

Adventures in Neutron Magnetometry of Magnetic Multilayers

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The Experimental Program to Stimulate
Competitive Research (EPSCoR)
Program Review

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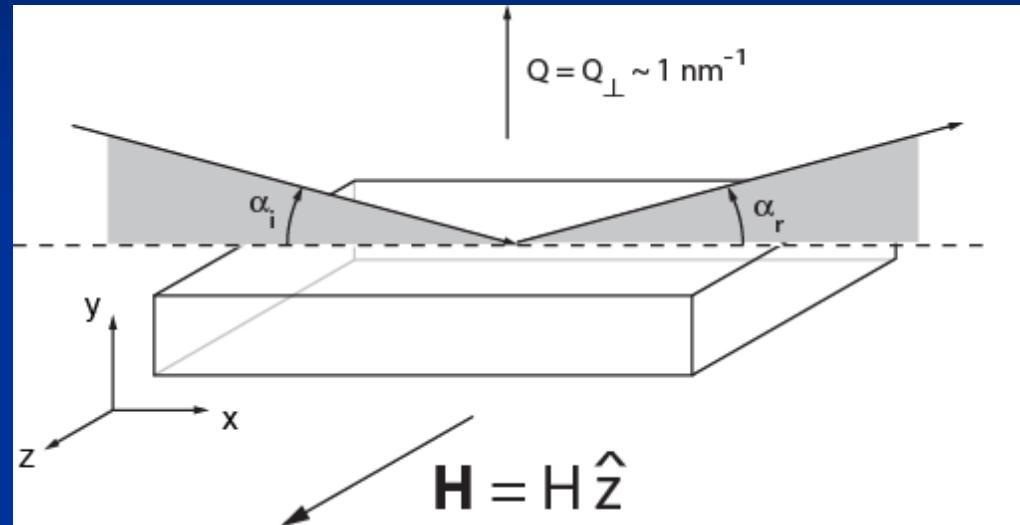


Collaborators:
Michael Fitzsimmons, LANL (LANSCE)
Gian P. Felcher, ANL (IPNS)
Julie Borchers, NIST





Neutron Reflectometry



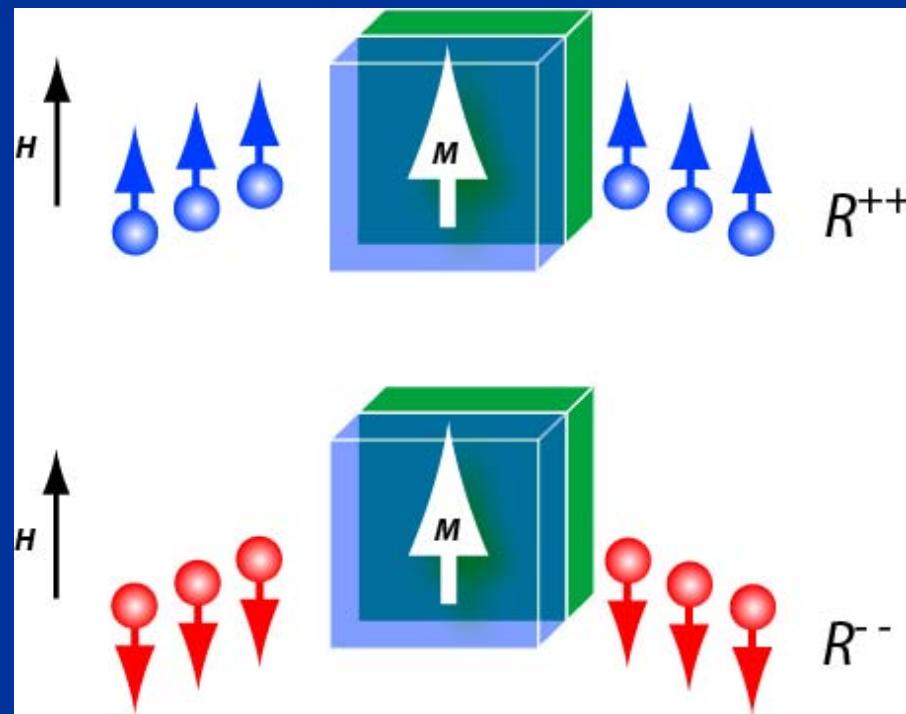
- Neutrons have spin
- Therefore the effective index of refraction of a material depends on its magnetization



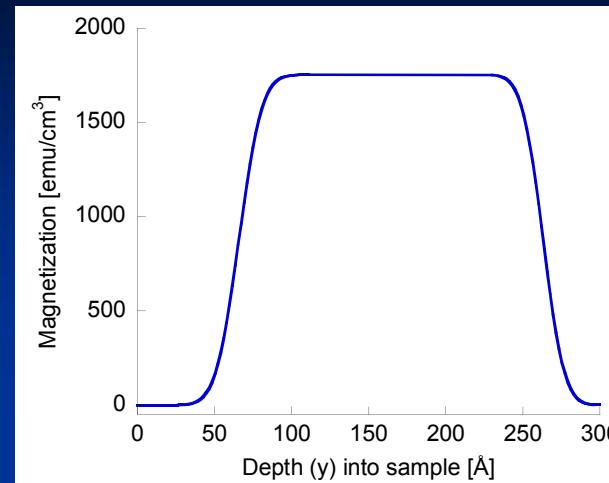
A Magnetic Material is Birefringent

$$V = \frac{2\pi\hbar^2}{m_n} (\rho_n \pm \rho_m)$$

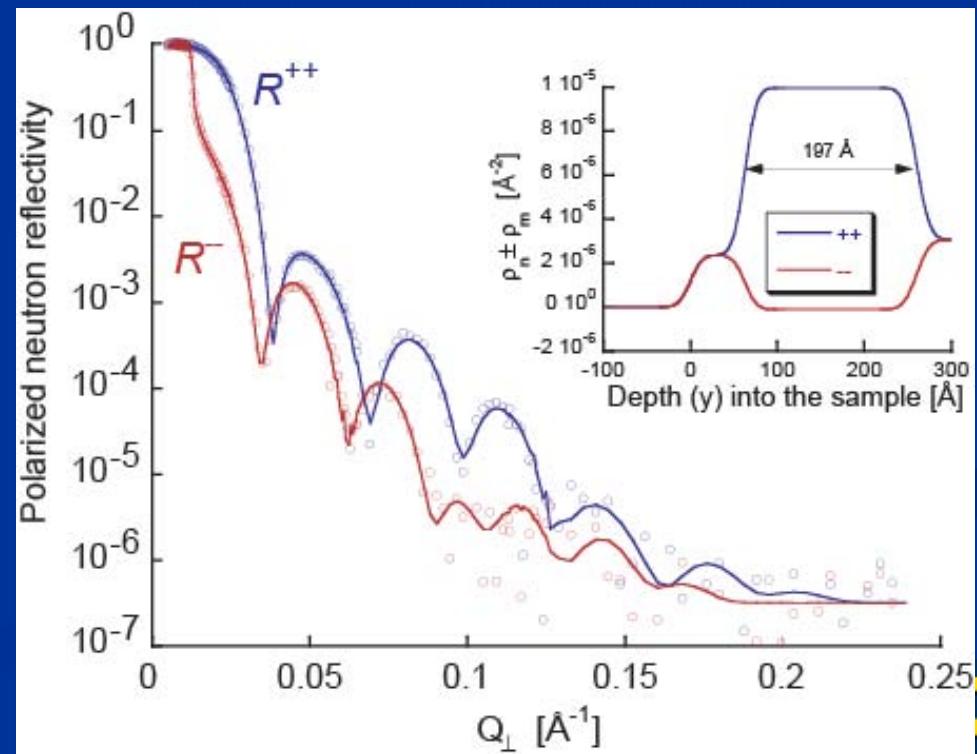
$$k_{\perp}^{\pm} = \sqrt{k_{0\perp}^2 - 4\pi(\rho_n \pm \rho_m)}$$



