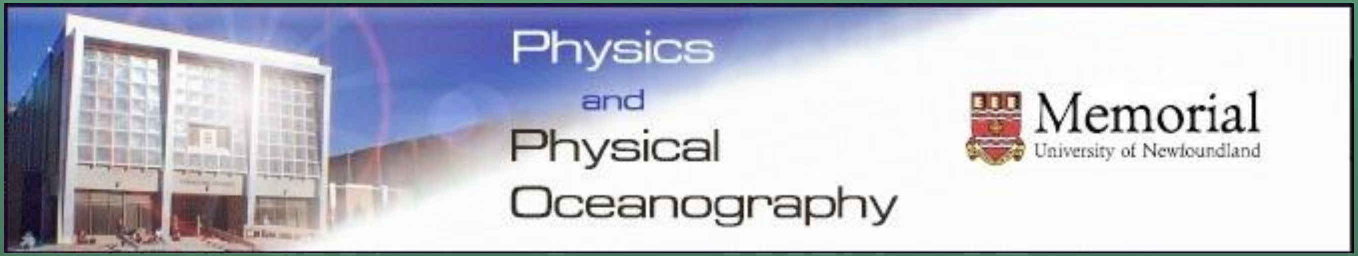
Polarized-neutron Reflectometry from Magnetic Multilayered Films

Lance Parsons

Department of Physics and Physical Oceanography

Memorial University of Newfoundland



Outline

- Neutron Scattering
  - Basic Theory
- Polarized-neutron Specular Reflectometry (PNR)
  - Typical Experimental Setup
- Magnetic Multilayered Films
  - GaMnAs/GaAs superlattices
  - Fe/Cr superlattices

Neutron Scattering

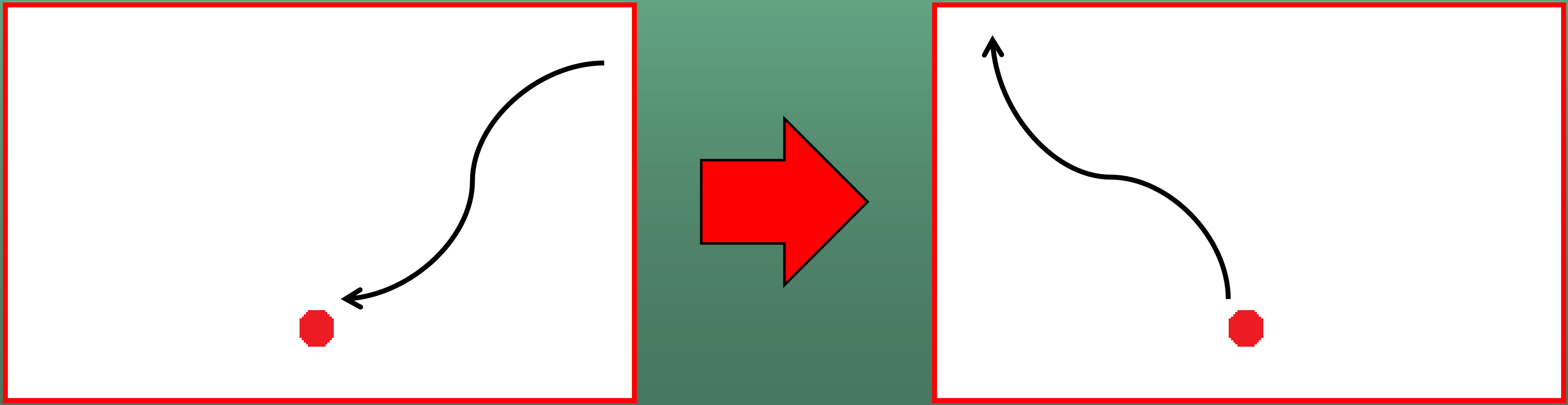
- Neutrons interact with atomic nuclei and magnetic field
- Thermal neutron ($\lambda \sim 10^{-10}$ m) incident on a nucleus ($r_{\text{nucleus}} \sim 10^{-15}$ m)

$$\boxed{\left[-\frac{\hbar^2}{2m_{\mathrm{n}}}\nabla^2\Psi_{\mathrm{n}} + V_{total}\left(\mathbf{r}\right)\right]\Psi_{\mathrm{n}}\left(\mathbf{r}\right) = E\Psi_{\mathrm{n}}\left(\mathbf{r}\right)}$$

$$\boxed{V_{total}\left(\mathbf{r}\right) \approx V_n + V_m}$$

$$\boxed{V_n\left(\mathbf{r}\right) = \frac{2\pi\hbar^2}{m_{\mathrm{n}}}b_n\delta\left(\mathbf{r}\right)}$$

$$\boxed{V_m\left(\mathbf{r}\right) = -\mu_{\mathrm{n}}\cdot\mathbf{B}\left(\mathbf{r}\right)}$$



Neutron Scattering

- Advantages
  - Sensitive for probing lighter atoms
  - Sensitive to isotopes
  - Highly-penetrating and typically non-perturbing
  - Can be used to probe the magnetic structure of samples
- Disadvantages
  - Expensive
  - Samples may become radioactive
  - Relatively lower flux and higher background

