TT 26: Skyrmions I (joint session MA/KFM/TT)

Time: Monday 15:00–18:30 Location: EB 301

Topical Talk TT 26.1 Mon 15:00 EB 301

Structure, Energetics, and Deterministic Writing of Skyrmions in Thin Film Ferromagnets — •Felix Büttner — MIT, Cambridge, MA, USA

Room temperature skyrmions were recently observed in magnetic multilayer systems [1-4], most of them in materials with sizable Dyzaloshinskii-Moriya interaction (DMI). In this talk, I will present a unified theory that analytically describes the energy of such skyrmions, including stray fields [1]. We can now rigorously define two types of skyrmions, "stray field skyrmions" and "DMI skyrmions". DMI skyrmions can be sub-10 nm at zero field and room temperature and moved with velocities exceeding 1000 m/s at 10^{12} A/m^2.

Experimentally, I will show that skyrmions can be nucleated by spin-orbit torque current pulses without any applied fields [2]. The nucleation mechanism is robust, ultra-fast (sub-nanosecond), and extremely easy to implement. I will discuss the mechanism of the skyrmion generation and explain why DMI can replace the need for in-plane fields.

[1] Büttner et al., Nat Phys. 11, 225 (2015). [2] Woo et al., Nat Mater. 15, 501 (2016). [3] Moreau-Luchaire et al., Nat Nano. 11, 444 (2016). [4] Boulle et al., Nat Nano. 11, 449 (2016). [5] Büttner et al., arXiv:1704.08489 [6] Büttner et al., Nat Nano. 12, 1040 (2017).

TT 26.2 Mon 15:30 EB 301

Skyrmion bubble size and density control in Ta/CoFeB/MgO wedges — •Christian Denker[1], Sören Nielsen[2], Enno Lage[2], Jeffrey McCord[2], and Markus Münzenberg[1] — [1]Institut für Physik, Universität Greifswald, Germany — [2]Nanoscale Magnetic Materials - Magnetic Domains, Institute for Materials Science, Universität Kiel, Germany

After the observation of skyrmion bubbles at room temperature in Ta/CoFeB/TaO$_x$ layers by A. Hoffmann's group, skyrmions have been found in various heavy metal/ferromagnet/oxide systems. For skyrmion generation and detection by magnetic tunnel junctions (MTJ), the Ta/CoFeB/MgO system is appealing due to high TMR ratios and its technological maturity. As a starting point typical MTJ bottom electrodes and barriers (5 nm Ta/x CoFeB/3 nm MgO) trilayers with an optional Ru capping were deposited by e-beam evaporation (MgO, Ru) and magnetron sputtering (Ta, CoFeB). We will present our results on skyrmion bubbles observed by magneto-optical Kerr effect microscopy as function of continuous variation of CoFeB thickness. The in- to out-of-plane transition for the magnetic anisotropy is found at about $x = 1.4$ nm. At slightly thinner CoFeB thicknesses skyrmions can be nucleated. Their size can be as small as 300 nm. The influence of CoFeB composition and annealing temperature on the skyrmion formation, as well as skyrmion stability will be discussed.

TT 26.3 Mon 15:45 EB 301

Small angle neutron scattering experiments of skyrmions far from equilibrium — •Alfonso Chacon[1], Marco Halder[1], Andreas Bauer[1], Wolfgang Simeth[1], André Heinemann[2], Sebastian Mühlbauer[2], and Christian Pfleiderer[1] — [1]Physik Department, Technische Universität München, Germany — [2]Heinz Maier-Leibnitz Zentrum, Garching, Germany

The prospect of the application of magnetic skyrmions in next-generation spintronic devices has recently created substantial scientific interest in this type of magnetic order. Stabilized by thermal fluctuations closed to the paramagnetic order, skyrmion lattices in cubic chiral magnets are constrained to a small window a few Kelvin wide. Recent developments have demonstrated how to expand this regime down to low temperatures by means of supercooling, electrical fields, or uniaxial pressure. Thus, it is possible to study this topological type of magnetism far from equilibrium. We report detailed small angle neutron scattering experiments on skyrmion lattices in B20 compounds at very low temperatures stabilized through fast cooling and discuss the role of disorder and magnetocrystalline anisotropies in their stabilization.

