Combined X-Ray and Neutron Scattering Studies of Magnetic Nanostructures

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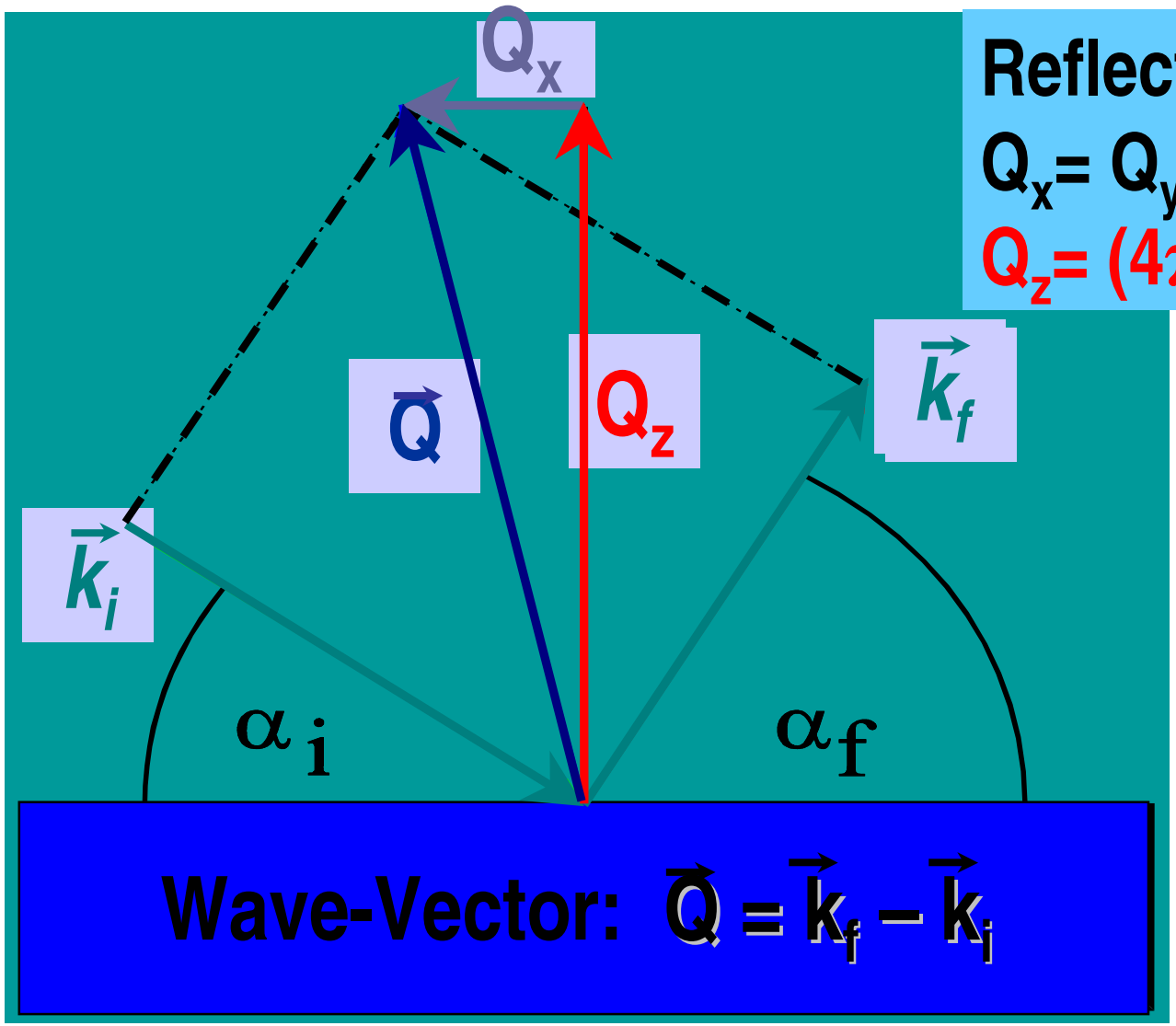
Importance of Interfaces

- Interface Roughness can affect many properties: coercive field, magnetoresistance, spin injection, etc.
- Magnetic profiles across interfaces (e.g. AF/F, etc.)
- Magnetic domain structure.

Scattering Geometry & Notation



Reflectivity:

$Q_x = Q_y = 0$

$Q_z = (4\pi/\lambda)\sin\alpha_i$

Wave-Vector: $\vec{Q} = \vec{k}_f - \vec{k}_i$

Specular Reflectivity

- Measures laterally *averaged* density profile normal to surface
- PNR with polarization analysis can measure *vector* magnetization profile
- Resonant X-Ray reflectivity at L- or M-edges using circularly polarized X-Rays can measure *element-specific* magnetization along k_0

NEUTRONS:

$$R_{++}(Q_z) - R_{--}(Q_z) \sim M_{xy,||}(Q_z)\, n(Q_z)$$

$$R_{+-}(Q_z) = R_{-+}(Q_z) \sim |M_{xy,\perp}(Q_z)|^2$$

X-RAYS:

$$R_{+}(Q_z) - R_{-}(Q_z) \sim M_{||}(Q_z)\, n(Q_z)$$

Magnetic Reflectivity in the Distorted Wave Born Approximation

The scattering factor in the dipole approximation is given by,

$$f = \underbrace{(\boldsymbol{e}_s^* \cdot \boldsymbol{e}_i)\left\{\frac{3}{8\pi}\lambda[F_1^1 + F_{-1}^1] - r_e Z\right\}}_{f_C} + \underbrace{\frac{3}{8\pi}\lambda i(\boldsymbol{e}_s^* \times \boldsymbol{e}_i)\cdot \boldsymbol{m}[F_{-1}^1 - F_1^1]}_{f_m} + (\boldsymbol{e}_s^* \cdot \boldsymbol{m})(\boldsymbol{e}_i \cdot \boldsymbol{m})[2F_0^1 - F_1^1 - F_{-1}^1]$$

- Note that, $I_+ - I_- \propto f_C \cdot f_m$

- Parrat recursive formula for calculating reflectivity generalized to include magnetism
- Magnetism introduced by calculating the **off diagonal terms of dielecric tensor**
- Separate **structural** and **magnetic roughness** terms introduced
- Reflectivity and diffuse scattering calculated using full theory in the context of **Distorted Wave Born Approximation**

S. A. Stepanov and S. K. Sinha, Phys. Rev. B **61**, 15302 (2000)

D.R. Lee, S.K. Sinha, D.Haskel, Y. Choi, J.C. Lang, S.A. Stepanov and G. Srajer, Phys. Rev. B **68**, 224409 (2003) ;

D.R. Lee, S.K. Sinha, C.S. Nelson, J.C. Lang, C.T. Venkataraman, G. Srajer and R.M. Osgood III, Phys. Rev. B **68**, 224410 (2003)

Resonant Magnetic X-Ray Scattering

$$f_{\alpha\beta}=A\delta_{\alpha\beta} -iB\sum_{\gamma}\varepsilon_{\alpha\beta\gamma}M_{\alpha}+CM_{\alpha}M_{\beta}$$

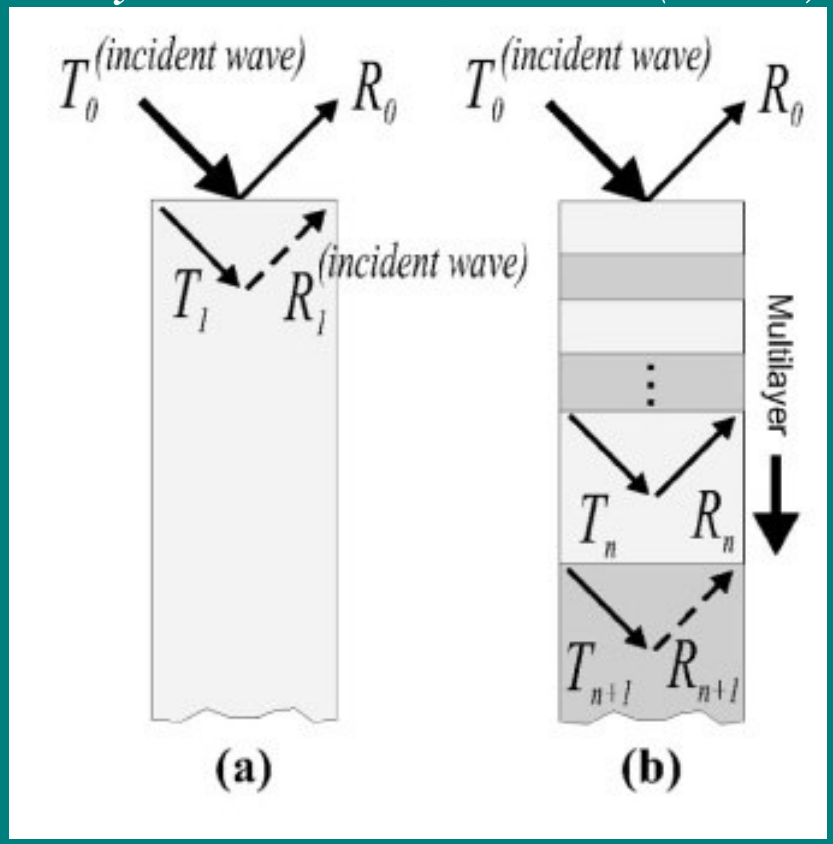
$$A = f_0 + 3\lambda/8\pi\,(F_{11} + F_{1-1})$$

$$B = 3\lambda/8\pi\,(F_{11} - F_{1-1})$$

$$C = 3\lambda/8\pi\,(2F_{10} - F_{11} - F_{1-1})$$

$$\chi_{\alpha\beta}(\mathbf{r}) = (4\pi/k_0^2)n_m(\mathbf{r})f_{\alpha\beta}(\mathbf{r})$$

