Confined Magnetism

Ivan K. Schuller
UCSD

Contributors
C. Fadley, A. Hoffmann, P. Crowell, T. Rahman, T. Schulthess, C. Leighton

Magnetism in confined geometries is an active and vital area of research which will surely produce much new science in the next 20 years. Although it is difficult to predict, based on past experience, this area may produce some novel applications in the storage, sensors and spintronics applications.

The main interest in the field of nanomagnetism is due to: a) confinement and quantization by the finite size and b) proximity effect due to the leakage of the wave function and magnetization outside of the physical structure of nanostructure. Since magnetism depends on a variety of length scales structural characterization must be made quantitatively at similar length scales. Relevant length scales and characterization tools are shown in Figure 1 below. Examples of confinement induced effects include: vortex state in magnetic nanodots and the modifications o the magnetic structure by surface defects. Proximity effects include coupling effects in Fe-Cr-Fe-Cr-Fe layers, magnetic proximity in Pd-NiO bilayers, training effects in exchange biased systems and changes in the magnetization (of NiO for instance) due to the proximity with other magnetic materials.

The main challenges and needs are:

- Mapping of the magnetization at nm length scales and sub nanosecond time scale. This is important both for basic research and applications.
- Study of buried interfaces
- Element sensitive structural, chemical and magnetic characterization
- All the above under different environments: high and low temperature, high pressure, and especially magnetic field
- Pump-Probe experiments under light, electric and magnetic stimulii
- Development of collective excitations such as phonons, magnons, polarons and excitons.
- Theoretical and numerical predictions of novel physics and unusual geometries beyond existing understanding
- Theoretical understanding of the interaction of X-rays with magnetic structures especially in the presence of surfaces, and interfaces and in conjunction with proximity configurations.

Systems which exhibit interesting and novel properties consist of dissimilar materials which include at least one magnetic component (ferromagnetic, antiferromagnetic, ferrimagnetic, etc). The interesting geometries are structured at the nm scale to form:

- Heterostructures
- Superlattices
- Nanostructures
- Arrays

It should be stressed that the field is ***beyond proof of concept***. Now there is need for use of these sophisticated and expensive technique for the solution of real physics-materials science problems. This implies detailed, quantitative, synchrotron radiation studies which are correlated which are correlated with growth and other physical property measurements.

Below we will describe more in detail some of the issues related to the grand challenges mentioned above.

Buried solid-solid interfaces are ubiquitous in nanomagnetic structures, and a detailed understanding of their chemical concentration profiles, element-specific chemical states and magnetic properties, as well as chemical and magnetic roughnesses, is critical to the characterization process. X-ray standing waves in the 500 eV to 10 keV range can provide an extremely powerful method for selectively studying such interfaces. Such standing waves can be created by Bragg reflection from any multilayer structure or from any set of atomic planes in a single crystal or epitaxial sample. Even a modest reflectivity of R = 5% is expected to yield an overall standing wave modulation of $\sim 4\sqrt{R} = 90\%$ or $\pm 45\%$. Interfaces that exhibit lateral spatial variations such a wedge profile, permits scanning the standing wave through the interface simply by moving a focused x-ray beam along the slope of the wedge [1]. Such data can be obtained under both non-resonant and resonant conditions, and with either photoelectrons or fluorescent x-rays as the detecting particle. Such measurements for an Fe/Cr interface with an excitation energy around 800 eV and photoelectron detection permit determining the compositional width of the buried interface, as well as, via MCD measurements, the magnetization profile across the interface of both Fe and Cr [1]. Using even higher energies in the 5-10 keV range would provide greater probing depths for both photoelectrons and x-rays. With a focused x-ray beam, such measurements would also provide lateral microscopy information. Further discussions of the current status of such standing wave experiments appear elsewhere [2].

The routine use of these other creative techniques for the studies of buried interfaces should provide solutions to many interesting and challenging problems.

[1] S.-H. Yang, B.S. Mun, N. Mannella, S.-K. Kim, J.B. Kortright, J. Underwood, F. Salmassi, E. Arenholz, A. Young, Z. Hussain, M.A. Van Hove, and C.S. Fadley, J. Phys. Cond. Matt. 14, L406 (2002)

[2] Issue dedicated to standing wave studies of surfaces and interfaces, Synchrotron Radiation News, Volume 17, Number 3 (2004).