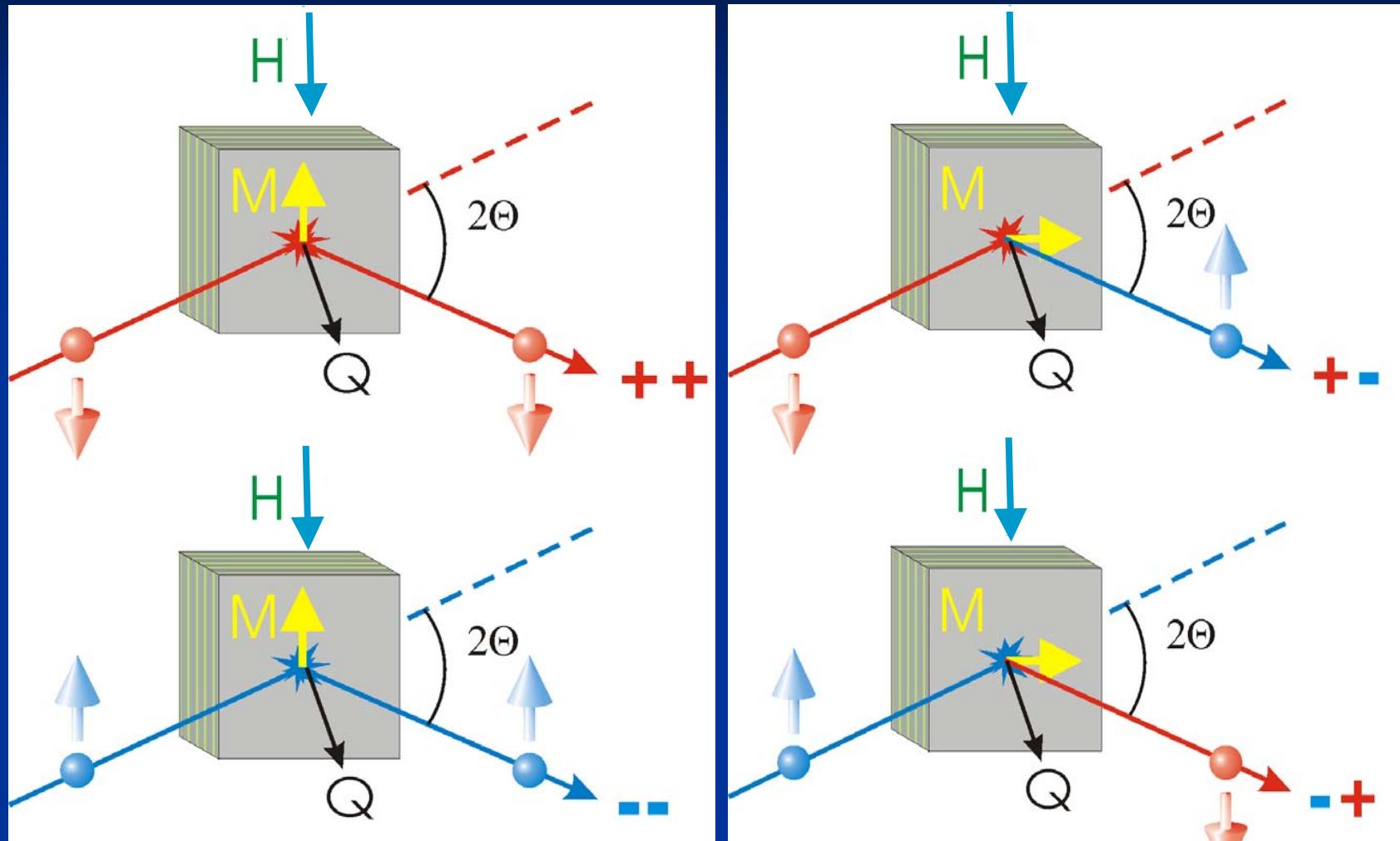
(Courtesy M. Fitzsimmons)



Fe film



Polarized Neutron Reflectometry

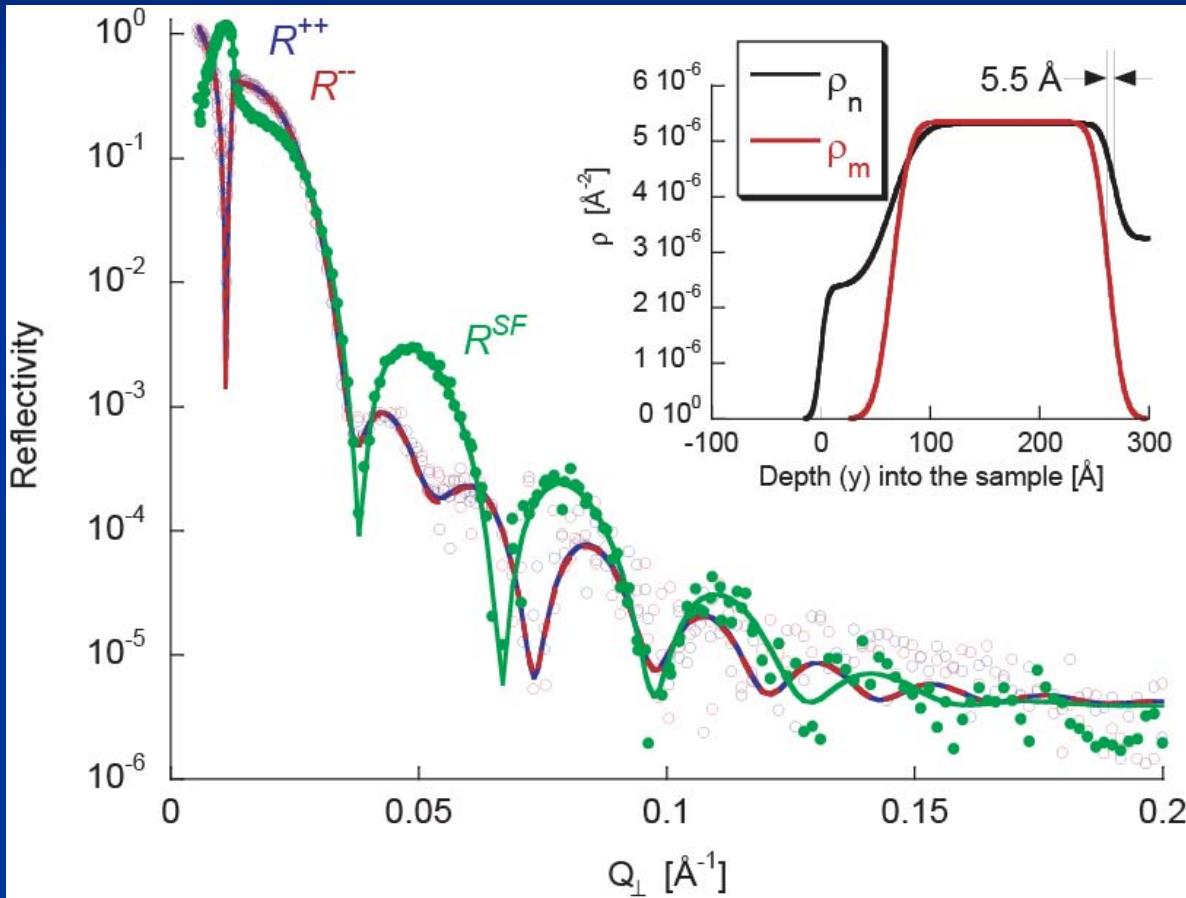
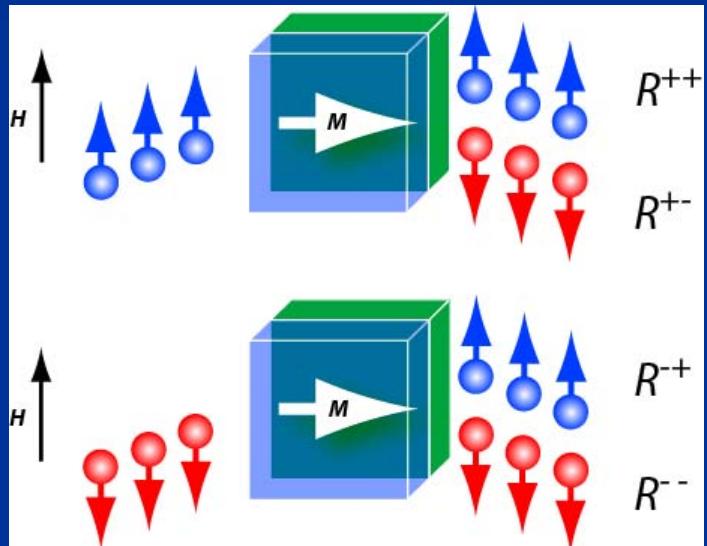


Non spin-flip cross-sections yield: $M_{||}$ as a function of Q .

Spin-flip cross-sections yield M_{\perp} as a function of Q .



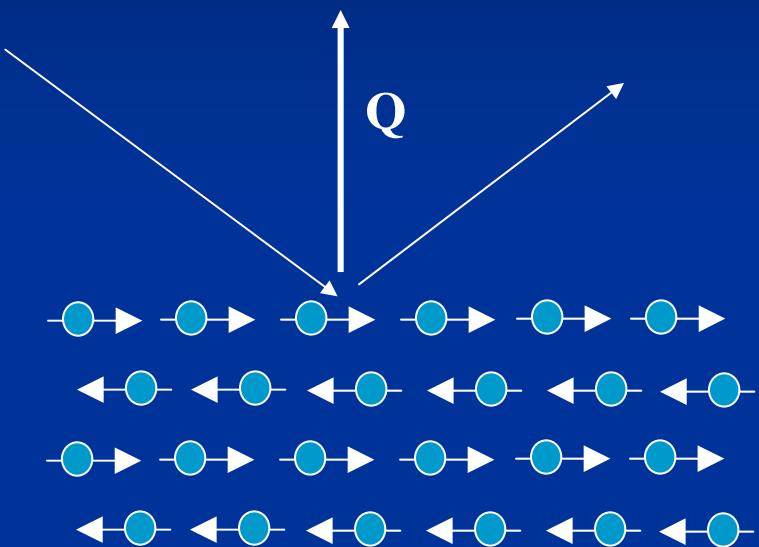
PNR Combines Vector Magnetometry With Depth Profiling



See also: S. Park et al., PRB 70 104406 (2006).



