MA 20: Focus Session: Revealing Multidimensional Spin Textures and their Dynamics via X-rays and Electrons

Non-collinear spin textures in magnetic materials and excitations within such spin arrangements moved into the focus of research. These system host topological spin states and unique excitations providing access to versatile future spintronic applications. The imaging of such complex internal magnetic orders of materials is a fundamental problem of extreme importance for the successful implementation of these applications. Characterizing the electronic, magnetic and transport properties of structures such as vortices, magnetic singularities or hopfions lead to the development of novel experimental and theoretical techniques. For instance, magnetic hopfions have been unveiled via a combination of X-ray photoemission electron microscopy and soft X-ray transmission microscopy using element-specific X-ray magnetic circular dichroism effects. Recently, time-resolved magnetic laminography enabled access to the temporal evolution of three-dimensional (3D) magnetic microdiscs with nanoscale resolution, while quantitative reconstruction of the 3D spintexture of skyrmions with sub-10 nm resolution was demonstrated by holographic vector field electron tomography or soft x-ray vector ptychography. Pivotal to these experimental developments are theoretical proposals for the detection and manipulation protocols. Although making a strong impact in the field of magnetism, this area of research calls for an in-depth exchange between experts of different techniques, experimental and theoretical, to unravel many of the open questions and puzzling behavior discovered within the last couple of years. This motivates the present focus session as an opportunity for discussions and to attract more researchers to this fascinating field. Organizers: Samir Lounis (Uni.Duisburg-Essen and FZ-Jülich) Matthias Althammer, Stephan Geprägs (Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching), Gisela Schütz (MPI-Intelligent systems, Stuttgart), Stefan Blügel (FZ-Jülich)

Time: Wednesday 9:30–13:00 Location: H37

Invited Talk MA 20.1 Wed 9:30 H37

Recent developments in X-ray three-dimensional magnetic imaging — •Valerio Scagnoli — ETHZ - PSI

Three dimensional magnetic systems hold the promise to provide new functionality associated with greater degrees of freedom. Over the last years we have worked towards developing methods to fabricate and characterize three dimensional magnetic structures. Specifically, we have combined X-ray magnetic imaging with new iterative reconstruction algorithms to achieve X-ray magnetic tomography and laminography [1-4]. In a first demonstration, we have determined the three-dimensional magnetic nanostructure within the bulk of a soft GdCo2 magnetic micropillar and we have identified the presence of Bloch points of different types [1] as well as three-dimensional structures forming closed vortex loops [3]. Subsequently, we have used the flexibility provided by the laminography geometry to perform time resolved measurements of the magnetization dynamics in a two-phase micrometer size GdCo disk. Therefore, X-ray magnetic three-dimensional imaging, with its recent extension to the soft X-ray regime [5], has now reached sufficient maturity that will enable to unravel complex three-dimensional magnetic structures for a range of magnetic systems.

[1] C. Donnelly et al., Nature 547, 328 (2017)
[2] C. Donnelly et al., New J. Phys. 20, 083009 (2018)
[3] C. Donnelly et al., Nat. Phys. 17, 316 (2021)
[4] C. Donnelly et al., Nat. Nanotechnol. 15, 356 (2020)
[5] K. Witte et al., Nano Letters 20, 1305 (2020)

Invited Talk MA 20.2 Wed 10:00 H37

Magnetic depth profiling with x-ray resonant magnetic reflectivity (XRMR) — •Timo Kuschel — Department of Physics, Bielefeld University, 33615 Bielefeld, Germany

Magnetic depth profiling is one of the important thin-film characterization techniques in today's condensed matter physics and, in particular, in the spintronic research field. The interference of reflected light from the interfaces of a magnetic thin-film system depends on its magnetic state. Thus, the detected reflectivity of typically circularly polarized light provides information on the depth profile of the sample's magnetization. By the use of synchrotron x-rays, this dependence becomes element-selective as long as the absorption energy of a specific chemical element is used as photon energy. Therefore, the analysis of the x-ray resonant magnetic reflectivity (XRMR) separates the individual magnetic depth profiles of different chemical elements [1].

