Skyrmions in Magnetic Materials

British-German WE-Heraeus-Seminar

1 – 5 December 2019
Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Subject to alterations!

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de.

Scope of the British-German WE-Heraeus-Seminar:

In condensed matter physics and particle physics analogies exist between large scale effects of local quantum degrees of freedom. In recent years the topological character of complex field configurations in magnetic materials has received great interest, namely properties that remain unchanged under elastic deformations. Alluding to interdisciplinary similarities in nuclear physics, soft matter and quantum Hall systems, so-called skyrmions, vortices and monopoles in chiral or frustrated magnets are being studied intensely.

The topological aspects of magnetic order are not only appealing from an esthetical and conceptual point of view, but offer strikingly simple explanations in terms of an emergent electrodynamics of materials properties that may seem surprising and intractable at first sight. In particular, the unusual properties of skyrmions in chiral magnets and related spin textures promise major progress in spintronics applications.

The scope of this first „British-German Wilhelm and Else Heraeus Seminar" will be to summarize and discuss the state of the art on skyrmions in magnetic materials, connecting this field also in an interdisciplinary spirit with nuclear physics, soft matter and quantum Hall systems.

Scientific Organizers:

Prof. Dr. Peter Hatton	Durham University, UK Physics Department E-mail p.d.hatton@durham.ac.uk
Prof. Dr. Christian Pfleiderer	Technical University Munich, Germany Physics Department E-mail Christian.Pfleiderer@frm2.tum.de

Administrative Organization:

Dr. Stefan Jorda
Jutta Lang

Wilhelm und Else Heraeus-Stiftung
Postfach 15 53
63405 Hanau, Germany

Phone	+49 (0) 6181 92325-0
Fax	+49 (0) 6181 92325-15
E-mail	lang@we-heraeus-stiftung.de
Internet	www.we-heraeus-stiftung.de

Venue:

Physikzentrum
Hauptstrasse 5
53604 Bad Honnef, Germany

Conference Phone +49 (0) 2224 9010-120

Phone	+49 (0) 2224 9010-113 or -114 or -117
Fax	+49 (0) 2224 9010-130
E-mail	gomer@pbh.de
Internet	www.pbh.de

Taxi Phone +49 (0) 2224 2222

Registration:

Jutta Lang (WE-Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (14:00 h – 20:00 h) and
Monday morning

Door Code:

(Key symbol button) 2 1 1 2 #
For entering the Physikzentrum
during the whole seminar

Program

Program

Sunday, 1 December 2019

14:00 – 20:00	Registration	
15:00 – 16:00	*Informal reception (coffee and cake)*	
16:00 - 16:10	Scientific organizers	**Opening and welcome**

Tutorials

16:10 – 17:10	Markus Garst	**Topological magnetism with a twist**
17:10 – 18:10	Christopher Marrows	**Skyrmions in chiral magnetic multilayers**
from 18:30	*BUFFET SUPPER / Informal get together*	

Monday, 2 December 2019

08:00	*BREAKFAST*	

Structures

09:00 – 09:40	Istvan Kézsmárki	**Effect of geometrical confinement on Néel-type magnetic modulations**
09:40 – 10:00	Thomas Hicken	**Muon-spin relaxation measurements on the substituted Néel-skyrmion system $GaV_4S_{8-y}Se_y$**
10:00 – 10:20	Rana Saha	**Magnetic anti-skyrmions in tetragonal inverse Heuslers**
10:20 – 10:40	Aisha Aqeel	**New skyrmion resonance modes in a chiral magnetic insulator**
10:40 – 11:10	*COFFEE BREAK*	

Program

Monday, 2 December 2019

Theory

11:10 – 11:50	Yuriy Mokrousov	**Skyrmions, quantum Hall effect, and non-commutative geometry**
11:50 – 12:30	Hans Fangohr	**Towards reproducible micromagnetics with Ubermag**
12:30	**Conference photo** (in the foyer of the lecture hall)	
12:40	*LUNCH*	

Thin films & surfaces

14:00 – 14:40	Kirsten von Bergmann	**Nanometer-scale magnetic skyrmions studied with STM**
14:40 – 15:00	Lena Wysocki	**Tailoring anomalous Hall resistivity by interfacial modifications in asymmetric $SrRuO_3$ - based heterostructures**
15:00 – 15:40	Katharina Zeissler	**Nucleation, motion and detection of skyrmions**
15:40 – 16:00	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 18:30	**Poster session**	
19:30	*DINNER*	

Program

Tuesday, 3 December 2019

08:00	*BREAKFAST*	
Spin excitations		
09:00 – 09:40	Shinichiro Seki	**Coherent signal transfer along skyrmion strings**
09:40 – 10:00	Rolf Versteeg	**Coupled dynamics of long-range and cluster-internal spin order in the cluster Mott insulator Cu_2OSeO_3**
10:00 – 10:20	Nikolai Kiselev	**Static and dynamic properties of heavy skyrmions**
10:20 – 10:40	Dongwook Go	**Current-induced orbital angular momentum and orbital torque for spin-orbitronics**
10:40 – 11:10	*COFFEE BREAK*	
Applications & devices		
11:10 – 11:50	Rolf Allenspach	**Chiral effects in nanomagnetic devices**
11:50 – 12:30	Karin Everschor-Sitte	**Skyrmions for unconventional computing**
12:30	*LUNCH*	
Other systems		
14:00 – 14:40	Benoit Douçot	**Skyrmion crystals in quantum Hall ferromagnets**
14:40 – 15:20	Ivan Smalyukh	**Three-dimensional crystals of topological knot solitons**
15:20 – 15:40	Filipp Rybakov	**Hopfions and skyrmions in magnets with competing interactions**
15:40 – 16:00	Charles Kind	**Existence and stability of skyrmion bags in thin magnetic films**
16:00 – 16:30	*COFFEE BREAK*	

Program

Tuesday, 3 December 2019

Nucleation & stability

16:30 – 17:10	Murray Wilson	**Measuring the formation energy barrier of skyrmions in zinc substituted Cu_2OSeO_3**
17:10 – 17:30	Valery Uzdin	**Stability and lifetimes of skyrmions at different spatial scales**
17:30 – 17:50	Denis Mettus	**Nucleation mechanism of the low-temperature skyrmion state in Cu_2OSeO_3**
17:50 – 18:10	Gerald Malsch	**Measurement of the low-temperature skyrmion phase in Cu_2OSeO_3 by Magnetic-Force-Microscopy**
18:30	*DINNER*	

Wednesday, 4 December 2019

08:00	*BREAKFAST*	

Emergent electodynamics & stability

09:00 – 09:40	Thorsten Hesjedal	**X-ray studies of ordered Skyrmions - Microscopic properties, 3D structure & dynamics**
09:40 – 10:00	Olena Gomonay	**Antiferromagnetic textures: Eigen modes and spin current induced dynamics**
10:00 – 10:40	Alfonso Chacon Roldan	**Relaxation of non-equilibrium skyrmions in $Fe_{0.5}Co_{0.5}Si$**
10:40 – 11:10	*COFFEE BREAK*	

Nuclear & particle physics

11:10 – 11:50	Nicholas Manton	**Skyrme's original skyrmions**
11:50 – 12:30	Ian Aitchison	**Tony Skyrme and the origins of skyrmions**
12:30	*LUNCH*	
from 13:30	Excursion (total footpath approx. 3 km) Guided tour through the "Bundeskanzler-Adenauer-Haus" in Rhöndorf (district of Bad Honnef) Wine tasting and *HERAEUS DINNER* at the winery "Broel" in Rhöndorf	

Program

Thursday, 5 December 2019

08:00	*BREAKFAST*	

Imaging

09:00 – 09:20	James Loudon	**Quantitative transmission electron microscopy of skyrmions**
09:20 – 09:40	Andras Kovács	**Quantitative magnetic field characterisation of Bloch and Néel type skyrmions using off-axis electron holography**
09:40 – 10:00	Gerrit van der Laan	**Surface versus bulk characterization of 3D skyrmion lattices in chiral magnets**
10:00 – 10:20	Max Birch	**Real-space imaging of confined magnetic skyrmion tubes**
10:20 – 10:40	Joachim Graefe	**Visualizing nanoscale spin waves using MAXYMUS**
10:40 – 11:10	*COFFEE BREAK*	

Manipulation

11:10 – 11:30	Jacob Gayles	**Distinct topological magnetic textures in Antiskyrmion hosting Heusler compounds Mn_xYZ with different Berry curvature responses**
11:30 – 11:50	Marijan Beg	**Field manipulation of Bloch points in helimagnetic nanostructures**
11:50 –12:10	Sebastian Schneider	**Towards the 3D quantification of skyrmions in thin helimagnets**
12:10 – 12:30	Scientific organizers	**Poster awards and closing remarks**
12:30	*LUNCH*	

End of the seminar *and FAREWELL COFFEE /* ***Departure***

Please note that there will be ***no*** *dinner at the Physikzentrum on Thursday evening for participants leaving the next morning.*

Posters

Posters

1.	Christopher Barker	**Skyrmions in a synthetic antiferromagnet**
2.	Andreas Bauer	**Complex magnetic textures in the non-centrosymmetric antiferromagnet $EuPtSi_3$**
3.	Venkata Krishna Bharadwaj	**Stability and dynamics of in-plane skyrmions**
4.	Carolina Burger	**Stability of the skyrmion lattice in $Fe_{1-x}Co_xSi$**
5.	Runze Chen	**A realistic skyrmionic synapse for deep spiking neural networks**
6.	Samme Manuel Dahir	**Interaction of skyrmions and pearl vortices in superconductor-chiral ferromagnet heterostructures**
7.	Malcolm Dearg	**Magnetic and structural properties of cobalt-zinc alloy thin films**
8.	Sebastián Díaz	**Skyrmion crystals as topological magnonics platforms**
9.	Sven Esser	**Interface-driven skyrmions in $SrRuO_3$ based heterostructures**
10.	Kathinka Gerlinger	**Optical skyrmion nucleation in co-based multilayers**
11.	Kelsea Gill	**Melting of two-dimensional magnetic skyrmion lattices**
12.	Moritz Alexander Goerzen	**Atomistic simulation of electric field assisted writing and deleting of magnetic skyrmions**
13.	Amelia Hall	**Intercalated transition metal dichalcogenides: Chiral soliton lattice**
14.	Zachary Hawkhead	**First-principles calculations of noncollinear magnetic structures in density functional theory**
15.	Michelle Hollricher	**Measurement of magneto-crystalline anisotropies in MnSi by means of torque magnetometry**

Posters

16.	Sam Holt	**Lorentz TEM simulations of magnetic structures**
17.	Alexandra Huxtable	**XMCD-STXM magnetic imaging of skyrmions with in-situ Hall transport measurements in Pt/Co/Ir multilayer Hall discs**
18.	Dmytro Ivaneiko	**Magnetic domain formation and its relation to the magneto-transport properties of ultra-thin $SrRuO_3$ epitaxial layers**
19.	Lisa-Marie Kern	**Spatial control of magnetic skyrmions in multilayers by ion irradiation**
20.	Ross Knapman	**Production of magnetic textures in different dimensions**
21.	Vladyslav Kuchkin	**Turning chiral skyrmion inside out**
22.	Vivek Kumar	**Topological Hall effect in the antiskyrmion hosting Heusler system Mn-Pt-Sn**
23.	Yu Li	**Tuneable Bloch-point dynamics during switching of skyrmions and antiskyrmions in chiral magnets**
24.	Sergiy Mankovskyy	**Extension of the Heisenberg model due to multispin interactions: First principle calculations and impact on the magnetic structure**
25.	Benjamin McKeever	**Characterizing breathing dynamics of magnetic skyrmions and antiskyrmions within the Hamiltonian formalism**
26.	Samuel Moody	**Origin of skyrmion lattice phase splitting in Zn-substituted Cu_2OSeO_3**
27.	Vanessa Nehruji	**Monte Carlo studies of metastable skyrmion lifetimes**
28.	Souvik Paul	**First-principles based study of skyrmions in Fe/Rh bilayers on Re(0001)**

29.	Markus Preißinger	**Topologically non-trivial magnetic and polar patterns in lacunar spinels**
30.	Baha Sakar	**Quantitative magnetic force microscopy of skyrmions in Co/Ru/Pt multilayers**
31.	Kartik Samanta	**Magnetic structure and Hall-effect study of $SrRuO_3$(SRO) films on $SrTiO_3$(STO) (001): Search for interface stabilized skyrmions in oxide structure**
32.	Wolfgang Simeth	**Antiferromagnetic superstructures with nontrivial topology in the rare-earth intermetallic HoCu**
33.	Ales Štefančič	**Establishing magneto-structural relationships in the search for skyrmion hosts within the $GaV_4S_{8-y}Se_y$ family of materials**
34.	Luke Turnbull	**Resonant soft x-ray imaging of topological spin textures in MnNiGa lamellae**
35.	Praveen Vir	**Large topological Hall effect in antiskyrmion hosting compound $Mn_{1.4}PtSn$**
36.	Edward Walton	**Smooth monopoles and skyrmion destruction**
37.	Lin Yang	**Anomalous Hall effect and magneto-optical Kerr effect of $SrRuO_3$ based epitaxial multilayers**
38.	Fengshan Zheng	**Experimental measurement of 3D magnetic spin texture of a target skyrmion**

Abstracts of Lectures

Sunday, 1 December 2019

(in chronological order)

Topological magnetism with a twist

M. Garst

Institut für Theoretische Festkörperphysik, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

Magnetic skyrmions are topological textures of the magnetization that arise in particular in the presence of a Dzyaloshinskii-Moriya interaction. The latter favours a twist of the magnetization vector that stabilizes localized skyrmion configurations. The non-trivial topology has various direct consequences for physical observables that we review in this talk. The topological density of the magnetic textures naturally arises in the description of the magnetization dynamics. As a consequence, the effective equation of motion of a skyrmion is qualitatively influenced by its non-trivial topology, which results in a skyrmion Hall effect when skyrmions are driven by spin currents. When electrons adiabatically traverse a skyrmion texture they adjust their magnetic moments to the local equilibrium magnetization. This results in a geometric constraint that leads to an emergent electrodynamics. Each skyrmion thus acts as a single flux of orbital magnetic field that gives rise to an emergent Lorentz force and a topological Hall effect. When skyrmions are moving, the electrons experience by Faraday's law an additional emergent electric field leading to a skyrmion-flow Hall effect. A similar emergent electrodynamics also arises for the spin waves, i.e., the small amplitude excitations scattering off skyrmions. In the presence of a skyrmion lattice, the spin waves experience a finite emergent magnetic field on average so that the spin waves form Landau levels giving rise to a topologically non-trivial magnon band structure.

Skyrmions in chiral magnetic multilayers

K. Zeissler[1], S. Finizio[2], K. Shahbazi[1], J. R. Massey[1], F. Al Ma'mari[1], A. J. Huxtable[1], D. Bracher[2], A. Kleibert[2], S. Wintz[1,3], S. Mayr[1,4], T. Weßels[5], A. Sadovnikov[6], M. Rosamond[7], E. H. Linfield[7], T. A. Moore[1], J. Raabe[2], G. Burnell[1], and C. H. Marrows[1]

[1]School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, United Kingdom
[2]Swiss Light Source, Paul Scherrer Institute, 5232 Villigen, Switzerland
[3]Institute of Ion Beam Physics and Materials Research, Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany
[4]Department of Materials, Laboratory for Mesoscopic Systems, ETH Zürich, 8093 Zürich, Switzerland
[5]Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons and Peter Grünberg Institute, Forschungszentrum Jülich, 52425 Jülich, Germany
[6]Laboratory "Metamaterials", Saratov State University, Saratov, 410012, Russia
[7]School of Electronic and Electrical Engineering, University of Leeds, Leeds LS2 9JT, United Kingdom

Magnetic skyrmions are topologically-nontrivial spin textures with particle-like properties [1]. Their size, topological stability, and mobility suggest their use in future generations of spintronic devices, the prototype of which is the skyrmion racetrack [2]. To realise a racetrack requires three basic operations: the nucleation (writing), propagation (manipulation), and detection (reading) of a skyrmion, all by electrical means. Here we show that all three are experimental feasible at room temperature in Pt/Co/Ir or Pt/CoB/Ir multilayers in which the different heavy metals above and below the magnetic layer break inversion symmetry and induce chirality by means of the Dzyaloshinskii-Moriya interaction, defining the structure of Néel skyrmion spin textures [3]. We show deterministic nucleation on nanosecond timescales using an electrical point contact on top of the multilayer [4], current-driven propagation along a wire in which they are channelled by defects in the multilayer [5], and detection by means of the Hall effect that reveals an unexpectedly large contribution to the Hall signal that correlates with the topological winding number [5]. Emphasis will be given to the experimental techniques that were used to obtain these results.

References

[1] N. Nagaosa & Y. Tokura, Nat. Nanotech. **8**, 899 (2013).
[2] A. Fert et al., Nature Nanotech. **8**, 152 (2013).
[3] K. Zeissler et al., Sci. Rep. **7**, 15125 (2017).
[4] S. Finizio et al., Nano Lett. **19**, 7246 (2019).
[5] K. Zeissler et al., arXiv:1908.04239.
[6] K. Zeissler et al., Nature Nanotech. **13**, 1161 (2018).