Neutron Diffraction Applied to Antiferromagnetic Materials



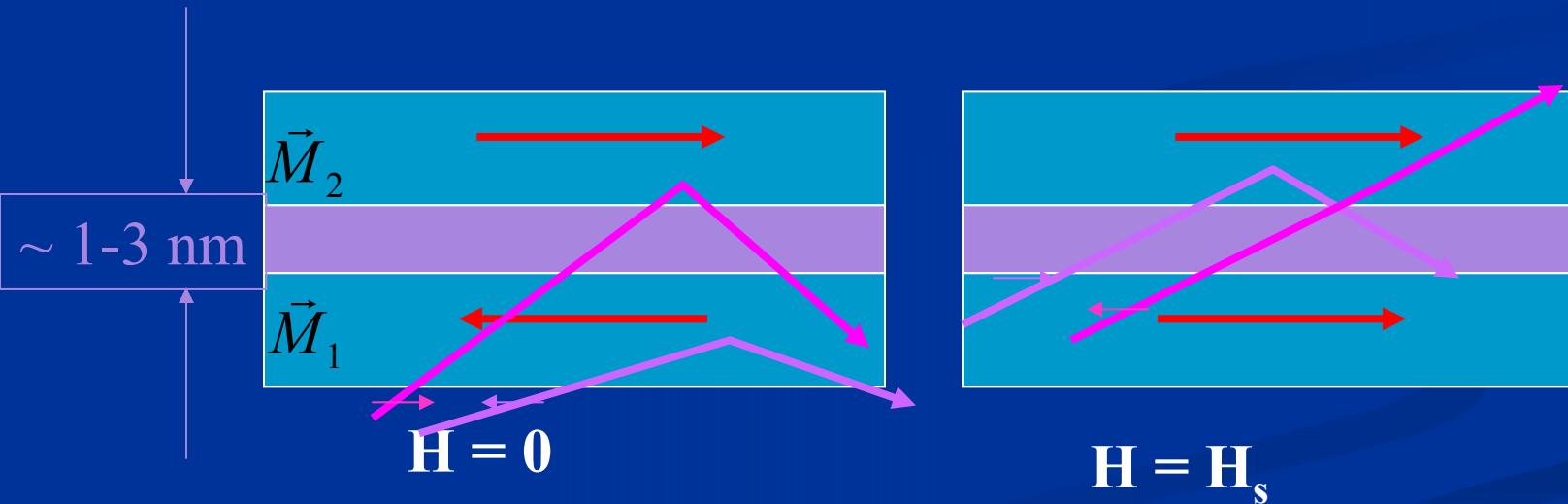
C. Shull, ORNL 1994 Nobel Prize

Nuclear (001) reflection forbidden
Magnetic (001) reflection allowed
Amplitude of AF (001) peak proportional to $(M_{AF})^2$



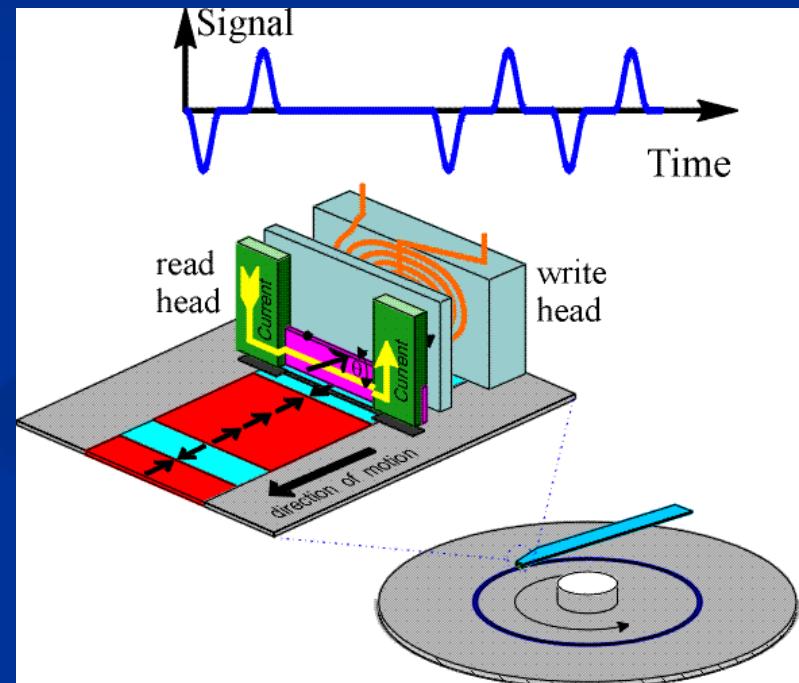
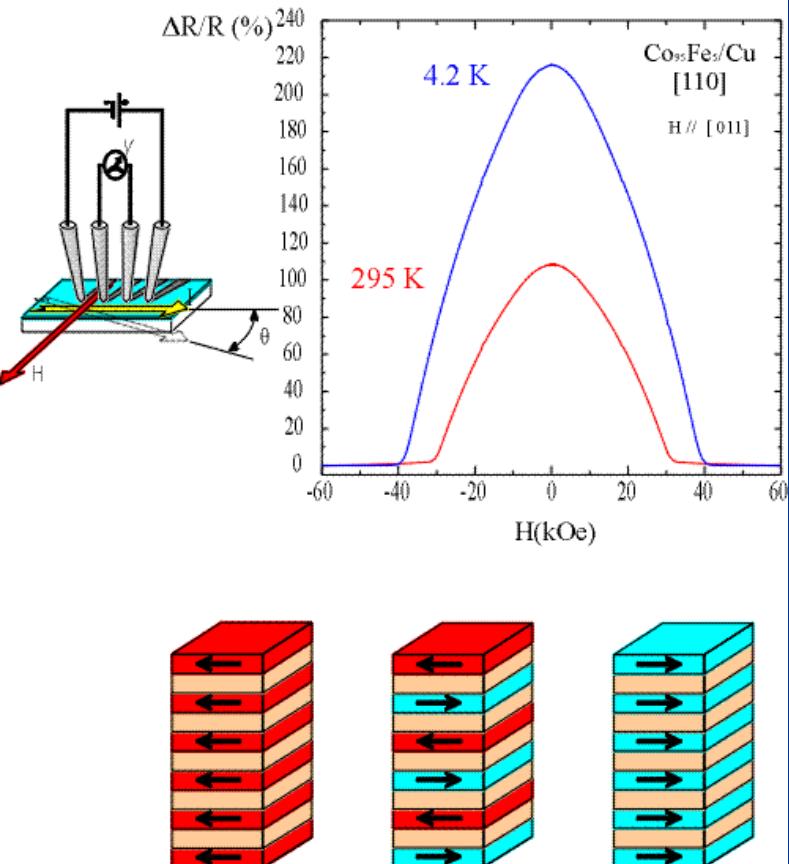
Giant Magnetoresistance

- Coupling across non-magnetic metals (RKKY)
- Magnetic field causes large changes in electrical resistance



