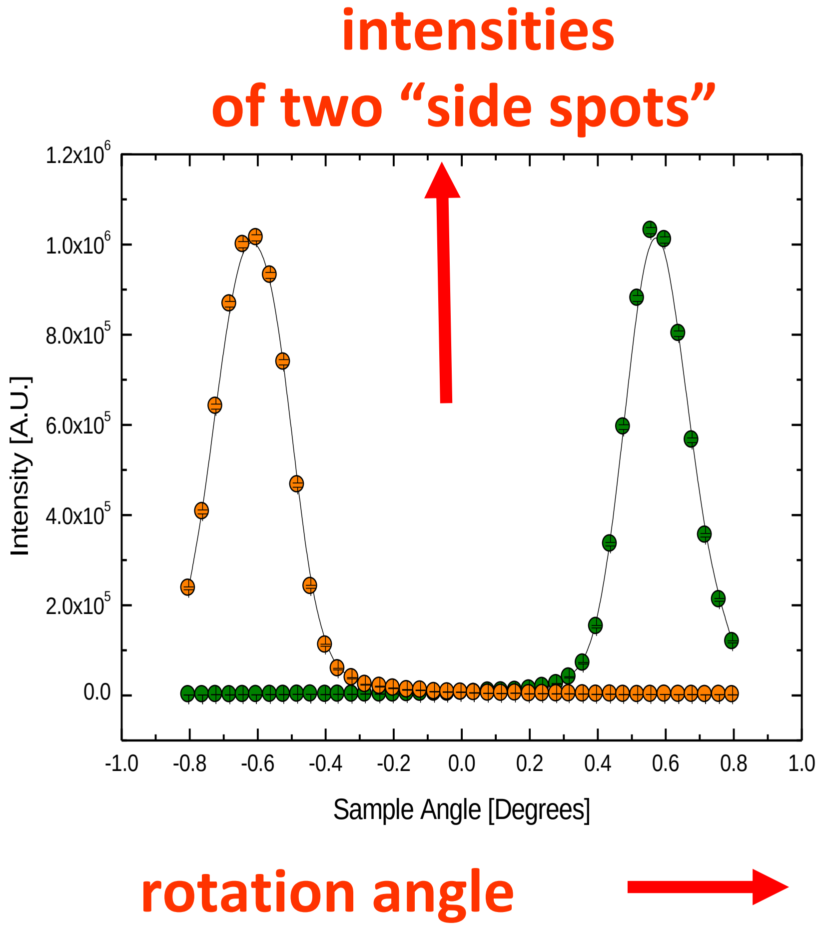
***B* nearly parallel to neutron beam:**



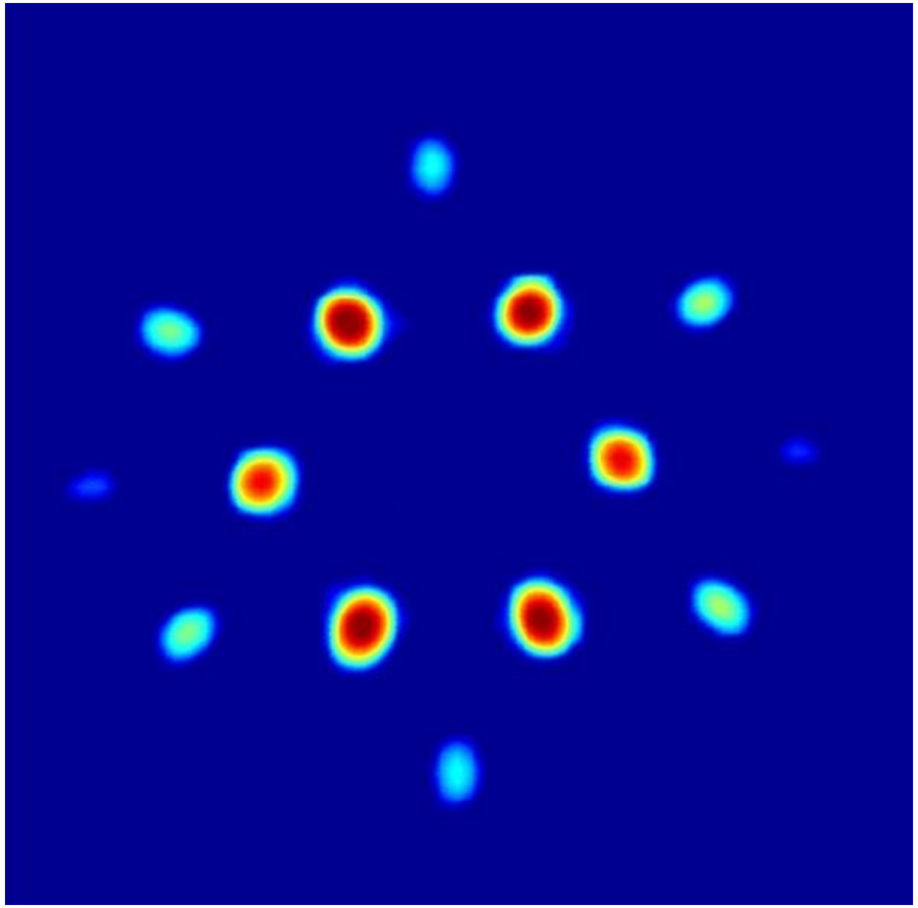
Scattering from vortex lattices

Rocking curve to put the system in the Bragg condition, rotating the sample relative to the beam





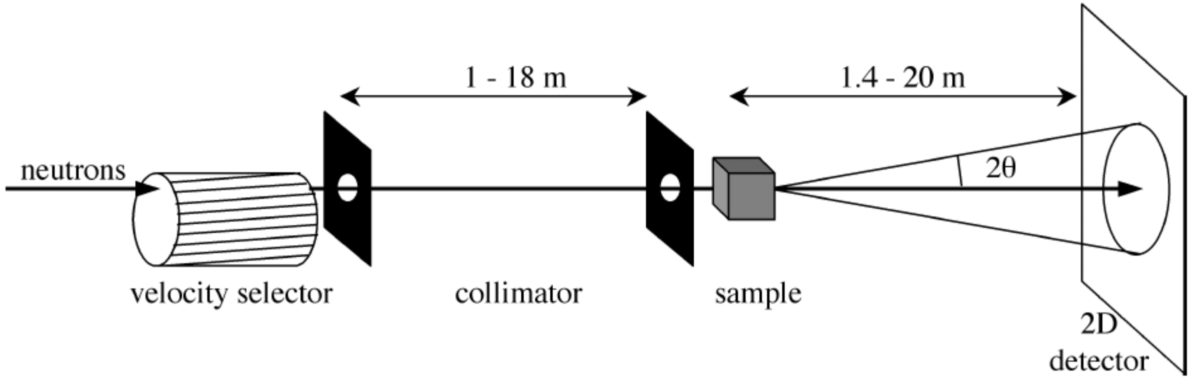
Scattering from vortex lattices



Note the effect of gravity…

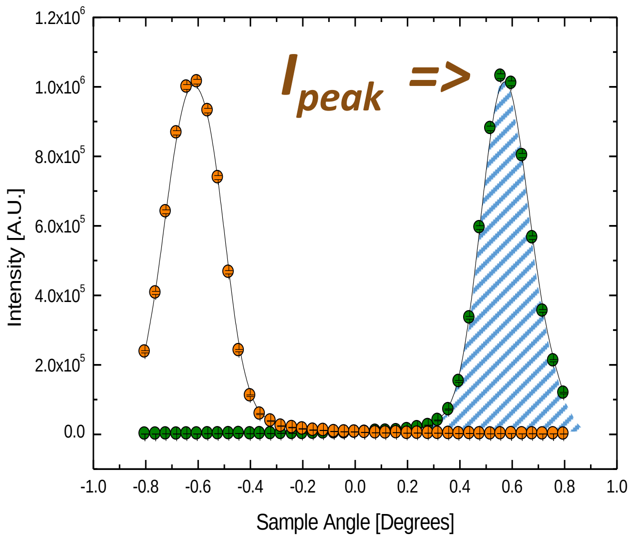
Sum over rocking curves

Real-space FLL is same shape as diffraction pattern but by 90°about *B*-axis



Extracting data in absolute units

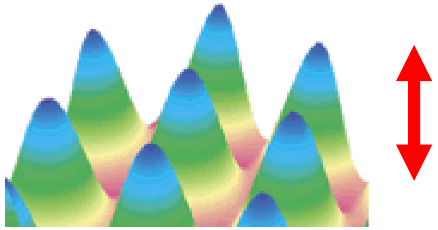
I_{hk} = intensity of q_{hk} spot integrated over the rocking curve



$I_{hk} \approx I_{peak} \times fwhm$

$$I_{hk} = I_{beam} \frac{2\pi \gamma^2 \lambda_n^2 t_{sample}}{16 \Phi_0^2 q_{hk}} \left| F_{hk} \right|^2$$

F_{hk}, "form factor" = Fourier component at q_{hk} of spatial variation of field inside FLL



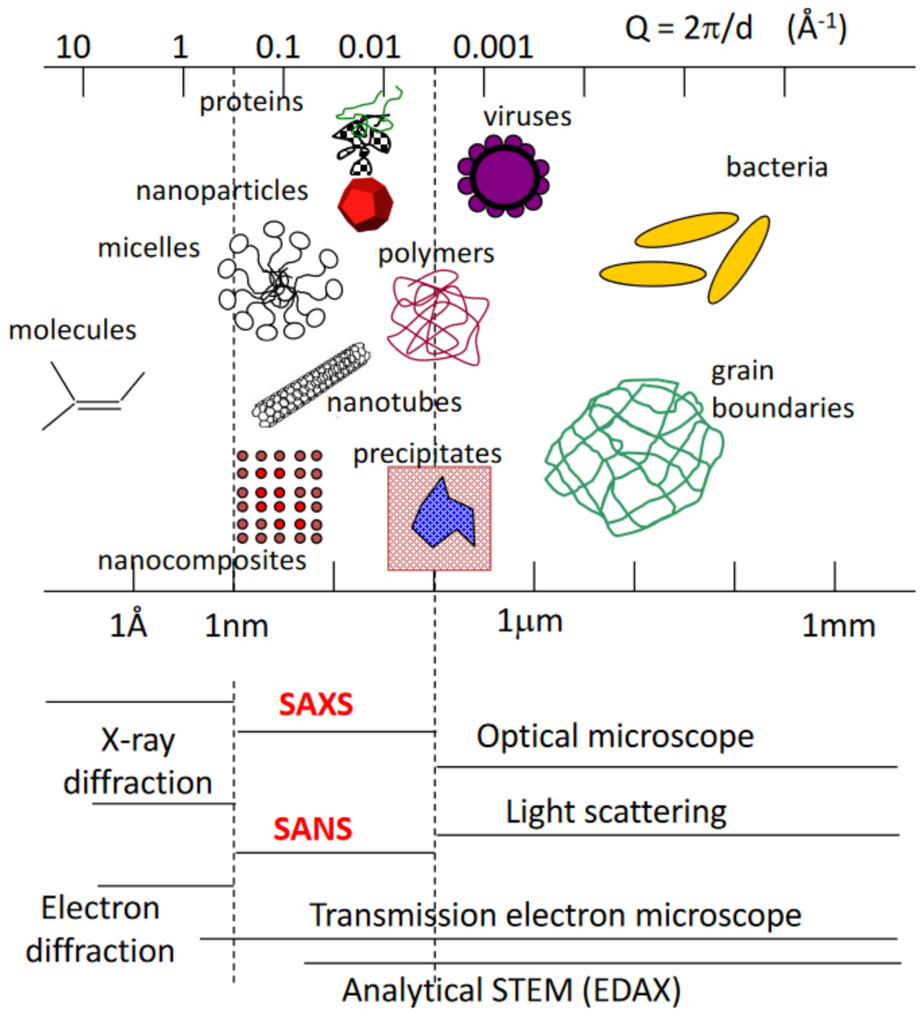
few × F_{10}

$$F_{10} = \left(\frac{\sqrt{3}}{8\pi^2} \right) \times \frac{\Phi_0}{\lambda_L^2}$$

