Neutron scattering studies of exchange bias in Fe_3O_4/CoO epitaxial thin films

Yumi Ijiri, Dept. of Physics and Astronomy, Oberlin College

Julie Borchers and Ross Erwin, NIST Center for Neutron Research

Thomas Schulthess, Oak Ridge National Laboratory

Pieter van der Zaag, Philips Research Laboratories

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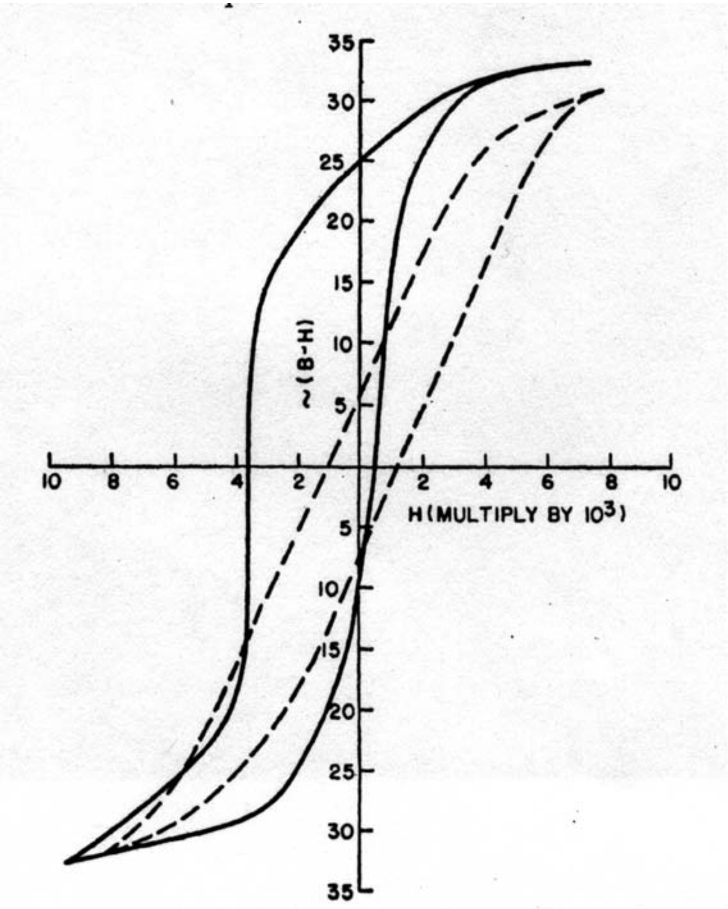
Outline

- Background on exchange biasing
  - Definitions and models
  - Approach
- Experimental details
  - System choice
  - Measurement geometry for neutron scattering experiments
- Experimental results
  - Perpendicular coupling of AF and F spins
  - Inequivalence of T_N vs T_B
  - Connecting perpendicular coupling to blocking temperature and biasing behavior
- Theoretical interpretation
  - Dzaloshinski/Moriya exchange

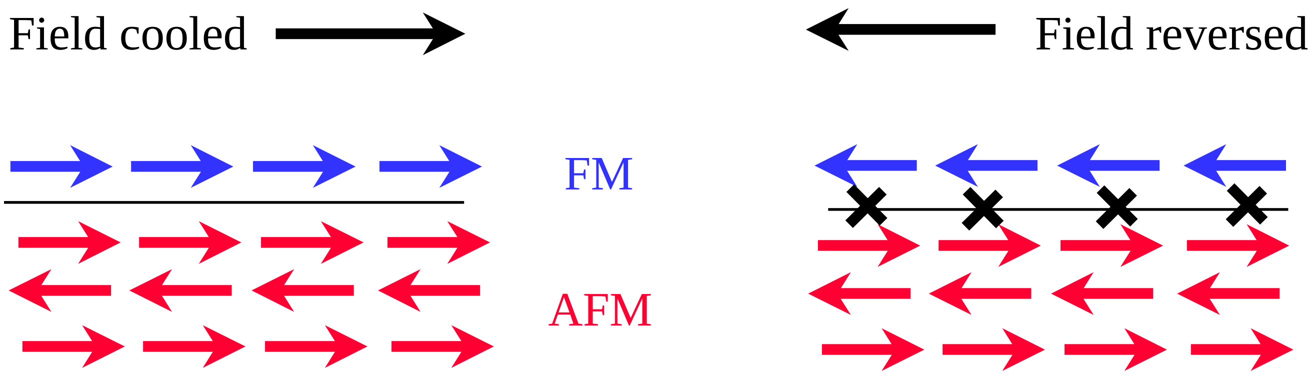
Background-Exchange Bias or Anisotropy

- Main features
  - AFM in direct contact with FM
  - Cool system in magnetic field, through AFM Néel temperature
  - Observe unidirectional shift along field axis
- Issues
  - Increase in coercivity?
  - Asymmetries in loop shape?
  - Onset of shifted hysteresis loops vs T_n?
- Uses in spin valves, read head sensors



Meiklejohn and Bean, *Phys. Rev.* **102**, 1413 (1956).

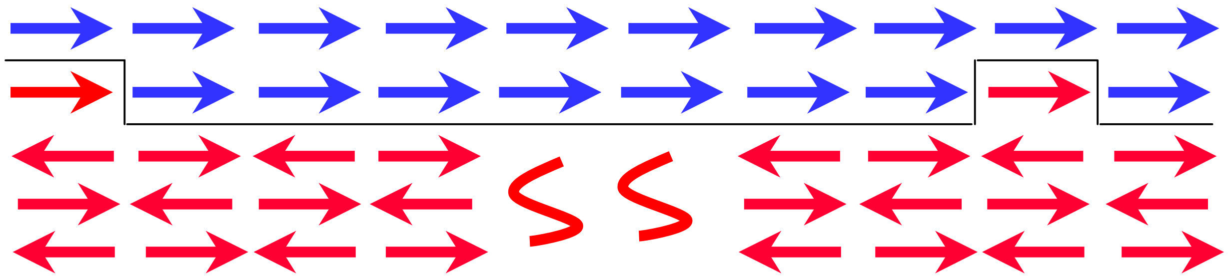
Earliest model: Meiklejohn, Bean



- Works well for a very well characterized system: Fe/Cr multilayers
  – Jiang, Felcher, Inomata, Goyette, Nelson, and Bader, *PRB* **61**, 9653 (2000)

