Non-Linear Magnetism

757. WE-Heraeus-Seminar

05 – 07 January 2022

hybrid

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

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

Aims and scope of the 757. WE-Heraeus-Seminar:

In this seminar we will discuss the effects and implications of non-linearity for magnetic and spintronic systems. In recent years, non-linearity has gained increasing focus within the scientific community. In particular, not only are the majority of natural phenomena intrinsically non-linear, but exploiting non-linearity in applications offers the possibility for highly efficient and powerful processing of information. In magnetism, the prospects of non-linearity range from novel computing approaches to non-linear effects in tailored geometries that stabilize magnetic textures with unusual or otherwise impossible properties.

This seminar will encompass four of the most relevant fields of research in which non-linearity either plays an important role or which in itself is linked inseparably to non-linear phenomena: Chiral magnetism and functional geometries as many non-linear effects can be found in chiral and specially designed three-dimensional systems; as well as ferri- and antiferromagnetic spintronics and novel computing, since in these areas non-linear effects are actively sought after to enhance device performance or create new responses such as for reservoir computing or topological spin structures for highly efficient spin dynamics.

The central aim of this seminar is to bring together researchers working at the forefront of material research, and others who develop and apply novel methods to characterise magnetic properties in such materials, with the scientists who directly investigate spin phenomena on a fundamental level and for applications. For this purpose, renowned scientists will present alongside young talents.

Scientific Organizers:

Dr. Claire Donnelly	MPI for Chemical Physics of Solids, Dresden E-mail: Claire.Donnelly@cpfs.mpg.de
Dr. Kai Litzius	MPI for Intelligent Systems, Stuttgart E-mail: litzius@mit.edu

Introduction

Administrative Organization:

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Registration:

Elisabeth Nowotka (WE Heraeus Foundation)
at the Physikzentrum, reception office
Tuesday (17:00 h – 21:00 h) and Wednesday morning

Program

Tuesday, 04 January 2022

17:00 – 20:00	Registration	
18:00	*BUFFET SUPPER and informal get-together*	

Wednesday, 05 January 2022

07:30	*BREAKFAST*	
08:45	Scientific organizers	**Welcome and opening**
09:00 – 09:45	Elena Vedmedenko *(online)*	**Imprinting and processing of different topological objects in the same material**
09:45 – 10:30	Jonathan Leliaert	**Skyrmion hall effect in spin-orbit torque driven topologically trivial and nontrivial structures**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Vincent Cros	**Non-collinear 3D textures in magnetic multilayers: from hybrid chiral textures to skyrmionic cocoons**
11:45 – 12:30	Pietro Gambardella	**Synthetic chiral magnets in two and three dimensions**
12:30 -	**Conference Photo** (in the front of the lecture hall)	
12:40	*LUNCH*	

Program

Wednesday, 05 January 2022

14:00 – 14:45	Mathias Kläui	**Ultra-fast chiral spin dynamics**
14:45 – 15:30	Jairo Sinova	**Altermagnetism: spin-momentum locked phase protected by non-relativistic symmetries**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	Denis Sheka *(online)*	**Curvilinear magnetism**
16:45 – 17:30	Amalio Fernández-Pacheco	**New effects in 3D magnetic nanostructures with complex geometries**
17:30 – 17:45	Maria Azhar	**Screw dislocations in chiral magnets**
17:45 – 18:00	Sebastián Díaz	**Steering Majorana braiding via skyrmion-vortex pairs: a scalable platform**
18:00	*DINNER*	
19:30	**Poster session I** online *(open end)*	

Program

Thursday, 06 January 2022

08:00	*BREAKFAST*	
09:00 – 09:45	Angela Wittmann	**Complex domain structures in the canted antiferromagnet α-Fe2O3**
09:45 – 10:30	Gisela Schütz	**Magnetization dynamics in the light of x-rays**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Jakob Walowski *(online)*	**THz imaging**
11:45 – 12:30	Stefan Blügel	**Search for isolated Hopfions in magnetic solids**
12:30	*LUNCH*	

Program

Thursday, 06 January 2022

14:00 – 15:30	**Poster session II** online	
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	Alice Mizrahi *(online)*	**Fully-nano spintronic neural networks**
16:45 – 17:30	Tomas Jungwirth *(online)*	**Antiferromagnets and altermagnets: From neuromorphics and ultra-fast optics to dissipationless nano-electronics**
17:30 – 17:45	Javier Hermosa	**Study of domain wall topology of Py microstructures by magnetic X-ray vector tomography**
17:45 – 18:00	Lisa-Marie Kern	**Controlled localization of magnetic skyrmion nucleation**
18:00	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	
19:30	**Poster session III** on site	

Program

Friday, 07 January 2022

08:00	*BREAKFAST*	
09:00 – 09:45	Oksana Chubykalo-Fesenko *(online)*	**Complex Bloch-point domain wall dynamics in cylindrical magnetic nanowires**
09:45 – 10:30	Daniel Wolf *(online)*	**Three-dimensional nanoscale magnetic imaging by holographic vector-field electron tomography**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Stuart Parkin	**Chiral antiferromagnets: current induced manipulation of the antiferromagnetic state**
11:45 – 12:30	Scientific organizers	**Best poster** **Best contributed talk** **Closing remarks**
12:30	*LUNCH*	

