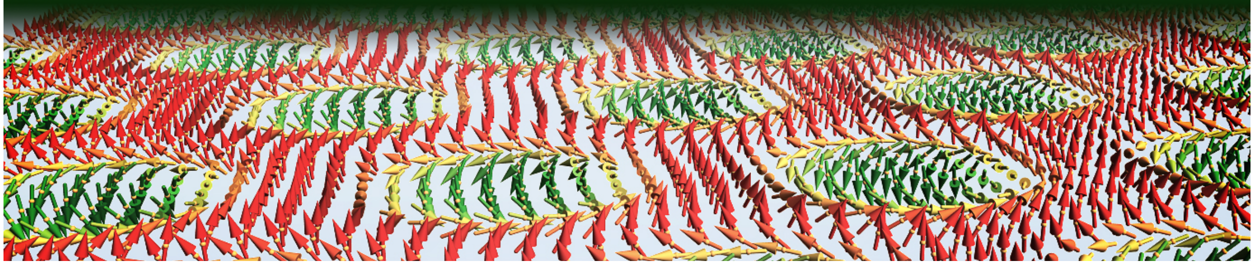
SKYRMIONICS: MATERIALS, PHENOMENA AND APPLICATIONS



In the past several years, there has been tremendous progress in the field of magnetic skyrmions, and the sub-field skyrmionics is beginning to emerge from these studies. The field is mainly driven by (1) discovery of new materials hosting skyrmions, (2) observation of novel properties of skyrmions, (3) conceptual developments of new skyrmion-based devices. Many new skyrmion-hosting systems have been discovered including multiferroics, inversion-symmetric magnets and heterostructures. Skyrmions in these materials couple to various external stimuli like electromagnetic fields, elasticity, and exhibit novel properties, which are awaiting to be exploited for device applications. On the theory side, better understanding of the skyrmion stabilization mechanisms, skyrmion-magnon/phonon/electric current coupling and skyrmion dynamics has been achieved. At the same time, the generation, manipulation and imaging of skyrmions in heterostructures have been demonstrated. Meanwhile, new challenges have emerged: (1) optimization and control of skyrmion properties, including size, helicity, lattice constant to make them suitable for device applications; (2) quantitative multiscale modeling of skyrmion materials; (3) development of new spectroscopy methods to characterize and image the skyrmion phase. With these developments and emergent challenges, it is timely to bring active researchers in this field together to discuss the materials, phenomena and future application challenges.

This workshop is aimed at providing a platform for exchanging ideas among researchers specialized in material synthesis, characterization, modeling and device applications. To reach out to the students and junior researchers, invited speakers are recommended to prepare the presentation in a pedagogical way. We will arrange talks and prominent poster sessions for student and junior researchers.

Topics to be covered during the workshop:

(a) new skyrmion magnetic materials and the stabilization mechanism
(b) skyrmion dynamics
(c) skyrmion at interface
(d) application of skyrmions

Program Committee:

Markus Garst, TU Dresden
Marc Janoschek, Los Alamos National Laboratory
Shizeng Lin, Los Alamos National Laboratory
Ivar Martin, Argonne National Laboratory
Filip Ronning, Los Alamos National Laboratory
Avadh Saxena, Los Alamos National Laboratory

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Schedule of Events

Monday August 7, 2017		
8:00 - 9:00		Breakfast
9:00 - 9:10	Marc Janoschek (Los Alamos National Lab, US)	Welcome and Introduction
Session chair	**Marc Janoschek (Los Alamos National Lab, US)**	**New Mechanism for Skyrmion Stabilization**
9:10 - 9:45	Tsuyoshi Okubo (University of Tokyo, Japan)	Multiple-q States and Skyrmion Lattice in Frustrated Spin Systems
9:45 - 10:20	Maxim Mostovoy (University of Groningen, Netherlands)	Stability, Dynamics and Ferroelectric Properties of Magnetic Skyrmions
10:20 - 10:50		Break
10:50 - 11:25	Cristian D. Batista (University of Tennessee, US)	Skyrmions, Vortices and Other Noncoplanar Phases in Frustrated Mott Insulators
11:25 - 12:00	Stefan Blügel (Peter Grünberg Institute, Germany)	Proposal of a Skyrmion-Antiskyrmion Racetrack Memory in Rank-1 DMI Materials
12:00 - 2:00		Lunch
Session chair	**Axel Hoffmann (Argonne National Lab, US)**	**Skyrmion Dynamics and Manipulation I**
2:00 - 2:35	Hector Ochoa (UCLA, US)	Dynamics and Hall Effect of Quantum Skyrmions
2:35 -3:10	Felix Rucker (Technische Universität München, Germany)	Exploration of Spin Transfer Torque Effects in $Mn_{1-x}Fe_xSi$ in Transport and Susceptibility Studies
3:10 - 3:30		Break
3:30 - 4:05	Siracusano Giulio (Giulio Siracusano, Italy)	Stabilization, Nucleation and Manipulation of Radial Vortices and Skyrmions
4:05 - 4:40	Shinichiro Seki (RIKEN, Japan)	Magnetoelectric Dynamics of Skyrmions
4:40 - 5:15	Stavros Komineas (University of Crete, Greece)	Dynamics of Skyrmions in Chiral Ferromagnets

Tuesday, August 8, 2017		
8:00 - 9:00		Breakfast
Session chair	**Stefan Blügel (Peter Grünberg Institute, Germany)**	**Skyrmions at Surfaces and Interfaces**

9:00 - 9:35	Mohit Randeria (Ohio State University, US)	Skyrmions in Magnets with Broken Bulk and Surface Inversion Symmetry
9:35 - 10:10	Eric Fullerton (UCSD, US)	Materials Optimization to Form Skyrmion and Skyrmion lattices
10:10 - 10:40		Break
10:40 - 11:15	Axel Hoffmann (Argonne National Lab, US)	Manipulating Room Temperature Magnetic Skyrmions
11:15 - 11:50	Katharina Zeissler (University of Leeds, UK)	Single Skyrmion Detection Using Electrical Transport in Pt/Co/Ir Multilayer Disc
11:50 - 2:00		Lunch
Session chair	**Mohit Randeria (Ohio State University, US)**	**Skyrmions in Low Dimensions**
2:00 - 2:35	Fengyuan Yang (Ohio State University, US)	Robust Zero-Field Skyrmion Formation in FeGe Epitaxial Thin Films
2:35 -3:10	Jiadong Zang (University of New Hampshire, US)	Topological Spin Textures in Nanodisks
3:10 - 3:30		Break
3:30 - 4:05	Geoffrey Beach (MIT, US)	Room temperature magnetic skyrmions in engineered metallic heterostructures
4:05 - 6:00		Poster session
6:00		Banquet

Wednesday, August 9, 2017		
8:00 - 9:00		Breakfast
Session chair	**Ivar Martin (Argonne National Lab, US)**	**Imaging of Skyrmions and the Underlying Magnetic Interactions**
9:00 - 9:35	Gong Chen (UC Davis)	Detecting and Tailoring Chiral Spin Textures in the Presence of Interfacial DMI
9:35 - 10:10	Peter D. Hatton (Durham University, UK)	Soft X-ray Diffraction Studies of Skyrmions
10:10 - 10:40		Break
10:40 - 11:15	David M Fobes (Los Alamos National Lab, US)	Spin Excitations of the Skyrmion Lattice in MnSi