- In general:
  – difficulties with size/temp. dependence/direction of shift
  – issues on thickness/growth/roughness/interfacial dependence
  – questions about the nature of exchange

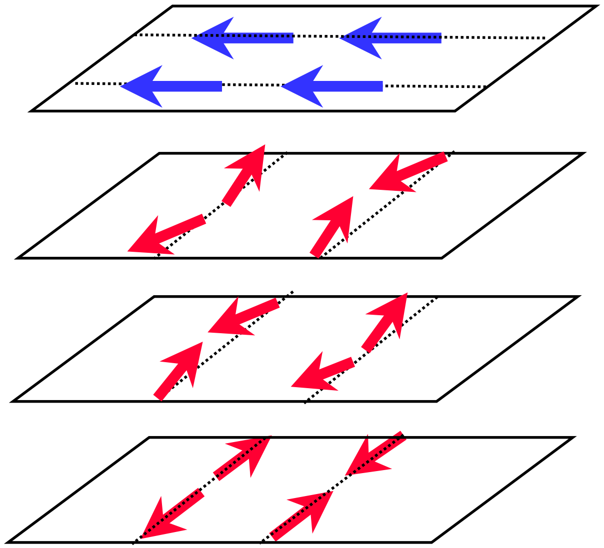
Models based on random field approach



- Essential features
  - AFM at interface mostly compensated, broken into domains with a net uncompensated moment
  - Cooling field aligns all uncompensated moments
  - Imry and Ma, *PRL* **35,** 1399 (1975); Malozemoff, *JAP* **63**, 3874 (1988).
- Experimental verification: moments, domains
  - Kappenberger, Martin, Pellmont, Hug, Kortright, Hellwig, Fullerton, *PRL* **91**, 267202 (2003)
  - Miltenyi, Gierlings, Keller, Beschoten, Gunterrodt, Nowak, and Usadel, *PRL* **84**, 4224 (2000)

Models based on spin flop coupling

- Essential features
  - FM spins align perpendicular to AFM easy axis, analogous to AFM in high magnetic field
  - Domain wall parallel to the interface
  - Hinchey and Mills, *PRB* **34**, 1689 (1986) and Koon, *PRL* **78**, 4865 (1997).



- Problems
  - Works for x-y spins, not Heisenberg, leading to coercivity not bias
  - Compatibility with random field model?
  - Schulthess and Butler, *PRL* **81**, 4516 (1998); Stiles and McMichael, *PRB* **59**, 3722 (1999)

Experimental approach

- Many exchange biasing issues centered on either the antiferromagnet or the interface spins
  - orientation of spins
  - temperature evolution
  - nature of domains

- Techniques to probe the antiferromagnet, (buried) interface
  - use large single crystals of AFM/companion samples
  - image with spin-polarized STM
  - x-ray magnetic circular dichroism
  - Neutron scattering

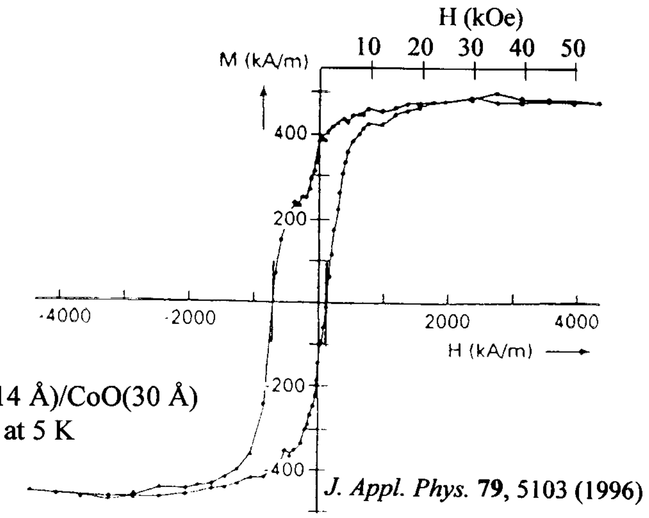
- Approach: to use neutron diffraction and reflectivity techniques along with other magnetization probes to correlate behavior

Fe_3O_4/CoO system

•Good growth due to structural match

-(Fe_3O_4 100 Å)/(CoO 17-100 Å)$_{x50}$

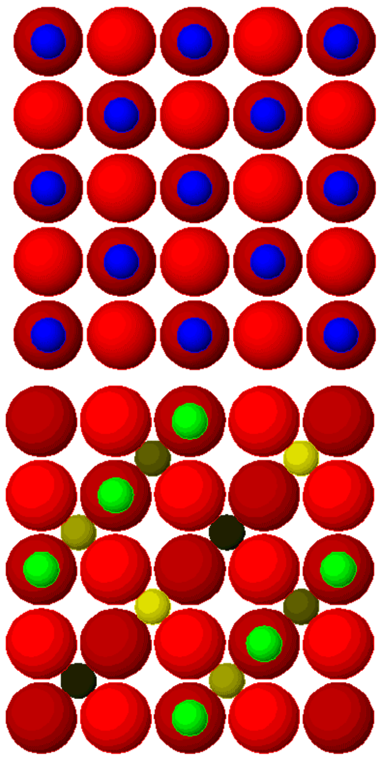
-(CoO 30 Å/MgO 30 Å)$_{x333}$ on MgO



(00l) planes

CoO (MgO)
Rock salt
2a = 8.508Å
(8.424 Å)

Fe_3O_4
Spinel
a=8.398 Å



•Magnetic properties

-Bulk CoO orders AFM at 291K, planes alternate in <111> directions, 3.9 μ_B on Co^{+2}

