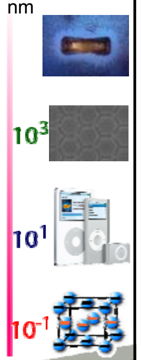
Nanomagnetism I:

Theoretical and Experimental Techniques in the Study of Nanomagnetic Systems

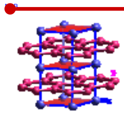


Sean Langridge
Large Scale Structures Group
Rutherford Appleton Laboratory, Chilton, Oxfordshire
s.langridge@rl.ac.uk

The big picture

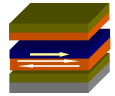
- In addition the surfaces and interfaces are particularly important
- Why?
- A break in symmetry

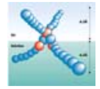
10^{-10}m



10^{-9}m

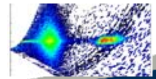
10^{-8}m





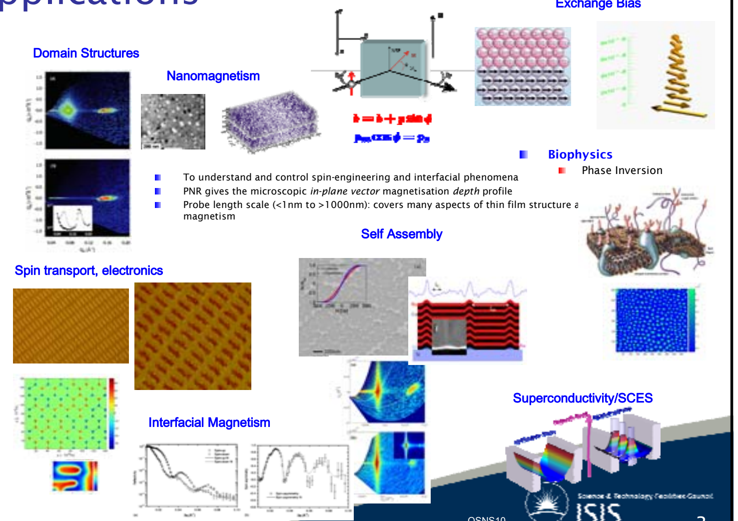
10^{-7}m

10^{-6}m

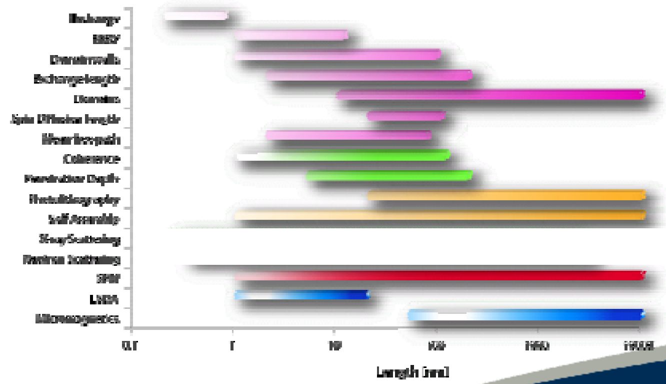


- The length scale from
  - 10^{-10}-10^{-6}m
  - covers a huge range of condensed matter science and technological applications

Applications



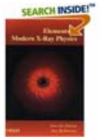
Relevance of scattering techniques to nanomagnetism



Adapted from I.K. Schuller *et al.* J. Magn. Magn.Mater. 200 (1999) 571.

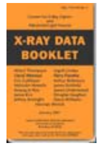
References

- Polarized Neutrons, W.G. Williams, Oxford (1988)
- Theory of Magnetic neutron and photon scattering, E. Balcar & S.W. Lovesey, Oxford (1988)
- Introduction to Thermal Neutron Scattering, G.L. Squires, Cambridge (1978)
- Elements of Modern X-Ray Physics, Als-Nielsen and McMorrow, Wiley & Sons (2001)
- Magnetism: from fundamentals to nanoscale dynamics, Stohr and Siegmann, Spinger (2006)
- www.ill.fr
- www.isis.rl.ac.uk
- www.esrf.fr
- www.diamond.ac.uk



Neutron and X-ray compendiums

http://xdb.lbl.gov/



http://www.ill.fr/

Complementarity

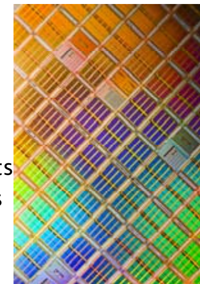
- Bulk measurements
  - Magnetometry
  - Transport…

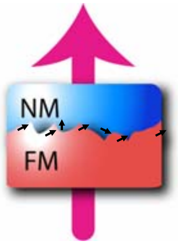
- X-rays
  - Element specific
  - Good Q-resolution
  - Weak interaction
  - High incident flux
  - Poor energy resolution (?)
  - Polarisation analysis


- Imaging
  - XPEEM
  - Lorentz
- Neutrons
  - Strong magnetic scattering
  - Penetrative probe
  - Good energy resolution
  - Absolute measurement
  - Polarisation analysis
  - Large coherence volume

Motivation

- Spin-Engineering
  - Transport of spin polarised currents
  - Spin Torque *etc.*
- Interfacial Phenomena
  - Influence on GMR
  - Exchange bias
  - Enhanced/reduced magnetic moments
  - Pinned/free moments
  - Magnetic Roughness
- Buried Interfaces
  - *c.f.* μ-scopy
  - Need for large area patterning if PN to contribute





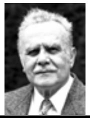
http://www.research.ibm.com

Basic Theoretical Ideas

Polarised Neutron Cross-Section

Historical Overview

- Pre-reactor
- Bloch 1936
  - theoretical description of the interaction between magnetic atoms and “magnetic” neutrons
- Schwinger 1937
  - Detailed QM treatment
  - Phys Rev **51** 544
- Halpern *et al.* (1937-1941)
  - Nuclear scattering
  - Paramagnetic scattering
- Alvarez and Block (1940)
  - Determination of the neutron moment
  - Phys Rev **57**,111
- Halpern *et al.* (1941)
  - Polarisation by reflection from magnetised mirrors
- Mid-late 1940’s Intense reactor sources
- Shull *et al.* (1951)
  - Neutron Scattering and polarisation by ferromagnetic materials Phys. Rev. 84 (1951) 912
- Blume (1963)
  - Polarization effects in the magnetic elastic scattering of slow neutrons Phys. Rev. 130 (1963) 16702
- Moon *et al.* (1969)
  - Polarisation Analysis of Thermal Neutron scattering Phys. Rev. 181 (1969) 920
- Nobel Prize (1994)
  - "for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter"



Basic Ideas-I

- Magnetic dipole moment:
- Differential cross-section

$$\boldsymbol{\mu}_n = -\gamma \frac{e\hbar}{2m} \boldsymbol{\sigma}$$

$$\frac{d^2\sigma}{d\Omega dE} = \frac{k'}{k}\left(\frac{m}{2\pi\hbar^2}\right)^2 \left|\langle k'\sigma'\lambda'|V_m|k\sigma\lambda\rangle\right|^2 \delta(E_\lambda - E_\lambda' + \hbar\omega)$$

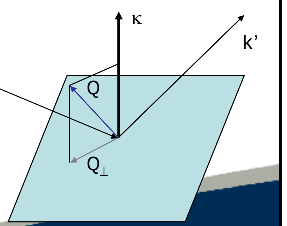
(See *e.g.* Squires eqn 7.15)

$$\hat{V}_m = -\hat{\boldsymbol{\mu}}_n \bullet \mathbf{B}$$

$$\langle k'|\hat{V}_m|k\rangle = -r_0 \hat{\boldsymbol{\sigma}} \bullet \hat{\mathbf{Q}}_\perp$$

$$\hat{\mathbf{Q}}_\perp = \sum_i \exp(i\boldsymbol{\kappa}\bullet\mathbf{r})\left(\boldsymbol{\kappa}\times(\hat{\mathbf{s}}_i\times\boldsymbol{\kappa}) - \frac{i}{\hbar\kappa}(\boldsymbol{\kappa}_i \times \hat{\mathbf{p}}_i)\right)$$

$$\mathbf{Q} = -\frac{1}{2\mu_B}\mathbf{M}(\boldsymbol{\kappa})$$



$$Q = Q_s + Q_l = -\frac{1}{2\mu_B}\mathrm{M}(\kappa)$$

Polarisation Analysis

$$\left(\frac{d^2\sigma}{d\Omega dE'}\right)_{\sigma\lambda\to\sigma'\lambda'} = \frac{k'}{k}\left|\sum_i \langle\sigma'\lambda'|\sigma\cdot\mathbf{Q}_\perp|\sigma\lambda\rangle\right|^2 \delta(E_\lambda - E_{\lambda'} + \hbar\omega)$$

- Components of the magnetisation, m give rise to
- m| |H: Non Spin Flip Scattering (NSF)
- m ⊥H: Spin Flip Scattering (SF)

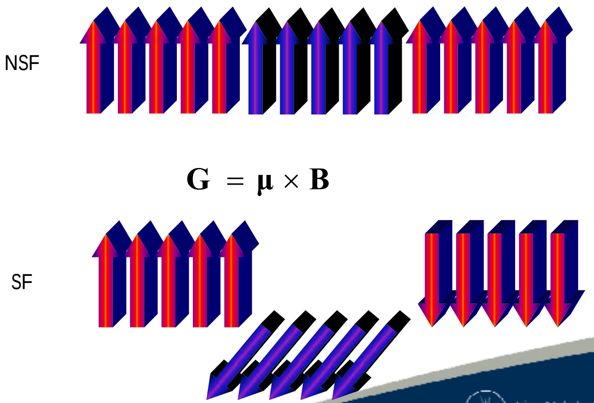
$$\langle\uparrow|\sigma\cdot\mathbf{Q}_\perp|\uparrow\rangle = Q_{\perp z} \quad (1)$$

$$\langle\downarrow|\sigma\cdot\mathbf{Q}_\perp|\downarrow\rangle = -Q_{\perp z} \quad (2)$$

$$\langle\uparrow|\sigma\cdot\mathbf{Q}_\perp|\downarrow\rangle = Q_{\perp x} + iQ_{\perp y} \quad (3)$$

$$\langle\downarrow|\sigma\cdot\mathbf{Q}_\perp|\uparrow\rangle = Q_{\perp x} - iQ_{\perp y} \quad (4)$$