Isotope effect X-ray techniques can be element specific however they normally do not distinguish between different isotopes. In contrast, neutron scattering is very sensitive to the specific isotope composition. This strong isotope contrast can be used in the case of neutron scattering to enhance scattering contrast for magnetic structures by reducing contrast for chemical structures [A. Hoffmann, *et al.*, Phys. Rev. B **65**, 024428 (2002)]. However, X-ray techniques also become isotope sensitive in the case of nuclear resonant scattering, which is related to the well-established Mössbauer effect. This technique is restricted to Mössbauer active isotopes of elements such as Fe, Sn, Sm, Dy, and Eu. Nuclear resonant scattering allows measuring the nuclear hyperfine fields, which can be directly related to the magnetization vector [L'abbé *et al.*, Phys. Rev. Lett. **93**, 037201 (2004)]. Several key differences to more traditional X-ray techniques (such as X-ray magnetic dichroism) is that (i) high spatial selectivity can be obtained by selective preparation of the sample with Mössbauer-active isotopes, (ii) the full direction of the magnetic moment in all three dimensions can be obtained, (iii) that even for transition metals (such as Fe) the penetration depth is long (up to 100 nm), since hard X-rays can be used for the magnetic contrast (instead of soft X-rays at the L-edge), and (iv) they can be sensitive to atomic scale magnetic order, such as antiferromagnetism.

Spin Dynamics A significant class of experiments addresses spin dynamics in nanoparticles using optical pump-probe techniques. With ultraviolet light, spatial resolution of 300 nm can be achieved presently in the laboratory. In cases where fast magnetic field pulses are generated with a stripline, the practical time resolution is of order 50 psec. Essentially, this allows us to study magnetic excitations at very long wavevector ($q < 2 \times 10^5$ cm^{-1}) at frequencies up to 10 GHz. Phenomena such as ultrafast switching, spin-wave localization, and vortex gyrotropic modes in individual nanoparticles have been explored.

These types of experiments have explored excitations that are predominantly magnetostatic in nature. In other words, the effects of exchange are relatively weak. As the confining dimension decreases to the order of the exchange length (~ 5 nm), the fundamental character of the excitations should change. A time-resolved probe that enhances the spatial resolution to ~ 50 nm would therefore make current measurements better, while a probe with 5 nm resolution would certainly allow us to do fundamentally new physics. In order to fully exploit the advantages of improved spatial resolution, there should be an accompanying increase in the temporal bandwidth. If, for example, a measurement could be done with 1 THz of bandwidth (i.e. 1 psec pulses) and 5 nm spatial resolution, then it would be possible to probe excitations that currently fall in the unexplored window of momentum space between time-resolved optical experiments and inelastic neutron scattering.

It should be stressed that these measurements rely on phase coherent repetitive measurements. Therefore these laboratory experiments are not sensitive to many possible stochastic effects. Thus single shot, time dependent, magnetic measurements in the subnanosecond time scales and nanometer length scales would be important, an maybe one of the important research directions for X-ray sources.

Theory Traditionally magnetism and magnetic material have been studied using phenomenological models. These models have done their job and each time they have failed, they have been supplemented by new terms to take into account the effect that the previous model failed to explain. This empirical approach provides good insights into the underlying science and provides benchmarks for the analysis of experimental data. However, such a parameter based approach has its limitations. It may not be able to provide explanations for characteristics that depend on the details of the system at the nanoscale and may not have predictive capabilities in some cases.

Magnetic properties at interfaces and surfaces, which make up a large fraction of nanostructured materials, are quite different from the bulk systems upon which simple models are built. Model Hamiltonian approaches to magnetic nanostructure thus have limitations: either the Hamiltonian is simple, based on bulk parameters, but will likely miss the essence of nanomagnetism, or the Hamiltonian is complex and consists of many terms with unknown parameters and thus becomes unsolvable. However, unlike other areas of materials science, the theory of magnetism and magnetic materials is on a firm footing. *Ab initio* electronic structure methods are capable of predicting basic materials properties such as the magnetization, magnetic anisotropy, the exchange, and the Curie or Neel temperatures. As the computer performance keeps increasing and computational methods become more efficient, these first principle methods approach the point where substantial portions of nanostructures can be simulated without the need of fitting parameters. These methods will provide information beyond what is accessible experimentally on the: (1) magnetic structure at the atomic scale in the interface and surface region of nanostructures; (2) effectiveness of models to study nanomagnetism at short time and length scales and 3) understanding of the interaction of X-rays with magnetic nanostructures. One important feature which theoretical calculations must include is specific predictions which are experimentally accessible. Models that are built on *ab-initio* theory and experimental observation will lead to systematic advances in our understanding of nanomagnetism.