-Bulk Fe_3O_4 orders ferrimagnetic at 858 K, net moment 4.2 μ_B

•Composite system shows bias

Scattering geometry

•Measure AFM reflection or FM reflection or low angle reflectivity

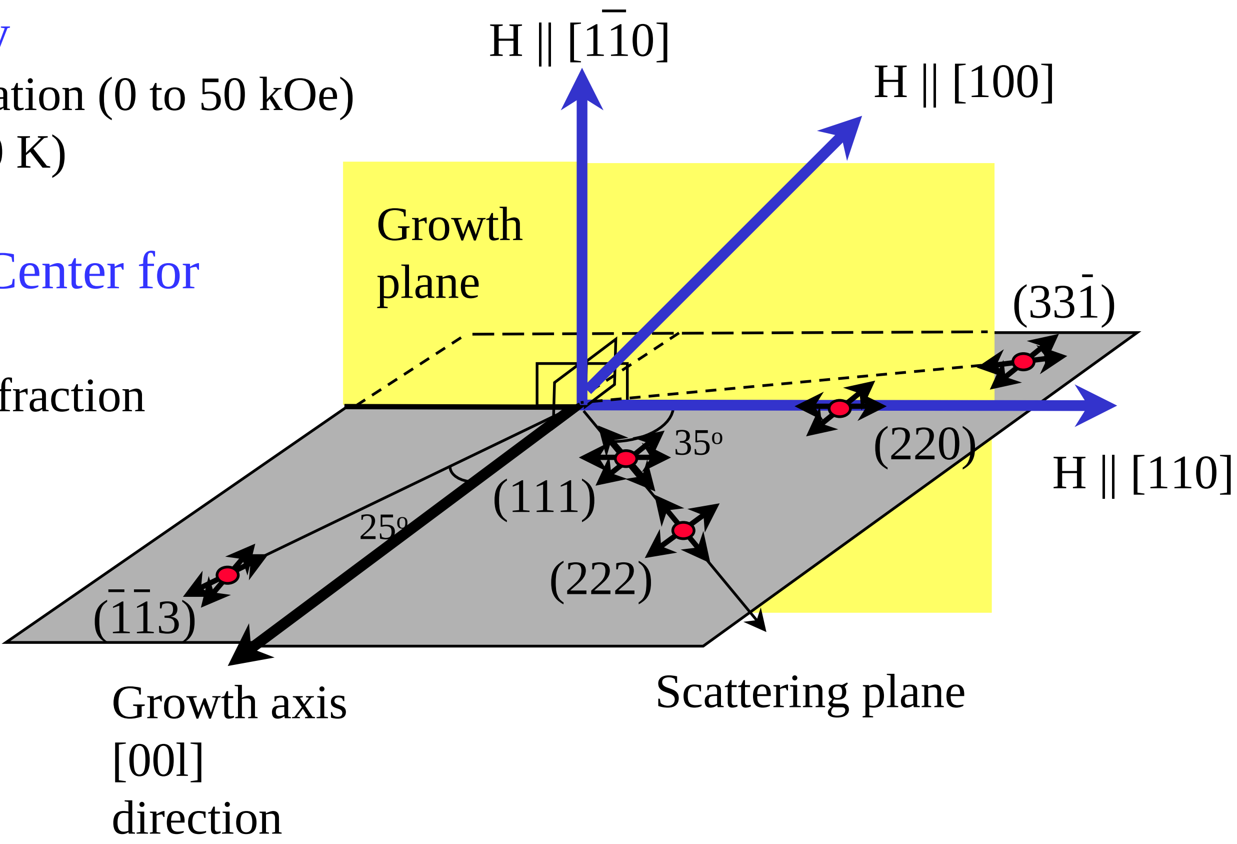
-vary field cooling preparation (0 to 50 kOe)

-vary temperature (10-550 K)

•Experiments at NIST Center for Neutron Research

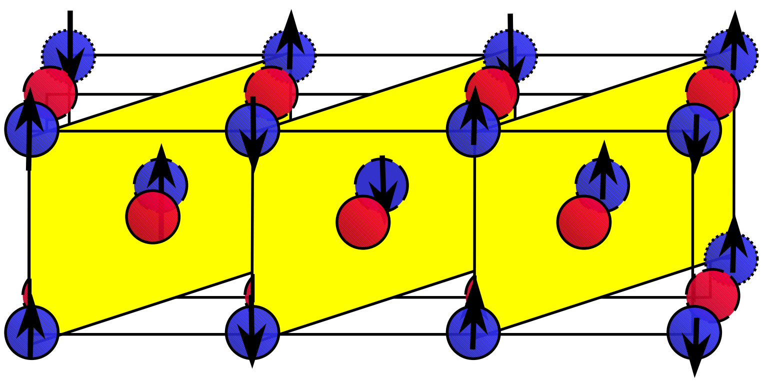
-BT2, BT9, SPINS for diffraction

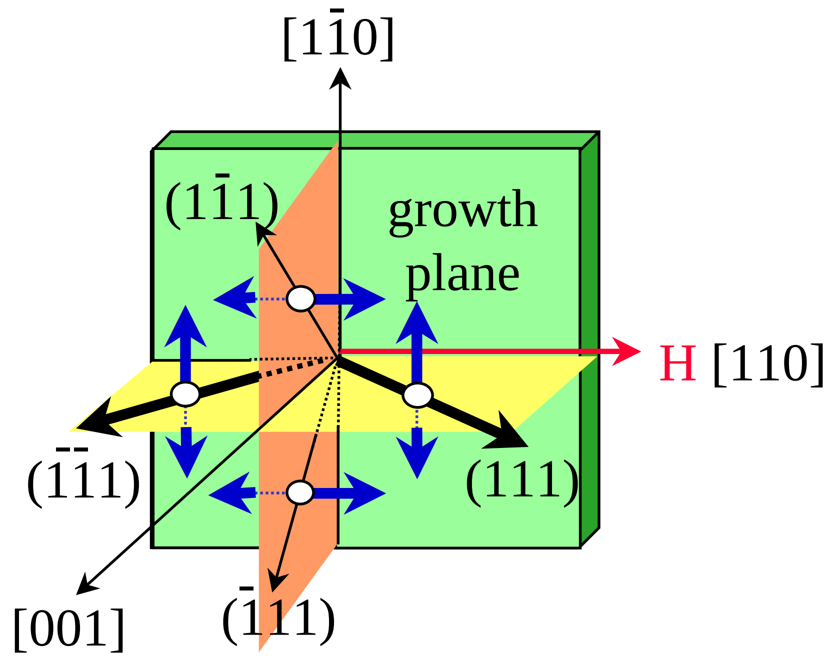
-NG1 for reflectivity



AFM spin directions for CoO

- New moment directions, substantially different from bulk
- Spins constrained within sample growth plane
- Observed for both Fe_3O_4/CoO and CoO/MgO superlattices