Abstracts of Lectures

Monday, 2 December 2019

(in chronological order)

Effect of Geometrical Confinement on Néel-type Magnetic Modulations

I. Kézsmárki

Center for Electronic Correlations and Magnetism, University of Augsburg, Augsburg, Germany

Néel-type skyrmions [1] and antiskyrmions [2], recently realized in axially symmetric magnets, are substantially different from Bloch-type skyrmions, widely explored in chiral cubic magnets, in terms of their internal magnetic structure, their stability range as well as their response to external stimuli. More specifically, the axial symmetry of the host gives rise to an extended stability range by restricting the wave vectors of magnetic modulations to the plane normal to the high-symmetry axis. Since such skyrmions and antiskyrmions do not co-align with external magnetic fields, instead their orientation keeps confined to the high-symmetry axis of the host, they become asymmetric in oblique magnetic fields [3, 4]. This distortion gives rise to an additional degree of freedom, which affects their dynamics. Moreover, it can result in either an attractive or a repulsive skyrmion-skyrmion interaction, depending on the relative orientation of the pair. Corresponding experimental results on various compounds in the lacunar spinel family, hosting a cycloidal spin state in zero field and a Néel-type skyrmion lattice state in moderate fields, will be reviewed together with the magnetoelectric nature of this new skyrmion prototype [1, 2, 5, 6] as well as their collective excitations [7,8,9].

After discussing the generic features of Néel-type skyrmions in unconstrained geometries, we are also going to discuss novel magnetic states emerging from strong geometrical confinement, which is realized in the lacunar spinel host naturally, via mesoscale polar domains.

References

[1] I. Kezsmarki et al., Nat. Mater. **14**, 1116 (2015).
[2] A. K. Nayak et al., Nature **548**, 561 (2017).
[3] A. O. Leonov and I. Kezsmarki, Phys. Rev. B **96**, 014423 (2017).
[4] A. O. Leonov and I. Kezsmarki, Phys. Rev. B **96**, 214413 (2017).
[5] E. Ruff et al., Sci. Adv. **1**, e1500916 (2015).
[6] S. Bordacs et al., Sci. Rep. **7**, 7584 (2017).
[7] D. Ehlers et al., Phys. Rev. B **94**, 014406 (2016).
[8] P. Padmanabhan et al., Phys. Rev. Lett. **122**, 107203 (2019).
[9] Y. Okamura et al., Phys. Re. Lett. **122**, 057202 (2019).

Muon-spin relaxation measurements on the substituted Néel-skyrmion system $GaV_4S_{8-y}Se_y$

T. J. Hicken[1], M. N. Wilson[1], M. Gomilsek[2], B. M. Huddart[1], S. J. R. Holt[3], A. Štefančič[3], G. Balakrishnan[3] and T. Lancaster[1]

[1] *Centre for Materials Physics, Durham University, Durham, UK*
[2] *Solid State Physics Department, Jožef Stefan Institute, Ljubljana, Slovenia*
[3] *Department of Physics, University of Warwick, Coventry, UK*

GaV_4S_8 and GaV_4Se_8 are two of only a small number of systems known to host Néel-type skyrmions in the bulk. Before these systems can be used in applications it is important to obtain their crystal and magnetic properties. One way of tuning such properties is through controlled chemical substitution, and here we report muon-spin relaxation measurements on $GaV_4S_{8-y}Se_y$ with $y = 0$, 0.1, 0.2, 7.9 and 8.

Our previous studies of $GaV_4S_{8-y}Se_y$ with $y = 0$, 4 and 8 [1] identified a signature of the skyrmion lattice in both transverse-field and longitudinal-field experimental geometries, allowing us to conclude that the skyrmion phase is confined to a smaller region of the phase diagram in polycrystalline GaV_4Se_8 than previously reported. We also showed glass-like magnetic behavior in the $y = 2$ and 4 cases, where the skyrmion lattice is not stablised.

Our most recent measurements show that the skyrmion lattice persists in samples with low-levels of chemical substitution, despite increased magnetic disorder. In these materials we have observed intriguing dynamic effects at low temperatures, and we discuss the possible origin of these in terms of the magnetic fluctuation spectra in the presence of disorder.

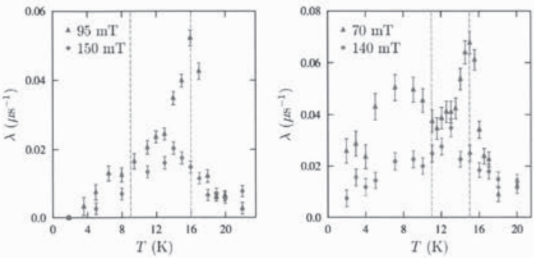

Figure 1: Muon-spin polarisation relaxation rate obtained from longitudinal field muon-spin relaxation measurements. Left: GaV_4Se_8. Right: $GaV_4S_{0.1}Se_{7.9}$. Dashed lines indicate the location of the skyrmion lattice at the lower-field (blue) points.

References

[1] K. J. Franke, B. M. Huddart, T. J. Hicken, *et al.*, Phys. Rev. B **98**, 054428 (2018)

Magnetic anti-skyrmions in tetragonal inverse Heuslers

Rana Saha[1], Tianping Ma[1], Abhay Srivastava[1], Ankit Sharma[1], Jagannath Jena[1], Vivek Kumar[2], Praveen Vir[2], Claudia Felser[2] and Stuart Parkin[1]

[1]Max Planck Institute of Microstructure Physics, Halle (Saale), Germany
[2]Max Planck Institute for Chemical Physics of Solids, Dresden, Germany

One of the major topics in spintronics today is the study of chiral non-collinear spin textures of various topologies. Recently, a novel chiral spin texture, magnetic anti-skyrmion [1-2] that has distinct topological features from that of Bloch and Néel skyrmions, was discovered in tetragonal inverse Heusler, $Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$ [3]. Anti-skyrmions have boundaries (the in-plane magnetization region between magnetization pointing up and pointing down) that have a complex structure consisting of successive left hand Bloch, left hand Néel, right hand Bloch, and right hand Néel wall segments. This complex structure is a result of an anisotropic Dzyaloshinskii-Moriya exchange interaction that is set by the symmetry of the underlying lattice. Interestingly, magnetic anti-skyrmions are stable over a wide range of temperature, magnetic field and thickness of the lamella in which they are formed [4]. In this presentation, I will discuss our recent in-situ Lorentz and magnetic force microscopic studies of nucleation, stabilization and size manipulation of anti-skyrmions in tetragonal inverse Heuslers.

References

[1] A. Bogdanov, et al. Phys. Rev. B 66, 214410 (2002)
[2] N. Nagaosa, et al. Nat. Nanotechnol. 8, 899 (2013).
[3] A. Nayak, et al. Nature 548, 561 (2017)
[4] R. Saha, et al. Nat. Commun. (Accepted, in press)

New skyrmion resonance modes in a chiral magnetic insulator

A. Aqeel[1], J. Sahliger[1], T. Taniguchi[1], D.Mettus[1], A. Bauer[1], M. Garst[2], C. Pfleiderer[1], C.H. Back[1]

[1]*Department of Physics, Technical University of Munich, Garching, Germany*

[2]*Institute for Theoretical Solid State Physics, Karlsruhe Institute of Technology, Karlsruhe, Germany*

Email: aisha.aqeel@tum.de

Recently, a new independent low-temperature skyrmion (LTS) phase has been discovered [1] in addition to the previously observed high temperature skyrmion pocket [2] in a chiral magnetic insulator Cu_2OSeO_3. Unlike high temperature skyrmion pocket, the LTS phase has a different stabilization mechanism favored by the cubic anisotropy contribution [1,3]. The key question here is how a different stabilization mechanism would influence the magnetization dynamic and modify the magnetic resonant response of skyrmions. Using a spin-wave spectroscopy technique, we systematically track the magnetic resonance response in different magnetic phases of Cu_2OSeO_3, focusing on the LTS phase at 5K. We identify distinct resonances associated with the newly discovered tilted conical and LTS phases of Cu_2OSeO_3. We observed a strong dependence of these modes on static magnetic field history. We identified an increase in the weights of skyrmion resonance modes by cycling magnetic field within this phase. The magnetic phase boundaries and effect of field cycling on the population of different phases agrees well with our magnetometery measurements. To understand the observed resonance spectra, we used a phenomenological model based on previous work [4] with an addition consideration of different cubic anisotropy contributions. Our theoretical model confirms that the cubic anisotropy contribution is the key ingredient for the observed resonance spectra. We believe that these results will be instrumental for existing possibilities for future skyrmion based microwave devices.

References

[1] A. Chacon, *et al.*, Nature Physics **14**, pages936–941 (2018),
[2] S. Seki, *et al.*, Science **336**, 198 (2012).
[3] M. Halder, *et al.*, Phys. Rev. B **98**, 144429 (2018).
[4] T. Schwarze, Nature Materials **14**, 478 EP (2015).

Skyrmions, Quantum Hall Effect, and Non-Commutative Geometry

Y. Mokrousov[1,2]

[1]Peter Grünberg Institut, Forschungszentrum Jülich, Germany
[2] Institute of Physics, University of Mainz, Mainz, Germany

Magnetic skyrmions are fascinating particle-like objects, whose key properties are governed by their non-trivial real-space topology. Microscopically, this topology manifests in the presence of the so-called emergent gauge field, which directly couples to electronic degrees of freedom thus giving rise to such fundamental effects as for example the topological Hall effect. In strongly spin-orbit coupled systems our perception of skyrmions as gauge-field generating particles has to be conceptually altered, however, and we show that this can be naturally done by referring to the paradigm of non-commutative geometry [1]. We show that in terms of this powerful language, also utilized in the realm of quantum Hall effect, nuclear physics and string theory, skyrmions re-emerge as entangled objects living in a complex non-commutative phase space. Inspired by our previous work on mixed Berry phases [2] and orbital magnetism of spin textures [3], we will demonstrate the emergence of a Hall effect in chiral magnetic textures which is neither proportional to the net magnetization nor to the topological emergent magnetic field. We show that this "chiral" Hall effect receives a natural interpretation in the language of non-commutative geometry, thus conceptually relating magnetic skyrmions to quantum Hall systems [4]. Moreover, we argue that the chiral Hall effect could provide a distinct magnetotransport signature of non-commutative geometry of complex spin textures which is distinctly different from that driven by the topological Hall effect. This talk was prepared together with Fabian Lux. We are grateful to Frank Freimuth and Stefan Blügel for numerous discussions on the subject. We acknowledge funding by the Deutsche Forschungsgemeinschaft (DFG) through Priority Programme SPP 2137.

References

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[2] F. Freimuth, R. Bamler, Y. Mokrousov and A. Rosch, Phys. Rev. B **88**, 214409 (2013)
[3] F. Lux, F. Freimuth, S. Blügel, and Y. Mokrousov, Comm. Phys. **1**, 60 (2018)
[4] J. Bellissard, A. van Elts, H. Schulz-Baldes, J. Math. Phys. **35**, 5373 (1994)

Towards reproducible micromagnetics with Ubermag

Hans Fangohr[1, 2] **and Marijan Beg**[1, 2]

[1] *European X-ray Free Electron Laser GmbH, Schenefeld, Germany*
[2] *University of Southampton, Southampton, United Kingdom*
E-mail: hans.fangohr@xfel.eu

In this work we discuss scientific reproducibility in this era of increasing use of data and computational science in research, and introduce Ubermag as – amongst other things – a step towards better reproducibility in computational magnetics.

Ubermag [1] is a software that allows to describe micromagnetic problems concisely in the Python programming language [2]. Ubermag can numerically solve the problem by translating the micromagnetic problem description so that it can be carried out by micromagnetic simulation package, such as OOMMF and Mumax3. Computed results are made available in the Python environment for further analysis.

The advantages of such a Python interface to micromagnetic calculations include: (i) scientists can carry out systematic parameter space exploration automatically using for-loops or algorithmic parameter optimisation, (ii) one can use existing data science libraries such as numpy, scipy, matplotlib, pandas, and scikit-learn for further analysis of the simulation results, (iii) the Python script to drive the simulation and analysis fully and reproducibly describes the procedure, (iv) one can carry out the same simulation with OOMMF or Mumax3 by just changing one line of code.

The Ubermag libraries are written so that they can be embedded in the Jupyter notebook: a complete computational study including simulation, results and annotation is thus possible within a single (Jupyter notebook) document, and the calculation can be carried out on a remote (cloud, university or facility provided) computational resource.

We discuss limitations and potential of Ubermag for research and reproducible micromagnetics, and briefly explore wider research and publication policy context.

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Nanometer-scale magnetic Skyrmions studied with STM

K. von Bergmann

Department of Physics, University of Hamburg, Germany

Magnetic skyrmions are topologically distinct particle-like knots in the magnetization. They are envisioned as the basis for future spintronic devices and can be stabilized by a favorable interplay of magnetic exchange, Dzyaloshinskii-Moriya interaction (DMI), and anisotropy. Skyrmions can become lowest energy states in applied magnetic fields but are only metastable configurations in zero magnetic field.

The Fe/Ir(111) interface is known to exhibit strong DMI [1] and serves as an ideal basis to build up materials that host single skyrmions on the nanometer length scale, which can be induced by external magnetic fields in these systems [2-4]. Such small magnetic objects can be imaged, characterized and manipulated using (spin-resolved) scanning tunneling microscopy (STM) [5], see Figure. In a Rh/Co atomic bilayer on Ir(111) we observe small circular magnetic objects in the virgin state [6]. They coexist in both oppositely magnetized ferromagnetic domains and resemble zero-field magnetic skyrmions with up- or downpointing core. Ab-inito calculations in combination with spin dynamics simulations shed light on the origin of these unusual properties.

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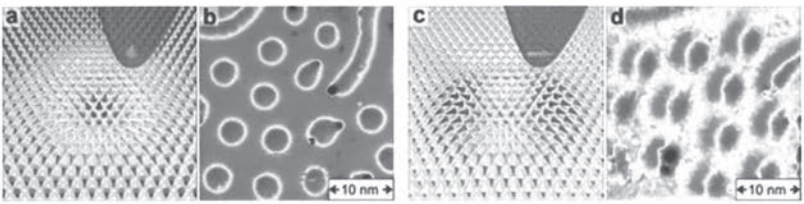

FIG: Sketches and measurements of spin-resolved STM experiments with tips sensitive to the out-of-plane (a,b) and in-plane (c,d) magnetization components, respectively. The sample is PdFe/Ir(111) and the measurements are performed at T = 4 K and B = 1.5 T.

Tailoring anomalous Hall resistivity by interfacial modifications in asymmetric $SrRuO_3$ - based heterostructures

Lena Wysocki[1], Lin Yang[1], Paul H.M. van Loosdrecht[1], and Ionela Lindfors-Vrejoiu[1]

[1]*University of Cologne, Institute of Physics II, Cologne, Germany*

Perovskite oxide multilayers yield a unique playground to tailor the physical properties of the materials by interfacial engineering. Recently, the 4d ferromagnet $SrRuO_3$ has been studied intensively after the observation of anomalies in the Hall resistivity resembling a topological Hall effect. These anomalies, firstly observed in bilayers where the $SrRuO_3$ was interfaced with the strong spin-orbit coupled oxide $SrIrO_3$, were related to the presence of Néel type skyrmions[1]. Alternative interpretations attribute the unconventional behavior to multiple channels contributing to the AHE due to $SrRuO_3$ layer inhomogeneities[2], off-stoichiometry[3], interface-induced electronic effects[4] or thickness variations within the sample[5]. Here we present the investigation of heterostructures with two $SrRuO_3$ layers with well-defined difference in thickness. The two $SrRuO_3$ layers were separated either by the strong SOC $SrIrO_3$ or by the bandgap insulator $SrZrO_3$. Our magneto-transport measurements demonstrate the additivity of the two conducting $SrRuO_3$ layers to the total AHE as well as the tailoring of the anomalous Hall resistivity by interfacial modifications.

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Nucleation, motion and detection of skyrmions

K. Zeissler[1], S. Finizio[2], C. Barton[3], A. J. Huxtable[1], J. Massey[1], R. Brearton[4,5], T. Hesjedal[4], G. van der Laan[5], M. C. Rosamond[1], E. H. Linfield[1], A. V. Sadovnikov[6,7], S. A. Nikitov[6,7], J. Raabe[2], O. Kazakova[3], T. A. Moore[1], G. Burnell[1] and C. H. Marrows[1]

[1] University of Leeds, Leeds, United Kingdom Institute
[2] Paul Scherrer Institut, Villigen, Switzerland
[3] National Physical Laboratory, Teddington, United Kingdom
[4] University of Oxford, Oxford, United Kingdom
[5] Diamond Light Source, Didcot, United Kingdom
[6] Saratov State University, Saratov 410012, Russia
[8] Kotel'nikov Institute of Radioengineering and Electronics, Moscow, Russia

The study of topological objects has emerged as a fascinating phenomenon in solid state research from both the fundamental and the applied perspectives. An exciting candidate in this field of research is the magnetic skyrmion which is unaltered by certain elastic transformations such as a stretching, bending or twisting [1]. The skyrmion's topology introduces unique characteristics in the way in which it interacts with electrons, other skyrmions, and defects and on how it responds to a driving force [2]. This talk will address aspects of skyrmion creation, motion and detection, at room temperature, in cobalt based multilayer devices. Skyrmions were nucleated using electrical current and local magnetic fields. Current driven motion was observed using scanning transmission x ray microscopy (STXM) in amorphous cobalt based devices. The skyrmion diameter dependence on the skyrmion Hall angle evaluated from STXM images is discussed. Individual skyrmion detection is demonstrated using Hall resistivity measurements [3]. STXM was used to image the devices' out of plane magnetization while the Hall resistance was measured in situ.