... where λ_L is the magnetic penetration depth,

and λ_L = 2500 Å <=> F_{10} ~ 8 Gauss

Other examples of small angle diffraction

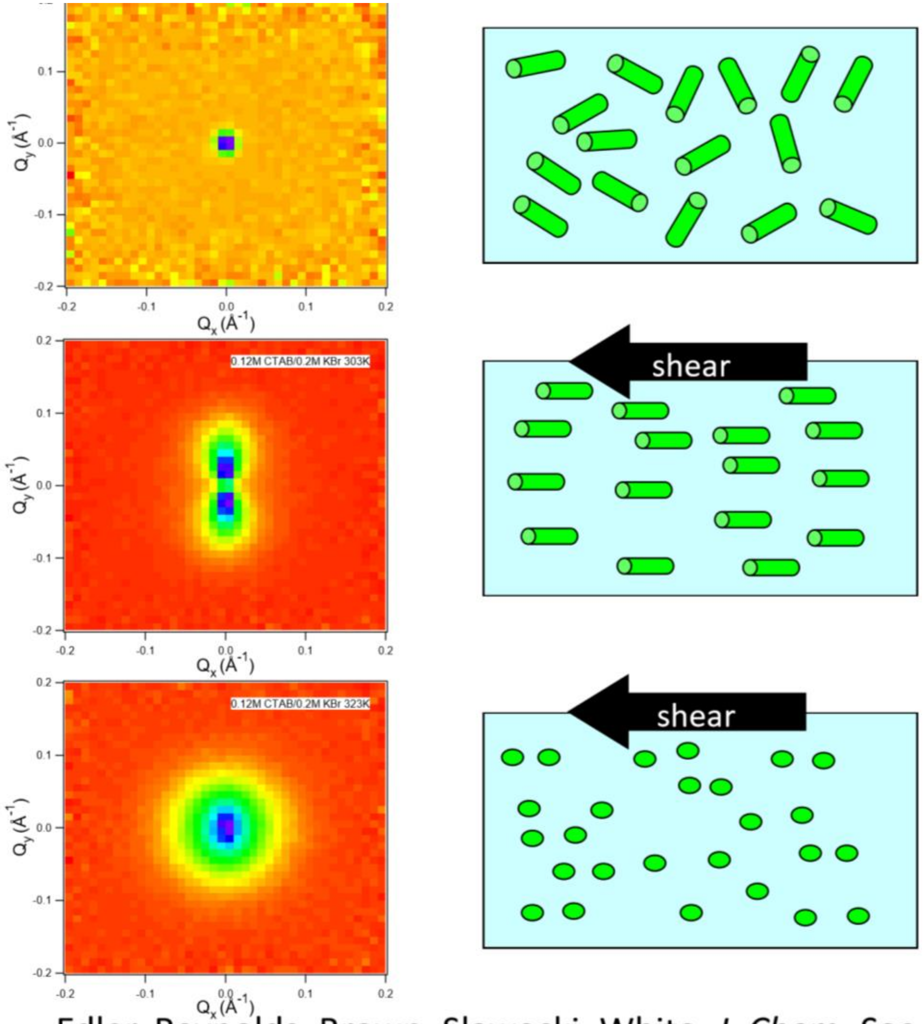


K. Edler, University of Bath

What sort of periodic structures exist on these lengthscales?

- Chemical structures with large unit cells.
- Ordered arrays of larger lengthscale objects.
- Magnetic superstructures.

Other examples of small angle diffraction



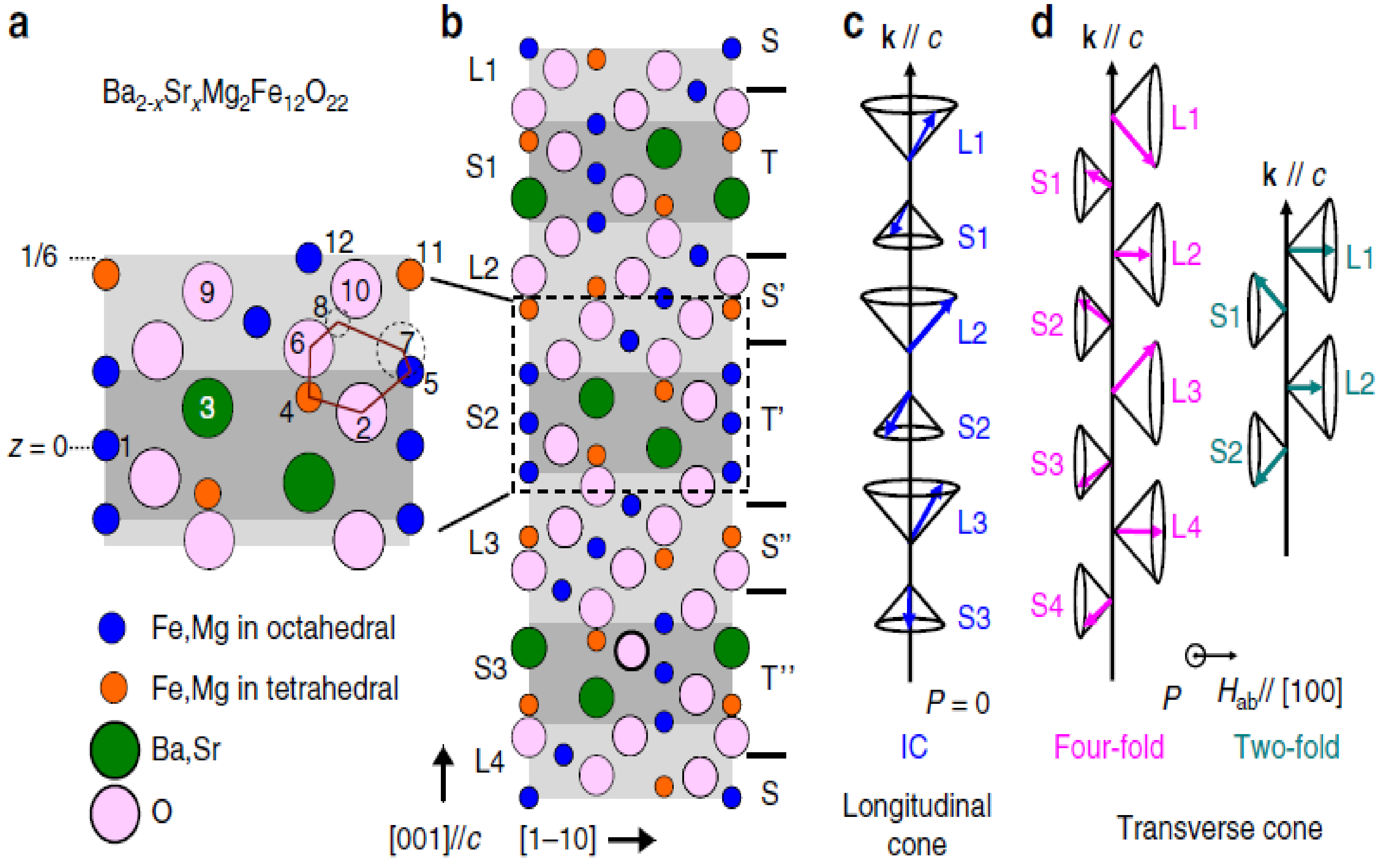
No shear
⇒Isotropic solution

Shear
⇒ aligned micelles

Shear + higher T
⇒ isotropic again

Edler, Reynolds, Brown, Slawecki, White, *J. Chem. Soc., Faraday Trans.* **1998,** *94*(9) 1287

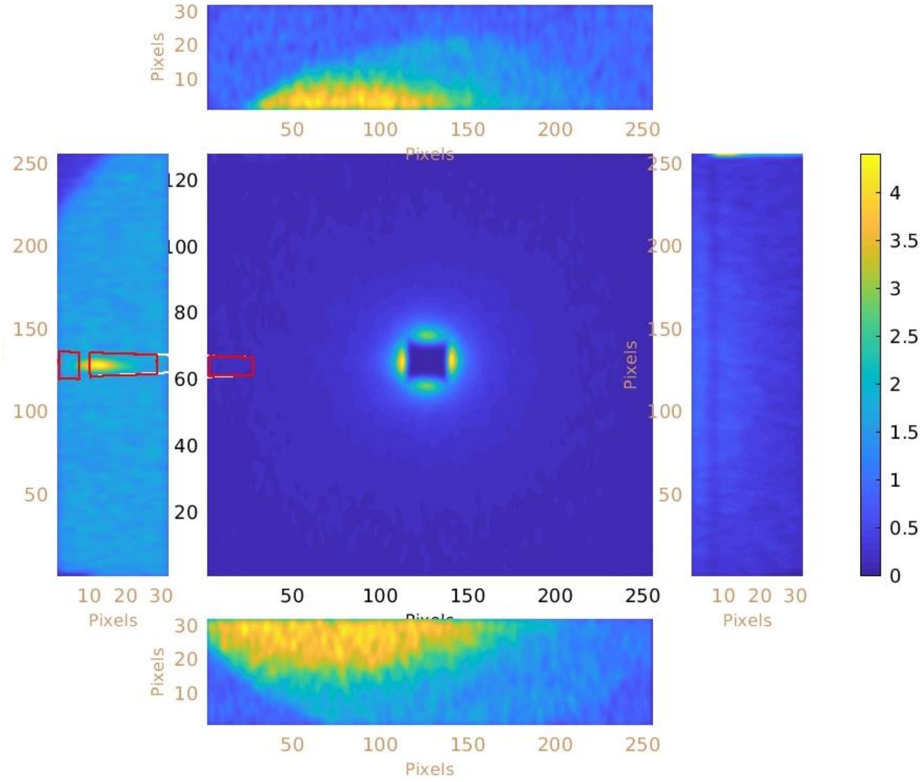
Other examples of small angle diffraction



Zhai *et al.*, Nature Comms **8**, 519 (2017).