11:15 - 11:50	Ted Monchesky (Dalhousie University, Canada)	Chiral Magnetic States in MnSi Thin Films
11:50 - 2:00		Lunch
Session chair	**Avadh Saxena (Los Alamos National Lab, US)**	**Skyrmion Dynamics and Manipulation II**
2:00 - 2:35	Karin Everschor-Sitte (Johannes Gutenberg Universität, Germany)	Magnetic Skyrmions in Two Dimensions: Their Creation and Possible New Applications
2:35 -3:10	Henrik M. Ronnow (Swiss Federal Institute of Technology in Lausanne, Switzerland)	Electric Field Control of Skyrmions
3:10 - 3:30		Break
3:30 - 4:05	Mathias Kläui (University of Mainz, Germany)	Topological Spin Dynamics
4:05 - 4:40	Charles Reichhardt (Los Alamos National Lab, US)	Fluctuations and Noise Signatures of Driven Magnetic Skyrmions

Thursday, August 10, 2017		
8:00 - 9:00		Breakfast
Session chair	**Geoffrey Beach (MIT, US)**	**Skyrmion in B20 Materials**
9:00 - 9:35	Boris Maiorov (Los Alamos National Lab, US)	Elasticity of MnSi on the Skyrmion Phase in Static and Dynamic conditions
9:35 - 10:10	Fumitaka Kagawa (RIKEN, Japan)	Current-Induced Viscoelastic Topological Unwinding of Metastable Skyrmion Strings
10:10 - 10:40		Break
10:40 - 11:15	Alfonso Chacon Roldan (Technische Universität München, Germany)	Stability of Skyrmions in Chiral Magnets
11:15 - 11:50	Jian-Xin Zhu (Los Alamos National Lab, US)	First-Principles Simulations and Low-Energy Effective Modeling of Skyrmion in Noncentrosymmetric B20 Compounds
11:50 - 2:00		Lunch
Session chair	**Markus Garst (TU Dresden)**	**Skyrmion-Like Excitations and Coupling to Non-Magnetic Degrees of Freedom**

2:00 - 2:35	Pablo García-Fernández (Universidad de Cantabria, Spain)	Second-Principles Simulations of Counter-Rotating Vortices Pairs in $PbTiO_3/SrTiO_3$ Superlattices
2:35 -3:10	Ramamoorthy Ramesh (University of California at Berkeley, US)	Emergent Phenomena in Oxide Superlattices
3:10 - 3:30		Break
3:30 - 4:05	Alois Loidl (Universität Augsburg, Germany)	Skyrmions with Ferroelectric Polarization in Multiferroic Lacunar Spinels
4:05 - 4:40	Ying Zhang (Chinese Academy of Science, China)	Topological Biskyrmions and the Manipulation Behavior in MnNiGa magnet
4:40 - 5:15	Satoru Hayami (Hokkaido University, Japan)	Vortex and Skyrmion Crystals in Frustrated Itinerant Magnets

Invited Talks

Multiple-q states and skyrmion lattice in frustrated spin systems

Tsuyoshi Okubo
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Hikaru Kawamura,
Department of Earth and Space Science, Osaka University

Ordering of geometrically frustrated magnets has attracted recent interest. Frustrated interactions often introduces novel magnetic orders forming non-collinear or non-coplanar spin structures. The antiferromagnetic (AF) Heisenberg model on the two-dimensional triangular lattice is a typical example of geometrically frustrated magnets. When AF nearest-neighbor interaction only, the ground state of this system is the 120 degree structure, which is commensurate to the underlying lattice. In contrast, when further-neighbor interaction becomes dominant, the ground state often takes an incommensurate spiral structure. In such a situation, the ground state generally possesses a three-fold degeneracy with respect to the choice of three equivalent directions of wavevectors on the lattice. In the case of the classical J1-J3 model which has the ferromagnetic nearest-neighbor interaction J1 and the antiferromagnetic third neighbor interaction J3, it is known that the system exhibits a first-order phase transition at a finite temperature associated with a breaking of such three-fold lattice symmetry [1].

In this talk we discuss the ordering of the J1-J3 model under magnetic fields investigated by a mean-field analysis and a Monte Carlo simulation [2]. We find that the T-H phase diagram containing not only a usual single-q state but also several types of multiple-q states where several wavevectors coexist. Interestingly, in the triple-q state, which is stabilized at intermediate magnetic fields, the spin configuration just corresponds to the skyrmion lattice recently discussed in conjunction with several ferromagnetic compounds with the anti-symmetric Dzyaloshinskii-Moriya (DM) interaction. In contrast to the skyrmion lattice stabilized by DM interactions, the skyrmion lattice of the present model is realized via a frustrated symmetric exchange interaction, which enables both skyrmions and anti-skyrmions and gives rise to a new Z phase, a domain state consisting of skyrmion and anti-skyrmion lattices.

[1] R. Tamura and N. Kawashima, J. Phys. Soc. Jpn. 77, 103002 (2008).
[2] T. Okubo, S. Chung, and H. Kawamura, Phys. Rev. Lett. 108, 017206 (2012).

Stability, dynamics and ferroelectric properties of magnetic skyrmions

Maxim Mostovoy
Zernike Institute for Advanced Materials, University of Groningen

Skyrmions form an important class of topological defects in ordered states with a vector order parameter. Their non-trivial topology is a source of rich and interesting physics. Magnetic skyrmions have been recently observed in chiral magnets, such as the ferromagnetic metal, MnSi, and ferrimagnetic insulator, Cu2OSeO3. Berry phase acquired by electrons and magnons propagating through the non-coplanar skyrmion spin configuration gives rise to complex coupled dynamics of charges and spins mediated by effective gauge fields. Low critical currents needed to manipulate skyrmions opened a new active field of research - skyrmionics, which has a goal of developing skyrmion-based magnetic memory and data processing devices.

It was shown theoretically that isolated skyrmions, skyrmion crystals and other unusual multiply periodic states can exist in magnets with conventional centrosymmetric lattices where they are stabilized by competing exchange interactions [1-4]. Non-collinear magnetic orders in frustrated magnets spontaneously break inversion symmetry and induce an electric polarization. In my talk I will discuss stability and dynamics of skyrmions and half-skyrmions near the Lifshitz point as well as their ferroelectric properties which make possible to control these topological defects with an applied electric field.

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Skyrmions, Vortices and Other Noncoplanar Phases in Frustated Mott Insulators

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I will discuss different mechanisms for the stabilization of multiple- modulated structures, such as skyrmion and vortex crystals, in frustrated magnets. We will see that the triangular lattice (and any other invariant lattice) provides a simple realization of a high-symmetry system with six equivalent orientations for the helical ordering. This symmetry allows for anharmonic interactions between triple- modulations and the uniform magnetization induced by external field because [1]. Indeed, classical Monte Carlo simulations of a frustrated classical Heisenberg model on a triangular lattice revealed a skyrmion crystal at finite temperature and magnetic field [2]. The origin of this phase is very different from the skyrmion crystals that emerge in chiral magnets out of the competition between Dzyaloshinskii-Moriya (DM) and ferromagnetic exchange interactions [3-5]. Moreover, because the chiral and U(1) symmetries are spontaneously broken in non-chiral magnets, their metastable single skyrmions have different properties [6-8].
In this presentation, I will discuss the role of symmetric exchange anisotropy and charge fluctuations on the stabilization of magnetic skyrmion and vortex crystals. We will see that both mechanisms provide efficient ways of stabilizing multiple- orderings. We will also see that non-magnetic impurities can induce magnetic vortices (merons) above the saturation field of frustrated Mott insulators [9] and stabilize skyrmion and vortex crystals below the saturation field [10,11].

