MA 37: Skyrmions 3 (joint session MA/KFM)

Time: Friday 9:30–12:45 Location: H37

MA 37.1 Fri 9:30 H37

Emergence of zero-field non-synthetic single and catenated antiferromagnetic skyrmions in thin films — •Amal Aldarawsheh[1,2], Imara Lima Fernandes[1], Sascha Brinker[1], Moritz Sallermann[1], Muayad Abusaa[3], Stefan Blügel[1], and Samir Lounis[1,2] — [1]Peter Grünberg Institute and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, D-52425 Jülich, Germany — [2]Faculty of Physics, University of Duisburg-Essen and CENIDE, 47053 Duisburg, Germany — [3]Department of Physics, Arab American University, Jenin, Palestine

Antiferromagnetic (AFM) skyrmions are envisioned as ideal topological magnetic bits in future information technologies. In contrast to ferromagnetic (FM) skyrmions, they are immune to the skyrmion Hall effect, might offer potential terahertz dynamics [1] while being insensitive to external magnetic. Although observed in synthetic AFM structures [2], their realization in non-synthetic AFM films has been elusive. Here[3], we unveil their presence in a row-wise AFM Cr film deposited on PdFe bilayer grown on fcc Ir(111) surface. Using first-principles, we demonstrate the emergence of single and catenated AFM skyrmions, which can coexist with the rich inhomogeneous exchange field, including that of FM skyrmions, hosted by PdFe. Besides the identification of an ideal platform of materials for intrinsic AFM skyrmions, we anticipate the uncovered solitons to be promising building blocks in AFM spintronics. -Work funded by (BMBF-01DH16027) [1] Gomonay et al., Nat. Physics 14, 213 (2018). [2] Legrand et al., Nat. Materials 19, 34 (2020). [3] Aldarawsheh et al., ArXiv:2202.12090 (2022).

MA 37.2 Fri 9:45 H37

Chiral standing spin waves in 3D skyrmion lattice — •Andrii Savchenko[1,2], Vladyslav Kuchkin[1], Filipp Rybakov[3,4], Stefan Blügel[1], and Nikolai Kiselev[1] — [1]Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, D-52425 Jülich, Germany — [2]Donetsk Institute for Physics and Engineering, National Academy of Sciences of Ukraine, 03028 Kyiv, Ukraine — [3]Uppsala University, SE-75120 Uppsala, Sweden — [4]KTH Royal Institute of Technology, SE-10691 Stockholm, Sweden

The resonance excitations of the three-dimensional skyrmions lattice in the finite thickness plate of an isotropic chiral magnet were studied using spin dynamics simulations. We calculated the absorption spectra and resonance mode profile configurations for the cases of in-plane and out-of-plane excitations. These results differ from those predicted by the two-dimensional model and the model of the unconfined bulk crystal. In the case of in-plane excitation, absorption spectra dependencies on film thickness have the periodic zones with fading intensity. This effect can be explained by the formation of chiral standing spin waves, which, contrary to conventional standing spin waves, are characterized by the helical profile of dynamic magnetization of fixed chirality defined by the Dzyaloshinskii-Moriya interaction [1]. The chiral standing spin waves are localized in the inter-skyrmion area or the skyrmion core. Under out-of-plane excitation, the absorption spectrum also demonstrates the appearance of standing spin waves, which are localized in the skyrmion shell. 1. A.S. Savchenko et al, arXiv:2205.05466

MA 37.3 Fri 10:00 H37

Generalization of the collective variables approach for skyrmion strings. — •Volodymyr Kravchuk[1,2] and Markus Garst[1] — [1]Karlsruhe Institute of Technology, Germany. — [2]Bogolyubov Institute for Theoretical Physics, Kyiv, Ukraine

In a bulk saturated chiral magnet, the skyrmion core penetrates the ferromagnet volume forming a string-like object [1]. Here we describe the small-amplitude dynamics of the string, applying the generalized collective variable approach. For the collective variables, we use the coordinate- and time-dependent string position defined as the first moment of topological charge calculated for the continuously stacked horizontal cross-sections perpendicular to the applied magnetic field. The simplest "plane-wave" solution corresponds to the helix-shaped deformation of the string. In a nonlinear regime, this solution is unstable due to the Lighthill criterion, that results in a self-modulation of the wave. Using a multiscale analysis both in space and time, we show that this modulation is captured by a non-linear Schroedinger equation of focusing type. Two classes of non-linear periodic waves of skyrmion string (so-called dc- and cn-waves) are analytically predicted and numerically verified. The separatrix soliton solution just corresponds to the solitary wave found previously [1]. The developed approach is generalized for the case of arbitrary meaning of the collective variables. The latter enables us to describe the string excitations of various symmetries, e.g. breathing and elliptical modes in a nonlinear regime.