Other examples of small angle diffraction

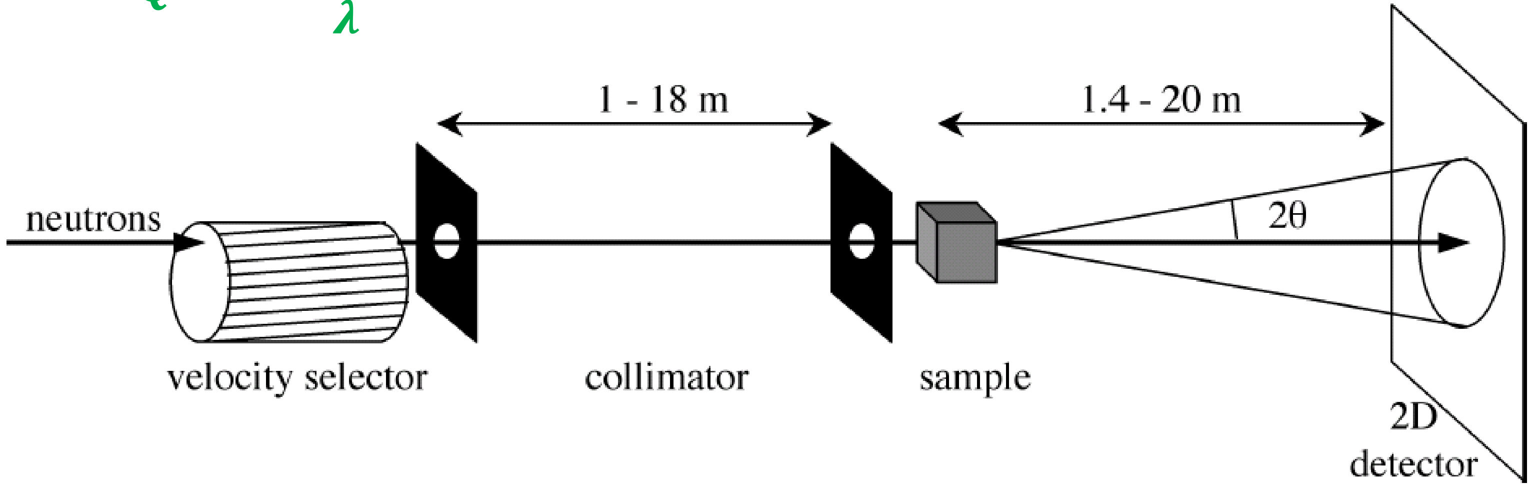
A magnetic Bragg peak measured on D33

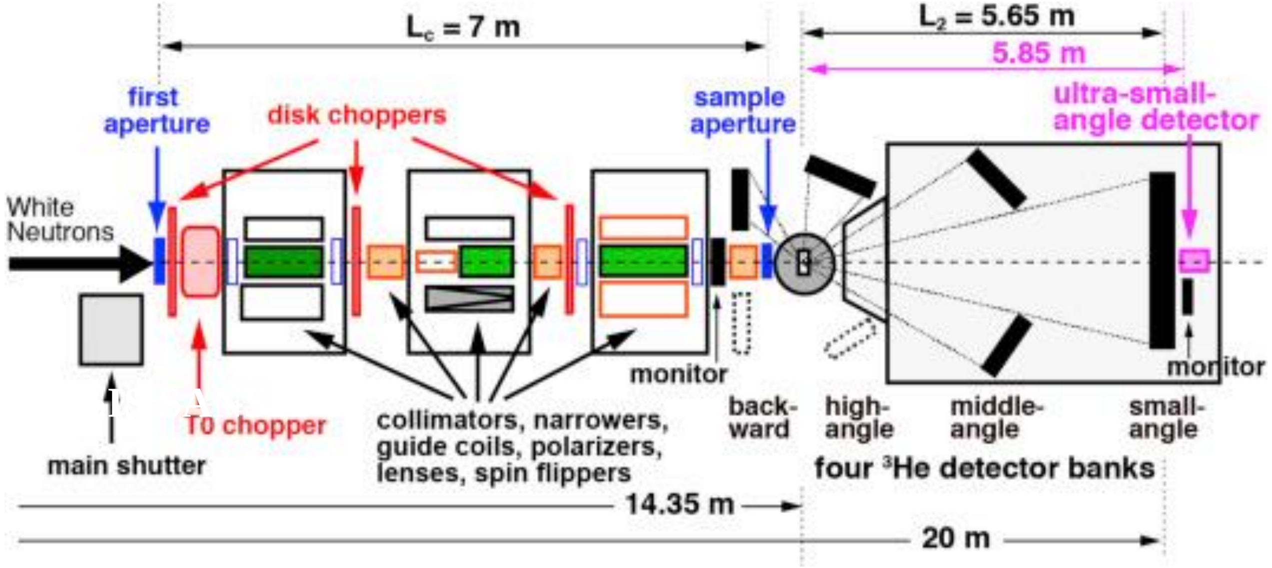


Time-of-flight vs monochromatic measurements

$$Q = \frac{4\pi \sin\theta}{\lambda}$$

Wavelength set for one measurement; move the detector to set Q range.





Detector fixed; multiple wavelengths detected using time-of-flight (TOF) – that spread sets Q range.

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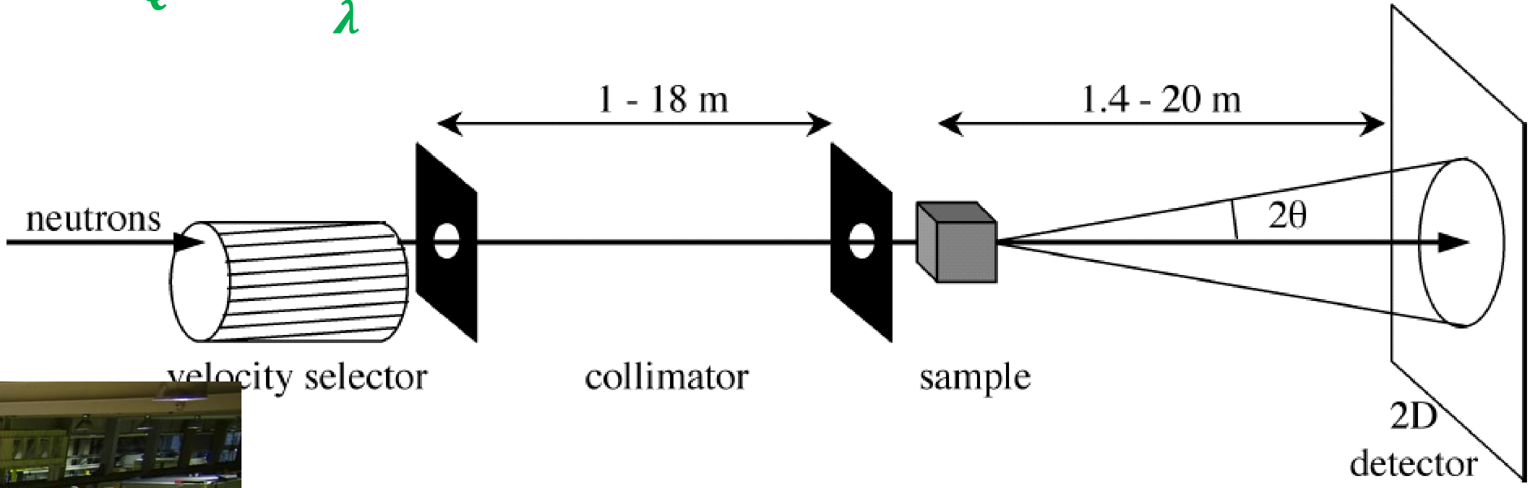
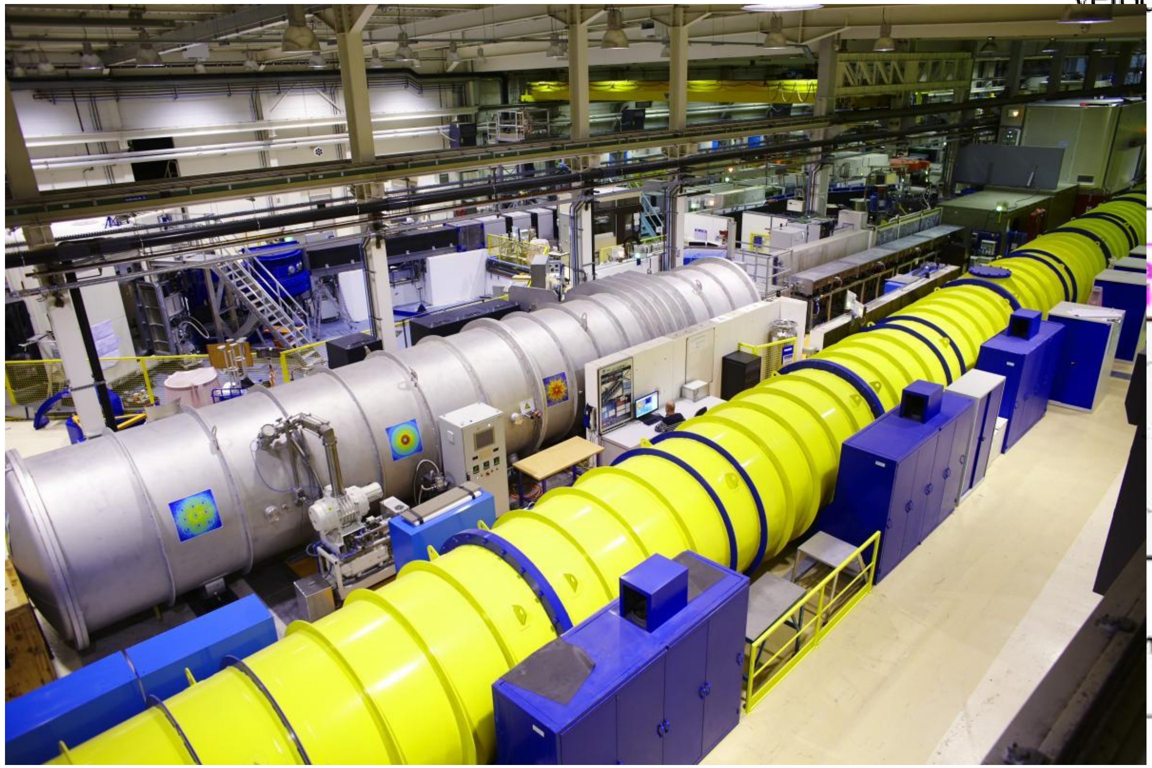
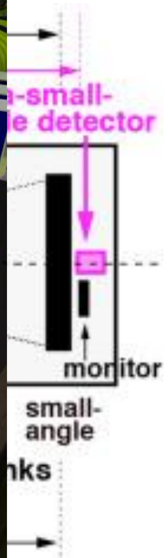


