Tuesday Afternoon, October 29, 2013

Magnetic Interfaces and Nanostructures
Room: 202 A - Session MI+AS+NS+SP-TuA

Advanced Probes in Magnetic Imaging and Characterization
Moderator: H. Ohldag, SLAC National Accelerator Laboratory

2:00pm **MI+AS+NS+SP-TuA1 Electron Correlation Spectroscopy on Magnetic Surfaces**, ***F.O. Schumann***, Max-Planck Institut für Mikrostrukturphysik, Germany **INVITED**

The emergence of long range magnetic order is a consequence of the mutual interaction between electrons. A key postulate of quantum mechanics is the requirement of the wave function to be antisymmetric upon exchange. This inclusion leads to a modification of the Coulomb interaction which is termed exchange interaction. For ferromagnets this leads to parallel spins while for antiferromagnets an antiparallel alignment is prefered.

Electron pair emission from surfaces is an advanced tool to study the relation between electrons which goes beyond the capabilities of single electron spectroscopy e.g. photoemission. The power of this approach will be demonstrated by two case studies on Fe and NiO films. The angular distributions of emitted electron pairs reveal a region of reduced intensity which can be traced back to the exchange-correlation hole.[1] This concept was introduced by Wigner, Seitz and Slater more than 75 years ago. It plays an important role in modern solid state theory. We performed experiments on Fe films to unravel the spin-dependence of the exchange-correlation hole. We find that the contribution of exchange is more extended than the Coulomb contribution as suggested by Slater.[2]

The investigation of correlation effects in solids is an active field of research. In this context metal oxides like NiO are usually termed "highly correlated", because the material properties are decisively determined by the electron-electron interaction. The very existence of a finite electron pair emission requires a finite electron-electron interaction. This immediately leads to the question whether the intensity level provides insight into the correlation strength. A theoretical study of pair emission from a strongly correlated system modeled by the Hubbard Hamiltonian gives an affirmative answer.[3] We tested this conjecture and find that the coincidence intensity for NiO is roughly an order of magnitude larger compared to the Ag(100) substrate.[4] This also holds for the comparison of other transition metals and their oxide phases. This result suggests that the electron correlation strength is accessible via the pair emission intensity.

Our results demonstrate that electron pair emission is a unique tool to unravel the nature of the electron correlation in solids.

[1] F.O. Schumann, C. Winkler, and J. Kirschner,Phys. Rev. Lett. **98**, 257604 (2007).

[2] F.O. Schumann, C. Winkler, J. Kirschner, F. Giebels, H. Gollisch, and R. Feder, Phys. Rev. Lett. **104**, 087602 (2010).

[3] B.D. Napitu and J. Berakdar, Phys. Rev. B **81**, 195108 (2010).

[4] F.O. Schumann, L. Behnke, C.H. Li, J. Kirschner, Y. Pavlyukh, and J. Berakdar, Phys. Rev. B **86**, 035131 (2012)

4:00pm **MI+AS+NS+SP-TuA7 Probing Magnetic Interfaces and Nanostructures with Hard X-ray and Standing-Wave Excited Photoemission Spectroscopy**, ***A.X. Gray***, SLAC National Accelerator Laboratory, *J. Minar,* Ludwig Maximillian University, Germany, *S. Ueda,* National Institute for Materials Science, Japan, *L. Plucinski,* Forschungszentrum Jülich GmbH, Germany, *A. Bostwick, E. Rotenberg,* Advanced Light Source, *C.M. Schneider,* Forschungszentrum Jülich GmbH, Germany, *H. Ebert,* Ludwig Maximillian University, Germany, *K. Kobayashi,* National Institute for Materials Science, Japan, *C.S. Fadley*, University of California, Davis **INVITED**

