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# Interlayer Magnetic Coupling in an Fe/Cr Superlattice

What gives rise to the giant magnetoresistance effect?

2008 SANS & Reflectometry Summer School • NIST Center for Neutron Research •

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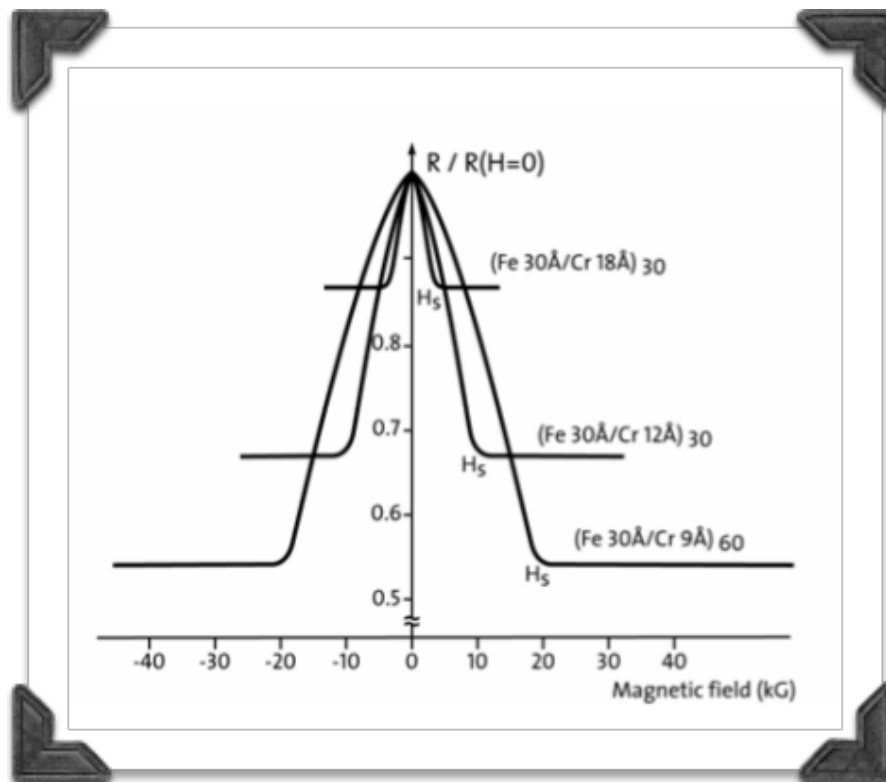


Figure 1: *Magnetic field dependent resistivities for a series of Fe/Cr superlattices<sup>1</sup> - a sample of the work that led to the 2007 Physics Nobel Prize.*

In the late 1980's research groups led by Albert Fert and Peter Grünberg found that structures composed of a few atomic layers of Fe separated by a few atomic layers of Cr

could exhibit extremely large changes in electrical resistivity in response to relatively small changes in magnetic field.<sup>2</sup> Fert coined the term “Giant Magnetoresistance” (GMR) to describe this phenomenon, and applications for GMR were recognized immediately. Within a decade, commercial computer hard drives were employing GMR to achieve unprecedented information storage densities. Thus, the discovery of GMR revolutionized magnetic data storage and earned the 2007 Nobel Prize in Physics for Fert and Grünberg.

### **What’s special about Fe/Cr superlattices?**

Figure 1 shows some of Fert’s groundbreaking magnetoresistance measurements on a series of Fe/Cr superlattices. At a temperature of 4.2 K, we can see that the resistivity of a series of Fe/Cr superlattices drops drastically when just a few kG of magnetic field is applied. So, why is it that the electrical resistance of Fe/Cr superlattice structures is so sensitive to magnetic fields? Specifically, why is the low field resistance so high? The answer is well known, but in the spirit of the recent Nobel award, we will perform a polarized neutron reflectometry (PNR) experiment that will clearly illustrate the special properties of Fe/Cr superlattices that lead to GMR. PNR is well suited for studying this type of system, as it is sensitive to the depth-dependent vector magnetization (moment per unit volume) and the depth-dependent nuclear profile of thin film structures.

