KFM 12: Skyrmions 1 (joint session MA/KFM)

Time: Tuesday 9:30–12:45 Location: H37

Invited Talk KFM 12.1 Tue 9:30 H37

Topological spin structures at surfaces — •Stefan Heinze — Institute of Theoretical Physics and Astrophysics, University of Kiel, Germany

Magnetic skyrmions are of great interest for future applications ranging from data storage to neuromorphic computing [1]. Fundamental insight into the properties of skyrmions and the underlying microscopic interactions can be obtained by studying them at surfaces [2,3]. Here, I will discuss the stabilization, creation, and annihilation mechanisms of nanoscale topological spin structures based on density functional theory and atomistic spin simulations [4-8]. A novel skyrmion annihilation mechanism, the Chimera collapse [4], is presented which has been confirmed by direct comparison with scanning tunneling microscopy (STM) experiments [5]. It is further shown that skyrmion stability can be tuned via applied electric fields [6] allowing writing and deleting of skyrmions. Higher-order exchange interactions (HOI) beyond Heisenberg exchange also play a role since they can stabilize skyrmion lattices [2] as well as isolated skyrmions or antiskyrmions [7]. Unexpectedly, HOI can induce not only non-collinear but also collinear two-dimensional multi-Q states observed via spin-polarized STM [8].

[1] A. Fert *et al.*, Nat. Rev. Mater. **2**, 1 (2017), [2] S. Heinze *et al.*, Nat. Phys. **7**, 713 (2011), [3] N. Romming *et al.*, Science **341**, 639 (2013), [4] S. Meyer *et al.*, Nat. Commun. **10**, 3823 (2019), [5] F. Muckel *et al.*, Nat. Phys. **17**, 395 (2021), [6] S. Paul *et al.*, npj Comput. Mater. **8**, 105 (2022), [7] S. Paul *et al.*, Nat. Commun. **11**, 4756 (2020), [8] M. Gutzeit *et al.*, arxiv:2204.01358 (2022).

KFM 12.2 Tue 10:00 H37

Controlling Magnetic Skyrmion Nucleation and Motion — •Lisa-Marie Kern[1], Victor Deinhart[1,4], Kathinka Gerlinger[1], Michael Schneider[1], Dieter Engel[1], Christian Günther[2,3], Katja Höflich[4,5], Riccardo Batistelli[4], Daniel Metternich[4], Felix Büttner[4], Bastian Pfau[1], and Stefan Eisebitt[1,3] — [1]Max-Born-Institut, Berlin, Germany — [2]Zentraleinrichtung für Elektronenmikroskopie (ZELMI), Technische Universität, Berlin, Germany — [3]Institut für Optik und Atomare Physik, Technische Universität, Berlin, Germany — [4]Helmholtz Zentrum für Materialien und Energie, Berlin, Germany — [5]Ferdinand-Braun-Institut, Berlin, Germany

Magnetic skyrmions are topological quasiparticles, stabilized in out-of-plane magnetized multilayers. Great advances have been reported in generating, annihilating and shifting skyrmions via spin-orbit torque from spin-polarized currents. Optical nucleation with single laser pulses offers a possibly faster and more energy-efficient alternative. While the underlying mechanisms of the nucleation are different, both methods suffer from a certain stochasticity in the spatial distribution of the skyrmions nucleated. However, in view of scientific and practical applications, a controllable localization of the skyrmion's nucleation site is typically required. Nanopatterning of a tailored magnetic anisotropy landscape using He+-ions provides a promising platform for enhanced control of skyrmions in thin films. Based on this technique, we have recently demonstrated reproducible skyrmion nucleation and motion - a prerequisite for any fundamental or applied research on topological structures.

