MA 3: Magnetic Textures: Statics and experimental imaging

Time: Monday 9:30–12:45 Location: HSZ 101

MA 3.1 Mon 9:30 HSZ 101

Topological orbital moments — what they are and where to find them — •Manuel dos Santos Dias, Juba Bouaziz, Mohammed Bouhassoune, Stefan Blügel, and Samir Lounis — Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, D-52425 Jülich, Germany

Unconventional magnetic structures, such as skyrmions, host ground state emergent magnetic fields that lead to orbital magnetism, even without the spin-orbit interaction. We have recently explored the properties of these emergent orbital moments [1], starting with first-principles calculations for trimers. Armed with this understanding, we study the orbital magnetism of skyrmions, and demonstrate that the contribution driven by the emergent magnetic field is topological. This means that the topological contribution to the orbital moment does not change under continuous deformations of the magnetic structure. Furthermore, we use it to propose a new experimental protocol for the identification of topological magnetic structures, by soft x-ray spectroscopy.

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[1] M. dos Santos Dias et al., Nat. Commun. **7**, 13613 (2016)

MA 3.2 Mon 9:45 HSZ 101

General classification of skyrmions among almost all space groups — •Miriam Hinzen[1,2], Stefan Blügel[1], and Christof Melcher[2] — [1]Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany — [2]Department of Mathematics I & JARA FIT, RWTH Aachen University, 52056 Aachen, Germany

In the past years, magnetic B20 compounds have been in the focus of research as prototype materials exhibiting chiral magnetic skyrmions at particular temperatures and magnetic fields. These compounds belong to the space group T. However, there are crystal classes with Dzyaloshinskii-Moriya interaction (DMI) that favour a different two-dimensional magnetic structure, some of which even have a different topological charge. Naturally, the question arises whether there is a possibility to transfer results from one crystal class to another, for example through a transformation formula. We went through all the crystal classes that can form skyrmions and for most of them identified those O(2) symmetry operations relating their magnetization configuration to the one of the B20 compound. Depending on the crystal structure we expect skyrmions or antiskyrmions of vortex, hedgehog or saddle-point type.

MA 3.3 Mon 10:00 HSZ 101

Metastable skyrmionic spin structures with various topologies in an ultrathin film — Levente Rózsa[1], •Krisztián Palotás[2,3], András Deák[2], Eszter Simon[2], Rocio Yanes[4], László Udvardi[2], László Szunyogh[2], and Ulrich Nowak[4] — [1]Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary — [2]Budapest University of Technology and Economics, Budapest, Hungary — [3]Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia — [4]University of Konstanz, Konstanz, Germany

Metastable localized spin configurations with topological charges ranging from $Q = -3$ to $Q = 2$ are observed in a $(Pt_{0.95}Ir_{0.05})$/Fe bilayer on Pd(111) surface by performing spin dynamics simulations, using a classical Hamiltonian parametrized by ab initio calculations [1]. It is demonstrated that the frustration of the isotropic exchange interactions is responsible for the creation of these various types of skyrmionic structures. The Dzyaloshinsky-Moriya interaction, present due to the breaking of inversion symmetry at the surface, energetically favors skyrmions with $Q = -1$, distorts the shape of the other skyrmionic objects, and defines a preferred orientation for them with respect to the underlying lattice. By performing spin-polarized scanning tunneling microscopy (SP-STM) calculations, a direct connection between experimentally measurable SP-STM contrasts and different topologies of skyrmionic systems is established [2].

[1] L. Rózsa et al., arXiv:1609.07012 (2016)
[2] K. Palotás et al., arXiv:1609.07016 (2016)

MA 3.4 Mon 10:15 HSZ 101

Antiskyrmions stabilized by anisotropic Dzyaloshinskii-Moriya interaction at interfaces of low symmetry — •Markus Hoffmann[1], Bernd Zimmermann[1], Gideon P. Müller[1], Daniel Schürhoff[1], Nikolai S. Kiselev[1], Christof Melcher[2], and Stefan Blügel[1] — [1]Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany — [2]Department of Mathematics I & JARA FIT, RWTH Aachen University, 52056 Aachen, Germany