### **Polarized Neutron Reflectometry**

For a detailed treatment of neutron reflectometry, see *The Theory of Small Angle Neutron Scattering and Reflectometry* by Andrew Jackson, which has been provided for you, and for *polarized* neutron reflectometry in particular, see the chapter by Fitzsimmons and Majkrzak in *Modern Techniques for Characterizing Magnetic Materials*<sup>3</sup> (available online at <http://www.ncnr.nist.gov/instruments/ngirefl/Fitz.pdf>) . In short, neutron reflectometry can measure the depth dependent scattering length density of thin film structures. Scattering length density, typically reported in units of  $\text{\AA}^{-2}$ , is a mathematically convenient quantity for those working in neutron scattering, but it may seem a bit unusual to those new to the technique. Crudely speaking, scattering length density is a

measure of the *scattering power* of a material. For a given compound, the *nuclear* component of the scattering length density is

$$(1) \rho_{\text{nuc}}(z) = \sum_i b_i N,$$

where  $b$  is the characteristic neutron scattering length of a given element (these values are known - see <http://www.ncnr.nist.gov/resources/n-lengths/>),  $N$  is the number of “molecules” of the compound per unit volume, and the summation is over each element in the compound. This component of the scattering comes from the interaction between the neutron and the constituent nuclei of the sample, and therefore is indicative of a material’s chemical composition. Additionally, because the neutron has a magnetic moment, there is also a magnetic component of the scattering length density which is directly proportional to the sample magnetization  $M(z)$

$$(2) \rho_{\text{mag}}(z) = (2.853 \times 10^{-9} \text{ cm}^3 \cdot \text{emu}^{-1} \cdot \text{\AA}^{-2})M,$$

for  $M$  in units of  $\text{emu} \cdot \text{cm}^{-3}$ . The utility of *polarized* neutrons is that they allow us to distinguish between the nuclear and magnetic components of the scattering length density. Using the formalism that + corresponds to neutron spin parallel to a magnetic field  $H$ , and - corresponds to neutron spin anti-parallel to  $H$ , we are interested in four polarized neutron cross sections. The non spin-flip (incident and scattered neutrons have the same polarization) cross sections  $R^-$  and  $R^{++}$  are dependent on the nuclear depth profile, and the depth profile of the component of  $M(z)$  parallel to  $H$ . The spin-flip cross sections  $R^+$  and  $R^{--}$  are purely magnetic in origin, and are dependent on the depth profile of the component of  $M(z)$  perpendicular to  $H$ . A schematic of the PNR geometry is shown in Figure 2.