For smooth surfaces, can be solved exactly using Boundary Conditions and iterative Matrix Method a la Born & Wolff or Parratt. Matrices here are 4 X 4 because of 2 ingoing and 2 outgoing waves with 2 polarizations each. Can be expressed in terms of 2 X 2 Matrices.
(*Stepanov and Sinha, Phys. Rev. B* ***61****, 15302 (2000)*)



Website:
http://sergey.gmca.aps.anl.gov/MAG_sl.html

Numerical Results for Specular Reflectivity of GdFe multilayer
Gd L_{III} Edge

15[Gd(50Å)Fe(35Å)]

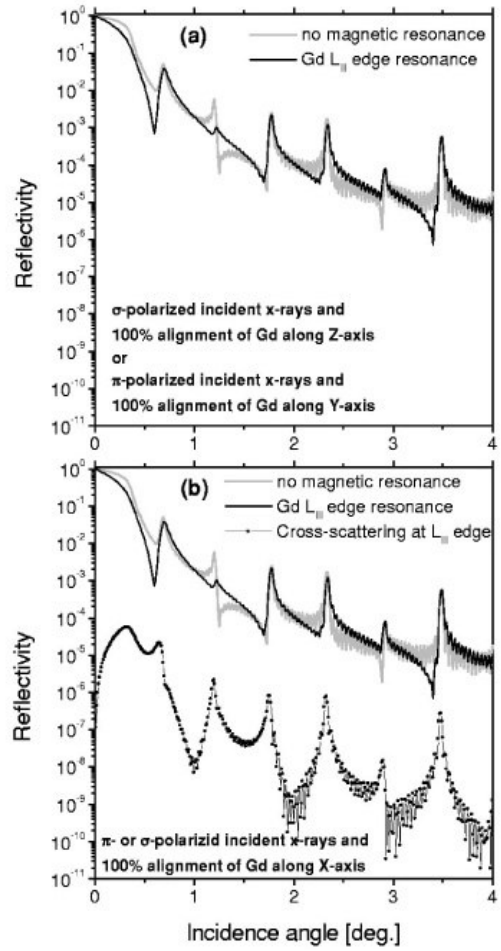


FIG. 3. Calculated resonant reflection of linearly polarized x rays from Gd/Fe multilayer at the Gd L_{III} edge (7.243 keV) for different directions of the magnetization and incident polarization.

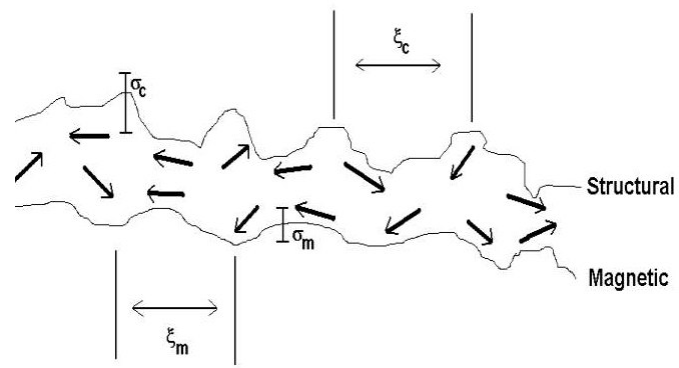
How to include both Chemical and Magnetic Roughness?

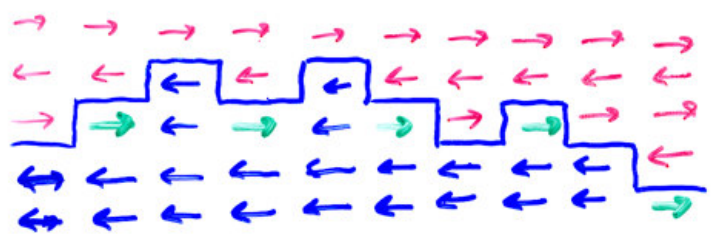
- Imagine for every interface there are *two* interfaces: chemical and magnetic.
- They may or may not be separated.
- They may or may not be correlated.

Osgood et al. J. Magn. Magnetic Materials, 198-199, 698 (1999)

D.R.Lee et al., Phys. Rev. B 68, 22409 (2003)

D.R.Lee et al., Phys. Rev. B 68, 22410 (2003)





Simulation of Reflectivity Expt. On Co film at Co L_{III} Edge

C.C.Kao et al. Phys. Rev. B 50, 9599 (1994)

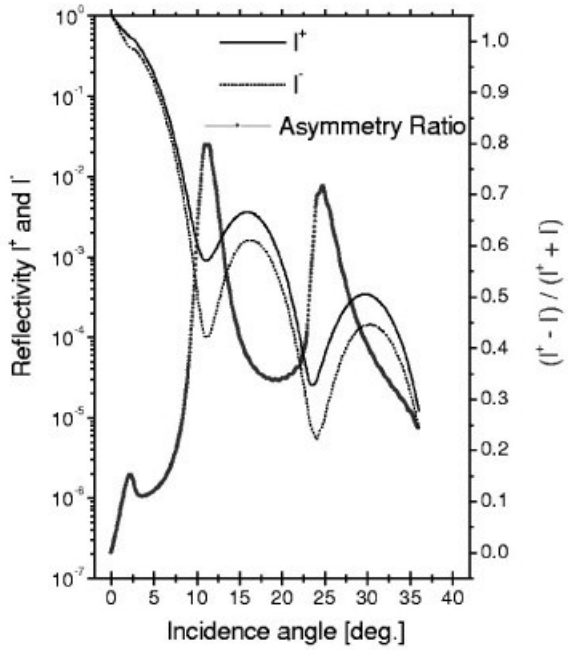


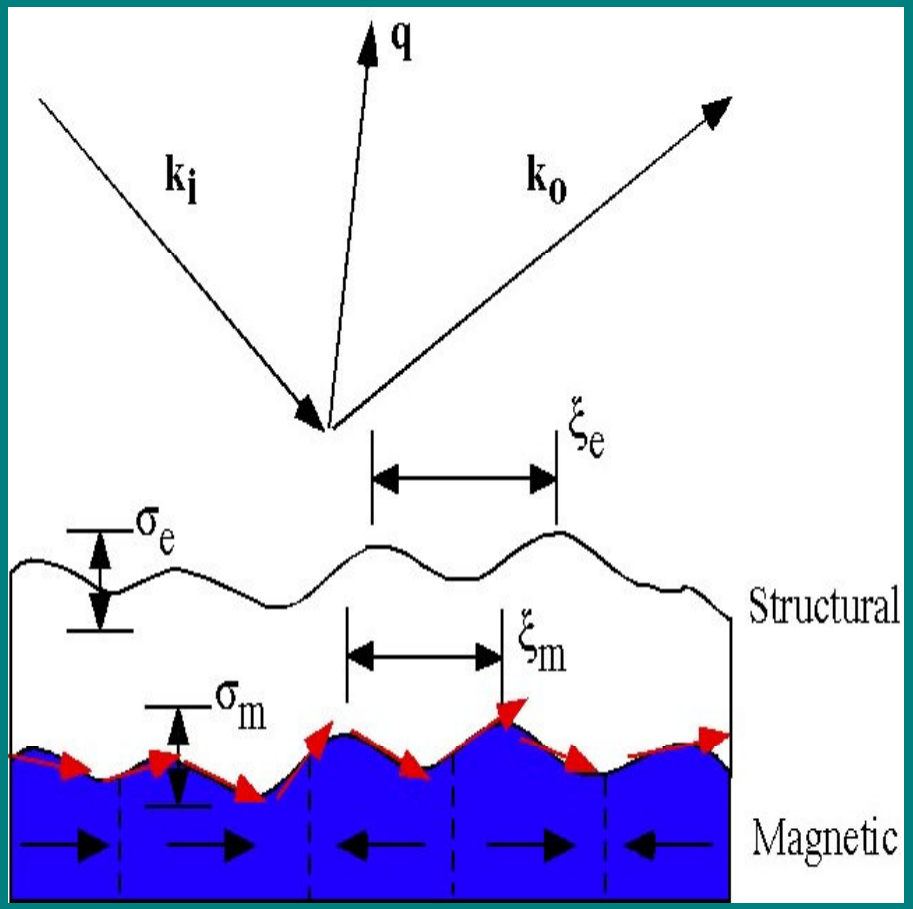
FIG. 5. The calculations of I^+ and I^- for the case presented in Ref. 30. The sample consists of 36-Å Al_2O_3, 39-Å Co, 5-Å Fe, and 560-Å ZnSe on GaAs substrate; the x-ray energy corresponds to the Co L_{III} edge (0.7865 keV).

