MA 30: Skyrmions II

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

Invited Talk MA 30.1 Wed 15:00 EB 301
Discovery of Hopfion rings in a cubic chiral magnet — •Nikolai Kiselev — Institute for Advanced Simulation and Peter Grünberg Institute, Forschungsyentrum Jülich, 52425 Jülich Germany

Magnetic skyrmions are two-dimensional topological solitons resembling vortex-like strings in the magnetization field that penetrate an entire sample. In contrast, hopfions are topological solitons localized in all three dimensions and manifest as closed loops of skyrmion strings, often taking the shape of a ring. While hopfions were theoretically predicted in specific magnetic systems [1], their direct observation has been elusive since, in most magnetic systems, isolated hopfions are unstable. Our discovery reveals that in crystals of cubic chiral magnets, hopfions become stable when linked with skyrmion strings [2]. This talk presents the direct observation of such hopfions in B20-type FeGe plates using transmission electron microscopy. Various aspects of hopfion rings will be discussed, including a reliable protocol for hopfion ring nucleation, a quantitative comparison between theory and experiment, a homotopy group analysis of these topological states, and an examination of zero modes of hopfion rings moving along skyrmion strings.

[1] Rybakov, F. N. et al. APL Mater. **10**, 111113 (2022).
[2] Zheng, F. et al., Nature **623**, 718 (2023).

MA 30.2 Wed 15:30 EB 301
Probing Chirality and Topology in Ferrimagnetic Multilayer Systems — •Tamer Karaman[1], Kai Litzius[1], Daniel Metternich[2], Timo Schmidt[1], Aladin Ulrich[1], Andrada-Oana Mandru[3], Reshma Peremadathil Pradeep[3], Hans Josef Hug[3], Manfred Albrecht[1], and Felix Büttner[1,2] — [1]University of Augsburg, Germany — [2]Helmholtz-Zentrum Berlin, Germany — [3]EMPA, Dübendorf, Switzerland

Chiral rare-earth transition metal ferrimagnets show promise for skyrmion-based spintronics applications due to their unique material properties, such as Néel-type bulk DMI, tunable anisotropy, and negligible stray fields [1, 2]. This class of ferrimagnets combines features from both ferromagnets and antiferromagnets [3]. Using Fresnel Lorentz Transmission Electron Microscopy, we investigate thick ferrimagnetic Dy/Co multilayer films. We observe the coexistence of skyrmions and topologically trivial bubbles under varying tilt and magnetic fields, revealing a delicate balance of micromagnetic interactions. Additionally, a stable worm domain pattern emerges, acting as a guiding pathway for normal domains. This study underscores the importance of local real-space probes in understanding chiral ferrimagnets, paving the way for further exploration and exploitation of these materials.

1. Kim, S. K. et al. Nat. Mater. 21, 24 (2022). 2. Fert, A., et al Nat. Rev. Mater. 2, 17031 (2017). 3. Caretta, L. et al. Nat. Nanotechnol. 13, 1154 (2018).

MA 30.3 Wed 15:45 EB 301
The dynamics of Skyrmion shrinking — •Frederik Austrup[1], Wolfgang Häusler[2], Michael Lau[1], and Michael Thorwart[1] — [1]I. Institut für Theoretische Physik, Universität Hamburg — [2]Institute of Physics, University of Augsburg

It is generally accepted that Skyrmions shrink in size before they decay when unstable. We present numerical studies to identify values for the external parameters, including the applied magnetic field and the Dzyaloshinskii-Moriya interaction strength, stabilizing Skyrmions in two-dimensional ferromagnets. Further, we follow their time evolution in the unstable cases, for different lattice constants and in the presence of Gilbert damping. Contrary to the commonly expected simply exponentially decreasing size we find a more complicated time dependence. The time evolution of the Skyrmion radius ρ_0 can be divided into three phases: $\rho_0(t)$ starts decreasing quadratically in time before it continues according to an exponential law over a certain period of time. However, before reaching a time t_c, a behavior consistent with a square root decay, $\sim (t - t_c)^{1/2}$, is found. Analytically, we derive a differential equation for $\rho_0(t)$ from the Landau-Lifshitz-Gilbert equation for the time-dependent topological charge density, utilizing a Skyrmion profile of triangular shape. Solving this equation, we find indeed a shrinking behaviour nicely following the observed exponential law that crosses over into a square root decay pattern. The time t_c is found to depend on Zeeman-field and on exchange field strengths, and on the initial Skyrmion size.