End of the seminar and departure

Posters

Poster session I online Wednesday

Nihad AbuAwwad	**Charge density waves as enablers for chiral magnetism in two-dimensional CrTe2**
Amal Aldarawsheh	**Formation of Antiferromagnetic skyrmions on a triangular lattice**
Hassan Al-Hamdo	**Magnetization dynamics in hybrid ferromagnetic / antiferromagnetic systems**
Matthias Althammer	**Magnon transport in YIG/Pt nanostructures with reduced effective magnetization**
Cristina Balan	**Electric field control of chiral magnetic textures in non-centrosymmetric multilayer thin films with perpendicular magnetic anisotropy (PMA)**
Riccardo Battistelli	**Revealing 3D magnetic textures in [Pt/Co/Cu]15 multilayers by coherent X-ray imaging with 5 nm resolution**
Sebastian Beckert	**Magneto-thermal transport in non-collinear antiferromagnetic thin films**
Yannic Behovits	**THz spin dynamics in antiferromagnetic Mn2Au reaching the non-linear regime**
Mauricio Bejarano	**A hybrid magnon-quantum system: magnetic vortices and spin centers in silicon carbide**
Phinifolo Cambalame	**XFeAs (X=Cu, Fe, Au) - Micromagnetic simulation, comparison with experiments and improvement perspectives**
Miguel Angel Cascales Sandoval	**Investigation of interlayer DMI interactions in synthetic anti-ferromagnets**
Pietro Diona	**Modeling and characterization of racetrack memories with VCMA synchronization**

Poster session I online Wednesday

Rouven Dreyer	**Imaging and phase-locking of non-linear spin waves**
Claudia Fernández González	**Chemically modulated Fe-Ni cylindrical nanowires with asymmetric magnetic response**
Simone Finizio	**Into the fourth dimension: Time-resolved soft X-ray magnetic laminography**
Olivier Fruchart	**Micromagnetics of chemical modulation in magnetic cylindrical nanowires**
John Fullerton	**Non-linear magnetic textures in strongly coupled cylindrical nanowires**
Maik Gaerner	**Quadratic and third-order magneto-optic Kerr effect in Ni(111) thin films with and without twinning**
Kathinka Gerlinger	**Time-resolved measurements of a topological phase transition**
Sumit Ghosh	**Optical generation of antiferromagnetic spin-spiral and underlying emergent interactions**
Dongwook Go	**Orbital current: Why it matters in spintronics**
Joao Godinho	**Current induced spin-orbit torque for switching and detection of reversed antiferromagnetic order in a synthetic antiferromagnet**
Olena Gomonay	**Magnetoelasticity-driven textures in antiferromagnets**
Janine Gückelhorn	**Magnon Hanle effect in easy-plane antiferromagnets**
Oliver Gueckstock	**Transition of laser-induced terahertz spin currents from torque- to conduction-electron-mediated transport**

Poster session I online Wednesday

Christopher Heins	**Spin wave frequency comb formation in a magnetic vortex**
Burkard Hillebrands	**Magnon Bose–Einstein condensate-based qubit calculus**
Yusuke Imai	**Echo state property in spin torque oscillator**
El Mostafa Jalal	**Magnetic and thermodynamic properties of mixed spin-3/2 and spin-1/2 Ising model on a hexagonal structure: Monte Carlo-Mean Field Treatment**
Sarah Jenkins	**Revealing the domain wall motion in Manganese Gold through Permalloy capping**
Fabian Kammerbauer	**Current-induced interlayer DMI in synthetic antiferromagnets**
Hiroshi Katsumoto	**Magnetic representation theory and dzyaloshinskii-moriya interaction in α-Fe_2O_3**
Volodymyr Kravchuk	**Chaotic antiferromagnetic nano-oscillator driven by spin-torque**

Poster session II online Thursday

Jonathan Kipp	**Chiral response of spin spiral states as the origin of chiral transport fingerprints of spin textures**
Tobias Kleinke	**Identification and characterization of plastics using THz-spectroscopy**
Christopher Klose	**Coherent correlation imaging: Resolving fluctuating states of matter**
Lukas Körber	**Linear and nonlinear spin-wave dynamics in magnetic nanotubes: Beyond the thin-shell approximation**
Chris Körner	**Frequency multiplication by collective nanoscale spin wave dynamics**
Andras Kovács	**Magnetic field mapping of 2-dimensional and 3-dimensional frustrated magnets using off-axis electron holography**
Volodymyr Kravchuk	**Nonlinear dynamics of skyrmion strings**
Jake Love	**Audio recognition with Skyrmion mixture reservoirs**
Fabian Lux	**Nonlinear band structure effects induced by noncollinear magnetic order**
Alberto Marmodoro	**Ab-initio studies of chiral crystals**
Giovanni Masciocchi	**Strain-controlled domain wall injection into nanowires for sensor applications**
Evgeny Mashkovich	**THz-light driven spin-lattice coupling in cobalt difluoride**
Maximilian Merte	**Photocurrents of charge and spin in single-layer Fe_3GeTe2**

