Executive Summary of the Workshop on Nanomagnetism Using X-ray Techniques

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Introduction

The goal of the Workshop on Nanomagnetism Using X-ray Techniques was three-fold. First, we worked to identify the scientific grand challenges in nanomagnetism that we can foresee from today's vantage point. Secondly, we worked to identify the contributions that synchrotron-based techniques could make within the next decade to address these challenges. Thirdly, we specifically discussed recommendations concerning the instrumentation needed at the Advanced Photon Source (APS) to enhance its premier status as a lead facility in the field of nanomagnetism. In this summary, the prevalent common themes throughout the workshop are discussed. A comprehensive review of the Workshop is in preparation and will be presented in a separate document.

Science

Since nanomagnetism covers a wide range of topics, the organizers identified three major themes prior to the Workshop for the purpose of facilitating scientific presentations. The themes were:

- Confined magnetism: Layered and artificially structured systems
- Cluster magnetism: Molecule-based magnets, spin ice and spin glasses
- Phase separated systems/complex oxides

The unifying idea throughout the Workshop was to understand the magnetic behavior of individual building blocks of matter and explore strategies to combine them into more complex structures leading to integrated systems with new functionalities. For example, multiferroics — the complex property of simultaneous ferromagnetism, ferroelectricity and ferroelasticity — is one example in the category of new, emerging functionalities. Another common theme that permeated the Workshop was the central role played by inhomogeneities in determining the collective magnetic response. Inhomogeneities can be driven by competing interactions at the nanoscale, as demonstrated in CMR colossal magnetoresistive (CMR) materials and high T_C superconductors, or may be artificially introduced through tailored synthesis, as found in the case of magnetic nanocomposites. Characterization of inhomogeneous systems requires measurements of the chemical, structural and magnetic properties in a phase-specific way. Since x-ray diffraction can isolate coexisting phases by coupling to their different crystal structures, it is desirable to combine resonant x-ray diffraction with nanometer-sized beams to image inhomogeneities in real-space by diffraction contrast imaging. Adding circularly polarized x-rays allows for diffraction-contrast, real-space imaging of structure and magnetic phases to be done simultaneously (by adding and subtracting scattered intensities for opposite helicities of light). The application of very high magnetic fields (above 20 T) during spectroscopic and diffraction examination is an important capability to separate competing states in highly-correlated electrons systems (*i.e.* CMR materials). The ability to probe chemical, structural and magnetic correlations in a phase-specific way and simultaneously in the same measurement is a key asset of synchrotron-based techniques. Resonances add invaluable element-specific information that is particularly useful in multi-element, heterogeneous systems.

In addition to fundamental science interest, there are a number of existing and emerging technologies that are driving today's nanomagnetism research. Fundamental scientific questions common to the technological pursuits are concerned with the origin of magnetic coupling, spin transport across interfaces, spin-lattice interactions in complex materials and the magnetic domain configuration and dynamics arising from contact between different kind of magnets, for example antiferromagnets and ferromagnets. Among these focus technologies are the magnetic information storage, advanced sensors, ultra-high-energy-product permanent magnets and nanostructured alloys for transformer applications. Of interest in the field of magnetic information technology are sandwiched magnetic sensors, spin valves, spin transistors and magnetic "media" consisting of ferromagnetic thin films and multilayers that can store information in nanometer-sized "bits". The phenomena of current-driven magnetic switching and the multiferroic response are integral to new sensor development, and self-assembled nanocomposite particle systems are envisioned to enable both ultra-hard permanent magnets and ultra-soft transformer alloys. In today's nanocomposite structures, magnetic switching times are about one nanosecond. The future of magnetic technologies is guided by "smaller and faster". Technology is dependent on the ability to synthesize new materials that are patterned or can self-assemble on the nanoscale. These materials must to be magnetically stable at room temperature, and methods are needed to manipulate the magnetization on the sub-nanosecond time scale. Such challenges coincide with forefront questions in basic magnetism research, namely the static or dynamic properties of small magnetic elements on very short time scales. This situation is illustrated in Figure 1 which shows that especially on the time scale below 1 ns our understanding of the relevant processes in magnets is still very limited. Spin-orbit coupling, precessional switching and magnetic anisotropy are correlated with time scales between 100 fs and 100 ps, which are rather difficult to access experimentally. However, using the time structure of the synchrotron and fast detectors like streak cameras will allow these fundamental questions to be addressed with high spatial resolution and sufficient elemental and magnetic sensitivity that will cover the relevant spatial scale of interest (5-50 nm). As a final comment, theoretical studies and modeling are ideally carried out concurrently to support the experimental scientific and technological efforts.

An exciting new emerging application is engineered nanomagnets for biomedical applications that provide opportunities for diagnostics and therapeutics in both *in-vivo* and *in-vitro* applications in biomedicine. The size of nanoparticles — similar to common biomolecules (< 50 nm) — makes them interesting for a wide range of biomedical applications[1] that includes intracellular tagging, contrast agents, targeted cancer treatment, antibody targeting and hyperthermia[2]. Key challenges include the modification of nanoparticles for enhanced aqueous solubility, biocompatibility or biorecognition, and optimization of their magnetic properties including their relaxation dynamics[3] over a broad range of frequencies and applied fields. In addition to surface functionalization[4], nanoengineering of particle surfaces to optimize both their magnetic and optical response is important for diagnostic and therapeutic applications. The APS is poised to play a critical role in realizing these advances by providing tools for structural indentification and chemical and magnetic characterization of these magnetic nanoparticles and core-shells structures with specific emphasis on the evolution of these properties as a function of their size and surface function.