Polarized-neutron Reflection

- Magnetization of ferromagnetic thin films

$$\boxed{V_{total}\left(\mathbf{r}\right) \approx V_n + V_m}$$

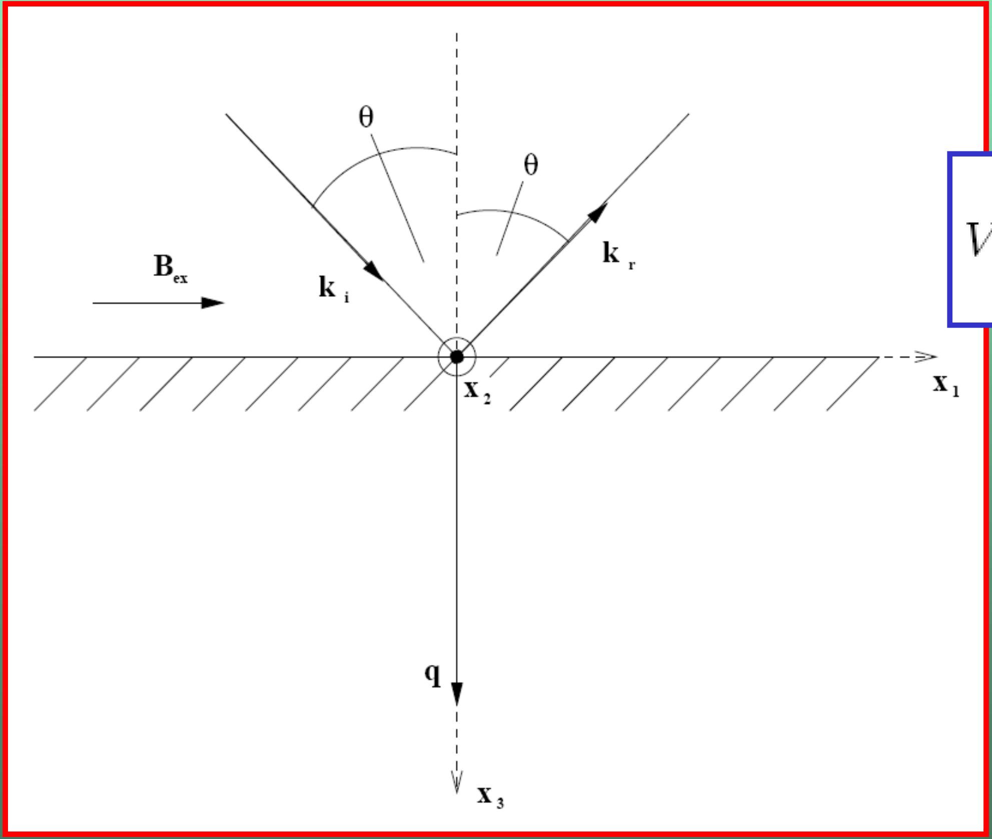
$$\boxed{V_n\left(\mathbf{r}\right) = \frac{2\pi\hbar^2}{m_{\mathrm{n}}} b_n \delta\left(\mathbf{r}\right)}$$

$$\boxed{V_m\left(\mathbf{r}\right) = -\mu_{\mathrm{n}} \cdot \mathbf{B}\left(\mathbf{r}\right)}$$

- Polarized-neutron specular reflectometry
  - Depth profile of the magnetization
- Polarized-neutron off-specular reflectometry
  - Lateral information about the magnetization

Polarized-neutron Specular Reflection

- Neutron magnetic dipole moment is aligned along $\mathbf{B}_{ex}$
- Neutron is reflected at angle θ from a flat surface
- The transfer wavevector **q** is perpendicular to the surface
- One-dimensional problem



$$\mathbf{q} = \mathbf{k}_i - \mathbf{k}_r$$

$$k_r \approx k_i$$

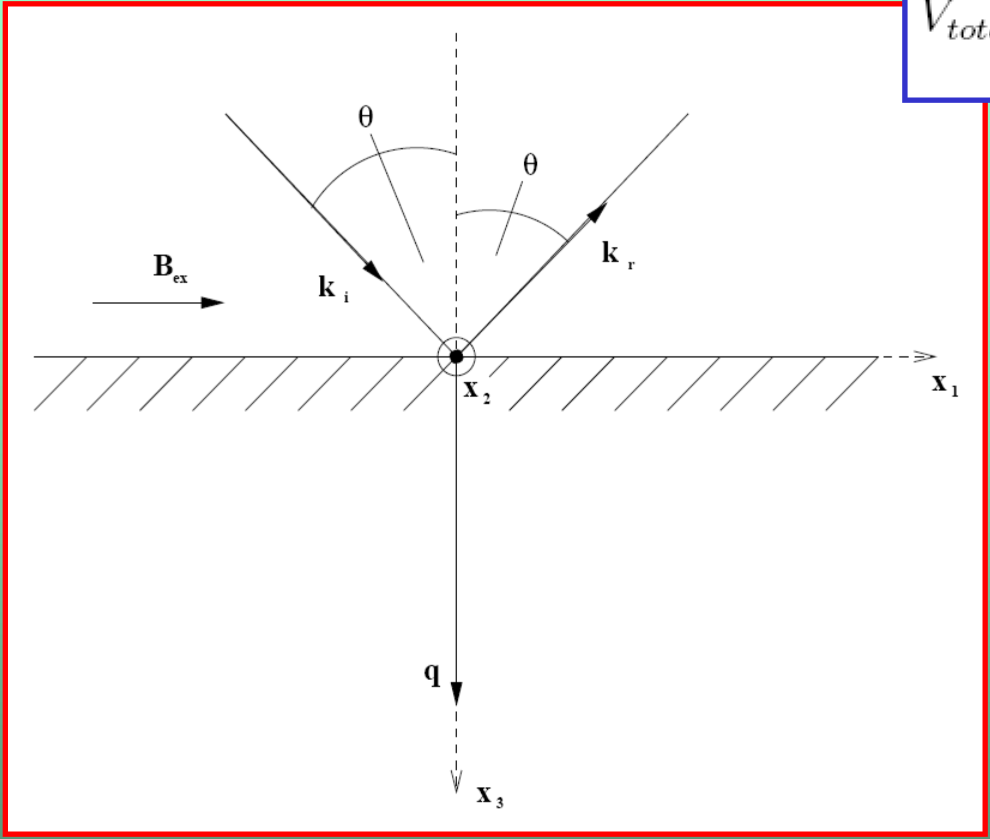
$$q = \frac{4\pi}{\lambda_n} \cos(\theta)$$

$$V_{total}(x_3) = \frac{\hbar^2}{2m_{\mathrm{n}}} N(x_3)\, b_n(x_3) - \mu_{\mathrm{n}} \cdot \mathbf{B}(x_3)$$