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Proposal of a Skyrmion-Antiskyrmion racetrack memory in rank-1 DMI materials

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The research on skyrmions – localized two-dimensional topological magnetization solitons – focused mainly on Bloch-type skyrmions in B20 alloys with cubic symmetry and Néel-type skyrmions stabilized by (111) oriented interfaces compatible with the growth mode introduced by sputtering techniques. Considering the micromagnetic theory both belong to the same equivalence class as in both types of systems, the Dzyaloshinskii-Moriya (DM) spiralization tensor D is characterized by a single parameter and both lie in the same orbit generated by a O(2) rotation symmetry. Also, antiskyrmions lie in this orbit but for solids of different symmetries e.g. D2d symmetry.
In a recent work [1] we extended the scope of skyrmions and antiskyrmions, and introduced a classification scheme partitioning chiral magnets into isotropic rank-three DM bulk and rank-two DM film magnets, with a DM interaction described, as above, by a single spiralization constant, for which antiskyrmions are stable only for bulk crystals with certain point group symmetries. Newly introduced are the anisotropic rank-two DMI film magnets, where skyrmions and antiskyrmions can coexist, while the sign of det(D) determines which of the two has the lower energy. Finally, zero determinant indicates a rank-one DMI material, for which skyrmions and antiskyrmions have the same energy.
In this contribution, I discuss our new classification scheme and give with Fe on W(110) an example of an anisotropic rank-two solid, for which we conjecture the presence of antiskyrmions based on DFT calculations combined with atomistic spin- dynamics carried out with the spirit code. Finally, we discuss the potential of rank-one solids for the design of a race track memory based on the coexistence of skyrmions and antiskyrmions of the same energy [2] as an alternative to the recently suggested race-track memory based on a combination of bobbers and skyrmions [3].
Acknowledgement: We acknowledge Miriam Hinzen and Hannes Jònsson for fruitful discussions. We acknowledge computing time on the JURECA supercomputer provided by the Jülich Supercomputing Centre (JSC) and funding from the European Union's Horizon 2020 research and innovation programme (grant no. 665095, FET-Open project MAGicSky), the Icelandic Research Fund (grant no. 152483-052), Deutsche Forschungsgemeinschaft (DFG grant no. ME 2273/3-1) and JARA-FIT.

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Dynamics and Hall effect of quantum skyrmions

Hector Ochoa and Yaroslav Tserkovnyak
University of California, Los Angeles

The dynamics of magnetic skyrmions is sometimes counterintuitive due to its topological nature, which, on the other hand, can be exploited for technological purposes. In this talk, I will discuss the manifestation of this topology in the quantum regime. Specifically, I will consider the non-equilibrium dynamics of skyrmions when their spatial extension is comparable to the lattice spacing of the underlying microscopic model. The effect of the lattice is treated quantum-mechanically, while the driving forces are taken as classical perturbations, varying smoothly in the scale of the lattice. The center of the skyrmion can be described as a quantum particle subjected to a magnetic field commensurate with the lattice. I will explain how the skyrmion states with good localization properties can be identified with coherent superpositions of magnon bound states in a constrained Hilbert space. The lattice potential introduces umklapp processes, removing the angular-momentum degeneracy and opening gaps at the edges of the Brillouin zone. New quantum numbers label the state: the crystalline momentum and the band index. I will show that these skyrmion bands are characterized by Berry curvatures and Chern numbers. The former is the quantum descendant of the Magnus force, whereas the latter is related to the appearance of skyrmion edge-states. Within the framework of the wave-packet dynamics, I will study the response of a skyrmion ensemble to a thermal bias. The circulation of energy provided by the skyrmion states at the boundaries of the system gives rise to a thermal Hall response.

Exploration of spin transfer torque effects in $Mn_{1-x}Fe_xSi$ in transport and susceptibility studies

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The interplay of conduction electrons and the Skyrmion lattice in chiral magnets results in a drift of the lattice above an ultra-low current density threshold j_c. In MnSi, electrical currents driving the motion of the Skyrmion lattice, as combined with AC susceptibility measurements at different excitation frequencies and amplitudes, reveal that the threshold j_c is affected strongly when a suitably chosen oscillating magnetic field is applied. By means of transport measurements and transverse susceptibility measurements we show further, that this threshold can be distinctly modified by doping or by the application of an oscillating magnetic field. For iron-doped $Mn_{1-x}Fe_xSi$, we find j_c to be described in a simple manner by defect-related pinning and the size of the topological Hall contribution quantifying the gyromagnetic coupling between conduction electrons and spin structure.

Stabilization, Nucleation and Manipulation of Radial Vortices and Skyrmions

Siracusano Giulio

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Solitons are very promising for the design of the next generation of ultralow power devices for storage and computation. The key ingredient to achieving this goal is the fundamental understanding of their

stabilization and manipulation. In particular, Néel skyrmions stabilized by the interfacial Dzyaloshinskii-Moriya Interaction (IDMI) in out-of-plane materials offer a scalability beyond the limit of CMOS technology for storage. However, main interesting aspect of skyrmions is their possible use for ICT devices such as oscillators [1] and detectors[2]. The oscillators can be achieved in the IDMI region parameter where the a dynamical skyrmion is stabilized by a dc spin-polarized current, while the unbiased detectors exhibit sensitivities (output voltage/input power) as larger as 2000V/W. Here, we discuss in details the results of micromagnetic simulations and experiments of different solutions for the realization of skyrmion based microwave oscillators and detectors [3].

In conclusions, our findings show the potential of skyrmions for the development of a skyrmion based technology [4].

The second part of the presentation will focus on the proprieties of radial vortices that can stabilized and manipulated in materials with in-plane easy axis and IDMI. In particular, I will discuss how the IDMI is able to lift the energy degeneracy of a magnetic vortex state by stabilizing a topological soliton with radial chirality. It has a non-integer Skyrmion number S ($0.5 < S < 1$) due to both the vortex core polarity and the magnetization tilting induced by the IDMI boundary conditions.

Micromagnetic simulations predict that a magnetoresistive memory based on the radial vortex state in both free and polarizer layers can be efficiently switched by a threshold current density smaller than 10^6 A/cm^2. The switching processes occur via the nucleation of topologically connected vortices and vortex-antivortex pairs, followed by spin-wave emissions due to vortex-antivortex annihilations.

Acknowledgements

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Magnetoelectric dynamics of skyrmions

Shinichiro Seki
RIKEN

In metallic system, skyrmions interact with conduction electrons through the spin transfer torque and emergent electromagnetic field, enabling the nontrivial manner of current-driven skyrmion manipulation. However, electric current in metallic system is always accompanied with joule heat loss, and more efficient alternative approach is highly demanded.

In this talk, I overview the static and dynamical responses of magnetic skyrmions against various external stimuli in insulating system, such as electric field, pressure and magnon spin current. In particular, the propagation character of spin wave in the skyrmion state will be discussed in detail.

If time allows, I will also introduce some new materials potentially hosting unique topological spin textures.

Dynamics of skyrmions in chiral ferromagnets

Stavros Komineas
University of Crete, Greece

Both a topological skyrmion with skyrmion number Q=1 and a non-topological skyrmionium with Q=0 are stable magnetization structures in Dzyaloshinskii-Moriya materials with easy-axis anisotropy. We study the dynamics of a skyrmion and a skyrmionium under an external field gradient as well as under spin-transfer torque. Our analysis is based on an important link between topology and dynamics which is established through the construction of unambiguous conservation laws. The non-topological Q=0 skyrmionium is accelerated in the direction of the force thus exhibiting ordinary Newtonian motion. In contrast, the topological Q=1 skyrmion undergoes Hall motion perpendicular to the direction of the force (the field gradient) with a drift velocity proportional to it. When the force is switched-off the Q=1 skyrmion is spontaneously pinned whereas the Q=0 skyrmionium continues propagation.