Neutrons and X-rays. Since there are two big machines which are relevant to address some of the issues outlined above it maybe worthwhile to highlight the advantages and drawbacks of each techniques. In the field of nanomagnetism neutron scattering has several notable advantages including that it is an old technique, it has deep penetration, it is sensitive to isotopic substitutions and the interpretation is straight forward. On the other hand, it has as major disadvantages the low intensity. On the other hand synchrotrons provide very high intensities (although this has to be normalized by the sensitivity to magnetism) and it is element sensitive. On the other hand, being a new technique the interpretation is not direct and the high photon flux may make heating a problem.

Instrument requirements It is important to outline from a user point of view the requirements beyond specific X-ray instrumentation. The key for most interesting applications is the sample environment. As first priorities it is crucial to cover similar parameter space to which interesting systems are commonly subject. These include:

- T range: 1 K-500K
- H fields up to 12 T
- 3D H field orientation
- Ultra low remanent field
- Pressure to ??????
- Optical, electrical access

Beyond this of course it would useful to have ultralow temperatures and very high fields in some applications. It is not clear whether *in-situ* preparation should be of high priority.

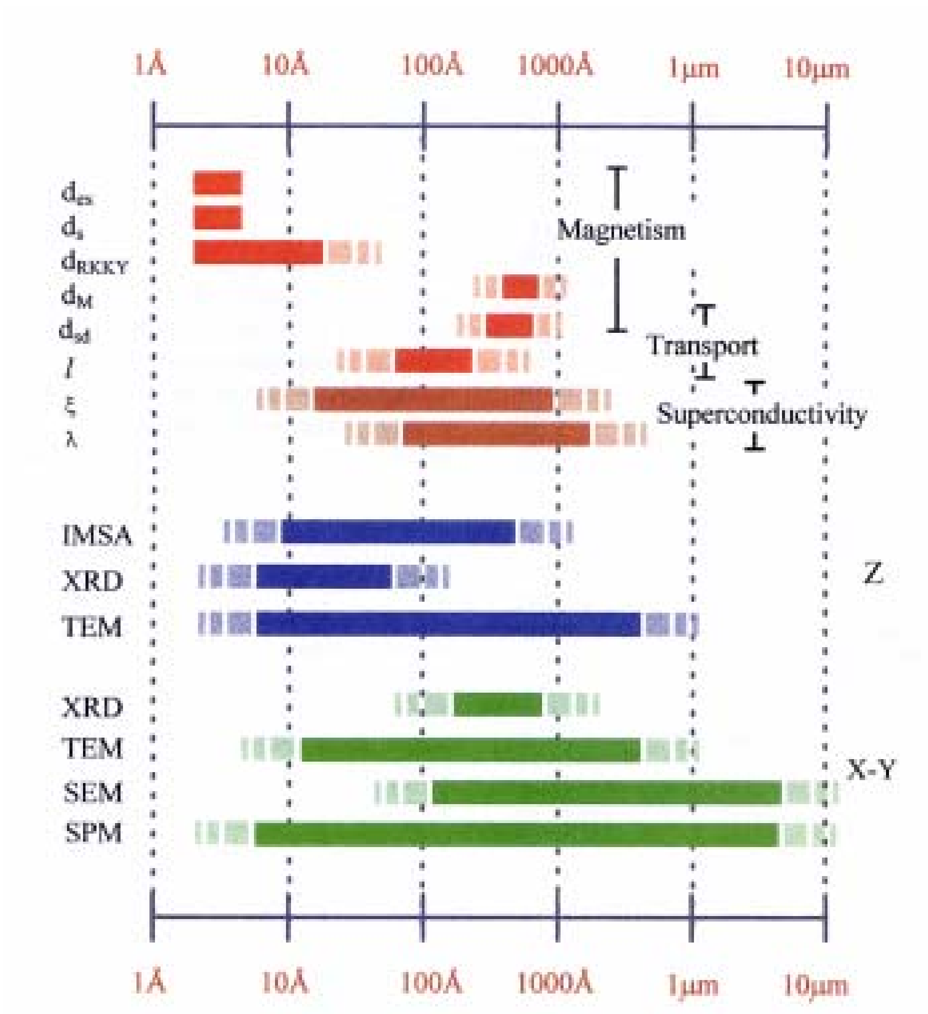

Fig 1. Important length scales in magnetism and superconductivity and relevant characterization tools. The density of vertical lines indicates the reliability and range of applicability of the tool at a particular length scale. After I. K. Schuller, S. Kim and C. Leighton, Jour. Mag. Mag. Mat. 200, 571(1999)