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Abstracts of Lectures

Tuesday, 3 December 2019

(in chronological order)

Coherent signal transfer along skyrmion strings

S. Seki[1,2]

[1] *Department of Applied Physics, University of Tokyo*
[2] *Center for Emergent Matter Science (CEMS), RIKEN*

Magnetic skyrmion, a topological soliton characterized by swirling spin texture appearing in two-dimensional system, has recently attracted attention as a stable particle-like object. In the three-dimensional system, skyrmion forms a string structure in analogy with the vortex-line in superconductors / superfluids and cosmic string in the universe, whose unique topology and symmetry may also host nontrivial response functions. In this talk, we discuss the propagation character of spin excitations on skyrmion strings. We found that these excitations show nonreciprocal propagation behavior, and the degree of nonreciprocity is strongly dependent on the character of excitation modes. The associated theoretical calculation establishes the dispersion relationship for skyrmion strings, which well reproduces the experimentally observed features. Notably, these spin excitations can propagate for more than 10^3 times longer distance than the single skyrmion radius, demonstrating the extremely good coherence of skyrmion strings with topologically-protected nature. The above results suggest the possibility of unidirectional information transfer through the skyrmion string.[1,2]

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Coupled dynamics of long-range and cluster-internal spin order in the cluster Mott insulator Cu_2OSeO_3

Rolf B. Versteeg,[1,*] Jingyi Zhu,[1] Christoph Boguschewski,[1] Fumiya Sekiguchi,[1] Anuja Sahasrabudhe,[1] Kestutis Budzinauskas,[1] Prashant Padmanabhan,[1] Petra Becker,[2] Daniel I. Khomskii,[1] and Paul H. M. van Loosdrecht[1]

[1]Institute of Physics 2, Faculty of Mathematics and Natural Sciences, University of Cologne, Zülpicher Straße 77, D-50937 Cologne, Germany
[2]Institute of Geology and Mineralogy, Faculty of Mathematics and Natural Sciences, University of Cologne, Zülpicher Straße 49b, D-50674 Cologne, Germany
**email: versteeg@ph2.uni-koeln.de*

Cu_4 triplet clusters form the relevant spin entities for the formation of long-range magnetic order in the cluster Mott insulator Cu_2OSeO_3.[1,2,3] Using time-resolved Raman spectroscopy,[4] we probed photoinduced spin and lattice dynamics in this cluster magnet. Multiple picosecond-decade spin-lattice relaxation dynamics is observed, evidencing a separation of the order parameter dynamics into disordering of long-range and cluster-internal order on the tens and 100s on the picosecond timescale, respectively. We argue that this separation originates in vastly different interaction strengths between low- and high-energy spin cluster excitations and acoustic phonons. Our results exemplify the double-order parameter dynamics intrinsic to the novel quantum material class of cluster Mott insulators. [5]

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Static and dynamic properties of heavy skyrmions

N.S. Kiselev

[1]*Institute for Advanced Simulation and Peter Grünberg Institut, Forschungscentrum Jülich, Germany*

In this presentation I will discuss a variety of skyrmion solutions with high topological charge, |Q|>1 [1]. Presented results are based on a quite general model of 2D chiral magnet valid for different crystal symmetries and different types of magnetocrystalline anisotropy. The first part of the presentation will be devoted to fundamental static properties of such objects in chiral ferro- and antiferromagnets such as dependence of skyrmion energy on the topological charge. Besides that, I will discuss dynamic properties of such skyrmions: skyrmion Hall effect, elastic and inelastic scattering of skyrmions.

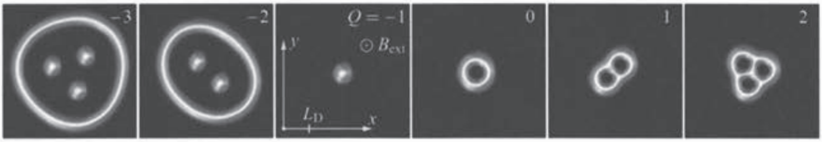

Fig1. Morphology of stable chiral skyrmions with topological charge Q varying between -3 and +2, see the index in the top right corner. All images are given on the same scale. Colors encode the direction of the magnetization vectors according to a standard scheme: black and white denote up and down spins, respectively, and red-green-blue reflect the azimuthal angle with respect to the x-axis.

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Current-induced orbital angular momentum and orbital torque for spin-orbitronics

Dongwook Go[1,2,3], Jan-Philipp Hanke[1], Frank Freimuth[1], Stefan Blügel[1], Yuriy Mokrousov[1,4], and Hyun-Woo Lee[2]

[1]Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA,52425 Jülich, Germany

[2]Department of Physics, Pohang University of Science and Technology, Pohang 37673, Korea

[3]Basic Science Research Institute, Pohang University of Science and Technology, Pohang 37673, Korea

[4]Institute of Physics, Johannes Gutenberg University Mainz, 55099 Mainz, Germany

Spin-orbit torque (SOT) plays a central role in many spin-orbitronic phenomena, such as current-induced magnetization switching and domain wall motion. It has been regarded that spin Hall effect and Rashba effect are dominant underlying mechanisms of the SOT, both of which results in the spin accumulation at the interface between a nonmagnet and ferromagnet. Recently, we proposed orbital analogues of these phenomena, called orbital Hall effect [1] and orbital Rashba effect [2], as ways to electrically generate orbital angular momentum. These can be understood as parental effects to the spin Hall effect and Rashba effect, which occurs regardless of the spin-orbit coupling, and the spin effects follow the orbital effects by the spin-orbit coupling.

In this presentation, we show that there exists an additional channel for the SOT generation through the orbital degree of freedom. When the orbital current is injected to a ferromagnet, it transfers the angular momentum and induces a torque to the magnetization. We call this orbital torque [3], analogous to spin torque caused by the spin-transfer mechanism. We found that SOT generation from the orbital channel can be of comparable magnitude as the SOT generation from the spin channel. The orbital torque and spin torque can be added up or cancel each other depending on material combinations, resulting in larger or smaller torque, respectively. This not only provides a way to enhance the torque efficiency, but also widens material choices since current-induced orbital angular momentum does not require heavy elements with large spin-orbit coupling. We discuss experimental implications briefly.

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Chiral effects in nanomagnetic devices

R. Allenspach

IBM Research – Zurich
8803 Rüschlikon (Switzerland)

About 15 years ago, the semiconductor industry changed its path in technology development: Processor clock speeds, determined to increase year after year for decades, remained constant, and performance improvements since then are due to shrinking sizes and multicore architectures. These impediments led to an increased attention to alternative device schemes. It was no longer taken for granted that silicon transistor technology and in particular the logic switch and the memory cell are here to stay forever. Many alternative schemes were proposed, among them also various nanomagnetic and spin-based concepts, such as (STT-)MRAM or the magnetic racetrack shift register. All these schemes are based on ultrathin magnetic heterostructures, and thus symmetry breaking is automatically built-in, but also spin-orbit interaction is present. Chiral effects hence play a role, in particular the interfacial Dzyaloshinksii-Moriya interaction (DMI).

In this contribution, I will consider a few nanomagnetic device concepts and discuss whether these concepts profit from chiral effects. A rich variety of spin textures can be induced by DMI, ranging from different wall types to spin spirals and skyrmions. Does it help device performance that skyrmions are topologically protected objects or that the achiral Bloch domain wall is transformed into a chiral Néel wall?

Skyrmions for unconventional computing

K. Everschor-Sitte[1]

[1] *Institute of Physics, Johannes Gutenberg-University Mainz, Germany*

The topological properties of magnetic skyrmions, their inherent compact particle-like nature and their complex and nonlinear dynamics make skyrmions interesting for spintronics applications and in particular unconventional computing schemes. [1]

In this talk I will address the potential of magnetic skyrmions for reservoir computing and stochastic computing.

Reservoir computing is a computational scheme that allows to drastically simplify spatial-temporal recognition tasks. We have shown that random skyrmion fabrics provide a suitable physical implementation of the reservoir [2,3] and allow to classify patterns via their complex resistance responses either by tracing the signal over time or by a single spatially resolved measurement. [4]

Stochastic computing is a computational paradigm which allows to speed up a calculation while trading for numerical precision. Information is encoded in terms of bit-streams as a probability. A key requirement and simultaneously a challenge is that the incoming bitstreams are uncorrelated. The Brownian motion of magnetic skyrmions allows to create a device that reshuffles the bit-streams. [5,6]

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Skyrmion crystals in quantum Hall ferromagnets

B. Douçot[1], D. Kovrizhin[2], R. Moessner[3]

[1]LPTHE, CNRS and Sorbonne Université, Paris, France
[2]LPTM, Université de Cergy-Pontoise, France
[3]MPIPKS, Dresden, Germany

In the presence of a strong magnetic field, and for an integer filling of the Landau levels, Coulomb interactions favor a ferromagnetic ground-state. It has been shown already more than twenty years ago, both theoretically and experimentally, that when extra charges are added or removed to such systems, the ferromagnetic state becomes unstable and is replaced by a Skyrmion crystal.

We have generalized this notion to an arbitrary number N of internal states for the electrons, which may correspond to the combination of spin, valley, or layer degrees of freedom. I will discuss the minimization of the Hartree-Fock energy functional in the SU(N)-symmetric case. The first non-trivial term in this functional is the usual CP(N-1) non-linear sigma model, which is known to exhibit a remarkable degeneracy of the many electron states obtained from holomorphic textures. This degeneracy is lifted by the sub-leading term in the effective Hamiltonian, which selects a hexagonal Skyrmion lattice and therefore breaks both translational and internal SU(N) symmetries.

We have analyzed the collective excitation spectrum, which separates into N^{2}-1 gapless acoustic magnetic modes and a magneto-phonon branch. From this viewpoint, Skyrmion crystals behave in a similar way as non-collinear anti-ferromagnets.

However, I will also show that the corresponding Hartree-Fock states remain undressed by quantum fluctuations, which is reminiscent of quantum ferromagnets.

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Three-dimensional crystals of topological knot solitons

Ivan I. Smalyukh

Department of Physics, Materials Science and Engineering Program, Soft Materials Research Center and Department of Electrical, Computer and Energy Engineering, University of Colorado, Boulder, Colorado 80309, USA

Renewable and Sustainable Energy Institute, National Renewable Energy Laboratory and University of Colorado, Boulder, Colorado 80309, USA

**Correspondence to: ivan.smalyukh@colorado.edu*

Starting from Gauss, Kelvin and Skyrme, knots in fields were postulated behaving like particles, but experimentally they were found only as transient features and couldn't self-assemble into three-dimensional crystals. We introduce energetically stable knots in helical fields of chiral liquid crystals and magnets, which we call "heliknotons" [1]. While spatially localized and freely diffusing in all directions, they resemble colloidal particles and atoms, self-assembling into triclinic and other crystalline lattices with open and closed structures. These knots are robust and topologically distinct from the host medium, though in liquid crystals they can be morphed and reconfigured by weak stimuli under conditions like in displays. A combination of free-energy-minimizing numerical modeling and optical imaging uncovers the internal structure and topology of individual helical field knots and various hierarchical crystalline organizations they form. I will discuss relations between heliknotons [1], three-dimensional skyrmions and hopfions [2,3] in both magnetic and liquid crystal systems, as well as a variety of crystals they can form.

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Hopfions and skyrmions in magnets with competing interactions

F. N. Rybakov[1], N. S. Kiselev[2], A. B. Borisov[3],
C. Melcher[4] and S. Blügel[2]

[1]*KTH-Royal Institute of Technology, Stockholm, Sweden*
[2] *Peter Grünberg Institut and Institute for Advanced Simulation, Jülich, Germany*
[3] *M.N. Miheev Institute of Metal Physics, Ekaterinburg, Russia*
[4] *RWTH Aachen University, Aachen, Germany*

Using real-time massively-parallel simulations, we will consider three-dimensional skyrmions/hopfions in magnets, where competing exchange interactions provide stability to such textures [1,2]. The effect of dipole-dipole interactions will be discussed. We will also see how such textures can be identified using the off-axis electron holography technique.

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Existence and stability of skyrmion bags in thin magnetic films

Charles Kind,[1] Sven Friedemann,[2] and Dan Read[3]
[1]*School of Mathematics, University of Bristol, Bristol BS8 1TW, UK*
[2]*HH Wills Physics Laboratory, University of Bristol, Bristol BS8 1TL, UK*
[3]*School of Physics and Astronomy, Cardiff University, Cardiff CF24 3AA, UK*
(Dated: November 13, 2019)

Skyrmion bags are spin textures of any integer topological degree, realised in micromagnetic simulations and experimentally in liquid crystals. They have been proposed as a promising new form of magnetic data storage due to their stability with respect to perturbations and the possibility of encoding different values in topologically distinct magnetisation configurations. We simulate skyrmion bags in magnetic thin films having a range of physically realistic material parameters. The results give a range over which stable skyrmion bags may be found in experiment and we extract a relationship to help guide production of these potentially useful quasiparticles.

Measuring the formation energy barrier of skyrmions in zinc substituted Cu_2OSeO_3

M. N. Wilson[1], M. Crisanti[2,3], C. Barker[1], A. Štefančič[3], J. S. White[4], M. T. Birch[1], G. Balakrishnan[3], R. Cubitt[2], and P. D. Hatton[1]

[1]Department of Physics, Durham University, DH1 3LE, Durham, United Kingdom
[2]Large Scale Structures Group, Institut Laue-Langevin, 38000, Grenoble, France
[3]Department of Physics, University of Warwick, CV4 7AL, Coventry, United Kingdom
[4]Laboratory for Neutron Scattering, Paul Scherrer Institut, 5232, Villigen, Switzerland

Skyrmions are a topologically protected spin texture that appear in certain chiral magnetic materials [1] and have been proposed for applications in spintronics devices [2]. This proposed application arises from their small size, and the stability given by the topological protection of skyrmions from neighbouring magnetic phases.

One chiral material in which skyrmions are observed is the magnetoelectric insulator Cu_2OSeO_3 [3]. This material is uniquely attractive for demonstrating control of skyrmions as the magnetoelectric nature allows the possibility of manipulating skyrmions by applying external electric fields. In a device context, this is much easier than manipulation with magnetic fields, and may require less energy than manipulation with electric currents.

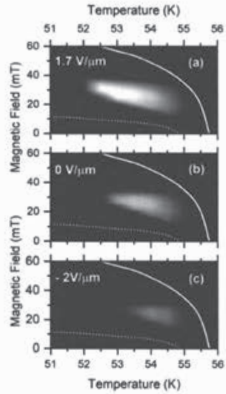
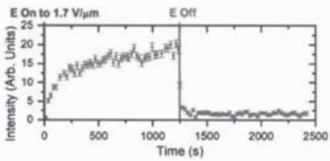


Figure 1. Expansion of the skyrmion region (white) by applying an electric field.

In this talk I will present our small angle neutron scattering (SANS) work studying the effect of electric fields on the skyrmion lattice in $(Cu_{1-x}Zn_x)_2SeO_3$ [4]. We find that electric fields parallel to the magnetic field dramatically expand the region of skyrmion stability. Furthermore, our data shows that over certain temperature ranges, after an electric field is applied, the skyrmion state forms slowly, over a time scale that can be measured by SANS. Tracking these formation times as a function of temperature allows us to determine an energy barrier for the formation of skyrmions. This is the first time a formation energy barrier for skyrmions has been measured.



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Stability and lifetimes of skyrmions at different spatial scales

I.S. Lobanov[1,2] and V.M. Uzdin[1,2]

[1] *St. Petersburg State University, St.Petersburg, Russia*
[2] *University ITMO, St.Petersburg, Russia*

Lifetime of skyrmions is calculated for arbitrary temperature within transition state theory for magnetic degrees of freedom [1]. This approach is based on an analysis of the multidimensional energy surface of magnetic systems, the construction of minimum energy paths between locally stable states and the calculation of energy barriers between them. The barrier between a metastable skyrmion and a homogenous ferromagnetic state determines the activation energy for skyrmion annihilation [2]. Minimal energy path itself gives information about mechanism of transition.

We have studied the stability of skyrmions as a function of the size, i.e. as a function of the ratio of the skyrmion radius and lattice constant. The number of magnetic moments in the system was taken from few thousands to more than a million and the dimensionality of the energy surface in the last case proves to be several millions. Saddle points for such large systems was found using Truncated Minimal Energy Path method [3]. While skyrmions in a continuum models are predicted to have topological protection, we found that the energy barrier for collapse of skyrmions in discrete lattice model is finite for any lattice constant even when the lattice constant becomes infinitesimal.

The pre-exponential factor in the Arrhenius law was estimated within the harmonic approximation to transition state theory for the same set of skyrmion structures. A new method for calculating the pre-exponential factor without calculation of eigenvalues of the Hessian is developed and used here. It makes it possible to calculate the lifetime of a system with millions of magnetic moments, that has not been possible by standard methods so far.