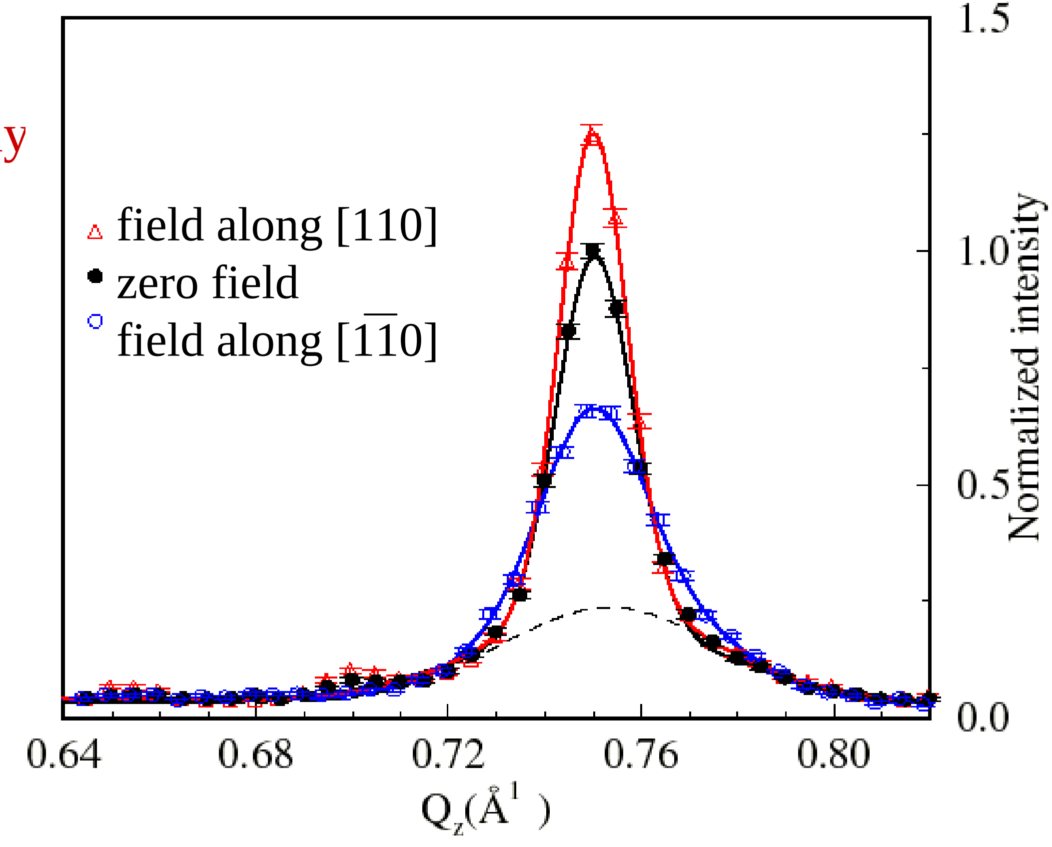




Ijiri, Borchers, Erwin, Lee, van der Zaag, Wolf, *PRL* **80** (608), 1998

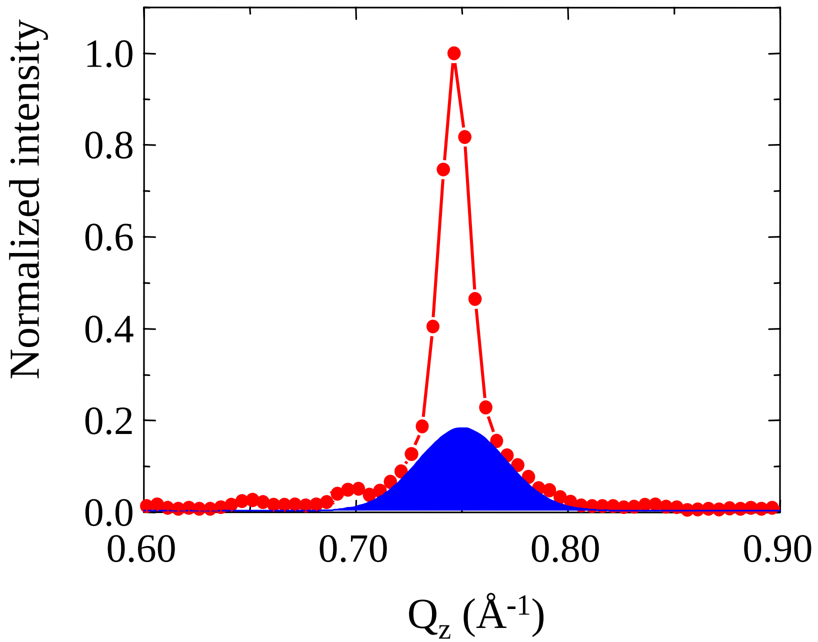
AFM/FM perpendicular alignment

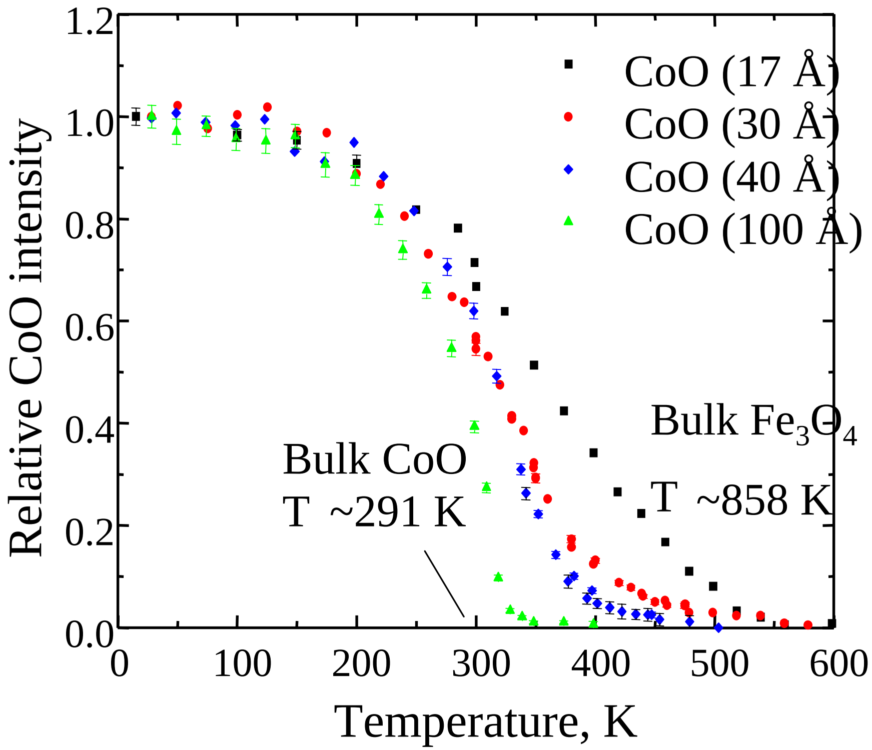
- AFM spins are preferentially perpendicular to FM spins
- Effect not observed for CoO/MgO superlattice



