MA 35: Skyrmions III (joint session MA/TT/KFM)

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

MA 35.1 Wed 15:00 EB 301

Skyrmion drag effect: — •Adel Abbout[1], Joseph Weston[2], Xavier Waintal[2], and Aurelien Manchon[1] — [1]King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia — [2]CEA Grenoble, France.

In this work, we study the motion of skyrmionic magnetic textures and analyze the current induced by this motion using time-dependent nonequilibrium Green's function formalism implemented on a real-space tight-binding model. We focus on the time dependent distribution of the nonequilibrium charge and spin densities and discuss the corresponding topological Hall effect. The perturbation induced by this motion applies a torque on the whole texture. The influence of the generated current on the whole texture is discussed and its signature is unveiled in the renormalization of the damping parameter. A cooperative effect due to the collective motion of skyrmions is proposed in order to enhance the skyrmion's velocity. The stationary regime is analyzed as a function of the different parameters of the system and explained using the formalism of electronic pumping. A simple formula for the current is proposed.

MA 35.2 Wed 15:15 EB 301

Theory of tunneling vector spin transport on a magnetic skyrmion — •Krisztián Palotás[1,2], Levente Rózsa[3], and László Szunyogh[4] — [1]Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia — [2]University of Szeged, Szeged, Hungary — [3]University of Hamburg, Hamburg, Germany — [4]Budapest University of Technology and Economics, Budapest, Hungary

Spin-polarized scanning tunneling microscopy (SP-STM) demonstrated the creation and annihilation of individual magnetic skyrmions [1] that is promising for future technological use. The detailed microscopic mechanisms for these processes are, however, unknown. In the present work the tunneling spin transport of a magnetic skyrmion is theoretically investigated in SP-STM. The spin-polarized charge current [2] and tunneling spin transport vector quantities, the longitudinal spin current and the spin transfer torque are calculated in high spatial resolution within a simple electron tunneling theory for the first time. Beside the vector spin transport characteristics, the connections between conventional charge current SP-STM images and the magnitudes of the spin transport quantities are analyzed.

[1] N. Romming et al., Science 341, 636 (2013).
[2] K. Palotás et al., Phys. Rev. B 96, 024410 (2017).

MA 35.3 Wed 15:30 EB 301

Quantum dynamics of skyrmions in chiral magnets — •Christina Psaroudaki — Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

We study the quantum propagation of a skyrmion in chiral magnetic insulators by generalizing the micromagnetic equations of motion to a finite temperature path integral formalism, using field theoretic tools. Promoting the center of the skyrmion to a dynamic quantity, the fluctuations around the skyrmionic configuration give rise to a time-dependent damping of the skyrmion motion. From the frequency dependence of the damping kernel, we are able to identify the skyrmion mass, thus providing a microscopic description of the kinematic properties of skyrmions. When defects are present or a magnetic trap is applied, the skyrmion mass acquires a finite value proportional to the effective spin, even at vanishingly small temperature. We demonstrate that a skyrmion in a confined geometry provided by a magnetic trap behaves as a massive particle owing to its quasi-one dimensional confinement. An additional quantum mass term is predicted, independent of the effective spin, with an explicit temperature dependence which remains finite even at zero temperature.

MA 35.4 Wed 15:45 EB 301

Optimizing the size of long-lived magnetic skyrmions — Anastasiya Varentsova[1], Stephan v. Malottki[2], Stefan Heinze[2], and •Pavel F. Bessarab[1,3] — [1]ITMO University, St. Petersburg, Russia — [2]University of Kiel, Kiel, Germany — [3]University of Iceland, Reykjavik, Iceland

Available experimental data on magnetic skyrmions in various materials demonstrate inverse correlation between the skyrmion size and skyrmion stability: small skyrmions tend to be less stable compared to large ones [1,2]. The question arises how fundamental this trend is and whether it is possible to obtain long-lived magnetic skyrmions at ambient conditions while keeping their size at the nanoscale.