This work was supported by Helmholtz-RSF joint research project (grant 19-42-06302)

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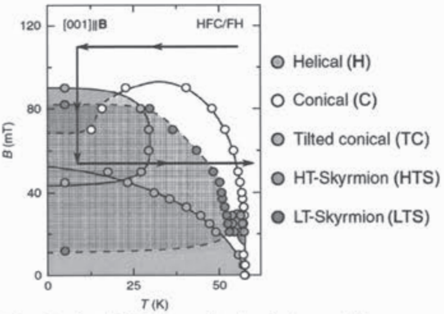
Nucleation mechanism of the low-temperature skyrmion state in Cu_2OSeO_3

D. Mettus[1], M. Halder[1], A. Chacon[1], A. Bauer[1] and C. Pfleiderer[1]

[1]*Technische Universität München, D-85748, Garching, Germany*

In the cubic chiral magnet Cu_2OSeO_3, a low-temperature skyrmion (LTS) state and an accompanying tilted conical (TC) state were discovered for magnetic field along <100> [1]. While the previously known high temperature skyrmion (HTS) phase is believed to exist near the helimagnetic to paramagnetic transition and to be stabilized by thermal fluctuations [2], it was demonstrated that magnetocrystalline anisotropies are key for the energetics of both LTS and TC phases [3]. However, the details of the nucleation process of the LTS state remained elusive so far.

In the present contribution, we report a study of the nucleation process of the LTS phase. Using first-order reversal magnetization curves, we establish that the nucleation occurs by means of the TC phase. Additionally, we consider the effects of magnetic field cycling on the LTS phase nucleation process. The topological winding processes involved in the nucleation give rise to a glassy regime of phase coexistence with very slow characteristic time scales, as substantiated by susceptibility data tracking the increase of the volume fraction of the LTS at costs of the TC state under magnetic field.



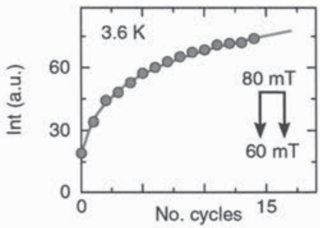


Fig. 1. (Left) Schematic depiction of the magnetic phase diagram. (Right) Increase of intensity of the LTS phase after high-field cooling as a function of the number of field cycles between 60 mT and 80 mT [1].

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Measurement of the low-temperature Skyrmion phase in Cu_2OSeO_3 by Magnetic-Force-Microscopy

Gerald Malsch[1], Peter Milde[1,2], Dmytro Ivaneiko[1], Christian Pfleiderer[3], H. Berger[4], Lukas M. Eng[1,2]

[1] *Institute of Applied Physic, TU Dresden, 01187 Dresden, Germany*
[2] *ct.qmat: Würzburg-Dresden Cluster of Excellence - EXC 2147, TU Dresden, Germany*
[3] *Physik-Department, Technische Universität München, D-85748 Garching, Germany*
[4] *Institut de Physique de la Matière Complexe, EPFL, 1015 Lausanne, Switzerland*

Cu_2OSeO_3 is known for hosting a (high-temperature) skyrmion phase around 57 K close to the helimagnetic transition temperature [1]. Both small-angle neutron scattering measurements (SANS) and theoretical calculations indicate that there might exist additional phases in Cu_2OSeO_3, including at least one additional skyrmion phase found at very low temperatures (LT) and only for magnetic fields applied along the <100> direction [2]. These phases are usually hidden beneath a metastable tilted conical phase, but can be revealed by modulating the applied magnetic field. Here we present a Magnetic-Force-Microscopy (MFM) analysis showing this LT skyrmion phase in real space. When imaging the ordering of skyrmions on a cubical Cu_2OSeO_3 single crystal, we find the skyrmion lattice to nucleate in µm-sized domains that coexist with tilted conical domains during the annealing process. Moreover, individual skyrmion domains are rotated relative to each other, leading to appreciable lattice mismatch and large distortions along skyrmion domain boundaries. In fact these skyrmion domains may be viewed as crystalline subunits in an "amorphous" crystal, resulting exactly in the ring-shaped halo as measured by SANS or REXS on a multidomain Cu_2OSeO_3 crystal [3].

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Abstracts of Lectures

Wednesday, 4 December 2019

(in chronological order)

X-Ray Studies of Ordered Skyrmions

Microscopic Properties, 3D Structure & Dynamics

S. L. Zhang[1,2], D. M. Burn[3], B. Kuerbanjiang[1], G. van der Laan[3] and T. Hesjedal[2]

[1]*Clarendon Laboratory, University of Oxford, Oxford, United Kingdom*
[2]*ShanghaiTech University, Shanghai, China*
[3]*Magnetic Spectroscopy Group, Diamond Light Source, Didcot, United Kingdom*

Magnetic skyrmions in noncentrosymmetric chiral magnets form ordered lattices with a periodicity ranging from 3-100 nm. This lengthscale lends itself to soft x-ray scattering experiments owing to the large resonant scattering cross-section for 3*d* elements, the excellent reciprocal space resolution, as well as the tunable surface sensitivity. We will present an overview of the capabilities of resonant elastic x-ray scattering (REXS) for the study of magnetic skyrmions [1], highlighting the following effects:

1) *Microscopic skyrmion properties* [2]: By exploiting the polarization dependence of REXS, the exact surface helicity angles of twisted skyrmions for both left- and right-handed chiral bulk Cu_2OSeO_3 was determined.
2) *Full 3D spin structure of skyrmions* [3]: Using polarization-dependent REXS we found a continuous transformation of the skyrmion tubes from pure Néel-twisting at the surface to pure Bloch-twisting in the bulk over a distance of several hundred nanometers.
3) *Rotating skyrmion lattices* [4]: In a magnetic field gradient, skyrmions undergo rotation with well-defined dynamics. This provides an effective way of controlling skyrmions in racetrack memory schemes.
4) *Skyrmion lattice dynamics* [5]: Using resonant elastic x-ray scattering to select a specific magnetic structure (i.e., a peak), its modal magnetization dynamics can be studied using x-ray detected ferromagnetic resonance.

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Antiferromagnetic Textures: Eigen Modes and Spin Current Induced Dynamics

O. Gomonay[1] and V. Kravchuk[2]

[1]JGU, Mainz, Germany
[2] KIT, Karlsrue, Germany

Searching for new functionalities of antiferromagnetic (AF) systems, controlled by spin and/or electric current, we focus on the (spin) current-induced magnetic dynamics of AF domain walls and skyrmions [1]. First, we review different types of forces acting on the domain walls in presence of spin-orbit torques and discuss underlying switching mechanisms together with interpretation of the recent experiments [2-4]. We demonstrate that spin-orbit torques which originate from the effective staggered field at the magnetic sublattices can effectively split degeneracy of non180 AF domains and induce fast domain wall motion toward unfavourable domain. We also compare dynamics induced by field-like and damping-like spin-orbit torques and calculate typical velocities for the current induced motion of AF domain walls and skyrmions. Second, we discuss free and forced magnetic dynamics of an isolated AF skyrmion [5] focusing mainly on the features which have no direct ferromagnetic counterpart. Basing on classification of localised modes according to their spin, angular mometum and frequency we show how the localised modes can be selectively excited by ac magnetic field or spin current. We show that DC magnetic field which removes degeneracy of clock- and couterclock-wise modes is an additional tool for manipulation of AF skyrmion dynamics. We believe that our results open a way for manipulation, control and detection of the dynamical states of AF textures.

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Relaxation of non-equilibrium skyrmions in $Fe_{0.5}Co_{0.5}Si$

M. Halder[1], A. Chacon[1], A. Bauer[1], J. Kindervater[1], S. Mühlbauer[2], and C. Pfleiderer[1]

[1]*Physik Department, Technische Universität München, D-85748 Garching, Germany*
[2] *Heinz Maier-Leibnitz Zentrum (MLZ), Technische Universität München, D-85748 Garching, Germany*

The development of spintronic applications based on magnetic skyrmions requires metastable states to be able to switch between magnetic configurations. The understanding of the decay paths of these states is also of big relevance as it defines the stability of these future devices. Here we present a thorough magnetization and neutron scattering study of the relaxation processes in $Fe_{0.5}Co_{0.5}Si$. Several studies on the family of compounds $Fe_{1-x}Co_xSi$ have shown their propensity to create metastable states depending on the specific temperature and magnetic field history followed. Using small angle neutron scattering we have identified the decay of the skyrmion lattice at zero field and then proceeded to measure its effect on the sample magnetization as a function of time at different temperatures. Using the time-temperature superposition principle (cf. Fig 1) we were able to obtain the activation energy distribution for metastable Skyrmions in zero field.

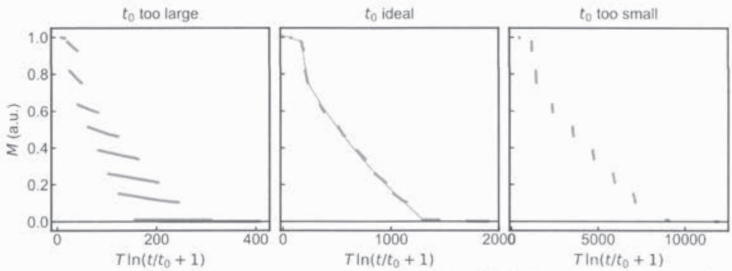

Figure 1: The time-temperature superposition principle yields the master curve when the shift factor t_0 is chosen correctly. The derivative of the master curve is the activation energy distribution.

Skyrme's original Skyrmions

N.S. Manton

DAMTP, University of Cambridge, U.K.

The original Skyrmion, discovered by Tony Skyrme around 1960, is a topologically stable soliton in three-dimensional space. After quantizing the Skyrmions's rotational degrees of freedom one obtains a model for a proton or neutron of finite size, with a pion field tail. The pion tails are responsible for forces between protons and neutrons. Many multi-Skyrmion solutions are now known. Quantizing these, and allowing for rotations and vibrations, one obtains models for larger nuclei like Carbon-12 and Oxygen-16. The ground state and many excited states match data quite well. Skyrmions therefore give insight into the intrinsic shapes of these nuclei. They are not spherical.

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Tony Skyrme and the Origins of Skyrmions

Ian J. R. Aitchison

SLAC National Accelerator Laboratory, USA and Oxford University, UK

I first discuss the main motivations for Tony Skyrme's highly original programme (1958-62) of making fermionic nucleons out of bosonic pion fields, as described in his Cosener's House talk in 1984. These include a dislike of point-like elementary particles, which he blamed for infinite renormalization, and a preference for extended objects distinguished by what we now call conserved topological quantum numbers. In this he was strongly influenced by William Thomson (Lord Kelvin), who was so impressed by Helmholtz's proof of the conservation of circulation ("wirbelbewegung") in fluid vortices that he developed an entire theory of atoms as knotted vortex rings in the aether fluid. Skyrme liked mechanical models, as did Kelvin, and he grew up fascinated by the ingenuity of Kelvin's machine for predicting tides, an example of which stood in his grandfather's house. This seems to have been connected to his strong preference for bosonic fields, which have a classical limit, over fermionic fields which do not. I then sketch the progress of Skyrme's ideas in the series of six papers in the years 1958-62, which passed largely unnoticed at the time. I emphasize his remarkable intuition that the kink solution of the classical Sine-Gordon equation would be a fermion when quantized; and the novelty of his identification of the Skyrmion winding number with baryon number in the three-dimensional case. I end by briefly describing how Skyrme's work was dramatically related to QCD in 1983-4.

Abstracts of Lectures

Thursday, 5 December 2019

(in chronological order)

Quantitative Transmission Electron Microscopy of Skyrmions

J. C. Loudon[1], A. C. Twitchett-Harrison[1], D. Cortés-Ortuño[2], M. T. Birch[3], L. A. Turnbull[3], A. Štefančič[4], F. Y. Ogrin[5], E. O. Burgos-Parra[5], N. Bukin[5], A. Laurenson[5], H. Popescu[6], M. Beg[2,7], O. Hovorka[2], H. Fangohr[2,7], P. A. Midgley[1], G. Balakrishnan[4], and P. D. Hatton[3]

[1]*Department of Materials Science and Metallurgy, University of Cambridge, 27 Charles Babbage Road, Cambridge CB3 0FS, UK.*
[2]*Faculty of Engineering and Physical Sciences, University of Southampton, Southampton SO17 1BJ, UK.*
[3]*Department of Physics, University of Durham, Durham DH1 3LE, UK.*
[4]*Department of Physics, University of Warwick, Coventry CV4 7AL, UK.*
[5]*School of Physics and Astronomy, University of Exeter, Exeter EX4 4QL, UK.*
[6]*Synchrotron SOLEIL, Saint Aubin, BP 48, 91192 Gif-sur-Yvette, France.*
[7]*European XFEL GmbH, Holzkoppel 4, 22869 Schenefeld, Germany.*

Transmission electron microscopy is a valuable method for imaging magnetic skyrmions. This talk will explain how electron microscopy can be used not just to identify skyrmions but to measure the magnetic fields associated with them in absolute units and how to make a quantitative comparison with simulations and other measurement techniques. As a case study it will demonstrate how images previously identified as showing biskyrmions [1,2] can be explained as showing conventional type-II magnetic bubbles [3].

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Quantitative magnetic field characterisation of Bloch and Néel type skyrmions using off-axis electron holography

A. Kovács[1], N.S. Kiselev[2], F. Zheng[1], J. Caron[1], T. Denneulin[1] and R. E. Dunin-Borkowski[1]

[1]*Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons and Peter Grünberg Institute, Forschungszentrum Jülich, 52425 Jülich, Germany*
[2]*Peter Grünberg Institute and Institute for Advanced Simulation, Forschungszentrum Jülich, 52425 Jülich, Germany*

Two and three dimensional (3D) magnetic spin structures (*e.g.* skyrmions) have generated considerable interest both for fundamental physics and for future applications in energy-efficient spintronic devices. Interesting how limited is our knowledge on their formation, spin arrangements and properties even in a well-studied system such as B20-type FeGe. In this work we use electron optical phase images to characterise Bloch spin structures in FeGe chiral magnet [1] and Néel skyrmions in sputter deposited heterostructures [2]. Phase images were obtained using off-axis electron holography [3] in an aberration-corrected transmission electron microscope. The phase measurements are combined with a model-based reconstruction algorithm to measure the projected in-plane magnetisation quantitatively. We assess the prospects of characterisation of complex 3D magnetic textures such as magnetic hopfions.

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Surface versus bulk characterization of 3D skyrmion lattices in chiral magnets

G. van der Laan[1], S.L. Zhang[2] and T. Hesjedal[2]

[1] *Magnetic Spectroscopy Group, Diamond Light Source*
[2] *Physics Department, University of Oxford*

Symmetry breaking at the surface modifies the properties of stable materials within the top few atomic layers of a bulk specimen. Exploiting the polarization dependence of resonant elastic x-ray scattering (REXS) beyond conventional diffraction and imaging techniques, we have determined the depth dependence of the full 3D spin structure of skyrmions—that is, topologically nontrivial whirls of the magnetization—below the surface of a bulk sample. For Cu_2OSeO_3 the skyrmions change exponentially from pure Néel- to pure Bloch-twisting over a distance of several hundred nanometers between the surface and the bulk, respectively. The exact surface helicity angles of twisted skyrmions for both left- and right-handed chiral bulk Cu_2OSeO_3, in the single as well as in the multidomain skyrmion lattice state, are determined, revealing their detailed internal structure. The experimental results are supported by theoretical models. It is shown that skyrmion surface reconstruction is a universal phenomenon, where the breaking of translational symmetry at the interface modifies the Dzyaloshinskii–Moriya interaction.

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Real-space imaging of confined magnetic skyrmion tubes

Max T. Birch[1,2], D. Cortés-Ortuño[3], L. A. Turnbull[1], M. N. Wilson[1], F. Groß[4], N. Träger[4], A. Laurenson[5], N. Bukin[5], S. H. Moody[1], M. Weigand[4], G. Schütz[4], H. Popescu[6], R. Fan [2], P. Steadman [2], J. A. T. Verezhak[7], G. Balakrishnan[7], J. C. Loudon[8], A. C. Twitchett-Harrison[8], O. Hovorka[3], H. Fangohr[3,9], F. Y. Ogrin[5], J. Gräfe[4] and P. D. Hatton[1]

[1] *Department of Physics, Durham University, DH1 3LE, UK*
[2] *Diamond Light Source, Harwell Innovation Campus, Didcot, OX11 0DE, UK*
[3] *Engineering, University of Southampton, Southampton SO17 1BJ, UK*
[4] *Max Planck Institute for Intelligent Systems, 70569 Stuttgart, Germany*
[5] *School of Physics and Astronomy, University of Exeter, Exeter, EX4 4QL, UK*
[6] *Synchrotron SOLEIL, Saint Aubin, BP 48, 91192 Gif-sur-Yvette, France*
[7] *Department of Physics, University of Warwick, Coventry, CV4 7AL, UK*
[8] *Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, CB3 0FS, UK*
[9] *European XFEL GmbH, Holzkoppel 4, 22869 Schenefeld, Germany*

Magnetic skyrmions are topologically nontrivial particles with a potential application as information elements in future spintronic device architectures. While they are commonly portrayed as two dimensional objects, in reality magnetic skyrmions are thought to exist as elongated, tube-like objects extending through the thickness of the sample. The study of this skyrmion tube state is vital for furthering the understanding of skyrmion formation and dynamics for future applications. However, direct experimental imaging of skyrmion tubes has yet to be reported. Here, we demonstrate the first real-space observation of skyrmion tubes in a lamella of FeGe using resonant magnetic x-ray imaging and comparative micromagnetic simulations, confirming their extended structure. Representative results are shown in Fig. 1. The formation of these structures at the edge of the sample highlights the importance of confinement and edge effects in the stabilisation of the skyrmion tube state in this geometry, opening the door to further investigations into this unexplored dimension of the skyrmion spin texture.