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

MA 37.4 Fri 10:15 H37

Fermi-surface origin of helical single Q-state and skyrmion lattice in centrosymmetric Gd compounds — •Juba Bouaziz[1], Eduardo Mendive-Tapia[1], Stefan Blügel[1], and Julie Staunton[2] — [1]Forschungszentrum Jülich, Germany — [2]University of Warwick, Coventry CV4 7AL, United Kingdom

We show from first principles that cylindrical structures within the Fermi surface are the origin of the single-Q helical state in the $GdRu_2Si_2$ and Gd_2PdSi_3 intermetallic compounds. The geometry of the Fermi surface nesting describes the strength and sign of the underlying pairwise Ruderman-Kittel-Kasuya-Yosida interactions between the Gd moments as the main mechanism. These interactions are quasi-two-dimensional, isotropic within the Gd layers, and provide a transition temperature and helix period in very good agreement with experiment. Using atomistic spin-dynamical simulations, we investigate the effects of magnetic anisotropy and construct a general magnetic phase diagram that explains the stabilization of the 2Q-skyrmion lattice observed in experiment with applied magnetic fields.

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MA 37.5 Fri 10:30 H37

Non-Abelian Vortices in Magnets — •Filipp Rybakov[1] and Olle Eriksson[1,2] — [1]Uppsala University, Sweden — [2]Örebro University, Sweden

The non-Abelian (non-commutative) topological states in ordered media may exhibit interesting physics emerging from purely topological arguments [1].

Here we show that non-Abelian vortices also can exist in magnets [2]. We give a topological classification of these vortices and reveal their connection with Abelian topological structures, such as usual vortices, merons, skyrmions. We analyze the potential of non-Abelian magnetic vortices for memory devices and emphasize their advantage, since they provide topological protection of all information, rather than individual bits, as in Abelian cases.

[1] N. D. Mermin, Rev. Mod. Phys. 51, 591 (1979).

[2] F. N. Rybakov and O. Eriksson, arXiv:2205.15264 (2022).

MA 37.6 Fri 10:45 H37

Thermal properties of magnetic skyrmions — •Balázs Nagyfalusi[1], László Udvardi[2,3], and László Szunyogh[2,3] — [1]Wigner Research Center for Physics, Institute for Solid State Physics and Optics, Budapest, Hungary — [2]Budapest University of Technology and Economics, Budapest Hungary — [3]MTA-BME Condensed Matter Research Group, Budapest, Hungary

We have recently implemented metadynamics in Monte Carlo simulation code[1], which has been modified to use the topological charge Q of magnetic skyrmions as collective variable. The free energy can thus be determined as a function of Q and its equilibrium value can be explored as a function of temperature. The knowledge of the free energy $F(Q;T)$ also permits to evaluate the chemical potential μ of the skyrmions.

We investigated the thermal evolution of magnetic skyrmions in a $Pt_{95}Ir_5$/Fe bilayer on Pd(111) and an FePd bilayer on Ir(111) substrate in the presence of a normal-to-plane external magnetic field. The equilibrium number of skyrmions and the phase boundaries are in good agreement with previous studies[2,3]. For the former system we found that Q has a maximum around 60 K and below this temperature this number drops rapidly, while for the later system it freezes in as the skyrmion lattice is a ground state of the system. The slope of $\mu(T)$ also distinguishes the different ground states of the two system.

1. Nagyfalusi *et al.*, Phys. Rev. B 100, 174429 (2019)
2. Rózsa *et al.*, Phys. Rev. B 93, 024417 (2016)

3. Schick *et al.*, Phys. Rev. B 103, 214417 (2021)

MA 37.7 Fri 11:00 H37

Constructing coarse-grained skyrmion potentials from experimental data with Iterative Boltzmann Inversion — •Jan Rothörl, Yuqing Ge, Maarten A. Brems, Nico Kerber, Raphael Gruber, Fabian Kammerbauer, Takaaki Dohi, Mathias Kläui, and Peter Virnau — Institut für Physik, Johannes Gutenberg-Universität, Staudinger Weg 9, D-55099 Mainz, Germany