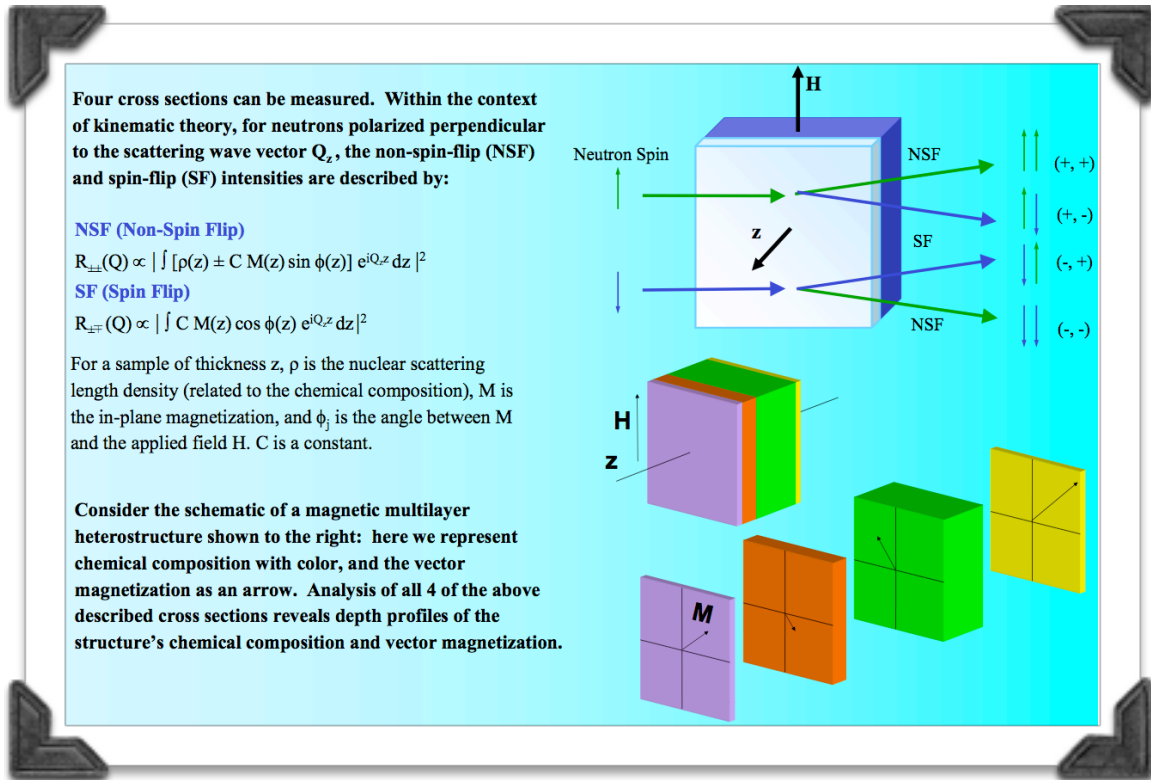


Figure 2: Illustration showing the geometry of polarized neutron reflectometry.

## Experimental Apparatus

For our PNR measurement, we will use the NG-1 Polarized Beam Reflectometer at the NIST Center for Neutron Research. Figure 3 shows the beamline. A pyrolytic graphite [002] triple crystal monochromator intercepts a polychromatic cold neutron beam, and reflects a monochromatic beam (wavelength  $\lambda = 4.75 \text{ \AA}$ ) down the beamline. Moving downstream, an Fe/Si supermirror is used to spin polarize the neutron beam. The magnetic field of the supermirror aligns the neutrons' spin along an axis normal to the floor, and its special layer structure causes one spin state (spin-up) to be reflected out of the beamline, while the other spin state (spin-down) is transmitted towards the sample. After the supermirror is a "Mezei" spin flipper, which consists of windings of aluminum (essentially transparent to neutrons) wire. When electrical current flows through the wires, the a magnetic field is produced that flips the neutron spin by  $180^\circ$ , thus allowing the user the choice of spin-up or spin-down neutrons. The sample is inside the aluminum tail-piece of "displex" refrigerator mounted in an electromagnet, which is attached to a ro-

tatable sample table. On the downstream side of the sample is the detector arm, which houses another Mezei flipper / supermirror analyzer assembly followed by a narrow “pencil” neutron detector. Like the polarizer, the analyzer supermirror transmits only spin-down neutrons, thus the downstream assembly allows for measurement of all 4 polarization cross-sections ( $--$ ,  $+-$ ,  $-+$ , and  $++$ ).

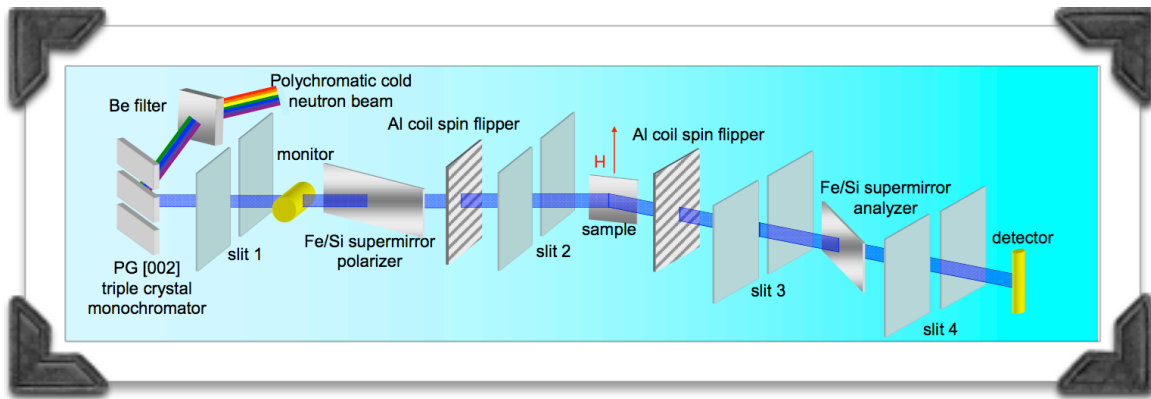


Figure 3: Elements of the NG1 Polarized Neutron Reflectometer.