MA 30.4 Wed 16:00 EB 301
Chemical potential of magnetic skyrmion quasiparticles in heavy metal/iron bilayers — •Balázs Nagyfalusi[1], László Udvardi[1], László Szunyogh[1,2], and Levente Rózsa[3,1] — [1]Budapest University of Technology and Economics, Budapest Hungary — [2]HUN-REN-BME Condensed Matter Research Group, Budapest, Hungary — [3]HUN-REN Wigner Research Center for Physics, Budapest, Hungary

We performed metadynamics Monte Carlo simulations to obtain the free energy as a function of the topological charge in the skyrmion-hosting magnetic model systems $(Pt_{0.95}Ir_{0.05})$/Fe/Pd(111) and Pd/Fe/Ir(111), using a spin model containing parameters based on ab initio calculations. Using the topological charge as collective variable, this method allows for evaluating the temperature dependence of the number of skyrmionic quasiparticles. In addition, from the free-energy cost of increasing and decreasing the topological charge of the system we determined chemical potentials as a function of the temperature. At lower temperature, the chemical potential for creating skyrmions and antiskyrmions from the topologically trivial state is different. This splitting of the chemical potential is particularly pronounced for large external magnetic fields when the system is in a field-polarized phase. We observed a change in the shape of the free-energy curves when skyrmion-skyrmion interactions become more pronounced.

MA 30.5 Wed 16:15 EB 301
Stability of nonlocal magnetic solitons in an all-magnetic van der Waals heterostructure — •Moritz A. Goerzen[1], Dongzhe Li[2], Soumyajyoti Haldar[1], Tim Drevelow[1], and Stefan Heinze[1,3] — [1]ITAP, University of Kiel, Germany — [2]CEMES, Université de Toulouse, CNRS, France — [3]KiNSIS, University of Kiel, Germany

Stabilizing and controlling multiple topological spin states in atomically thin van der Waals (vdW) materials gained tremendous attention due to high tunability, enhanced functionality, and miniaturization. Here, using first-principles and atomistic spin simulations [1], we investigate the existence of multiple topological spin textures in an all-magnetic vdW heterostructure $Fe_3GeTe_2/Cr_2Ge_2Te_6$ (FGT/CGT). These states obey opposite rotational senses at the two sides of the FGT/CGT interface, which is in agreement with recent experimental measurements [2]. Magnetic skyrmions at the FGT layer and bimerons at the CGT layer persist in the heterostructure with zero magnetic field while the later undergo bimeron-skyrmion transformation if a field is applied. Furthermore, we show evidence of nonlocal spatial expanse, which makes them subject to finite-size effects. We analyze how this affects the stability of states in confined materials.

[1] Li *et al.*, Phys. Nano Lett. **22**, 7706-7713 (2022)
[2] Wu *et al.*, Adv. Mater. **34**, 2110583 (2022)

MA 30.6 Wed 16:30 EB 301
Laser-induced real-space topology control of spin wave resonances — •Tim Titze[1], Sabri Koraltan[2], Timo Schmidt[3], Marcel Möller[4], Florian Bruckner[2], Claas Abert[2], Dieter Suess[2], Claus Ropers[4], Daniel Steil[1], Manfred Albrecht[3], and Stefan Mathias[1] — [1]University of Göttingen, Germany — [2]University of Vienna, Austria — [3]University of Augsburg, Germany — [4]Max Planck Institute for Multidisciplinary Sciences, Göttingen, Germany

Materials exhibiting magnetic spin textures promise advanced magnetic control via the generation of laser-induced ultrafast and non-equilibrium spin dynamics. We investigate ferrimagnetic $[Fe(0.35\,nm)/Gd(0.40\,nm)]_{160}$ multilayers, which host a rich diversity of magnetic spin textures including stripe domains, a dense bubble/skyrmion (B/SK) lattice, and a single domain state [1, 2]. Using fs Kerr spectroscopy, we can unambiguously identify the different magnetic spin textures, as we observe distinct coherent spin wave dynamics in response to weak laser excitation. Strong laser excitation allows us to achieve versatile control of the coherent spin dynamics via non-equilibrium and ultrafast transformation of magnetic spin textures by both creating and annihilating B/SKs. We further corroborate these findings by micromagnetic simulations and Lorentz transmission electron microscopy with in-situ optical excitation [3].