TT 26.4 Mon 16:00 EB 301

Entropy limited topological protection of skyrmions in Fe$_{1-x}$Co$_x$Si — Johannes Wild[1], •Thomas Meier[1], Simon Pöllath[1], Matthias Kronseder[1], Andreas Bauer[2], Alfonso Chacon[2], Marco Halder[2], Marco Schowalter[3], Andreas Rosenauer[3], Josef Zweck[1], Jan Müller[4], Achim Rosch[4], Christian Pfleiderer[2], and Christian Back[1] — [1]Institut für experimentelle und angewandte Physik, Universität Regensburg — [2]Physik-Department, Technische Universität München — [3]Institut für Festkörperphysik, Universität Bremen — [4]Institut für Theoretische Physik, Universität zu Köln

Topologically protected magnetic textures in materials with broken inversion symmetry are considered as future high-density data storage media. The life time of these textures therefore plays a crucial role for data retention. We have used Lorentz transmission electron microscopy to infer the energetics of the topological decay of magnetic skyrmions far from equilibrium in the chiral magnet Fe$_{1-x}$Co$_x$Si. We investigated the decay of a lattice of sykrmions at different magnetic fields and temperatures by imaging the magnetic configuration of the system in real-time with a high speed camera. We observed that the skyrmion life time τ extracted from these movies depends exponentially on temperature following an Arrhenius law, $\tau \propto \tau_0 \exp(\Delta E/k_B T)$. The prefactor τ_0 of this Arrhenius law changes by more than 30 orders of magnitude for small changes of magnetic field reflecting a substantial reduction of the life time of skyrmions by entropic effects and thus an extreme case of enthalpy-entropy compensation.

TT 26.5 Mon 16:15 EB 301

Magnetotransport and Hall effect of MnSi thin film under pressure — •David Schroeter[1], Stefan Süllow[1], Dirk Menzel[1], Hiroyuki Hidaka[2], Hideto Okuyama[2], and Hiroshi Amitsuka[2] — [1]Institut für Physik der Kondensierten Materie, TU Braunschweig, Germany — [2]Graduate School of Science, Hokkaido University Sapporo, Japan

In the recent years thin films of the B20 compound MnSi became subject of great interest, since the magnetic properties of bulk MnSi are modified due to the dimensional reduction and the uniaxial anisotropy with a suspected stabilized skyrmionic phase [1]. In comparison to bulk material MnSi thin film shows an enhanced ordering parameter with ongoing research about the nature of the magnetic order in thin film state [2].

The ordering temperature and critical fields of MnSi decrease with applied hydrostatic pressure, with thin film material recovering bulk values for the transition temperature at $p_{recover} \approx 2.3$ GPa and a qualitatively similar behavior to bulk MnSi with respect to the ordering temperature above $p_{recover}$ [3]. We present magnetotransport and Hall effect measurements on MnSi thin films under applied pressure of up to around 4 GPa and discuss our results concerning the magnetic phase diagram under pressure.

[1] A. B. Butenko et al., Phys. Rev. B 82, 052403 (2010).
[2] M. N. Wilson et al., Phys. Rev. B 86, 144420 (2012).
[3] J. Engelke et al., Phys. Rev. B 89, 144413 (2014).

TT 26.6 Mon 16:30 EB 301

Magnetic anisotropy in the itinerant helimagnet MnSi — •Schorsch M. Sauther[1], Andreas Bauer[1], Dirk Grundler[2], Christian Pfleiderer[1], and Marc A. Wilde[1] — [1]Phys.-Dep. E51, TU München — [2]LMGN, IMX, STI, EPF Lausanne

We report torque magnetometry in Manganese silicide (MnSi). In our experiment, we employ cantilever magnetometry in a 2D magnetic field $\vec{B} = B \cdot (\sin\varphi \quad \cos\varphi)$ to measure the torque τ resulting from the anisotropic magnetization $\vec{M}_\perp$ of a high-quality, single-crystalline bulk sample of MnSi. The angular dependence $\tau(\varphi)$ displays distinct oscillations with differently pronounced extrema. The oscillation amplitude between several extrema does not saturate for our maximum field of 4.5 T. In the field dependence $\tau(B)$ we observe an unexpected hysteresis above H_{c2}. Furthermore, the hysteretic behavior below H_{c2} changes drastically with temperature below T_c. We utilize our observations to determine the anisotropy constants and discuss our results in the context of complementary experiments[1].