## Experiment

Our sample is a 1x1 cm Fe/Cr superlattice, provided by Dr. Shah Valloppilly of the Indiana University Cyclotron Facility. The sample consists of:  $45 \text{ \AA} \text{ TiO} / 14 \text{ \AA} \text{ Ti} / [15 \text{ \AA} \text{ Cr} / 38 \text{ \AA} \text{ Fe}]_{10}$  on a MgO substrate. For our experiment we will use PNR to measure the *magnetic* depth profile of the sample at 45 G (we cannot measure in true *zero* field, as we need some small field to guide the neutrons) after cooling the sample in zero field to 5 K. The sample’s layer composition, thickness, and roughness, have already been determined using x-ray reflectometry. So, if we make a few more assumptions, we can *guess* at what the PNR spectra from the sample will look like. Let’s assume that the TiO, Ti, and MgO layers are non-magnetic (not a stretch), the Cr layers while magnetically ordered as a *spin density wave* (another Nobel Prize!<sup>4</sup>) have no *net* magnetization, and that the Fe layers are ferromagnetic with  $M = 1750 \text{ emu/cc}$  (typical of Fe). We can then calculate the magnetic scattering length density for the Fe layers from equation 2.

Further, let's assume that the easy magnetic axis happens to be  $45^\circ$  away from our neutron polarization direction, so that after cooling in zero field, the magnetization vectors of the Fe layers have components both parallel and perpendicular to the neutron spin. We can also make reasonable guesses for the nuclear scattering length densities. The NCNR maintains a handy online calculator (<http://www.ncnr.nist.gov/resources/sldcalc.html>) that calculates  $\rho_{nuc}$  from a compound's mass density (the calculator "knows" the nuclear scattering lengths and atomic masses of the elements). The important quantities for simulating the PNR spectra from our sample are shown in Table 1.

compound	$t$ (Å)	$\rho_{nuc}$ ( $10^{-6}$ Å <sup>-2</sup> )	$\rho_{mag}$ ( $10^{-6}$ Å <sup>-2</sup> )	angle between H and M (deg)
TiO	45	1.1	0	0
Ti	14	-1.95	0	0
Cr	15	3.03	0	0
Fe	38	8.02	5	45
MgO	substrate	5.98	0	0

**Table 1: Layer dependent properties for our simulation. Note that these are guesses - the real parameters you measure (especially the magnetic ones) may vary. The Fe and Cr layers (light blue) are repeated ten times.**

From the values in table 1, we can use the *Reflpol*/PNR fitting and calculation software to guess at what the PNR spectra from our sample might look like. The simulation is shown in Figure 4, with  $R^{++}$  is in orange,  $R^{--}$  is in blue, and  $R^{+-} = R^{-+}$  is in green. Note that the  $R^{++}$  and  $R^{--}$  cross sections are different - due a component of the sample magnetization parallel to the neutron spin. Also note that we see significant scattering in the  $R^{--}$  and  $R^{+-}$  cross sections - due to an in-plane magnetization component perpendicular to the neutron spin. Finally, note the large peak in all of the cross sections at  $Q \approx 0.12$  Å<sup>-1</sup>. This is known as the superlattice Bragg position, and it corresponds to the repeat thickness of the Fe and Cr,  $Q \approx 2\pi / (15 \text{ Å} + 38 \text{ Å})$ . These are key features in the PNR spectra

that we will be quick to take notice of when we perform our experiment. If the measured spectra look similar, we'll know that our initial guess was close to correct, and some quick data fitting will be all that is needed to flesh out the details of the sample profile. However, if the spectra are grossly different, we will immediately know something interesting is afoot...