Giant Magnetoresistance: Better Magnetic Sensors

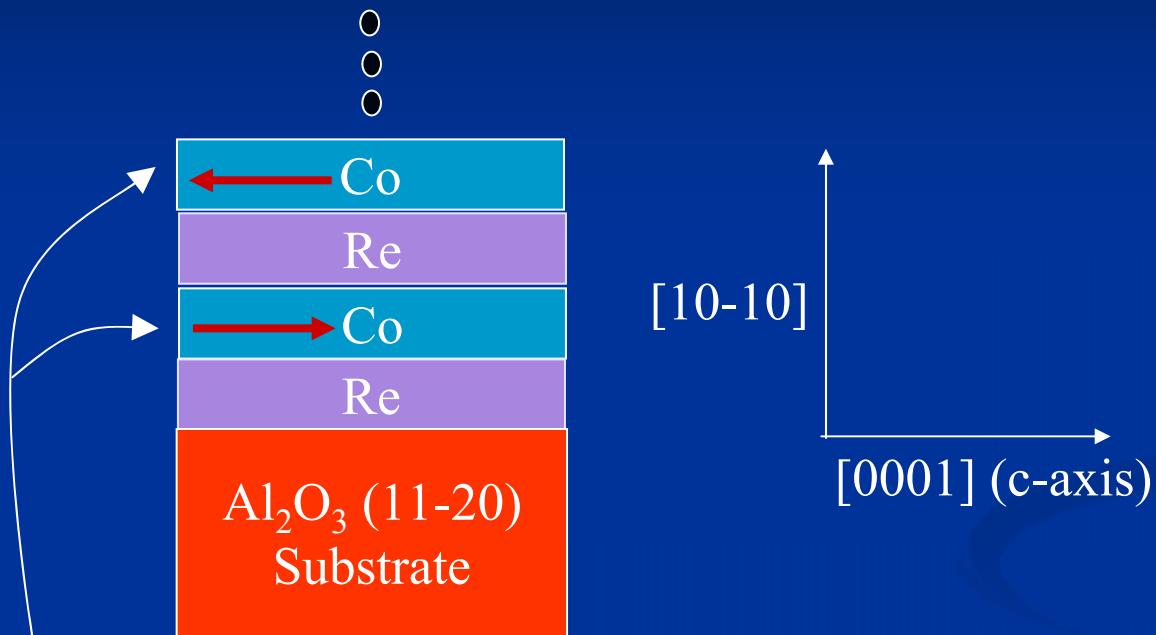
Giant Magnetoresistance



2007 Physics Nobel Prize, Fert & Grunberg



Epitaxial Co/Re Superlattices

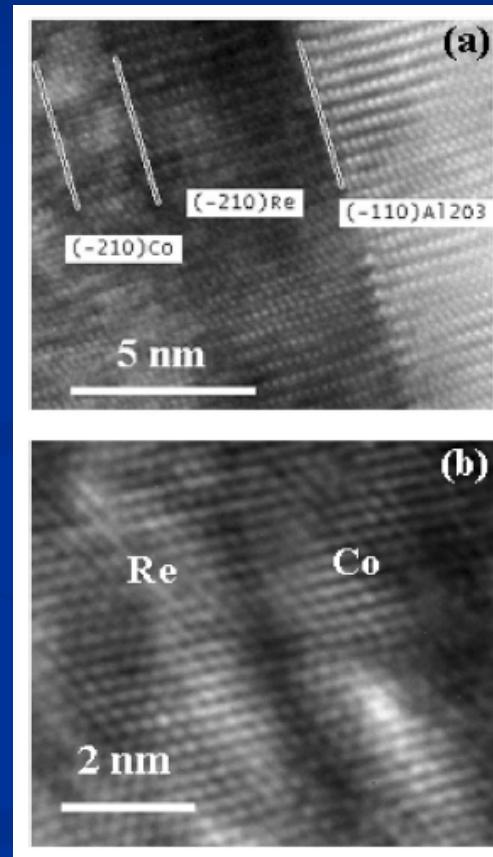
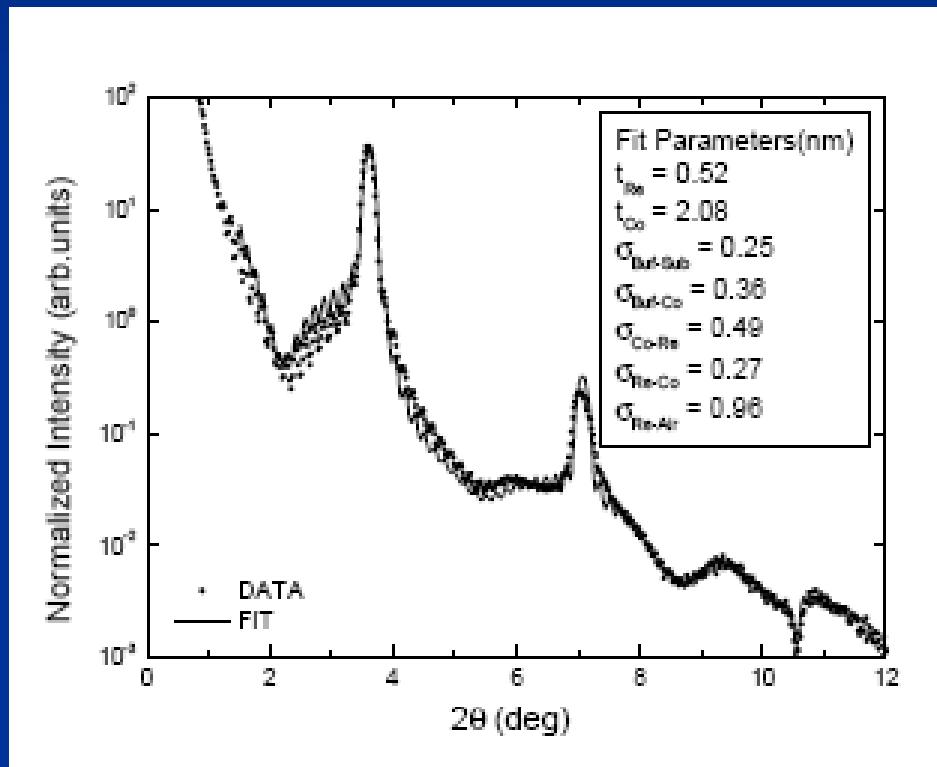


Spontaneous antiferromagnetic coupling between ferromagnetic Co layers leads to Giant Magnetoresistance (GMR)

In-plane c-axis leads to anisotropic magnetotransport



Co/Re Superlattice Structure

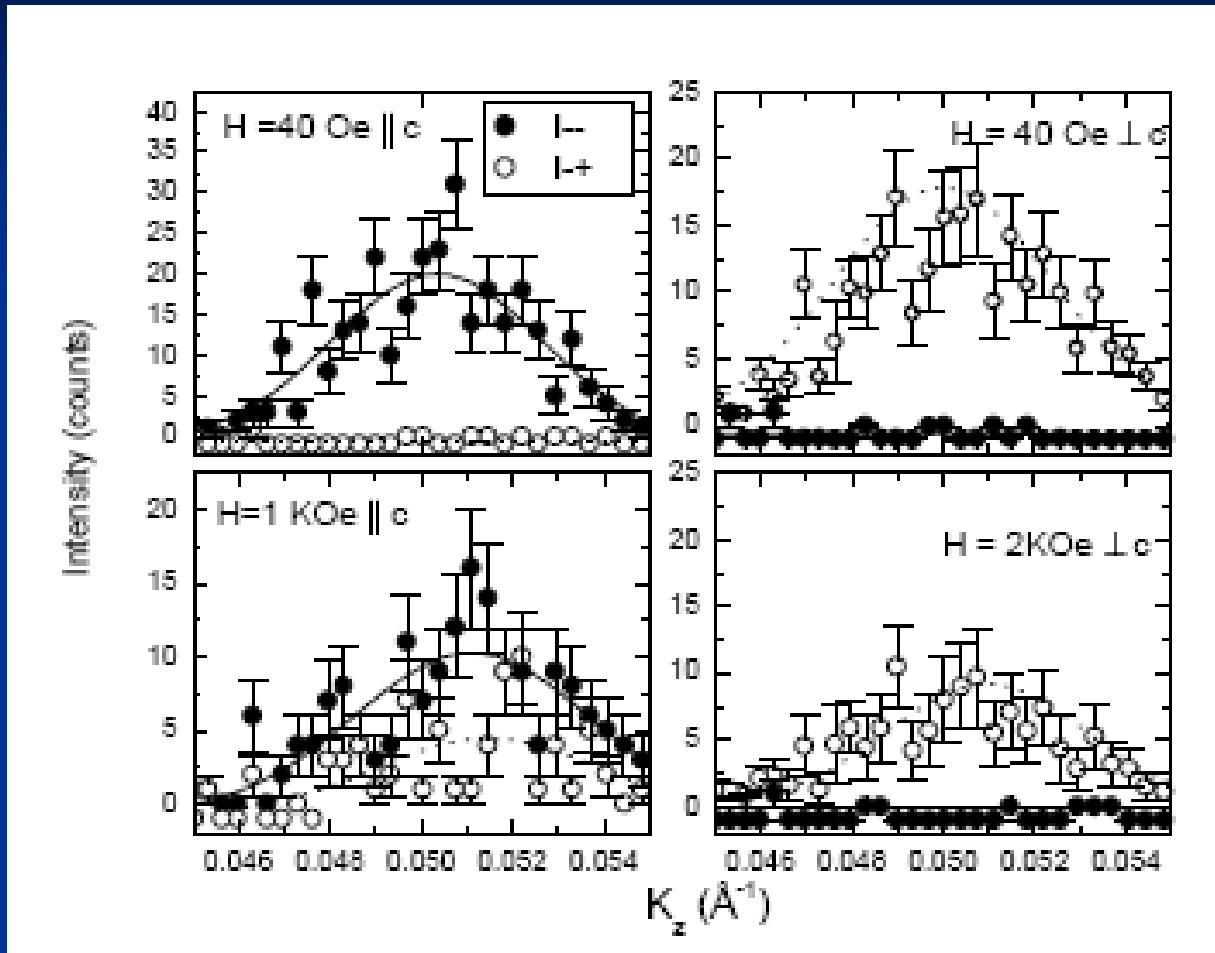


X-ray reflectivity
(Gives structural information)

TEM
(Xu et al., JAP **101**, 103920 (2007))