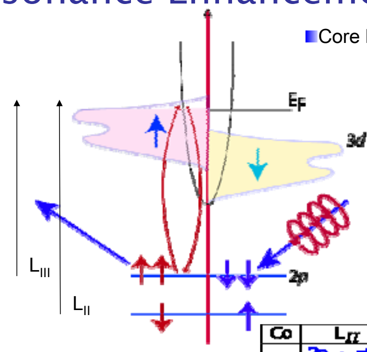
Spin Flip and non-spin flip



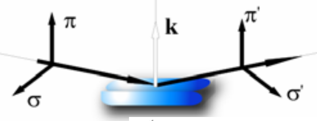
$$\mathbf{G} = \boldsymbol{\mu} \times \mathbf{B}$$

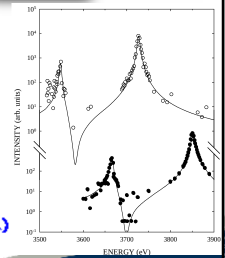
Resonance Enhancement

- Core level spectroscopy



Co	L_{II}	L_{III}
	$2p_{1/2} \Rightarrow d$	$2p_{3/2}$
	793.2eV	778.1eV





$$f_n^{res} = \begin{pmatrix} 1 & 0 \\ 0 & \mathbf{k}_i \cdot \mathbf{k}_f \end{pmatrix} F_n^{(0)} + i \begin{pmatrix} 0 & -\mathbf{k}_i \cdot \mathbf{M}_n \\ \mathbf{k}_f \cdot \mathbf{M}_n & (\mathbf{k}_i \times \mathbf{k}_f) \cdot \mathbf{M}_n \end{pmatrix} F_n^{(1)}$$

$$I = Tr(\widetilde{f_n^{res}} \cdot \rho \widetilde{f_n^{res}}^{*})$$

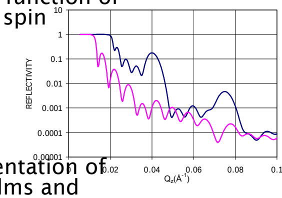
- Hannon, J. P., *et al.* 1988, *Phys. Rev. Lett.* **61**, 1245
- J. P. Hill and D. F. McMorrow, Acta Crystallogr., Sect. A: Found. Crystallogr. **52**, 236 (1996)

Specular Scattering

Neutron and x-ray reflectivity

Spin polarised Neutron Reflectivity

- Measure the reflected neutrons as a function of their perpendicular momentum and spin eigenstate



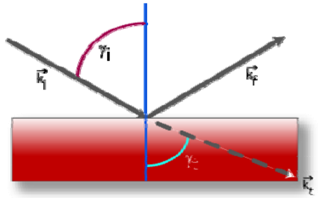
- $k^{\pm} = \sqrt{k - 4\pi N(b \pm cB)}$
- Can observe the magnitude and orientation of atomic magnetic moments in thin films and multilayer media.
- Probe length scale (<1nm to >1000nm): covers many aspects of thin film structure and magnetism
- Complementary to:
  - VSM/SQUID
  - MOKE average magnetisation over the sample thickness
  - SEMPA, Lorentz surface domain magnetisation
  - XMCD/XRMS-element specific
- PNR gives the microscopic *in-plane vector* magnetisation *depth* profile.

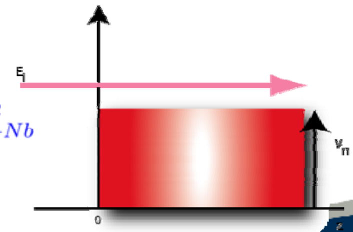
Index of Refraction: Neutrons

$$
\begin{aligned}
n &= \frac{\sin \gamma_i}{\sin \gamma_t} \\
&= \frac{|\vec{k}_t|}{|\vec{k}_i|}
\end{aligned}
$$

$$
\begin{aligned}
n^2 &= \frac{|\vec{k}_t|^2}{|\vec{k}_i|^2} \\
&= \frac{E_t}{E_i} \\
&= \frac{E_i - V_n}{E_i} \\
&= 1 - \frac{4\pi}{k_i^2} Nb
\end{aligned}
$$

$$V_n = \frac{2\pi\hbar^2}{m_n} Nb$$



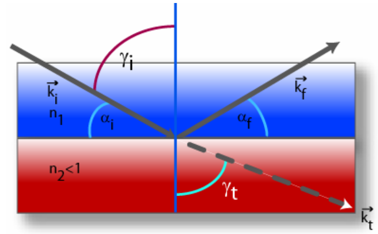


Critical Reflection

- $\frac{\cos \alpha_i}{\cos \alpha_f} = \frac{n_2}{n_1}$
- At the critical angle
  $\frac{\cos \alpha_i}{\cos 0} = n$

$$
\begin{aligned}
Q_c &= \frac{4\pi}{\lambda} 2k \sin \alpha_c \\
&= 2k\sqrt{1 - \cos^2 \alpha_c} \\
&= \sqrt{4k^2 \left(1 - n^2\right)} \\
&\cong \sqrt{4k^2 \cdot 2\delta} \\
&= \sqrt{16\pi Nb}
\end{aligned}
$$

- Q_c only depends on the material!



Basic Ideas

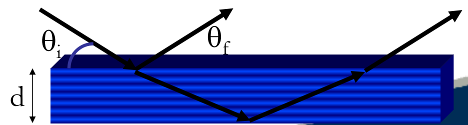
- Neutron Potential

$$
\begin{aligned}
V &= V_{Nuclear} + V_{Magnetic} \\
&= \frac{\hbar^2}{2m_n} Nb + \mathbf{B} \cdot \hat{\mathbf{s}}
\end{aligned}
$$

- Kinematical Approximation

$$R(Q) = 16\frac{\pi^2}{Q^4} \left| \int \rho(z) \exp i(q/s) z dz \right|^2$$

$$
\begin{aligned}
F_j &= \frac{k_{j+1} - k_j}{k_{j+1} + k_j} \\
r_j &= \exp(-ik_j d_j) \times \frac{r_{j+1} + F_j}{r_{j+1} F_j + 1} \\
R &= |r|^2
\end{aligned}
$$



- QM solution

$$-\frac{\hbar^2}{2m_n}\nabla^2\Psi(\vec{r}) + V(\vec{r})\Psi(\vec{r}) = E\Psi(\vec{r}) \quad (1)$$

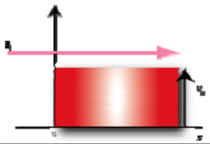
$$E = \frac{\hbar^2}{2m_n}\left|\vec{k^2}\right| + V_0 = \frac{\hbar^2}{2m_n}\left(k_x^2 + k_y^2 + k_z^2\right) + V_0 \quad (2)$$

$$V(\vec{r}) = \frac{2\pi\hbar^2}{m_n} N(\vec{r}) b(\vec{r}) \quad (3)$$

$$\Gamma(\vec{r}) = 4\pi N(\vec{r}) b(\vec{r}) = \frac{2m_n V(\vec{r})}{\hbar^2} \quad (4)$$

$$\nabla^2\Psi(\vec{r}) + (k^2 + \Gamma_0 - \Gamma(\vec{r}))\Psi(\vec{r}) = 0 \quad (5)$$

$$\frac{\partial^2\psi(z)}{\partial z^2} + (k^2 + \Gamma_0 - \Gamma(z))\Psi(z) = 0 \quad (6)$$



- $$\psi(x) = \alpha \exp(ik_n z) + \beta \exp(-ik_m z) \quad (1)$$

$$k_m = \sqrt{k_z^2 + \Gamma_0 - \Gamma_z} \quad (2)$$

for

$$k_z^2 + \Gamma_0 - \Gamma(z) = 0 \quad (3)$$

$$\psi(x) = \alpha + \beta x \quad (4)$$

for

$$-\infty < z \leq 0$$

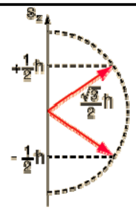
$$\psi(z) = \exp(ik_m z) + r \exp(-ik_m z) \quad (5)$$

$$R = rr^* \quad (6)$$

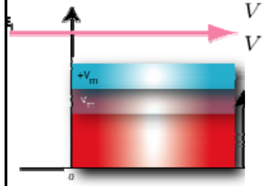
$$R(q_i) = \frac{\left|q_i - q_{i+1}\right|^2}{\left|q_i + q_{i+1}\right|^2} \quad (7)$$

A. Van der Graaf (1997)

Using the neutron's spin



- The neutron is a spin ½ particle
- The neutron possesses an intrinsic magnetic moment: spin
- Caution…



Nuclear Magnetic

$$
\begin{aligned}
V &= V_n + V_m & (1)\\
V &= \frac{\hbar}{2\pi m}Nb - \mu\cdot\mathbf{B} & (2)\\
&= -4\pi\mu_n \cdot M & (3)\\
&= -\frac{2\hbar\pi^2}{m_n}p(z)\sin(\theta) & (4)\\
&= \frac{2\hbar\pi^2}{m_n}\frac{M_p}{M_s}N\frac{m_n\mu_n\mu_0}{2\pi\hbar^2}\mu_s & (5)
\end{aligned}
$$

$$\vec{\mu_n} = \gamma\mu_N\vec{\sigma}$$

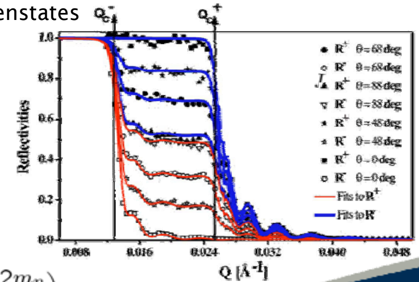
$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

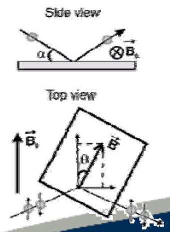
Caveat to Classical Description

- CD predicts a continous variation of critical edge

$$\frac{4\pi\sin(\alpha_c^{\pm})}{\lambda} = Q_c^{\pm} = \sqrt{\frac{2m_n}{\hbar^2}(V_n \pm |\mu|\,|B_s|\cos(\theta))}$$