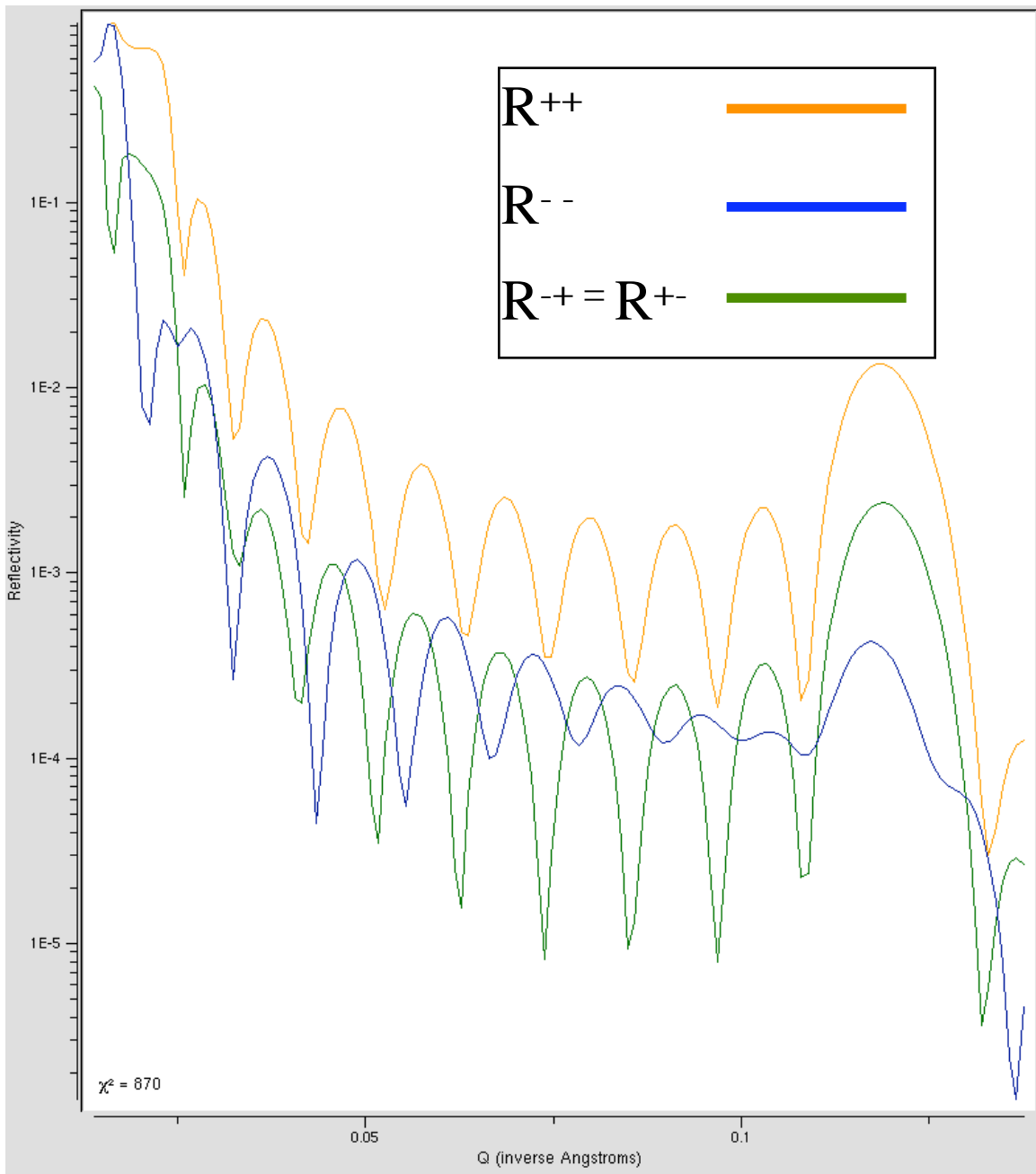


Figure 4: Simulated PNR spectra for our sample.

<sup>1</sup> M. N. Baibich, J. M. Borto, A. Fert, F. Nguyen van Dau, F. Petroff, P. Eitenne, G. Creuzet, A. Friederich, and J. Chazelas, *Physical Review Letters* **61**, 2472 (1988).

<sup>2</sup> G. Binasch, P. Grünberg, F. Saurenbach, and W. Zinn, *Physical Review B* **39**, 4828 (1989).

<sup>3</sup> M. R. Fitzsimmons, and C. F. Majkrzak, in *Modern Techniques for Characterizing Magnetic Materials*, edited by Z. Zhu (Kluwer, New York, 2005).

<sup>4</sup> C. G. Shull and M. K. Wilkinson, *Review of Modern Physics* **25**, 100 (1953).