$$V_{total}(x_3) = \frac{\hbar^2}{2m_{\mathrm{n}}} N(x_3)\, b(x_3)$$

$$\mathbf{B}(x_3) \propto \mathbf{M}_{in}(x_3)$$

Polarized-neutron Specular Reflection



$$V_{total}\left(x_3\right) = \frac{\hbar^2}{2m_{\mathrm{n}}} N\left(x_3\right) b_n\left(x_3\right) - \mu_{\mathrm{n}} \cdot \mathbf{B}\left(x_3\right)$$

$$\mathbf{B}\left(x_3\right) \propto \mathbf{M}_{in}\left(x_3\right)$$

parallel → “+”-state

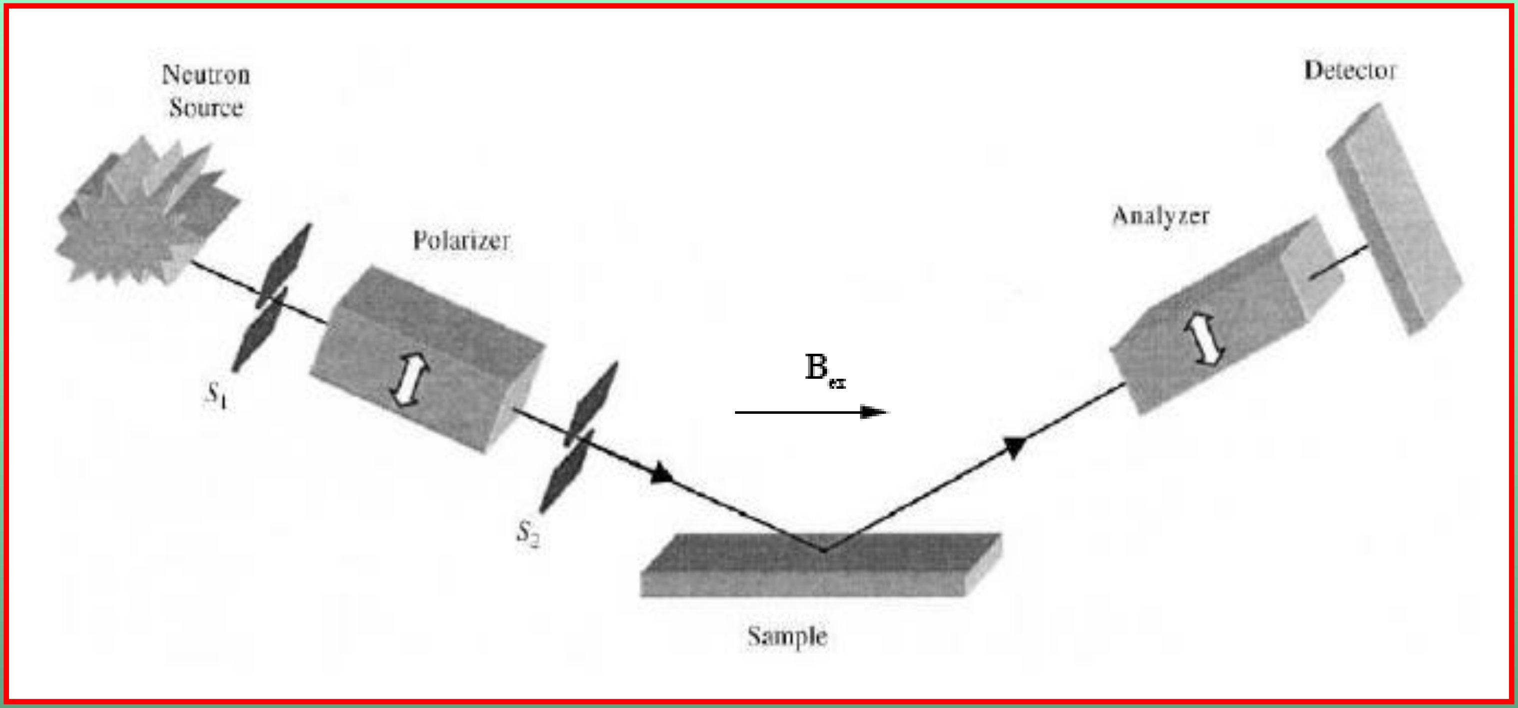
Anti-parallel → “-”-state

$$P_{NSF} \propto \left[\mathbf{M}_{in}\left(x_3\right)\right]^{\parallel} \qquad P_{SF} \propto \left[\mathbf{M}_{in}\left(x_3\right)\right]^{\perp}$$

- Neutron magnetic dipole moment may flip when reflected from a ferromagnetic material of magnetization **M**

Polarized-neutron Specular Reflectometry

- Experiment is carried out in a magnetic field

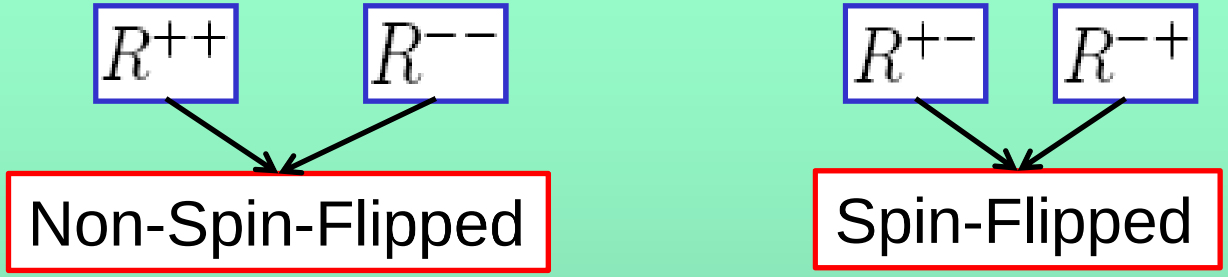


J.F. Ankner and G.P. Felcher, J. Magn. Magn. Mater. 200, 741, (1999).