Poster session II online Thursday

Daniel Metternich	**Peculiar behavior of sputter-grown DyCo near its compensation temperature**
Peter Oppeneer	**Theory of electrically-induced spin and orbital accumulation in transition-metal thin films**
Kalthoum Riahi	**Effect of iron and excitation frequency on nonlinear magnetic signal of Synomag® nanoparticles**
Davi Röhe Rodrigues	**Exploiting nonlinear dynamics of topological textures**
Bruno Rosinus Serrano	**Spatially resolved terahertz spectroscopy using spintronic-terahertz-emitter**
Levente Rózsa	**Nutation dynamics in antiferromagnets**
Sandra Ruiz-Gomez	**Magnetization in cylindrical nanowires: the role of chirality**
Rana Saha	**Intrinsic stability and size tunability of magnetic antiskyrmions in tetragonal inverse Heuslers**
Tom G. Saunderson	**Uncovering the hidden Rashba spin and orbital textures present in bulk Fe_3GeTe_2 from first-principles**
Alexander Schäffer	**Chiral logic computing with twisted antiferromagnetic magnon modes**
Tom S. Seifert	**Terahertz spin and charge dynamics in magnetic systems: From ferro- and ferri- towards antiferromagnets**
Maria Shkanakina	**Angular dependence of the spin-torque diode effect on the external magnetic field**
Krzysztof Sobucki	**Resonant control of phase of spin-wave reflected from subwavelength Gires-Tournois interferometer**

Poster session II online Thursday

Finn-Frederik Stiewe	**THz-2D scanning spectroscopy**
Jeel Swami	**Coulomb and exchange interaction in antiferromagnetic $LaCrO_3$**
Diego Turenne	**Non-equilibrium self-assembly of spin-wave solitons in FePt nanoparticles**
Clemens von Korff Schmising	**All optical switching on the nanometer scale excited and probed with femtosecond extreme ultraviolet pulses**
Teresa Weßels	**Continuous illumination picosecond imaging of magnetisation dynamics in a transmission electron microscope**
Steffen Wittrock	**Exceptional points controlling oscillation death in coupled spintronic nano-oscillators**

Abstracts of Talks

(in alphabetical order)

Screw dislocations in chiral magnets

<u>Maria Azhar</u>[1], Volodymyr P. Kravchuk[1,2], and Markus Garst[1,3]

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The Dyzaloshinskii-Moriya interaction stabilizes helimagnetic order in cubic chiral magnets for a large range of temperatures and applied magnetic field. In this helimagnetic phase the magnetization varies only along the helix axis, that is aligned with the applied field, giving rise to a one-dimensional periodic magnetic texture. This texture shares many similarities with generic lamellar order like cholesteric liquid crystals, for example, it possesses disclination and dislocation defects [1]. Here, we investigate both analytically and numerically screw dislocations of helimagnetic order. Whereas the far-field of these defects is universal, we find that various core structures can be realized even for the same Burgers vector of the screw dislocation. In particular, we identify screw dislocations with smooth magnetic core structures, that close to the transition to the field-polarized phase continuously connect either to vortices of the XY-order parameter or to skyrmion strings. In addition, close to zero fields we find singular core structure comprising a chain of Bloch points with alternating topological charge [2].

References

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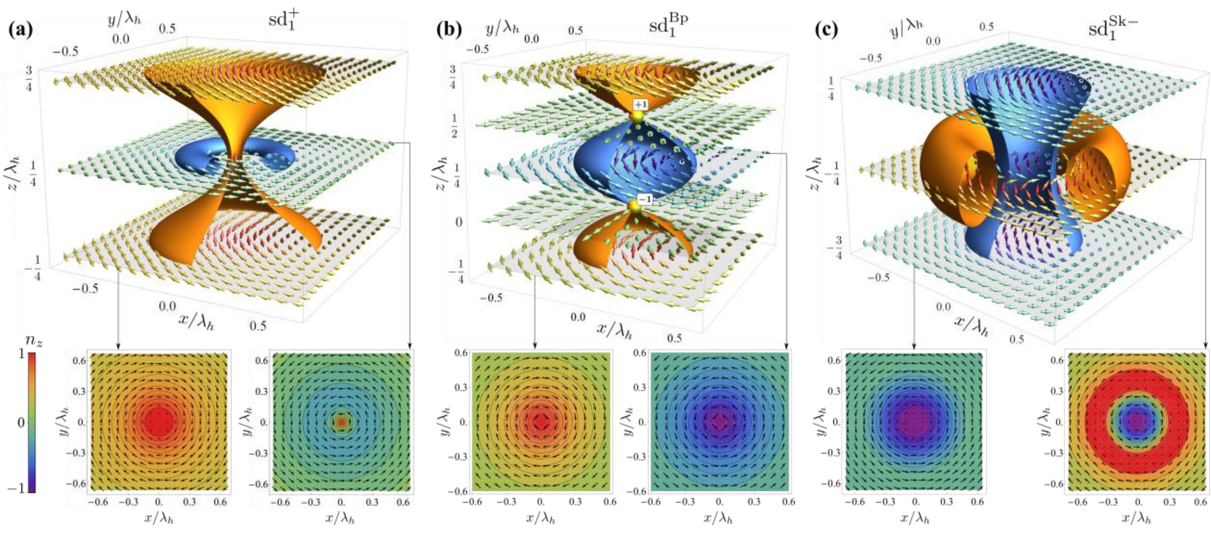