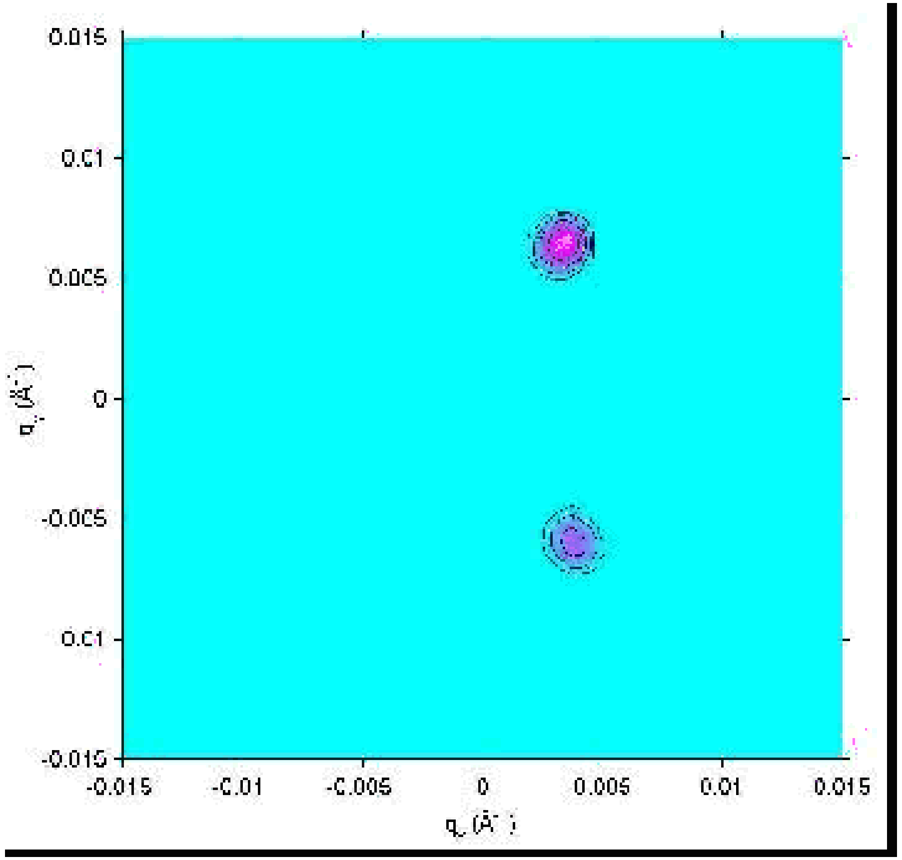


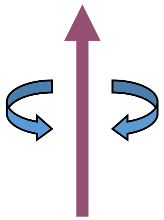


Detector fixed; multiple wavelengths detected using time-of-flight (TOF) – that spread sets Q range.

An illustration of Time-of-flight vs monochromatic effects

Monochromatic measurement

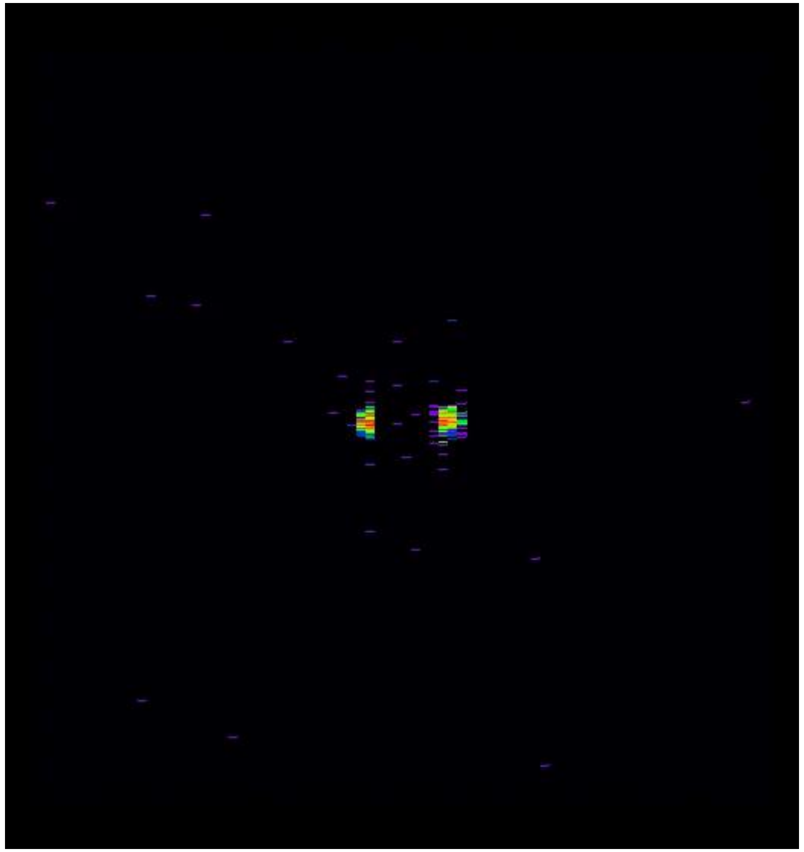




rotation axis

Niobium

TOF measurements



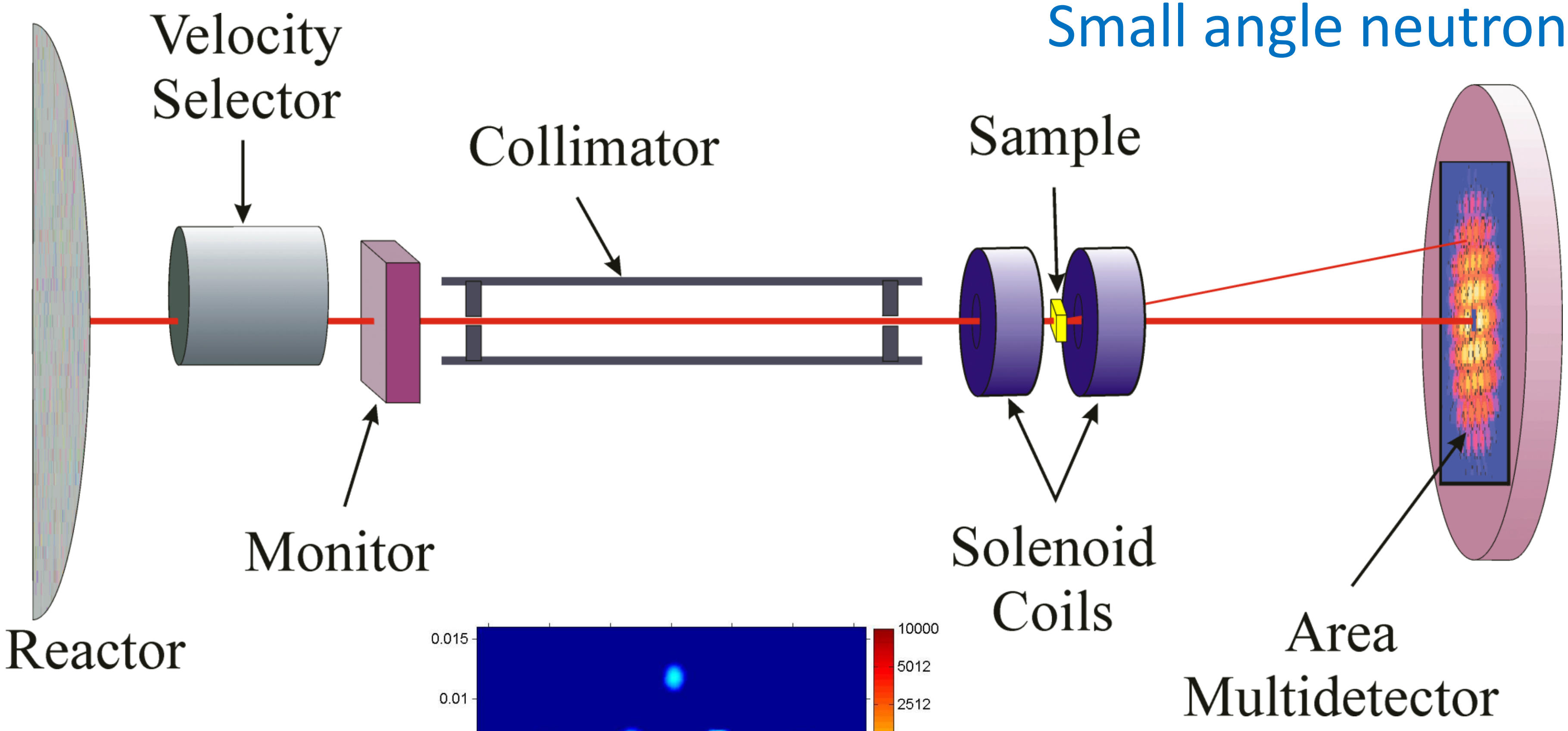
Frames are different wavelength bins

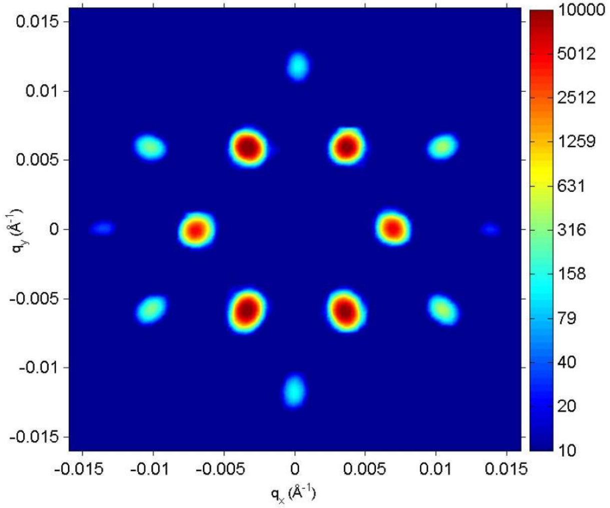
(Fe,Co)Si – a skyrmion lattice

Data from Diego Alba-Venero (ISIS) and Katia Pappas (Delft)