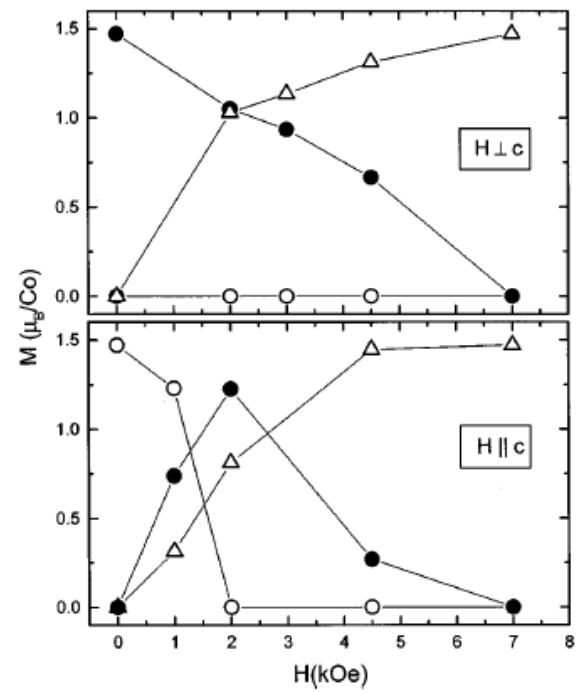
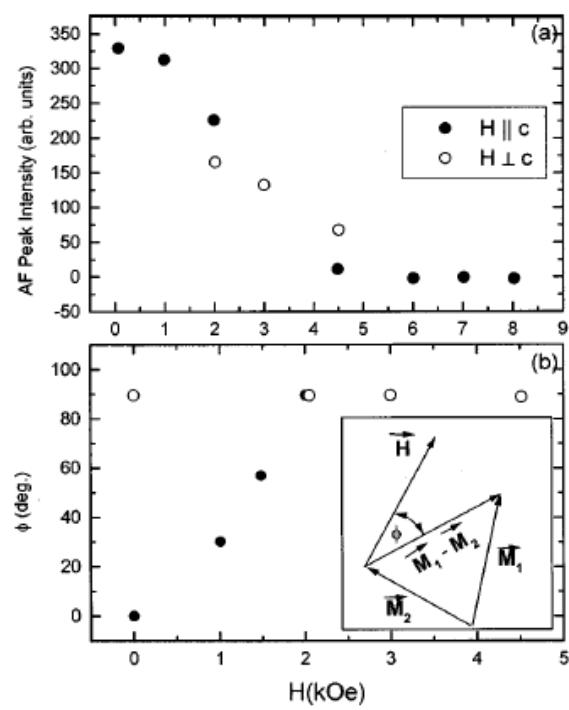
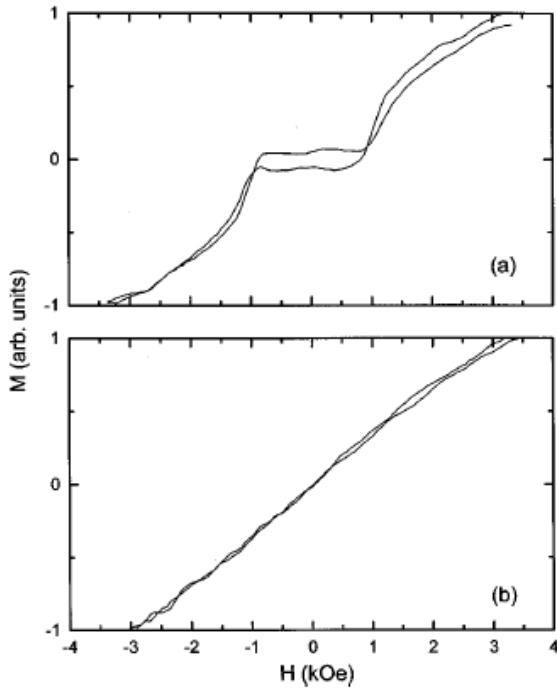
Using Simple PNR for Magnetometry



T. Charlton, D. Lederman, and G. Felcher, Vol. 674, *Materials Symposium Proceedings* (Materials Research Society, Pittsburgh, 2001), p. T1.4.1.

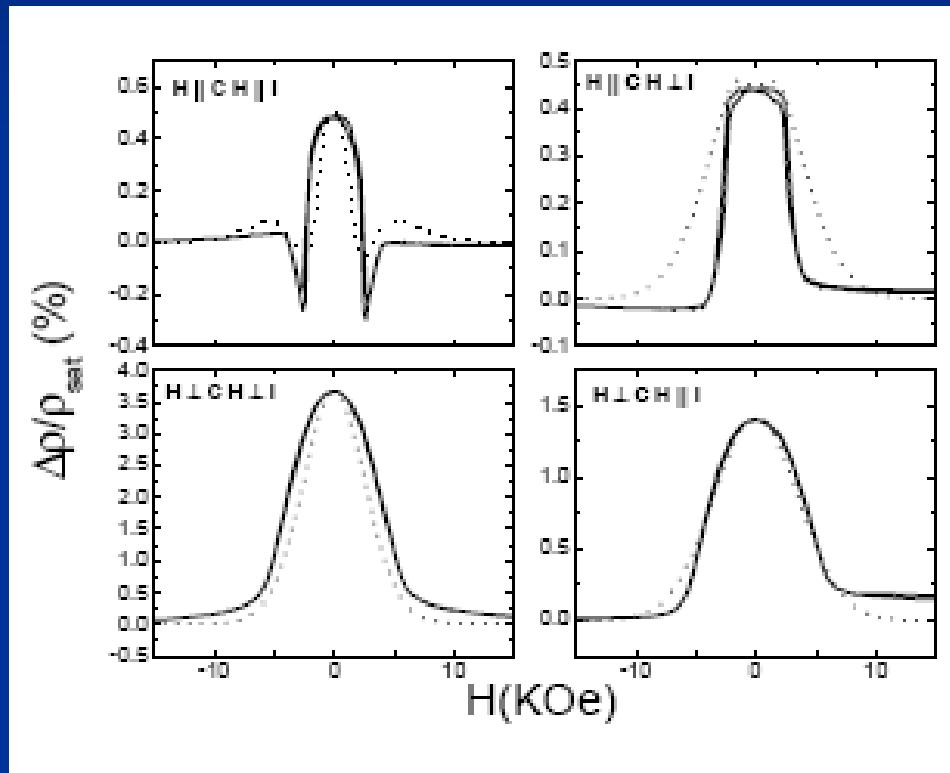


PNR Yields Magnetometry



$M_{AF\perp}$ (●), $M_{AF\parallel}$ (○), and M_F (△)

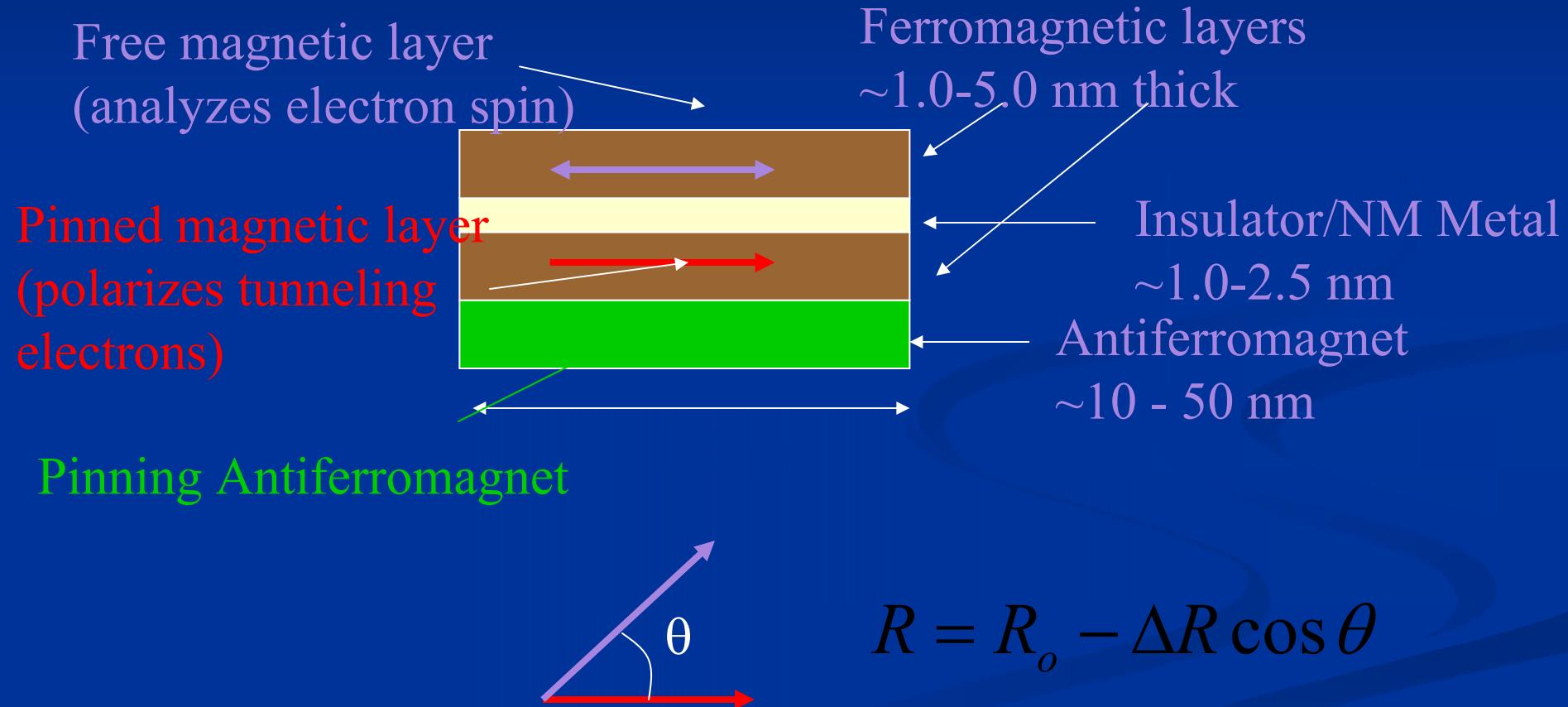
PNR Magnetometry Used to Explain Magnetotransport