Data to extract T_N

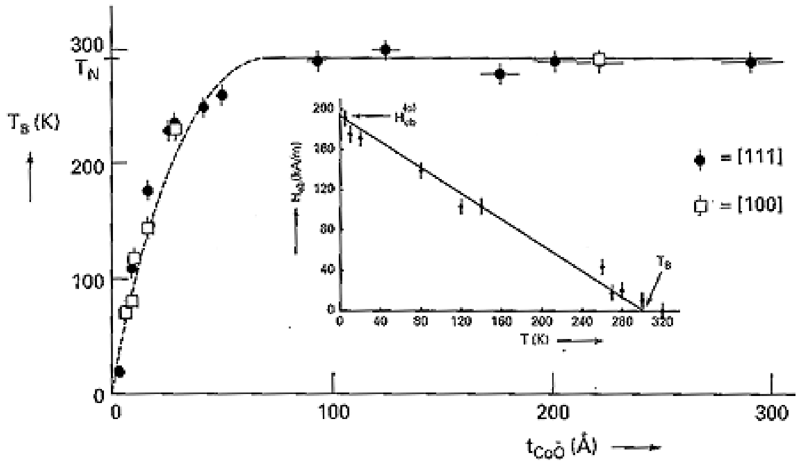
- 2 component line shape to reflection
  - Broad-Fe_3O_4 contribution
  - Narrow-CoO contribution

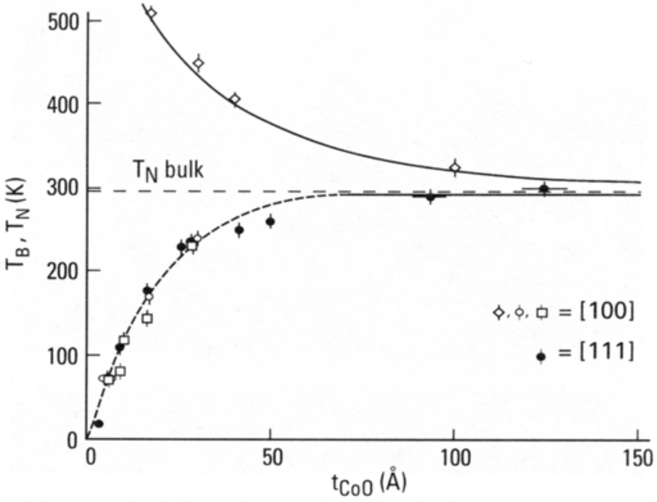




- T_N increases with decreasing CoO thickness

Comparison of T_N to T_B





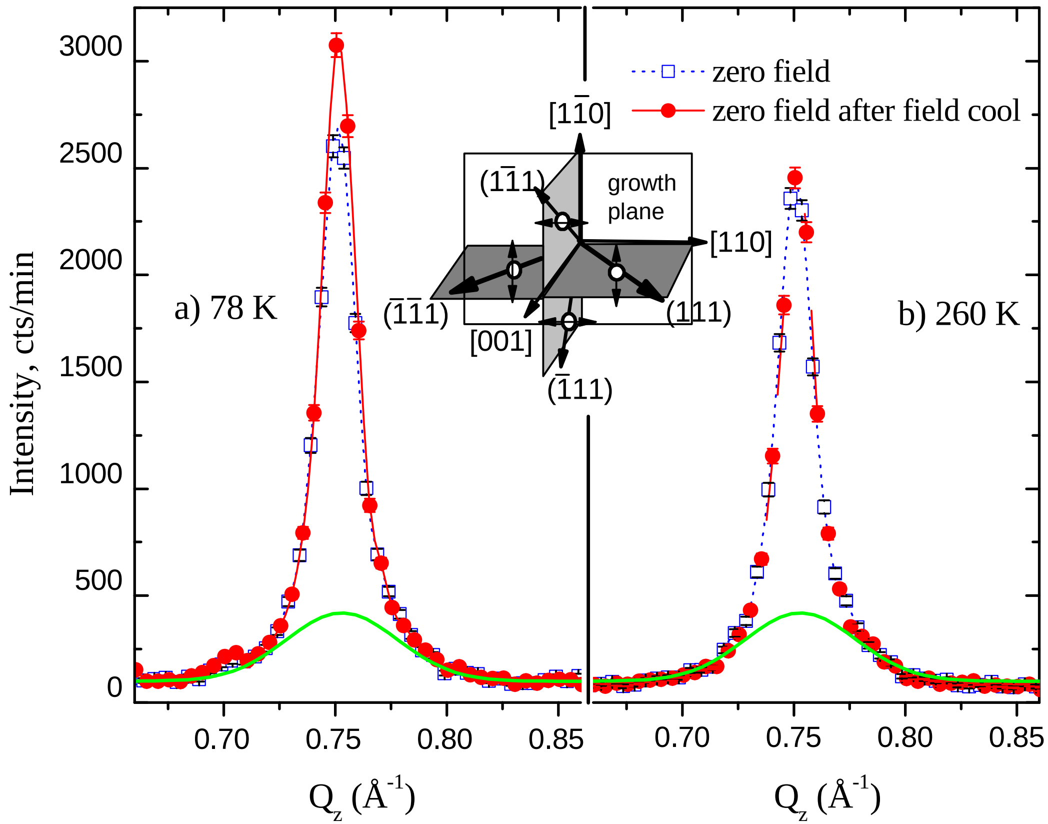
- T_B from SQUID magnetometry shows opposite trend to T_N

  -van der Zaag, Ijiri, Borchers, Feiner, Wolf, Gaines, Erwin, Verheijen, *PRL* **84** (6102), 2000