Unexpected problems …

Small angle neutron scattering





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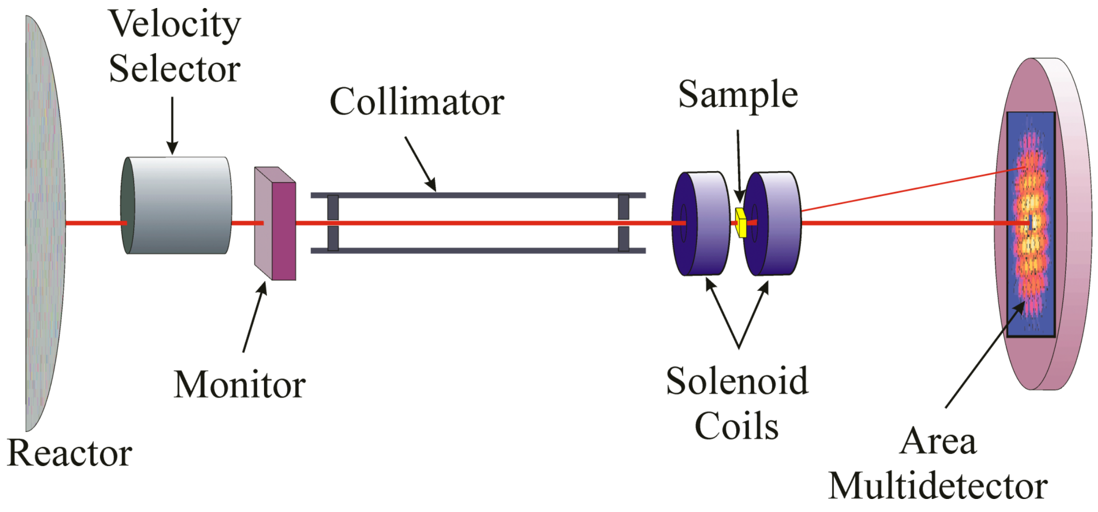
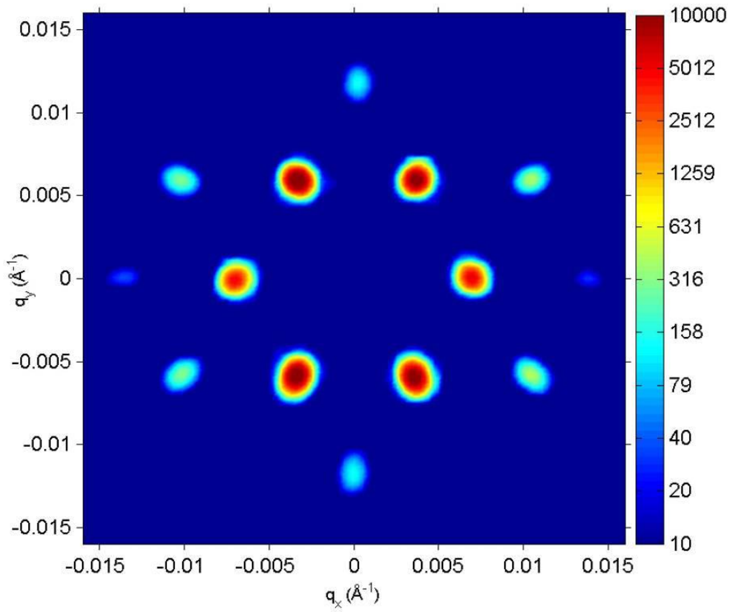
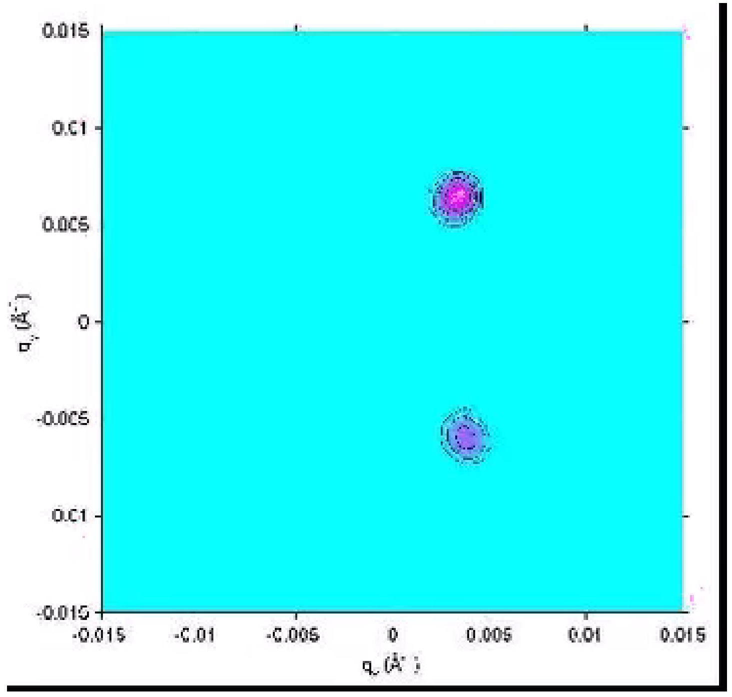


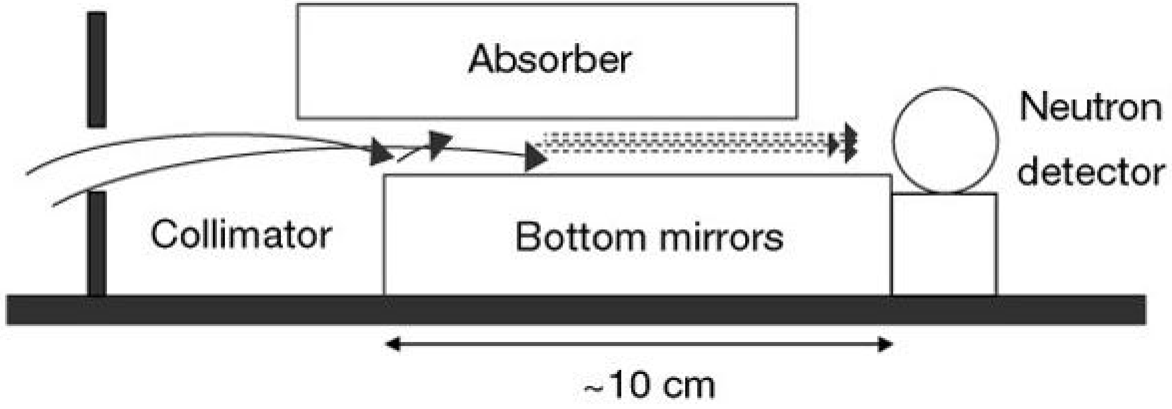


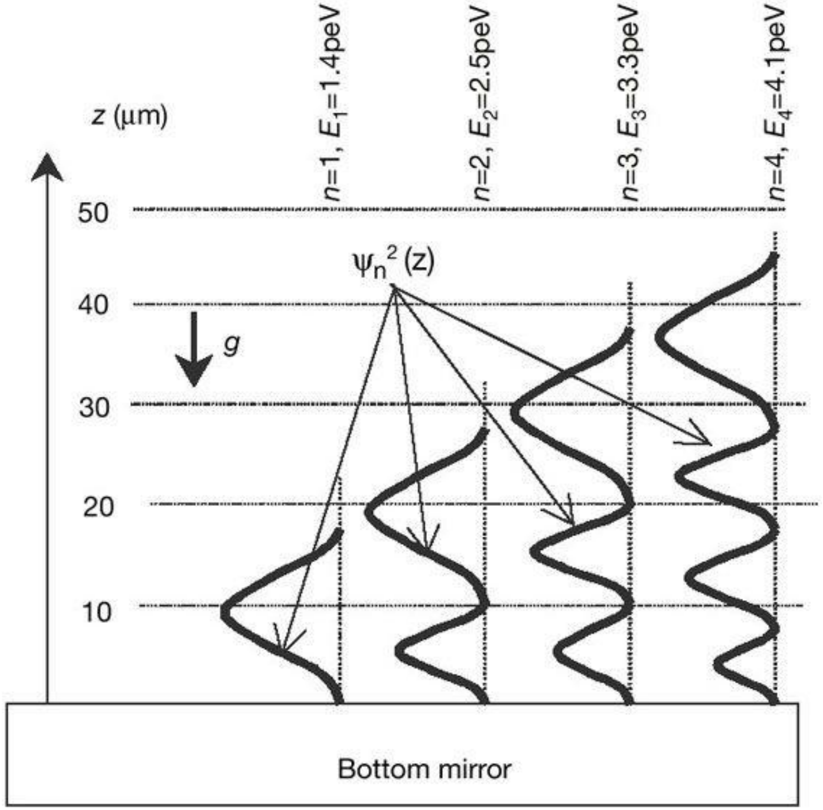


Unexpected problems … giving rise to opportunities

We can see the effects of gravity, so

Perhaps we can see bound quantum states if we can create a gravitational potential well.





Nesvishevsky *et al.*, Nature **415**, 297 (2002).

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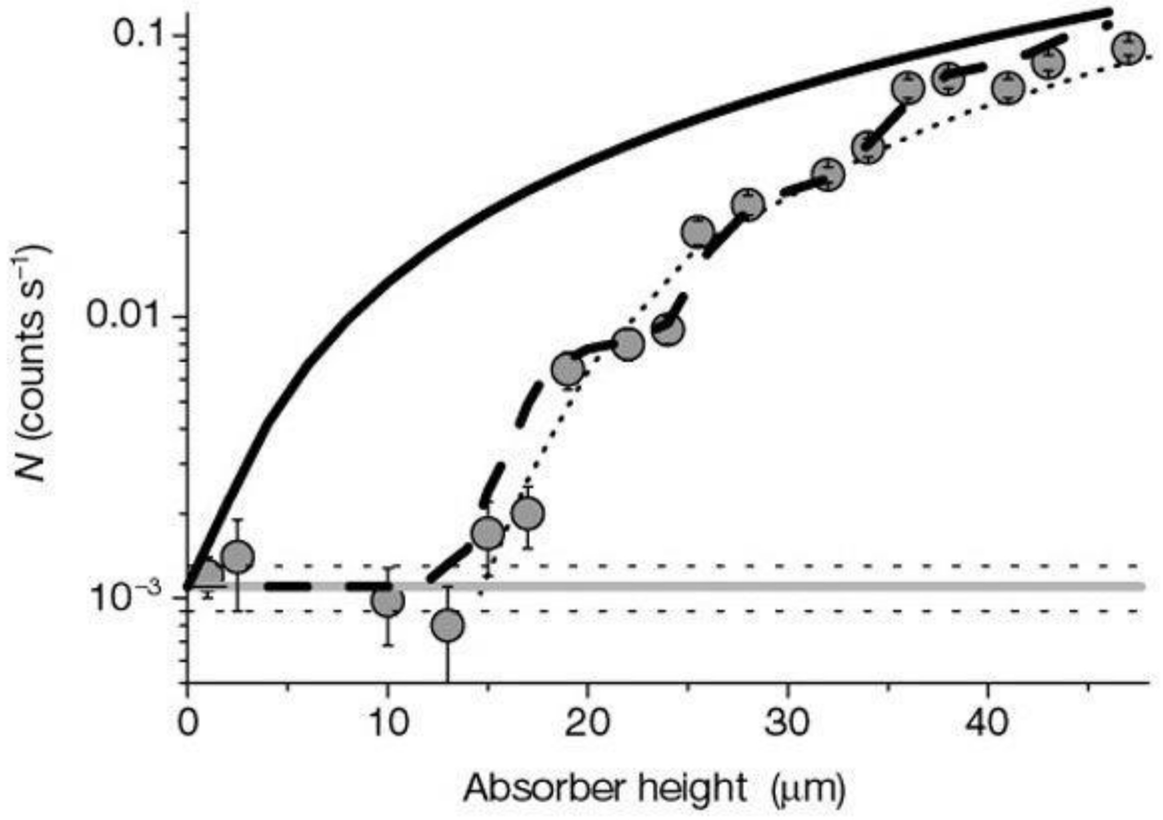