In my contribution, I will introduce this experimental technique and emphasize advantages over standard x-ray magnetic circular dichroism detection [2]. I will discuss the quantitative comparability of XRMR with other experimental techniques [3] and present recent results on the magnetic proximity effect in platinum (Pt), palladium (Pd) and vanadium (V). Finally, I will highlight the cation- and lattice-site sensitivity of XRMR for the study of Fe_3O_4 and its interfaces [4].

[1] S. Macke, E. Goering, J. Phys. Cond. Matter 26, 363201 (2014)
[2] T. Kuschel et al., Phys. Rev. Lett. 115, 097401 (2015)
[3] D. Graulich, TK et al., Appl. Phys. Lett. 118, 089901 (2021)
[4] T. Pohlmann, TK et al. Phys. Rev. B. 102, 220411(R) (2020)

Invited Talk MA 20.3 Wed 10:30 H37

Magnetic Bragg Ptychography Studies of Spin Caloritronic — •Dina Carbone[1], Peng Li[2], Stephan Geprägs[3], Rudolf Gross[3,4], Paul Evans[5], Virginie Chamard[6], and Dan Mannix[7] — [1]MAX IV Laboratory, Lund SE — [2]Diamond Light Source, Didcot UK — [3]Walther-Meißner-Institut, BAdW, Garching DE — [4]Physik-Department, TUM, Garching DE — [5]Univ. of Wisconsin, Madison USA — [6]Institut Fresnel, Marseille FR — [7]ESS, Lund SE & Institut Néel, Grenoble FR

Spin-caloritronics refer to a class of materials in which spin, charge and heat currents can be interconverted. This gives rise to diverse functional properties that offer a great potential towards a new generation of fast and low power consumption electronics. Advances in the design and understanding of future spintronic nanotechnologies require the development of state-of-the-art 3D magnetic characterisation tools.In particular, for crystalline magnetic materials grown at nanoscales, understanding the interdependence of their magnetic properties with crystal structure and strain is crucial.

We have developed a magnetic and structural microscopy based on scanning diffraction, by combining circular polarisation and focussing of the X-ray beam. This has revealed spin texture in prototype spin caloritronics device structures and its relation with crystal orientation down to micron resolution[1]. New results obtained with coherent X-rays, using magnetic Bragg ptychography, push this technique towards a 3D spin microscopy with a resolution of few tens of nm.

[1] Evans et al., Sci. Adv. 6, eaba935, 2020

15 min. break

Invited Talk MA 20.4 Wed 11:15 H37

Imaging the 3D magnetic texture of skyrmion tubes and approaches towards determining their Hall signature — •B. Rellinghaus[1], S. Schneider[1,2], D. Wolf[2], U.K. Rössler[2], M. Schmidt[3], A. Kovács[4], R.E. Dunin-Borkowski[4], D. Pohl[1], A. Thomas[2], D. Krieger[2], B. Büchner[2], and A. Lubk[2] — [1]DCN, cfaed, TU Dresden, Germany — [2]IFW Dresden, Germany — [3]MPI CPfS, Dresden, Germany — [4]FZ Jülich, Germany

Despite the large interest in magnetic skyrmions, their 3D magnetic texture when being extended to skyrmion tubes (SkTs) in volume samples is largely unknown. We have therefore determined the magnetic structure of SkTs using low temperature holographic vector field electron tomography in an external magnetic field [1]. The resulting high-resolution 3D magnetic images reveal deviations from a homogeneous Bloch character, a collapse of the skyrmion texture near surfaces, the coexistence of longitudinal and transverse skyrmion textures, and a correlated axial modulation of the SkTs. Spatially resolved energy density maps calculated from the experimental magnetic induction data prove that these magnetic solitons are stabilized by the Dzyaloshinskii-Moryia interaction, which overcompensates the exchange energy in the centers of the tubes. In order to correlate the occurrence of skyrmionic structures with anomalies in their magneto-transport properties, we have devised a setup for the in-situ measurement of the Hall effect in a transmission electron microscope, first results of which will be highlighted. The work is gratefully supported by DFG within SPP 2137.

[1] D. Wolf et al., Nature Nanotechnology 17 (2021) 250.