- Reduced T_B not a finite size effect of T_N

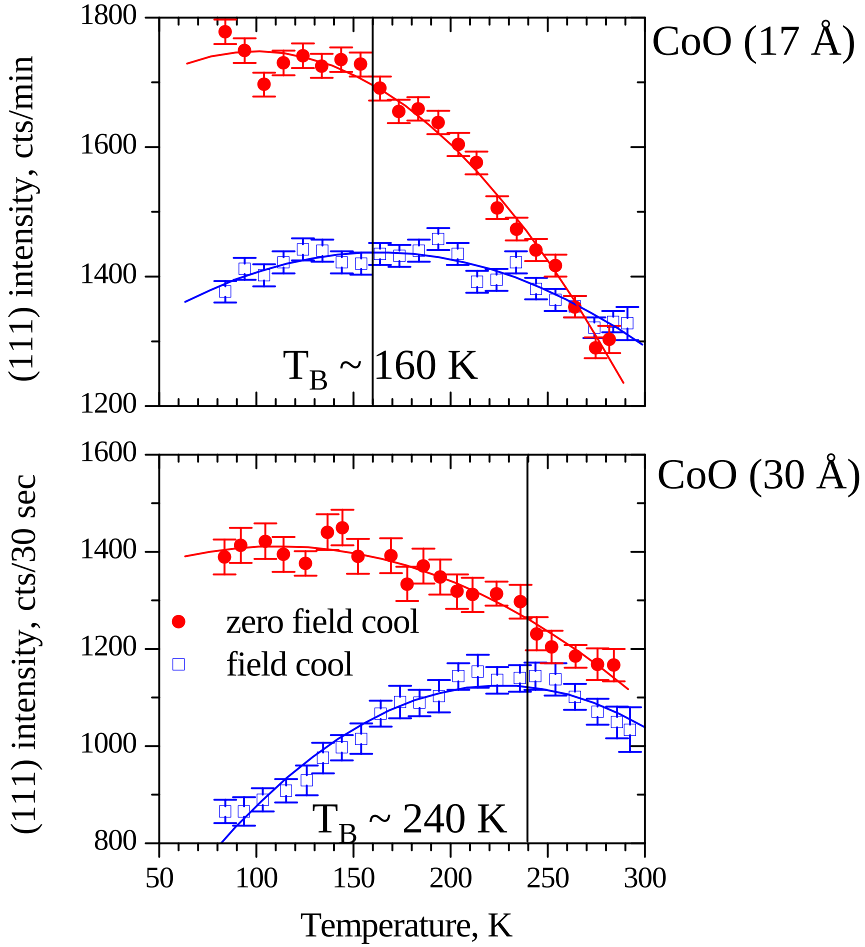
AFM behavior associated with T_B

- Below T_B, preferred AFM directions appear locked in
- Above T_B, AFM directions randomized



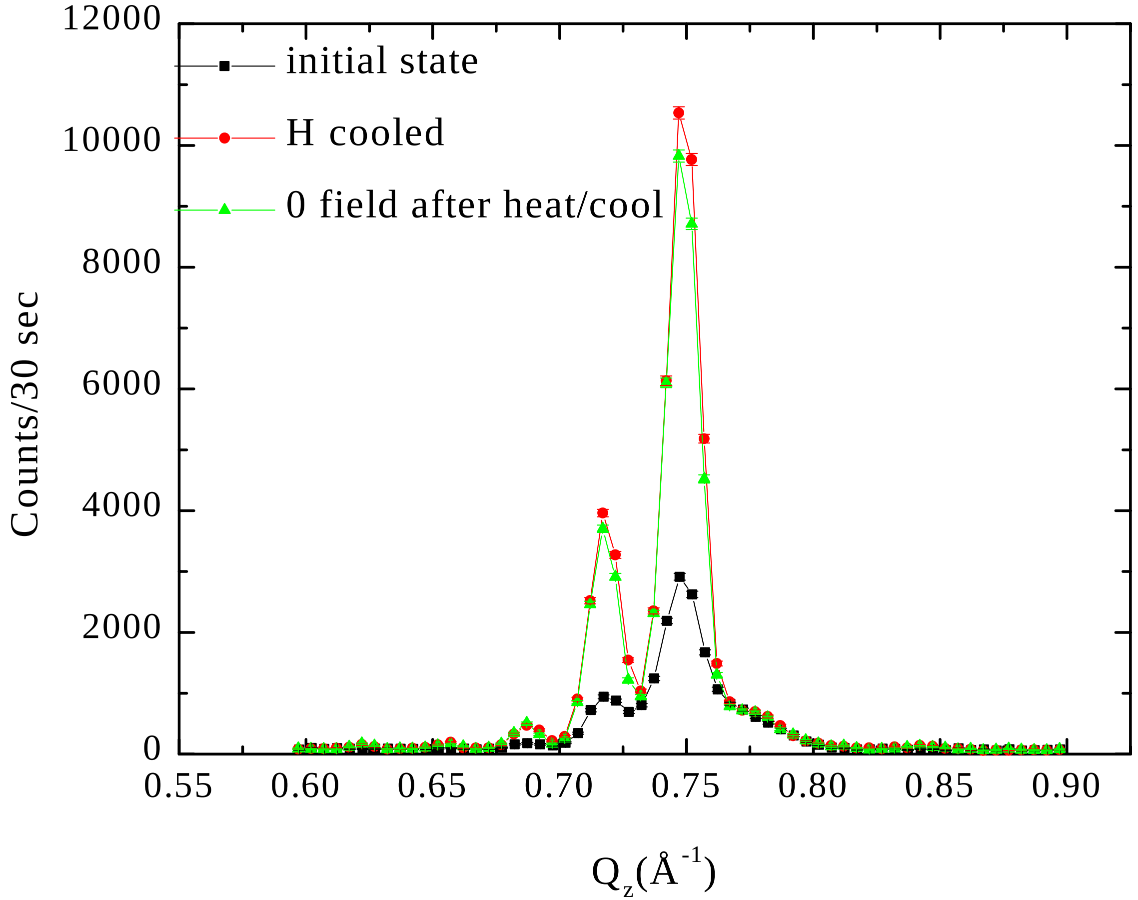
Perpendicular coupling and T_B

- Track (111) intensity vs. temp. with and without field treatment
- Observe peak~ plateau corresponding to T_B
- Unlocking of spins from preferential perpendicular coupling direction at T_B