While skyrmions – localized and topologically protected vortex-like magnetic textures – are the main focus within the current research field of chiral magnets, we discuss in this contribution the emergence of *antiparticles*, so-called antiskyrmions, magnetic textures with a topological charge opposite to the one of skyrmions. On the level of micromagnetics, we show that chiral magnets cannot only host skyrmions, but also antiskyrmions as least-energy configurations over all non-trivial homotopy classes. We derive practical criteria for their occurrence and coexistence with skyrmions that can be fulfilled by interfaces of low symmetry in dependence of the electronic structure. We propose a whole class of materials as possible candidates for the realization of antiskyrmions, namely ultrathin magnetic films grown on heavy metal substrates with C_{2v} symmetry. An experimentally well-investigated system of this class is the double layer of Fe grown on a W(110) substrate. Combining Density Functional Theory calculations with spin dynamic simulations employing an atomistic-spin model we show that this system hosts stable antiskyrmions rather than skyrmions.

MA 3.5 Mon 10:30 HSZ 101

Observation of topological magnetic defects in helimagnetic FeGe — •Peggy Schönherr[1], Jan Müller[2], Laura Köhler[3], Naoya Kanazawa[4], Manfred Fiebig[1], Yoshi Tokura[4,5], Achim Rosch[2], Markus Garst[3], and Dennis Meier[1,6] — [1]ETH Zürich, Switzerland — [2]Universität zu Köln, Germany — [3]Technische Universität Dresden, Germany — [4]University of Tokyo, Japan — [5]Riken, Japan — [6]Norwegian University of Science and Technology, Norway

Complex spin textures, like helical spin spirals with a fixed wavelength, can occur due to chiral magnetic interactions. Chiral magnets are a striking nanoscopic analog to liquid crystals, possessing lamellar phases and ordered topological defects. Defects are of great importance as they strongly influence order and mobility of the spin system. Here we present the experimental observation of such 1D and 2D objects with non-trivial topology in the helimagnetic phase of FeGe using magnetic force microscopy. We show that the depinning and subsequent motion of edge dislocations govern the local magnetization dynamics. Moreover, the defects can form chains and build topological domain walls, which are distinctly different from classical antiferro- and ferromagnets. Experimentally, three main types of domain walls are found depending on the angle between neighboring domain orientations. The domain walls can also carry a skyrmion charge, which implies a coupling to spin currents and contributions to the topological Hall effect. Thus, going beyond skyrmions, chiral magnets reveal a zoo of magnetic nano-objects with non-trivial topology.

MA 3.6 Mon 10:45 HSZ 101

Direct observation of magnetic surface states in a chiral magnet — •Nikolai S. Kiselev[1], Andras Kovács[2], Filipp N. Rybakov[3], Zi-An Li[2,4], Stefan Blügel[1], and Rafal E. Dunin-Borkowski[2] — [1]Peter Grünberg Institute and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany — [2]Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons and Peter Grünberg Institute, Forschungszentrum Jülich, 52425 Jülich, Germany — [3]M.N. Miheev Institute of Metal Physics of Ural Branch of Russian Academy of Sciences, Ekaterinburg 620990, Russia — [4]Institute of Physics, Chinese Academy of Sciences, 100190 Beijing, China

We report on the first direct observation of magnetic surface states, which had previously been predicted theoretically, in a chiral magnet [1]. We study the in-field behavior of a thin film of FeGe using Lorentz transmission electron microscopy and off-axis electron holography and infer the projected in-plane component of magnetization in the film from our experimental results using a model-based reconstruction technique. We observe the formation and evolution of surface spin spirals that exhibit hysteretic behavior. In good agreement with theoretical predictions, the observed surface spin spirals show much lower contrast and a much larger modulation period than ordinary helical spin spirals, which appear in lower fields. A comparison of our experimental data with micromagnetic simulations reveals that dipole-dipole interactions play a significant role in the quantitative description of such systems.

[1] F. N. Rybakov et al., New J. Phys. 18, 045002 (2016).

15 min. break.