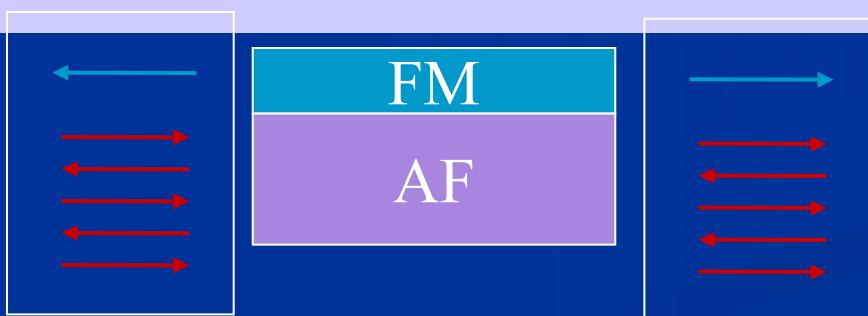
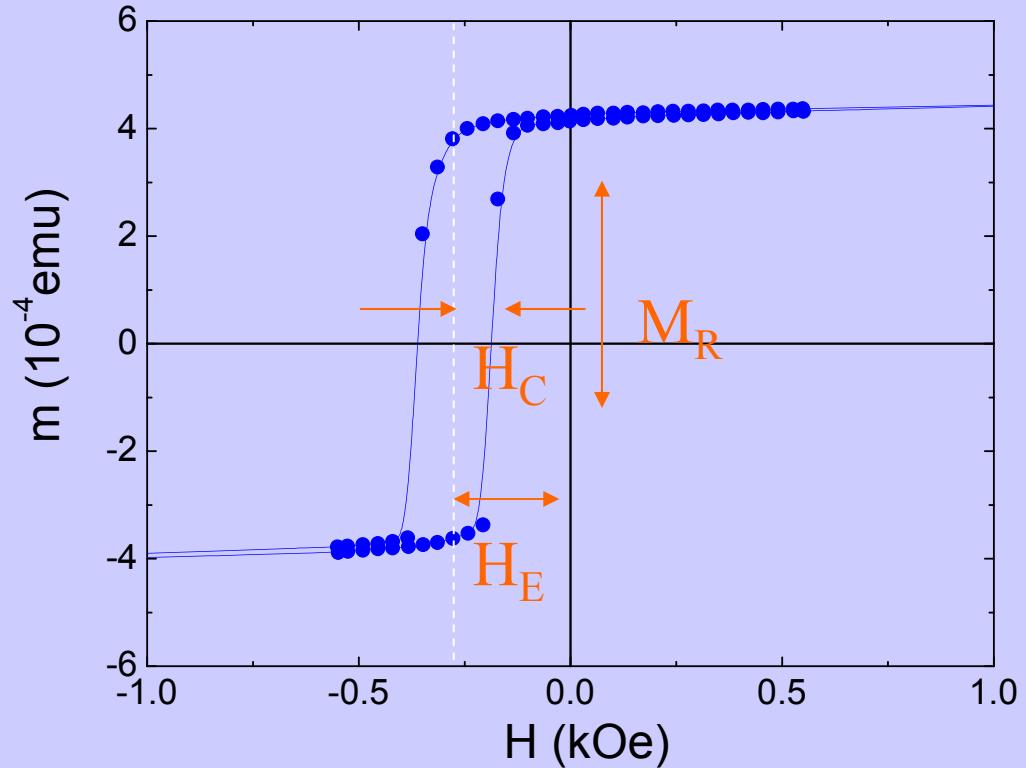
Dotted line = theory
Solid line = data



Exchange Bias



Exchange Bias



M_R : “Remanent” magnetization

- Maximum value of M
- Depends on FM

H_C : Coercivity

- Depends on FM magnetic anisotropy
- Represents energy required to reverse magnetic domain

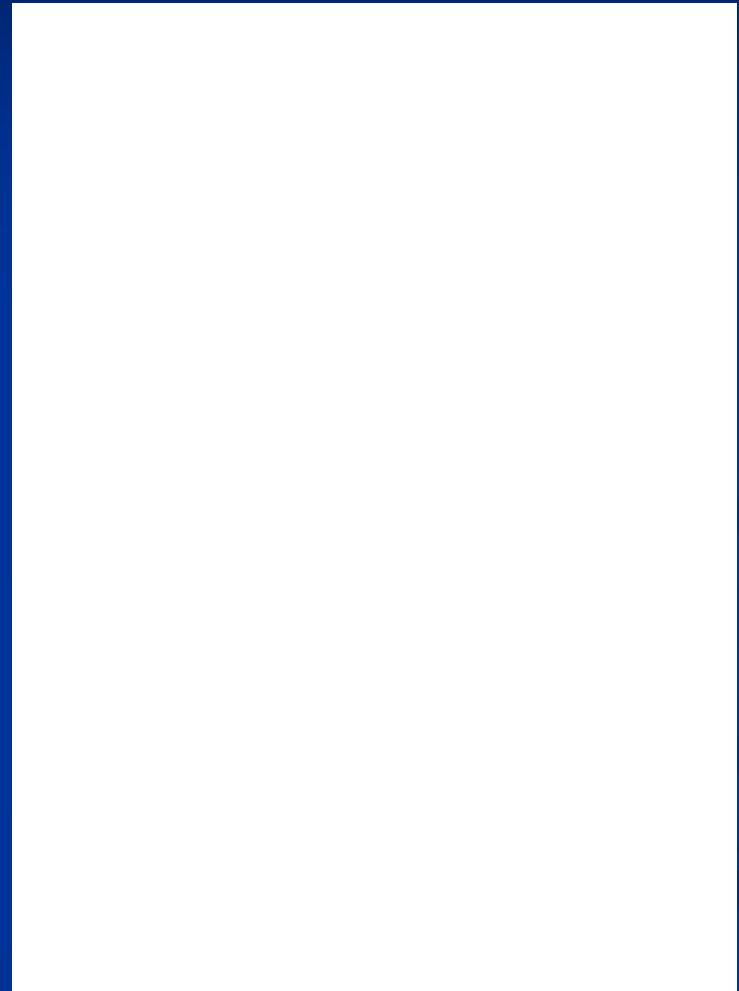
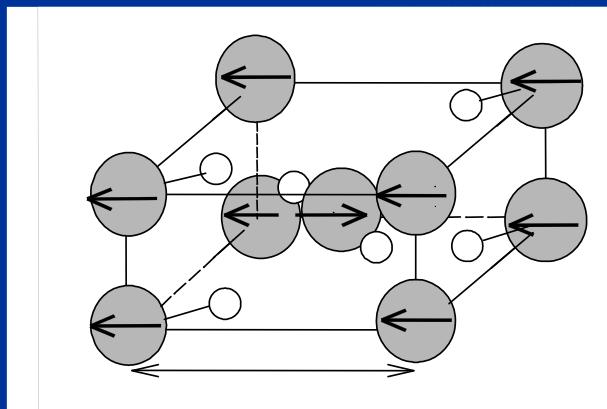
H_E : Exchange Bias

- Absent in pure FM, due to AF-FM interactions



Comparing T_B to T_N

- NiF₂/Co bilayers
- Temperature above which $H_E=0$ (T_B)
- Does $T_B = T_N$?
- Measure T_N via neutron diffraction