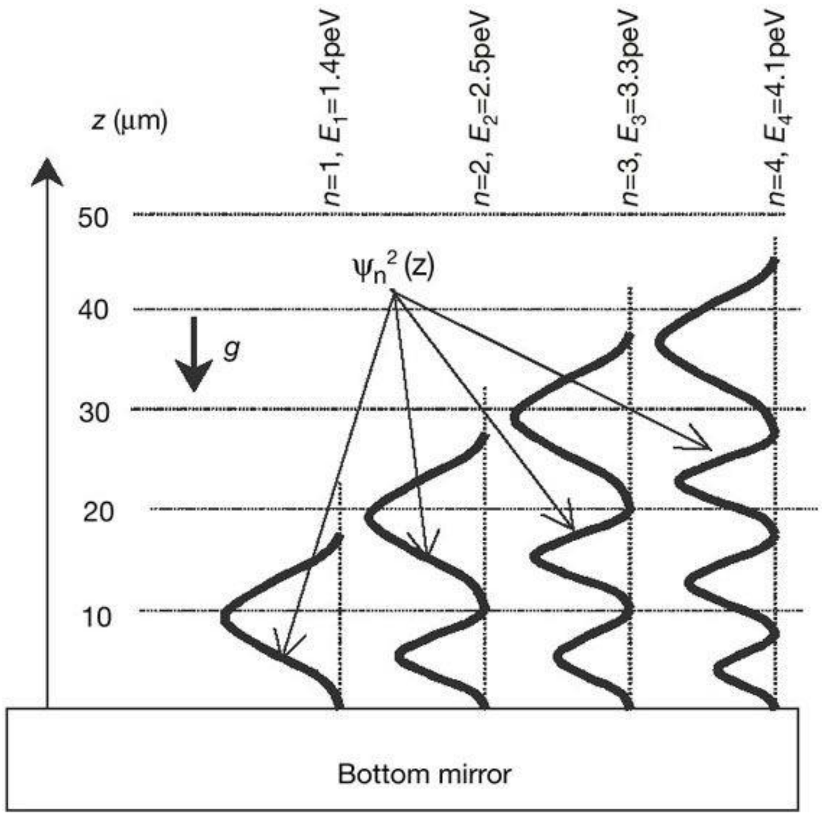

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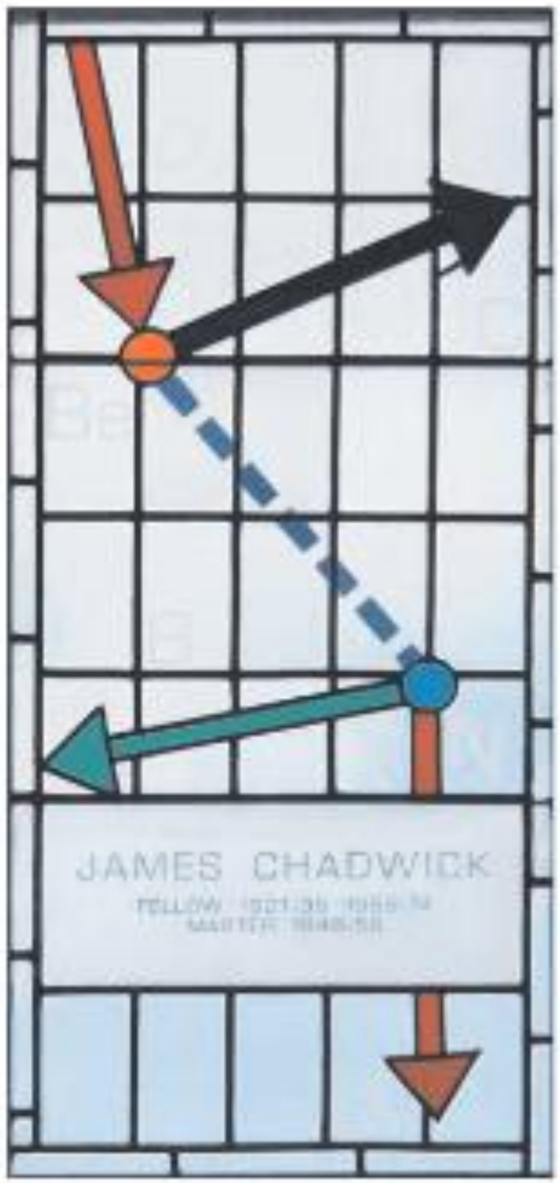
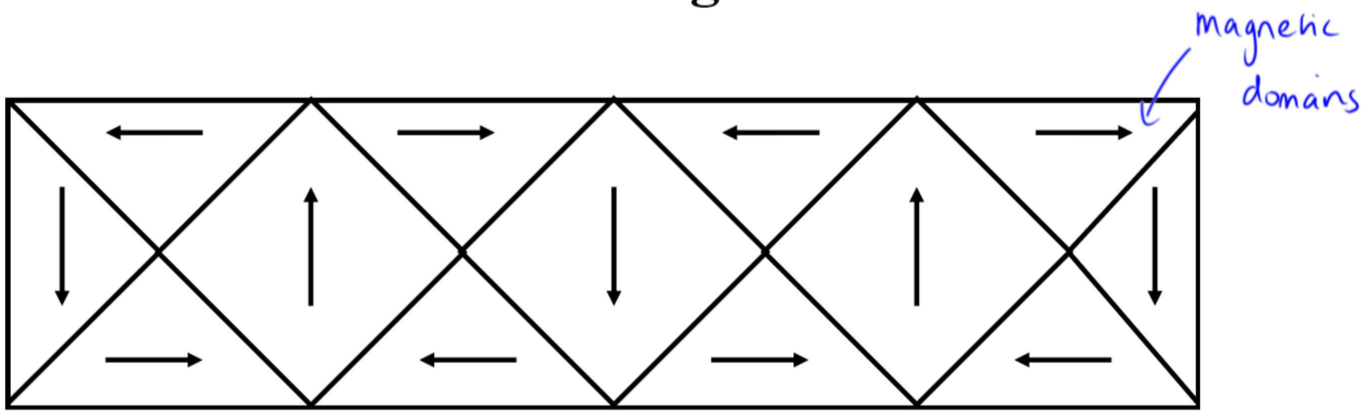
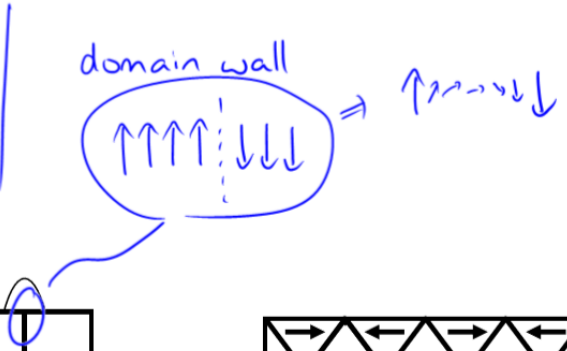