Search for isolated Hopfions in magnetic solids

Stefan Blügel[1]

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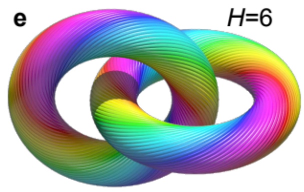
Topological magnetic textures or multidimensional magnetic topological defects are currently of great interest in condensed matter physics due to their rich science and potential applications in information technology. In contrast to two-dimensional chiral magnetic skyrmions, which are currently under intense scrutiny both theoretically and experimentally, their three-dimensional (3D) counterpart, known as Hopfions, were only recently observed experimentally [1] and only in confined geometries. Hopfions are stable solutions of the magnetization field with a knotted topological structure. In particular, their simplest spin texture can be described as a closed torus with a topologically nontrivial spin texture in the cross-section profile. Instead of topological charges, the topological invariants are linking numbers. Based on an advanced micromagnetic theory we derived analytical conditions of Heisenberg exchange parameters Ref. [2] under which isolated Hopfions can be expected. So far, no hopfion carrying material is known.



In this presentation I give a brief introduction to Hopfions and report on our theoretical and computational effort to explore suitable classes of materials that host magnetic hopfions. The method of calculation comprises three steps: (i) calculation of the ground-state electronic structure within density functional theory (local spin density approximation and generalized gradient approximation) employing the Korringa-Kohn-Rostoker Green function method [3], (ii) extraction of exchange parameters to fit the Heisenberg model [4], and (iii) Monte Carlo simulation based on the Heisenberg model.

The work is carried out in collaboration with Imara L. Fernandes, Roman Kováčik, Christof Melcher, Nikolai Kiselev and Filip Rybakov.

Funding is provided by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant 856538 – 3D MAGiC) and the Joint Lab Virtual Materials Design (JL-VMD). Support of computing time from JARA-CSD and Jülich Supercomputer Center is gratefully acknowledged.

References

[1] N. Kent *et al.*, Nat. Commun. **12**, 1562 (2021).
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[4] A. I. Liechtenstein *et al.,* J. Magn. Magn. Mater. **67**, 65 (1987).

Complex Bloch-point domain wall dynamics in cylindrical magnetic nanowires

F Felipe Tejo[1], Jose A. Fernandez-Roldan[2], Oksana Chubykalo-Fesenko [1]

[1]Instituto de Ciencia de Materiales de Madrid, ICMM-CSIC, Spain
[2] Department of Physics, University of Oviedo, Spain

Dynamics of the Bloch point domain wall (BPDW) in cylindrical nanowires has many fascinating properties related to its chiral character and non-zero gyrovector. Particularly, the absence of the Walker breakdown phenomena present in the stripe geometry has been predicted [1]. However, velocity of any rigid magnetic object should be in principle limited by the spin-Cherenkov effect [2]. Here we present our recent modelling results and analyze complex dynamics of the BPDW under external field or electric current in Ni and Fe- based magnetic cylindrical nanowires. In Ni-based alloys nanowires the dynamical transformation from the BPDW to the vortex-antivortex domain wall takes place, which limits the propagation velocity [4]. Interestingly, the BPDW can propagate not only against the current direction but also along it, attributed to the BPDW mass.

A very important result was obtained in Fe cylindrical nanowires for BPDW dynamics under applied field. We show that the BPDW has a conical shape and the cone length increases when the external field increases. In some range of applied field values the cone breaks and the BP disappears, giving rise to a more complex configuration with lower velocity, similar to a Walker breakdown phenomenon. However, for a slightly higher field we again observe a steady high-velocity BPDW propagation. The high velocity is attributed to a propulsion effect via the backward spinwave and/or additional BPs-pairs emission. We report that in Fe nanowires unprecedent velocities of the BPDW, higher than 10 km/s can be obtained.

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References

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Non-collinear 3D textures in magnetic multilayers: from hybrid chiral textures to skyrmionic cocoons

W. Legrand[1], M. Grellier[1], C. Leveillé[1], Y. Sassi[1], F. Ajejas[1], E. Burgos-Parra[1], S. Collin[1], K. Bouzehouane[1], A. Fert[1], C. Leveillé[2], H. Popescu[2], N. Jaouen[2], S. Flewett[3], P. Gargiani[4], R. Batistelli[5], F. Büttner[5], M. Valvideres[4], N. Reyren[1], V. Cros[1]

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Two-dimensional magnetic textures such as skyrmions or chiral domain walls were mostly under focus for the last decade, but recently interest has surged for more complex objects which display an inhomogeneous behavior over the vertical dimension. In particular, the impact of the interlayer dipolar fields must be carefully identified in multilayers (MML) and I will also address more specifically its role that are not only responsible for an increase of the skyrmion diameter but also for the stabilization of hybrid chiral textures [1]. A solution is to use ferromagnetic layers coupled antiferromagnetically through Ruderman-Kittel-Kasuya-Yoshida (RKKY) interaction, namely synthetic antiferromagnetic (SAF) MML [2].