For each interface, 3 correlation functions

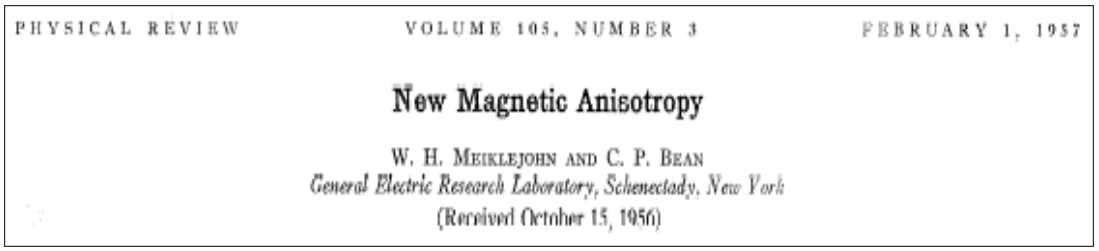
$C_{ss}(\mathbf{R}) \rightarrow \sigma_{ss}, \ \xi_{ss}, \ h_{ss}$

$C_{mm}(\mathbf{R}) \rightarrow \sigma_{mm}, \ \xi_{mm}, \ h_{mm}$

$C_{ms}(\mathbf{R}) \rightarrow \sigma_{ms}, \ \xi_{ms}, \ h_{ms}$

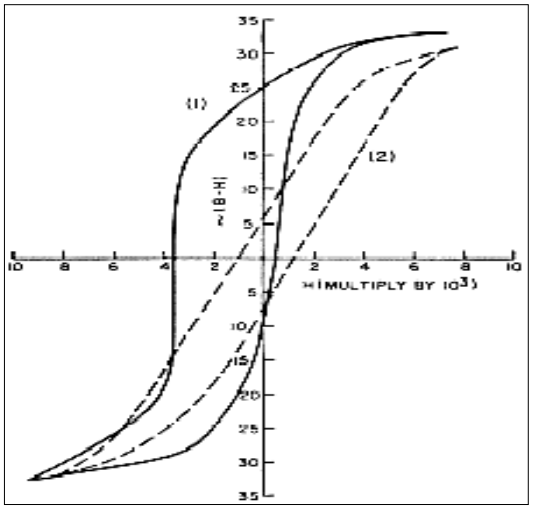


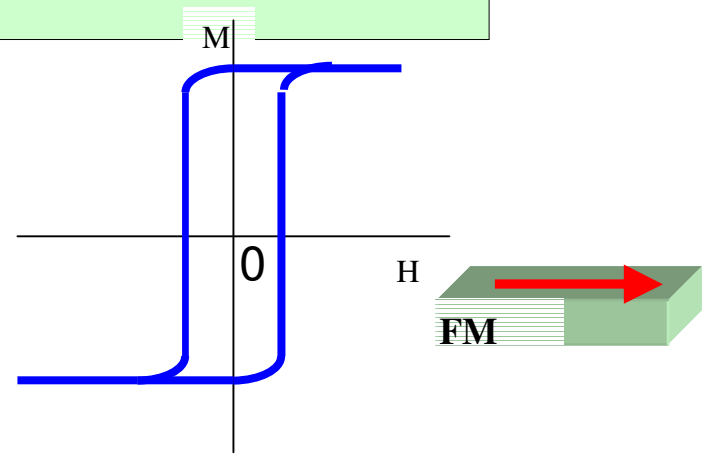
The Exchange Bias Phenomenon

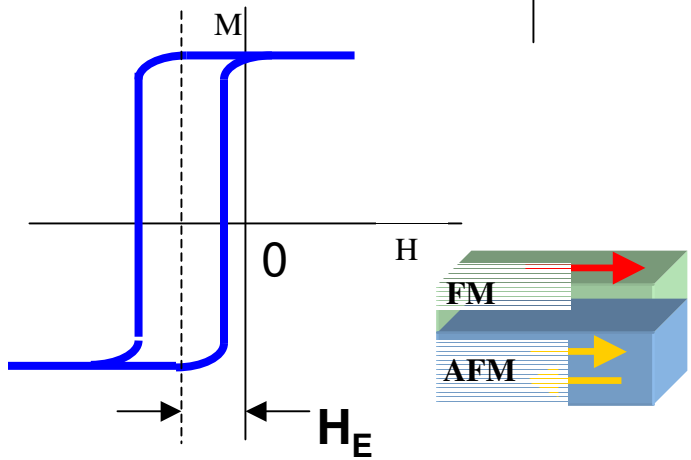

PHYSICAL REVIEW VOLUME 105, NUMBER 3 FEBRUARY 1, 1957

New Magnetic Anisotropy

W. H. MEIKLEJOHN AND C. P. BEAN
General Electric Research Laboratory, Schenectady, New York
(Received October 15, 1956)







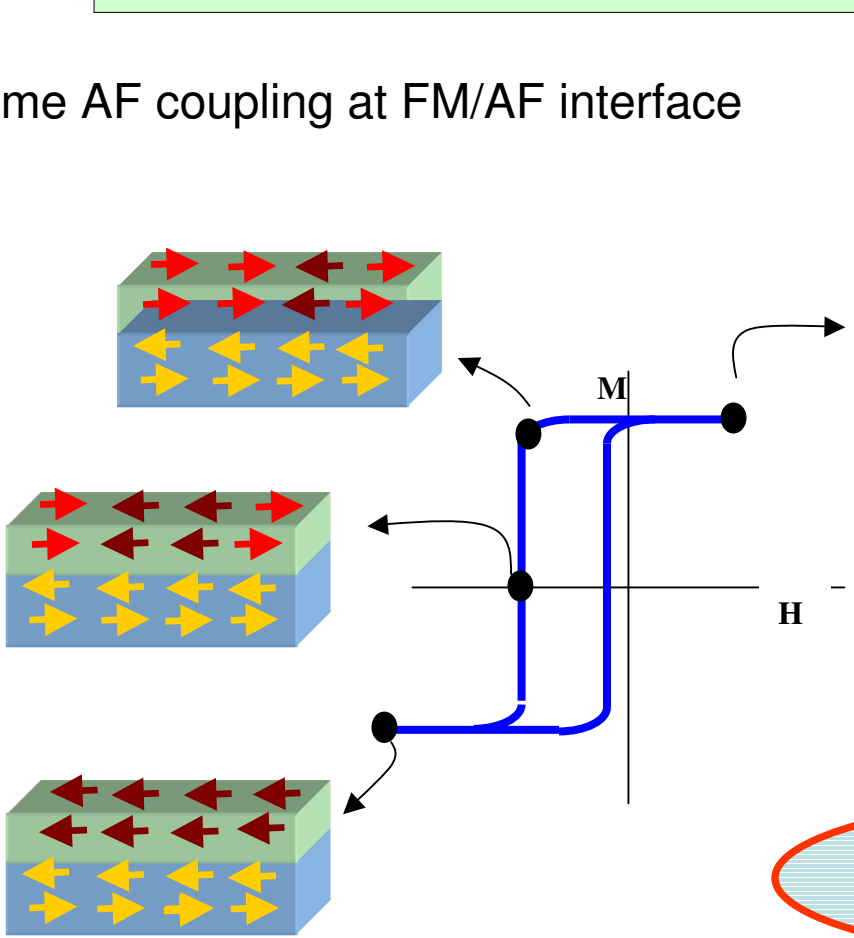
$$H_E = -\frac{JS_{AF}S_{FM}}{M_{FM}t_{FM}}$$

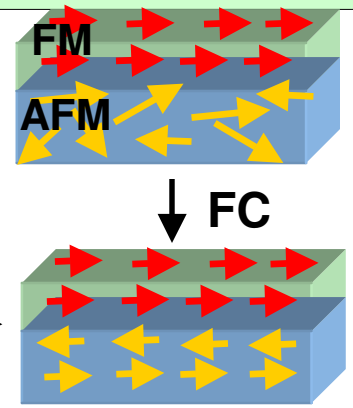
W.H. Meiklejohn, C.P. Bean, *Phys. Rev.* **105**, 904 (1957).
J. Nogués, Ivan K. Schuller, *JMMM* **192**, 203 (1999).
A.E. Berkowitz, K. Takano, *JMMM* **200**, 552 (1999).

- **EB vanishes above T_N ; Must be related to the AF**

Simplified Explanation of EB

Assume AF coupling at FM/AF interface





$T_N < T < T_C$

$T < T_N$

$$H_E = -\frac{JS_{AF}S_{FM}}{M_{FM}t_{FM}}$$

Non-vanishing AF moment

The formula does not represent reality !!