Here, we demonstrate by means of transition state theory [3] and minimum energy path calculations [4] that the skyrmion lifetime at a given temperature is not a unique function of the skyrmion size and that it is possible to systematically tune material parameters so as to minimize the size of skyrmions while keeping their stability at a desired level. Based on this analysis we identify the most promising materials for the use as storage media based on magnetic skyrmions.

[1] W. Jiang *et al.*, Science **349**, 283 (2015).
[2] N. Romming *et al.*, Science **341**, 636 (2013).
[3] P.F. Bessarab *et al.*, Phys. Rev. B **85**, 184409 (2012).
[4] P.F. Bessarab *et al.*, Comput. Phys. Commun. **196**, 335 (2015).

MA 35.5 Wed 16:00 EB 301

Critical Phenomena in Confined Skyrmion Systems — •Jonathon Waters[1], Timothy Sluckin[1], Denis Kramer[1], Hans Fangohr[2], and Ondrej Hovorka[1] — [1]University of Southampton, Southampton, UK — [2]European XFEL, Germany

There have been extensive studies which establish the magnetic phases and quantify the thermal phase transition behaviour in bulk helimagnetic materials. However, many proposed device applications, which will utilise the skyrmion phase of these materials, are expected to assume operation in confined geometries and, therefore, it is critical to access the role of the confinement and finite size effects on the stability of skyrmion phases. So far, there have been few studies aimed at understanding the finite system size effects on the thermal phase transition behaviour in these systems. This presentation will discuss our recent developments of systematic analysis of these fundamental effects.

We present large-scale Monte-Carlo simulations of cubic nanoparticles, modelled by a general Heisenberg model with Dzyaloshinskii-Moriya interaction (DMI), and establish phase diagrams for different combinations of exchange and DMI strengths. We apply several different annealing protocols when generating the phase diagram in order to establish the role of metastability and hysteresis in the phase behaviour of these systems. Finally we discuss the results of a finite system size scaling analysis and establish the dependence of critical phase transition temperature on the particle size.

MA 35.6 Wed 16:15 EB 301

Magnetic skyrmion dynamics in thin cylindrical nanodots — •Konstantin Guslienko[1,2] and Zukhra Gareeva[3] — [1]Depto. Física de Materiales, Universidad del País Vasco, UPV/EHU, 20018 San Sebastián, Spain — [2]IKERBASQUE, the Basque Foundation for Science, 48013 Bilbao, Spain — [3]Institute of Molecule and Crystal Physics, Russian Academy of Sciences, 450075 Ufa, Russia

Magnetic skyrmions, robust particle-like nanosize objects, attracted considerable attention due to promising applications in spintronics and information technologies. Being a kind of magnetic topological solitons in 2D spin systems, skyrmions exhibit a wide variety of unusual properties related to their topology. In this talk we focus on the low and high frequency dynamics of magnetic skyrmions in the systems of restricted geometry: isolated cylindrical nanodots. We consider Bloch- and Neel skyrmions as the ground magnetic state of thin circular nanodots stabilized due to an interplay of the isotropic and Dzyaloshinskii-Moriya exchange interactions, perpendicular magnetic anisotropy and magnetostatic interaction. We calculate spectrum of spin excitations over the skyrmion background and classify the eigenmodes according to their spatial symmetry. We show that only one gyrotropic mode (rotation of the skyrmion center position with the frequency about of 1 GHz) exists for the skyrmion of definite polarity and the other low frequency modes that are observed in the skyrmion excitation spectra correspond to spin waves. We found an asymmetry between azimuthal spin waves propagating in the clockwise and counter-clockwise directions that is closely related to the skyrmion topology.