Invited Talk MA 20.5 Wed 11:45 H37

Determination of spin chirality and helicity angle by circular dichroism in soft x-ray absorption and resonant elastic scattering — •Gerrit van der Laan — Diamond Light Source, Didcot, UK

The depth profile of the full 3D spin structure of magnetic skyrmions below the surface of bulk Cu2OSeO3 was obtained using the polarization dependence of resonant elastic x-ray scattering (REXS) [AIP Advances 11, 015108 (2021)]. While the bulk spin configuration showed the anticipated Bloch type structure, the skyrmion lattice changes to a Néel twisting (i.e., with a different helicity angle) at the surface within a distance of several hundred nm. The experimental penetration length of the Néel twisting is 7x longer than the theoretical value given by the ratio of J/D. This indicates that apart from the considered spin interactions, i.e., Heisenberg exchange interaction J and Dzyaloshinskii-Moriya interaction D, as well as the Zeeman interaction, other effects must play an important role.

A new rule for the rotational symmetry invariance of the XMCD signal is presented [PRB 104, 094414 (2021)]. A threefold symmetric kagome lattice with negative spin chirality can give a nonzero x-ray magnetic circular dichroism (XMCD), despite a total spin moment of zero. A necessary condition is the existence of an anisotropic XMCD signal for the local magnetic atom. The maximum dichroism is not aligned along the spin direction but depends on the relative orientation of the spin with respect to the atomic orientation.

Invited Talk MA 20.6 Wed 12:15 H37

Identification of complex spin-textures by novel Hall effects — •Juba Bouaziz[1], Hiroshi Ishida[2], Samir Lounis[1], and Stefan Blügel[1] — [1]Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich & JARA, D-52425 Jülich, Germany — [2]College of Humanities and Sciences, Nihon University, Sakurajosui, Tokyo 156-8550, Japan

Chiral magnetic phases of matter are commonly found in non-centrosymmetric materials. The complex magnetic order is stabilized by the Dzyaloshinskii-Moriya interaction, which promotes topologically non-trivial spin textures such as skyrmions. These entities imprint a characteristic signature on the Hall signal known as the topological Hall effect, allowing their detection employing magneto-transport measurements. In this talk, relying on perturbation theory, we disentangle the multiple contributions to the Hall signal originating from non-collinear magnetism and relativistic effects. We unveil a new contribution, the non-collinear Hall effect (NHE) [1], whose angular form is determined by the magnetic texture, the spin-orbit field of the electrons, and the underlying crystal structure. The NHE together with other components of the Hall resistivity enables the decoding of exotic non-collinear magnetic textures that have been observed in itinerant magnets [1,2]. The impact of the NHE on the Hall signal of several two and three-dimensional spin textures such as magnetic hopfions is examined. [1] J. Bouaziz et al. PRL 126, 147203 (2021), [2] A. Neubauer et al. PRL 102, 186602 (2009).

MA 20.7 Wed 12:45 H37

All-electron holography of hopfions enabled by magneto-induced charges — •Moritz Winterott[1,2] and Samir Lounis[1,2] — [1]Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich & JARA, D-52425 Jülich, Germany — [2]Faculty of Physics, University of Duisburg-Essen and CENIDE, 47053 Duisburg, Germany

In recent years, far-reaching progress has been made in the field of topological particles. In addition to the well-known skyrmions, three-dimensional topological particles such as hopfions, bobbers and cocoons, are also becoming increasingly interesting. Thereby, a major challenge is the visualisation and recognition of such topological particles hidden in bulk materials. An intuitiv approach is to resolve their magnetic contrast, which is highly non-trivial, especially for antiferromagnetic textures where the overall signals are expected to vanish. Here we demonstrate that the charge carried by such topological objects carries specific dependencies on the misalignement of the magnetic moments, which enable their identification without the need for spin-resolved measurements. We utilize multiple-scattering theory and address the case of ferro- and anti-ferromagnetic hopfions. We identify the achiral and chiral-induced charges. Spin-orbit interaction (SOI) gives rise to the latter in 1^{st} order similarly to the Dzyaloshinskii-Moriya interact and to anisotropic terms, 2^{nd} order in SOI. We proceed to a systematic electron holography of the distinct magneto-induced charges, which provide a direct link to experiments.