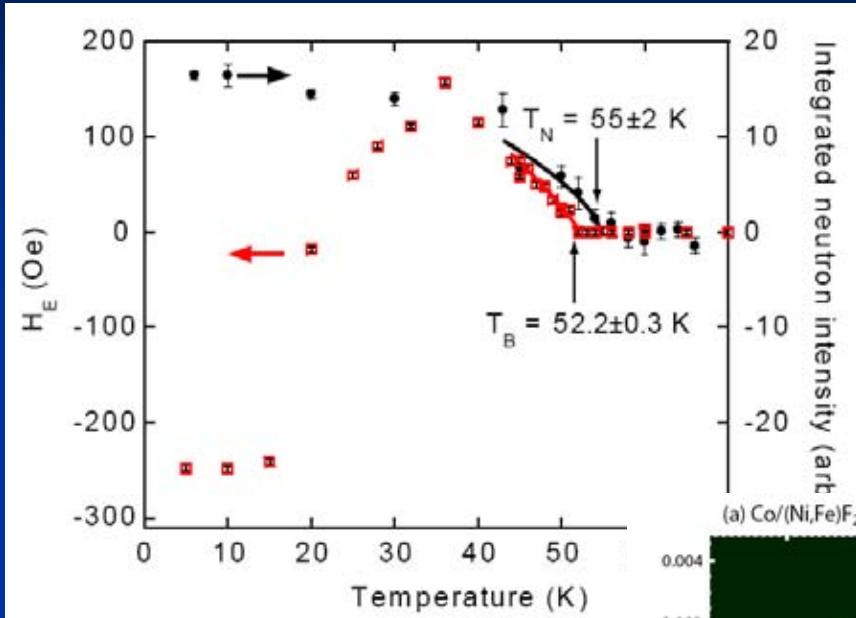


$$t_{\text{NiF}2} = 12 \text{ nm}$$

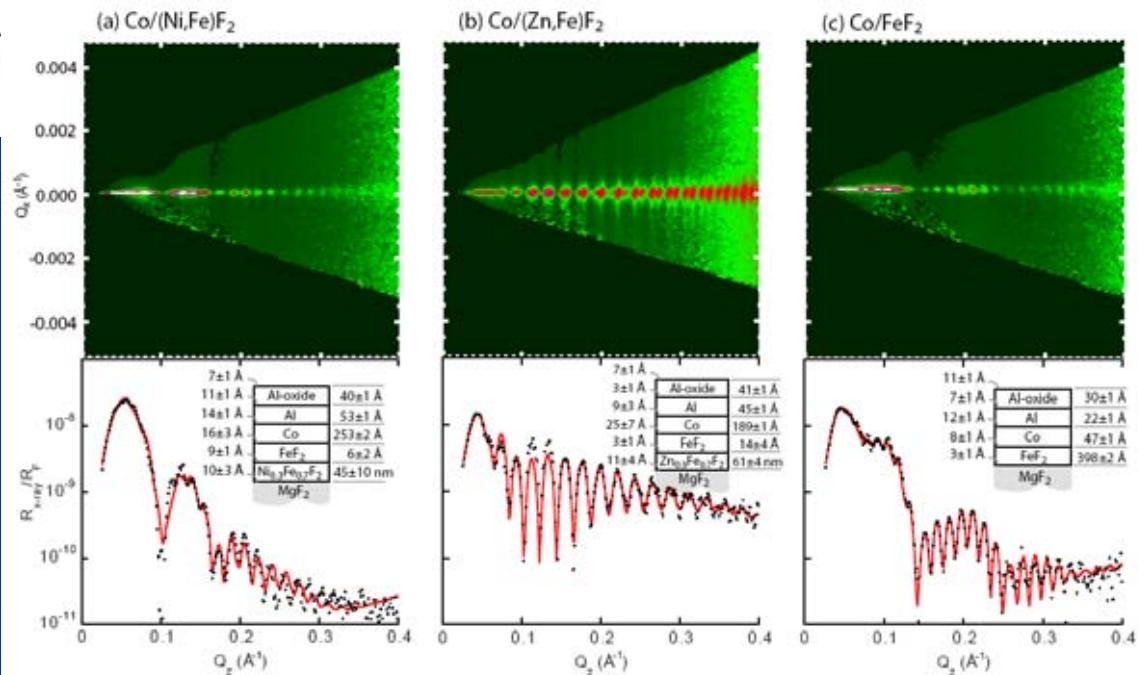
H. Shi et al, PRB **69**, 214416 (2004)



Dependence of H_E on AF Domain Size



M. R. Fitzsimmons et al., PRB **77**, 224406 (2008)

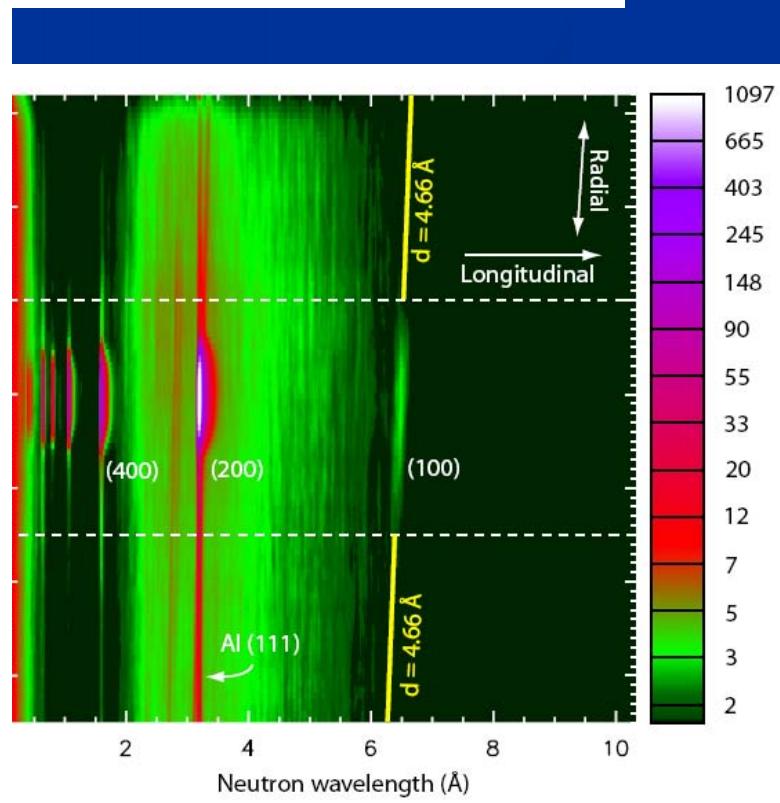
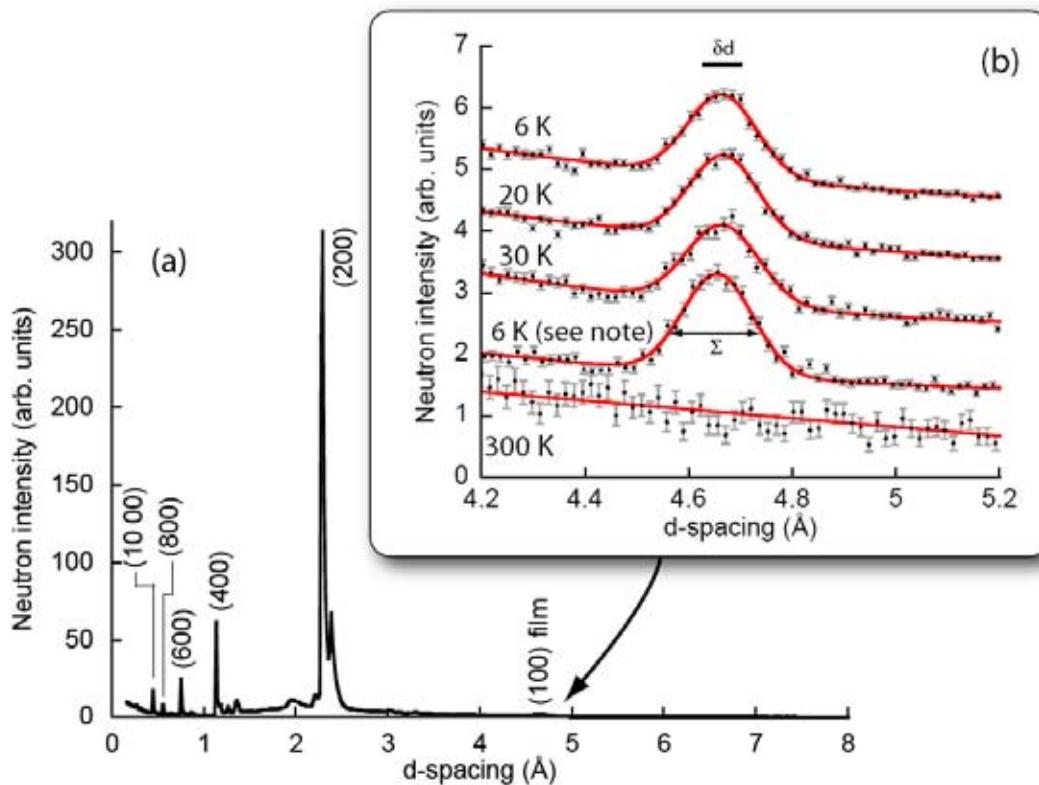
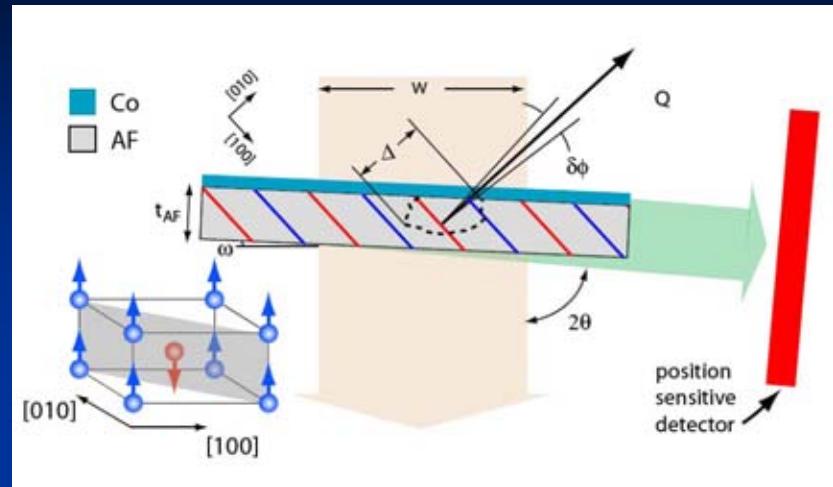