We study further the motion of the skyrmionium in the case of spin-transfer torque and observe that its velocity can be analyzed in two parts: one due to the current flow and a second one acquired by Newtonian acceleration. Upon switching-off the current, the first part of the velocity is eliminated but the skyrmionium continues its motion with the acquired velocity until, eventually, dissipation will cause it to come to rest.

Skyrmions in magnets with broken bulk and surface inversion symmetry

Mohit Randeria
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I will first describe our theoretical results [1] on 3D systems that break mirror reflection symmetry in addition to bulk inversion. This leads to two distinct Dzyaloshinskii-Moriya interactions (DMI) -- Rashba DMI and Dresselhaus DMI. We show that the skyrmion crystal (SkX) phase occupies a larger region of the phase diagram with increasing ratio of Rashba to Dresselhaus DMI, extending into the regime of easy-plane anisotropy. The spin texture and topological charge density of easy-plane skyrmions is quite different from those in the easy-axis regime, and one needs a Chern number to define the quantized topological charge in the SkX unit cell. Next, I will describe T=0 calculations for B20 thin films, where we show that surface topological spin textures called chiral bobbers are stabilized by interface Rashba DMI [2]. Finally, I will present the results of extensive finite temperature Monte Carlo simulations for strict 2D and for thin film geometries and discuss the appearance of a high temperature skyrmion liquid phase [3].

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Materials optimization to form skyrmion and skyrmion lattices

Eric Fullerton
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There is increasing interest in materials systems where magnetic skyrmions can be observed. I will discuss two materials systems where we observe chiral spin structures at room temperature. The first system is ferrimagnetic Fe/Gd multilayer where we observe sub-100-nm skyrmions and skyrmion lattices [1-4]. However, the chirality of the skyrmions are random indicating they are dipole stabilized (similar to of bubble memory in the 1970s) as opposed to by DMI that favors a fixed chirality. This further allows the formation of bi-skyrmions which result from the merging of two skyrmions of opposite chirality and anti-skyrmions. We find that there is a transition from stripe domains to a skyrmion lattice and then individual skyrmions with magnetic fields and this behavior is sensitive to alloy composition, film thickness, temperature, and field history and only emerges in a narrow range of parameters. Using micromagnetic modeling we are able to quantitatively reproduce our experimental observations. The modeling suggests that the domain wall is Bloch-like in the center of the films but broadens and transitions to more Néel-like towards the surface forming closure domains. The Bloch-like centers have an equal population of the two helicities while the Néel-like part of the walls will have the same helicity at the top of the film and the opposite helicity at the bottom of the film. The modeling further suggests the existence of localized spin-wave modes that are dependent on the helicity of the dipole skyrmion. The second system is Pt/Co(1.1 nm)/Os(0.2 nm)/Pt heterostructures. Using Kerr microscopy to observe skyrmions for a narrow temperature and field range. With relatively low currents, it is possible to move these skyrmions both within patterned wires and full films and we further have observations of the skyrmion Hall effect.

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Manipulating Room Temperature Magnetic Skyrmions

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Magnetic skyrmions are topologically distinct spin textures and can be stable with quasi-particle like behavior, such that they can be manipulated with very low electric currents [1]. This makes them interesting for extreme low-power information technologies [2], where data is envisioned to be encoded in topological charges, instead of electronic charges as in conventional semiconducting devices. Using magnetic multilayers we demonstrated that inhomogeneous charge currents allow the generation of skyrmions at room temperature in a process that is remarkably similar to the droplet formation in surface-tension driven fluid flows [3]. Micromagnetic simulations reproduce key aspects of this transformation process and suggest a possible second mechanism at higher currents that does not rely on preexisting magnetic domain structures [4]. Indeed, we demonstrated this second mechanism experimentally using non-magnetic point contacts. Using this approach, we demonstrated that the topological charge gives rise to a transverse motion on the skyrmions, i.e., the skyrmion Hall effect [5], which is in analogy to the ordinary Hall effect given by the motion of electrically charged particles in the presence of a magnetic field. Lastly, by optimizing our magnetic heterostructures, we show that we can stabilize skyrmions with sizes around 100 nm even in the absence of externally applied magnetic fields.
This work was supported by the U.S. Department of Energy, Office of Science, Materials Sciences and Engineering Division.

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Single skyrmion detection using electrical transport in Pt/Co/Ir multilayer disc

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Magnetic quasiparticles such as skyrmions are important objects in the quest for novel magnetic information storage. They have been observed in bulk materials as well as in multilayer systems (1). In the latter, skyrmions are stabilized by the interfacial Dzyaloshinskii-Moriya interaction (DMI). In such material systems the equilibrium configuration of the stabilized skyrmions depends highly on the ferromagnetic and the heavy metals chosen, their thicknesses and the number of repeat. Due to this tunability and the skyrmion stability at room temperature these multilayers are of great interest for devices (2-5). Active focal areas are the influence of pinning due to growth imperfections (6), skyrmion manipulation and electrical detection.

In the experiment outlined here a single skyrmion in a Ta (3.5 nm)/Pt (3.8 nm)/[Co (5.0 nm)/Ir (5.0 nm)/Pt (1.0 nm)]x10 Pt (3.2 nm) multilayer nanodisc was imaged using the PolLux scanning transmission X-ray microscopy as a function of out-of-plane magnetic field. The Hall resistance was measured in situ just before each image was taken. The circular polarized X-rays were tuned to L3 cobalt edge and were transmitted perpendicular to the sample plane. The light and dark X-ray magnetic circular dichroism (XMCD) contrast extracted from the images reflect antiparallel, out of plane magnetic domains and can be used to extract the out of plane magnetisation. The Hall resistance shows a clear difference between uniform magnetised states and a single skyrmion state. This shows that electrical transport measurements can be used to detect single skyrmions in nanostructures.

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Robust Zero-Field Skyrmion Formation in FeGe Epitaxial Thin Films

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Magnetic skyrmions are topological spin textures, which have attracted significant interests in recent years due to their intriguing magnetic interactions and attractive attributes for magnetic storage and other spintronic applications. B20 phase magnetic materials, such as FeGe and MnSi, enable magnetic skyrmions due to the spin-orbit coupling and non-centrosymmetric structure. One major effort in this emerging field is the stabilization of skyrmions at room temperature and zero magnetic field. We grow phase-pure, high crystalline quality FeGe epitaxial films on Si(111) by ultra-high vacuum off-axis magnetron sputtering [1]. FeGe film thicknesses of 100, 65, and 36 nm are used for this study. All FeGe films exhibit pure B20 phase as shown in the X-ray diffraction scans. Scanning transmission electron microscopy (STEM) images clearly reveal the B20 lattice of the FeGe film and its epitaxial relationship with the diamond structure of the Si substrate. The three FeGe films were patterned into a standard Hall bar structure, on which longitudinal and Hall resistivity measurements were taken using a Physical Property Measurement System (PPMS). The Hall resistivity hysteresis loops show three regions of distinct features: 1) a linear background at large fields (> 2 T) due to the ordinary Hall effect, 2) a magnetic reversal behavior at intermediate fields that follows the magnetization hysteresis loop due to the anomalous Hall effect, and 3) a hysteresis loop within 3000 Oe due to the topological Hall effect (THE). The THE signals were extracted by subtracting out the anomalous Hall effect and ordinary Hall effect, demonstrating the existence of the skyrmion phase in FeGe films between 5 and 275 K. The topological Hall resistivity reaches 918 nOhm cm at 250 K, the highest reported to date. In particular, a large remanent topological Hall resistivity (77% of the maximum THE signal) was observed at zero magnetic field and 5 K. This substantial topological Hall effect at zero field shows a robust skyrmion phase without the need of an external magnetic field.

