KFM 6: Skyrmions I (joint session MA/KFM)

Time: Wednesday 10:00–13:15 Location: H5

Invited Talk KFM 6.1 Wed 10:00 H5

Anatomy of skyrmion-defect interactions and their impact on detection protocols — •Samir Lounis — Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich & JARA, 52425 Jülich, Germany — Faculty of Physics, University of Duisburg-Essen and CENIDE, 47053 Duisburg, Germany

Magnetic skyrmions are topological swirling spin-textures with enormous potential for new technologies that store, transport and read information. However, imperfections intrinsic to any real device lead to pinning or repulsion of skyrmions, generate complexity in their motion and challenge their application as future bits of information. I will discuss our first-principles investigations of the electronic, magnetic and transport properties of single skyrmions interacting with 3d and 4d impurities embedded in PdFe/Ir(111). We found that the skyrmions energy landscapes have a universal shape as function of the defect's electron filling, enabling predictions of the repulsive or attractive nature of the impurity [1]. This finding can be used to design complex energy profiles with targeted properties via atom-by-atom manufacturing of multi-atomic defects [2,3]. Finally, I address how the latter affect the electronic structure and the chiral orbital magnetism, with consequences for the efficiency of skyrmion detection protocols [4], either all-electrical or optical.

– Work funded by Horizon 2020–ERC (CoG 681405–DYNASORE).

[1] Fernandes et al., Nat. Commun. 9, 4395 (2018); [2] Arjana et al. Sci. Rep. 10, 14655 (2020); [3] Fernandes et al., JPCM 32, 425802 (2020); [4] Fernandes et al., Nat. Commun. 11, 1602 (2020).

KFM 6.2 Wed 10:30 H5

In the eye of the storm – A high resolution view at the details of the 3D magnetic texture of Skymions tubes — S. Schneider[1,2], D. Wolf[2], A. Lubk[2], U.K. Rössler[1], A. Kovács[3], M. Schmidt[4], R.E. Dunin-Borkowski[3], B. Büchner[2], and •B. Rellinghaus[1] — [1]Dresden Center for Nanoanalysis, TU Dresden, Dresden, Germany — [2]IFW Dresden, Dresden, Germany — [3]FZ Jülich, Jülich, Germany — [4]MPI CPfS, Dresden, Germany

Low temperature holographic vector field electron tomography in an external magnetic field was used to quantitatively reconstruct the 3D magnetic texture of skyrmion tubes (SkTs) in an FeGe needle [1]. The resulting high-resolution 3D magnetic images reveal various previously unseen details of the SkTs in FeGe. Our findings include the occurrence of local deviations from a homogeneous Bloch character within the tubes. They highlight the collapse of the skyrmion texture upon approaching the surfaces of the needle, provide evidence for the coexistence of longitudinal and transverse skyrmion textures, and reveal an axial modulation of the SkTs that is found to be strongly correlated among neighboring tubes in the needle. Based on the quantitative 3D magnetic induction data, we have calculated spatially resolved energy density maps across the SkTs that provide experimental evidence for the energetic stabilization of these magnetic solitons through an energy gain due to the Dzyaloshinskii-Moryia interaction, which overcompensates the exchange energy in the tube centers. Details of the novel experimental setup and limitations of the approach will be discussed.

[1] D. Wolf et al., arXiv:2101.12630 [cond-mat.mtrl-sci]

KFM 6.3 Wed 10:45 H5

Real-space observation of skyrmion dynamics in an insulating magnet with a small heat gradient — Xiuzhen Yu[1], Fumitaka Kagawa[1,2], Shinichiro Seki[2], Masashi Kubota[1], •Jan Masell[1], Fehmi S. Yasin[1], Kiyomi Nakajima[1], Masao Nakamura[1], Masashi Kawasaki[1,2], Naoto Nagaosa[1,2], and Yoshinori Tokura[1,2] — [1]RIKEN CEMS, Wako, Japan — [2]University of Tokyo, Tokyo, Japan

Magnetic skyrmions are whirls in the magnetization with a non-trivial real-space topology. They are frequently discussed as potential building blocks for future information technology devices due to their topological protection and high mobility: Skyrmions can be moved by electrical currents and magnetic field gradients. It was also proposed to move skyrmions by magnons or thermal gradients [1].

We report the first observation of skyrmion dynamics in a linear thermal gradient. While nanometer-sized skyrmions remain pinned even with large thermal gradients [2], we observe a depinning threshold on the order of only 10 K/m in the insulating chiral magnet Cu_2OSeO_3 where skyrmions are 60nm large and the Gilbert damping is low. The observed velocity on the scale of 1μm/s agrees with our estimates for skyrmion motion due to a thermally activated magnon current.