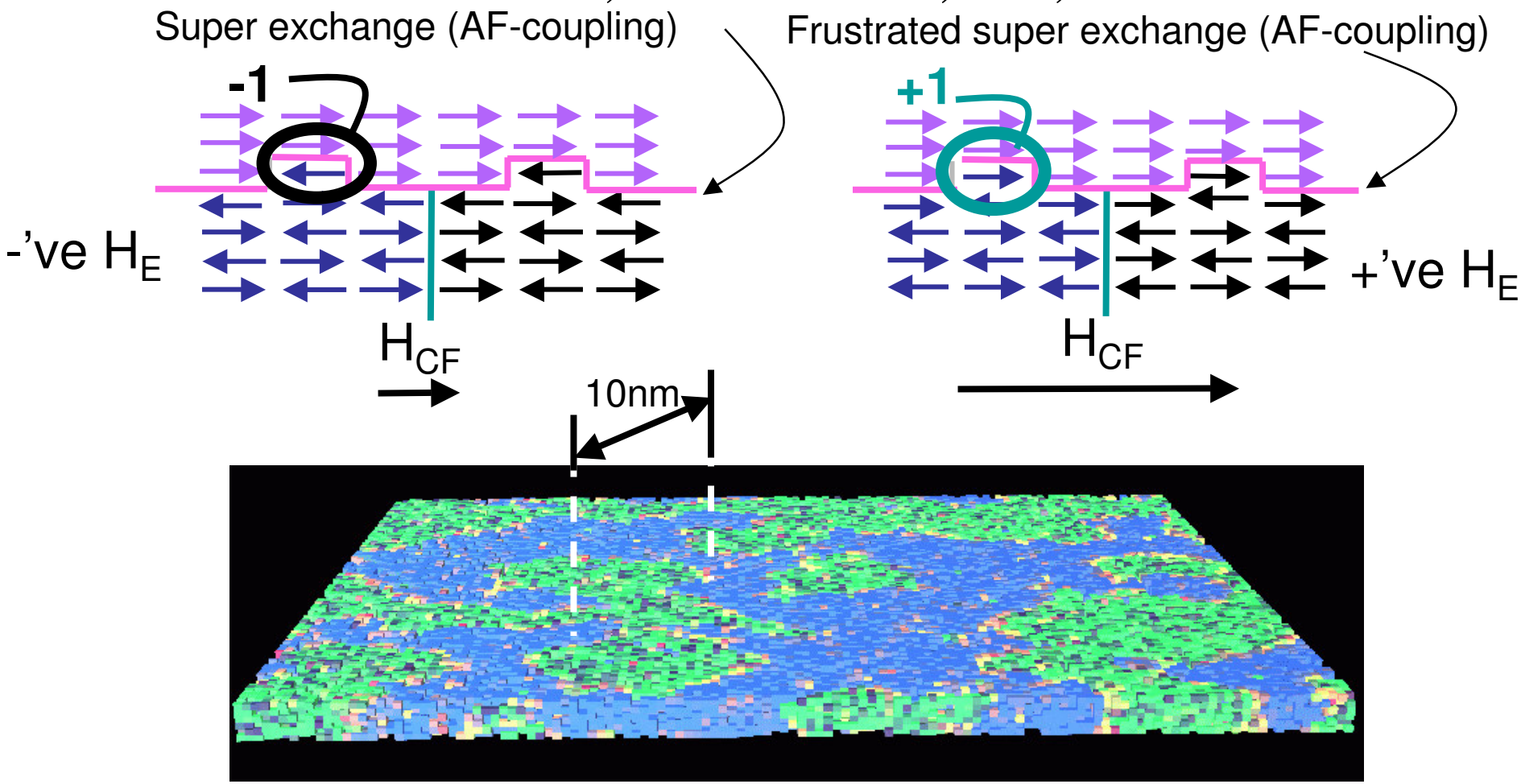
$$H_E = -\frac{JS_{AF}S_{FM}}{M_{FM}t_{FM}}$$

- Gives bias values 2-3 order higher
- Does not explain why exchange bias is observed for compensated AF surfaces like Fe/FeF_2
- **Does not realistically represent the FM/AF interfacial environment**

Various models proposed:

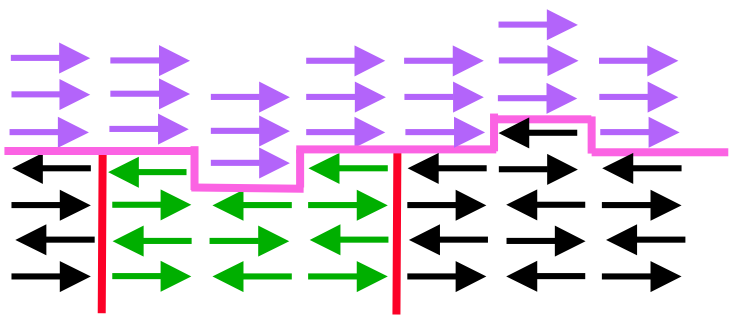
- ✓ Random Field Model (Malozemoff, *Phys. Rev.* B 35 (1987) 3679)
- ✓ Domain Wall Model (Mauri *et al, J. Appl. Physics* 62 (1987) 3047)

Random-field, domain state, etc., models



U. Nowak et. al., *J. Magn. Magn. and Mater.,* **240**, 243 (2002).
A.P. Malozemoff, *J. Appl. Phys.,* **63,** 3874 (1988).

Interfacial Spin Structure is a key to understand EB



✓ Interface properties could be very different from bulk

✓ Roughness could be a source of AF uncompensated moments

✓ Compelling need to determine spin structure across F/AF interface (e.g. domain structure, magnetic roughness, etc.)

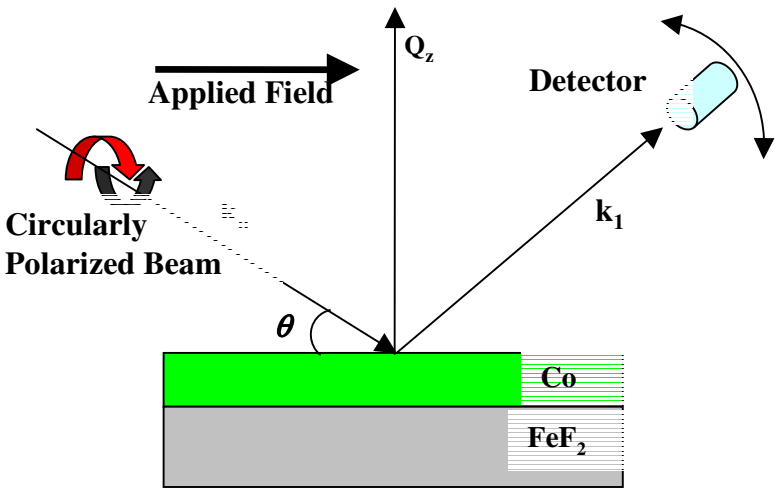
- **Need interface sensitive experimental technique**

Measuring Reflectivity using resonance X-ray scattering technique

- Can *quantitatively* determine depth dependent magnetic density
- Interface sensitive
- Element Specific
- Diffuse scattering – lateral structures like domains, magnetic roughness etc.

The Experimental Procedure: Magnetic x-ray reflectivity

Resonant X-ray scattering measurements performed on Beamline 4.0.2 at the ALS using Kortright endstation



Field of 1 T applied at 300 K along (001) direction

Sample field cooled through T_N to 20 K

Three types of measurements:

(1). Hysteresis loops by switching incident beam polarization at L_3 edge of Co and Fe

(2). Reflectivity measurements as function of Q_Z by switching applied field

Info about both pinned and rotating moments

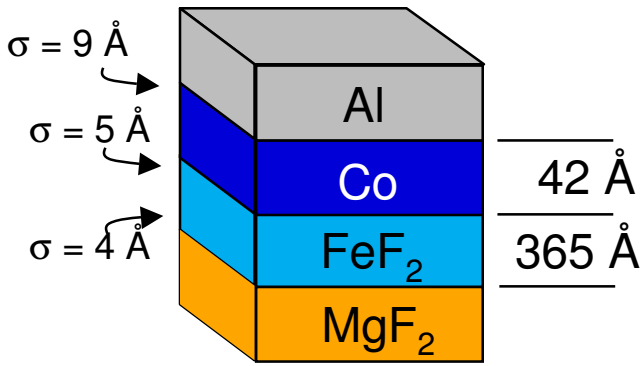
(3). Measurement of diffuse scattering

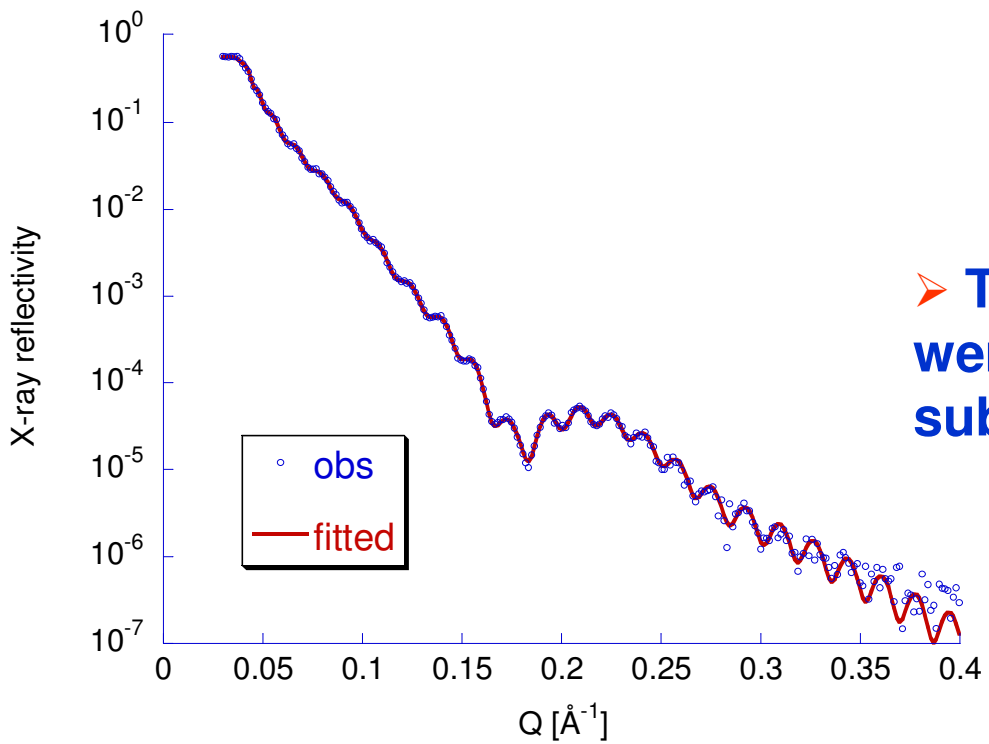
The Sample

FeF_2 grown epitaxially on MgF_2, Co is polycrystalline

(001) – Easy axis of FeF_2, T_N = 78 K

Exhibits **positive** exchange bias





- **The thicknesses and roughness were constrained to be same for subsequent resonant reflectivity fits**