R^{++} R^{--} → Non-Spin-Flipped

R^{+-} R^{-+} → Spin-Flipped

Polarized-neutron Specular Reflectometry



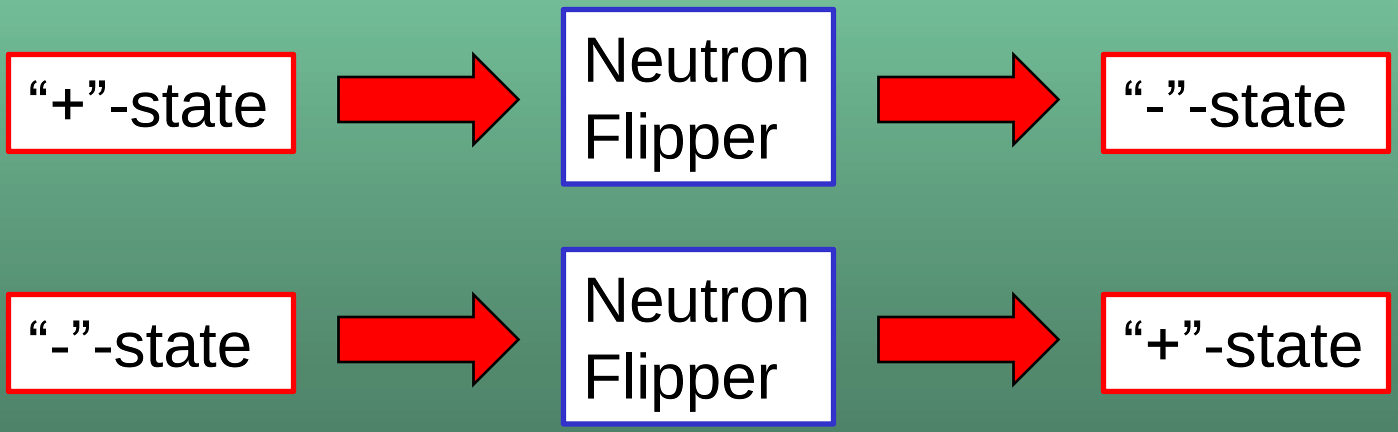
R^{++} R^{--}

Non-Spin-Flipped

R^{+-} R^{-+}

Spin-Flipped

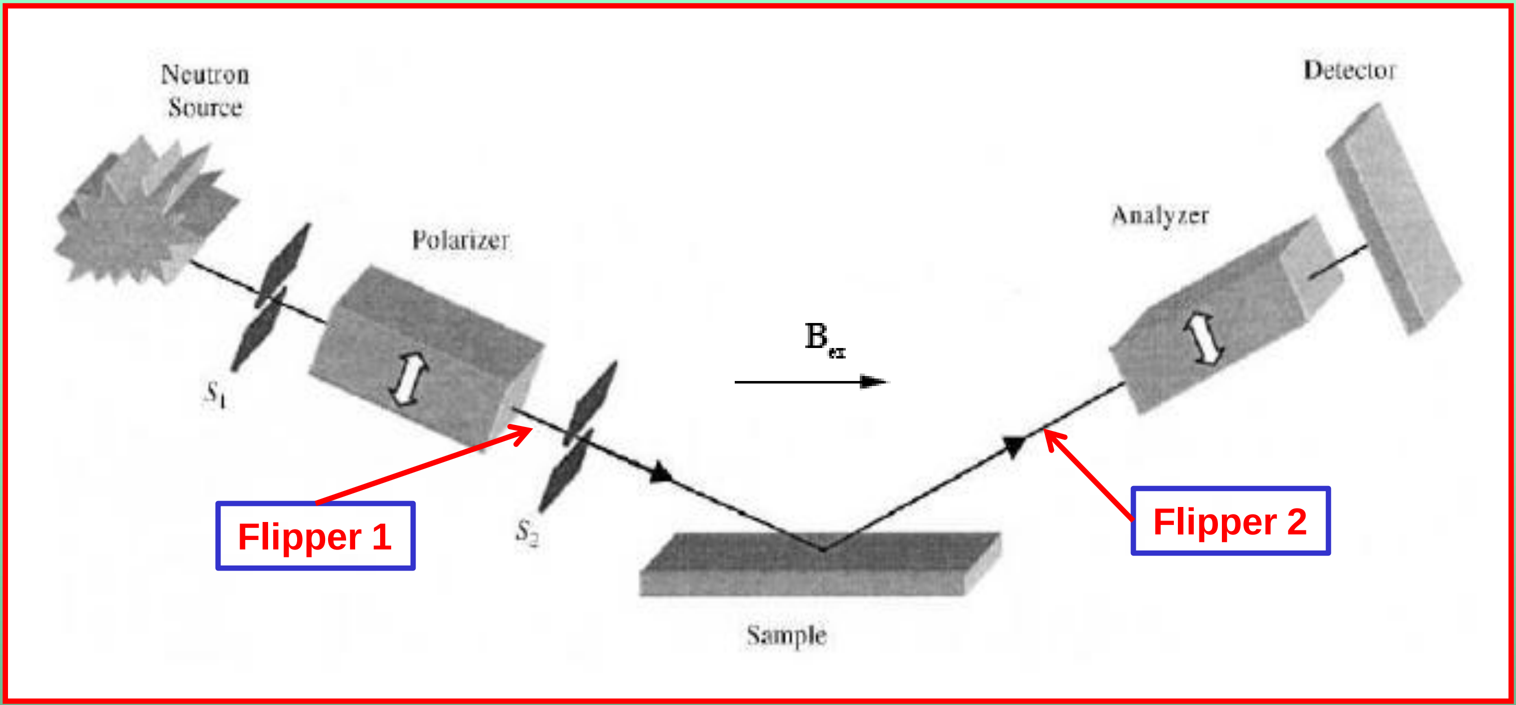
Use a neutron flipper to flip the polarization