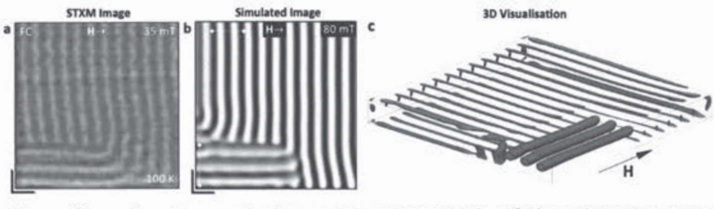

Figure 1: **a**, Scanning transmission x-ray micrograph of the skyrmion tube spin texture embedded in the conical state in an FeGe lamella. **b**, Comparative simulated image of the skyrmion tube state. **c**, Three dimensional visualisation of the micromagnetic simulation of the skyrmion tube state.

Visualizing nanoscale spin waves using MAXYMUS

J. Gräfe[1]

[1]Max Planck Institute for Intelligent Systems, Stuttgart, Germany

Manipulation of spin waves, the so called field of magnonics, has gained significant scientific interest in the past years [1-4]. For that purpose nano-structured materials with locally alternating magnetic properties are utilized. By structuring on the length scale of the exchange and dipole interactions the dispersion properties of spin waves can be engineered [2-4]. These nanostructures have great potential for technological applications in data processing and storage, and spintronics [3, 4]. However, the spin wave behaviour is not only altered on the nano-scale, but it can be directly imaged by advanced x-ray microscopy with magnetic contrast (MAXYMUS@BESSY) with a spatial and temporal resolution of 18 nm and 35 ps respectively. Thus, emergent spin wave phenomena can be directly observed in real space on a scale beyond the capabilities of conventional BLS or MOKE measurements.
In the first part of the talk, we will present new techniques for time-resolved x-ray microscopy including ultra-sensitive detection of spin deflection angles [5] and arbitrary excitation signal generation. In the second part, we will showcase these capabilities for three examples: generation of sub-100 nm wavelength magnons; detection of magnetization reversal angles and size expansion of nanoscale droplet solitons [6]; and propagation, extinction and localization of spin waves in quasicrystalline magnonic crystals [7].

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Distinct topological magnetic textures in Antiskyrmion hosting Heusler compounds Mn_xYZ with different Berry curvature responses

Jacob Gayles,[1] Yan Sun,[1] and Claudia Felser[1]

[1] *Max Planck Institute for Chemical Physics of Solids, D-01187 Dresden, Germany*
(Dated: August 15, 2019)

Recently, the Heusler compounds $Mn_{1.4}PtSn$ and $Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$ were shown to stabilize an antiskyrmion lattice above room temperature and with out an external magnetic field [1]. These Heusler compound forms in a superstructure with the D_{2d} symmetry, which allows for an anisotropic Dzyaloshinskii-Moriya interaction (DMI) perpendicular to the tetragonal axis. Furthermore, many of these compounds show a spin reorientation transition where the topological Hall effect is much larger below the transition than above in the known anti-skyrmion regime [2]. We use density functional theory calculations in combination with atomistic spin dynamic calculation of Mn_xYZ compounds to extract the relevant exchange interactions that determine the rich phase diagrams in these materials. The exchange interactions are between the large moments on the Mn atoms $\sim 4\mu_B$, which show magnetic states that are non-collinear ferrimagnetic up to the spin reorientation. The major role of the spin-orbit driven DMI is due to the Z ion, either In, Ga,Sn or Sb where the Y ion (Ru,Rh,Pd,Ir, or Pt) *d*-states lowered in energy due to the Jahn-Teller distortion. The content of Mn also plays a large role in the stabilization of the magnetic textures. The Fermi level can be tuned by the Y ion, either In,Sn or Sb. We last calculate the anomalous Hall effect and topological Hall effects in these regimes, to capture the influence of the electronic structure on the Berry curvature.

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Field manipulation of Bloch points in helimagnetic nanostructures

M. Beg[1,2], R. A. Pepper[1], D. Cortés-Ortuño[1], O. Hovorka[1], and H. Fangohr[1,2]

[1]Faculty of Engineering and Physical Sciences, University of Southampton, Southampton SO17 1BJ, United Kingdom
[2] European XFEL, Holzkoppel 4, 22869 Schenefeld, Germany

Recent research demonstrated that confined helimagnetic nanostructures can host ground state skyrmionic states [1, 2]. However, the epitaxially grown thin films from which the skyrmion hosting nanostructures are etched, are usually granular. More precisely, they contain helimagnetic grains with different chirality and consequently different sign of the Dzyaloshinskii-Moriya constant. In this work, we perform finite element micromagnetic simulations using Finmag [3] on a FeGe thin film nanostructures containing grains with different chirality. After we show that a zero-field stable Bloch point [4, 5] emerges at the grain boundary in a thin film disk geometry, we demonstrate that it also emerges in a very wide range of planar geometries, including nanostripes. By applying an external magnetic field in the out-of-plane direction, we demonstrate that the system undergoes hysteretic behaviour and that it is possible to switch between two different stable types of Bloch points (head-to-head and tail-to-tail). Finally, we apply an in-plane external magnetic field and show that in a planar helimagnetic nanostructure, Bloch points can be moved in an arbitrary in-plane direction. Our demonstration of the stability and manipulation of a Bloch point in a planar sample [6], apart from being of fundamental physical interest, suggests a possible use in future spintronics, data storage, and processing devices. We acknowledge the financial support from the Horizon 2020 European Research Infrastructures OpenDreamKit project (676541), EPSRC CDT in Next Generation Computational Modelling EP/L015382/1, and the EPSRC grant EP/N032128/1.

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Towards the 3D quantification of Skyrmions in thin helimagnets

S. Schneider[1,2], D. Wolf[1], M. J. Stolt[3], S. Jin[3], M. Schmidt[4], D. Pohl[2], B. Rellinghaus[2], D. Negi[5], B. Büchner[1,2], S. T. B. Goennenwein[2], K. Nielsch[1,2], J. Rusz[5,1] and A. Lubk[1]

[1]IFW Dresden, Dresden, Germany
[2]TU Dresden, Dresden, Germany
[3]University of Wisconsin-Madison, Madison, USA
[4]MPI CPfS, Dresden, Germany
[5]Uppsala University, Uppsala, Sweden

The anticipated application of Skyrmions as information carriers in magnetic thin film devices depends crucially on the stability and mobility of these solitons. Accordingly the microscopic magnetic structure of Skyrmions, which determines their transport properties, is investigated by means of magnetic measurement methods in transmission electron microscopy. To study the spin texture of Bloch Skyrmions in thin platelets of $Fe_{0.95}Co_{0.05}Ge$ focal series electron holography and off-axis electron holography is employed to determine quantitative maps of the projected in-plane magnetic induction of Skyrmions. Although these magnetic induction maps carry the clear signature of Bloch Skyrmions, their magnitude is much smaller than the values expected for homogeneous Skyrmions extending throughout the thickness of the film. Such a reduction can amongst others be caused by a modulation of the underlying spin textures along the out-of-plane *z* direction [1].
In order to determine the three-dimensional spin texture of the Bloch Skyrmions first off-axis electron holographic tomography experiments are performed on a FeGe needle prepared by FIB. In order to stabilize the magnetic structure within the rotating sample, an external magnetic field was applied by placing a ring magnet of Sm_2Co_{17} underneath the sample in the TEM holder.
Complementary to electron holography, electron energy-loss magnetic chiral dichroism (EMCD) is used to probe the out-of-plane magnetic properties of FeGe. A set of rules is derived, as how to set-up a geometry for a classical EMCD experiment for a given crystal structure to obtain maximum dichroic signals. Applying these rules, our EMCD measurements reveal for the first time a clear dichroic signal in the so-called field polarized phase of FeGe [2].

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Abstracts of Posters

(in alphabetical order)

Skyrmions in a synthetic antiferromagnet

C. E. A. Barker*,[1] A. J. Huxtable,[1] T. A. Moore,[1] and C. H. Marrows[1]

[1] *School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, United Kingdom*

**E-mail: pyceab@leeds.ac.uk*

Skyrmions are topologically protected vortex-like spin structures that have been observed in bulk materials that lack inversion symmetry [1], and in magnetic multilayers, where symmetry is broken across an interface [2]. Their stability and ability to be driven under low current densities compared to domain walls makes them an ideal candidate for potential racetrack memory devices [3], and their research is a quickly advancing field.

At present the main obstacle in developing a working skyrmion-based memory device is the skyrmion Hall effect [4], which causes skyrmions to drift in a perpendicular direction to the driving current. In a device this would lead to skyrmions annihilating at the edge of the racetrack. A potential solution is to deploy two skyrmions coupled together in a synthetic antiferromagnet (SAF) [5]. In principle the skyrmion Hall effects of each skyrmion will compensate the other, and they will move parallel to the direction of the applied current.

In this poster we demonstrate early experimental results of such a system—using two layers of CoB coupled together antiferromagnetically with Ru in order to form a SAF. We also complement this data with micromagnetic simulations of the dynamics of skyrmions driven by a current density in such a SAF.

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Complex magnetic textures in the non-centrosymmetric antiferromagnet $EuPtSi_3$

A. Bauer[1], A. Senyshyn[2], C. Franz[1,2], W. Simeth[1], R. Bozhanova[1], S. Gottlieb-Schönmeyer[1], and C. Pfleiderer[1]

[1]*Physik-Department, Technische Universität München, D-85748 Garching, Germany*
[2]*Heinz Maier-Leibnitz Zentrum (MLZ), Technische Universität München, D-85748 Garching, Germany*

We report a comprehensive study of optically float-zoned single crystals of the non-centrosymmetric rare-earth compound $EuPtSi_3$. Measurements of the magnetization, ac susceptibility, specific heat, resistivity, and Hall effect at temperatures down to 2 K and in magnetic fields up to 14 T consistently indicate a complex anisotropic magnetic phase diagram. Remarkably, the Hall effect may not be described by the superposition of a normal and a conventional anomalous contribution only, exhibiting an additional contribution of up to 106 nΩcm across the entire phase diagram. By means of powder and single-crystal neutron diffraction in zero field, we identify a long-wavelength magnetic structure, $\lambda \approx 100$ Å, presumably in the form of Néel-type cycloidals with local antiferromagnetic coupling. In combination with the Hall effect, this finding suggests that the magnetic phase diagram of $EuPtSi_3$ comprises spin textures of non-trivial topology.

Stability and dynamics of in-plane Skyrmions

Venkata Krishna Bharadwaj[1], Ricardo Zarzuela[1], Kyoung-Whan Kim[2], Jairo Sinova[1], and Karin Everschor-Sitte[1]

[1]Johannes Gutenberg-University, Mainz
[2]Center for Spintronics, Korea Institute of Science and Technology, South Korea

Magnetic skyrmions are topological magnetic whirls with a trivial magnetization configuration at their boundary and are believed to offer advantages in the development of novel spintronics technologies. In this work [1] we analyze skyrmions in in-plane magnets, which have recently been experimentally observed. By thorough symmetry analysis we offer possible material candidates to observe these skyrmions and determine their stability as well as their properties in those crystal symmetries. We calculate the nature of different phases arising from the energy functional corresponding to the monoclinic system *Cm*. While in the absence of stray fields a global spin rotation maps an in-plane skyrmion to its out-of-plane counterpart exactly, the presence of magnetostatic interactions changes the size and profile of the skyrmion. We also show by means of micromagnetic simulations that in-plane skyrmions can be produced via two mechanisms, namely, i) the 'blowing bubbles' technique, i.e. the creation of skyrmions due to current flow through constricted geometries and ii) shedding of skyrmions from a magnetic impurity driven by spin-transfer torques, which have been observed to their out-of-plane analogues. Furthermore, we study the spin-orbit torques driven skyrmion dynamics both analytically and through micromagnetic simulations which shows a mechanism to control the speed of skyrmions by changing the relative angle between current and uniform background magnetization direction. Our results also indicate a possibility of designing the racetrack for in-plane skyrmions might be promising candidates for storing information in racetrack memories.

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Stability of the skyrmion lattice in $Fe_{1-x}Co_xSi$

A. Bauer[1], C. Burger[1], A. Chacon[1], M. Halder[1], J. Kindervater[1], S. Mühlbauer[2], A. Heinemann[2] and C. Pfleiderer[1]

[1]*Physik-Department, Technische Universität München, D-85748 Garching, Germany*
[2] *Heinz Maier-Leibnitz Zentrum (MLZ), Technische Universität München, D-85748 Garching, Germany*
E-mail: andreas.bauer@frm2.tum.de

We report on the magnetization and susceptibility of single-crystal $Fe_{1-x}Co_xSi$, x = 0.5, complemented by small-angle neutron scattering. In small magnetic fields, this compound hosts a hexagonal lattice of topologically non-trivial skyrmions, that may metastably persist down to lowest temperatures when field-cooled. We show that signatures characteristic of the skyrmion lattice survive field values up to the field-polarized regime as well as field inversion. This stability highlights the topological protection of skyrmions allowing to exploit their unique properties, even when being present only in metastable form.

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A realistic skyrmionic synapse for deep spiking neural networks

R. Chen[1], Y. Li[1] and C. Moutafis[1]

[1]Nano Engineering and Spintronic Technologies (NEST) research group, Department of Computer Science, School of Engineering, the University of Manchester, Information Technology Building, Oxford Road, Manchester, United Kingdom, M13 9PL

Most recently, magnetic skyrmions have been proposed for developing Boolean gates and full logic systems, utilising the flow through nanowire tracks and leveraging the rich physics of skyrmions: the spin-Hall effect, the skyrmion-Hall effect, skyrmion-skyrmion repulsion, skyrmions-boundaries repulsion, and electrical current-control of notch depinning[1]–[3]. At the same time, magnetic skyrmions have attracted extensive interest in inventing CMOS-compatible nanodevices that can emulate biological synapses due to their unique physical characteristics. Specifically, a multi-bit storage device using skyrmions as information carriers (bits) has recently been proposed, where the state of the device is modulated by an electric current shifting the skyrmions in and out of the device[4]. Such a behaviour, in which the state of the system ("weight") can be dynamically adapted to the environment, is thought of analogous to the functioning of a biological synapse and its synaptic plasticity. Such multi-state systems are paramount in realising neuromorphic computing technologies including artificial synapses, artificial neurons, artificial neural networks (ANNs), spiking neural networks (SNNs) as well as reservoir computing. Specifically, the effort is needed to demonstrate results for such concepts in realistic conditions that should be of interest to the industrial and experimental communities. Therefore, such a gap is meant to be filled by this project by investigating skyrmion-based novel nano-computational paradigms under realistic conditions.

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Interaction of Skyrmions and Pearl Vortices in Superconductor-Chiral Ferromagnet Heterostructures

Samme M. Dahir[1] , **Anatoly F. Volkov**[1] **and Ilya M. Eremin**[1]

[1]*Institute für Theoretische Physik III, Ruhr-Universität Bochum, D-44780 Bochum, Germany*

We investigate a hybrid heterostructure with magnetic skyrmions (Sk) inside a chiral ferromagnet interfaced by a thin superconducting film via an insulating barrier. The barrier prevents electronic transport between the superconductor and the chiral magnet, such that the coupling can occur only through the magnetic fields generated by these materials. We find that Pearl vortices (PV) are generated spontaneously in the superconductor within the skyrmion radius, while anti-Pearl vortices ($\overline{PV}$) compensating the magnetic moment of the Pearl vortices are generated outside of the Sk radius, forming an energetically stable topological hybrid structure. Finally, we analyze the interplay of skyrmion and vortex lattices and their mutual feedback on each other. In particular, we argue that the size of the skyrmions will be greatly affected by the presence of the vortices, offering another prospect of manipulating the skyrmionic size by the proximity to a superconductor.

Magnetic and Structural Properties of Cobalt-Zinc Alloy Thin Films

M. Dearg[1], G. Burnell[1], S. Langridge[2], and C. H. Marrows[1]

[1]School of Physics and Astronomy, University of Leeds, UK
[2]Rutherford Appleton Laboratory, Science and Technology Facilities Council, UK

CoZn alloys are known to host a β-Mn phase [1], creating a structurally chiral cubic magnet which breaks spatial inversion symmetry. Such alloys can host DMI stabilised skyrmions at and above room temperature [2], making them a candidate for developing skyrmion technologies. To date these materials have primarily been studied as bulk crystals, but to realise technological applications it is necessary to produce thin films on planar substrates from which devices can be fabricated.