KFM 12.3 Tue 10:15 H37

Current-Induced H-Shaped Skyrmion Creation and Their Dynamics in the Helical Phase — •Ross Knapman[1,4], Davi R Rodrigues[2], Jan Masell[3], and Karin Everschor-Sitte[4,5] — [1]Institute of Physics, Johannes Gutenberg University Mainz, 55128 Mainz, Germany — [2]Department of Electrical and Information Engineering, Politecnico di Bari, 70126 Bari, Italy — [3]RIKEN Center for Emergent Matter Science (CEMS), Wako 351-0198, Japan — [4]Faculty of Physics, University of Duisburg-Essen, 47057 Duisburg, Germany — [5]Center for Nanointegration Duisburg-Essen, University of Duisburg-Essen, 47057 Duisburg, Germany

A potential application of magnetic skyrmions is in racetrack memory devices. [1] While efforts have often been concentrated on the use of ferromagnetic and antiferromagnetic racetracks, previous work has suggested that the use of helimagnets could be more effective. [2] Here, the helices provide a means to naturally confine the skyrmions to quasi-1D channels, mitigating the skyrmion Hall effect. They additionally allow for high-speed skyrmion motion. Moreover, inspired by previous works which demonstrated electric-current-controlled skyrmion injection at magnetic impurities, [3] we propose a method of creating skyrmions in a helical background. [4]

[1] Fert, A. et. al., Nat. Nanotechnol. **8**, 152-156 (2013)
[2] Müller, J. et. al., Phys. Rev. Lett. **119**, 137201 (2017)
[3] Everschor-Sitte, K. et. al., New J. Phys. **19**, 092001 (2017)
[4] **Knapman, R.** et. al. J. Phys. D: Appl. Phys. **54**, 404003 (2021)

KFM 12.4 Tue 10:30 H37

Skyrmion automotion in confined geometries for applications — •Kilian Leutner[1], Thomas Brian Winkler[1], Hans Fangohr[2,3], and Mathias Kläui[1] — [1]Johannes Gutenberg University, Institute for Physics, Staudinger Weg 7, 55128 Mainz, Germany — [2]Max-Planck Institute for the Structure and Dynamics of Matter, Luruper Chaussee 149, 22761 Hamburg, Germany. — [3]University of Southampton, SO17 1BJ, Southampton, United Kingdom

Magnetic skyrmions are promising candidates for energy-efficient applications due to their quasi-particle nature and their topological stabilization. We present here a new concept for a multi-turn sensor-counter based on skyrmions. The skyrmion-boundary force in confined geometries leads with the topology-dependent dynamics to the effect of automotion in certain cases. Automotion describes the movement of magnetic structures without the supply of external energy. For our case, we describe and investigate this effect with micromagnetic simulations and the coarse-grained Thiele equation. Automotion has already been demonstrated for domain walls [1], but is not well explored in skyrmionic systems yet.

[1] M.-A. Mawass et al, Phys. Rev. Applied 7, 044009, 2017

KFM 12.5 Tue 10:45 H37

Walking Skyrmions — •Alla Bezvershenko and Achim Rosch — Institute for Theoretical Physics, University of Cologne, 50937 Cologne, Germany

We study the pinning - unpinning transition of the skyrmion lattice in bulk MnSi under applying a slowly oscillating transverse magnetic field. We model the system using an elastic model for skyrmion strings in the presence of pinning forces. With this effective model we show that the presence of a transverse magnetic field reduces the critical current density needed to depin the skyrmion lattice, reaching zero at the critical magnetic field value. Further, the complete phase diagram of this model will be discussed. Below the threshold amplitude, the skyrmion lines stay fully pinned. Upon increasing the amplitude, a so-called "walking" phase starts, where the skyrmion lines start to unpin. If in this phase a sufficiently large electric current is being applied, the skyrmion lattice starts to move. Obtained results are compared to the experimental data on the transverse susceptibility measurements for this system.

KFM 12.6 Tue 11:00 H37

Small-angle neutron scattering of kinetically driven skyrmion lattice motion — •Denis Mettus[1], Alfonso Chacon[1], Andreas Bauer[1], Sebastian Mülbauer[2], and Christian Pfleiderer[1] — [1]Physik-Department, Technische Universität München, D-85748 Garching, Germany — [2]Heinz Maier-Leibnitz Zentrum (MLZ), Technische Universität München, Garching, Germany

Skyrmions are topologically non-trivial spin textures that exhibit an exceptionally efficient coupling to spin currents, notably spin-polarized charge currents and magnon currents as observed in MnSi, FeGe, and Cu_2OSeO_3. This raises the question for the microscopic mechanisms that control the pinning of the skyrmion lattice, and how they depend on the topology, electronic structure, and disorder. We report neutron scattering measurements of kinetically driven skyrmion lattice unpinning and motion by means of Time-Involved Small Angle Neutron scattering Experiment (TISANE). In our study we examined the unpinning process under changing field orientation for different materials including the metallic systems $Mn_{1-x}Fe_xSi$ and the insulator Cu_2OSeO_3. We discuss our results in the light of methodological aspects of the TISANE technique and recent theoretical predictions of walking skyrmions.