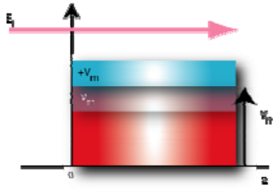
- Stern-Gerlach effect? Only 2 eigenstates



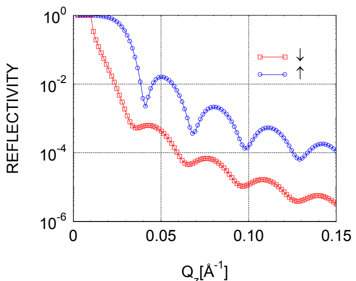


$$k_{\pm}^2 = \left(\frac{2m_n}{\hbar^2}\right)(V_n \pm |\mu|\,|B|)$$

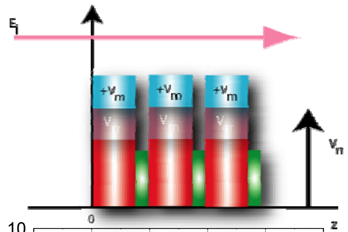
PNR from a single layer

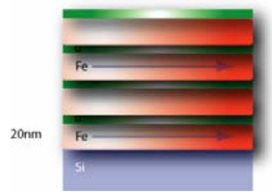


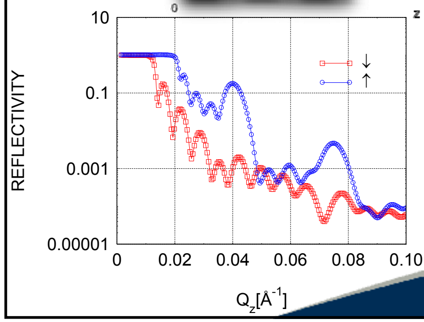
$$
\begin{aligned}
V &= V_n + V_m & (1)\\
V &= \frac{\hbar}{2\pi m}N(b \pm p) & (2)
\end{aligned}
$$



PNR from a multiple layers

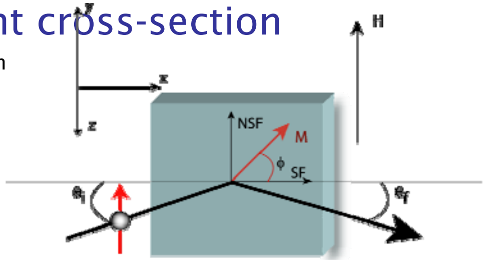






Spin dependent cross-section

- In-plane orientation of magnetisation obtainable from 4 spin dependent cross-sections



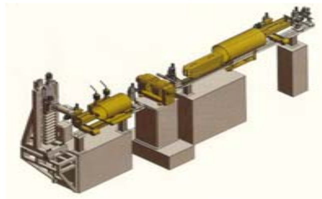
- Components of the magnetisation, m give rise to
- m||H: Non Spin Flip Scattering (NSF)
- m ⊥H: Spin Flip Scattering (SF)
- Dynamical analysis gives absolute depth dependence profile

$$b = b + p\sin\phi$$

$$p_m \cos\phi = p_x$$

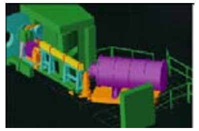
$$\left[\frac{-\hbar^2}{2m_n}\nabla^2 + V(r)\right]\Psi^{\uparrow,\downarrow} = E\Psi^{\uparrow,\downarrow}$$

Reflectometers



- Continuous or tof mode of operation
- 5Å Monochromator (6Å Polarised)
- White beam flux 9.6×10^9 n/s/cm^2

- The CRISP reflectometer at ISIS is a white beam time of flight (tof) polarised neutron reflectometer viewing a 20K hydrogen moderator.



http://www.ill.fr/YellowBook/D17/

http://www.ill.fr/YellowBook/ADAM/

Simulation Packages

Simulation Packages: neutron

- Neutron
  - Polly
  - http://www.isis.rl.ac.uk/LargeScale/CRISP/data_analysis_software.htm

Simulation Packages: photon

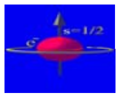
- X-ray
  - http://sergey.gmca.aps.anl.gov/
  - http://solst.phys.msu.su/andreeva

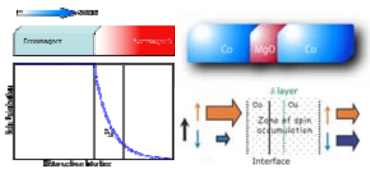
Depth dependent vector magnetometry

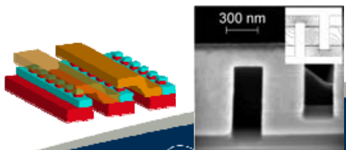
Interlayer Exchange Coupling

Spintronics

- Spintronics offer:
  - Nonvolatile, high speed, low power, scaleable
  - Reconfigurable
  - Integrated MO devices
  - Quantum information
- MgO tunnel barriers
- Spin Accumulation
  - δ-doping
  - Forthcoming experiments at SRS, NSLS
- Spin-torque
  - Large area arrays
    - e-beam
- Precessional pumping

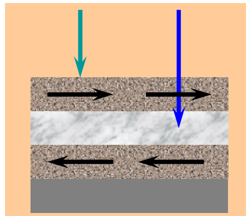




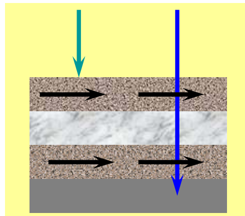


Blamire *et al.*

The GMR Effect



Anti-parallel alignment of moments produces a large electronic resistance



Parallel alignment of moments produces a low electronic resistance

$$\frac{1}{\rho} = \frac{1}{\rho_\uparrow} + \frac{1}{\rho_\downarrow} \Rightarrow \rho \approx \rho_\downarrow$$

$$\rho = \frac{\rho_\uparrow + \rho_\downarrow}{4} \gg \rho_\downarrow$$

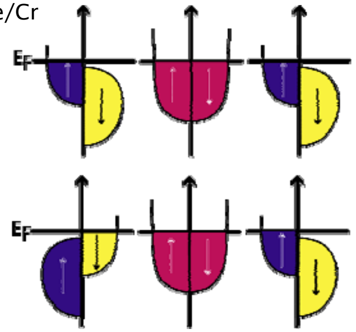
- Applications
  - Computer read/write heads
  - ABS sensors
  - Opto-isolators
  - MRAM

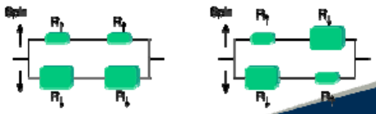
Baibich *et al.* Phys. Rev. Lett. **61** 2472 (1988)

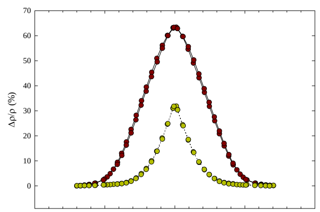
Quantum Well State

- Band matching important *e.g.* Fe/Cr

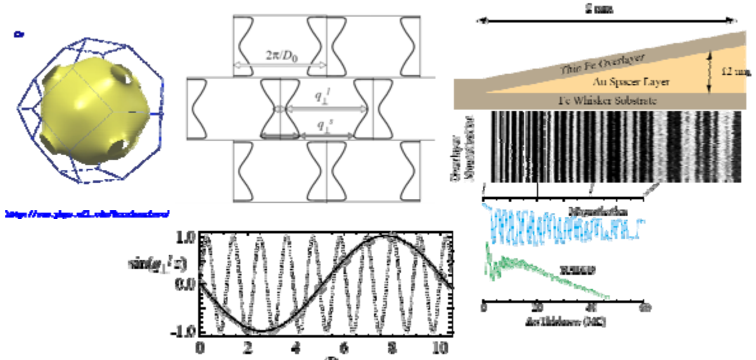
Co/Cu GMR







Interlayer Coupling



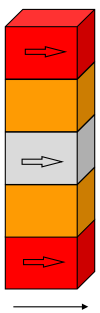
- $$\frac{E}{A} = -J\hat{m}_1 \cdot \hat{m}_2 \qquad (1)$$
  $$\frac{E}{A} = -J_2\left(\hat{m}_1 \cdot \hat{m}_2\right)^2 \qquad (2)$$

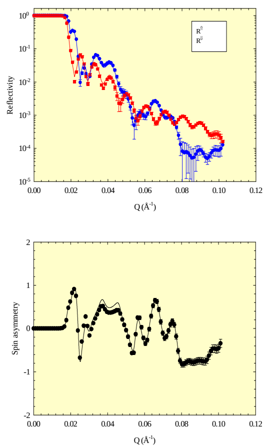
- J. Unguris, *et al.* J. Appl. Phys. 75, 6437 (1994).

- M Stiles (2002)

Spin valve structures

Si/Cu(494Å)/FeNi(71Å)/Cu(31Å)/Co(46Å)/Cu(31Å)/FeNi(74Å)/Cu(46Å)



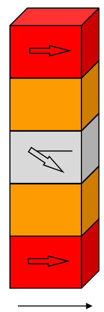


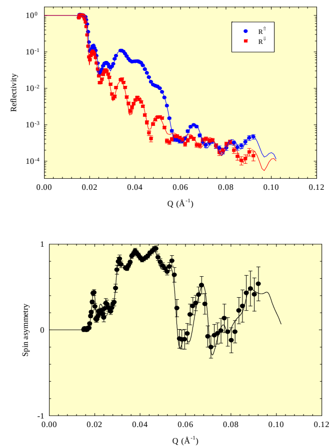
- Saturation field all moments align along applied external field

J.A.C Bland *et al.* Phys. Rev B **60** (1999) 7304

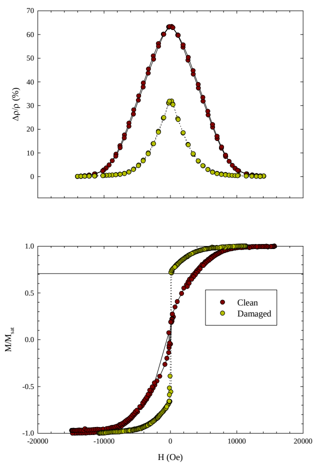
20G applied field

- In 20G the Co is able to rotate by 60°
- PNR gives <u>*absolute*</u> moments with <u>*layer*</u> sensitivity



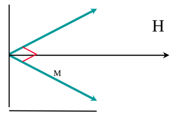


GMR and MOKE



$$\frac{\Delta\rho}{\rho} \Rightarrow -\left(\frac{M_0}{M_s}\right)^2$$

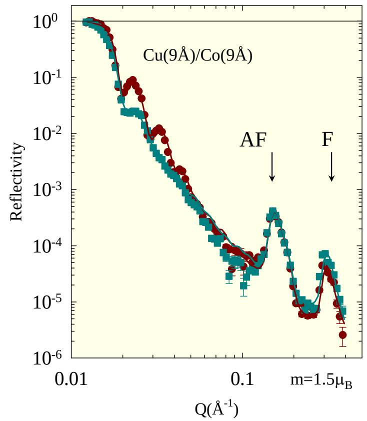
$$\approx \frac{\sqrt{2}M}{2}$$

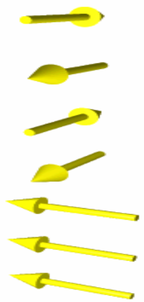


$$\frac{\sqrt{2}M}{2}$$

- Room temperature measurements
- Reduction in gmr and zero field remanence
- Biquadratic coupling?