We show the results of CoZn thin film alloys present with the β-Mn phase ($P4_132/P4_332$ space group), thus possessing an appropriate point group symmetry to give rise to a bulk DMI and are potential candidates for an above room-temperature thin film skyrmion material. The films were grown by co-sputtering alloys from elemental targets on Si/SiO2 substrates at room-temperature. In their as-deposited form they are amorphous or nanocrystalline, lacking Bragg peaks in XRD or showing weak contributions from constituents' crystalline phases. After annealing at 400 °C for 48 hours, crystallites with the β-Mn structure form, as shown by the presence of Bragg reflections in XRD (fig. 1b) and further confirmed by TEM imaging (fig. 1c). Typical lateral crystallite sizes are of the order of 40-50 nm. Annealed samples also show an above room-temperature transition of almost 420 K (fig. 1a).

This work was supported in part by the STFC ISIS Neutron and Muon Source.

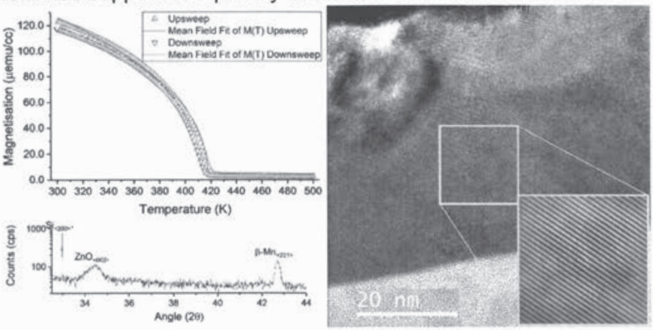

Fig. 1. (a) M(T) of $Co_{47}Zn_{53}$ alloy, annealed at 400 °C for 48 hrs; (b) XRD of sample (a), clearly identifying the ⟨221⟩ β-Mn phase; (c) TEM image of crystalline order in a Zn-rich sample under the same preparation conditions.

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Skyrmion Crystals as Topological Magnonics Platforms

S. A. Díaz[1], T. Hirosawa[2], J. Klinovaja[1], and D. Loss[1]

[1]*Department of Physics, University of Basel, Basel, Switzerland*
[2] *Department of Physics, University of Tokyo, Tokyo, Japan*

Utilizing magnons, the quanta of spin waves, as information carriers is a highly promising approach for low-power consumption devices devoid of Joule heating. The quest to harness magnonic spin waves, aided by insights from topological matter, has led to the emergence of the new field of topological magnonics. Owing to their spatially periodic noncollinear magnetic texture, skyrmion crystals have been predicted to support topologically protected magnonic edge states. We show that antiferromagnetic skyrmion crystals also host such topological edge states even within the first bulk magnon gap. Furthermore, we show that the control of robust magnon spin currents, essential for applications, could be achieved in ferromagnetic skyrmion crystals. Taking advantage of a topological phase transition in their spin wave spectrum, we show that an external magnetic field allows one to switch on and off chiral magnon currents carried by topological edge states. Our findings establish a profound symbiotic research direction for the fields of magnonics and magnetic skyrmions, positioning skyrmion crystals as novel platforms for topological magnonics.

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Interface-driven Skyrmions in $SrRuO_3$ based heterostructures

Sven Esser[1], Sebastian Esser[1], Anton Jesche[1], Vladimir Roddatis[2] and Philipp Gegenwart[1]

[1] *Experimental Physics VI, University of Augsburg, Augsburg, Germany*
[2] *Interface Geochemistry, Helmholtz Centre Potsdam, Potsdam, Germany*

Formation of Néel-type skyrmions at oxide interfaces is supported by Dzyaloshinskii-Moriya (DM) interaction through introducing a breaking of the inversion symmetry. Recently, artificial perovskite bilayers of the ferromagnetic metal $SrRuO_3$ (SRO) and spin-orbit semimetal $SrIrO_3$ (SIO) have been proposed to host two-dimensional Néel-type skyrmions [1].

Utilizing metal-organic aerosol deposition we have grown $[(SrIrO_3)_2/(SrRuO_3)_5]_k$ bilayers with k =1,5,10 repetitions on cubic (001)-oriented $SrTiO_3$ substrate to investigate the interface induced changes of the electronic and magnetic properties. The fully epitaxially strained state of the thin films was verified by X-ray diffraction patterns in combination with reciprocal space mapping and TEM images. Measurements of the in-plane magnetization indicate a systematic change with the number of interfaces between SRO and SIO layers. A contribution of the topological Hall effect to the Hall resistance can be observed for temperatures between 10K and 80K, which may hint at the formation of skyrmions.

Measurements of the angular-dependent Hall resistivity display additional contributions that are not observed in pure SRO thin films. Basically the shape can be described in good agreement with a 2-Channel anomalous Hall effect (AHE), leaving some characteristic contributions most likely related to the SRO/SIO interface.

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Optical Skyrmion Nucleation in Co-based Multilayers

K. Gerlinger[1]

[1]IMax-Born-Institute, Max-Born-Str. 2A, 12489 Berlin, Germany

Magnetic skyrmions are topological quasi-particles on the nanometer scale that can be created and annihilated in the presence of a symmetry-breaking external magnetic field using single femtosecond IR laser pulses above a material dependent fluence threshold at room temperature. In the view of potential application of skyrmions as information carriers in spintronics, optical writing schemes promise faster and more energy efficient operation of future devices.

Until now, optically nucleated skyrmions have mostly been studied in materials with high Dzyaloshinskii-Moriya interaction (DMI) like Pt/CoFeB/MgO multilayers. Skyrmions in materials with large DMI are homochiral and can be moved deterministically by electrically generated spin-polarized currents. In materials with weak DMI, such as Co/Pt multilayers, skyrmions can also be nucleated with an optical laser pulse.

Here we present a systematic study of the optical nucleation of skyrmions in magnetic materials with strong and weak DMI respectively. While the number of nucleated skyrmions varies with the applied external magnetic field both materials show no increase in skyrmion number if the fluence is increased beyond a certain critical value. In an intermediate fluence regime, the position of skyrmions nucleated by single laser pulse remains unchanged for subsequent laser shots. At high laser fluence, each shot generates a spatially completely new skyrmion arrangement. Optical skyrmion nucleation is highly dependent on the right choice of laser fluence and the external magnetic field of the sample and an understanding of the different regimes is critically needed for the development of optically operated skyrmionic devices.

Melting of Two-dimensional Magnetic Skyrmion Lattices

Kelsea Gill and Niels R. Walet

Magnetic skyrmions are particle-like spin textures that can be found in chiral magnets with non-trivial topology. At zero temperature, skyrmions often form triangular lattices similar to other two-dimensional solids. We study the temperature induced transition from solid to liquid for two-dimensional magnetic skyrmions. Using Monte-Carlo simulations, we show by examining the rate of decay of the topological charge correlations (figure 1a), we can clearly identify solid and liquid phases, as well as a potential intermediate phase. We quantify this decay by examining the ratios of the correlation function peaks (figure 1b). These ratios exhibit a steep drop within a small temperature range indicating a possible first-order transition, which is further supported by the occurrence of hysteresis when comparing melting and freezing scenarios. We compare the nature of this transition to that of typical two-dimensional solids which may also experience two-step melting passing through a hexatic phase before transitioning to a liquid. We find no evidence of the existence of a hexatic phase in our system.

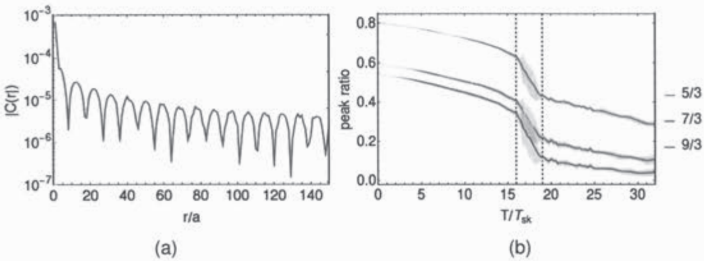

Figure 1: (a) Spatial correlation function of the topological charge density for a skyrmion solid, where a is the lattice spacing. Odd peaks indicate correlation and even peaks indicate anti-correlation. (b) Plot of the ratio of the correlation peaks five, seven, and nine to peak three against temperature, where T_{sk} is the scale of temprature expressed in terms of interaction strengths.

Atomistic simulation of electric field assisted writing and deleting of magnetic skyrmions

Moritz A. Goerzen[1], *Stephan v. Malottki*[1], *Pavel F. Bessarab*[2] *& Stefan Heinze*[1]
[1] *Institute of Theoretical Physics and Astrophysics, University of Kiel, Germany*
[2] *School of Engineering and Natural Sciences - Science Institute, University of Iceland, Iceland*
E-mail: goerzen@physik.uni-kiel.de

Future magnetic skyrmion technologies require a high degree of control of writing and deleting processes. While first experimental results demonstrate, that skyrmions can be nucleated and annihilated at will by varying electric field of a scanning-tunneling microscope tip [1], a theoretical understanding of the underlying effects is still missing. We attempt to clarify the role of the electric field in skyrmion creation and annihilation processes by means of atomistic spin dynamics simulations, minimum energy path calculations, transition state theory and density functional theory [2]. The influence of the electric field is modelled within linear response approximation to the surface magneto-electric effect and Rashba effect. We systematically study how the ground state and skyrmion stabilities are influenced by this parameter change caused by the electric field in Pd/Fe/Ir(111) system.

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Intercalated Transition Metal Dichalcogenides: Chiral Soliton Lattice

A. Hall[1], D. Mayoh[1], S. R. Holt[1], M. R. Lees and G. Balakrishnan[1]

[1]*Department of Physics, University of Warwick, Coventry, England*

Chiral helimagnetism is an incommensurate form of magnetism that arises from competition between the antisymmetric Dzyaloshinskii-Moriya interaction and the symmetric ferromagnetic exchange interaction in noncentrosymmetric materials. These magnets can host several interesting magnetic phenomena, including skyrmions and chiral soliton lattices.

This poster presents research on a family of noncentrosymmetric intercalated transition metal dichalcogenides (TMDs) of the form $M_{1/3}XS_2$, where M is the intercalate and X = Ta, Nb. The TMDs are layered materials that, when intercalated with different first row transition metals, show a diverse range of magnetic behaviours [1].

These materials crystallise in the noncentrosymmetric chiral hexagonal *P6₃22* space group. Of this family, $Cr_{1/3}NbS_2$ has been shown to host a chiral soliton lattice (CSL) when a magnetic field is applied perpendicular to the *c*-axis [2]. Magnetic solitons can be described as magnetic domain walls surrounded by regions of forced ferromagnetism. In $Cr_{1/3}NbS_2$, they are fast-moving and robust against perturbation, and so have great potential for spintronic device applications [2]. Our research aims to discover whether any other members of this family are capable of hosting chiral soliton lattices or other interesting phenomena.

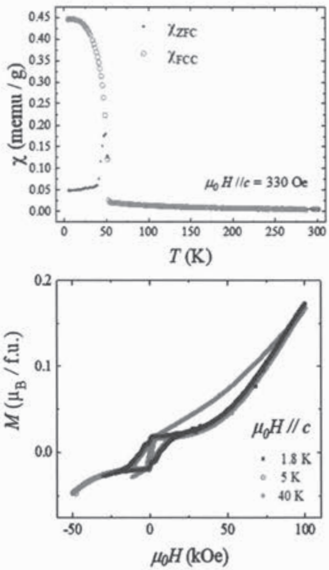

Figure 1: The *dc* susceptibility as a function of temperature (top) for $V_{1/3}NbS_2$, showing an ordering temperature of 50 K. The *dc* magnetisation for the same sample as a function of field (bottom) clealy does not saturate up to 100 kOe.

We have successfully prepared polycrystalline samples of several members of this family, as well as single crystals using chemical vapour transport with iodine as the transport agent. We present comparative phase diagrams for both $Cr_{1/3}NbS_2$ and $Mn_{1/3}NbS_2$ and the results of our magnetic property investigations for several of these materials, including $V_{1/3}NbS_2$ (as shown in Fig. 1) and $Cr_{1/3}TaS_2$.

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First-principles calculations of noncollinear magnetic structures in density functional theory

Z. Hawkhead[1], P.J.P. Byrne[2], T. Lancaster[1] and S.J. Clark[1]

[1]Univeristy of Durham, Durham, United Kingdom
[2] University of York, York, United Kingdom

Noncollinear magnetic systems typically have interactions on energy scales much smaller than those that determine the electronic structure. An attempt to use first-principles techniques to determine the magnetic structure of a systems using an unconstrained minimisation method is therefore unlikely to yield a reliable solution. Here we present a method to constrain noncollinear magnetic structures within self-consistent spin-density functional theory, that we have implemented using the CASTEP plane wave code [1]. This method involves the inclusion of an energy penalty in the Hamiltonian that is minimised when the magnetisation of the constrained atom lies in the desired direction [2]. We present an example of the method by applying constraints to a triangular lattice of Mn atoms to calculate a range of magnetic configurations.

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Measurement of magneto-crystalline anisotropies in MnSi by means of torque magnetometry

M. Hollricher[1], S. Sauther[1], A. Bauer[1], and C. Pfleiderer[1]

[1]Physik Department, Technische Universität München, D-85748 Garching, Germany

The formation and stabilization of skyrmions in magnetic materials may be driven by a multitude of interactions, such as Dzyaloshinskii-Moriya interactions, frustrated and four-spin exchange interactions, long-range magnetic dipolar interactions, and magneto-crystalline anisotropies.

Despite typically being associated with the weakest energy scale, seminal work by Bogdanov *et al.* in the 1980s [1] showed that magnetic anisotropies may stabilize skyrmion lattices in certain types of non-cubic compounds. The first observation of a skyrmion lattice in a magnetic material, however, was reported about a decade ago, in the cubic chiral magnet MnSi [2], where thermal fluctuations play a key role for its stabilization. Just recently an independent second skyrmion phase was discovered at low temperatures in a different cubic chiral magnet, Cu_2OSeO_3 [3]. While the high-temperature skyrmion lattice, that is commonly found in this class of compounds, forms independently for all crystallographic directions, this second novel state can only be observed for magnetic fields applied along the <100> axes, highlighting the importance of magneto-crystalline anisotropies for stabilizing this state [4]. So far, however, information on the quantitative strength of the magneto-crystalline anisotropies in cubic chiral magnets is scarce [5,6,7,8].

Here, we report a comprehensive study of the archetypical cubic chiral magnet MnSi using the standard technique for the determination of anisotropies in magnetic systems, namely torque magnetometry. We discuss our results in terms of a Ginzburg-Landau description of the magnetic properties and give an outlook on future studies on related systems.

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Lorentz TEM simulations of magnetic structures

S. J. R. Holt[1], J. C. Loudon[2], D. Cortés-Ortuño[3], & G. Balakrishnan[1]

[1]Department of Physics, University of Warwick, Coventry, CV4 7AL, United Kingdom
[2] Department of Materials Science and Metallurgy, University of Cambridge, 27 Charles Babbage Road, Cambridge, CB3 0FS, United Kingdom
[3] Faculty of Engineering and the Environment, University of Southampton, Southampton, SO17 1BJ, United Kingdom

Lorentz Transmission Electron Microscopy is an extremely useful and prominent technique that enables in situ imaging of magnetic structures in < 200 nm thick materials and can provide resolution on the nanometre scale [1]. In contrast to classical TEM, Lorentz TEM uses the phenomenon of the Lorentz force that deflects incoming electrons in the sample's magnetic field. These deflections can be viewed by changing how far out focus an image is taken, creating regions of interference giving a series of bright and dark patterns. The nature of this force means it is only sensitive to the in-plane component the magnetic field throughout the sample, hence it is not trivial to work out the Lortentz TEM pattern produced from an arbitrary magnetisation structure in a material.

We have produced a simulation programme capable of creating Lorentz TEM, Electron holography, and X-ray holography images from a magnetisation input, such as micromagnetic simulations. Using the software, we will present direct comparisons of micromagnetic simulations of skyrmions to experimental images from Lorentz TEM, and simulated imaging of skyrmions in confined geometries and those viewed under different rotations.

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XMCD-STXM Magnetic Imaging of Skyrmions with in-situ Hall Transport measurements in Pt/Co/Ir multilayer Hall discs

Alexandra Huxtable

University of Leeds, School of Physics / Condensed Matter, Leeds/UK

Transport measurements of skyrmions and their interpretation, by connection to the magnetic state at the time of measurement, are essential for their potential application in data storage. In-situ Hall transport measurements combined with XMCD-STXM imaging of the magnetic texture have been developed by Finizio et al. [1] and used in the investigation of the discrete hall resistivity contribution due to Néel skyrmions by Zeissler et al. [2]. Continued research into the skyrmion contribution to Hall resistivity is needed to explain the discrepancy in the magnitude of the contribution observed in Ref. 2 compared to that predicted by theory. Hall discs of ~1 μm diameter are imaged using combined X-ray Magnetic Circular Dichroism and Scanning Transmission X-ray Microscopy at the PolLux endstation at PSI [1]. The Hall devices are [Pt/CoB/Ir] multilayers grown by DC magnetron sputtering on Si_3N_4 membranes and patterned by electron beam lithography. The devices are imaged during in-situ Hall resistivity measurements in order to verify the texture of the magnetisation in the samples and yield images and Hall resistance data which can be decomposed into the independent ordinary, anomalous, and topological Hall effects. The topology of the magnetisation of skyrmions is defined by the skyrmion winding number, $S=1/4\pi \int M\cdot (\partial M/\partial x \times \partial M/\partial y)\, dxdy$, and the imaging during transport measurements allows the topology associated with the Hall resistivity measurements to be known.