The ever-growing demand for miniaturization and increased speeds of next-generation electronic devices has taken science to the quantum frontier in which emergent phenomena at the nanoscale require a clear differentiation between surface, bulk and interface properties. Thus, for many technologically-promising novel materials electronic structure varies dramatically as a function of depth and proximity to other materials. Therefore, novel depth-resolved characterization techniques are required to disentangle these rich electronic behaviors, including magnetism and spin. In this talk I will describe several new directions in the field of x-ray photoelectron spectroscopy, made possible with the advent of third-generation synchrotron light sources and recent advances in the fields of x-ray optics and photoelectron detection. I will present several case-studies wherein hard x-ray photoelectron spectroscopy (HAXPES) in the multi-keV regime is used to probe the bulk properties of complex thin-film materials and heterojunctions, which would be otherwise impossible to investigate using conventional soft x-ray XPS. I will present the first results of hard x-ray angle-resolved photoemission measurements (HARPES), at excitation energies of 3 and 6 keV. Compared to the traditional ARPES, carried out in the UPS regime (20-100 eV), this new technique enables one to probe on average 10-40 times deeper into the bulk. Finally, I will introduce a new photoemission technique (SWARPES) which combines soft x-ray ARPES with standing-wave (SW) excited photoelectron spectroscopy, wherein the intensity profile of the exciting x-ray radiation is tailored within the sample in order to provide a depth-selective probe of the electronic structure of buried layers and interfaces.

4:40pm **MI+AS+NS+SP-TuA9 Imaging Magnetization Dynamics on its Genuine Time Scale**, ***G. Meier***, University of Hamburg, Germany **INVITED**

A variety of excellent microscopies that provide magnetic contrast on the nanoscale matured to powerful tools. Today's scanning-probe techniques feature ultimate spin resolution, namely imaging of the magnetization of single adatoms [1]. The temporal resolution of optical and x-ray methods reaches down to femtoseconds. It is intriguing to have spatial and time resolution simultaneously. The relevant frequency scale for ferromagnets is given by the ferromagnetic resonance which lies in the GHz range. Thus the required time resolution is in the sub-nanosecond regime. Magnetic microscopies available at synchrotron sources enable real-time imaging and provide lateral resolution down to the nanometer scale [2,3].

We investigate the switching criteria of nanometer-scaled magnetic vortices in micron-sized Permalloy squares. The vortices are excited by high frequency magnetic fields. Continuous core reversal is demonstrated for a wide range of frequencies and amplitudes of excitation by ferromagnetic absorption spectroscopy and for selected frequencies and amplitudes with time-resolved scanning x-ray microscopy. The boundary of this switching regime is derived from the Thiele equation when a critical velocity of $v_{crit} \approx$ 250 m/s is considered [4].

Complexity created by periodic arrangement of well-understood building blocks plays an important role in biochemistry, photonics, and nanoelectronics. The periodic arrangement of atoms or molecules as basis determines the physical and even the chemical properties of crystals. With the flexibility of nanometer-precise electron-beam lithography we engineer magnetic interactions yielding two-dimensional magnonic crystals that benefit from the magnetic vortex core as crystal basis. Using scanning transmission x-ray microscopy at the MAXYMUS beamline at BESSY II in Berlin, Germany we image the magnonic crystal dynamics. We observe self-organized vortex core state formation by adiabatic reduction of high frequency magnetic field excitation [5]. The experimental results are described analytically by coupled Thiele equations of motion and are compared to micromagnetic simulations.

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References

[1] A. Khajetoorians et al., Science **332**, 1062 (2011)

[2] P. Fischer and C. Fadley, Nanotechnol. Rev. **1**, 5 (2012)

[3] A. Vogel et al., Phys. Rev. Lett. **106**, 137201 (2011)

[4] M. Martens et al., Phys. Rev. B **87**, 054426 (2013)

[5] C. Adolff et al., submitted

5:20pm **MI+AS+NS+SP-TuA11 Towards Magnetic 3dim X-ray Imaging**, ***P. Fischer***, *M.-Y. Im, W. Chao, E.H. Anderson*, Lawrence Berkeley National Laboratory

Nanomagnetism research focused on a fundamental understanding and controlling spins on a nanoscale. As the next step beyond the nanoscale, mesoscale phenomena have been recognized[1], since those add essential parameters to meet future challenges in terms of speed, size and energy efficiency of spin driven devices. The development and application of multidimensional visualization techniques, such as tomographic magnetic imaging will be crucial to achieve mesoscience goals.