In an effort to understand skyrmion behavior like skyrmion lattice formation [1] or commensurability effects [2], skyrmions are often described as 2D quasi particles on a coarse-grained level evolving according to the Thiele equation. In particular, the interaction potentials are the key missing parameters for predictive modeling of experiments. We apply the Iterative Boltzmann Inversion technique commonly used in soft matter simulations to construct potentials for skyrmion-skyrmion and skyrmion-magnetic material boundary interactions from a single experimental measurement without any prior assumptions of the potential form. We find that the two interactions are purely repulsive and can be described by an exponential function for experimentally relevant micrometer-sized skyrmions. This captures the physics on experimental time and length scales that are of interest for most skyrmion applications and typically inaccessible to atomistic or micromagnetic simulations. [3]

[1] J. Zázvorka et al., Adv. Funct. Mater. 30, 2004037 (2020). [2] C. Song et al., Adv. Funct. Mater. 2010739 (2021) [3] Y. Ge et al., arXiv:2110.14333 [cond-mat.mtrl-sci] (2021)

MA 37.8 Fri 11:15 H37

Development of a current solver for studying non-linear skyrmion dynamics — •Thorben Pürling[1,2], Daniele Pinna[3], Fabian Lux[4], Jonathan Kipp[1,3], Stefan Blügel[1,3], Abigail Morrison[2,5], and Yuriy Mokrousov[3,4] — [1]Department of Physics, RWTH Aachen University, Aachen, Germany — [2]Institute of Neuroscience and Medicine 6 and Institute for Advanced Simulation 6 and JARA BRAIN Institute I, Jülich Research Centre, Jülich, Germany — [3]Peter Grünberg Institute 1 and Institute for Advanced Simulation 1, Forschungszentrum Jülich and JARA, Jülich, Germany — [4]Institute of Physics, Johannes Gutenberg University Mainz, Mainz, Germany — [5]Computer Science 3 - Software Engineering, RWTH Aachen University, Aachen, Germany

Transport phenomena in skyrmionic textures have recently gained attention owing to possible applications in spintronics and in cognitive computing. While the reservoir computing aspect of skyrmions relies heavily on their nonlinear response properties, little is known about the real-space distribution of the current density that reflects the nontrivial structure of the local conductivity tensor of these complex objects. Here we report on the development of a method that provides the local current distribution for arbitrary spin textures under bias, and apply that method to study the current distribution of isolated skyrmions. We address the importance of diagonal and Hall components of the conductivity tensor for the current distribution and discuss possible relevance of our findings to reservoir computing applications.

MA 37.9 Fri 11:30 H37

Atomistic spin simulations of electric-field assisted nucleation and annihilation of magnetic skyrmions — •Moritz A. Goerzen[1], Stephan v. Malottki[1,4], Grzegorz J. Kwiatkowski[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, Reykjavík, Iceland — [3]St. Petersburg, Russia — [4]Thayer School of Engineering, Dartmouth College, Hannover, USA

We demonstrate electric-field assisted thermally activated writing and deleting of magnetic skyrmions in ultrathin transition-metal films. We apply an atomistic spin model which is parameterised from density functional theory (DFT) calculations for a Pd/Fe bilayer on the Ir(111) surface for electric fields of $\mathcal{E} = 0, \pm 0.5$ V/Å. Based on harmonic transition-state theory [1,2], we calculate the transition rates for skyrmion nucleation and annihilation. Using these rates we quantify the probability for electric-field assisted deleting and writing of skyrmions by means of Master equations. The magnetic-field dependent skyrmion probability can be directly related to the free energy differences of the skyrmion and the ferromagnetic state and resembles a Fermi-Dirac distribution function. The obtained probability function at opposite electric fields is in striking agreement with experimental results [3].

[1] Bessarab *et al.*, Sci. Rep. **8**, 3433 (2018)
[2] von Malottki *et al.*, Phys. Rev. B **99**, 060409 (2019)
[3] Romming *et al.*, Science **341**, 636 (2013)

MA 37.10 Fri 11:45 H37

Strain and electric field control of magnetic skyrmions in Fe3GeTe2 van der Waals heterostructures — •Dongzhe Li[1], Soumyajyoti Haldar[2], and Stefan Heinze[2] — [1]CEMES, Université de Toulouse, CNRS, 29 rue Jeanne Marvig, F-31055 Toulouse, France — [2]Institute of Theoretical Physics and Astrophysics, University of Kiel, Leibnizstrasse 15, 24098 Kiel, Germany

Magnetic skyrmions are topologically protected chiral spin structures with particle-like properties, which are often induced by the Dzyaloshinskii-Moriya interaction (DMI). The recent discovery of truly two-dimensional (2D) magnetic materials opened up new opportunities for exploring magnetic skyrmions in atomically thin vdW materials. Here, using density functional theory and atomistic spin simulations, we predict the emergence of a large DMI in 2D vdW heterostructures where a 2D ferromagnetic metal Fe3GeTe2 monolayer is deposited on a nonmagnetic vdW layer. In particular, the DMI turns out to be highly tunable by strain and electric-field, leading to giant DMI comparable to that of ferromagnetic/heavy metal interfaces, which have been recognized as prototype multilayer systems to host skyrmion states. Our atomistic spin simulations further show that the efficient control of the DMI, the exchange coupling, and the magnetic anisotropy energy by strain, lead to the stabilization of isolated skyrmions.