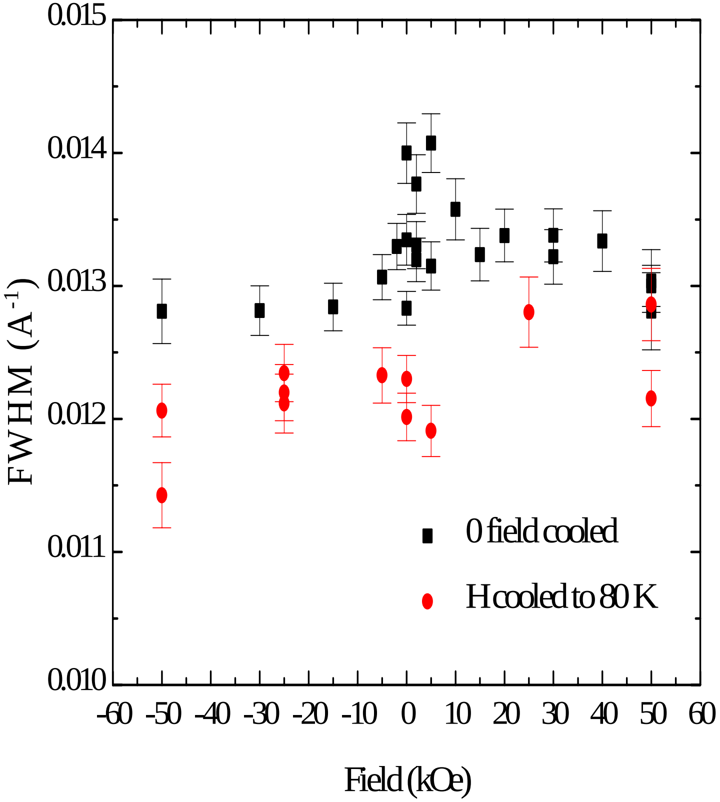
Behavior for $T_B \sim T_N$

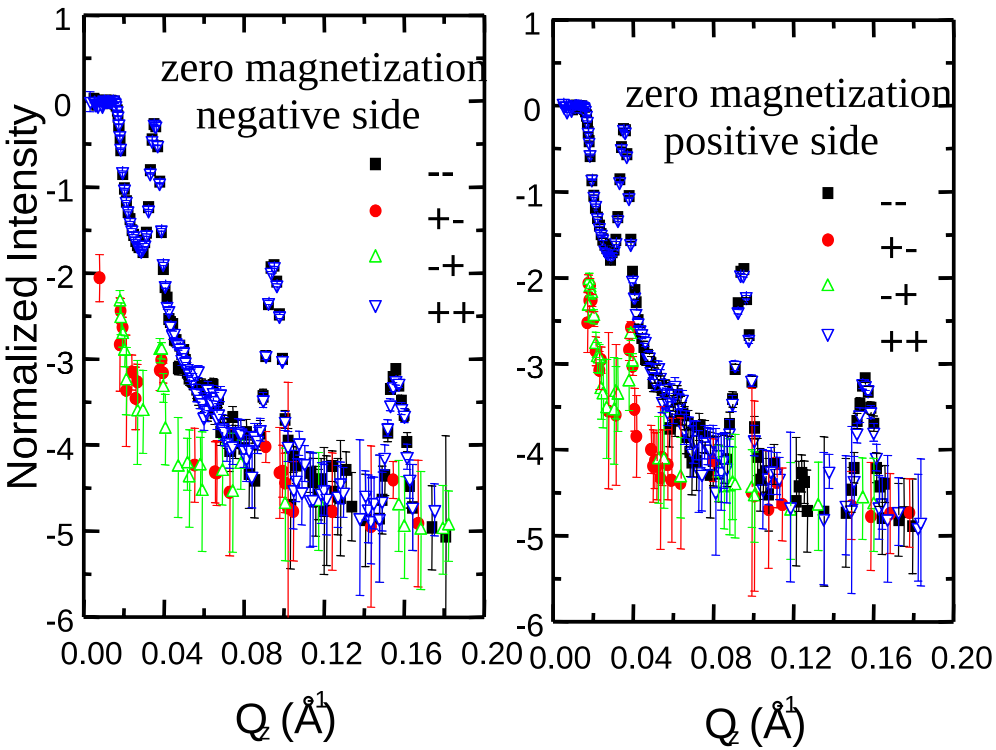
- Field preparation memory despite re-randomizing the CoO above T_N
- Evidence of response to Fe_3O_4



Character of AFM, FM domains

- Few changes on field cycling





- Similar to random field model, little evidence of twists, changes in average domain sizes

Theoretical understanding

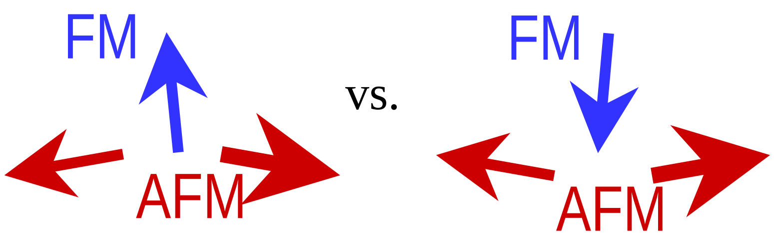
- Experimental results:
  - Perpendicular coupling clearly associated with biasing-connection to T_B
  - Otherwise random field like

How to connect the two?