[1] L. Kong & J. Zang, PRL **111,** 067203 (2013)
[2] M. Hirschberger, J. Masell, *et al.*, PRL **125,** 076602 (2020)
[3] X.Z. Yu, J. Masell, *et al.*, preprint: https://doi.org/10.21203/rs.3.rs-156692/v1

KFM 6.4 Wed 11:00 H5

Screw dislocations in chiral magnets — •Maria Azhar[1], Volodymyr Kravchuk[1,2], and Markus Garst[1] — [1]Institut für Theoretische Festkörperphysik, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany — [2]Bogolyubov Institute for Theoretical Physics of National Academy of Sciences of Ukraine, 03680 Kyiv, Ukraine

The Dyzaloshinskii-Moriya interaction stabilizes helimagnetic order in cubic chiral magnets for a large range of temperatures and applied magnetic field. In this helimagnetic phase the magnetization varies only along the helix axis, that is aligned with the applied field, giving rise to a one-dimensional periodic magnetic texture. This texture shares many similarities with generic lamellar order like cholesteric liquid crystals, for example, it possesses disclination and dislocation defects [1]. Here, we investigate both analytically and numerically screw dislocations of helimagnetic order. Whereas the far-field of these defects is universal, we find that various core structures can be realized even for the same Burgers vector of the screw dislocation. In particular, we identify screw dislocations with smooth magnetic core structures, that close to the transition to the field-polarized phase continuously connect either to vortices of the XY-order parameter or to skyrmion strings. In addition, close to zero fields we find singular core structure comprising a chain of Bloch points with alternating topological charge.

[1] P. Schoenherr et al. Nature Physics 14, 465 (2018).

KFM 6.5 Wed 11:15 H5

Skyrmion Diffusion in Confined Geometries — •Jan Rothörl[1], Chengkun Song[2], Nico Kerber[1], Yuqing Ge[1], Klaus Raab[1], Boris Seng[3], Maarten Alexander Brems[1], Florian Dittrich[1], Robert Reeve[1], Jianbo Wang[2], Qingfang Liu[2], Peter Virnau[1], and Mathias Kläui[1] — [1]Institute of Physics Johannes Gutenberg-University Mainz — [2]Key Laboratory for Magnetism and Magnetic Materials of the Ministry of Education Lanzhou University China — [3]Institut Jean Lamour Université de Lorraine France

Magnetic skyrmions are topologically stabilized quasi-two-dimensional whirls of magnetization. Diffusion of skyrmions in continuous films [1] can be exploited for novel computing approaches, which often require understanding the behavior of skyrmions in confined geometries. We were studying this behavior in different confined geometries like circles, triangles and squares using experiments and coarse-grained computer simulations. Our results indicate that mobility is not only governed by skyrmion density but also by the interplay between skyrmion numbers and geometry. For triangular or square geometries, we found that this behavior is drastically dependent on the commensurability of the skyrmion number with the shape of the confinement [2].

[1] Zázvorka et al., Nat. Nanotechnol. 14, 658 (2019) [2] Song et al., Adv. Funct. Mater. 31, 2010793 (2021)

KFM 6.6 Wed 11:30 H5

Effects of interlayer exchange on collapse mechanisms and stability of magnetic skyrmions — •Hendrik Schrautzer[1,2], Stephan von Malottki[1,2], Pavel F. Bessarab[2,3], and Stefan Heinze[1] — [1]Institute of Theoretical Physics and Astrophysics, University of Kiel,Germany — [2]University of Iceland, Reykjavik, Iceland — [3]ITMO University, St. Petersburg, Russia

Despite the great success of realizing magnetic skyrmions in multilayers, even at room temperature [1], very little is known about the thermal stability of skyrmions in these systems. In this study, we investigate by means of minimum energy path calculations and harmonic transition state theory the skyrmion decay mechanisms, corresponding energy barriers, and thermal collapse rates in systems incorporating several magnetic monolayers as a function of interlayer exchange coupling (IEC). The magnetic interactions within each layer are chosen so as to mimic the well-established Pd/Fe/Ir(111) system parametrized by first principles density functional theory calculations. We find that skyrmions in different monolayers collapse successively (simultaneously) for weak (strong) IEC. For intermediate IEC regime, we find a rich diversity of decay mechanisms, including the chimera collapse stabilized by IEC. Counter-intuitively, an optimal value of the IEC strength exists for a certain stacking of the magnetic layers. It corresponds to maximum skyrmion stability. We use the determined skyrmion collapse mechanisms to ultimately evaluate the skyrmion lifetime in magnetic multilayers.