This work was primarily supported by the U.S. DOE under Grant No. DE-SC0001304 and in part by NSF under Grant No. DMR-1507274 and No. DMR-1420451.

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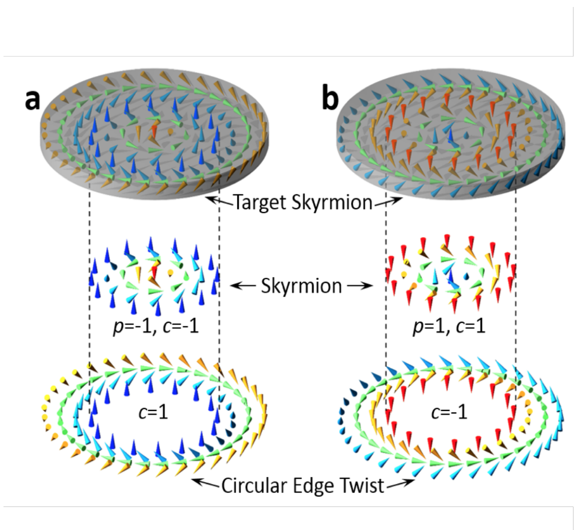
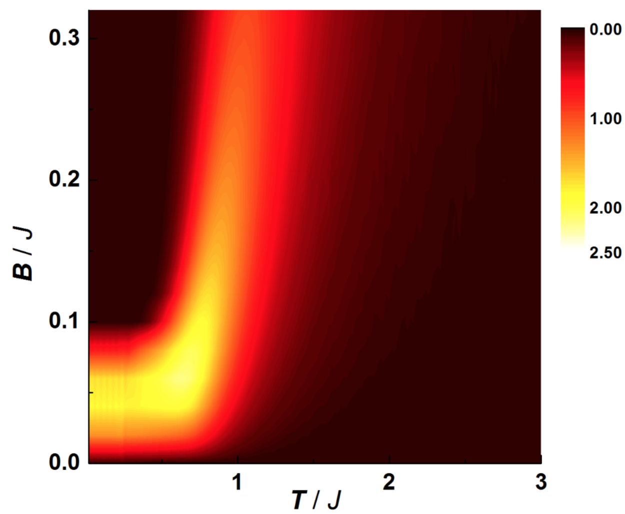
Topological Spin Textures in Nanodisks

Jiadong Zang

The magnetic skyrmion is a nanostructured spin texture stabilized by the spin-orbital coupling. Its nontrivial topology enables unique dynamical property and thermal stability, which give out promise on future magnetic memory devise. However, to enable its applications, it is essential to understand the skyrmion properties in confined geometries and tackle key challenges including the creation and detection of skyrmions, preferably without magnetic fields. In this talk, I will present our recent theory-experiment collaboration results on magnetic skyrmions in ultrasmall nanodisks. A new type of skyrmion, the target skyrmion is observed therein. Zero field skyrmions and their polarization switch will be discussed. New topological textures in this geometry be presented. In the second half of the talk, I will discuss nontrivial topology driven by thermal fluctuations.





Room temperature magnetic skyrmions in engineered metallic heterostructures

Geoffrey Beach
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Detecting and tailoring chiral spin textures in the presence of interfacial DMI

Gong Chen
UC Davis

Chirality in magnetic materials holds great potential for logic and memory devices. In this talk, I will introduce our results of exploring chiral spin textures using spin-polarized electron microscopy in magnetic multilayer films, including zero-field stabilized skyrmion and Néel-type skyrmion bubbles with Bloch components in both out-of-plane and in-plane magnetized films. I will also show that magnetic chirality of spin spirals with a period of 100 nm can induce a significant magnetic circular dichroism in an X-ray scattering experiment, allowing efficient characterization of chiral spin textures with extremely small size.

The work was done by collaboration with A Mascaraque, C Ophus, P Shafer, S Kang, HY Kwon, X Xiao, J Hong, JH Liang, L Sun, AT N’diaye, E Arenholz, C Won, ZQ Qiu, YZ Wu, AK Schmid and K Liu. GC is supported by UCOP (MRP-17-454963).

Soft X-ray Diffraction studies of Skyrmions

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Diffraction studies of magnetic skyrmions has tended to be dominated by Lorentz TEM and small-angle neutron scattering. However resonant soft x-ray diffraction techniques can provide a detailed understanding of the skyrmion lattice, and hence the skyrmion size. It can also be used to provide information on the winding number of skyrmions and the skyrmion domain distribution. In this talk I will review the use of resonant soft x-ray diffraction studies of magnetic skyrmions using synchrotron radiation at the L-edges of the 3d transition metals. I will outline the information obtained to date, and some of the challenges involved in studying both bulk single crystals and thin film samples. Prospects for future studies of the magnetic anisotropy of skyrmions and their dynamics will be described.

Spin excitations of the skyrmion lattice in MnSi

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In the less than a decade since skyrmions, topologically-protected three-dimensional spin textures, were originally discovered in MnSi, considerable experimental and theoretical research efforts have gone towards exploiting their properties for future applications in solid-state memory and spintronics. In non-centrosymmetric materials, it is well understood that skyrmions arise due to competition between ferromagnetic exchange and the Dzyaloshinskii-Moriya interaction, which directly relates to their potential for applications, since individual skyrmion size is proportional to the ratio of these interactions. Although the strength of the underlying magnetic interactions can typically be inferred directly from the spin wave dispersion, the mesoscopic size of skyrmions implies a tiny magnetic Brillouin zone, requiring momentum-transfer resolution beyond the current state-of-the-art in neutron spectroscopy to resolve the spin waves, an outstanding experimental challenge. Here we overcome this challenge via a new generation of resolution deconvolution, enabling, for the first time, mesoscopic neutron spectroscopy of the spin excitations associated with the skyrmion lattice. The spin wave dispersion and underlying magnetic interactions determined in the skyrmion phase of the prototypical material MnSi through this new approach is in excellent quantitative agreement with our mean-field treated Ginzburg-Landau model.

Chiral Magnetic States in MnSi thin films

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A number of recent calculations and experiments have identified that strain and finite size effects are important contributions that influence the stability of the magnetic textures in MnSi thin films. Both of these effects play an important role in MnSi films grown on Si substrates and have an important influence on the magnetic phase diagram. However, there continues to exist controversy over the interpretation of the phase diagram. With insights from ferromagnetic resonance, magnetometry, Hall effect and polarized neutron reflectometry in out-of-plane fields, a consistent picture emerges with the cone phase as the sole equilibrium phase below the saturation field. Standing helimagnon waves are observed and represent the spin excitations from this ground state.

I will address recent controversy about the phase diagram in-plane magnetic fields [1-2]. We have explored the magnetic textures in three dimensions with the combination of PNR and small angle neutron scattering (SANS) measurements. While surface twists drive the skrymions into the film center, SANS demonstrates a large degree of disorder within the plane of the film.