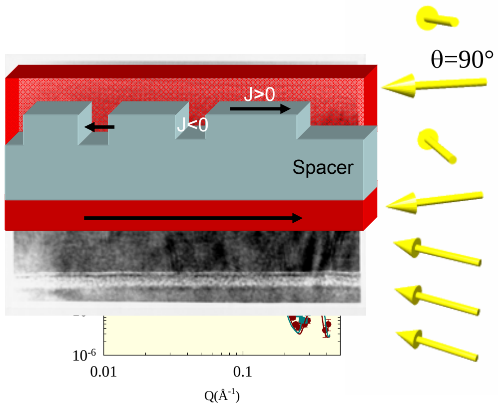
Clean AF coupled sample





- Small spin dependence
- Large gmr
- Ferromagnetic contribution at bottom of stack

Biquadratic sample

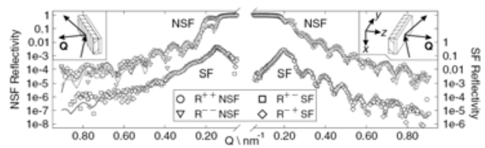


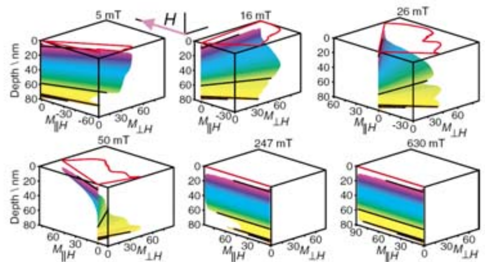
- Damaged sample
- Spin dependence
- Reduced gmr
- Direct observation of 90˚ coupling
- Single domain

Marrows *et al.* Physical Review B **62** 11340 (2000)

Front-back reflectivity

- $Ni_{80}Fe_{20}(50)/Fe_{55}Pt_{45}(20nm)$
- Exchange Spring magnet





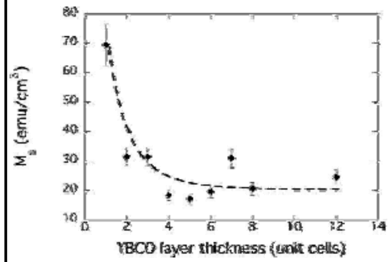
K.V. O'Donovan *et al. Phys. Rev. Lett.* **88** (2002) 067201

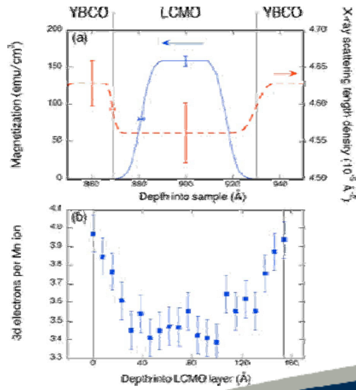
Proximity Magnetism

Interfacial magnetism

Surpressed Magnetisation through PNR/EELS

- $La_{0.7}Ca_{0.3}MnO_3/YBa_2Cu_3O_{7-\delta}$ superlattices
- Proximity effects
  - Variation in superconducting transition temperature
  - Critical current
- Half-metallicity
- Charge transfer key



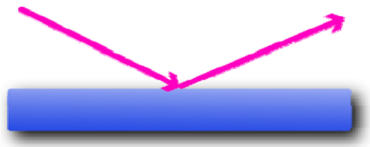


- Hoffmann *et al.* Phys. Rev. B **72** 140407 (R) (2005)

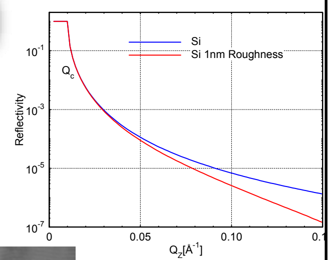
Roughness

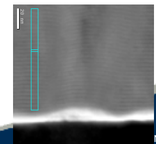
Structural and magnetic interfacial phenomena

Structural Roughness



$$R(Q) = R_F \exp\left(-Q^2\sigma^2\right)$$

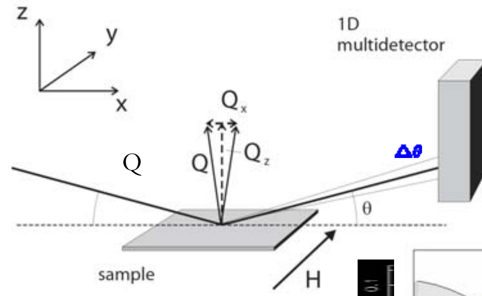




Off-specular scattering

Probing in-plane lengthscales

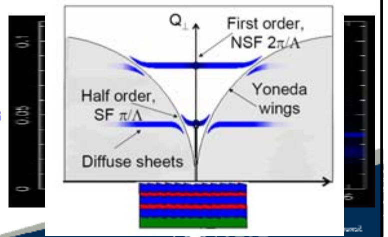
Experimental Geometry



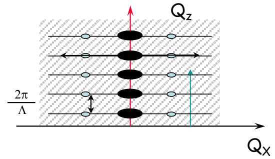
$$Q_x = |Q| \sin\theta \times \Delta\theta$$
$$Q_y = |Q| \times \Delta\phi$$

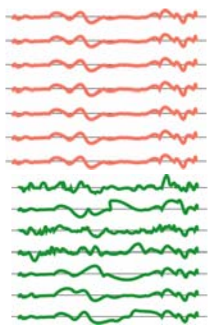
- λ range 0.5-6.5Å
- 1-d Detector
- Typical acquisition~2hours/field
- Measured coherence length ~30μm

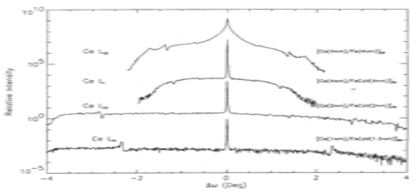
θ



Diffuse scattering







(Ce/Fe) Tixier, Mannix et al.

Holý and Baumbach, prb, 49, 10668, (1994)

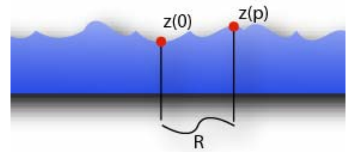
PHYSICAL REVIEW B VOLUME 38, NUMBER 4 1 AUGUST 1988

X-ray and neutron scattering from rough surfaces

S. K. Sinha, E. B. Sirota, and S. Garoff*
Corporate Research Science Laboratory, Exxon Research and Engineering Company, Clinton Township, Route 22 East, Annandale, New Jersey 08801

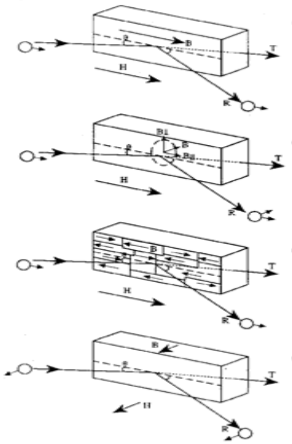
H. B. Stanley†
University of Maryland, College Park, Maryland 20742
(Received 30 November 1987)

$$C(R) = \left\langle \left[z(x,y) - z(x',y') \right]^2 \right\rangle$$
$$= \sigma^2 \exp(-r/\xi)^{2h}$$



- σ= roughness
- ξ= cut-off length:
  - for R > ξ, interface appears smooth,
  - for R < ξ, interface appears rough, fractal behaviour
- h=3-D Hurst parameter for jaggedness(0<h<1)
  - smooth: D=2, h=1
  - very rough D=3, h=0

Effects of magnetisation on neutron reflectivity



(a) Spin dependent reflectivity, potential is Zeeman split

(b) Rotation of the neutron polarisation. Resonance or spin flip channel

(c) Average of the 2 spin states

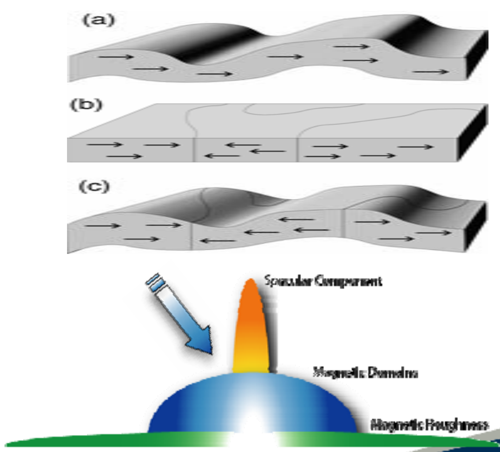
(d) Pure nuclear, the component of B normal to the surface is continuous across the surface

$$\nabla \cdot \vec{B} = 0$$

G.P. Felcher, Physica B, **192**, (1993), 137

Magnetic Roughness

Magnetic Surfaces



- Schematic mechanisms for magnetic disorder giving rise to diffuse scattering
- Reciprocal Space description

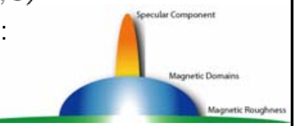
Modelling of Data

- Consider spatially inhomogeneous magnetisation profile: m(r):

$$m(\vec{r}) = m_0(cos(\phi(\vec{r})), sin\phi(\vec{r}), 0)$$

- Introduce a correlation function:

$$M(\vec{r}) = \sigma_m^2 exp(-r/\xi_m)$$



- Within the Born approximation:

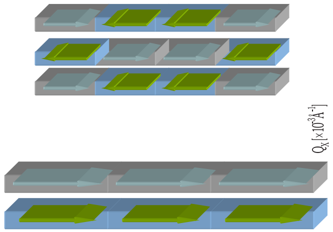
$$S(\vec{Q}) \propto \sum_{\alpha\beta} \int d^3 r exp(i\vec{Q}\cdot\vec{r})(\delta_{\alpha\beta} - \hat{Q}_\alpha \hat{Q}_\beta) \left\langle m_\alpha(\vec{r}) m_\beta(0) \right\rangle$$

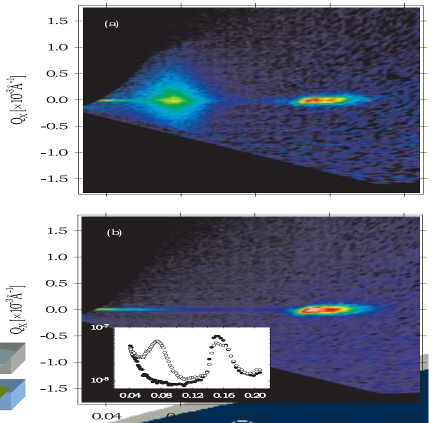
- Averaging for a Gaussian distribution of orientations:

$$\begin{aligned} S(\vec{Q}) &= S_{spec} + S_{diff} \\ &= 4\pi^2 D\delta(Q_{\|}) + D \int d^2 r exp(i\vec{Q_{\|}} \cdot \vec{r})[s + m + sm] \end{aligned}$$

Diffuse scattering

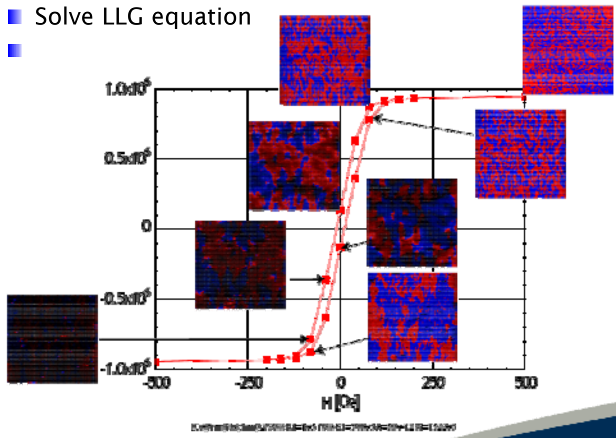
- Coherent AF order
- No evidence for uncorrelated roughness





μ-magnetics

- Solve LLG equation
-



$$\frac{d\mathbf{M}}{dt} = -|\gamma|\mathbf{M}\times\mathbf{H}_{eff} + \frac{\alpha}{M_s}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right)$$

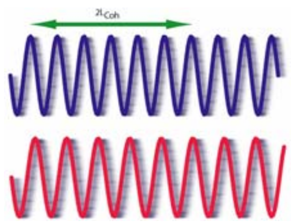
http://math.nist.gov/oommf

Probe coherence:

Consideration in scattering experiments

Probe Coherence (Longitudinal + transverse)

$$\begin{aligned} 2L_{Coh} &= N\lambda \\ &= (N+1)(\lambda-\delta\lambda) \\ N &\approx \frac{\lambda}{\Delta\lambda} \\ L_{Coh} &= \frac{\lambda^2}{2\Delta\lambda} \end{aligned}$$

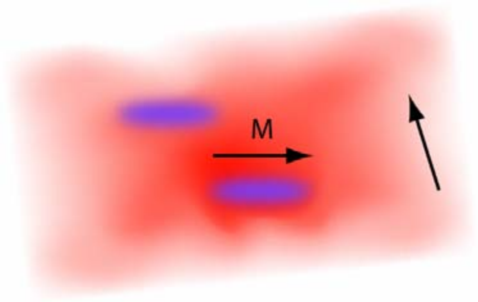


- Similarly for transverse (d is the slit width, l the distance)

$$L_{Trans} = \frac{\lambda}{2}\left(\frac{l}{d}\right)$$

L_{Coh}<Domain size

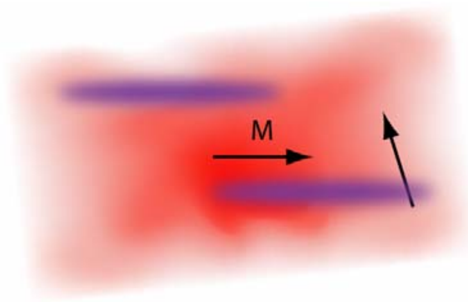
- $I \propto \sum_i \left(A_i^2\right)$
- Only specular scattering



L_{Coh}>Domain size

$I \propto (\sum_i A_i)^2$

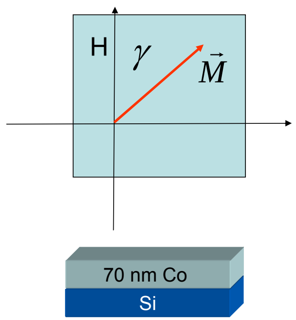
- Only diffuse scattering



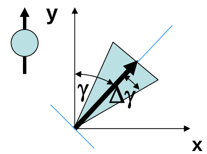
Domains and the coherence volume

Many thanks to H. Zabel for slides

Simulation of a Co film on a substrate



Magnetic parameters



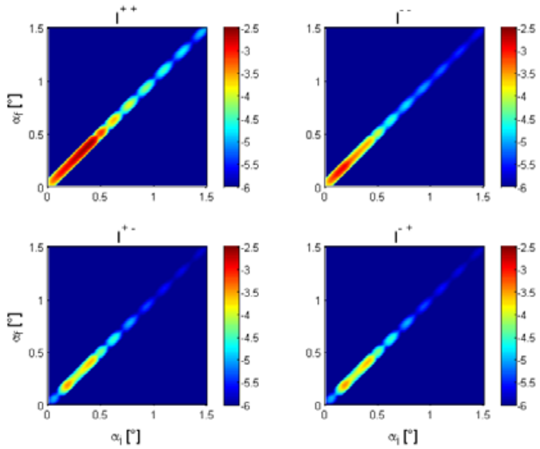
$\langle\cos\gamma\rangle = 0.7$

$\langle\sin^2\gamma\rangle = 0.25$

$\langle\cos\Delta\gamma^2\rangle, \langle\sin^2\Delta\gamma^2\rangle$

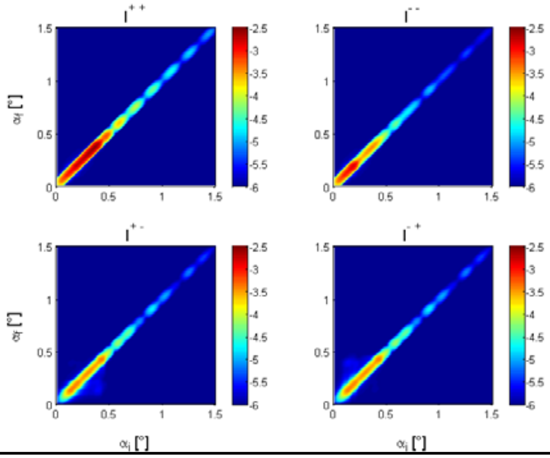
$L_c \approx 100\mu m$

Domain size: 100 μm (> L_c)