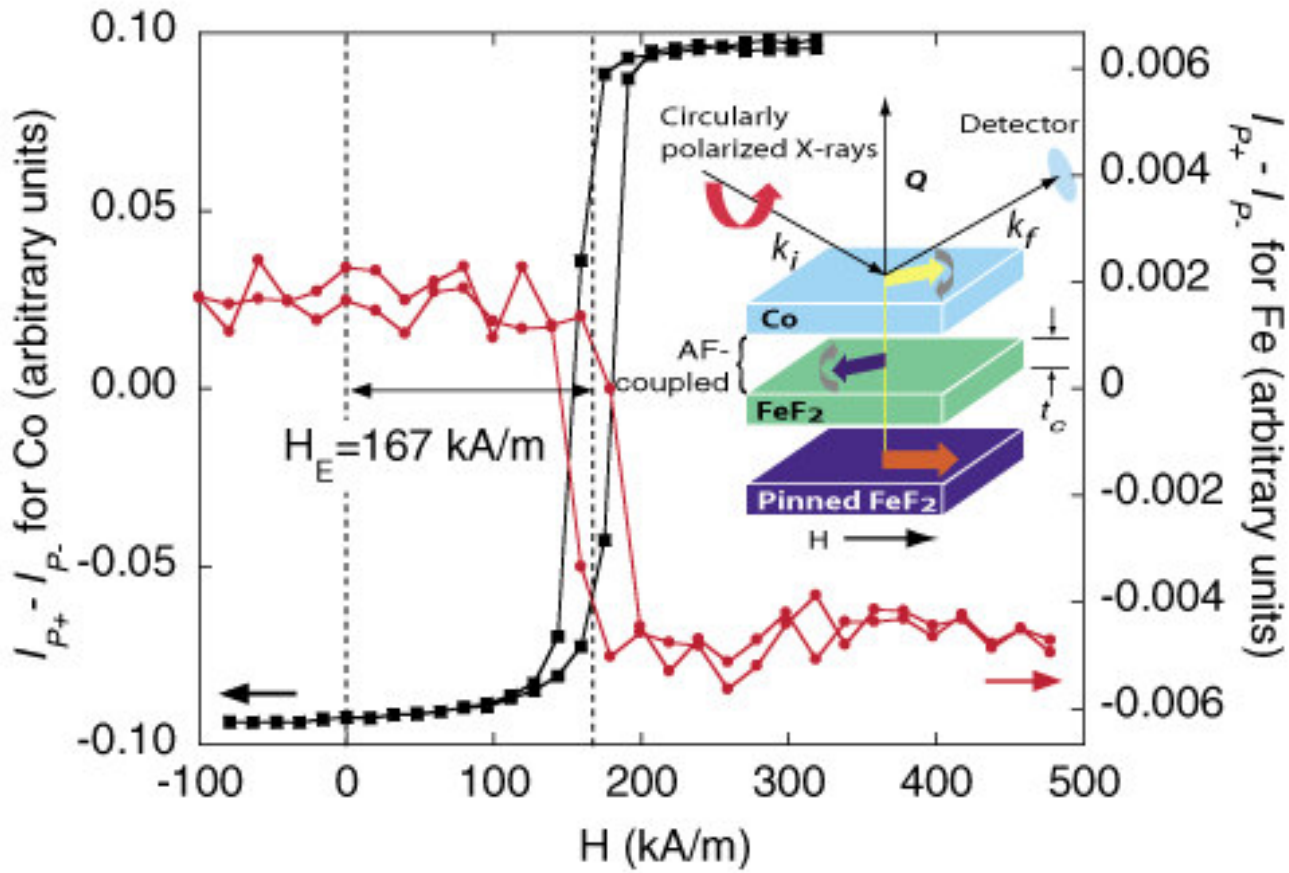


FIG. 1 (color). Hysteresis loops at $Q = 0.49$ and $0.38\ \mathrm{nm}^{-1}$ for Co (■) and Fe (red ●), respectively. Inset: representations of the x-ray experiment and sample.