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Magnetic skyrmions in two dimensions: their creation and possible new applications

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Major challenges towards skyrmion-based technologies include i) the controlled and systematic creation of magnetic skyrmions without the need of complex setups and ii) designing devices that efficiently use the properties of magnetic skyrmions.
In the first part of the talk, I will present how to create skyrmions and other magnetic textures in ferromagnetic thin films by means of a homogeneous DC current. [1] This is possible by exploiting an instability arising by the interplay of current-induced spin-transfer torque and a spatially inhomogeneous magnetization which can be achieved, e.g., by locally engineering the anisotropy, the magnetic field, or other magnetic interactions. The magnetic textures are created controllably, efficiently, and periodically with a period that can be tuned by the applied current strength. We propose a specific experimental setup realizable with simple materials, such as cobalt based materials, to observe the periodic formation of skyrmions. We show that adding chiral interactions will not influence the basics of the generations but the consequent dynamics w.r.t. the stabilization of topological textures.
In the second part of the talk, I will address the potential of magnetic skyrmions for alternative models of information processing capable of imitating the high-energy efficiency of neuromorphic information processing. I will focus on reservoir computing networks as a possible realization of cognitive computing. We propose that a skyrmion network embedded in frustrated magnetic films may provide a suitable physical implementation for reservoir computing applications. [2] The significant key ingredient of such a network is a two-terminal device with non-linear voltage characteristics originating from magnetization dependent magnetoresistive effects. The most basic element for a reservoir computing network built from “skyrmion fabrics” is a single skyrmion embedded in a ferromagnetic ribbon. To pave the way towards reservoir computing systems based on skyrmion fabrics, we simulated and analyzed i) the current flow through a single magnetic skyrmion due to the anisotropic magnetoresistive effects and ii) the combined physics of local pinning and the anisotropic magneto-resistive effect.

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Electric field control of skyrmions

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A pivotal challenge for skyrmion applications is ability to create, control, detect and erase them. Skyrmion motion (linear or rotation) has been demonstrated by use of currents, thermal gradients and combinations thereof. Exploiting the magnetoelectric coupling in the insulating skyrmion host Cu2OSeO3, we pursue electric field effects on the skyrmion phase. Combining bulk methods (magnetoelectric susceptibility), small angle neutron scattering (SANS) and magnetic contrast transmission electron microscopy (LTEM), we report rotation of the skyrmion lattice, as well as writing and erasing of skyrmions under very moderate electric fields. Furthermore, we report a theoretical framework providing semi-quantitative account of the measurements.

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Topological Spin Dynamics

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In our information-everywhere society IT is a major player for energy consumption. Novel spintronic devices can play a role in the quest for GreenIT if they are stable and can transport and manipulate spin with low power. Devices have been proposed, where switching by energy-efficient approaches, such as spin-polarized currents is used [1,2].

Firstly to obtain ultimate stability, topological spin structures that emerge due to the Dzyaloshinskii-Moriya interaction (DMI) at structurally asymmetric interfaces, such as chiral domain walls and skyrmions with enhanced topological protection can be used [3-5]. We have investigated in detail their dynamics and find that it is governed by the topology of their spin structures [3]. By designing the materials, we can even obtain a skyrmion lattice phase as the ground state of the thin films [4]. By injecting current pulses, we can reliable transform a stripe domain phase into a skyrmion lattice and we investigate the underlying physical mechanisms by temperature dependent measurements.

Secondly, for ultimately efficient spin manipulation, we use spin-orbit torques, that can transfer more than 1? per electron by transferring not only spin but also orbital angular momentum. We combine ultimately stable skyrmions with spin orbit torques into a skyrmion racetrack device [4], where the real time imaging of the trajectories allows us to quantify the novel skyrmion Hall effect [5].

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Fluctuations and Noise Signatures of Driven Magnetic Skyrmions

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Magnetic skyrmions are particle-like objects with topologically-protected stability which can be set into motion with an applied current. Using a particle-based model we simulate current-driven magnetic skyrmions interacting with random quenched disorder and examine the skyrmion velocity fluctuations parallel and perpendicular to the direction of motion as a function of increasing drive. We show that the Magnus force contribution to skyrmion dynamics combined with the random pinning produces an isotropic effective shaking temperature. As a result, the skyrmions form a moving crystal at large drives instead of the moving smectic state observed in systems with a negligible Magnus force where the effective shaking temperature is anisotropic. We demonstrate that spectral analysis of the velocity noise fluctuations can be used to identify dynamical phase transitions and to extract information about the different dynamic phases, and show how the velocity noise fluctuations are correlated with changes in the skyrmion Hall angle, transport features, and skyrmion lattice structure.

Elasticity of MnSi on the Skyrmion phase in static and dynamic conditions

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Los Alamos National Laboratory

Skyrmions in bulk materials are topological linear defects with localized spin-texture resembling vortex lines. Skyrmions also form an ordered lattice with hexagonal symmetry and can be moved by an electrical current. Their compact size and the ability of being moved by relatively small currents position Skyrmions as memory units.
We report the first complete measurement of the elastic tensor of a MnSi single crystal around the Skyrmion phase using Resonant Ultrasound Spectroscopy (RUS). At the Skyrmion phase we observe stiffening and softening of different compression and shear moduli. With the changes in shear moduli much smaller than those found for the compression moduli. While still observing resonant conditions, the elastic signature of the Skyrmion phase is lost when an applied electric current density exceeds a critical value (jc). We associate the decoupling at j_c with the skyrmion lattice moving with respect to the atomic crystal. The critical current density has a non-monotonic temperature dependence consistent with a temperature dependence of the order parameter strength (condensation energy), and shows a small peak effect near the upper phase boundary akin to $j_c(T)$ observed in MnSi through non-linear Topological Hall Effect studies.
We also investigate the anisotropic nature of magneto-crystalline coupling between the crystallographic and skyrmion crystal (SKX) lattices in the chiral magnet MnSi by magnetic field-angle resolved resonant ultrasonic spectroscopy. Abrupt changes are observed in the elastic modulus and attenuation when the magnetic field is parallel to the [011] crystallographic direction. These observations are interpreted in a phenomenological Ginzburg-Landau theory that identifies switching of the SKX orientation to be the result of an anisotropic magneto-crystalline coupling potential. Our work sheds new light on the nature of magneto-crystalline coupling potential relevant to future spintronic applications.
Therefore, our studies show that RUS can be used to determine the static and dynamic properties of emergent topological spin texture in magnets under different conditions.

Current-induced viscoelastic topological unwinding of metastable skyrmion strings

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RIKEN CEMS

In the MnSi bulk chiral magnet, magnetic skyrmion strings of 17 nm in diameter appear in the form of a lattice, penetrating the sample thickness, 10 ~ 1000 μm. Although such a bundle of skyrmion strings may exhibit complex soft-matter-like dynamics when starting to move under the influence of a random pinning potential, the details remain highly elusive. Here, we show that a metastable skyrmion-string lattice [1,2] is subject to topological unwinding under the application of pulsed currents of 3?5?10^6 A/m^2 rather than being transported, as evidenced by measurements of the topological Hall effect. The critical current density above which the topological unwinding occurs is larger for a shorter pulse width, reminiscent of the viscoelastic characteristics accompanying the pinning-creep transition observed in domain-wall motion. Numerical simulations reveal that current-induced depinning of already segmented skyrmion strings initiates the topological unwinding. Thus, the skyrmion-string length is an element to consider when studying current-induced motion.