MA 3.7 Mon 11:15 HSZ 101

Cycloidal and Néel-type skyrmion lattice phases in polar lacunar spinels — •Sándor Bordács[1], Jonathan S White[2], Ádám Butykai[1], Charles D Dewhurst[3], Robert Cubitt[3], Vladimir Tsurkan[4], Alois Loidl[4], and István Kézsmárki[1] — [1]Department of Physics, Budapest University of Technology and Economics and MTA-BME Lendület Magneto-optical Spectroscopy Research Group, Budapest, Hungary — [2]Laboratory for Neutron Scattering and Imaging, PSI, Villigen, Switzerland — [3]Institut Laue-Langevin, Grenoble, France — [4]Experimental Physics V, Center for Electronic Correlations and Magnetism, University of Augsburg, Augsburg, Germany

Magnetic skyrmions arising from the competition between symmetric and antisymmetric exchange interactions in chiral magnets have attracted much attention due to their potential application in ultra-dense data storage. Recently, we have shown that multiferroic materials - polar magnets - can also host skyrmions. These Néel-type skyrmions have different helicity and they are decorated with non-trivial polarization patterns as well, which may open new ways to manipulate magnetic skyrmions via the electric fields.

In this talk we will report a systematic small angle neutron scattering (SANS) study of polar lacunar spinels, where we observed several phases with modulated magnetic order such as cycloidal and Néel-type skyrmion lattice phases. SANS allowed us to characterize the various phases realized in compounds with easy-axis, easy-plane type magnetic anisotropy as well as lacunar spinels with crystal structures streched and compressed along the polarization.

MA 3.8 Mon 11:30 HSZ 101

Multiscale model for the chiral magnet FeGe — •Sergii Grytsiuk, Markus Hoffmann, Bernd Zimmermann, Gustav Bihlmayer, Nikolai S. Kiselev, and Stefan Blügel — Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany

The formation of non-collinear spin textures in noncentrosymmetric cubic B20 materials, such as germanides and silicides, developed into a fascinating topic over the past decade also due to their potential for skyrmion-based memory devices. Further studies of skyrmion properties require precise Heisenberg exchange and Dzyaloshinskii-Moriya interaction parameters entering advanced spin models. We calculate these parameters using density functional theory (DFT), focusing on the FeGe alloy. Among the B20 compounds it has the highest Curie temperature and a helical propagation vector of 70 nm, resulting in a B-field in a skyrmion structure of about the same size. Moreover, spin-fluctuations for FeGe, which are difficult to catch with DFT, are much less important than for e.g. MnSi. We use a multiscale approach combining *ab initio* results, spin dynamics and Monte Carlo simulations to investigate properties of skyrmions in the presence of a magnetic field and electric current. In addition, we extend our studies of chiral magnetism of FeGe from the bulk to thin films where skyrmions are stabilized in a much wider range of temperatures and fields.

Simulations were performed with computing resources granted by JARA-HPC from RWTH Aachen University under project jara0161 and FZJ under projects JIAS1A, IAS-1, and JIFF13.

MA 3.9 Mon 11:45 HSZ 101

Investigation of three-dimensional skyrmion structure of MnGe from first-principles — •Marcel Bornemann, Paul F. Baumeister, Roman Kovacik, Bernd Zimmermann, Phivos Mavropoulos, Samir Lounis, Nikolai S. Kiselev, Peter H. Dederichs, Rudolf Zeller, and Stefan Blügel — Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany

The magnetic B20 compounds are an interesting class of chiral bulk magnets hosting skyrmions at appropriate temperature and magnetic fields. Among those is MnGe for which experiments [1] indicate a three-dimensional skyrmionic magnetic texture that is currently not understood. In this work we approach the understanding from a full first-principle ansatz based on density-functional theory (DFT). From a methodological point of view such an *ab initio* treatment requests the non-collinear treatment including spin-orbit interactions of easily a few thousand atoms – a challenge, which we can meet with the recently developed Korringa-Kohn-Rostoker Green-function program KKR*nano* [2]. Key to performing such calculations is a linear-scaling behaviour of the code on massively parallel computers with regards to compute time and memory requirements.

Work is supported by the Exascale Innovation Center Jülich. Simulations were performed with computing resources granted by JARA-HPC and Forschungszentrum Jülich.

[1] T. Tanigaki *et al.*, Nano Lett. **15**, 5438 (2015).
[2] A. Thiess *et al.*, Phys. Rev. B **85**, 235103 (2012).