MA 35.7 Wed 16:30 EB 301

Internal structure and stability of skyrmions in ferromagnet/heavy-metal multilayers — •Ksenia Chichay[1], Joseph Barker[2], and Oleg Tretiakov[2,3] — [1]Center for Functionalized Magnetic Materials (FunMagMa), Immanuel Kant Baltic

Federal University, Kaliningrad, Russia — [2]Institute for Materials Research, Tohoku University, Sendai, Japan — [3]School of Natural Sciences, Far Eastern Federal University, Vladivostok, Russia

Magnetic Skyrmions are one of the fascinating and promising objects because of their small size and stability to perturbations such as electric currents and magnetic fields. The major mechanism to stabilize small skyrmions in ferromagnet/heavy-metal bilayers is the presence of Dzyaloshinskii-Moriya interaction (DMI).

In this work we investigate the stability and internal structure of an isolated skyrmion in bilayer (ferromagnet/heavy metal) and trilayer (heavy metal 1/ferromagnet/heavy metal 2) nanodisks. We study the static properties of the skyrmions and obtain the phase diagrams of the skyrmion existence depending on the thickness of the ferromagnetic layer and the DMI strength. We demonstrate the importance of fully taking into account the dipolar interaction even for a few atomic layers thin nanodisk and that together with DMI it has the stabilizing effect and defines the Skyrmion configuration. For the trilayer structures with two heavy-metal interfaces, we show that the type and configuration of the skyrmion can be controlled by the thickness of ferromagnet. Furthermore, the interplay of two interfacial DMIs can lead to the formation of magnetic structures with higher winding number.

MA 35.8 Wed 16:45 EB 301

Skyrmion dynamics under the influence of defects from DFT to ASD — •Jonathan Chico, Imara Lima Fernandes, Stefan Blügel, and Samir Lounis — Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich & JARA, D-52425 Jülich, Germany

Any potential skyrmionic application must be able to handle the impact of defects on the movement of skyrmions. Until now, most approaches focussed on large skyrmions and thus phenomenological schemes in the micromagnetic regime. In this work we discuss the technologically much more promising small skyrmions.

Using a combination of first-principles calculations and atomistic spin dynamics, the motion of small skyrmions in Pd/Fe/Ir(111) with $3d$ and $4d$ atomic defects is studied. In general, two types of defects are found, attractive and repulsive [1]. It can be observed that depending on the chemical nature of the defect the current threshold needed to overcome the energy barriers, resulting from the impurities, varies. The obtained dynamical behaviour is richer than what is expected from the Thiele equation. The complexity of the different motion regimes are revealed and compared with what is known for larger skyrmions. The present study also shines light on how one can engineer defects-based pathways for controlled skyrmion motion.

[1] I. L. Fernandes *et al.* submitted (2017).

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MA 35.9 Wed 17:00 EB 301

First-principles study of skyrmion formation at $3d/4d$ transition-metal interfaces — •Soumyajyoti Haldar[1], Stephan von Malottki[1], Pavel F. Bessarab[2], and Stefan Heinze[1] — [1]Institute of Theoretical Physics and Astrophysics, University of Kiel, 24098, Kiel, Germany — [2]School of Engineering and Natural Sciences, University of Iceland, 107, Reykjavik, Iceland

Typically, it is assumed that for the formation of skyrmions with a diameter of a few nanometers a $3d/5d$ transition metal (TM) interface is required due to the large spin-orbit coupling of heavy TMs which leads to large Dzyaloshinskii-Moriya interaction (DMI). Here, we use density functional theory (DFT) as implemented in the FLEUR code [1] to demonstrate that ultrasmall skyrmions can also emerge at $3d/4d$ TM interfaces. We have calculated the magnetic interactions in atomic bilayers of Pd/Fe on the Rh(111) surface – a system which is similar to Pd/Fe/Ir(111) [2, 3] since Rh and Ir are isoelectronic $4d$- and $5d$-TMs. From our DFT calculations we parametrize an atomistic spin model including exchange interactions, DMI and the magnetocrystalline anisotropy energy (MAE). We find that both DMI and MAE are reduced with respect to Pd/Fe/Ir(111) which still allows a spin spiral phase at zero magnetic field due to DMI. Using spin dynamics simulations we find that a skyrmion phase occurs for both fcc and hcp stacking of the Pd layer at small magnetic fields of ~ 1 T. Depending on the stacking the skyrmion diameters amount to 4 to 6 nm.