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Stability of Skyrmions in Chiral Magnets

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The non-trivial topological winding of skyrmions in chiral magnets distinguishes them from conventional forms of magnetic order and micromagnetic textures. This topological protection of skyrmions promises a new route to advanced non-volatile high density data storage devices. We report a detailed study of the stability and the decay of skyrmion lattices in chiral magnets when prepared in a metastable state. We consider possible decay mechanisms and discuss the underlying energy scales associated with the topological protection.

First-principles simulations and low-energy effective modeling of skyrmion in noncentrosymmetric B20 compounds

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Theoretical Division, Los Alamos National Laboratory

A magnetic skyrmion observed experimentally in chiral magnets is a topologically protected spin texture. For their unique properties, such as high mobility under current drive, skyrmions have great potential for applications in next-generation spintronic devices. For this purpose, a fundamental understanding of skyrmion properties in real materials becomes essential. In this talk, I will present our study of skyrmion properties in non-centrosymmetry B20 compounds MnSi and MnGe, within the framework of density functional theory and low-energy effective modeling. We have explored the pinning effects from atomic defects on the skyrmions by taking MnSi as an example. In addition, we have elucidated the varying properties of skyrmions in MnSi and MnGe within a correlation-driven low-energy effective model constructed from DFT-based band structure.

Second-principles simulations of counter-rotating vortices pairs in PbTiO_3/SrTiO_3 superlattices

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When ultrathin ferroelectric layers of PbTiO_3 are embedded in superlattices with a paraelectric material, such as SrTiO_3, the interplay between elastic, electrostatic, and gradient energies produces complex patterns of the electrical polarization. In particular, nanometer scale of clock- and anti-clock-wise rotating vortices arrays have been recently detected [1] and exotic properties such as the emergence of a negative capacitance have been measured [2]. In this work we carry out atomistic simulations to determine the properties of these emergent structures.

Performing predictive simulations in these systems is difficult due to the long spatial scales involved in the formation of counter-rotating vortices pairs, the strong competition between a large number of phases and the sensitivity of the results to external perturbations like strain, periodicity, temperature or electric fields. In order to overcome these problems we employ a recently developed second-principles method [3] that can cope with all the degrees of freedom associated to a large number of atoms retaining high accuracy. Our simulations predict the existence of several quasi-degenerate phases at low energies each displaying different properties including net polarization, non-null topological constants and chirality. The later prediction supports the findings of optical activity in x-ray circular dichroism experiments. We are currently working on finding the conditions that govern the balance between these phases in order to externally control chirality and other characteristics of these systems.

Contributors to this work include Pablo Aguado-Puente (Queen's University Belfast), Jorge Íñiguez (Luxembourg Institute of Science and Technology) and Javier Junquera (Universidad de Cantabria).

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Emergent Phenomena in Oxide Superlattices

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The complex interplay of spin, charge, orbital, and lattice degrees of freedom has provided for a plethora of exotic phase and physical phenomena. Among these, in recent years, topological states of matter and spin textures have emerged as fascinating consequences of the electronic band structure and the interplay between spin and spin-orbit coupling in materials. In this lecture, I will discuss work on oxide superlattices that leverage the competition between charge, orbital, and lattice degrees of freedom. I will particularly focus on superlattices of PbTiO3/SrTiO3 as a model system in which we can create complex, vortex-antivortex pairs (that exhibit smoothly varying ferroelectric polarization with a 10 nm periodicity) that are reminiscent of topological features such as skyrmions and merons. The key role of a combination of advanced layer-by-layer growth techniques, atomic-resolution mapping of structure and local polar distortions using scanning-transmission electron microscopy, x ray spectromicroscopy and phase-field modeling approaches will be discussed. Finally, the implications of these observations are discussed as they pertain to producing new states of matter and emergent phenomena (such as chirality) in such superlattices. I will finish up by spending some time on the broader context of oxide superlattices.

Skyrmions with ferroelectric polarization in multiferroic lacunar spinels

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The lacunar spinels GaV4X8 (X = S, Se) undergo orbital ordering close to 40 K and reveal complex magnetic phase diagrams at low temperatures, including ferromagnetic, cycloidal and skyrmion-lattice phases [1,2]. Skyrmions are topologically protected nanoscale spin vortices with fascinating physical properties and high potentials for future data storage. Both compounds investigated are magnetic semiconductors and are the first bulk systems revealing Néel-type skyrmions characterized by spins rotating in the radial plane from the core to the periphery. The existence of skyrmions has been deduced from magnetic susceptibility, atomic-force microscopy and small-angle neutron scattering [1,2]. In lacunar spinels the influence of magnetic anisotropy on the stability of the skyrmion lattice phase can be studied in detail: The sulphur compound, with strong easy-axis anisotropy, exhibits only a rather narrow skyrmion pocket. In contrast, the selenide reveals weak easy-plane anisotropy, with a strongly enhanced skyrmion stability and with the skyrmion lattice phase extending even to 0 K.

Based on measurements of dielectric constants, heat capacity and pyrocurrent, all as function of temperature and magnetic field, we provide a thorough study of the polar properties of both compounds, revealing that the orbitally ordered phase are ferroelectric with sizable polarization. Moreover, spin-driven excess polarizations emerge in all magnetic phases; hence, lacunar spinels host a zoo of multiferroic phases, including the skyrmion lattice dressed with ferroelectric polarization [3,4]. By taking into account the crystal symmetry and the spin patterns of the magnetically ordered phases, exchange striction is identified as the main microscopic mechanism behind the spin-driven ferroelectric polarization of all multiferroic phases [3].

In the second part of this talk, we present detailed results on excitations utilizing THz and broadband microwave spectroscopy. We find an intriguing relaxation dynamics in the THz range indicating the divergence of relaxation times coupled to the orbital dynamics and establishing an orbitally driven ferroelectric phase [5]. In addition, using coplanar waveguide absorption spectroscopy we study the generic magnetic excitations of the skyrmion lattice, as well as magnetic resonances of the helical and induced ferromagnetic phases [6].

This work supported by Deutsche Forschungsgemeinschaft (DFG) via the Transregional Research Collaboration TRR 80 “From Electronic Correlations to Functionality” (Augsburg, Munich, Stuttgart)

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Topological biskyrmions and the manipulation behavior in MnNiGa magnet

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The formation of biskyrmion magnetic nanodomains in a hexagonal $(Mn_{1-x}Ni_x)_{65}Ga_{35}$ with x = 0.5 magnet was clearly demonstrated by direct real-space Lorentz TEM observations and confirmed by THE over an extremely wide temperature and magnetic field range. The biskyrmion density after the electric current manipulation can be significantly increased in contrast to the scattered biskyrmions induced directly by applying magnetic fields. Furthermore, the transition from the ferromagnetic state to stripe domains can be terminated by electric current, leading to a biskyrmion dominated residual domain. These residual biskyrmions are extremely stable and can further evolve into high-density biskyrmion lattices over a temperature range of 12 K-330 K.

Vortex and skyrmion crystals in frustrated itinerant magnets

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Noncoplanar spin textures in itinerant magnets have been attracting much interest in condensed matter physics, since they act as a huge effective magnetic field for itinerant electrons through the spin Berry phase mechanism and bring about unusual quantum transport phenomena. Chiral magnets with the spin-orbit coupling (SOC) are good platforms of stabilizing noncoplanar spin configurations, such as skyrmion crystals. Recently, however, another origin of noncoplanar spin configuration has been explored in itinerant magnets. The key ingredient is the instability of the Fermi surfaces at particular electron fillings, which does not need the presence of the SOC. Here, we investigate a further possibility of noncoplanar spin configurations in itinerant magnets.