[1] A. Bauer *et al.*, Phys. Rev. B **95**, 024429 (2017)

15 min break

TT 26.7 Mon 17:00 EB 301

Inelastic neutron scattering studies of magnons in the field polarized, conical and Skyrmion phase of MnSi — •Lukas Beddrich[1], Tobias Weber[3], Robert Georgii[1,2], and

Peter Böni[1] — [1]Physik-Department E21, Technische Universität München, 85748 Garching, Germany — [2]Heinz Maier-Leibnitz Zentrum (MLZ), Technische Universität München, 85748 Garching, Germany — [3]Institut Laue-Langevin (ILL), 38000 Grenoble, France

Cubic chiral magnets, such as MnSi, are prototypical systems for the investigation of various spin structures. They are stabilized by the Dzyaloshinsky-Moriya interaction (DMI), which also gives rise to a universal magnon dispersion [1], [2].

Recently, the effect of non-reciprocal spin wave excitations, which generally emerge from the lack of inversion symmetry, were intensively studied in the field-polarized and helimagnetic phase of MnSi with inelastic neutron scattering [3]. Due to the excellent compatibility between the low-energy theory and the comprehensive measurements, we currently apply a related approach to describe the magnetic excitations found in the skyrmion phase.

[1] M. Janoschek et al. *Phys. Rev. B*, 81:214436, Jun 2010 doi:10.1103/PhysRevB.81.214436

[2] M. Kugler et al. *Phys. Rev. Lett.*, 115:097203, Aug 2015. doi:10.1103/PhysRevLett.115.097203

[3] T. Weber et al. *submitted for publication*

TT 26.8 Mon 17:15 EB 301

Orientation dependence of the magnetic phase diagram of the chiral magnet Cu_2OSeO_3 — •Marco Halder[1], Alfonso Chacon[1], Andreas Bauer[1], Helmuth Berger[2], and Christian Pfleiderer[1] — [1]Technische Universität München, Physik-Department E21, D-85748 Garching, Germany — [2]École Polytechnique Fédérale de Lausanne, Crystal Growth Facility, CH-1015 Lausanne, Switzerland

In recent years, the cubic chiral insulator Cu_2OSeO_3 attracted great scientific interest, combing the skyrmion lattice phase with strong magneto-electric coupling. We report a comprehensive study of the magnetic properties of single-crystal Cu_2OSeO_3 by means of measurements of the magnetization, ac susceptibility, and specific heat, in particular tracking the influence of crystal orientation, cooling history and demagnetizing effects on the formation of skyrmion order.

TT 26.9 Mon 17:30 EB 301

Time resolved Lorentz-TEM measurements of dynamical skyrmion lattice defects in $\mathbf{Cu_2OSeO_3}$ — •Simon Pöllath[1], Johannes Wild[1], Lukas Heinen[2], Thomas Meier[1], Matthias Kronseder[1], Leonard Tutsch[1], Andreas Bauer[3], Helmuth Berger[4], Christian Pfleiderer[3], Josef Zweck[1], Achim Rosch[2], and Christian Back[1] — [1]Institut für Experimentelle und Angewandte Physik, Universität Regensburg, Deutschland — [2]Institut für Theoretische Physik, Universität zu Köln, Deutschland — [3]Physik-Department, Technische Universität München, Deutschland — [4]Crystal Growth Facility, École Polytechnique Fédérale de Lausanne, Schweiz

We report non-stroboscopic time resolved Lorentz-Transmission-Electron-Microscopy (LTEM) measurements of skyrmion lattice defects in the chiral magnet Cu_2OSeO_3. The multiferroic insulator hosts a hexagonal skyrmion lattice which can be observed in real space using LTEM. It is known, that the radial temperature profile caused by the illumination of the sample with the TEM electron beam sets the skyrmion lattice into rotation [1]. We utilize this effect to study the dynamics of defects and grain boundaries that naturally occur during the lattice rotation. The structural and dynamical behaviour of the defects is similar to that of 2D hexagonal particle lattices and therefore the particle character of the skyrmion in its lattice phase is stressed by our findings [2].

[1] Mochizuki, M. et al. Nat. mater. 13.3 (2014): 241-246
[2] Pöllath S, et al. PRL 118.20 (2017): 207205

TT 26.10 Mon 17:45 EB 301

Large-scale *ab initio* investigations of complex magnetic textures — •Marcel Bornemann, Sergii Grytsiuk, Paul F. Baumeister, Phivos Mavropoulos, Nikolai S. Kiselev, Samir Lounis, Rudolf Zeller, and Stefan Blügel — Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany

We have developed a unique electronic structure code, KKR*nano* [1], specifically designed for petaFLOP computing. Our method scales linearly with the number of atoms, so that we can realize system sizes of up to half a million atoms in a unit cell. Recently, we implemented a relativistic generalization of the algorithm enabling the calculation of complex non-collinear magnetic structures in real space.
We present two applications: (i) In the helimagnet B20-MnGe different experimental groups have observed either a spin spiral in [001] direction or a 3Q-state composed of three spin spirals [2,3]. We present an *ab initio* comparison of both states. (ii) We performed a large-scale evaluation of low-lying thermal excitations, so-called "nodons", in Cr which could explain the formation of a spin density wave in this system [4].
Simulations were performed with computing resources granted by JARA-HPC, Forschungszentrum Jülich and HLRS in Stuttgart.
[1] A. Thiess *et al.*, Phys. Rev. B **85**, 235103 (2012).
[2] O.L. Makarova *et al.*, Phys. Rev. B **85**, 205205 (2012).
[3] T. Tanigaki *et al.*, Nano Lett. **15**, 5438 (2015).
[4] V. Vanhoof *et al.*, Phys. Rev. B **80**, 184420 (2009).

TT 26.11 Mon 18:00 EB 301

Giant structural response of Dzyaloshinskii-Moriya interaction in MnGe B20 compounds — •Sergii Grytsiuk, Marcel Bornemann, Markus Hoffmann, Bernd Zimmermann, Phivos Mavropoulos, Gustav Bihlmayer, and Stefan Blügel — Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany

Non-centrosymmetric cubic B20 materials are currently under intensive investigation. An important feature of these materials is the competition between the antisymmetric Dzyaloshinskii-Moriya interaction (DMI) and the symmetric exchange interaction resulting in a rich variety of magnetic phases with respect to temperature, magnetic fields, material compositions and geometries. The possibility of engineering chiral structures and the effective switching between different magnetic phases requires the investigation of possible factors that influence the strength of the magnetic interactions. In this work, we show by first-principles calculations based on DFT that under pressure magnetic and structural properties of MnGe reveal a hysteretic behavior near the state where energies of high and low spin states coincide. We observe that pressure strongly enhances the DMI (by a factor 5), while the spin-stiffness gets smaller. In order to understand such giant enhancement of the micromagnetic DMI we computed atomistic DMI vectors. Surprisingly, the absolute value of the DMI vectors do not depend significantly on the lattice parameter and the enhancement of micromagnetic DMI stems mainly from the change of the DMI vectors' orientation with respect to bonds between Mn atoms.

TT 26.12 Mon 18:15 EB 301

Spin-orbit coupling effects in magnetic and response properties of B20 $\mathbf{A_{1-x}B_xGe}$ **alloys (A, B = Mn, Fe, Co, Rh)** — •Sergiy Mankovsky[1], Sebastian Wimmer[1], Svitlana Polesya[1], Nicolas Martin[2], Isabelle Mirebeau[2], and Hubert Ebert[1] — [1]Dept. Chemistry, LMU Munich, D-81377 Munich, Germany — [2]Lab. Léon Brillouin, CEA, CNRS, Uni. Paris-Saclay, France

The composition-dependence of the isotropic exchange (J_{ij}) and Dzyaloshinskii-Moriya interaction (DMI) ($\vec{D}_{ij}$) of $Mn_{1-x}Fe_xGe$, $Mn_{1-x}Rh_xGe$, $Mn_{1-x}Co_xGe$ and $Fe_{1-x}Co_xGe$ B20 alloys have been investigated by first-principles calculations using the relativistic multiple scattering Korringa-Kohn-Rostoker (KKR) formalism. The $D^{\alpha\alpha}$ ($\alpha = x, y, z$) elements of the DMI tensor exhibit a strong dependence on the composition, changing sign at $x \approx 0.85$ in $Mn_{1-x}Fe_xGe$ and at $x \approx 0.5$ in $Fe_{1-x}Co_xGe$, in line with previous theoretical calculations as well as with experimental results. The spin-orbit torque (SOT), anomalous and spin Hall conductivities (AHC and SHC, respectively) of $Mn_{1-x}Fe_xGe$ alloys have been investigated. A sign change at $x \approx 0.5$ is predicted for the Fermi sea contribution to the SOT, as this is closely related to the DMI. In the case of anomalous and spin Hall effects it is shown that the calculated Fermi sea contributions are rather small and the composition-dependence of these effects are determined mainly by the electronic states at the Fermi level. The spin-orbit-induced scattering mechanisms responsible for both effects are suggested to cause the minimum of the AHC and the sign change of the SHC.