Magnetic soft X-ray microscopy is a unique analytical technique combining X-ray magnetic circular dichroism (X-MCD) as element specific magnetic contrast mechanism with high spatial and temporal resolution [2]. Three-dimensional (3D) soft X-ray tomography using Fresnel zone plate based full

field and scanning transmission soft x-ray microscopies have been developed and are routinely used at various synchrotron sources but mostly for biological imaging [3]. However, magnetic X-ray tomography is of large interest to understand e.g. interfaces in magnetic multilayers, the inner structure of magnetic nanocrystals, nanowires or the functionality of artificial 3D magnetic nanostructures.

There are several approaches for 3D X-ray imaging, such as utilizing standing waves in Bragg conditions [3], X-ray imaging in reflection geometry [4], X-ray ptychography [5] or computational reconstruction of projection X-ray images [6]. We have developed and implemented at the full-field soft X-ray microscopy beamline 6.1.2 at the ALS in Berkeley CA a new stage for tomography, which allows recording an angular series (up to 360 deg) of high precision 2D projection images. Applying state-of-the-art reconstruction algorithms it is possible to retrieve the full 3D structure. We will present recent results on prototype systems, such as glass capillaries coated with magnetic films . We will also discuss the complementarity of magnetic X-ray tomography to other 3D imaging approaches such as electron microscopy [7].

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[1] BESAC report: From Quanta to the Continuum: Opportunities for Mesoscale Science (2012), http://science.energy.gov/~/media/bes/pdf/reports/files/OFMS_rpt.pdf

[2] P. Fischer, Materials Science & Engineeering R72 81 (2011)

[3] A.X. Gray, et al. Appl Phys Lett 97, 062503 (2010)

[4] G. Denbeaux, et al. IPAP Conf. Series 7 pp.375-386 (2006)

[5] D.Y. Parkinson et al, J. Struct. Biology 177 259 (2012)

[6] M. Dierolf et al. Nature 467, 436 (2010)

[7] C. Phatak et al, Ultramicroscopy 109 264 (2009)

5:40pm **MI+AS+NS+SP-TuA12 Direct Visualization of Magnetoelectric Domains**, ***W. Wu***, *Y. Geng, X. Wang, S-W. Cheong,* Rutgers University*, C.J. Fennie,* Cornell University*, M. Mostovoy*, University of Groningen, Netherlands

The coupling between the magnetic and electric dipoles in multiferroic and magnetoelectric materials holds promise of conceptually new electronic devices[1-4]. The device miniaturization calls for development of local probes of the magnetoelectric response, in particular because such response is strongly affected by defects in magnetic and ferroelectric orders. For example, multiferroic hexagonal rare earth manganites exhibit a dense network of boundaries between six degenerate states of their crystal lattice, which are locked to both ferroelectric and magnetic domain walls. Here we present the first application of a newly-developed Magnetoelectric Force Microscopy (MeFM), which combines Magnetic Force Microscopy (MFM) with *in-situ* modulating high electric fields. This technique allowed us to directly image the magnetoelectric response of the domain patterns in hexagonal manganites. We found that this response changes sign at each structural domain wall. This MeFM result is corroborated by a symmetry analysis and a phenomenological model derived from microscopics and first-principles calculations[5], providing compelling evidence for a lattice-mediated magnetoelectric coupling. Furthermore, our measurements reveal a diverging magnetoelectric response near a critical point below 2 K originating from enhanced critical fluctuations and the high sensitivity of spin ordering to applied electric and magnetic fields. The direct visualization of magnetoelectric domains at mesoscopic scales opens up explorations of emergent phenomena in multifunctional materials with multiple coupled orders.

1. Eerenstein, W., Mathur, N. D., and Scott, J. F., *Nature* **442** (7104), 759 (2006).

2. Ramesh, R. and Spaldin, N. A., *Nature Materials***6** (1), 21 (2007).

3. Cheong, S. W. and Mostovoy, M., *Nat. Mater.***6** (1), 13 (2007).

4. Spaldin, N. A., Cheong, S.-W., and Ramesh, R., *Physics Today* (2010).

5. Das, H., Wysocki, A. L., and Fennie, C. J., *arXiv:1302.1099* (2013).

Authors Index

Bold page numbers indicate the presenter