"+"-state → Neutron Flipper → "-"-state

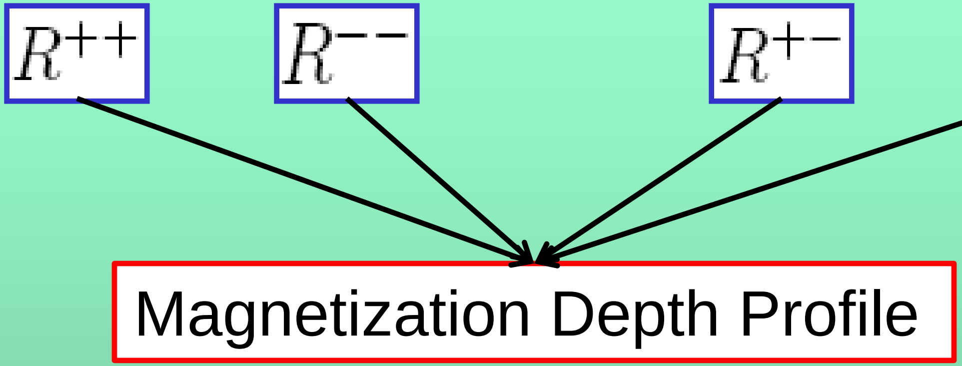
"-"-state → Neutron Flipper → "+"-state

Polarized-neutron Specular Reflectometry



Polarizer Orientation	Flipper 1	Flipper 2	Reflectance
+	No	No	R^{++}
+	Yes	No	R^{-+}
+	No	Yes	R^{+-}
+	Yes	Yes	R^{--}

Polarized-neutron Specular Reflectometry



R^{++}

R^{--}

R^{+-}

R^{-+}

Magnetization Depth Profile

- R(**q**) is the Fourier transform of the scattering length b(x$_3$)
- **q** can be probed by either varying the angle θ at fixed neutron wavelength λ or by varying λ at a fixed θ

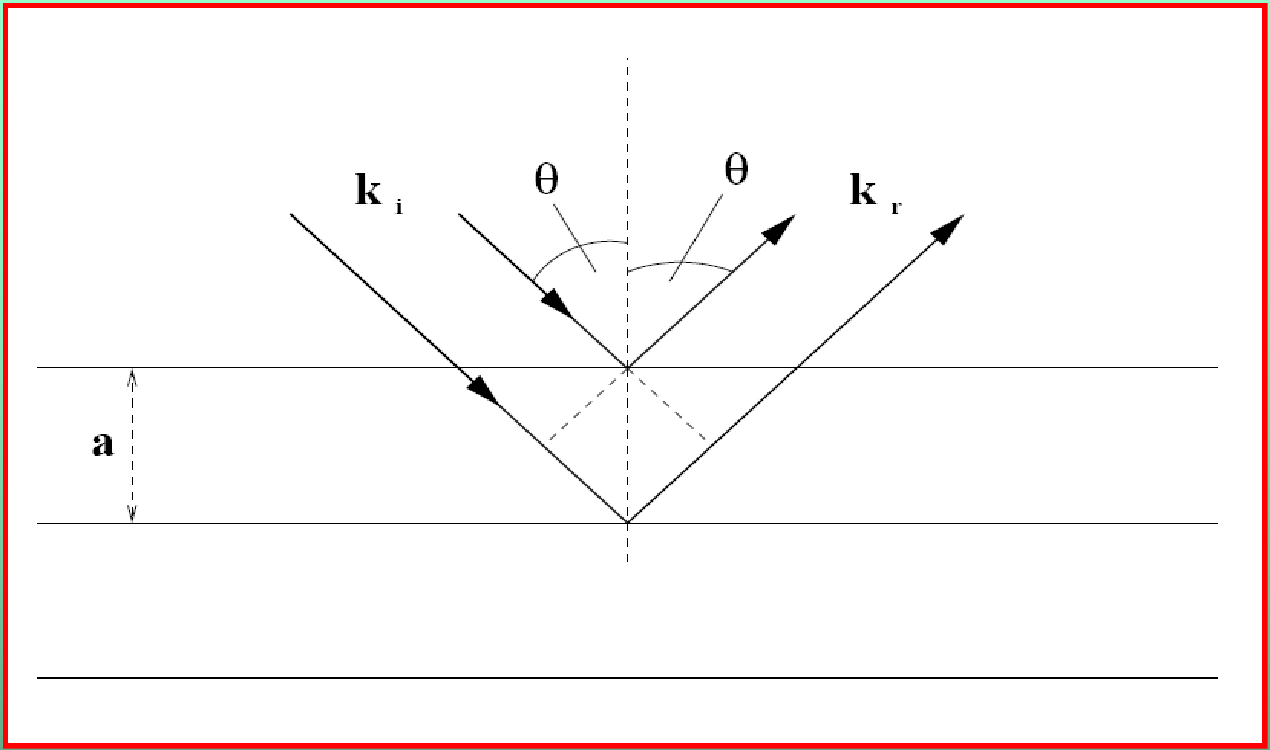
$$q = \frac{4\pi}{\lambda_n}\cos\left(\theta\right)$$

$$V_{total}\left(x_3\right) = \frac{\hbar^2}{2m_{\mathrm{n}}} N\left(x_3\right) b\left(x_3\right)$$

$$V_{total}\left(x_3\right) = \frac{\hbar^2}{2m_{\mathrm{n}}} N\left(x_3\right) b_n\left(x_3\right) - \mu_{\mathrm{n}} \cdot \mathbf{B}\left(x_3\right)$$