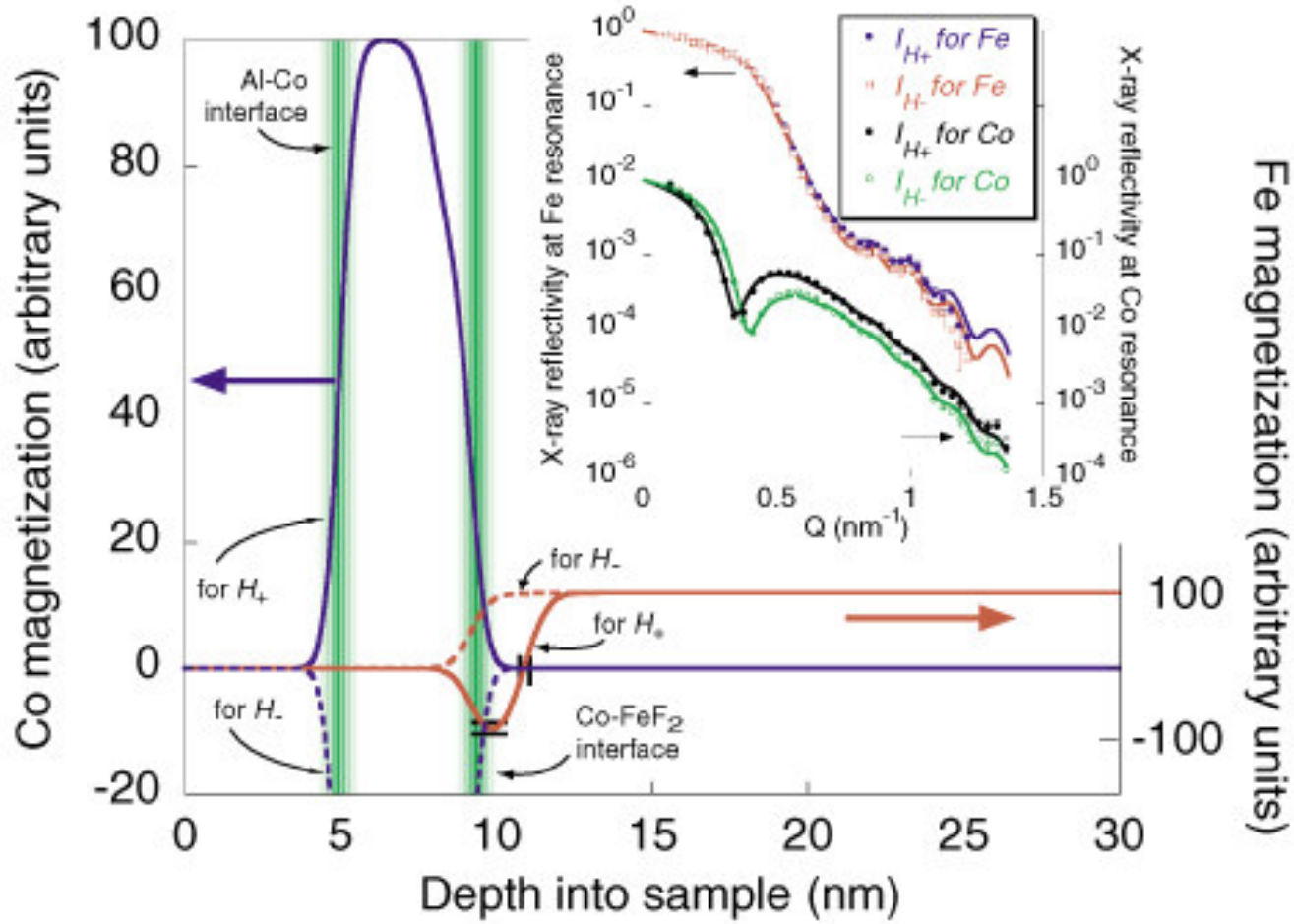
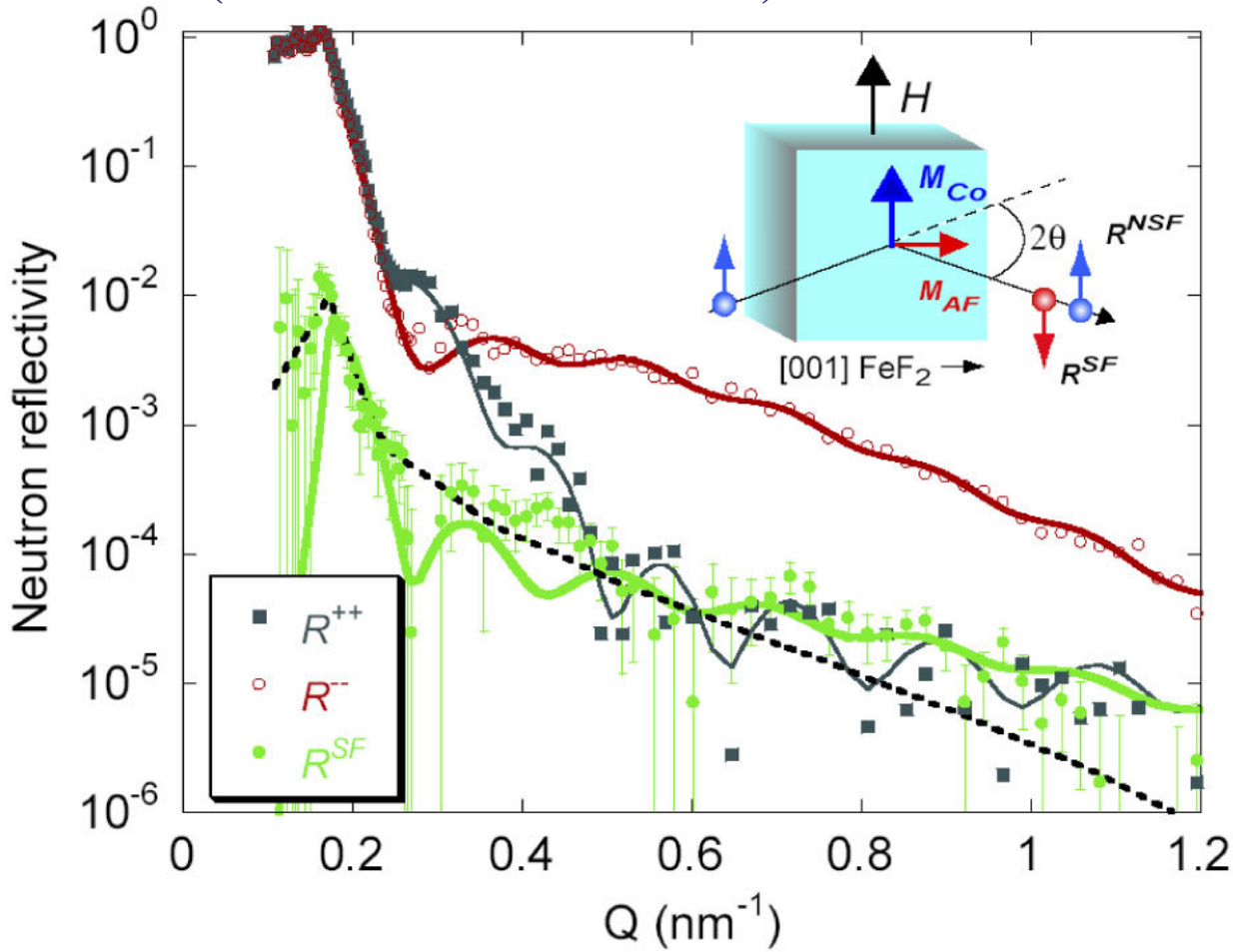
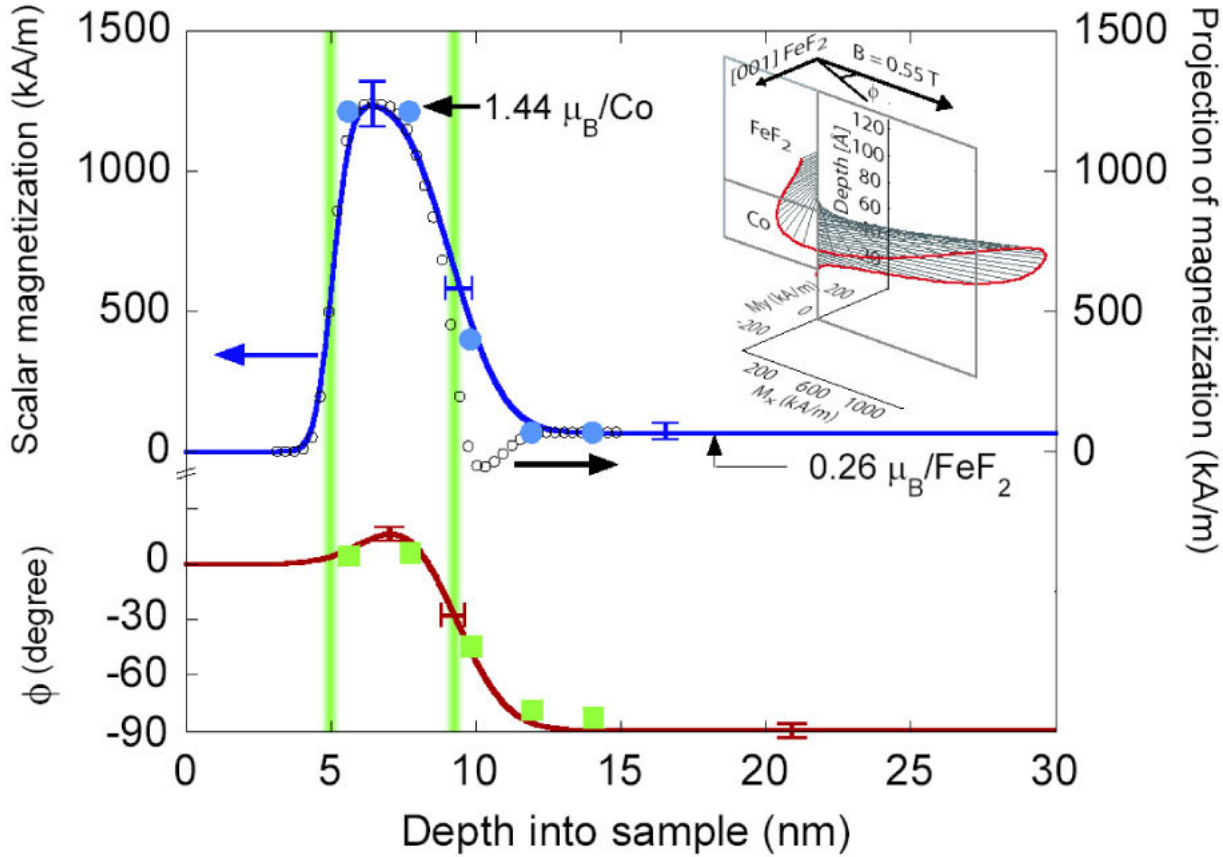
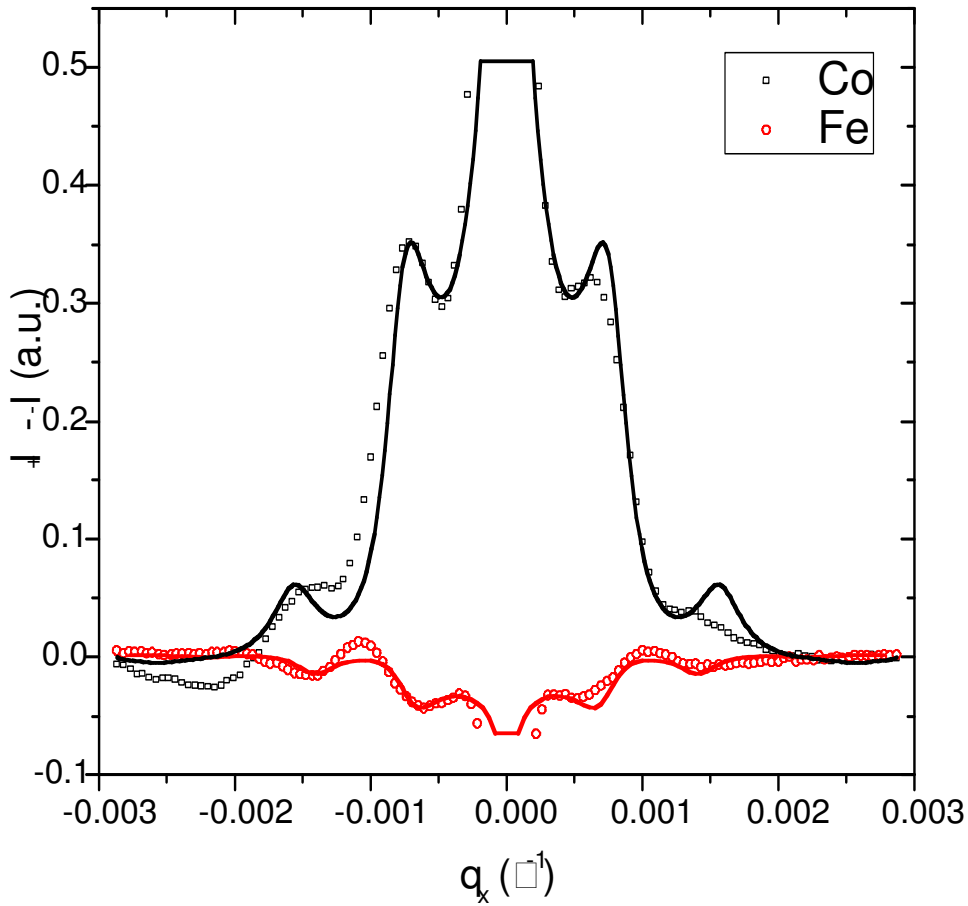


FIG. 2 (color). Spin density depth profiles for Co (blue) and Fe (red) spins obtained from the specular x-ray reflectivities (inset) at $H_{\pm} = \pm 796$ kA/m.

