# Magnetic Localization in a Compositionally Graded Ferromagnet

## BACKGROUND

For a magnetically ordered material, there is a characteristic temperature below which the material exhibits long-range order. For example in a ferromagnet, exchange between spins promotes parallel alignment of those spins below the Curie temperature $T_C$. The exchange strength $J$ differs among ferromagnetic materials, leading to different values of $T_C$. If ferromagnets with different characteristic $J$ are interfaced, exchange coupling between those materials leads to emergent behavior. Suppose ferromagnet 1 has a nominal Curie temperature greater than ferromagnet 2, $T_{C1} > T_{C2}$. In principle, thermodynamic considerations dictate that when interfaced, there is but a single transition temperature for the entire composite system. i.e., for a temperature T such that, $T_{C1} > T > T_{C2}$, ferromagnet 2 will still exhibit *some* magnetic ordering *everywhere* because it is exchange coupled to ferromagnet 1. In practice however, this is a highly proximity dependent effect. The magnetic order parameter of the weaker ferromagnet will be strongly enhanced near the interface, exponentially approaching zero with increasing distance [1].

We have recently considered the case of a *continuum* of interfaces between ferromagnets with differing exchange strengths - specifically a linear gradient in exchange strength across the thickness of a ferromagnetic film [2]. We were curious - would everything exchange couple, or could we exert continuous control over the magnetic properties? Nickel-copper alloy, $Ni_xCu_{1-x}$, is a ferromagnet with $T_C$ that changes linearly with $x$, and was an ideal model system. Using polarized neutron reflectometry (PNR) and numerical simulations, we found that the exchange coupling plays a very minor role in the spatial evolution of the ferromagnetic phase transition at length scales greater than 1 nm. A 100 nm $Ni_xCu_{1-x}$ film with a 10 % gradient in $x$

was observed to behave predominantly as if comprised of an uncoupled continuum of ferromagnets with differing $T_C$. Thus, we showed that the effective Curie temperature could be controlled continuously via composition gradients.

## EXPERIMENT

As a next step, we would like to understand the practical limits of using composition grading to control the effective $T_C$. Can we really vary $T_C$ with 1 nm resolution, or does the system become non-localized at lengthscales much larger than a nanometer? To investigate this question, our collaborators at the CIC nanoGune Consolider in San Sebastian Spain have grown a series of cobalt-ruthenium alloy $Co_{1-x}Ru_x$ films, where $x$ varies sinusoidally as a function of depth. Similar to nickel-copper allloy, $Co_{1-x}Ru_x$ exhibits a linear dependence between x and $T_C$, as well as a linear dependence between $x$ and the saturation magnetization, as shown in Figure 1 [3]. Therefore, by looking at sinwave profiles of different wavelength $\lambda_x$, we hope to determine the lengthscale at which the system ceases to behave as a series of independent ferromagnets, and instead behaves collectively.

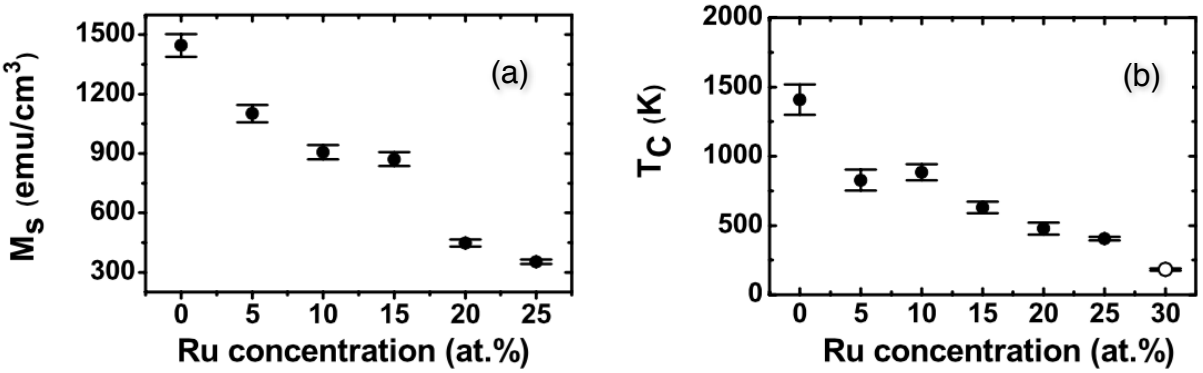


Figure 1: Composition-dependent magnetic properties of $Co_{1-x}Ru_x$ alloy films. (a) Saturation magnetization, (b) Curie temperature.

We will perform specular PNR, a technique used to characterize the depth profiles of the nuclear composition and magnetization of thin films and multilayers [4]. Specifically, the non spin-flip reflectivities $R^{++}$ and $R^{--}$ provide sensitivity to the in-plane magnetization component parallel to the applied field $H$, and the nuclear scattering length density

$$\rho_N = \Sigma_i N_i b_i,$$

where $N$ is the number density, $b$ is the nuclear scattering length corresponding to a particular isotope [5], and the summation is over each isotope present in the scattering volume. For these measurements, we will use the PBR beamline, shown in Figure 2. Using a tightly collimated 0.475 nm neutron beam, we will measure measure the spin-dependent reflectivities as a function of wavevector transfer along the sample growth direction ($Q_z$) using a $^3$He pencil detector. The sample will be mounted inside a closed-cycle refrigerator, and an electromagnet will be used to apply $H$ perpendicular to both the sample growth direction and the neutron propagation direction (i.e. field applied vertically). An Fe/Si supermirror / Al-coil spin flipper