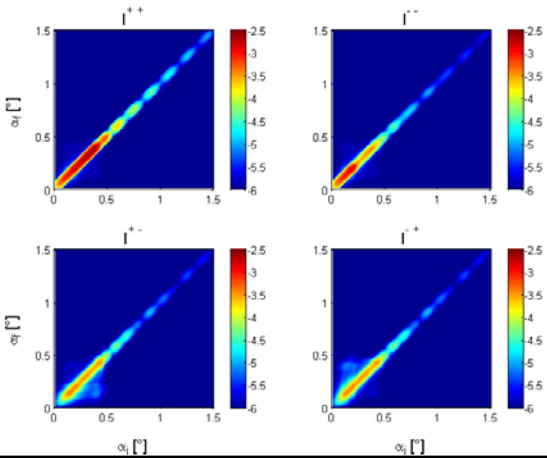
61

Domain size: 100 μm



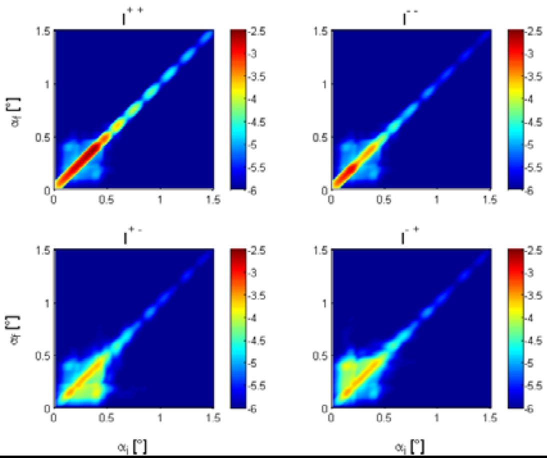
62

Domain size: 50 μm



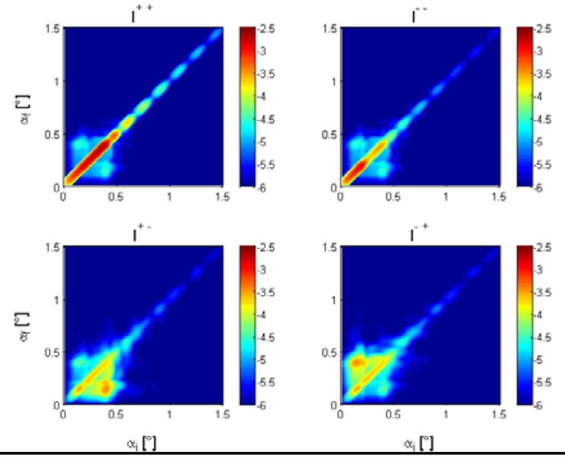
63

Domain size: 10 μm

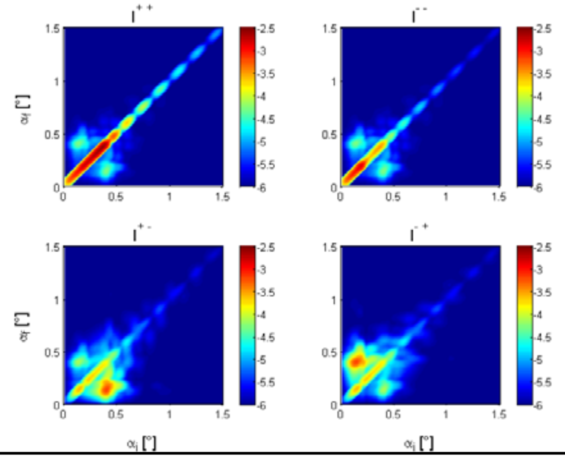


64

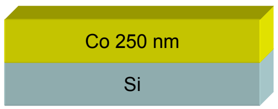
Domain size: 5 μm

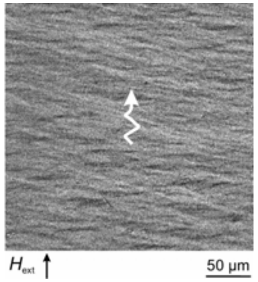


Domain size: 1 μm



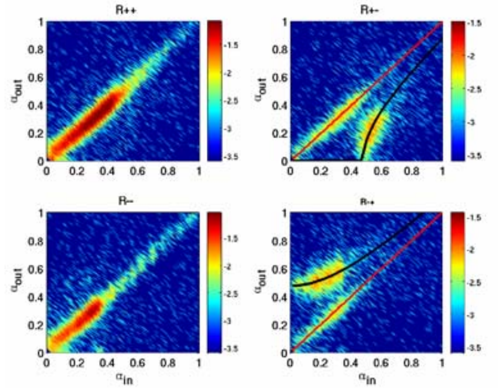
Single ferromagnetic film in the domain state



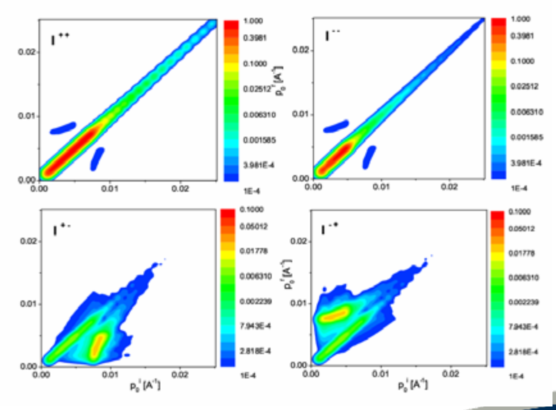


F. Radu *et al*, J. Phys.: Condens. Matter **17** (2005) 1711-1718

Banana shape off-specular scattering from domain state



Simulation of domain state



B.P. Toperverg Physica B **297** (2001) 160-168

Complementarity of techniques

- Photon
  - Element specific
  - Band selective
  - Large resonant enhancements
  - Strong absorption (resonant)
  - Polarisation dependence
  - Small coherence length (<10μm)
- Neutron
  - Large, absolute cross-section
  - Low absorption
  - Polarisation dependence
  - Long coherence length (~100μm)

Nanomagnetism II:

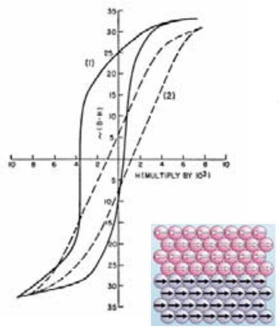
Applications of the nanomagnetism tools

Sean Langridge
Large Scale Structures Group
Rutherford Appleton Laboratory, Chilton, Oxfordshire

s.langridge@rl.ac.uk

Exchange bias

Shifted hysteresis loop away from zero field due to exchange coupling with the last af layer



- Bias field orders of magnitude too large

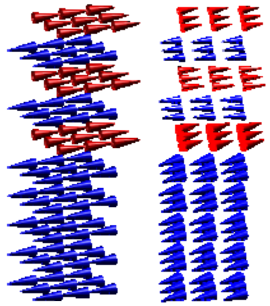
$$H_E = 2JS^2/(a^2Mt)$$

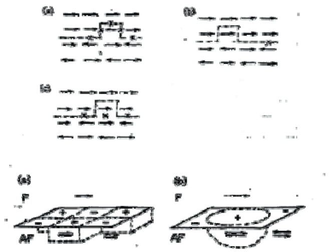
- No coercivity enhancement
- Temperature dependence
- Compensated interfaces

Meiklejohn and Bean Phys. Rev. **105** 904 (1957)

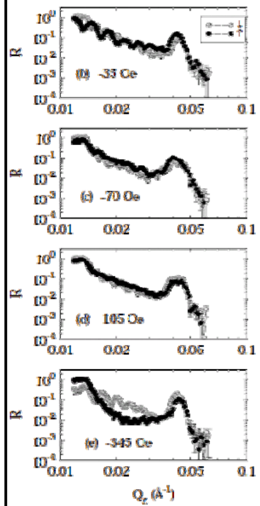
Domain Wall Structure

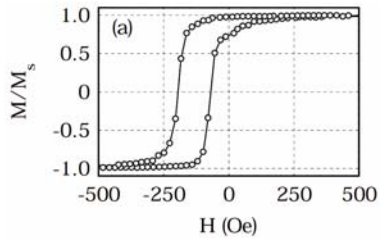
- Parallel Domain wall
  - Mauri *et al. J. Appl. Phys.* ***62, 3047 (1987)***
  - Exchange energy spread into the AF layer
- Perpendicular Domain wall
  - A.P. Malozemoff *Phys. Rev. B.* ***35****, 3679 (1988)*
  - Random field from defects breaks AF into domains





As grown sample

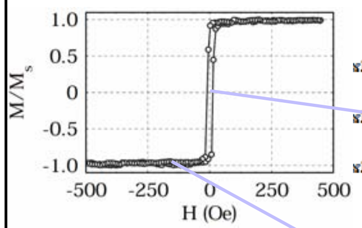


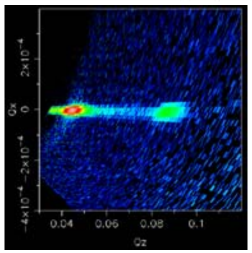


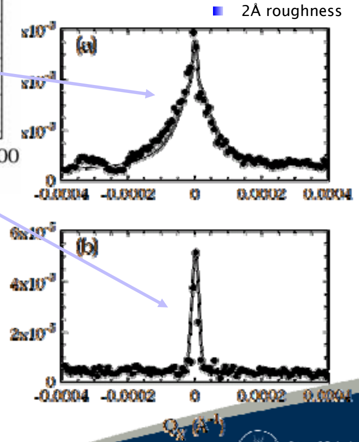
- 150Å bilayer spacing
- Broadening of Bragg peak
  - loss of vertical coherence

T>Blocking Temperature

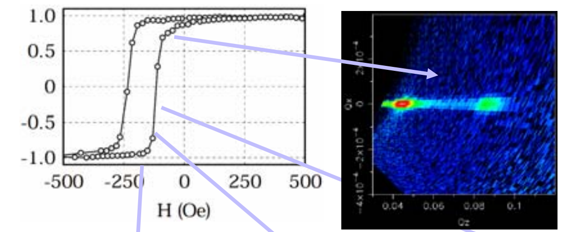
- H_c= 20 Oe
- T=200ºC
- σ=1.9 μm
- 2Å roughness



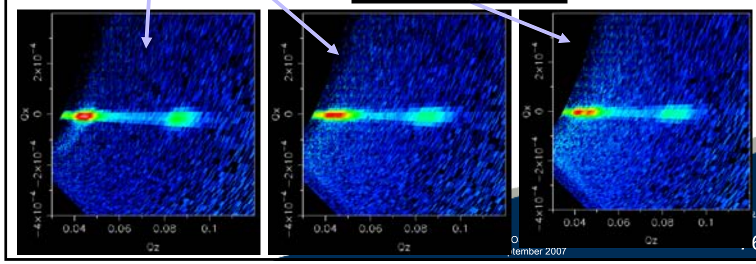




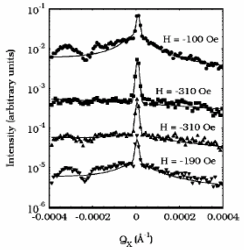
Hysteresis Measurements

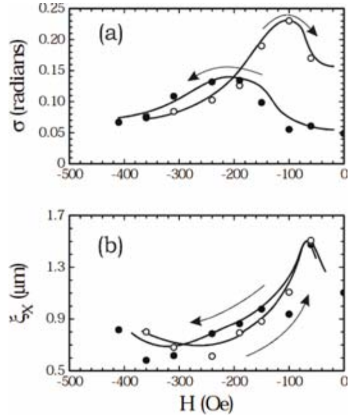


- Field Cooled
- Unpolarised
- Uncorrelated disorder



Field Cooled



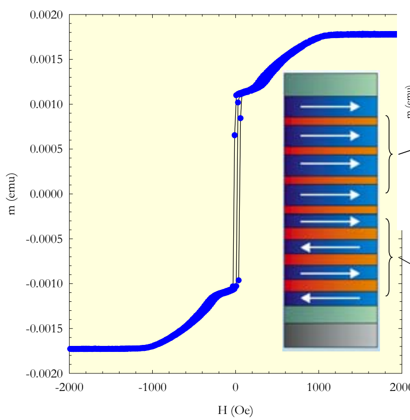


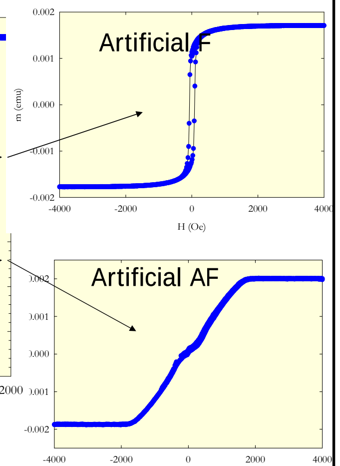
- Asymmetric
- Small domain size
  - Domain size reduces from 1.5µm to 1µm upon reversal
- $\varepsilon_{fc} < \varepsilon_{t>Tb}$