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[1] Q.A. Pankhurst *et al.*, Applications of magnetic nanoparticles in biomedicine, J. Phys. D.: Appl. Phys., 36, R167-181 (2003)

[2] Marcela Gonzales and Kannan Krishnan, "Synthesis of Magnetoliposomes with Monodisperse Iron Oxide Nanocrystal Cores for Hyperthermia", JMMM (in press)

[3] S. H. Chung, A. Hoffmann, S. D. Bader, L. Chen, C. Liu, B. Kay and L. Makowski, "Biological Sensors based on Brownian Relaxation of Magnetic Nanoparticles", Appl. Phys. Lett. 85, 2971 (4 Oct., 2004).

[4] Yuping Bao and Kannan Krishnan, "Tailored and functionalized cobalt nanocrystals for biomedical applications". JMMM (in press)

To summarize the science drivers, nanomagnetism plays a vital role in:
- New paradigms for condensed matter science, specifically where competing interactions lead to phase separation.
- Sustaining progress in information technologies, specifically in the following areas:
    - MRAM: Magneto-resistive random access memory
    - Novel magnetic structures
    - Spin-based quantum computing
    - Magnetic semiconductors and spin transport
    - Molecule-based magnets and organic spintronics
    - Switching characteristics of nanomagnets
- Contributing to energy independence
    - Ultra-strong permanent magnets via nanocomposites for motor applications
    - Highly-responsive magnetic nanocomposites for transformer applications
    - Efficient, multi-functional sensors
- Nanomagnets in biomedical applications

Frontier Technical Requirements
The important length scale in nanomagnetism is ~ 5 nm, which is the length scale of the exchange interaction. Developing synchrotron-based instrumentation and technique to probe structural and magnetic properties at with nanometer resolution is a major technical requirement. Furthermore, the ability to study magnetization dynamics at the time resolution greater than 1 ps would provide an opportunity to study spin dynamics. Finally, combination of the two spatial (~ 5 nm) and temporal (~ 1 ps) probes would enable forefront studies of new phenomena in nanomagnetism. Extreme sample environments such as high magnetic field (> 20 T) and low temperatures (~ mK) are essential in the study of competing phases in complex magnetic materials.

Recommendation:
Currently, the APS has two superb, but oversubscribed, beamlines dedicated to magnetism studies. One beamline is in the high-energy range (2.6 – 45 keV) and the other is in the intermediate energy range (500 – 3000 eV). As requests for beamtime exceeds the available shifts by a factor of three, the present facilities are insufficient to provide adequate tools to a growing synchrotron user community. In addition, the number of techniques (magnetic scattering, spectroscopy and imaging) presently employed at each of the beamlines are too numerous to optimize each one in order to meet frontier technical requirements. However, by separating scattering and spectroscopy techniques, the APS can provide competitive tools for nanomagnetism studies. One can envision building two new beamlines, one in the hard energy range and the other in the intermediate energy range. The new hard x-ray beamline should be optimized for resonant magnetic diffraction studies in high magnetic fields. The new intermediate energy beamline should be optimized for resonant inelastic scattering, diffraction and imaging. The presently-existing beamlines would then be optimized for spectroscopy techniques.

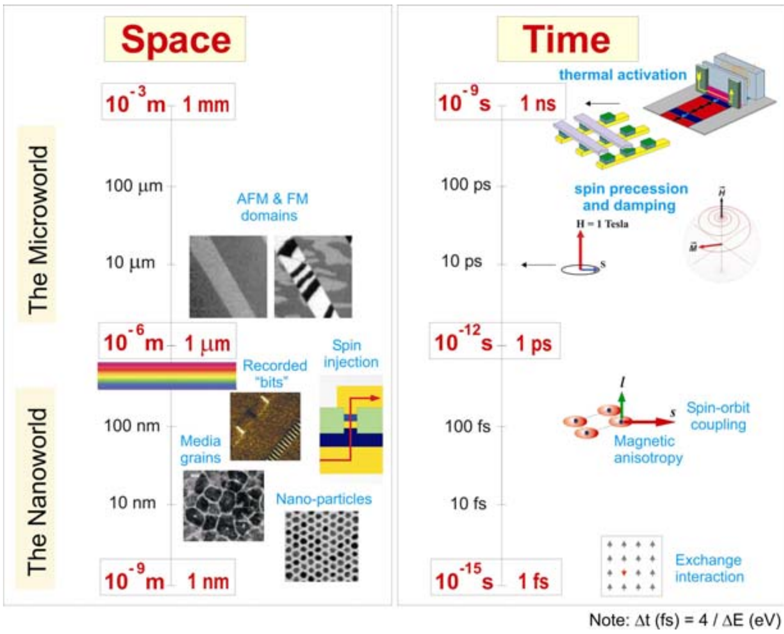

Fig. 1 Examples of magnetic structures relevant to computer technologies (left) and summary of state-of–the-art ultra-fast time scales relevant to the scientific exploration of magnetic phenomena needed for tomorrow's technologies (Courtesy of A. Ohldag).