[1] S. A. Montoya *et al.*, Phys. Rev. B **95**, 2024415 (2017)
[2] M. Heigl *et al.*, Nat. Commun. **12**, 261 (2021)
[3] T. Titze *et al.*, arXiv preprint arXiv:2309.12956 (2023)

15 min. break

MA 30.7 Wed 17:00 EB 301

Reversible topological transformation of skymions and trivial bubbles — •Timo Schmidt[1], Sabri Koraltan[2], and Manfred Albrecht[1] — [1]Universität Augsburg, Augsburg, Germany — [2]Universität Wien, Wien, Austria

Magnetic skyrmions and type-2-bubbles represent topologically distinct spin textures that have garnered significant attention in the field of condensed matter physics due to their unique properties and potential applications in information storage and processing. While these objects can be stabilized in a wide variety of materials by different mechanisms, this work focusses on dipolar stabilized spin textures in amorphous Fe/Gd-multilayer thin films. These systems are sputter-deposited on SiN-membranes.

Using Lorentz transmission electron microscopy (LTEM) round spin textures can be imaged as they nucleate from the stripe domain state by applying a magnetic field in out-of-plane direction. We observe distinct locations on the membrane where certain types of spin objects are stabilized predominantly and attribute this to the wrinkling of the membrane. Due to this wrinkling, which originates in the sample manufacturing process, there are intrinsically tilted regions on the membrane, resulting in an effective in-plane field component. Tilting of the whole sample in the range of up to 18° shows, that by changing the contribution of the ip-field, topologically trivial type-2-bubbles can be transformed into topologically protected skyrmions and vice versa.

MA 30.8 Wed 17:15 EB 301

Skyrmion motion in magnetic anisotropy gradients: Acceleration caused by deformation — •Ismael Ribeiro de Assis, Ingrid Mertig, and Börge Göbel — Institut für Physik, Martin-Luther-Universität, Halle (Saale), Germany

Magnetic skyrmions are nano-sized topologically non-trivial spin textures that can be moved by external stimuli such as spin currents and internal stimuli such as spatial gradients of a material parameter. Since the total energy of a skyrmion depends linearly on most of these parameters, like the perpendicular magnetic anisotropy, the exchange constant, or the Dzyaloshinskii-Moriya interaction strength, a skyrmion will move uniformly in a weak parameter gradient. In this paper, we show that the linear behavior changes once the gradients are strong enough so that the magnetic profile of a skyrmion is significantly altered throughout the propagation. In that case, the skyrmion experiences acceleration and moves along a curved trajectory. Furthermore, we show that when spin-orbit torques and material parameter gradients trigger a skyrmion motion, it can move on a straight path along the current or gradient direction. We discuss the significance of suppressing the skyrmion Hall effect for spintronic and neuromorphic applications of skyrmions. Lastly, we extend our discussion and compare it to a gradient generated by the Dzyaloshinskii*Moriya interaction.

MA 30.9 Wed 17:30 EB 301

Unveiling the origin of square skyrmion lattice in $GdRu_2Si_2$ and effect of uniaxial pressure: Insights from theory — •Rohit Pathak[1], Sagar Sarkar[1], Olle Eriksson[1,2], and Vladislav Borisov[1] — [1]Department of Physics and Astronomy, Uppsala University, Box 516, SE-751 20 Uppsala, Sweden — [2]Wallenberg Initiative Materials Science for Sustainability, Uppsala University, 75121 Uppsala, Sweden

The miniaturization of skyrmion holds promise for high-density memory technology applications [1]. This study delves into the magnetic properties of the $GdRu_2Si_2$ alloy, experimentally known to host nanometer-sized square skyrmion lattices [2]. Employing the first-principle density functional theory (DFT) [3] and atomistic spin dynamics simulations [4], we aim to understand the microscopic origins of the formation of the skyrmion lattice. Our investigation reveals that the interplay between frustration in exchange interactions and uniaxial anisotropy plays an essential role here. Additionally, we intend to explore the impact of uniaxial pressure on exchange interactions and magnetic anisotropy, thereby examining alterations to the magnetic phase diagram. [1] Göbel, B. et al., Phys. Rep. 895, 1*28 (2021). [2] Khanh, N. D. et al., Nat. Nanotechnol. 15, 444*449 (2020) [3] Wills, J. M. et al. Full-Potential Electronic Structure Method (Springer, 2010) [4] Eriksson et al. Atomistic Spin Dynamics: Foundations and Applications (Oxford University Press, 2017). This work was financially supported by the Knut and Alice Wallenberg (KAW), Göran Gustafsson, and Carl Tryggers Foundations.