Beyond skyrmions, there has been recently a blooming interest for new types of three dimensional magnetic textures. It include bobbers which could become remarkable assets for the development of logic devices [3] or the recently observed hopfions [4] or even different skyrmions phases [5]. In this presentation, I will also how we engineer and explore three-dimensional textures allowed us to observe the signature of new textures, which we name skyrmionic cocoons. At low magnetic field, they resemble tubular skyrmions but upon an increase of the out-of-plane field, they shrink and disappear in the outer layers becoming elongated ellipsoids. By carefully tuning the thickness of each magnetic layer, it is possible to observe in a single sample two distinct objects, as shown by the strong difference in the Magnetic Force Microscopy (MFM) contrasts or in x-ray holography. With the support of micromagnetic simulations, we identify them as two vertically coupled cocoons (large contrast) and single cocoons only present in half of the layers (weak contrast). The existence and field-dependent behavior of such textures could represent interesting possibilities for potential applications.

References

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Acknowledgements :

FLAGERA SographMEM (ANR-15-GRFL-0005) and LABEX NANOSACLAY "SPICY"

Steering Majorana braiding via skyrmion-vortex pairs: a scalable platform

J. Nothhelfer[1], S. A. Díaz[1], S. Kessler[2], T. Meng[3], M. Rizzi[4,5], K. M. D. Hals[6], and K. Everschor-Sitte[1]

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Majorana zero modes are quasiparticles that hold promise as building blocks for topological quantum computing. However, the litmus test for their detection, the observation of exotic non-abelian statistics revealed by braiding, has so far eluded experimental efforts. Here we take advantage of the fact that skyrmion-vortex pairs in superconductor-ferromagnet heterostructures harboring Majorana zero modes can be easily manipulated in two spatial dimensions. We adiabatically braid the hybrid topological structures and explicitly confirm the non-abelian statistics of the Majorana zero modes numerically using a self-consistent calculation of the superconducting order parameter. Our proposal of controlling skyrmion-vortex pairs provides the necessary leeway toward a scalable topological quantum computing platform.

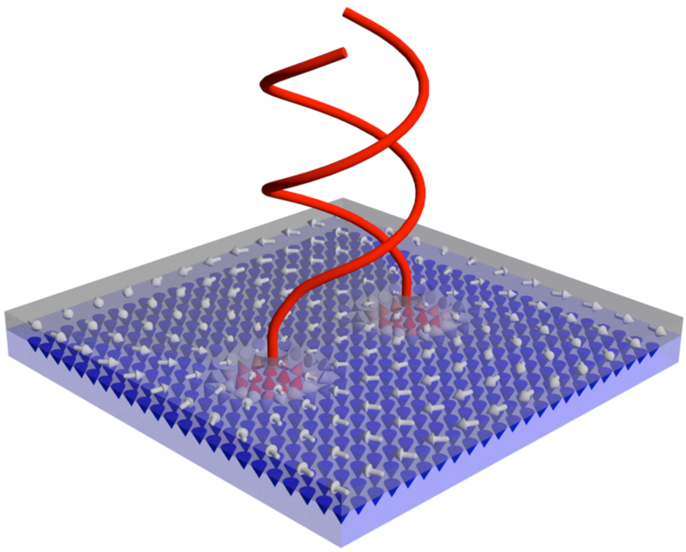

Fig. 1. Braiding of two skyrmion-vortex pairs in a superconductor-ferromagnet heterostructure.

References

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New effects in 3D magnetic nanostructures with complex geometries

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[3] *Cavendish Laboratory, University of Cambridge, UK*

The expansion of nanomagnetism to three dimensions provides exciting opportunities to explore new physical phenomena, and at the same opens great prospects to create 3D magnetic devices for future technologies [1].

To get full access to the rich phenomenology predicted to emerge when moving to 3D, we have recently developed a new computational framework for the "3D nano-printing" of materials using focused electron beam induced deposition [2], which enables the fabrication of complex-shaped 3D magnetic structures with sub-100nm resolution.

Making use of this tool, in combination with advanced magneto-optical and X-ray magnetic microscopy methods, we are studying the controlled motion of domain walls along the whole space in 3D magnetic interconnectors, either via external fields [3] or geometrical effects [4]. We are also studying the magnetoelectrical signals generated in these devices, where the non-collinear configuration of magnetic states and electrical currents results in deviations from standard angular dependences normally obtained in planar devices. In general, this leads to a nonzero contribution of the magnon magnetoresistance at all field angles [5].

I will also present our recent work on chiral effects in 3D helical geometries formed by interlaced nanowires, where exchange and dipolar interactions are balanced to result in a very rich phenomenology. The freedom provided to control magnetic effects in this type of geometries has been exploited to form chiral interfaces between domain walls of opposite chirality, allowing us to imprint topological spin defects at localized regions [6]. Furthermore, helical structures may also form strongly coupled domain wall pairs, which result in complex stray magnetic field configurations with topological features [7].

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Synthetic chiral magnets in two and three dimensions

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The ability to engineer the interactions in assemblies of nanoscale magnets is central to the development of artificial spin systems and spintronic technologies. Here we explore novel concepts to couple adjacent nanomagnets based on the Dzyaloshinskii-Moriya interaction (DMI), which emerges from the combination of spin-orbit coupling and broken inversion symmetry at the interface of ferromagnets (FM) and heavy metals. We consider two types of structures, namely 2D nanomagnets coupled by the intralayer DMI and 3D magnetic multilayers coupled by the interlayer DMI.