KFM 12.7 Tue 11:15 H37

Spin Wave Driven Skyrmions in Antiferromagnets —

•Michael Lau[1], Wolfgang Häusler[2], and Michael Thorwart[1] — [1]I. Institut für Theoretische Physik, Universität Hamburg — [2]Institute of Physics, University of Augsburg

In a two-dimensional lattice of antiferromagnetically coupled classical magnetic moments of unit length it is theoretically possible to stabilize Skyrmions when appropriately adjusting the Dzyaloshinskii-Moriya interaction (DMI) and a uniaxial anisotropy. We present simulations on a discrete lattice which reveal that these Skyrmions can be moved by spin waves injected at one edge of the lattice. It is known that in ferromagnets spin waves are scattered by Skyrmions, imposing a driving force on them. In antiferromagnets, we find similar scattering of spin waves by Skyrmions, exerting a net driving force. However, contrary to ferromagnets, the driving force acts in the direction of spin wave propagation and the Skyrmion accelerates like a classical particle with finite mass, as typically found for antiferromagnetic solitons. Additionally, we exploit the fact that antiferromagnetic spin waves can appear left- or right handed and study the impact of spin waves of different polarizations on the Skyrmion. It turns out that chirality, frequency and amplitude of the spin waves all significantly influence the Skyrmion motion.

KFM 12.8 Tue 11:30 H37

Skyrmion lattice dynamics — •Daniel Schick, Markus Weissenhofer, Levente Rózsa, and Ulrich Nowak — Universität Konstanz, Konstanz, Germany

We investigate the movement of skyrmions in lattices by performing molecular dynamics simulations based on the Thiele equation [1], using different effective skyrmion-skyrmion interactions. We compare mean-square displacement and the dynamical orientational correlation function $g_6(t)$ for different values of damping α and different topological charges and find the topological charge to change the effect of damping on the examined quantities. Furthermore, we find that for finite topological charge, the mean-square displacement in low-density skyrmion lattices increases compared to free diffusion. By comparing to trivial topology, we can demonstrate the increase in mean-square displacement to be the result of the gyrocoupling of skyrmions.

[1] A.A. Thiele, Phys. Rev. Lett. 30, 6 (1973)

KFM 12.9 Tue 11:45 H37

Skyrmion Pinning Energetics in Thin Film Systems — Raphael Gruber[1], Jakub Zázvorka[1], •Maarten A. Brems[1], Davi R. Rodrigues[1], Takaaki Dohi[1], Nico Kerber[1], Boris Seng[1], Mehran Vafaee-Khanjani[1], Karin Everschor-Sitte[2], Peter Virnau[1], and Mathias Kläui[1] — [1]Institute of Physics, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany — [2]CENIDE, University of Duisburg-Essen, 47057 Duisburg, Germany

Magnetic skyrmions in thin films have been shown to exhibit thermal diffusion, making them a promising system for applications in probabilistic computing [1] as well as Brownian computing [2]. In such applications, pinning effects are of crucial importance as the pinning strength is often comparable to thermal excitations and thus impacts the operation of skyrmion-based devices. Using thermal skyrmion dynamics, we characterize the pinning in a sample and ascertain the spatially resolved energy landscape [3]. To understand the mechanism of pinning, we image the skyrmion pinning details and find a strong size-dependence. We observe that the skyrmion is pinned at its boundary (domain wall) and not as previously considered at its core. As a consequence, we find that the size-dependence follows from different favorable overlaps of the skyrmion boundary with the pinning regions, which is supported by micromagnetic simulations. This allows us to switch pinning sites on and off by small tuning of external fields. [1] J. Zázvorka et al., Nat. Nanotechnol. 14, 658 (2019). [2] M. A. Brems et al., Appl. Phys. Lett. 119, 132405 (2021). [3] R. Gruber et al., under review (2021).