MA 37.11 Fri 12:00 H37

Resonant optical Hall conductivity from skyrmions — •Sopheak Sorn[1], Luyi Yang[2], and Arun Paramekanti[3] — [1]Institute for Quantum Materials and Technologies, Karlsruhe Institute of Technology, Karlsruhe, Germany — [2]Department of Physics, Tsinghua University, Beijing, China — [3]Department of Physics, University of Toronto, Toronto, Canada

Metallic magnets hosting topological skyrmions exhibit the topological Hall effect, which arises from a real-space Berry-phase mechanism, and it has been used as an indirect signature of skyrmions in transport experiments. This talk will focus on the less explored impact of skyrmions on optical Hall conductivity which is studied using a two-dimensional model of conduction electrons coupled to a background skyrmion spin texture via an effective Hund's coupling. For a skyrmion crystal, a Kubo-formula calculation reveals a resonant feature in the optical Hall response at a frequency set by the Hund's coupling. A linear relation between the area under the Hall resonant curve and the skyrmion density is discovered numerically and is further elucidated in a gradient expansion analysis. The presence of the resonance is robust, persisting in a system with an isolated skyrmion and even in a three-site system hosting a trimer of noncoplanar spins, which implies the indispensable role of the local noncoplanarity. Our results suggest that the resonance can be used as a basis for a magneto-optical Kerr microscopy for visualizing skyrmions.

MA 37.12 Fri 12:15 H37

Artificial neuron based on a magnetic biskyrmion — •Ismael Ribeiro de Assis, Börge Göbel, and Ingrid Mertig — Institut für Physik, Martin-Luther-Universität Halle-Wittenberg

Skyrmionics and neuromorphics are among the most promising fields of physics with the perspective of creating future devices and technologies. Magnetic skyrmions are extremely stable and can be moved by currents which has lead to the prediction of a skyrmion-based artificial neuron [1]: When a skyrmion is pushed by current pulses, it will eventually reach a designated location and can be detected electrically. This resembles the excitation process of a neuron that fires ultimately. However, a realistic refractory process has not been achieved, so far, for such a device. The skyrmion-based neuron would keep on firing when more current pulses are applied which renders this device not useful.

In this talk we suggest that a biskyrmion solves this major issue. The attractive interaction of the two partially overlapping skyrmions and their skyrmion Hall effects lead to a unique trajectory when they are driven by current pulses: The two subskyrmion move along opposite directions to the two designated detection areas where they reverse their direction of motion until they come back and eventually reestablish the biskyrmion. During the second period the skyrmion cannot fire again. Our suggested device resembles the response of a biological neuron better than all existing skyrmion-based devices so far.

[1] S. Li et al., Nanotechnology 28, 31LT01 (2017)

MA 37.13 Fri 12:30 H37

Magnetoelastic surface states of skyrmion textures — •Lars Franke and Markus Garst — Institute for Theoretical Solid State Physics, Karlsruhe Institute for Technology, Germany

At the surface of chiral magnets uncompensated Dzyaloshinskii-Moriya interaction modifies the boundary conditions for the magnetization resulting in a so-called a surface twist. Consequently, skyrmions are expected to change their helicity from Bloch-like within the bulk of the chiral magnet to Néel-like close to the surface [1]. Resonant elastic X-ray scattering experiments [2] have confirmed this predicted change of helicity close to the surface, but the experimentally observed penetration depth was found to be an order of magnitude larger than theoretically expected. In order to account for this discrepancy, we investigate theoretically the influence of a magnetoelastic coupling on the surface twist. Analytical calculations are complicated by broken translational invariance and nontrivial boundary conditions at the surface. However, as in the uncoupled system the length scale for helicity variations is already encoded in the bulk equation. We demonstrate how to extract the length scale from a perturbative approach. The validity of these calculations is checked using micromagnetic simulations, extended with magnetoelastic coupling, of the complete surface state including boundary conditions.

[1] Three-dimensional skyrmion states in thin films of cubic helimagnets, F. N. Rybakov et al. Phys. Rev. B 87, 094424 (2013).

[2] Reciprocal space tomography of 3D skyrmion lattice order in a chiral magnet, S. Zhang et al. PNAS 201803367 (2018).