$$\mathbf{B}\left(x_3\right) \propto \mathbf{M}_{in}\left(x_3\right)$$

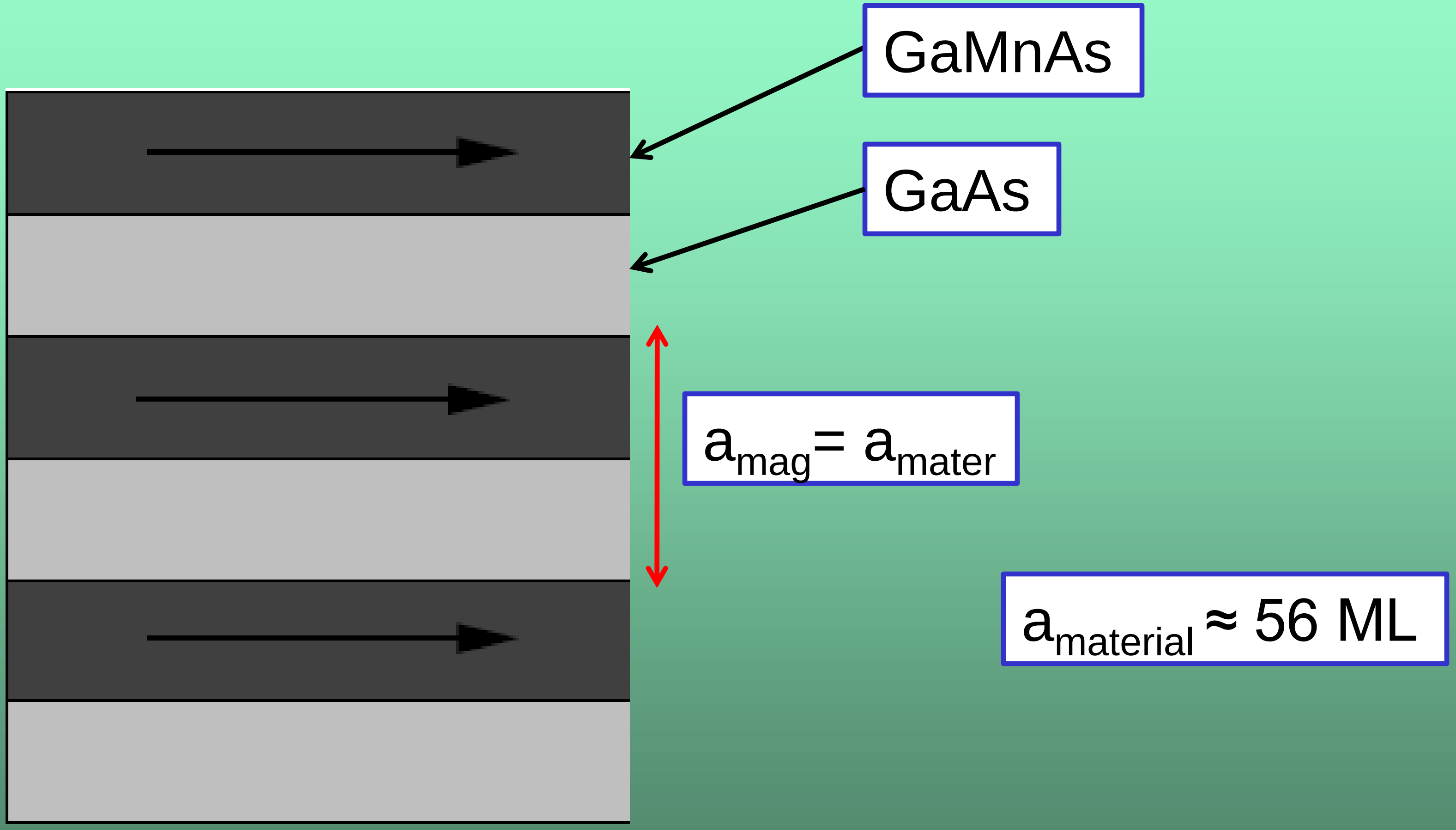
Bragg Reflection



$$\boxed{2a\cos\theta = m\lambda_{\mathrm{n}}} \longrightarrow \boxed{q = \frac{4\pi}{\lambda_n}\cos(\theta)} \longrightarrow \boxed{q_b = \frac{2\pi m}{a}}$$