[1] Moreau-Luchaire, *et al.*, Nat. Nanotechnol. 11, 444 (2016).

KFM 6.7 Wed 11:45 H5

Exploring the phase diagram of thin film MnSi — •Grace Causer[1], Maria Azhar[2], Alfonso Chacon[1], Andreas Bauer[1], Thorsten Hesjedal[3], Markus Garst[2], and Christian Pfleiderer[1] — [1]Physics Department, Technical University of Munich, Garching, Germany — [2]Institute for Theoretical Solid State Physics, Karlsruhe Institute of Technology, Karlsruhe, Germany — [3]Clarendon Laboratory, University of Oxford, Oxford, United Kingdom

We have charted the magnetic phase diagram of thin film MnSi grown on a Si substrate via the magnetisation, magnetic susceptibility, planar Hall, and small-angle neutron scattering data, tracking carefully the field and temperature history. Our experimental results are supported by micromagnetic simulations, which jointly reveal a magnetic phase diagram dominated by a field-induced unwinding of an out-of-plane propagating helical wavevector. Below 2 K a discrete phase regime can be discerned unambiguously. These observations provide insights into the integral role of magnetic anisotropy and dimensionality on the low-temperature phase diagram of thin film MnSi.

KFM 6.8 Wed 12:00 H5

Optimizing the skyrmion profile for technological applications — •Markus Hoffmann, Sarina Lebs, Moritz Sallermann, and Stefan Blügel — Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany

Chiral magnetic skyrmions are of great scientific interest and of potential relevance in information technology. Important properties – such as their lifetime, mobility, and robustness with respect to external influences – depend hereby on the specific application. Thus, skyrmion properties must be tuned to outperform existing technologies.

Based on a combination of micromagnetic arguments and atomistic spin-dynamics simulations carried out with `Spirit` (https://spirit-code.github.io), we investigate the dependence of aforementioned properties on the skyrmion profile, *i.e.*, on the spatial dependence of the magnetization field, and analyze how the skyrmion profile can be tuned to optimize the skyrmion's properties. To obtain static properties, we perform LLG and GNEB simulations, which provide us the energy barrier and the corresponding saddle point structure, and combine those with HTST calculations to determine the lifetime prefactor [1]. Additionally, we perform LLG simulations to investigate the dynamics of skyrmions, including their velocity as well as the skyrmion Hall angle.

We acknowledge funding from the DARPA TEE program through grant MIPR (#HR0011831554) from DOI, and DFG through SPP-2137 and SFB-1238 (project C1).

[1] M. Hoffmann *et al.*, Phys. Rev. Lett. **124**, 247201 (2020).

KFM 6.9 Wed 12:15 H5

Emergence of Magnetic Skyrmions in Ultrathin Films of Manganese on W(001) at High Magnetic Fields — •Reiner Brüning, Kirsten von Bergmann, André Kubetzka, and Roland Wiesendanger — Festkörper- und Nanostrukturphysik, Hamburg, Deutschland

Topological spin textures like skyrmions with diameters on the order of a few nanometers are promising objects for the application in the field of spintronics. Whereas typical skyrmion systems like Pd/Fe bilayers on Ir(111) [1] have a hexagonal crystal symmetry, here, we investigate a monolayer of Mn on the square lattice of W(001) using spin-polarized scanning tunneling microscopy at 4.2 K. In absence of an external magnetic field, the known magnetic ground state of a 2.2 nm spin spiral is observed [2]. Between 90° rotational domains two types of magnetic domain walls can be identified.

The measurements at 9 T show that the external magnetic field leads to a decrease in the size of the domains and initializes the transition from the spin spiral to small skyrmion areas which results in a coexistence state of the spin spiral and skyrmion phase. Inside the small skyrmionic areas, the skyrmions arrange in a hexagonal-like order, in agreement with recent simulations [3]. By high voltage pulses of 1-2 V, we can locally induce transitions between spiral phase and skyrmion phase.