For this purpose, we consider the Kondo lattice model on two-dimensional square and triangular lattices. By performing a large-scale simulation based on Langevin dynamics, we find double-Q vortex crystals on the square lattice, while we find triple-Q skyrmion crystals with an unusual topological number of two on the triangular lattice at zero magnetic field. We examine the stabilization mechanism by two methods in a complementary way: perturbation expansion with respect to the spin-charge coupling and variational calculations. All these studies give consistent results and shows that noncoplanar multiple-Q states become a new ground state in itinerant magnets. We also discuss the effective spin model to capture the underlying physics of the instability toward noncoplanar multiple-Q states in itinerant magnets, which will be helpful to avoid laborious calculations for the itinerant electron systems.

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Posters

Revisiting static and dynamic magnetic correlations in the chiral helimagnet Cr1/3NbS2

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Transition metal dichalcogenides have been shown to have a chiral, hexagonal space group. Previous SANS work by this group have found in Cr1/3NbS2 a non-centrosymmetric long-period helimagnetic structure with higher order harmonics both at zero field and in an applied field. A perfect helical state (ie sinusoidal modulation), would display no higher order peaks at zero field. Odd higher order peaks can be explained by a 'squaring up' of the spin wave but not even harmonics that have been seen which implies the magnetic ground state of Cr1/3NbS2 is not completely understood.

Dzyaloshinskii-Moriya interaction and interlayer exchange coupling in Pt/Co/Ir multilayer films

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One of the key ingredient to realize Skyrmions in multilayer films is the interfacial Dzyaloshinskii-Moriya interaction (iDMI) which favors a faster rotation of the spins in multilayer films with perpendicular magnetic anisotropy (PMA). It has been reported that the Skyrmions can be stabilized in Pt/Co/Ir multilayer thin films which have large additive iDMI between Pt/Co and Co/Ir interfaces. In this work, we show how the iDMI in Pt/Co/Ir films depends on the film parameters such as the thicknesses of magnetic and non-magnetic layers. In addition, we also describe the interlayer exchange coupling (IEC) in Pt/Co/Ir thin films. The IEC may provide an additional magnetic energy to tune Skyrmions. More importantly, the antiferromagnetic IEC in Pt/Co/Ir films with iDMI and PMA may stabilize new types of Skyrmions such as antiferromagnetic Skyrmions.

Resonant Ultrasonic Spectroscopy: A new access to Skyrmion lattice

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We employed Resonant Ultrasonic Spectroscopy (RUS) measurements as an approach to the Skyrmion crystal (SKX) lattice. The elastic modulus and attenuation of MnSi were systematically investigated. The important findings are: (1) We reported the first complete measurement of the elastic tensor of MnSi with RUS, and studied their behaviors near the SKX phase. The phase diagram is mapped out. (2) In the presence of a DC current, we studied the decoupling of SKX and the crystallographic lattice and got a critical current density jc?61.8 kA/m2. (3) With a field angular dependent RUS measurement, we observed abrupt changes of the elastic modulus and attenuation when the magnetic field is parallel to the [011] crystallographic direction. Calculations based on phenomenological Ginzburg-Landau theory were performed to understand the nature of magneto-crystalline coupling between the SKX lattice and the underlying crystallographic lattice.

Polarized neutron reflectometry study of in-plane skyrmions in MnSi thin films

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For epitaxial MnSi/Si(111) films, a hard-axis out-of-plane magnetocrystalline anisotropy destabilizes skyrmions for out-of-plane fields over the entire phase diagram. For in-plane fields the case is different and micromagnetic calculations of MnSi/Si(111) thin films show that magnetocrystalline anisotropy is capable of stabilizing skyrmions with their axis of symmetry pointing in the plane of the film. A polarized neutron reflectometry (PNR) study is presented that reveals evidence of in-plane skyrmions that are confined to the center of the film due to the potential well formed by the surface twists. PNR measurements, which provide a depth profile of the magnetization, are interpreted with the aid of micromagnetic simulations. Comparisons between the simulations and the data demonstrate that helicoids, skyrmions and twisted ferromagnetic phases can be clearly distinguished in the experiments. The presence of skyrmions is further supported by small-angle neutron scattering measurements.

Magnetic Skyrmions on a Two-Lane Racetrack

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Magnetic skyrmions are often discussed as potential data carriers in future memory devices since they promise to combine small size and topological quantization with the possibility of efficient electric manipulation. The skyrmion racetrack memory has been suggested: a shift register type memory where information is encoded in the distance between skyrmions moving in a one-dimensional nanostrip.

I propose an alternative shift register design where skyrmions move in two (or more) parallel lanes on a shared racetrack [1]. Here, the information is stored in the lane number of each skyrmion but not in the distance between them. Such a multilane racetrack can be constructed by controlling the height profile of the nanostrip. Repulsive skyrmion-skyrmion interactions in sufficiently narrow nanostrips guarantee that skyrmions on different lanes cannot pass each other. Current pulses can be used to induce a lane change. Combining these elements provides a robust, efficient design of skyrmion-based storage devices.

[1] J. Müller, New Journal of Physics 19, 025002 (2017)

Skyrmions in a Layered Antiferromagnet

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Magnetic skyrmions are non-coplanar nano-sized spin structures, similar to tiny knots. First observed in 2009, they were found to have highly unusual physical properties, which make them suitable for spintronics applications, such as low-dissipation data processing and memory devices. Studying the phase diagram of materials which could potentially be host to skyrmions and understanding their dynamics is crucial for progress in this new promising field. We have studied a model of the magnetically frustrated dihalide, Fe(x)Ni(1-x)Br(2), with stacked triangular layers of classical spins, competing intralayer exchange interactions and the antiferromagnetic interlayer interaction. We show that skyrmion crystals and isolated skyrmions are stable for a wide range of parameters of this model, which suggests that skyrmions can be found in realistic frustrated magnets.

Large scale spin-lattice simulations using LAMMPS

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Deriving from the DFT formalism, a semi-classical methodology referred to as spin dynamics (SD) can be used as a reliable tool for the simulation of the magnetization dynamics in systems containing a large number of interacting magnetic spins [1], like spin lattices [2], or spin liquids [3]. More recently, it has also been shown possible to couple spin degrees of freedom to lattice vibrations by combining the formalism of molecular dynamics to spin dynamics [4], using empirical potentials [5].
The goal of our project is to construct an efficient parallel implementation of SD in Sandia's widely-used LAMMPS molecular dynamics code [6]. This will allow spin-lattice simulations to use parallel computers to access length and timescales much larger than currently possible. This work will leverage LAMMPS' sophisticated integration algorithms and the highly parallel structures.

Finally, we will show how combining spin-dependent DFT results to SD simulations can be used as a reliable tool in the study of topologically stabilized spin structures, like skyrmions [7].

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Room Temperature Topological Hall Effect in Microfabricated FeGe Crystals

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Overcoming the challenge of low-noise measurements, I was able to measure the topological Hall Effect (THE) on a microscopic bulk sample of FeGe, for the first time. I find that in a 750 nm thick sample, the THE is only present at room temperature, in the same region of field and temperature deduced from magnetic measurements in bulk single crystals. Surprisingly, I find a THE amplitude similar to that of MnSi at low temperature, despite the lower effective magnetic field of FeGe skyrmions. I also found a new region of negative topological Hall Effect which seems to be a helicoid or inhomogenous chiral spin state, precursor of the skyrmion phase. I microfabricated the electrical transport samples from single crystals of FeGe using a Focused Ion Beam (FIB).