Artificial Exchange bias:

double superlattices

Magnetisation

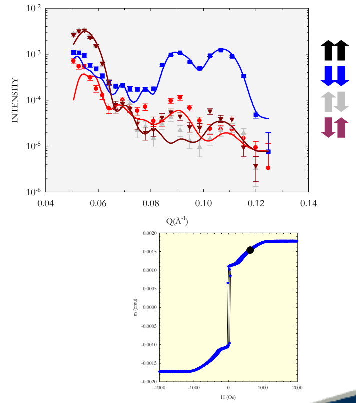


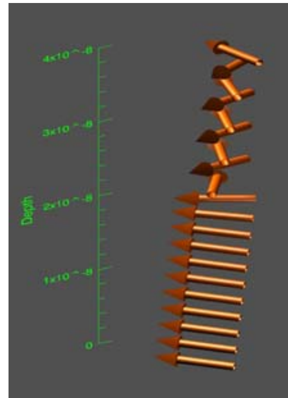


- Good AF (0.25mJ/m²) and F coupling in respective components

Spin-flop phase - I

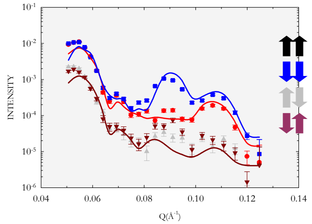
- H=600Oe

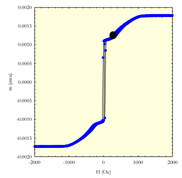


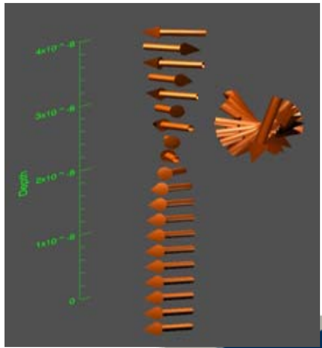


Exchange Spring phase - II

- Exchange spring
- H=160Oe





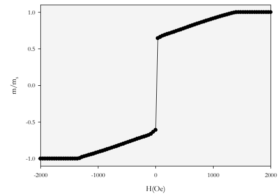


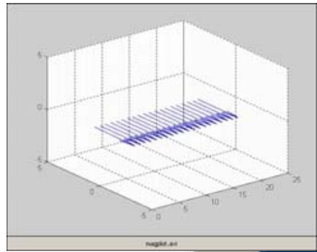
Energy Minimisation

- Minimise the free energy per unit area

$$\epsilon = -\sum \mu_0 m H t cos(\theta_i) - J_i cos(\theta_i - \theta_{i+1})$$

- Monte Carlo algorithm

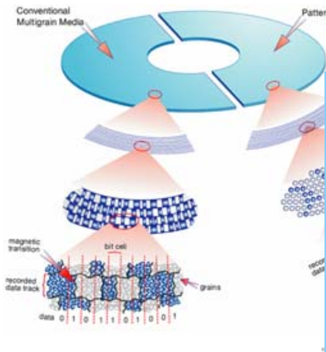


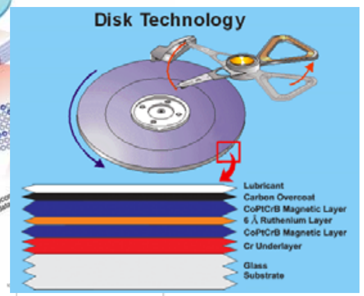


Patterning of magnetic systems

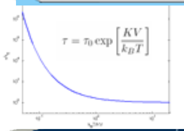
A route to higher recording densities…

Moore's Law for Media



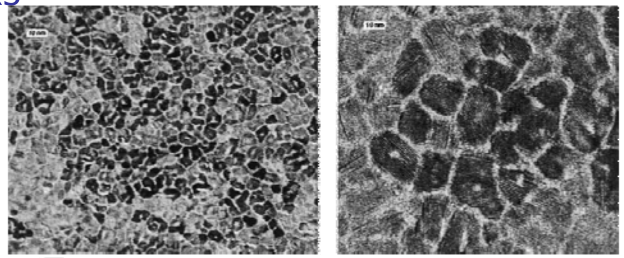


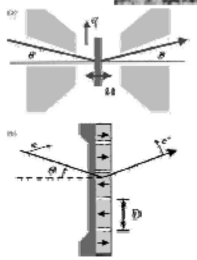
- Perpendicular media recently released
- 270Gb/in² by 2007
- www.hitachigst.com



xrmSAXS

- CoCrPtB
- Amorphous grain boundaries





- xrmSAXS geometry

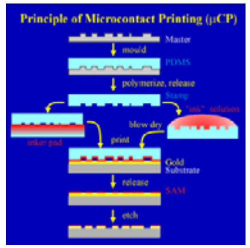
$$f_{E1} = \left[(\hat{\epsilon}' \cdot \hat{\epsilon}) F^0 - i (\hat{\epsilon}' \times \hat{\epsilon}) \cdot \hat{z}_n F^1 + (\hat{\epsilon}' \cdot \hat{z}_n)(\hat{\epsilon} \cdot \hat{z}_n) F^2 \right]$$

- Expect to observe struc-struc and struc-mag correlations

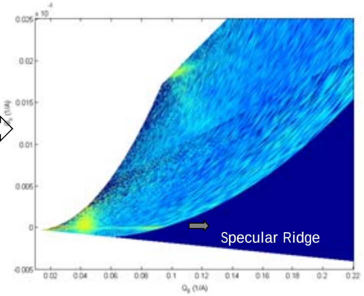
E.E. Fullerton *et al.* Nucl. Instr. and Meth. in Phys. Res. B 200 (2003) 202–209

Stamping magnetic structures

- Micro-stamp production
- 200/200nm stripes
- 20nm high



IBM Zurich



A. Kumar and G. M. Whitesides, Appl. Phys. Lett. **63**, 2002 (1993).

Co L_{III} resonance

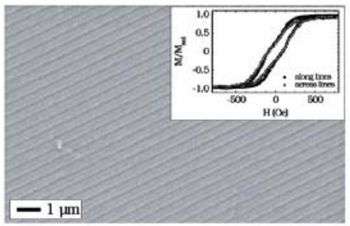
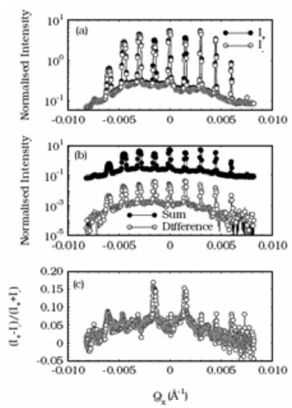
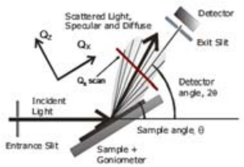


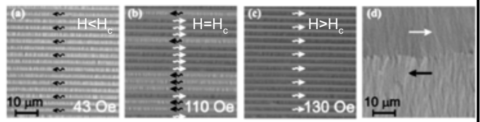
FIG. 1. A scanning electron micrograph of the sample. Inset is a Kerr loop of the sample with the field applied in the plane, both along (•) and across (○) the direction of the lines.

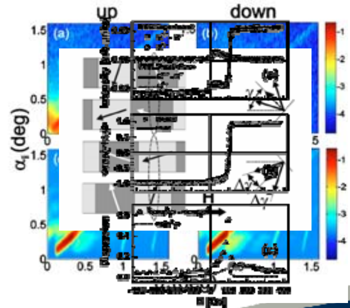




Complementarity: real and reciprocal space

- Combination of real and reciprocal techniques
  - Kerr Microscopy
  - PNR-pa
- CoFe 3µm periodicity
- Ripple domain structure
- dwba analysis
  - S. K. Sinha, E. B. Sirota, S. Garoff, and H. B. Stanley, Phys. Rev. B **38**, 2297 (1988)
  - B. P. Toperverg, Physica **B 297**, 160 (2001); Appl. Phys. A: Mater. Sci. Process. **74**, S1560 (2002)

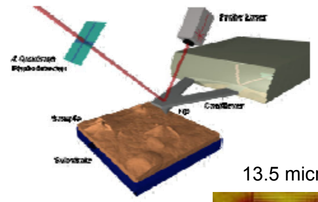


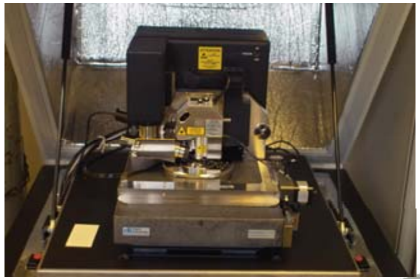


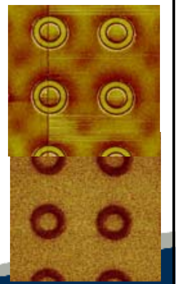
Theis-Brohl *et al.* Phys. Rev. B. 020403(R) (2005)

SPM

- Large sample area
- MFM
- Capacitance
- Liquid Surface adapter
- Torsion Mode



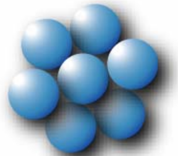


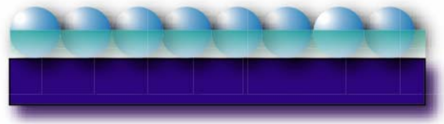


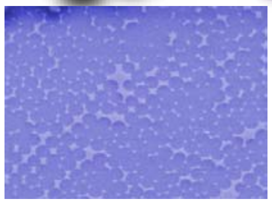
Controlled Surface Morphology

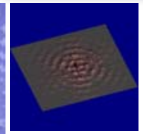
- Self Assembly of 0.2μm latex spheres
  - $[Co(2nm)Ru(1.8nm)]_{50}$

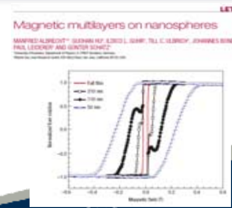
V. Ng, Y. V. Lee, B. T. Chen, and A. O. Adeyeye, Nanotechnology **13**, 554 (2002).