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Magnetic domain formation and its relation to the magneto-transport properties of ultra-thin $SrRuO_3$ epitaxial layers

G. Malsch[1], D. Ivaneyko[1], P. Milde[1], L. Wysocki[2], L. Yang[2], P. H.M. van Loosdrecht[2], I. Lindfors-Vrejoiu[2] and L. M. Eng[1,3]

[1] Institute for Applied Physics, TU Dresden, 01062 Dresden, Germany
[2] II. Physikalisches Institut, Universität zu Köln, 50937 Köln, Germany
[3] Center for Advancing Electronics Dresden (cfaed), TU Dresden, 01062 Dresden, Germany

In the last decade, the new magnetic phases with non-trivial topology, such as skyrmions, have been in the focus of experimental and theoretical physics. These hold promise for unique applications in magnetic data storage devices, due to their topological protection and the possibility to form skyrmions below a 100-nm critical size, even at room temperature. Beyond bulk and ultra-thin metallic films, skyrmions formation can also be realized in ferromagnetic ultra-thin polycrystalline layers with perpendicular magnetic anisotropy.

One such system are the $SrRuO_3$-based perovskite oxide ultra-thin films. It was postulated recently, that epitaxial layers of 4-unit-cells $SrRuO_3$ and its heterostructures thereof might possibly show the expected skyrmion formation [1], as commonly investigated and proven through macroscopic transport measurements, then indicating the topological nature through anomalies observed in the Anomalous Hall effect (AHE) resistivity loops, hence claimed Topological Hall effect (THE). Doubts on the validity and soundness of those data has considerably increased lately. This is where our study starts, by correlating the macroscopic transport findings with both macroscopic Magneto-Optical-Kerr-Effect (MOKE) and nanoscopic Magnetic Force-Microscopy (MFM) investigations. As a result, we are able to prove that local variations within the 4-uni-cell $SrRuO_3$ layer cause variations in the local switching fields, that in turn mimic THE [2].

Our analysis allows associating topographic sample features of overgrown individual layers to their residual magnetization, as is shown here to be relevant for interpreting the macroscopic AHE data. Although the hump-like features in the AHE suggest a magnetically textured skyrmion phase to exist around 55 K associated to the THE, both our MOKE and MFM data cannot support this theory. In contrast, our SFM/MFM local scale analysis finds the local coercive field to be strongly dependent on the effective layer thickness, with huge impact on the local band-structure [2].

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Spatial Control of Magnetic Skyrmions in Multilayers by Ion Irradiation

L.-M. Kern[1], K. Gerlinger[1], M. Schneider[1], C.-M. Günther[2,3], D. Engel[1], K. Höflich[4], F. Büttner[5], G.S.D. Beach[5], B. Pfau[1] and S. Eisebitt[1,3]

Affiliations: [1]Max-Born-Institut, 12489 Berlin, Germany, [2]Zentraleinrichtung für Elektronenmikroskopie (ZELMI), Technische Universität Berlin, 10623 Berlin, Germany, [3]Institut für Optik und Atomare Physik, Technische Universität Berlin, 10623 Berlin, Germany, [4]Helmholtz Zentrum für Materialien und Energie Berlin, 14109 Berlin, Germany, [5]Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA.

Magnetic skyrmions are two-dimensionally localized, particle-like spin textures in a magnetization vector field. Due to their fascinating intrinsic and emerging properties, they are considered as novel information carriers in high-density, non-volatile memory devices such as the so-called skyrmion racetrack memory . The memory's three basic operations – writing, deleting and shifting – were already realized by sending a current through the skyrmion racetrack.

Femtosecond laser pulses offer an alternative way of manipulating magnetization. This kind of excitation has led to the observation of picosecond demagnetization, all-optical switching, and the creation of skyrmions. In order for skyrmions to become next generation information carriers in spintronics devices, the nucleation sites of skyrmions need to be well-defined and reproducible.

Our current project focuses on the controlled optical generation as well as manipulation and annihilation of skyrmions using ion irradiation to achieve tailored nanostructuring of Co-based multilayer samples. Tuning the magnetic anisotropy and coercive field leads to a well-defined patterning without changing the topography. We are currently optimizing the nanofabrication such that our samples provide channels for skyrmion nucleation and regions with different domain sizes with the prospect to control the localization of single-shot skyrmion nucleation in the next step.

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Production of Magnetic Textures in Different Dimensions

R. Knapman[1], D. R. Rodrigues[1], V.K. Bharadwaj[1], J. Sinova[1,2] and K. Everschor-Sitte[1]

[1]Institut für Physik, Johannes Gutenberg-Universität Mainz, Mainz, Germany
[2] Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic

A mechanism to create magnetic textures is to exploit the interplay of current-induced forces with magnetic inhomogeneities. In a 1D wire, it has been shown that this mechanism allows for the periodic production of domain walls[1-3] and in 2D it allows for the shedding of magnetic skyrmion-antiskyrmion pairs[4-6]. In 1D, it is possible to obtain an analytical solution to the problem which agrees very well with the results of micromagnetic simulations. In 2D there are more degrees of freedom and within numerical simulations, we found that the degree of elasticity in the shedding process results in a change in the periodicity of the shedding, going beyond the previous results. We are therefore constructing a model to capture this effect. Furthermore, we aim to extend our work to the investigation of the shedding of 3D magnetic textures from localised impurities. For this, we aim to investigate quantitative aspects such as the dependence of critical current and shedding frequency on the nature of the impurity, as well as qualitative aspects such as the nature of the objects shed.

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Turning chiral skyrmion inside out

Vladyslav M. Kuchkin,[1,2,*] Filipp N. Rybakov,[3,†] Nikolai S. Kiselev,[1,‡] and Stefan Blügel[1]

[1] *Peter Grünberg Institute and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany*
[2] *Department of Physics, RWTH Aachen University, 52056 Aachen, Germany*
[3] *Department of Physics, KTH-Royal Institute of Technology, Stockholm, SE-10691 Sweden*

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We consider the basic two-dimensional (2D) model of a chiral magnet including the Heisenberg exchange interaction, the Dzyaloshinskii-Moriya interaction (DMI), the interaction with the external magnetic field and the uniaxial magnetocrystalline anisotropy for both cases of easy-axis ($K_\mathrm{u} > 0$) and easy-plane ($K_\mathrm{u} < 0$). The exchange interaction and DMI are assumed to be isotropic, the direction of the homogeneous external magnetic field $\mathbf{B}$ is defined by polar θ, and azimuthal angle, φ, $\mathbf{B} = B\,(\sin\theta\,\cos\varphi, \sin\theta\,\sin\varphi, \cos\theta)$.

It is shown that for any $0 \leq \theta \leq \pi$ there is always a finite range of $B_\mathrm{min} < B < B_\mathrm{max}$ where both magnetic skyrmions with $Q = -1$ and $Q = +1$ remain stable. It is shown that by varying the absolute value of the magnetic field with the tilt angle one can *continuously* transform the axisymmetric skyrmion at $h\uparrow\uparrow\hat{\mathbf{e}}_\mathrm{z}$ (or $h\downarrow\uparrow\hat{\mathbf{e}}_\mathrm{z}$) into non-axisymmetric skyrmion with opposite polarity and opposite helicity which remains stable even in fully inverted field $h\downarrow\uparrow\hat{\mathbf{e}}_\mathrm{z}$ ($h\uparrow\uparrow\hat{\mathbf{e}}_\mathrm{z}$), in other words, one can turn chiral skyrmion inside out. The energy difference between a skyrmion, $Q = -1$, and an antiskyrmion, $Q = +1$, depends on the tilt angle of the applied magnetic field, $\mathbf{B}$. It absolute value reaches maxima for $\theta = 0$ and π, and vanishes when magnetic field is in-plane, $\theta = \pi/2$. In contrast to earlier theoretical studies [1-9], we found in case of the tilted magnetic field $\theta \neq 0$ that the anisotropic potential of inter-skyrmion interactions has a number of local minima corresponding to equilibrium states of coupled skyrmions. Varying the tilt angle, θ, and the absolute value of the applied magnetic field, B, one can control the interactions between skyrmions and switch the repulsive character of the inter-skyrmion interaction to an attractive one. The peculiarities of the skyrmion-skyrmion, skyrmion-antiskyrmion, and antiskyrmion-antiskyrmion interactions are discussed in details. It is shown that the results obtained for the 2D model are also valid for the case of the thin films with finite thickness. Moreover, the observed phenomena are proven to be stable in the presence of demagnetizing fields.

The discovery of new phenomena due to the attractive interaction between skyrmions and the coexistence of skyrmions with opposite topological charges over a range of external field tilt angles opens up new directions for fundamental research and can be useful in practical applications of magnetic skyrmions.

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* v.kuchkin@fz-juelich.de
† f.n.rybakov@gmail.com
‡ n.kiselev@fz-juelich.de

Topological Hall effect in the antiskyrmion hosting Heusler system Mn-Pt-Sn

V. Kumar[1,2], N. Kumar[1], M. Reehuis[3], J. Gayles[1], C. Shekhar[1], P. Adler[1] and C. Felser[1]

[1]Max-Planck-Institut für Chemische Physik fester Stoffe, Dresden, Germany
[2]Technische Universität München, München, Germany
[3]Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin, Germany

Heusler compounds having D_{2d} crystal symmetry gained much attention recently due to the stabilization of antiskyrmions in $Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$ [1]. The antiskyrmions differ from Bloch and Néel skyrmions by an anisotropic winding of the in-plane moments and by having opposite topological charge. The topological winding induces a real space Berry curvature that strongly influences all transport properties. Among them the topological Hall effect is a unique electrical transport property which is used to detect the skyrmions or other non-coplanar spin structures [2].
Here, we present a comprehensive powder neutron diffraction study of $Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$ in order to unravel the detailed magnetic structure. This compound undergoes a spin-reorientation transition at ~135 K and transforms from a high temperature collinear ferromagnetic state to a low temperature non-collinear spin configuration. Further, we show the structural, magnetic and electrical transport properties of two series of Heusler compounds $Mn_{1.4}Pt_{1-x}Pd_xSn$ ($0 \le x \le 0.3$) and $Mn_{1.4}Pt_{1-y}Rh_ySn$ ($0.1 \le y \le 0.8$). The chosen elements Pd (isoelectronic substitution) and Rh (varying the number of valence electrons) are substituted in the place of the heavy metal Pt in $Mn_{1.4}PtSn$. Both Pd and Rh substitutions are employed to alter the spin orbit coupling, whereas Rh substitution additionally affects the electron occupancy, which aims to change the position of the Fermi level. As a consequence the magnetocrystalline anisotropy, exchange and Dzyaloshinskii-Moriya interactions are altered. We observed the topological Hall effect below the spin reorientation transition in a broad composition range owing to the field induced non-coplanar spin structure. Interestingly, some compounds show an inverse hysteretic feature in the Hall resistivity compared to the magnetization which suggests the formation of antiskyrmions.

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Tuneable Bloch-point dynamics during switching of skyrmions and antiskyrmions in chiral magnets

Yu Li[1], Leonardo Pierobon[2], Michalis Charilaou[3], Hans-Benjamin Braun[2,4], Niels R. Walet[5], Jörg F. Löffler[2], James J. Miles[1], Christoforos Moutafis[1,2]

[1]Nano Engineering and Spintronic Technologies (NEST) group, Department of Computer Science, University of Manchester, Manchester M13 9PL, United Kingdom. [2]Laboratory of Metal Physics and Technology, Department of Materials, ETH Zurich, 8093 Zurich, Switzerland. [3]Department of Physics, University of Louisiana at Lafayette, Lafayette LA 70504, USA. [4]Dublin Institute of Advanced Studies, Dublin D04 C932, Ireland. [5]Theoretical Physics, Department of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom.

Magnetic skyrmions are chiral spin textures with spins in the central core pointing out of plane, and smoothly twisting and rotating into the antiparallel direction. By virtue of the antisymmetric Dzyaloshinskii-Moriya interaction (DMI), skyrmions and other skyrmionic textures, including antiskyrmions, and skyrmioniums can be found in the magnetic materials with a corresponding quantised topological charge [1-3]. Recent advances highlight the magnetic transitions of skyrmionic bubbles which provides rich insights of transitions of topological charge [4], and the existence of skyrmions in room temperature [2] suggests skyrmionic-based devices to become promising candidates on high-density and high-stability storage devices.

In this work, we numerically show that the formation/annihilation of both skyrmions and antiskyrmions is mediated by the transient creation and propagation of Bloch points. During the dynamical processes, an emergent electric field [5, 6] can be radiated with substantial magnitude and frequency in a terahertz range. Furthermore, we also demonstrate the underlying connections of Bloch point dynamics with magnetic parameters, which enables the controllability of the terahertz electromagnetic signals. To take a step further, the design of realistic notches provides a brand-new degree of manipulating energy barriers of skyrmionic switching in chiral magnetic systems, making it possible to realise deterministic skyrmionic switching mechanisms [7].

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Extension of the Heisenberg model due to multispin interactions: first priciple calculations and impact on the magnetic structure

S. Mankovsky, S. Polesya, and H. Ebert

Dept. of Chemistry / Phys Chemistry, LMU Munich, Butenandtstrasse 11, D-81377 Munich, Germany

We present an efficient approach for the calculation of the interatomic exchange interaction parameters of the extended Heisenberg model Hamiltonian. This approach is based on the fully relativistic multiple scattering Korringa-Kohn-Rostoker (KKR) formalism and gives access to bilinear isotropic exchange and Dzyaloshinskii-Moriya interactions (DMI), as well as to higher-order multispin interaction terms entering the Heisenberg Hamiltonian beyond the classical version. The formation of skyrmions is in most cases attributed to the competition of DMI with the isotropic exchange and external magnetic field, while the exchange interactions of higher order are usually ignored. However, their impact on the stabilization of various magnetic structures including skyrmions can be crucial and only first principles calculations of these interactions allow to conclude which of them can be neglected. We discuss the properties of chiral biquadratic and three-spin interactions, distinguishing two types of the latter having relativistic and topological origin. We consider also a possible impact of different multispin interactions on a skyrmionic magnetic structure.

Characterizing breathing dynamics of magnetic skyrmions and antiskyrmions within the Hamiltonian formalism

B. F. McKeever[1], **D. R. Rodrigues, D. Pinna, Ar. Abanov, Jairo Sinova, and K. Everschor-Sitte**

[1]*Institute of Physics, Johannes Gutenberg-Universität, 55128 Mainz, Germany*
[2]*Graduate School Materials Science in Mainz, Staudingerweg 9, 55128 Mainz, Germany*
[3]*Department of Physics & Astronomy, Texas A&M University, College Station, Texas 77843-4242, USA*
[4]*Institute of Physics ASCR, v.v.i, Cukrovarnicka 10, 162 00 Prag 6, Czech Republic*

We derive an effective Hamiltonian system describing the low energy dynamics of circular magnetic skyrmions and antiskyrmions using collective coordinates [1]. An effective energy landscape reveals two qualitatively different types of breathing behavior. For small perturbations we reproduce the well-known small breathing mode excitations, where the magnetic moments of the skyrmion oscillate around their equilibrium solution. At higher energies we find a rotational breathing behavior, continuously transforming the helicity between Neel and Bloch skyrmions. For a damped system we observe the transition from the continuously rotating and breathing skyrmion into the weakly oscillating one. We analyze the characteristic frequencies of both types, as well as their amplitudes and energy dissipation rates. For rotational (oscillatory) breathing modes we predict on average a linear (exponential) decay in energy. This stark difference in dissipative behavior should be observable in the frequency spectrum of excited skyrmions and antiskyrmions.

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Origin of skyrmion lattice phase splitting in Zn-substituted Cu_2OSeO_3

A. Štefancic[1], S. H. Moody[2], T. J. Hicken[2], M. T. Birch[2], G. Balakrishnan[1], S. A. Barnett[3], M. Crisanti[1,4], J. S. O. Evans[5], S. J. R. Holt[1], K. J. A. Franke[2], P. D. Hatton[2], B. M. Huddart[2], M. R. Lees[1], F. L. Pratt[6], C. C. Tang[3], M. N. Wilson[2], F. Xiao[7,8] and T. Lancaster[2]

[1]University of Warwick, Department of Physics, Coventry CV4 7AL, United Kingdom
[2]Durham University, Department of Physics, South Road, Durham DH1 3LE, United Kingdom
[3]Diamond Light Source, Harwell Science and Innovation Campus, Didcot OX11 0DE, United Kingdom
[4]Institut Laue-Langevin, Large Scale Structures Group, 71 Avenue des Martyrs CS 20156, 38042 Grenoble, Cedex 9, France
[5]Durham University, Department of Chemistry, South Road, Durham DH1 3LE, United Kingdom
[6]ISIS Facility, STFC Rutherford Appleton Laboratory, Chilton Didcot, Oxfordshire OX11 0QX, United Kingdom
[7]Laboratory for Neutron Scattering, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
[8]Department of Chemistry and Biochemistry, University of Bern, CH-3012 Bern, Switzerland

We present an investigation into the structural and magnetic properties of Zn-substituted Cu_2OSeO_3, a system in which the skyrmion lattice (SkL) phase in the magnetic field–temperature phase diagram was previously seen to split as a function of increasing Zn concentration. We find that splitting of the SkL is only observed in polycrystalline samples and reflects the occurrence of several coexisting phases with different Zn content, each distinguished by different magnetic behavior. No such multiphase behavior is observed in single-crystal samples.