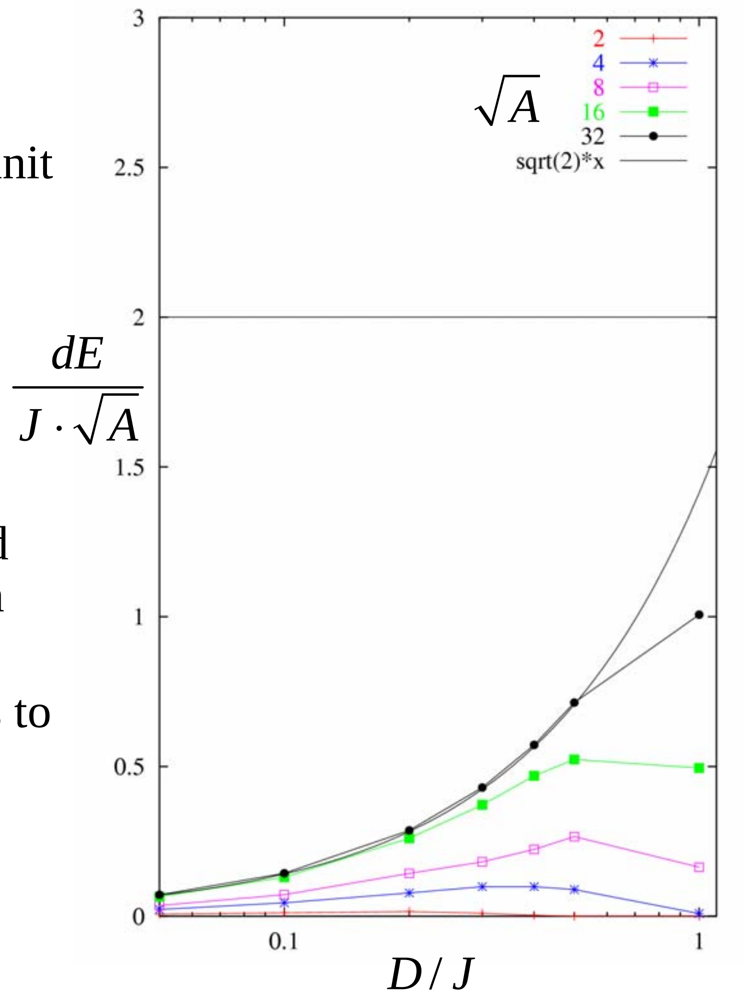
- Role of anisotropic exchange term?
  - $E_{A\text{-}F} = -J_{A\text{-}F}\mathbf{S}_A \bullet \mathbf{S}_F + \mathbf{D}_{A\text{-}F} \bullet (\mathbf{S}_A \mathrm{x} \mathbf{S}_F)$
  - Dzialoshinski, Sov. Phys. *JETP* **5**, 1259 (1957); Moriya, *Phys. Rev.* **120**, 91 (1960)
  - D term from spin orbit coupling and superexchange interaction
  - Nonzero for noncollinear spins
  - Nonzero only for low/broken symmetry

D-M exchange for biasing

- Recent simulations
  - Calculate energy difference for 2 configurations ~ $2(D^z_{net})\sin\theta$ for one unit

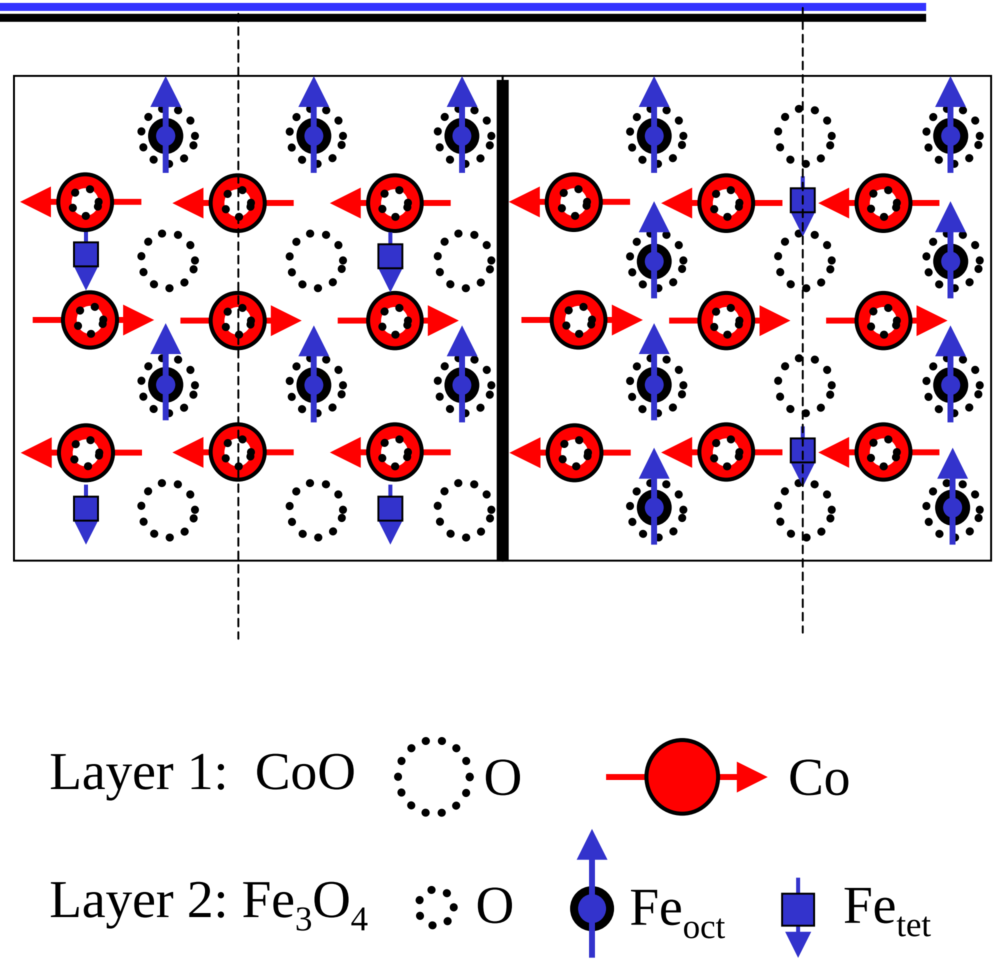


  - D/J ~ .3, Heisenberg spins, randomized bias comparable to Ising spins, random field model
  - Size effect to coupling directions-leads to coercivity
  - Schulthess, MRS Symp. Proc. **346**, 31 (2003).



DM exchange for Fe_3O_4/CoO

- Consider interface
  - CoO domains longer range
  - Fe_3O_4 domains shorter due to antiphase boundaries
  - Hibma, *et al.*, *JAP* **85**, 5291 (1999)



- Tetrahedral irons can have significant DM exchange

Conclusions and Further Work

- Summary of main results for Fe_3O_4/CoO system
  - Preference for perpendicular coupling of FM and AFM spins
  - Inequivalence of T_N vs T_B
  - Association of T_B with the unfreezing of perpendicular coupling
  - Results consistent with a model of anisotropic exchange

- Implications of work
  - Interfacial spins can be very different from the bulk
  - Need for more sophisticated exchange considerations

- Further work to explore model of anisotropic exchange
  - Quantitative match?
  - Density of antiphase domains, etc. vs. size of bias?