X-ray reflectivity

Dependence of H_E on AF Domain Size

Width of AF diffraction peak is larger for smaller AF domains (L)

Several theories predict $H_E \sim 1/L$



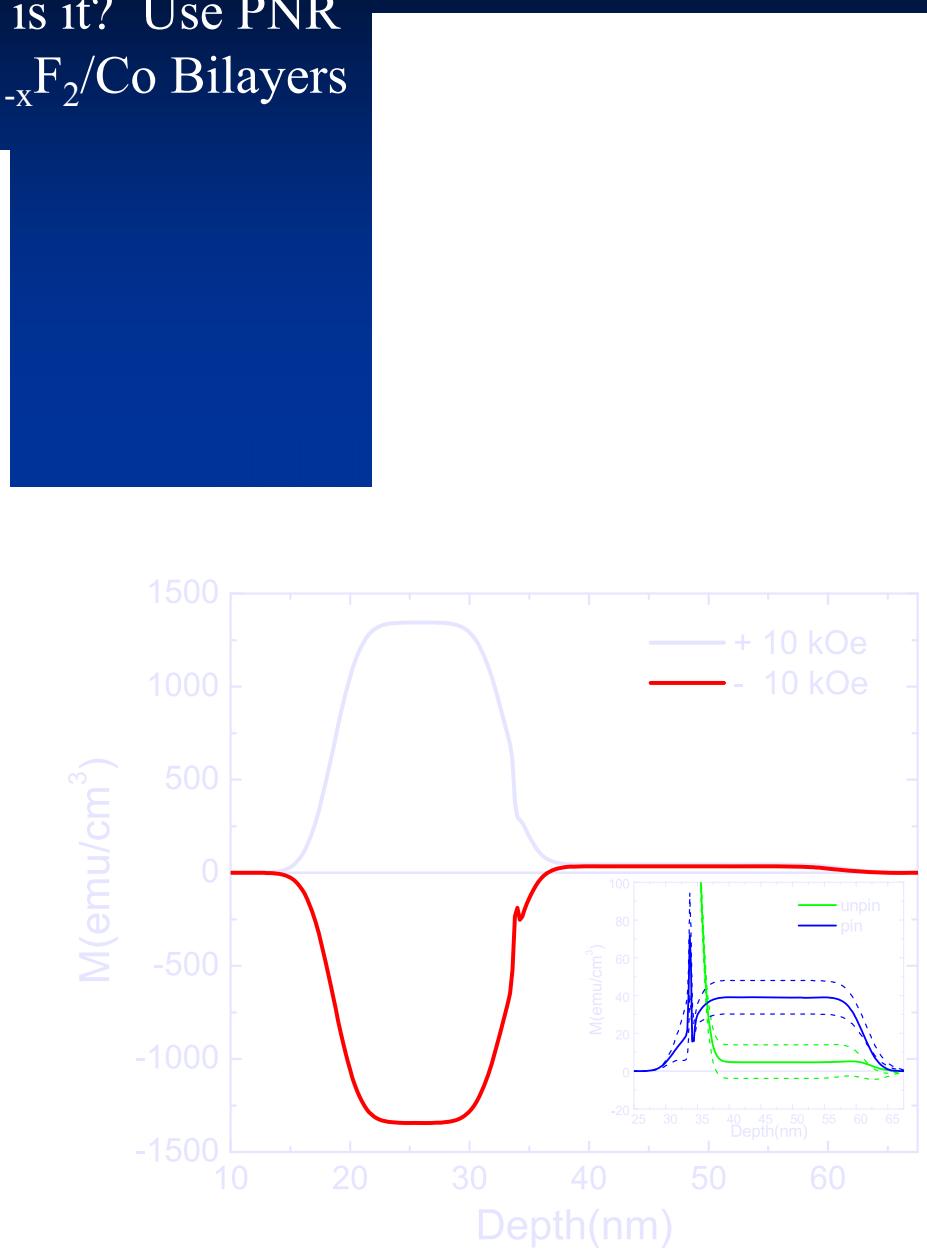
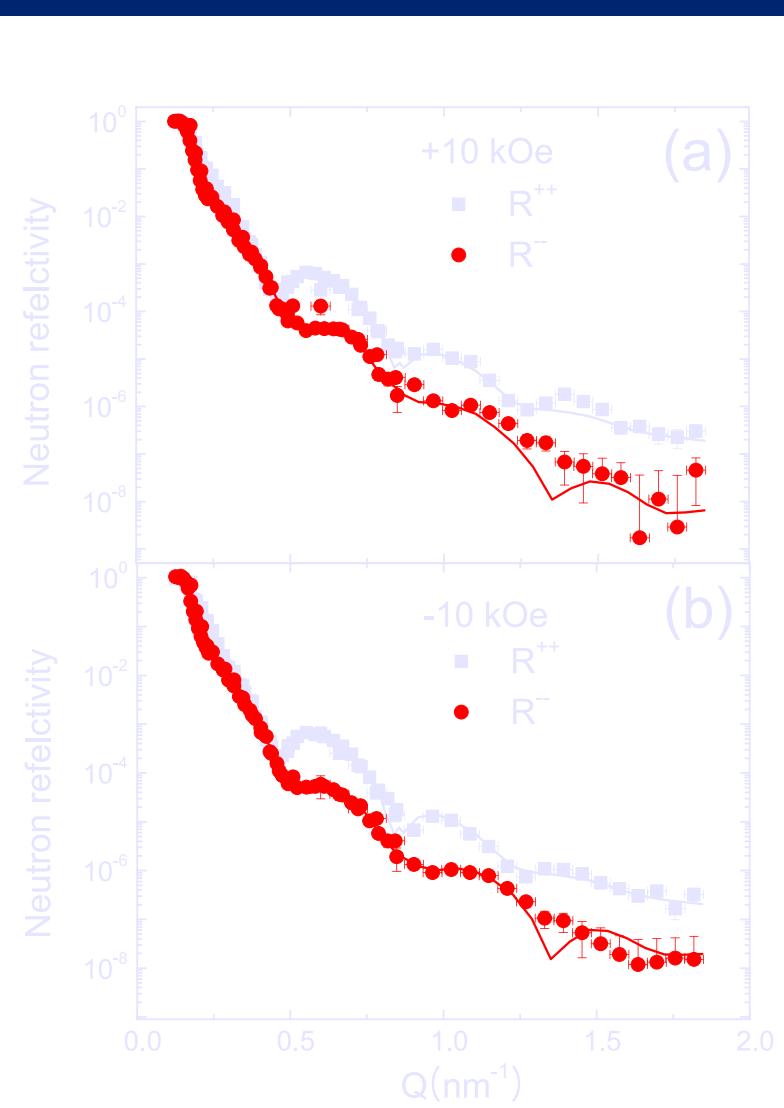
Sample	H_E (Oe)	H_C (Oe)	$ J_{int} $ (erg/cm ²)	Δ_{100} (Å)	Σ (Å)	AF film thickness (Å)
Co/Ni _{0.55} Fe _{0.45} F ₂	+466	217	1.7	894±376	0.052±0.004	450
Co/Zn _{0.30} Fe _{0.70} F ₂	-234	45	0.6	419±85	0.058±0.004	610
Co/FeF ₂	+1750	1000	1.2	343±42	0.061±0.003	400

$H_E \sim 1/L$ doesn't pan out??



AF Pinned Magnetization and H_E

Where is it? Use PNR
 $\text{Fe}_x\text{Zn}_{1-x}\text{F}_2/\text{Co}$ Bilayers



Conclusions

- Neutron scattering provides essential information about magnetic nanostructures, including:
 - Magnetometry with depth dependence
 - Magnetic domain size
 - Relation between magnetic and nuclear structure