[1] N. Romming *et al.*, Science, **341**, (2013)
[2] P. Ferriani *et al.*, Phys. Rev. Lett. **101**, 027201 (2008)
[3] A. K. Nandy *et al.*, Phys. Rev. Lett. **116**, 177202 (2016)

KFM 6.10 Wed 12:30 H5

Application of Thermal and Induced Skyrmion Diffusion in Non-Conventional Computing — •Maarten A. Brems, Mathias Kläui, and Peter Virnau — Institute of Physics, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany

Magnetic skyrmions are two-dimensional magnetic quasi-particles with interesting properties for possible future applications in memory storage devices and non-conventional computing. We have shown that skyrmions in thin film magnetic multilayers exhibit thermal diffusion [1]. These properties make skyrmions promising candidates for signal carriers (tokens) in Brownian computing, which exploits thermal fluctuation for computations. We design a crossing-free layout for a composite half-adder module to overcome the problem that crossings generate for the fabrication of circuits [2]. To address the key issue of slow computation based on thermal excitations, we propose to combine artificial diffusion induced by an external excitation mechanism [2,3]. For magnetic skyrmions, induced diffusion by spin-orbit torques or other mechanisms can increase the computation speed by several orders of magnitude. This method can be employed to accelerate conventional Brownian computing as necessary and thereby greatly enhance the application scenarios of token-based computing for instance for low power devices such as autonomous sensors.

[1] J. Zázvorka et al., Nat. Nanotechnol. 14, 658 (2019). [2] M. A. Brems, P. Virnau and M. Kläui, ArXiv: 2107.02097 [Cond-Mat] (2021). [3] M. A. Brems, P. Virnau and M. Kläui, European patent disclosure, EP21164676.5 (2021).

KFM 6.11 Wed 12:45 H5

Solitary-waves excitations and current-induced instabilities of skyrmion strings — •Volodymyr Kravchuk[1,3], Shun Okumura[2], and Markus Garst[1] — [1]Karlsruhe Institute of Technology, Germany. — [2]The University of Tokyo, Japan. — [3]Bogolyubov Institute for Theoretical Physics, Kyiv, Ukraine

Field-polarized chiral magnets possess topological line excitations where the magnetization within each cross-section perpendicular to the applied field forms a skyrmion texture. We introduce and discuss an effective field-theoretical description for the low-energy dynamics of such a skyrmion string. It predicts, in particular, that skyrmion strings support solitary waves that propagate along the string while maintaining their shape. Using integrals of motion, we derive the profile of these waves analytically, and we find quantitative agreement with numerical micromagnetic simulations [1]. In addition, we discuss the influence of a spin-polarized current on the string. Whereas it is well-known that a current flowing perpendicular to the string results in a skyrmion string motion, we demonstrate that a longitudinal current destabilizes the string. This destabilization occurs via the pumping of the Goldstone mode of the string that results in a helical-shaped string deformation that increases with time. Whereas in a clean system an infinitesimal current suffices, a finite threshold current is required to destabilize the string in the presence of disorder. Moreover, we show that this current-induced instability also holds for skyrmion lattices.

[1] V. Kravchuk, U. Rößler, J. van den Brink, M. Garst, PRB, 102, 220408(R) (2020).

KFM 6.12 Wed 13:00 H5

Magnetoelastic coupling and phases in the skyrmion lattice magnet Gd_2PdSi_3 discovered by high-resolution dilatometry — •Sven Spachmann[1], Rüdiger Klingeler[1], Ahmed Elghandour[1], Matthias Frontzek[2], and Wolfgang Löser[3] — [1]Kirchhoff Institute for Physics, Heidelberg University, Germany — [2]Oak Ridge National Laboratory, Oak Ridge, USA — [3]Leibniz Institute for Solid State and Materials Research (IFW), Dresden, Germany

We report high-resolution capacitance dilatometry measurements on single crystals of the centrosymmetric skyrmion-hosting intermetallic Gd_2PdSi_3 in magnetic fields up to 15 T which are complemented by specific heat and magnetization studies. Our data enable us to complete the magnetic phase diagram and to establish yet unreported phase boundaries. We find strong magnetoelastic effects associated with antiferromagnetic order at T_{N1}= 22.3 K and T_{N2} = 19.7 K as well as an additional feature at $T^* \approx 13$ K. Grüneisen analysis shows the onset of magnetic contributions around 60 K, i.e., well above T_{N1}, and strong field effects in an applied magnetic field of 15 T are found up to 200 K (150 K) for B $\parallel$ c (B $\parallel$ a^*, i.e., B $\perp$ c). Our data allow us to extract the uniaxial pressure dependence of the different phase boundaries. We elucidate thermodynamic properties of the recently discovered skyrmion lattice phase and show that it is strongly enhanced by uniaxial pressure.