KFM 12.10 Tue 12:00 H37

Coexistence of topologically distinct spin textures — •Börge Göbel[1], Jagannath Jena[2], Stuart Parkin[2], and Ingrid Mertig[1] — [1]Institut für Physik, Martin-Luther-Universität Halle-Wittenberg — [2]Max-Planck-Institut für Mikrostrukturphysik, Halle

Over the last decade, the field of skyrmionics has attracted great research interest, as skyrmions (small, whirl-like spin textures) possess a topologically-induced stability that allows to consider them as the carriers of information in future data storage devices. However, due to their integer topological charge there are two major shortcomings of skyrmion-based racetrack storages: The skyrmions do not move parallel to a current and multiple skyrmions attract and repell each other.

A solution to these problems is the utilization of alternative magnetic nano-objects that go beyond conventional skyrmions; see review [1]. In this talk, we show via simulations, Lorentz transmission electron microscopy measurements [2,3] and Hall transport measurements [4] that skyrmions, antiskyrmion and topologically trivial bubbles [5] can coexist in Heusler materials. They can even appear fractionally near the sample's edges [6]. We propose an advanced version of the racetrack storage device based on these results.

[1] BG et al. Physics Reports 895, 1-28 (2021), [2] Jena, BG et al. Nat. Com. 11, 1115 (2020), [3] Jena, BG et al. Science Advances 6, eabc0723 (2020), [4] Sivakumar, BG et al. ACS Nano 14, 13463 (2020), [5] BG et al. PRAppl. 15, 064052 (2021), [6] Jena, BG et al. Nat. Com. 13, 2348 (2022)

KFM 12.11 Tue 12:15 H37

Topological magnetism in multiferroic lacunar spinels — •Vladislav Borisov[1], Patrik Thunström[1], Anna Delin[2], and Olle Eriksson[1,3] — [1]Ångström Laboratory, Uppsala University, Uppsala, Sweden — [2]Department of Applied Physics, School of Engineering Sciences, KTH Royal Institute of Technology, Stockholm, Sweden — [3]Örebro University, Örebro, Sweden

Several skyrmionic magnetic systems have been discovered since the first observation of skyrmions in a B20 compound MnSi. Only a few of them host not just magnetism but also ferroelectricity and prominent examples are lacunar spinels GaV_4S_8 and GaV_4Se_8. These bulk systems are rather unique, because they host Neel skyrmions, which are otherwise only observed in metallic multilayers. Detailed description of magnetic phenomena in the multiferroic spinels is challenging for theory due to correlations within the V_4 clusters.

We study the role of the magnetic state of these clusters and electronic correlations for the Heisenberg and Dzyaloshinskii-Moriya interactions in V- and Mo-based lacunar spinels. The character of magnetic interactions is discussed in relation to the crystal symmetry and electronic properties derived from the V_4 molecular orbitals. Based on micromagnetic simulations, we determine the role of different interactions for the formation of magnetic textures.

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KFM 12.12 Tue 12:30 H37

Systematic identification and assessment of topological spin textures via saddle point searches — •Hendrik Schrautzer[1,2], Grzegorz Kwiatkowski[1], Hannes Jónsson[1], Pavel F. Bessarab[1,3], and Stefan Heinze[2] — [1]University of Iceland, Reykjavik, Iceland — [2]Christian-Albrechts-University, Kiel, Germany — [3]Linnaeus University, Kalmar, Sweden

Magnetic systems hosting topological textures such as skyrmions have been of great technological and fundamental interest in recent years. The growing zoo [1] of co-existing meta-stable states makes investigation of such systems challenging. Here, we present a methodology combining global optimization based on recursive traversing between energy minima via saddle points on the energy surface [2,3], and harmonic transition state theory. The methodology provides a systematic approach to predict previously unknown metastable states, identify their lifetime at a given temperature and compute kinetics of their mutual transformations. We apply the method to the widely studied Pd/Fe/Ir(111) skyrmionic system, parametrized using density functional theory, and predict a variety of new transition mechanisms and spin textures including skyrmions with chiral kinks [1], which have been unknown so far in this system.

1: V. M. Kuchkin, *et al.*, Phys. Rev. B **102**.14 (2020): 144422.

2: A. Pedersen, *et al.*, International Workshop on Applied Parallel Computing (pp. 34-44) (2010). Springer, Berlin, Heidelberg.

3: G. P. Müller *et al.*, Phys. Rev. Lett. **121**.19 (2018): 197202