MA 30.10 Wed 17:45 EB 301

Skyrmions and Hopfions: topological chirality emerging from dipole-dipole interactions — •Svitlana Kondovych[1] and Igor Luk'yanchuk[2] — [1]Institute for Theoretical Solid State Physics, IFW Dresden, 01069 Dresden, Germany — [2]Laboratory of Condensed Matter Physics, University of Picardie, 80039 Amiens, France

Confined ferroics display non-uniform vector field texturing, driven by the interplay of dipole-dipole interactions, elastic strains, anisotropic energy, and confinement effects. Topologically non-trivial, chirality-endowed structures like Bloch domain walls, merons, skyrmions, and Hopfions attract attention for their fundamental importance and diverse applications. In magnetic [1-3] and ferroelectric [4,5] materials, chirality spontaneously emerges to minimize stray fields, even without the local, Dzyaloshinskii-Moriya-like antisymmetric exchange.

We present a theoretical framework to elucidate the role of dipole-dipole interactions in formation of chiral topological states in nano-sized ferroic structures. Through various examples, we illustrate non-uniform confined vector fields, highlighting the possibility to tailor and manipulate their swirling and handedness.

S.K. acknowledges the support from the Alexander von Humboldt Foundation.

[1] E. Berganza, et al., Sci. Rep. 12, 3426 (2022).
[2] F. Büttner, et al., Sci. Rep. 8, 1-12 (2018).
[3] J. Schöpf, et al. Nano Letters 23.8, 3532-3539 (2023).
[4] I. Lukyanchuk, et al., Nat. Commun. 11, 2433 (2020).
[5] Y. Tikhonov, et al., Sci. Rep. 10, 8657 (2020).

MA 30.11 Wed 18:00 EB 301

Ab-initio study of the topological Hall effect in Pd/Fe/Ir(111) — •Adamantia Kosma[1], Philipp Rüssmann[1,2], Stefan Blügel[1], and Phivos Mavropoulos[3] — [1]Forschungszentrum Jülich — [2]University of Würzburg — [3]National and Kapodistrian University of Athens

This study comprises an ab-initio computational investigation of the topological Hall effect (THE) arising from magnetic skyrmions in thin film Pd/Fe/Ir(111)[1]. The research is motivated by the significance of electrically detecting magnetic skyrmions for spintronic applications. To achieve the formation of stable magnetic skyrmions in this system, we employ non-collinear spin-density-functional theory within the Korringa-Kohn-Rostoker (KKR) Green function method. The multiple scattering problem is solved using the full-potential relativistic KKR method [2], and subsequently, the spin-transport calculations are carried out using the Boltzmann formalism [3] to find the resistivity and the topological Hall angle. We investigate the influence of the skyrmion size on the Hall angle and explore the impact of additional electron scattering, modeled as random disorder broadening, on the THE. Our findings indicate a significant correlation between the THE and the degree of disorder in a sample.

We thank the ML4Q (EXC 2004/1 - 390534769) for funding.

[1] N. Romming *et al.*, Science **341** 6146 (2013).
[2] JuDFTteam/JuKKR (2022). doi: 10.5281/zenodo.7284738
[3] A. Kosma *et al.*, Phys. Rev. B **102** 144424 (2020).

MA 30.12 Wed 18:15 EB 301

Classification of real- and reciprocal space topology in skyrmion crystals — •Pascal Prass[1], Fabian R. Lux[2], Duco van Straten[3], and Yuriy Mokrousov[1,4] — [1]Institute of Physics, Johannes Gutenberg University Mainz, Germany — [2]Department of Physics, Yeshiva University, New York, NY 10016, USA — [3]Institute of Mathematics, Johannes Gutenberg University Mainz, Germany — [4]Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, Germany

As the length scale of a two-dimensional skyrmion crystal approaches the lattice constant of its host material, topological gaps may form in the associated electronic system. However, the smooth texture approximation for the usual geometric approach of emergent magnetic fields is no longer satisfied. Instead, we adopt a fully algebraic view to describe a class of multi-q textures [1], including skyrmion crystals, and apply noncommutative K-theory to compute all admissible Chern numbers. As a central application, we tune the texture parameters, creating discontinuous jumps in the real-space winding number [2,3] for which we observe the relation with Chern numbers of the electronic spectrum. In conclusion, our work gives an exhaustive classification of the electronic state topology in skyrmion crystals and can form the basis for a sophisticated design of topological electronic states in more general magnetic multi-q systems. [1] Lux et al. Phys. Rev. Res. *in press* (2023/24). [2] Hayami et al. Nat. Commun. 12, 6927 (2021). [3] Shimizu et al. Phys. Rev. B 105, 224405 (2022).