[1] http://www.flapw.de [2] N. Romming *et al.*, Science **341**, 6146 (2013) [3] B. Dupé *et al.*, Nature Comm. **5**, 4030 (2014).

MA 35.10 Wed 17:15 EB 301

Frustration of the Dzyaloshinskii-Moriya interaction in ultrathin Co films — •Sebastian Meyer[1], Stephan Von Malottki[1], Bertrand Dupé[2], and Stefan Heinze[1] — [1]Institute of Theoretical Physics and Astrophysics, Christian-Albrechts-Universität zu Kiel, Leibnizstrasse 15, 24098 Kiel — [2]Institute of Physics, Johannes Gutenberg Universität Mainz, Staudingerweg 7, 55128 Mainz

Non-collinear spin structures such as chiral domain walls and skyrmions are being intensively studied since they are promising for spintronic applications [1, 2]. The Dzyaloshinskii-Moriya interaction (DMI) is crucial for stabilizing these non-trivial magnetic states favoring a unique rotational sense. Here, we show frustration of the DMI in ultrathin Co films using density functional theory (DFT) as implemented in the FLEUR code [3]. We study Co monolayers and Pt/Co bilayers on the Ir(111) surface and calculate the energy dispersion of homogeneous flat spin spirals including spin-orbit coupling. Clockwise rotating spin spirals are preferred for large periods close to the ferromagnetic state while below a certain spin spiral period an anticlockwise sense is obtained. This effect arises due to competing DMI interactions with different neighbors that are of opposite sign. With our results from DFT, we parametrize an atomistic spin model and simulate domain wall properties using spin-dynamics simulations.

[1] S. S. P. Parkin *et al.*, Science **320**, 190 (2008)
[2] A. Fert *et al.*, Nature Nano. **8**, 152 (2013)
[3] www.flapw.de

MA 35.11 Wed 17:30 EB 301

Isolated skyrmions with vanishing anisotropy in Co/Ru(0001) — •Marie Böttcher[1,2], Marie Hervé[3], Jairo Sinova[1,4], Wulf Wulfhekel[3], and Bertrand Dupé[1] — [1]Johannes Gutenberg-Universität Mainz, Mainz, Germany — [2]Graduate School Materials Science in Mainz, Mainz, Germany — [3]Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany — [4]Academy of Sciences of the Czech Republic, Praha, Czech Republic

Magnetic skyrmions are localized and topologically stabilized non-collinear spin structures. They offer attractive perspectives for future spintronics applications, because they can be manipulated at lower current densities than domain walls [1]. The stabilization of skyrmions is usually attributed to a large Dzyaloshinskii-Moriya interaction (DMI). Here, we show that a strong DMI is not a necessary condition to obtain skyrmions in ultra-thin films. Co/Ru(0001) possesses a spin spiral ground state, although the DMI is weak. We attribute the stability of this spin texture to the simultaneous vanishing of anisotropy [2]. We determine the B-T phase diagram for this system using Monte Carlo simulations and show the magnetic field dependence of isolated skyrmions at magnetic fields with a ferromagnetic ground state. [1] A. Fert, *et al.* Nature Nano. **8**, 152 (2013). [2] M. Hervé *et al.* arXiv:1707.08519 (2017)

MA 35.12 Wed 17:45 EB 301

Magnetic skyrmions in curvilinear films — •Volodymyr Kravchuk[1,2], Denis Sheka[3], Attila Kakay[4], Oleksii Volkov[4], Ulrich Roessler[1], Jeroen van den Brink[1], Denys Makarov[4], and Yuri Gaididiei[2] — [1]Leibniz-Institut fuer Festkoerper- und Werkstoffforschung, D-01171 Dresden, Germany — [2]Bogolyubov Institute for Theoretical Physics of National Academy of Sciences of Ukraine, 03680 Kyiv, Ukraine — [3]Taras Shevchenko National University of Kyiv, 01601 Kyiv, Ukraine — [4]Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany

Topological magnetic solitons on curvilinear magnetic films acquire new properties if the curvature radius is comparable with the size of the soliton. Earlier we demonstrated [1] that ferromagnetic skyrmions can be stabilized due to the curvature effects only without intrinsic chiral magnetic interactions. However, the curvature induced skyrmion is an excitation of the ground state, as well as a skyrmion in a planar film. Here we show that the combined action of the curvature and the chiral interaction can make skyrmion the ground state of the system [2]. Moreover, ferromagnetic skyrmion pinned on a curvilinear defect demonstrates a discrete set of equilibrium states. Transitions between different states can be controlled by external magnetic field. Thus, the periodically arranged curvilinear defects can result in a reconfigurable skyrmion lattice. This opens new perspectives on processing and storing of the information.

[1] V. Kravchuk et al., BRB 94, 144402 (2016). [2] V. Kravchuk et al., arXiv 1706.05653 (2017).

MA 35.13 Wed 18:00 EB 301

Skyrmion-Lattice Collapse and Defect-Induced Melting in Chiral Magnetic Films — •Leonardo Pierobon[1], Christoforos Moutafis[2], Michalis Charilaou[1], and Jörg Löffler[1] — [1]Laboratory of Metal Physics and Technology, Department of Materials, ETH Zurich, Switzerland — [2]School of Computer Science, University of Manchester, Manchester, UK

Complex spin textures arise in nanostructured magnets due to competing interactions, primarily the Heisenberg exchange and the Dzyaloshinskii-Moriya interaction (DMI), which promote spin collinearity and canting, respectively. Upon rotational-symmetry breaking, particle-like objects with non-trivial spin configurations, i.e., skyrmions, can be created. The winding of skyrmions bestows a topological protection on the system, and the transition to the topologically trivial ferromagnetic state requires a phase transition. Here, we systematically compare isotropic and anisotropic DMI systems by means of high-resolution numerical simulations. We show that in perfect systems skyrmion lattices can be inverted in a field-induced first-order phase transition, whereas the existence of even a single defect replaces the inversion with a second-order phase transition following a defect-induced lattice melting process. This radical qualitative change signifies the importance of employing such an analysis for all realistic systems in order to correctly interpret experimental data. Our results shed light on fundamental processes behind magnetic phase transitions, and pave the way for their experimental realization in technologically relevant multilayer materials.

MA 35.14 Wed 18:15 EB 301

Reservoir Computing with Random Skyrmion Fabrics — •Daniele Pinna[1], George Bourianoff[2], and Karin Everschor-Sitte[1] — [1]Institute of Physics, Johannes Gutenberg University Mainz, Mainz, Germany — [2]Intel Labs, Intel Corp, Austin, TX

Thanks to their many nanoscale properties, skyrmions are promising in applications ranging from non-volatile memory[1] and spintronic logic devices[2], to enabling the implementation of unconventional computational standards[3, 4]. In this talk we will discuss how a random skyrmion "fabric" composed of skyrmion clusters embedded in a magnetic substrate can be effectively employed to implement a functional reservoir computer. This is achieved by leveraging the nonlinear resistive response of the individual skyrmions arising from their current dependent AMR[5]. Complex time-varying current signals injected via contacts into the magnetic substrate are shown to be modulated nonlinearly by the fabric's AMR due to the current distribution following paths of least resistance as it traverses the geometry. By tracking resistances across multiple input and output contacts, we show how the instantaneous current distribution, reminiscent of Atomic Switch Networks, effectively carries temporally correlated information about the injected signal. This in turn allows us to numerically demonstrate simple pattern recognition.

[1] A. Fert, et al., Nature Nanotech. 8, 152-156 (2013). [2] X. Zhang, et al., Sci. Rep. 5, 9400 (2015). [3] D. Pinna, et al., arXiv:1701.07750 (2017). [4] G. Bourianoff, et al., arXiv:1709.08911 (2017). [5] D. Prychynenko, et al., arXiv:1702.04298 (2017).