Lateral coupling mediated by the DMI between out-of-plane and in-plane magnetic regions is shown to dominate the behavior of nanomagnets below a critical size. Using this concept, we demonstrate lateral exchange bias and field-free current-induced switching of ferromagnetic Co dots on Pt. We also realize synthetic antiferromagnets, skyrmions, as well as artificial spin ices covering a broad range of length scales and topologies [1,2]. We then exploit the chiral coupling to realize magnetic racetracks that work as domain-wall inverters, diodes, and reconfigurable minority logic gates that perform logic operations with current-induced domain-wall motion [3,4].

In magnetic multilayers, the DMI and RKKY interaction have been shown to promote canted magnet states [5-7]. Here we report the first observation of interlayer DMI coupling in FM/NM/FM magnetic trilayers with orthogonal magnetizations [8]. The DMI effective field reaches up to 13 mT for a single Pt spacer and decreases monotonically with Pt thickness. The strong interlayer coupling affects the magnetic field required to switch the magnetization of one layer depending on the orientation of the other layer.

These results show how the intralayer and interlayer DMI can be exploited to design synthetic chiral magnets with tailored properties for applications in memory and logic devices.

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Study of domain wall topology of Py microstructures by magnetic X-ray vector tomography

J. Hermosa[1], A. Hierro-Rodríguez[1,2], M. Vélez[1,2], A. Sorrentino[3], L. Aballe[3], E. Pereiro[3], J. I. Martín[1,2], C. Quirós[1,2] and S. Ferrer[3]

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Domain walls in bulk magnetic materials and thin films have been extensively studied in terms of the basic Bloch and Néel models, that evolve into more complex configurations depending on sample geometry. The analysis of the magnetic behavior can also be performed in terms of topological singularities such as vortices, antivortices and edge half vortices in 2D magnetic nanostructures (defined by their planar winding number), skyrmions and merons in DMI and perpendicular magnetic anisotropy materials (defined by their planar skyrmion charge) or Bloch points defined by an integer 3D topological charge.
Recently, magnetic vector tomography [1, 2] techniques have provided the needed tools for a quantitative characterization of magnetization vector fields in thin films and nanostructures. Then, vector analysis methods can be applied to understand experimental 3D domain walls in terms of the emergent fields [1], magnetic vorticity [2] and topological charges.
In this work we have studied the 3D magnetization vector field of a 140 nm thick permalloy microstructure in an arbitrary remanent state characterized by magnetic soft X-ray vector tomography at MISTRAL beam line in Alba Synchrotron. A central asymmetric Bloch wall extends across the sample, dividing the structure into two domains with opposite magnetization direction in a closed-flux configuration. Several Bloch points decorate this central wall, marked by contrast kinks in the X-ray transmission microscopy images. Emergent field lines, calculated from the experimental magnetization vector field, are concentrated in high magnetic vorticity tubes (similar to those in [2]) that connect oppositely charged Bloch points and intersect the sample surface at specific magnetic textures. The interaction of emergent field tubes and domain walls will be discussed, as well as topological charge conservation rules.

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Antiferromagnets and altermagnets: From neuromorphics and ultra-fast optics to dissipationless nano-electronics

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Fifty years ago, Louis Néel pointed out in his Nobel lecture that while interesting from theoretical viewpoint, antiferromagnets did not seem to have any applications. Indeed, the alternating directions of magnetic moments on neighboring atoms and the resulting zero net magnetization have made antiferromagnets hard to control by the magneto-recording tools common in ferromagnets. This has hindered both the research and utility of these abundant magnetic materials. Our experimental demonstrations of reading and writing information in antiferromagnets have prompted the current rapidly growing interest in this traditionally overlook class of magnets. Besides electronic memory devices, antiferromagnetic spintronics has also demonstrated its utility in the research of ultra-fast optical manipulation of magnets, or analog neuromorphic logic-in-memory computing. Most recently, the research of antiferromagnetic spintronic phenomena inspired us to revisit the fundamentals of magnetism. As a result, we have delimited from antiferromagnets a third distinct class of magnetic order, the so-called altermagnetism, in which the spin direction alternates in both the crystal-structure and band-structure of the magnet. This can have consequences in fields ranging from spintronics to topological dissipationless nano-electronics.

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Controlled Localization of Magnetic Skyrmion Nucleation

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Magnetic skyrmions are vortex-like topological quasiparticles that are stabilized in out-of-plane magnetized multilayer structures providing a high DMI [1-2]. Great advances have been reported in generating, annihilating and shifting skyrmions via spin-orbit torque from spin-polarized currents [3-5]. Optical nucleation with single laser pulses offers a possibly faster and more energy-efficient alternative to create skyrmions [6-7]. While the underlying mechanisms of current-induced and laser-induced nucleation are different, both methods suffer from a stochasticity in the spatial distribution of the skyrmions nucleated. However, in view of a scientific and practical application of magnetic skyrmions, a controllable localization of the skyrmion's nucleation site is typically required.