Preferential reflection at the Bragg wavevector

GaMnAs/GaAs Superlattice

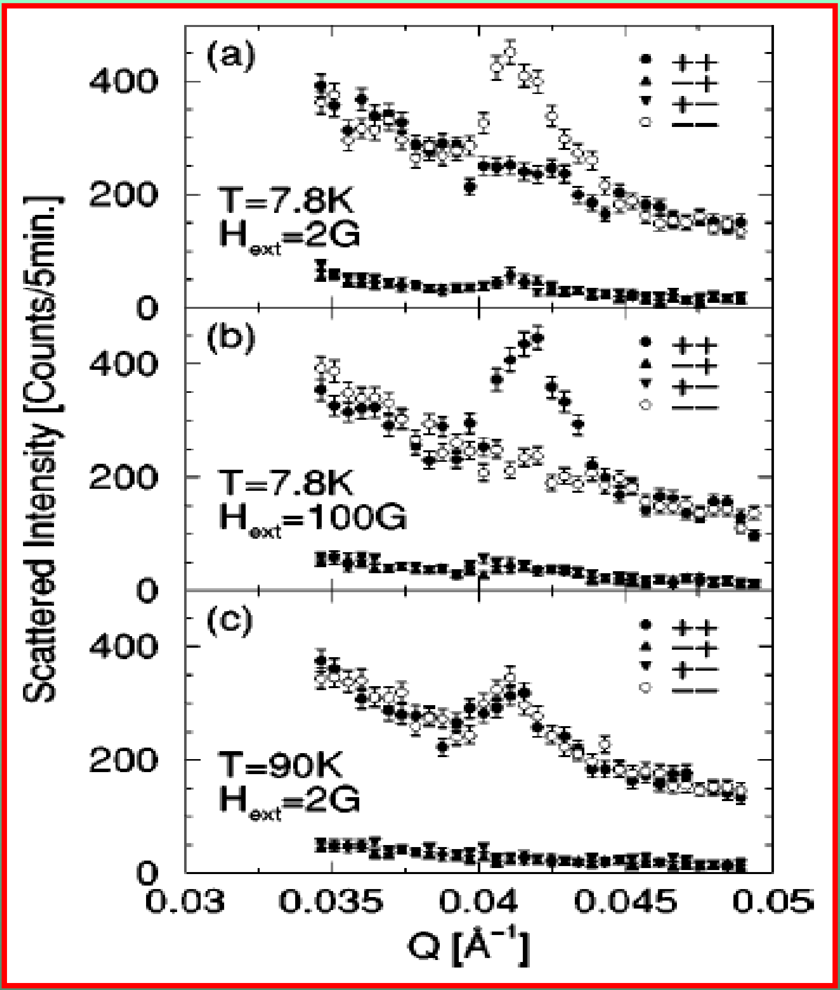


$a_{mag} = a_{mater}$

$a_{material} \approx 56$ ML

Ferromagnetic coupling between the GaMnAs layers

GaMnAs/GaAs Superlattice



H. Kepa *et al.*, Phys. Rev. B 64, 121302, (2001).

$a_{mag} = a_{mater}$

$$q_b = \frac{2\pi m}{a}$$

$$P_{NSF} \propto \left[\mathbf{M}_{in}\left(x_3\right)\right]^{\parallel}$$

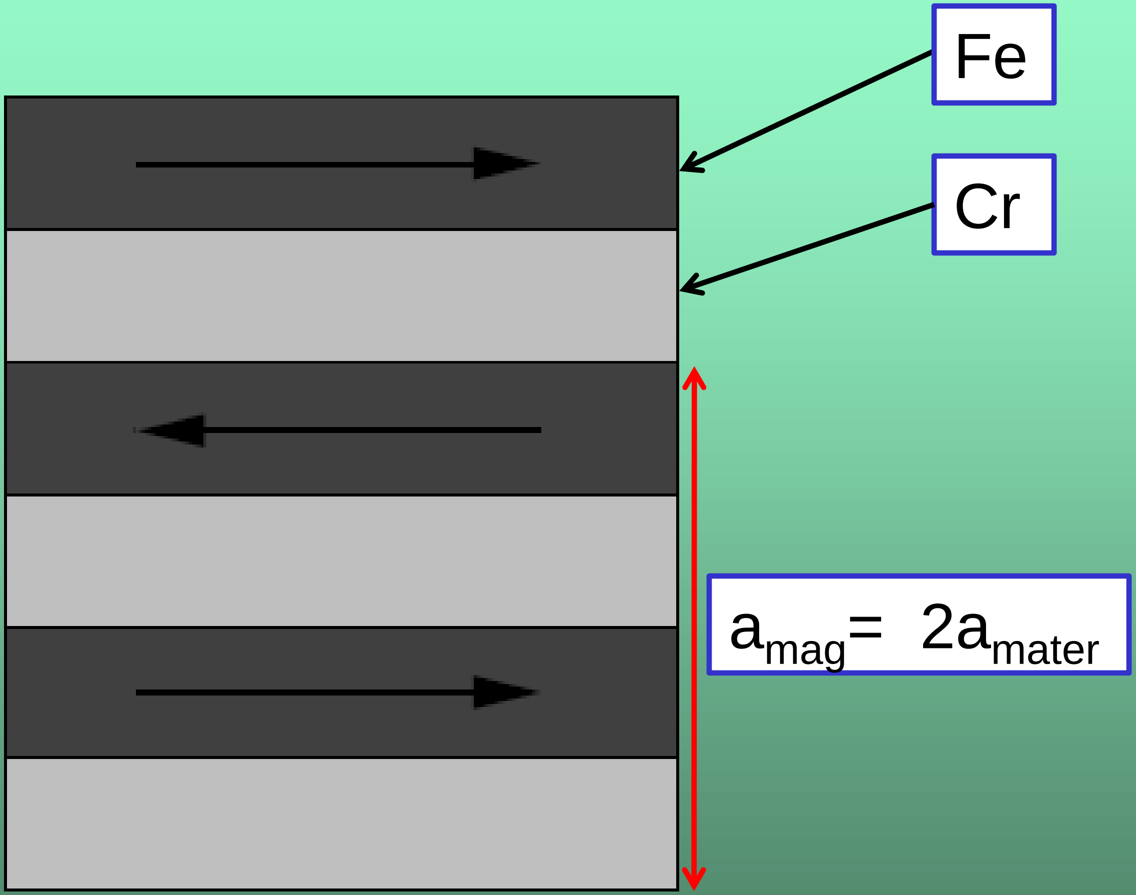
$$P_{SF} \propto \left[\mathbf{M}_{in}\left(x_3\right)\right]^{\perp}$$

$$V_{total}\left(x_3\right) = \frac{\hbar^2}{2m_{\mathrm{n}}} N\left(x_3\right) b_n\left(x_3\right) - \mu_{\mathrm{n}} \cdot \mathbf{B}\left(x_3\right)$$

→

$$V_{total}\left(x_3\right) = \frac{\hbar^2}{2m_{\mathrm{n}}} N\left(x_3\right) b_n\left(x_3\right) \pm \mu_{\mathrm{n}} B\left(x_3\right)$$