Polarized Neutron Reflectivity (ASTERIX/LANSCE)




Scalar magnetization (kA/m)
Projection of magnetization (kA/m)
1500
1000
500
0
1.44 μB/Co
0.26 μB/FeF2
φ (degree)
0
-30
-60
-90
0
5
10
15
20
25
30
Depth into sample (nm)
[0001] FeF2
B = 0.55 T
φ
FeF2
Co
Depth [Å]
120
100
80
60
40
My (kA/m)
200
0
-200
200
600
1000
Mx (kA/m)


Co
Fe
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.003
-0.002
-0.001
0.000
0.001
0.002
0.003
I+ - I- (a.u.)
qx (Å-1)

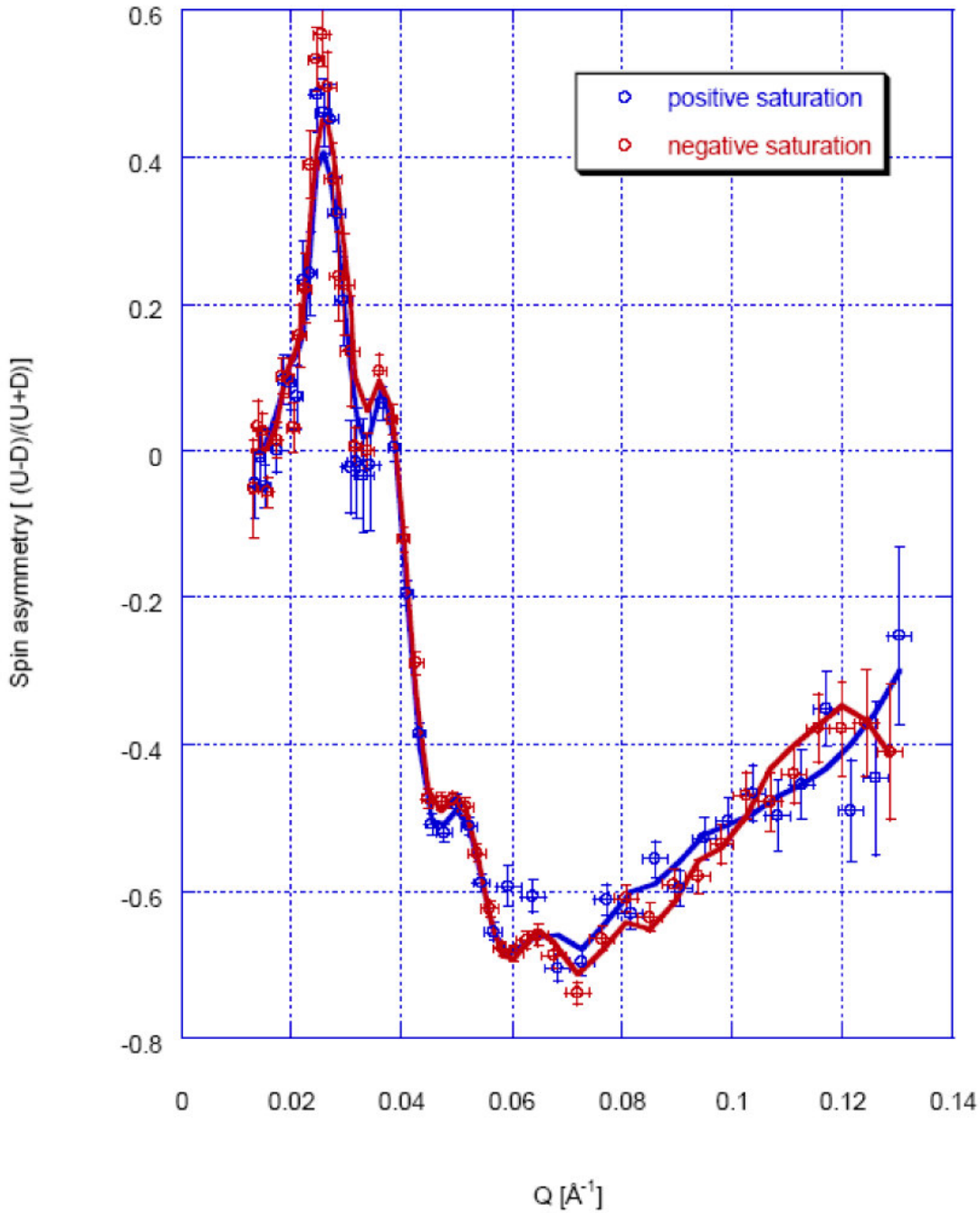


Figure 4 The spin asymmetry defined as (up-down)/(up+down) for measurements (symbols) taken in

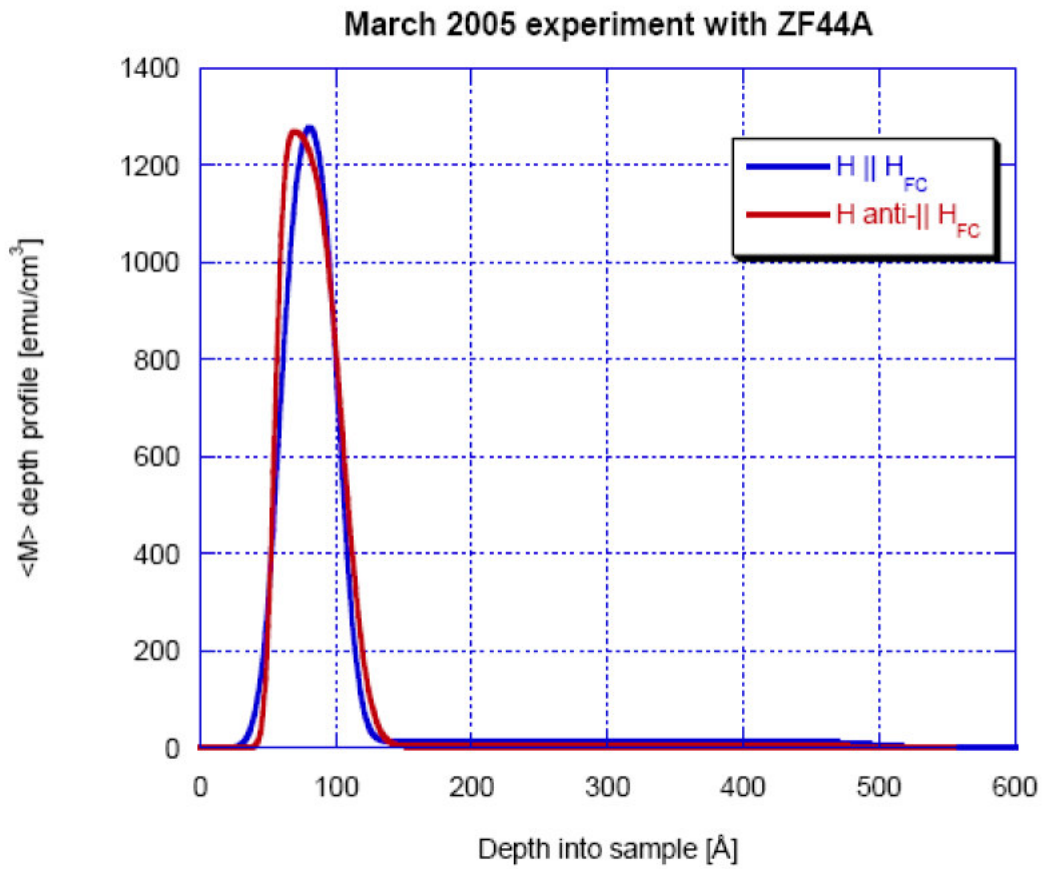


Figure 5 The magnetization depth profiles yielding the reflectivity curves shown in Figures 2 & 3.