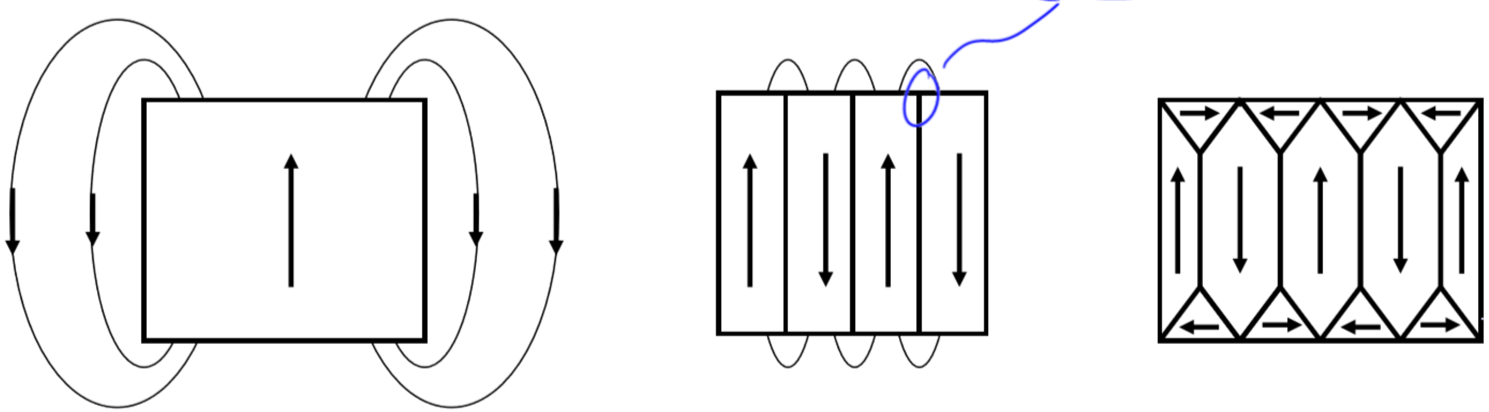
Effects of alignment in a ferromagnet

Real Ferromagnets

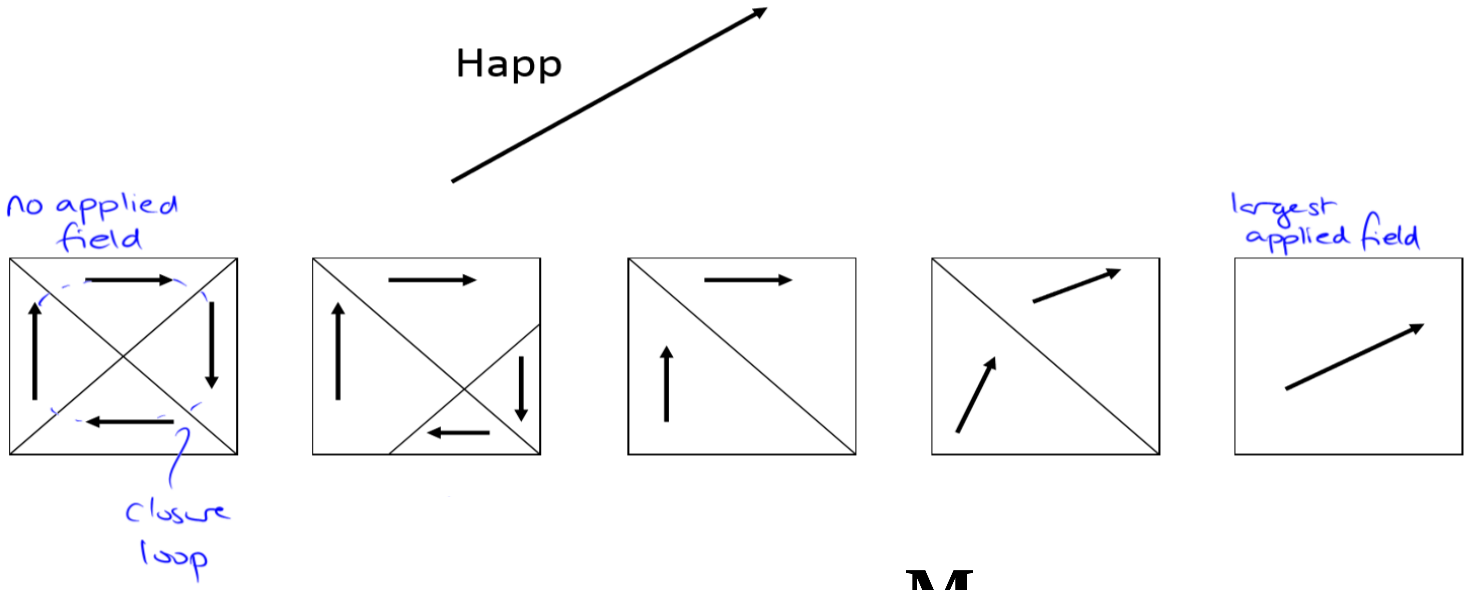


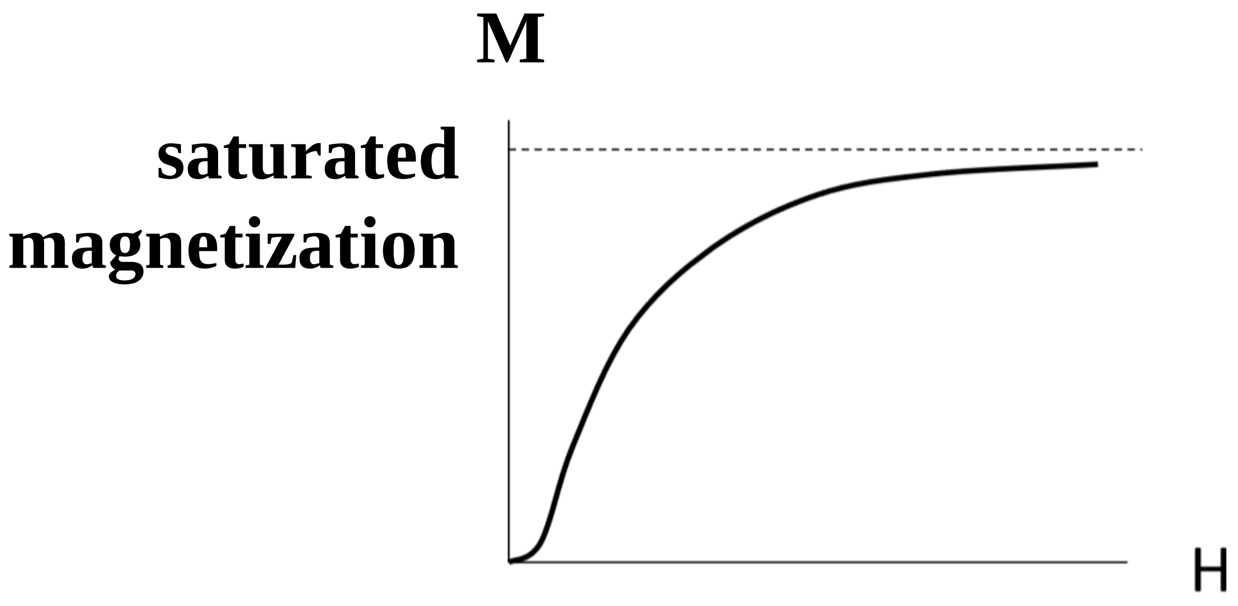
$$U = \frac{B^2}{2\mu_o\mu_r}$$





Effects of alignment in a ferromagnet





Effects of alignment in a ferromagnet

J. Phys.: Condens. Matter **26** (2014) 383201 Topical Review

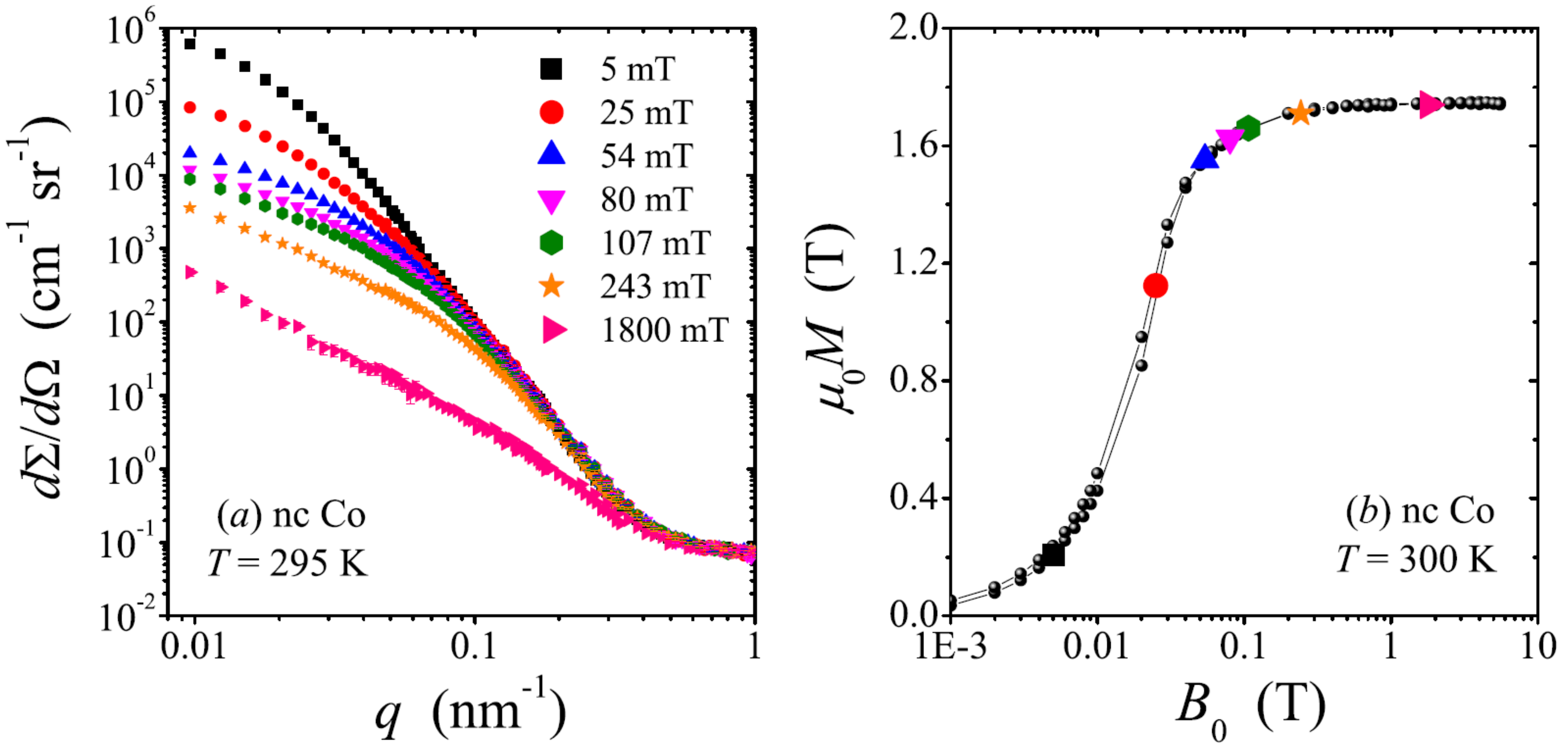
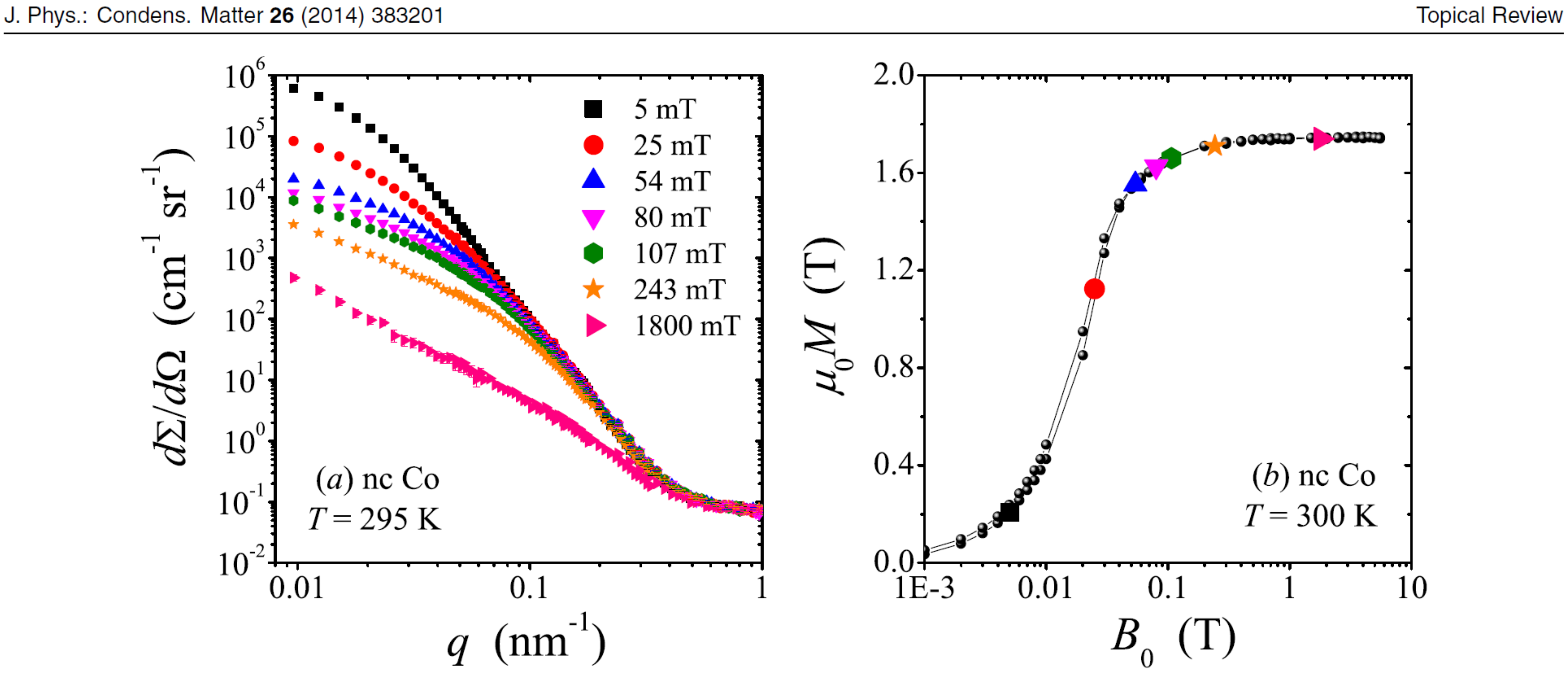


Figure 3. (a) Azimuthally-averaged unpolarized SANS cross-section $d\Sigma/d\Omega$ of nanocrystalline Co metal (average grain size: 9.5 ± 3.0 nm) as a function of momentum transfer q ($\mathbf{k}_0 \perp \mathbf{H}_0$) at selected applied magnetic fields (see inset) (log–log scale). (b) (●) Room-temperature magnetization curve of nanocrystalline Co (log-linear scale) [62]. The $M(B_0)$ values where the SANS measurements shown in (a) have been carried out are indicated by the large data points. Reprinted with permission from [63]. Copyright 2003 by the American Physical Society.