Fe/Cr Superlattice



Fe

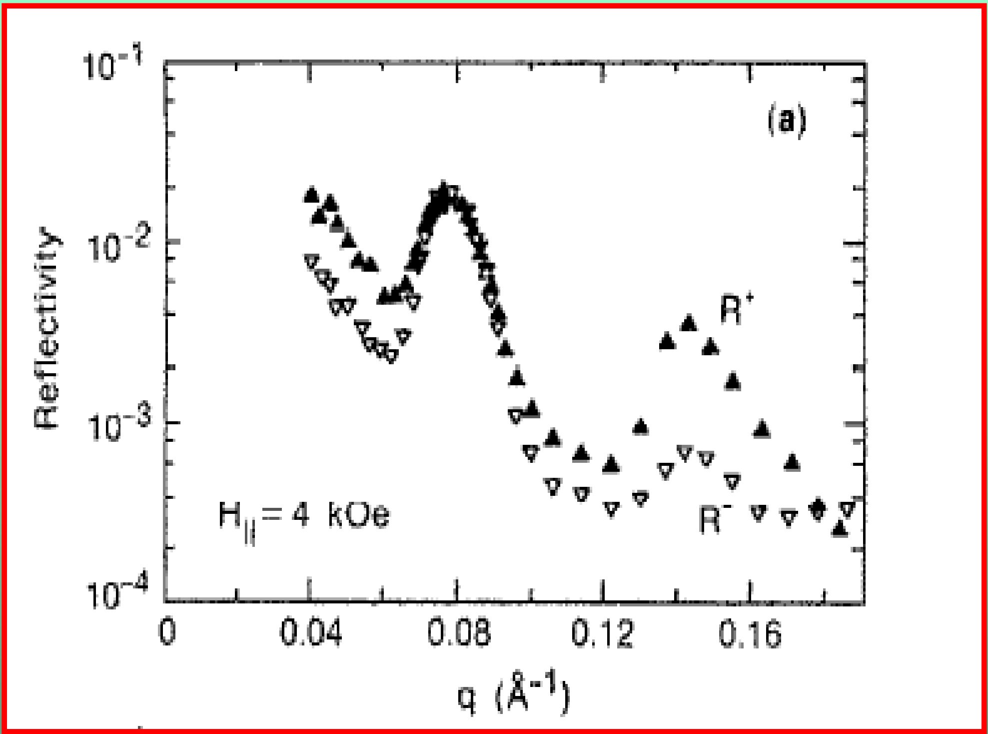
Cr

$a_{mag} = 2a_{mater}$

Anti-ferromagnetic coupling between the Fe layers

Fe/Cr Superlattice

$\mathbf{B}_{\mathbf{ex}}$= 4 kOe



S.S. P. Parkin, A. Mansour, and G.P. Felcher. Appl. Phys. Lett. 58, 14, (1991).

$a_{material} = 42*10^{-10}$ m

$a_{mag} = 2a_{mater}$

$$q_b = \frac{2\pi m}{a}$$

$$P_{NSF} \propto \left[\mathbf{M}_{in}\left(x_3\right)\right]^{\parallel}$$

$$V_{total}\left(x_3\right) = \frac{\hbar^2}{2m_{\mathrm{n}}} N\left(x_3\right) b_n\left(x_3\right) - \mu_{\mathrm{n}} \cdot \mathbf{B}\left(x_3\right)$$

Fe/Cr Superlattice

$\mathbf{B}_{\mathbf{ex}}$= 17 G

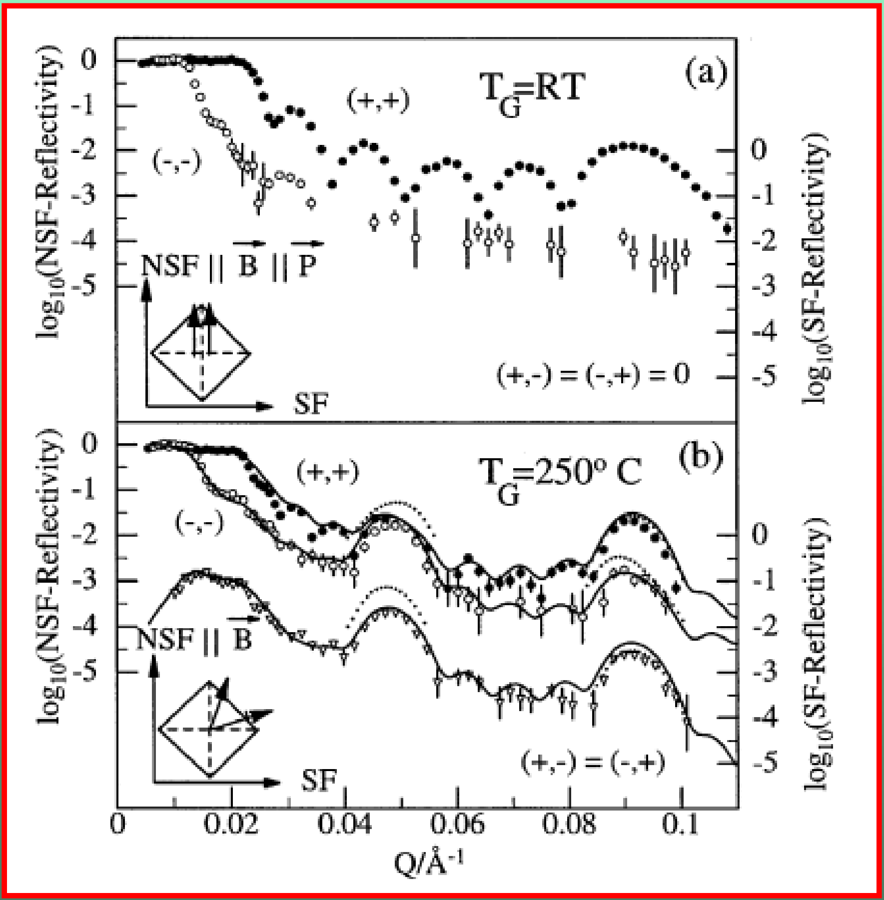
$a_{material} = 69*10^{-10}$ m

$a_{mag} = 2a_{mater}$

$$q_b = \frac{2\pi m}{a}$$

$$P_{NSF} \propto [\mathbf{M}_{in}(x_3)]^{\parallel}$$

$$P_{SF} \propto [\mathbf{M}_{in}(x_3)]^{\perp}$$



A. Schreyer *et. al* Physica B 221, 366, (1996).

Summary of Results

- Polarized-neutron specular reflectometry can be used to obtain depth profiles of the magnetization of magnetic thin films
- Studies on GaMnAs/GaAs and Fe/Cr multilayered films have shown displayed peaks in intensity corresponding to the periodicity of magnetic interaction
- The effects of external magnetic field and temperature on the sample magnetization have been investigated