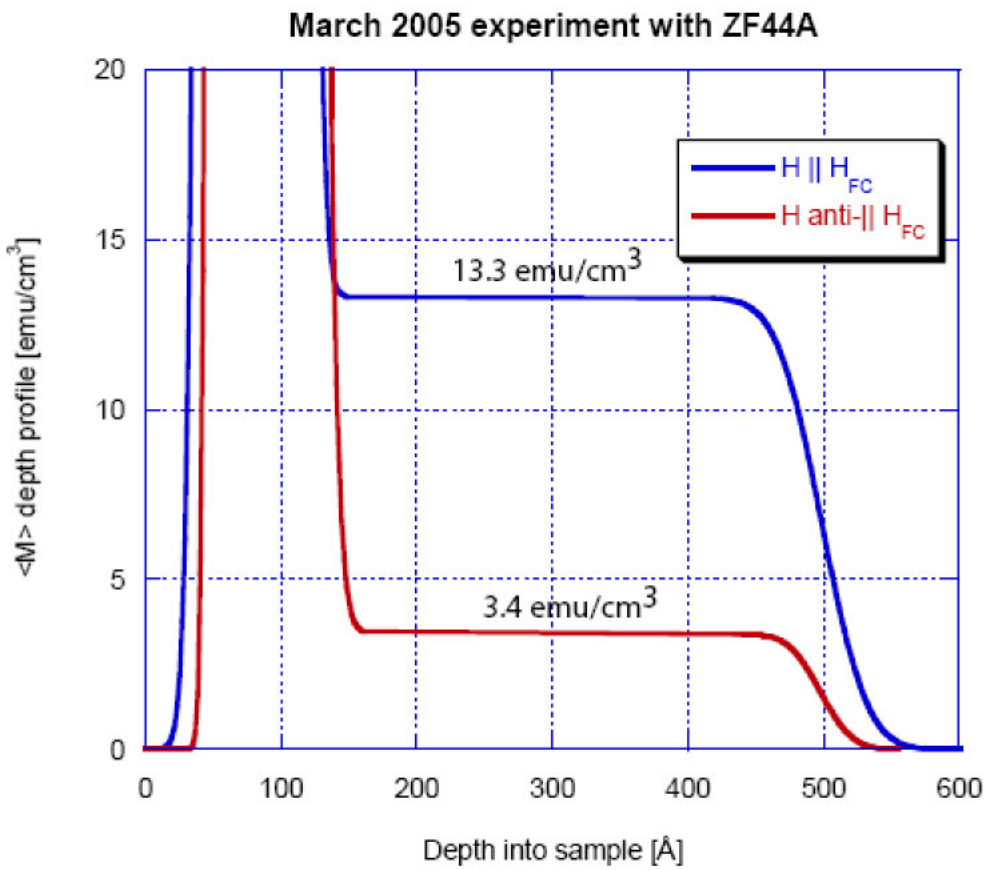
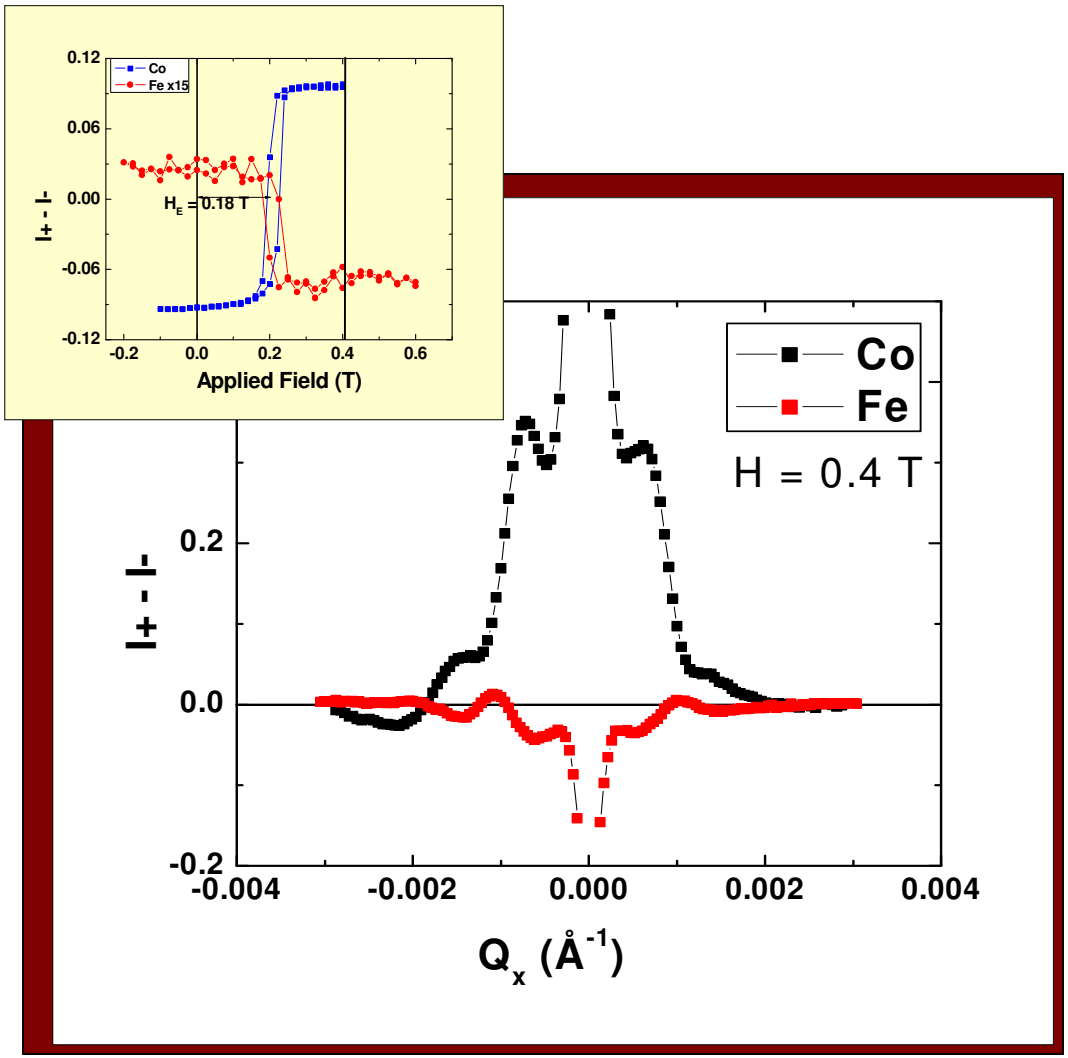
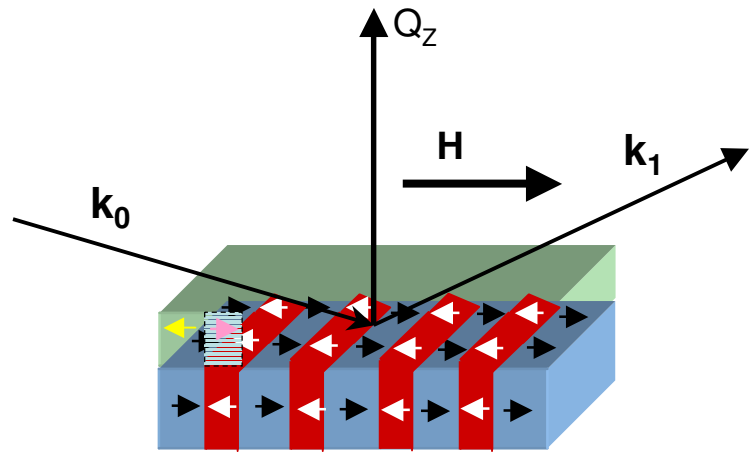


Figure 6 Note the levels of the uncompensated magnetizations in the AF for positive and negative saturation conditions. As discussed in the text, the net pinned magnetization is 4.95 emu/cm^3.

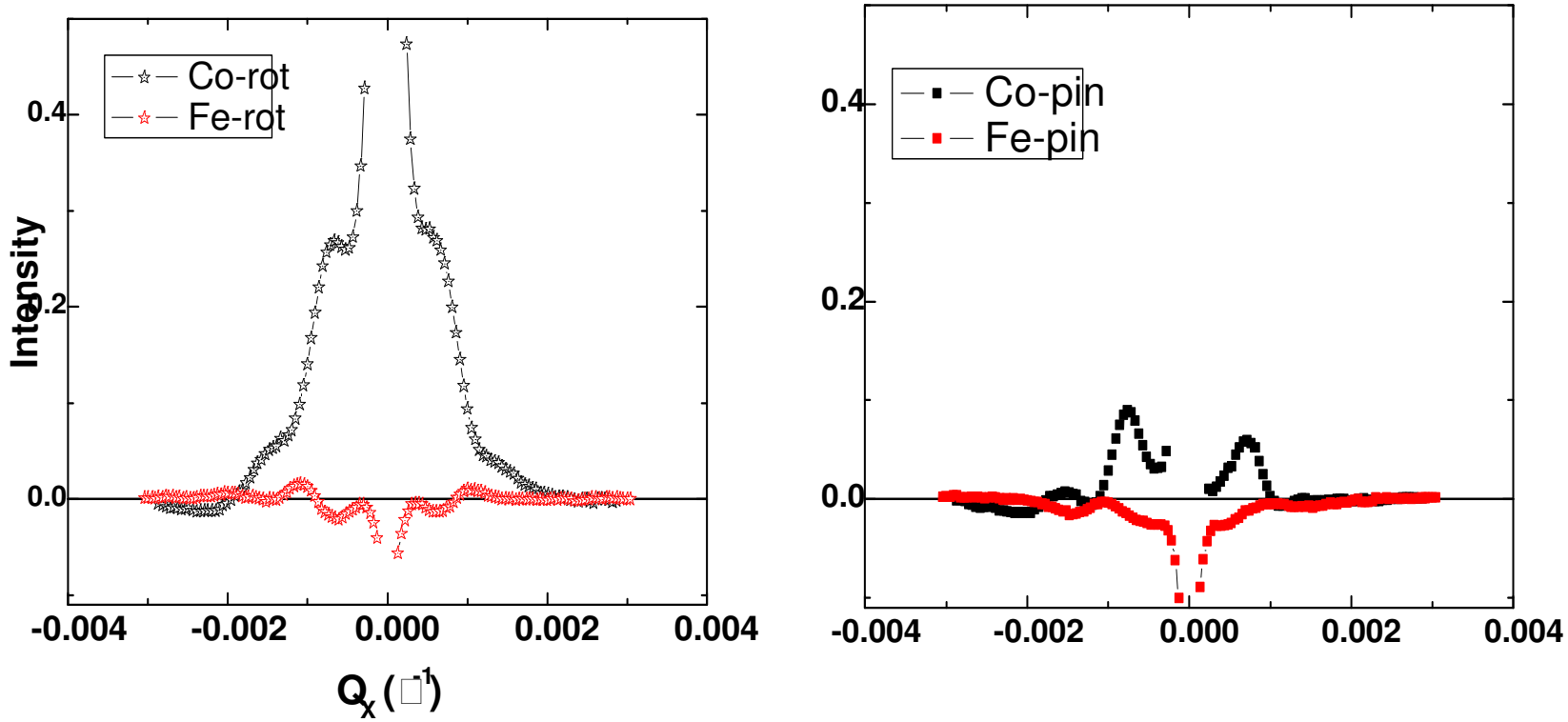
Diffuse Scattering at an Applied Field of 1 T





- Off specular scattering show peaks due to domains.
- Domains in the FM and AF are oppositely aligned
- Domains correlated with structural features (roughness or defect)

R. M. Osgood III, S. K. Sinha, J. W. Freeland, Y. U. Idzerda and S. D. Bader, JMMM 198-199, 698 (1999)


Co-rot
Fe-rot
Intensity
0.4
0.2
0.0
-0.004
-0.002
0.000
0.002
0.004
Co-pin
Fe-pin

UCSD

Conclusions

- Resonant X-Ray scattering combined with polarized neutron reflectivity is a powerful tool to determine in an element sensitive way the depth profileand direction of magnetism in a magnetic thin film structure

- For Co/FeF_2 system we found that

  - ✓ interface coupling is antiferromagnetic
  - ✓ existence of pinned and rotating moments for Fe
  - ✓ interface mostly contains rotating moments while the bulk contains pinned moments (from neutron scattering results)
  - ✓ exchange bias is due to exchange interaction between Fe pinned and Fe rotating moments
  - ✓ Diffuse scattering indicates formation of domains

Acknowledgements

- Sujoy Roy, Michelle Dorn UCSD
- Ivan Schuller, O.Petracic, Zhipan Li, Igor Roshchin UCSD
- Jeff Kortright, Karine Chesnel LBL
- Mike Fitzsimmons, Sungkyun Park LANL
- DOE/BES