MA 3.10 Mon 12:00 HSZ 101

Isolated skyrmions with vanishing anisotropy in Co/Ru(0001) — •B. Dupé[1], M. Hervé[2], R. Lopez[3], M. Böttcher[1], M. D. Martins[3], T. Balashov[2], L. Gerhard[2], C. Gorenflo[2], J. Sinova[1], and W. Wulfhekel[2] — [1]Johannes Gutenberg Universität, Mainz — [2]Karlsruhe Institute of Technology (KIT), Karlsruhe — [3]Centro de Desenvolvimento da Tecnologia Nuclear, Belo Horizonte, Brazil

Skyrmions are localized and topologically stabilized non-collinear spin structures. Skyrmions offer attractive perspectives for future spintronics applications, because they can be manipulated at lower current densities than domain walls [1]. The stabilization of skyrmions is usually attributed to a large Dzyaloshinskii-Moriya interaction (DMI). DMI is enhanced at surfaces and interfaces via the hybridization of the magnetic atoms with 5d elements [2]. The resulting strong DMI has been able to explain the presence of isolated skyrmions in Co/Pt(111) thin films [3], and [Ir/Co/Pt] superlattices [4]. Here, we show that a strong DMI is not a necessary condition to obtain skyrmions in ultra-thin films. Co/Ru(0001) possesses a spin spiral ground state, although the DMI is weak. We attribute the stability of this spin texture to the simultaneous vanishing of anisotropy. We determine the magnetic interactions in this system using density functional theory and explain the occurrence of isolated skyrmions by Monte-Carlo simulations. [1] A. Fert, et al Nature Nano. 8, 152 (2013). [2] B. Dupé, et al Nature Comm. 7, 11779 (2016). [3] O. Boulle, el al Nature Nano. 11, 449 (2016) [4] C. Moreau-Luchaire, et al Nature Nano. 11, 444 (2016).

MA 3.11 Mon 12:15 HSZ 101

Non collinear magnetism in a Co monolayer probed by spin resolved scanning tunnelling microscopy — •Marie Hervé[1], Bertrand Dupé[2], Rafael Lopez[3], Marie Böttcher[2], Maximiliano D. Martins[3], Timofey Balashov[1], Lukas Gerhard[1], Christian Gorenflo[1], Jairo Sinova[2], and Wulf Wulfhekel[1] — [1]Physikalisches Institut, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany — [2]Institut für Physik, Johannes Gutenberg Universität Mainz, 55128 Mainz, Germany — [3]Centro de Desenvolvimento da Tecnologia Nuclear Serviço de Nanotecnologia Laboratório de Nanoscopia, Belo Horizonte, Brazil

In magnetic thin films the Heinsenberg exchange interaction often leads to a parallel or antiparallel alignment of neighboring spins in the crystal. When inversion symmetry is broken e.g. by a surface or an interface, the non-collinear Dzyaloshinskii-Moriya interaction competes with the Heisenberg exchange interaction. This competition can lead, in some case, to the stabilization of complex spin textures such as spin spirals or skyrmions. We report here on the characterization of a non-collinear magnetic structure in Co(1 ML)/Ru(0001) with spin polarized STM. A chiral spin spiral of 40 nm periodicity in the 1st monolayer as a ground state is evidence. Under magnetic field isolated skyrmions can be stabilized.

MA 3.12 Mon 12:30 HSZ 101

Influence of the surface reconstruction on magnetic interactions in an Fe double-layer on Ir(111) — •M. Dupé[1], S. Heinze[2], and B. Dupé[1,2] — [1]Institut für Physik, Johannes Gutenberg Universität, Mainz — [2]Institut für Theoretische Physik und Astrophysik, Cristian-Albrechts Universität, Kiel

Skyrmions are localized and topologically stabilized non-collinear spin structures. Isolated skyrmions offer attractive perspectives for future spintronic applications because they can be manipulated at lower current densities than domain walls [1]. Isolated skyrmions have been stabilized and manipulated in the Pd/Fe ultra-thin film on Ir(111) [2]. An effective Hamiltonian parameterized via density functional theory (DFT) has predicted a Curie temperature (Tc) of 100K [3]. Recently, we have shown that Tc could be increased in a multilayer geometry [4]. Here we report on a DFT study of the magnetic interactions of an Fe double-layer on Ir(111) [5]. We determine the magnetic interactions depending on the surface reconstruction and show that the Fe double-layer can be stabilized by the reconstruction from a (111) to a (110) surface. [1] A. Fert, et al Nature Nano. 8, 152 (2013). [2] N. Romming, et al 341, 636 Science (2013). [3] L. Rózsa, et al Phys. Rev. B 93, 024417 (2016). [4] B. Dupé, et al Nature Comm. 7, 11779 (2016). [5] P.-J. Hsu, et al Phys. Rev. Lett. 116, 017201 (2016).