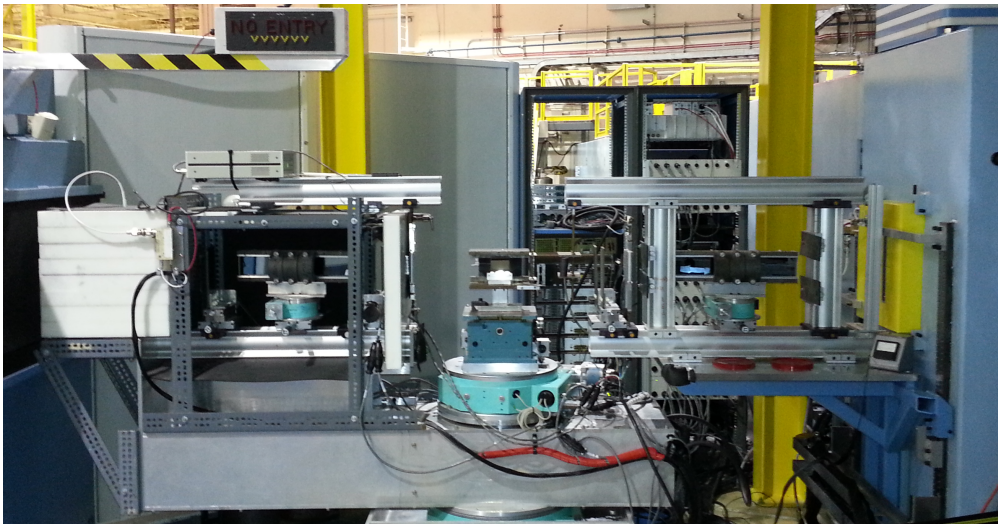


Figure 2: PBR beamline. The sample is mounted on the center goniometer, while the white detector housing is shown at far left. Polarizing supermirrors and spin flippers are visible on either side of the sample position.

assembly will be used to polarize the incident neutron magnetic moment either parallel (+) or antiparallel (-) to *H*. A second supermirror/flipper array will be used to analyze the spin state of the scattered beam.

Specifically, we will study the nuclear and magnetic depth profiles of a $Co_{1-x}Ru_x$ sample with $\lambda_x$ = 10 nm, and amplitude varying from $x$ = 0.21 to $x$ = 0.31, as shown in Figure 3. We will cool the sample to 5 K with 0.5 T applied along the easy axis and then reduce the field to a near-remenant 1 mT before measuring $R^{++}(Q_z)$ and $R^{--}(Q_z)$ at several temperatures. Model-fitting will be performed using the NCNR Refl1D software [6].

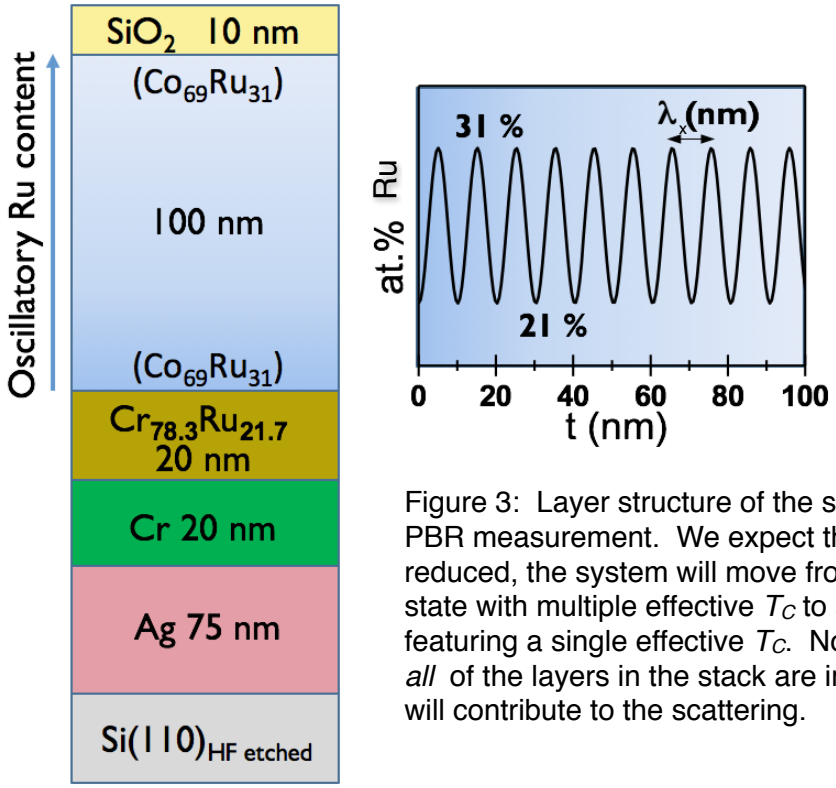


Figure 3: Layer structure of the sample for the PBR measurement. We expect that as $\lambda_x$ is reduced, the system will move from a localized state with multiple effective $T_C$ to a collective state featuring a single effective $T_C$. Note that for PNR *all* of the layers in the stack are important, as all will contribute to the scattering.

We hope to address the following questions:

1) Was the sinusoidal profile achieved? If so, is it consistent with the intended $x$ values?

2) Is the system magnetically localized? Do regions with different $x$ exhibit different temperature-dependent magnetizations?

3) If the system is local, can we determine an effective $x$-dependent $T_C$? How does it compare to what we expect for isolated $Co_{1-x}Ru_x$ films?

We are greatly indebted to Lorenzo Fallarino, Mateo Pancaldi, Patricia Riego, and Andreas Berger of CIC nanoGune for the $Co_{1-x}Ru_x$ samples described, as well as for coming up with the idea to study them!

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