Monte Carlo studies of metastable skyrmion lifetimes

V. Nehruji[1] and O. Hovorka[1]

[1]*University of Southampton, Southampton, Hampshire*

With the increasing need for nano-scale devices with enhanced functionalities and greater data storage capacities, there is a rising interest in the field of spintronics as an alternative to the currently-used semiconductor devices. Future devices based on skyrmions – a topologically protected magnetic particle-like domains – can potentially replace electron charge as the elementary data particle[1]. Unfortunately, in most practical materials skyrmions exists only in a narrow region of the field-temperature phase diagram[2]. On the other hand, metastable skyrmions can persist into a much broader range of field and temperatures, including room temperatures, and have been subject of investigations in order to increase their life-time and stability properties. Numerous studies have suggested the possibilities to increase the lifetime of the metastable skyrmions, such as by increasing the disorder in the system[3] or optimising the field cooling protocols[4]. Here we report our preliminary results based on Monte-Carlo simulations of metastable skyrmion phases and their dependence on the rate-of-change of the external field and temperature within the state-preparation protocol for selected material systems, and quantify the associated skyrmion life-times and the corresponding energy barriers.

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First-principles based study of skyrmions in Fe/Rh bilayers on Re(0001)

S. Paul[1] and S. Heinze[1]

[1]Institute of Theoretical Physics and Astrophysics, Christian-Albrechts-Universität zu Kiel, Leibnizstrasse 15, 24098 Kiel, Germany

Transition-metals monolayer on superconducting Re are promising candidates for realizing Majorana bound states which is an essential component of a topological quantum computer [1,2]. The prerequisite is a noncollinear structure within the transition-metal layer. Rh/Fe bilayers on Ir(111) exhibits complex magnetic structures due to a competition of Dzyaloshinskii-Moriya interaction (DMI) and higher-order exchange interactions (HOEI) [3]. The above facts indicate that Fe/Rh bilayers on Re(0001), a 5d transition-metal substrate with strong spin-orbit coupling (SOC) which becomes superconductor at T= 2.4 K, would be an interesting system to investigate. Using density functional theory (DFT), we calculate spin-spiral (SS) energy dispersion with and without SOC and also compute HOEI constants for Fe/Rh and Rh/Fe bilayers on Re(0001). Our results show that the magnetic ground state of Fe/Rh/Re(0001) can easily be tuned by changing the stacking sequences of Fe/Rh bilayers. One of our system, where SS is the ground state, are promising for hosting isolated skyrmions. We mapped DFT energies of that system onto a spin Hamiltonian to investigate the stability of magnetic skyrmions using atomistic spin dynamics simulations.

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Topologically Non-trivial Magnetic and Polar Patterns in Lacunar Spinels

M. Preißinger[1], H.-A. Krug von Nidda[1], A. Lubk[2], S. Bordács[3], H. Nakamura[4], V. Tsurkan[1] and I. Kézsmárki[1]

[1]Experimentalphysik V, Zentrum für Elektronische Korrelation und Magnetismus, Institut für Physik, Universität Augsburg, Germany

[2]Advanced Methods of Electron Microscopy, Electron Microscopy and Spectroscopy, Institut für Festkörperforschung, Leibniz-Institut für Festkörper- und Werkstoffforschung Dresden, Germany

[3]Magneto-Optical Spectroscopy Group, Department of Physics, Faculty of Natural Science, Budapest University of Technology and Economics, Hungary

[4]Department of Materials Science and Engineering, Kyoto University, Japan

The lacunar spinels $Ga(V/Mo)_4(S/Se)_8$ have been the first candidates, where the emergence of Néel-type skyrmions, induced by Dzyaloshinsky-Moriya interaction, has been reported. This group of materials undergo a Jahn-Teller transition at about 40K losing inversion symmetry in the process. Upon further cooling the system enters a magnetically ordered state. The ground state is a cycloidal phase, while critical fields strongly depend on the direction in which the magnetic field is applied [1][2]. In an attempt to image skyrmions with Lorentz-transmission-electron microscopy (LTEM), we succeeded to find the cycloidal ground state in $GaV_4(S/Se)_8$, while in $GaMo_4S_8$ no magnetic texture has been found. In the thin lamellae of $GaV_4(S/Se)_8$ (<100nm) the magnetic ordering appears to happen at a hugely increased temperature simultaneously to the Jahn-Teller distortion. As a consequence of this distortion the materials form polar structural domains, in order to minimize the depolarisation energy. In thin lamellae of $GaMo_4S_8$ no magnetic texture but a regular pattern of polarised structural domains has been found, presumably indicating polar skyrmions.

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Quantitative Magnetic Force Microscopy of Skyrmions in Co/Ru/Pt multilayers

B.Sakar[1,2], A.Fernandez-Scarioni[1], S.Sievers[1], M.Bieler[1], F.Ajejas[3], W.Legrand[3], N.Reyren[3], V. Cros[3], V.Neu[4] , O.Öztürk[2], H.W.Schumacher[1]

[1] *Physikalisch Technische Bundesanstalt, Braunschweig, Germany*
[2] *Gebze Technical University, Kocaeli, Turkey*
[3] *Unité Mixte de Physique CNRS/Thales, Palaiseau, France*
[4] *IFW Dresden, Dresden, Germany*

In this last decade magnetic skyrmions appealed great interest due to their potential in applications such as spintronic devices. Within these couple of years, there have been reports for different efficient methods to create and manipulate nanometer-sized skyrmions. Nevertheless, despite these advances, there are still difficulties in measuring their quantitative physical properties such as effective magnetic moment and/or magnetization pattern. Quantitative magnetic force microscopy (qMFM) is a technique for measuring the stray field distribution of a magnetic surface by using the so-called tip transfer function (TTF) approach. In this technique, measurements of a well-defined reference sample yield the TTF calibration parameter of the specific MFM tip which can then be used for quantitative stray field imaging of the sample under investigation.

In this study, a micropatterned multilayer stack of Ta/Pt/[Co(1 nm)/Ru(1.4 nm)/Pt(0.6 nm)]10/Pt is investigated. Skyrmions are generated by current-induced nucleation. Stray field, size and distribution of skyrmions are investigated by qMFM as function of external field applied during the nucleation and measurement, respectively. The TTF calibration is based on a Si(100)/SiOx/Ta/Pt(5 nm)/[Co(0.4 nm)/Pt(0.9 nm)]100 /Pt reference sample as validated by an international qMFM comparison.

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Magnetic structure and Hall-effect study of $SrRuO_3$(SRO) films on $SrTiO_3$(STO) (001): Search for interface stabilized Skyrmions in oxide structure

***Kartik Samanta[1]**, Marjana Ležaić[1], Yuriy Mokrousov[1] and Stefan Blügel[1]*
[1]Peter Grünberg Institut and Institute for Advanced Simulation
Forschungszentrum Jülich and JARA, 52425 Jülich, Germany

Abstract:

Oxides interfaces offer a new perspective to stabilize the magnetic skyrmion due to their response to electric fields, low Ohmic losses, variety of interface symmetry as well as the prospective anisotropic Dzyaloshinskii-Moriya interaction (DMI). Here, we investigate by virtue of spin density functional theory (DFT) as realized in the ***FLEUR*** code [1], magnetic structure and topological transport properties of ultrathin film of $SrRuO_3$ on $SrTiO_3$ (001) substrate to search the interface stabilized skyrmion in oxide structure. At the mono-layer limit of $SrRuO_3$ film, magnetic ground state is found to be an anti-ferromagnetic insulator. We found that large energy level splitting of Ru-t_{2g} states, caused by compressive strain into the thin film layer, stabilized the anti-ferromagnetic ground state. The computed topological transport properties showed a large Hall response for the anti-ferromagnetic insulating ground state (with zero net magnetic moment). From the systematic investigation of our results we found that broken *time-reversal and other symmetries* which are caused by arrangement of non-magnetic atoms in the mono-layer of SRO, generated large Hall response. Very recently [2] this kind of Hall effect was predicted theoretically in collinear anti-ferromagnet and termed as ***crystal Hall effect (CHE).*** At the mono-layer limit, a sizable amount of orbital magnetic moment (**0.14** μ_B) is found at the Ru sites compared to the bulk $SrRuO_3$. We hope that strong spin-orbit coupling at Ru sites together with broken inversion symmetry in the ultrathin film will give rise DMI which can stabilize the Skyrmion in this system.

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Antiferromagnetic Superstructures with nontrivial Topology in the Rare-Earth Intermetallic HoCu

W. Simeth[1], M. Rahn[2], A. Bauer[1], C. Pfleiderer[1]

[1] TU München, Germany
[2] TU Dresden, Germany

In rare-earth intermetallics the competition of several interactions often leads to intriguing magnetic ground states, which possibly possess topological properties. We present a study on the intermetallic compound HoCu, which is antiferromagnetic and a candidate material for hosting topologically nontrivial ground states, even though it is centrosymmetric. We found rich magnetic properties, such as a complex magnetic phase diagram and an unconventional Hall effect, which indicates the emergence of finite Berry phases. To determine magnetic structures, we used sophisticated neutron scattering techniques. We found antiferromagnetic ground states, which are multi-*k* and have long-wavelength modulations. Furthermore, our results suggest an important interplay between topology of magnetic and electronic structure.

Establishing magneto-structural relationships in the search for skyrmion hosts within the $GaV_4S_{8-y}Se_y$ family of materials

A. Štefančič[1], S. J. R. Holt[1], C. Ritter[2], M. J. Gutmann[3], M. R. Lees[1], & G. Balakrishnan[1]

[1] *Department of Physics, University of Warwick, Coventry, United Kingdom*

[2] *Institut Laue Langevin, Grenoble Cedex, France*

[3] *ISIS Facility, Rutherford Appleton Laboratory, Oxfordshire, United Kingdom*

Recently, there has been considerable interest in the physics of magnetic skyrmions and the materials in which they are hosted due to their potential uses in spintronic devices [1]. Magnetic skyrmions are topological magnetic spin structures that were originally identified in materials belonging to the B20 class but have recently been found in other non-centrosymmetric materials [2].

Multiferroic GaV_4S_8 and GaV_4Se_8 have been shown to host Néel type skyrmions [3,4]. These two materials are isostructural and at low temperature crystallize in non-centrosymmetric $R3m$ space group, but they exhibit very different magnetic phase diagrams at low temperatures. In GaV_4S_8 and GaV_4Se_8 the magnetocrystalline anisotropies favor the formation of skyrmion magnetic spin textures constrained to particular crystallographic axis. We have undertaken investigations of several intermediate compositions of $GaV_4S_{8-y}Se_y$ to try to identify variations in magnetic behavior across the series, in an attempt to investigate the possibility of observing skyrmions in the intermediate phases.

Phase-pure polycrystalline solid-solutions of the $GaV_4S_{8-y}Se_y$ ($0 \leq y \leq 8$) family have been successfully synthesized of and high-quality single crystals grown using the chemical vapour transport technique. We present the results of our detailed investigations of the crystal and magnetic structures of this series of materials as both powders and single crystals, using X-ray as well as neutron diffraction techniques. These results are further supported by dc and ac magnetic susceptibility, and heat capacity measurements within the series.

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Resonant Soft X-ray Imaging of Topological Spin Textures in MnNiGa Lamellae

L. A. Turnbull[1], M. T. Birch[1], N. Bukin[2], H. Popescu[3], F. Y. Ogrin[2], J. Gräfe[3], P. D. Hatton[1]

[1]*Durham University, Durham, UK*

[2]*University of Exeter, Exeter, UK*

[3]*Max Plank Institute for Intelligent Systems, Stuttgart, Germany*

There is an intense research effort directed towards magnetic skyrmions, due to their potential applications in spintronic devices. This has led to the reported observation of exotic spin textures such as the bound-pair biskyrmion, in centrosymmetric systems such as the Ni_2-In structured $(Mn_{0.5}Ni_{0.5})_{65}Ga_{35}$ (MnNiGa) [1][2]. All previous imaging of biskyrmions has used Lorentz transmission electron microscopy (LTEM), which is sensitive to projected magnetic fields. Here we show imaging of the out of plane magnetization textures in MnNiGa lamellae, using a high resolution, resonant x-ray holographic technique known as HERALDO [3]. By tilting the sample relative to the incoming beam, the in-plane components of magnetisation can also be measured and used to identify the topological properties of such spin textures. Following procedures previously reported to generate biskyrmions, holographic images of textures in MnNiGa were produced. The characteristic twin core of a biskyrmion was not observed, and this forms part of the work by Loudon et. al, suggesting that reports of magnetic biskyrmions may be misidentified type-II bubbles [4]. These measurements were further corroborated with scanning transmission x-ray microscopy (STXM) images.

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Large topological Hall effect in antiskyrmion hosting compound $Mn_{1.4}PtSn$

P. Vir[1], J. Gayles[1], A. S. Sukhanov[1], N. Kumar[1], Y. Sun[1], C. Shekhar[1], and C. Felser[1]

[1]Max Planck Institute for Chemical Physics of Solids, Dresden, Germany

Email: Vir@cpfs.mpg.de

Skyrmions are topologically stable vortex-like spin structure which are considered as potential candidate for future high-density memory devices. They have been detected in many chiral and polar compounds such as MnSi, FeGe, Co-Mn-Zn, GaV_4S_8, and $VOSe_2O_5$. Three types of vortex spin structure have been predicted and observed so far namely, Bloch, Néel and antiskyrmions. Existence of these exotic spin structures depends upon the crystal symmetry. Recently, by means of Lorentz transmission electron microscopy, antiskyrmions have been discovered in Mn-based tetragonal Heusler compound $Mn_{1.4}PtSn$ and $Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$. Antiskyrmion is considered to be anti-particle of Néel or Bloch type skyrmion because it consists opposite topological winding number. Due to this topologically stable spin nature, it can give rise to non-vanishing Berry phase in real space. This could result in nonzero topological Hall Effect (THE). Here, we report large THE and its origin in single crystals of antiskyrmion hosting compound $Mn_{1.4}PtSn$. We show for the first time that THE has contributions both from real and momentum-space Berry phase.

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Smooth monopoles and Skyrmion destruction

E. Walton

Department of Applied Mathematics and Theoretical Physics,
University of Cambridge, Cambridge, United Kingdom
E-mail: e.walton@damtp.cam.ac.uk

The transition between the Skyrmionic and helical phases of a chiral magnet is mediated by emergent magnetic monopoles. In the usual micromagnetic theory, these are singular defects in the magnetisation field, put in 'by hand'.

We present a theory which smoothly resolves the short-distance behaviour of the micromagnetic theory. The theory admits non-singular (anti)monopole configurations confined by tubes of Skyrmion density flux. The monopoles are usually dynamically unstable, but become (meta)stable at the Skyrmion-to-helix phase transition.

When the theory is critically coupled, the monopole-Skyrmion configurations are described by solutions to first order equations which admit a clear interpretation. Families of exact energy-minimising Skyrmion solutions can then be found in the thin film limit, even for some films with curved geometry.

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Anomalous Hall effect and magneto-optical Kerr effect of $SrRuO_3$ based epitaxial multilayers

Lin Yang, Lena Wysocki, Jörg Schöpf, Paul H. M. van Loosdrecht, Ionela Lindfors-Vrejoiu

[1]*II. Physikalisches Institut, Universität zu Köln, 50937 Köln, Germany*

Ferromagnetic heterostructures with strong interfacial Dzyaloshinskii-Moriya interaction (DMI) have been extensively studied, because they can host topologically non-trivial spin textures, such as skyrmions. The formation of skyrmions stabilized by interfacial DMI can be probed by the occurrence of the topological Hall effect (THE) in measurements of the anomalous Hall effect (AHE). We developed an experimental setup in which the AHE transverse resistivity can be simultaneously measured with the magneto-optic Kerr effect (MOKE). Here, we focus on the study of the AHE and MOKE of epitaxial heterostructures composed of ferromagnetic $SrRuO_3$ and large spin-orbit coupling perovskite oxides, such as $SrIrO_3$. We aim to elucidate the origins of the THE like anomalies in the Hall resistivity exhibited by these heterostructures.

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Experimental measurement of 3D magnetic spin texture of a target skyrmion

F. Zheng[1], Jan Caron[1], A. Kovács[1], J. Zang[2] and R. E. Dunin-Borkowski[1]

[1]Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons and Peter Grünberg Institute, Forschungszentrum Jülich, 52425 Jülich, Germany
[2]Department of Physics, University of New Hampshire, Durham, New Hampshire 03824, USA

A target skyrmion is a flux-closed spin texture that has twofold degeneracy and thus is promising as a binary state in next generation universal memories. Its existence has been experimentally verified recently in an FeGe nanodisk [1]. Such a target skyrmion can be stabilized even without the external magnetic field, enabling the three-dimensional spin texture to be measured using off-axis electron holography and electron tomography in the transmission electron microscope. With the aid of a model-based iterative reconstruction algorithm [2], the three-dimensional spin texture of a target skyrmion can be retrieved from a tilt series of holographic phase images. The experimental results will be compared with micromagnetic simulation.

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