With focused He^+-ion beam irradiation we employ an elegant technique to nanopattern our magnetic multilayers – even without changing the topography of the material [8-9]. Based on this method, we have just recently demonstrated the controlled and reproducible skyrmion nucleation and motion in our magnetic multilayers. Nanopatterning with He^+-ions to pre-define a tailored magnetic anisotropy landscape transforms the skyrmion nucleation into a deterministic process and thus provides a promising platform for enhanced control of skyrmions in thin films – a prerequisite for fundamental or applied research on these topological structures.

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Ultra-fast chiral spin dynamics

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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 to manipulate topological spin structures [1,2].

Firstly, to obtain ultimate stability of states, 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]. Here we will introduce these spin structures ad we have investigated in detail their dynamics and find that it is governed by the topology of the spin structure [3,5,6]. By designing the materials, we can even obtain a skyrmion lattice phase as the ground state [4]. Beyond 2D structures, we recently developed also systems with chiral interlayer exchange interactions that lend themselves to the formation of chiral 3D structures [7].

We study in particular the chiral order dynamics using time-resolved x-ray scattering at the free electron laser FERMI [8]. By small angle x-ray scattering in a pump-probe experiment after excitation with a infrared laser, we ascertain the timescale of the formation of collinear magnetization in domains and the formation of chiral domain walls. Surprisingly we find that the latter occurs on a faster timescale, showing the robust formation of chiral spin structures [8]. Additionally, we observe oscillations in the recovery of the order, which are novel features that will be discussed in this presentation [9].

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Skyrmion Hall effect in spin-orbit torque driven topologically trivial and nontrivial structures

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The dynamics of magnetic skyrmions are governed by the complex interplay between driving forces, thermal fluctuations and material disorder. This interplay leads to rich behavior, e.g. a creep motion that persists up to almost 100 m/s, which needs to be fully understood before skyrmions can be reliably used in technological applications like the racetrack memory [1].

To assist in this understanding, there exist theoretical approaches which rely on the assumption that skyrmions are rigid objects. However, especially in the technologically relevant regime where skyrmions are under the constant influence of disorder and temperature, they do not behave as rigid objects, making micromagnetic simulations indispensable to bridge theoretical models and experimental results. To this end, we developed an algorithm offering a twentyfold speedup without a loss of accuracy to perform simulations at nonzero temperatures [2]. After validating this methodology against theoretical results for skyrmion diffusion [3], we use it in a large-scale study of the impact of temperature and disorder on the skyrmion motion and compare the results against experimental data of the velocity and skyrmion Hall (SkH) angle as function of the driving force [4].

Our results show that the skyrmion velocity as a function of current density falls on a universal curve when the the temperature dependence of the spin-orbit torques is accounted for. This allows the skyrmion trajectories in a device to be engineered, although the problem remains that high velocities are accompanied by large SkH angles, which could eventually lead to the annihilation of the skyrmion after a collision with the edge of the racetrack.

Recently, it was suggested that this problem could be mitigated by replacing skyrmions by topologically trivial structures like two coupled skyrmions in a synthetic antiferromagnet or a skyrmionium. Both structures have no net topological charge, which in the case of spin-transfer torque driven motion also results in a zero SkH angle. However, we show that this notion is generally false for spin-orbit torque driven objects [5]. Instead, the SkH angle is directly related to the objects' helicity and imposes an unexpected roadblock for developing faster and low-power racetrack memories based on spin-orbit torques.

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Fully-nano Spintronic Neural Networks

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Neuromorphic computing takes inspiration from the architecture of the brain to build miniaturized, ultra-low power hardware for artificial intelligence. In recent years, nanoscale devices that perform key functions of neurons (nonlinear activation) and synapses (weighted sum of neuron outputs) have been realized. However, neurons and synapses are made from different materials, with different circuitry, making it difficult to connect them into deep networks, where layers of neurons and synapses are alternated.
Here we show that the multifunctionality of spintronics overcomes this challenge by using the same magnetic tunnel junctions to mimic neurons and synapses [1, 2], and connecting them in a multilayer neural network using the radio frequency (RF) signals that these devices can transmit as well as filter and rectify in a wide frequency band (10 MHz -20 GHz).
We experimentally demonstrate a fully nanoscale RF spintronic neural network with a hidden layer, composed of nine magnetic tunnel junctions, and show that it can natively classify RF signals with high accuracy.
These results pave the way for miniaturized and deep neural networks that exploit the multifunctionality of spintronics to achieve dense architecture and connectivity.

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Chiral antiferromagnets: current induced manipulation of the antiferromagnetic state

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Chiral antiferromagnets (AFs), such as Mn_3Ge and Mn_3Sn, that exhibit a Kagome lattice of Mn magnetic moments, display an anomalous Hall effect (AHE) that is derived from Berry curvature. The AHE is highly anisotropic and is large when the current passes through the Kagome plane, thereby allowing the antiferromagnetic structure to be probed. The ground state is composed of six equivalent AF domains, each with the same energy. The system can be set predominantly into one of these domains by a small in-plane magnetic field. We discuss the possibility of manipulating the magnetic state of thin films of Mn_3Sn rather by spin-orbit torques derived from spin currents created in adjacent tungsten or platinum thin layers via electrical current pulses and the spin Hall effect in these layers. We show that the spin-orbit torque sets the magnetic state of only a thin interfacial “seed” layer in the chiral AF layer adjacent to the Pt or W layer. The magnetic state of the AF layer is set only when the entire layer is heated to a temperature close to its magnetic ordering temperature and cooled down in the presence of the spin orbit torque. This mechanism of “seeded spin orbit torque (SSOT)” allows for the manipulation of the AF structure of layers of chiral AFs that are much thicker than the spin diffusion length. This novel mechanism is not only very interesting from a fundamental perspective, but also for technological applications.