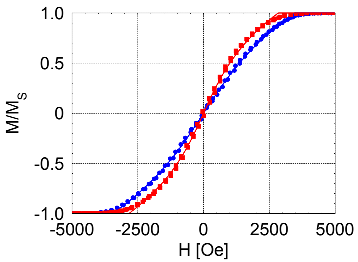





LETTERS
Magnetic multilayers on nanospheres

Exchange Coupling Strength

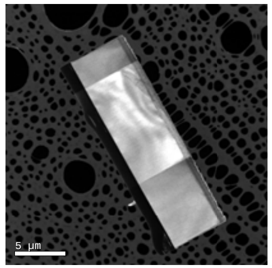
- Separation of bilinear/biquadratic
  - Fullerton & Bader Phys. Rev. B. **53**, 5112 (1996)
  - $\epsilon \approx \mu_0 H m t(\cos\theta_1 + \cos\theta_2) - \mathcal{J}_1 \cos\Theta - \mathcal{J}_2 \cos^2\Theta$
  - $\frac{\mu_0 H m t}{4} = \mathcal{J}_1 - 2\mathcal{J}_2 \cos\theta + 4\mathcal{J}_2 \cos^3\theta$

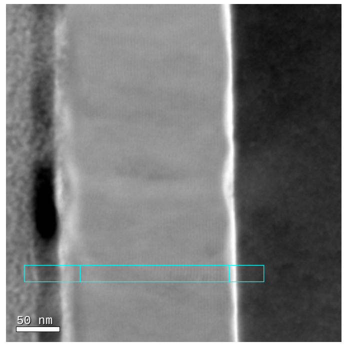


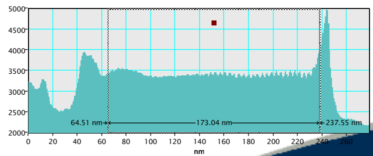
	Clean	Patterned
$\mathcal{J}_1$	-0.62mJm^{-1}	-0.58mJm^{-1}
$\mathcal{J}_2$	-0.05mJm^{-1}	-0.07mJm^{-1}

XTEM

- 320Kx



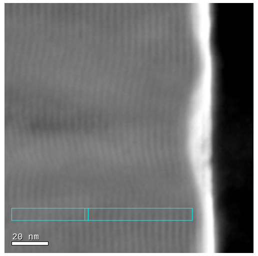


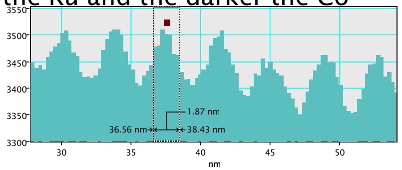


XTEM

910Kx

- The brighter lines are the Ru and the darker the Co



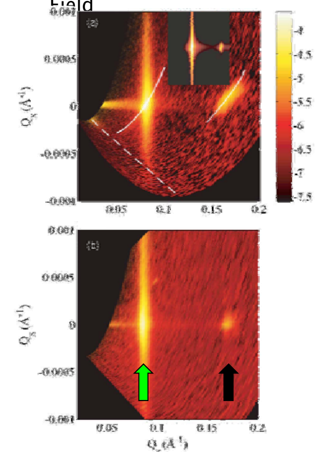


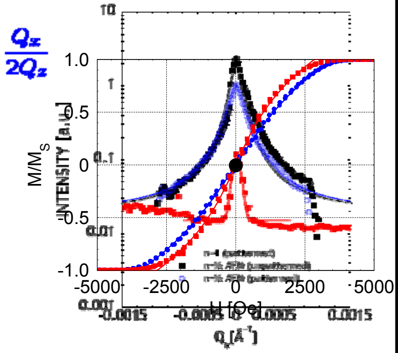
- Layer thicknesses in good agreement with nominal structure

Patterned System

$$\theta = \frac{Q_z}{2Q_i} - \frac{Q_x}{2Q_z}$$

- Coercive Field

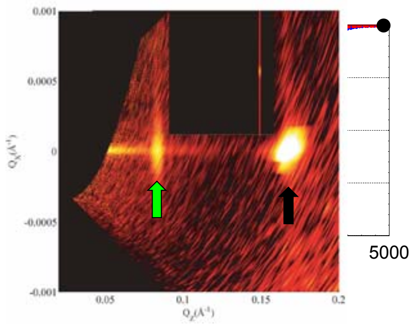


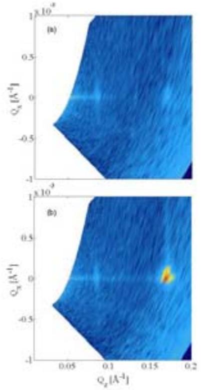


- Vertically correlated anti-ferromagnetic domains
- No evidence for ferromagnetically coupled domains
- ξ_p =3.4±0.5μm, ξ_c =3.9±0.5μm
- Randomly oriented
- Single domain state spheres

Saturation Field

- *Near*-Saturation field

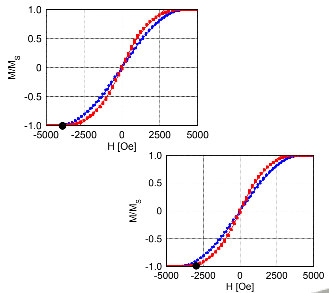


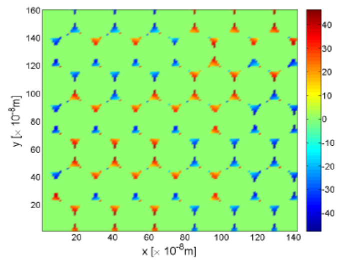


- Magnetic Roughness (cross-correlation of structure and magnetism)
  - Diffuse scattering transferred from AFM to FM Bragg peak
  - ξ_M<2000Å

μ-magnetics

- Simulation reveals rich phase diagram
  - Quantitative agreement
    - AFM domain size
    - Degree of disorder
  - Qualitative agreement with correlation length

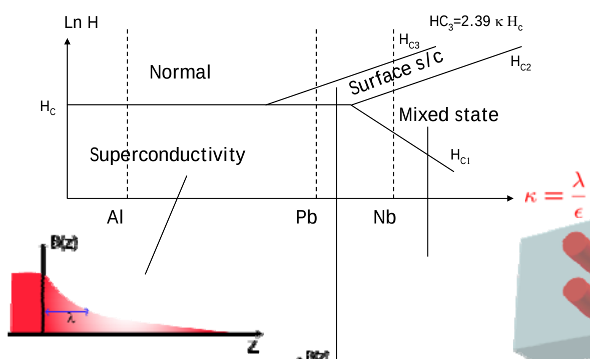


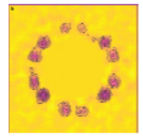


Superconductivity:

flux penetration and proximity effects

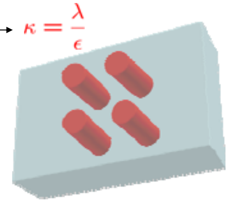
Flux penetration in superconductors



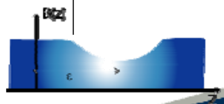


R.J. Cubitt *et al* Phys. Rev. Lett. **91** 047002 (2003)

$\kappa = \frac{\lambda}{\epsilon}$

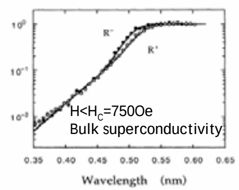


Flux lattice



- $H<H_c$ magnetic induction vanishes except within a penetration depth λ
- $H>H_c$ destroys bulk s/c and magnetic flux penetrates sample
- $H_{c3}>H>H_{c2}$ surface s/c approximately equal to the coherence length, ε
- Pb T_c=7.2K, H_c =800Oe

Flux penetration in superconductors



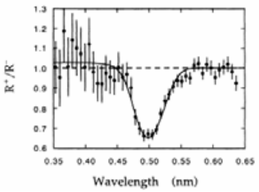


FIG. 2. The spin-dependent reflectivities R^+ and R^- measured in an applied magnetic field of 6.0×10^4 A/m (750 Oe). The continuous lines are the reflectivities calculated for the two polarization states, with the same instrumental and surface parameters as in Fig. 1, and an exponential decay of magnetic induction with a penetration depth of 39 nm.

PHYSICAL REVIEW B VOLUME 49, NUMBER 22 1 JUNE 1994-II

Magnetic-induction profile in a type-I superconductor by polarized-neutron reflectometry

M. P. Nutley*
Institut Laue-Langevin, 156X, 38042 Grenoble CEDEX, France

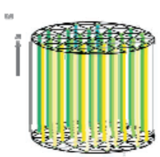
A. T. Boothroyd and C. R. Staddon
Department of Physics, Clarendon Laboratory, University of Oxford, Parks Road, Oxford, OX1 3PU, United Kingdom

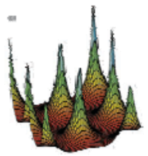
D. M^{c}K. Paul
Department of Physics, University of Warwick, Coventry, CV4 7AL, United Kingdom

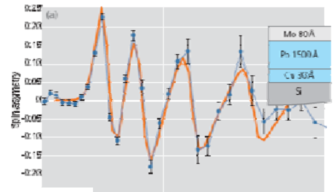
J. Penfold
ISIS Science Division, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon., OX11 0QX, United Kingdom
(Received 17 February 1994)

- 1μm Pb film
- PbO surface layer
- B(z)=μ_0H exp(-z/λ)
- λ=39±1nm
- No field dependence

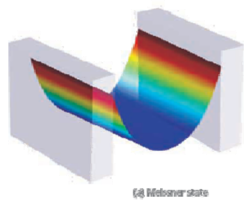
Flux distributions in s/c samples







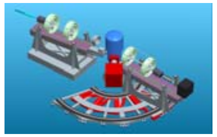
- $\Phi_0 = \frac{h}{2e}$



A. Drew *et al* Phys. Rev. Lett. **95** 197201 (2005)

Summary

- Summary
  - Scattering techniques are ideally suited to a wide range of topical problems in Nanomagnetism research across the magnetic periodic table
  - Ability to characterise μg to pico-grammes of magnetic material
- Acknowledgements
  - Hours on the beamline with…



Acknowledgments

- L.A. Michez, ***C.H. Marrows***, B.J. Hickey
- P. Steadman
- ***C. Kinane***
- Rob Dalgliesh, ***Tim Charlton***
- H. Zabel
- D.G.Bucknall, H-L. Zhang
- J. Dvorak, D. Arena
- R. Springell, G.H. Lander, W.G. Stirling
- EPSRC funded research: EPSRC