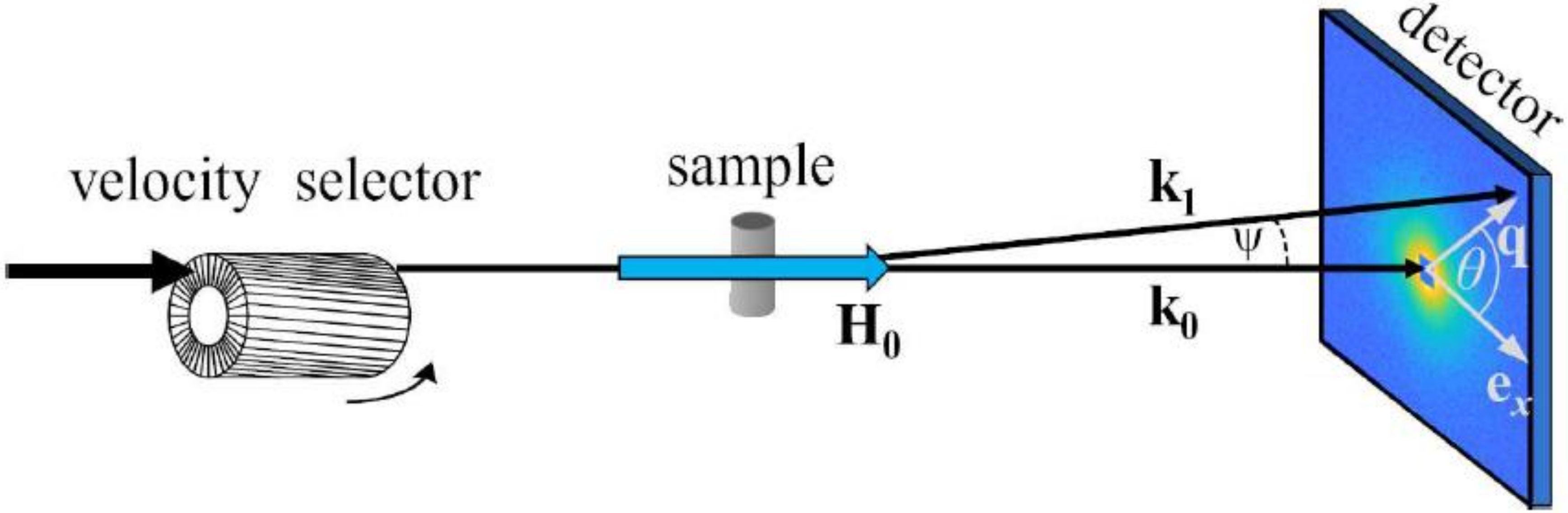
Effects of alignment in a ferromagnet



The neutron can see transverse deviations in the magnetization (defects/domain walls/etc) after the magnetization measurements are flat.

For our ferromagnet, the perfect background is:

Apply as large a field as you can, field parallel to the beam. Use this as the contrast-free background.



Why put the field parallel to the beam? Should make $\mathbf{q}_x$ and $\mathbf{q}_y$ scattering equal, permitting a radial averaging.

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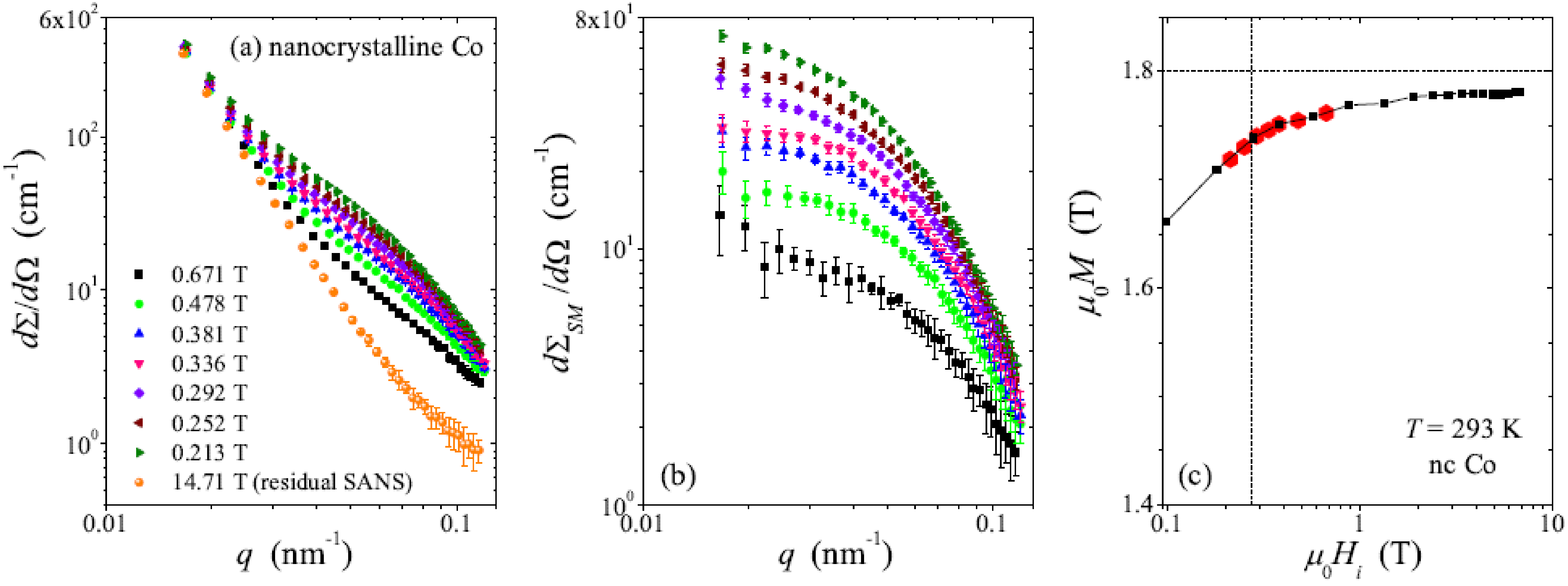


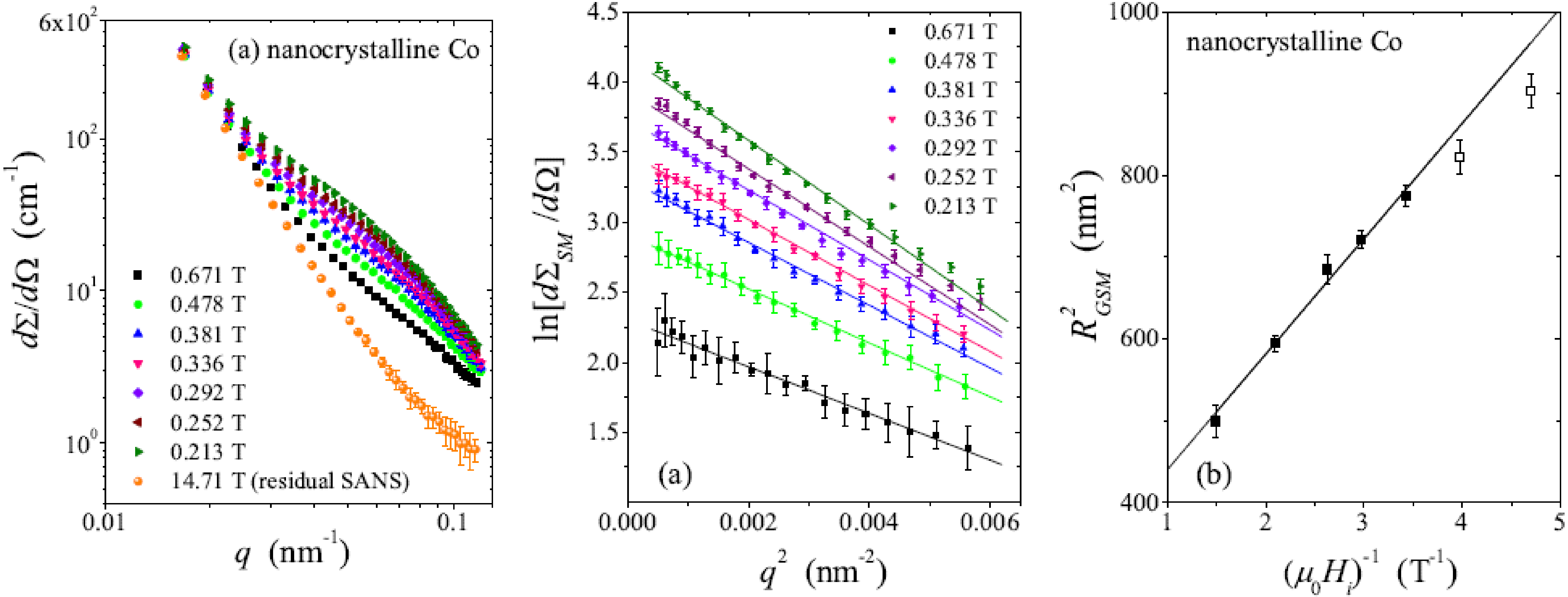
Odd field values due to application of demagnetization factor

Michels *et al.*, IUCrJ **7**, 136 (2020)

For our ferromagnet, the perfect background is:

Adapted ‘magnetic’ Guinier approximation

$$R^2_{\mathrm{GSM}}(H_\mathrm{i}) = R^2_{\mathrm{GH}} + 6 l^2_{\mathrm{H}}(H_\mathrm{i}) = R^2_{\mathrm{GH}} + \frac{12A}{\mu_0 M_\mathrm{s} H_\mathrm{i}}$$



Michels *et al.*, IUCrJ **7**, 136 (2020)

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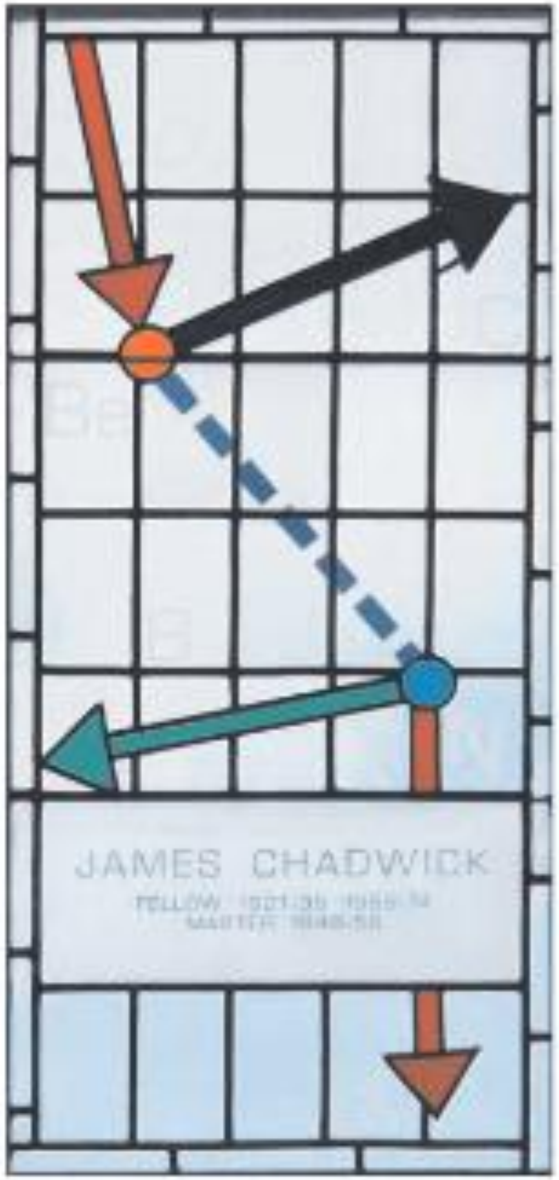

Useful references

Introduction to the Theory of Thermal Neutron Scattering, G. L. Squires, Dover (1996).

Theory of Neutron Scattering from Condensed Matter (2 volumes), S. W. Lovesey, Clarendon Press (1984).

Neutron Data Booklet: https://www.ill.eu/fileadmin/user_upload/ILL/1_About_ILL/Documentation/NeutronDataBooklet.pdf

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Magnetic small-angle neutron scattering

Sebastian Mühlbauer, Dirk Honecker, Élio A. Périgo, Frank Bergner, Sabrina Disch, André Heinemann, Sergey Erokhin, Dmitry Berkov, Chris Leighton, Morten Ring Eskildsen, and Andreas Michels

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