Magnetization dynamics in the light of x-rays

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The field of spintronics and magnonics has become a flourishing synonym of future low-power, ultra-fast and persistent advanced information technologies with fantastic promises. However, the relevant magnetization dynamics with spatial and temporal dimensions in the sub µm and sub ns range are hard to access experimentally. An effective (and maybe the only) magnetic imaging technique is provided by time-resolved X-ray microscopy. By the combination with soft x-ray spectroscopy and the strong effects of circular and linear magnetic dichroism even element-specific information on the local actual sample thickness, magnetization, hysteresis behavior and the absolute spin waves amplitudes are provided. The physical and technical basics of this method, the potentials and difficulties and insights into non-linear effects are discussed by several magnetization movies in metallic systems, multilayers, van der Waals flakes and oxides.

Curvilinear magnetism

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Recent advances in nanotechnologies have enabled fabrication of the novel class of 3D curved magnetic nanoarchitectures, where the fundamental properties are determined by the geometry [1]. Active exploration of this new material class turns light on the fundamentals of magnetism of nanoobjects with curved geometry and applications of 3D-shaped curved magnetic nanoarchitectures, leading to remarkable developments in shapable magnetoelectronics, magnetic sensorics, spintronics, 3D magnonics, and microrobotics. Today, fundamental and applied research of curved nanoarchitectures and related curvature-induced effects in these objects are united in curvilinear magnetism, which is a rapidly developing research area of modern magnetism aimed to explore geometry-induced effects in curved magnetic wires and films [2].

By exploring geometry-governed magnetic interactions, curvilinear magnetism offers a number of intriguing effects in curved magnetic wires and curved magnetic films. Emergent interactions, induced by the curvilinear geometry manifest themselves in topological magnetization patterning and magnetochiral effects in conventional magnetic materials. These curvature-induced interactions can be not only local (when they stem from the exchange energy) [3] but also non-local (when they are due to magnetostatics) [4]. As a consequence, family of novel curvature-driven effects emerges, resulting in theoretically predicted unlimited domain wall velocities, chirality symmetry breaking etc. Current and future challenges of the curvilinear magnetism will be discussed [5].

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Altermagnetism: spin-momentum locked phase protected by non-relativistic symmetries

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The search for novel magnetic quantum phases, phenomena and functional materials has been guided by relativistic magnetic-symmetry groups in coupled spin and real space from the dawn of the field in 1950s1{3 to the modern era of topological matter. However, the magnetic groups cannot disentangle10,11 non-relativistic phases and effects, such as the recently reported unconventional spin physics in collinear antiferromagnets from the typically weak relativistic spin-orbit coupling phenomena. Here we discover that more general spin symmetries in decoupled spin and crystal space categorize non-relativistic collinear magnetism in three phases: conventional ferromagnets and antiferromangets, and a third distinct phase combining zero net magnetization with an alternating spin-momentum locking in energy bands, which we dub "altermagnetic". For this third basic magnetic phase, which is omitted by the relativistic magnetic groups, we develop a spin-group theory describing six characteristic types of the altermagnetic spin-momentum locking. We demonstrate an extraordinary spin-splitting mechanism in altermagnetic bands originating from a local electric crystal field, which contrasts with the conventional magnetic or relativistic splitting by global magnetization or inversion asymmetry. Based on first-principles calculations, we identify altermagnetic candidates ranging from insulators and metals to a parent crystal of cuprate superconductor. Our results underpin emerging research of quantum phases and spintronics in high-temperature magnets with light elements, vanishing net magnetization, and strong spin-coherence.

Imprinting and Processing of different topological Objects in the same Material

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The realization of systems integrating interlayer magnetic chiral interactions paves the way for the creation of unprecedented magnetic effects in the emerging field of three-dimensional nanomagnetism and spintronics [1-3]. Particularly, magnetic interfacial and interlayer Dzyaloshinskii-Moriya interaction in multi-layered thin films can lead to exotic chiral spin states like standard and multi-π skyrmions, antiferromagnetic and ferrimagnetic skyrmions, antiskyrmions, chiral domain walls or merons, which are of paramount importance for future spintronic technologies [4]. The logical chiral bits 0 and 1 are usually encoded in terms of the absence and presence of a topological quasiparticle. This approach suffers from the challenging demand of fixed spatial distances between quasiparticles and lacks either the controllability of the created species or the mobility of the quasiparticles. One of the ways to overcome this difficulty is encoding of 0 and 1 in different topological particles. This is, however, a challenging requirement, because different objects require different material properties. Here, novel concepts for imprinting and subsequent steering of mixed sequences of topologically distinct objects in the same material will be presented.

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THz imaging

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The generation of THz radiation using spin polarized current pulses has been explored recently extensively, developing a vivid research community. The currents are generated by exciting electrons in ferromagnetic thin layers by ultrashort laser pulses. The resulting charge current is then deflected perpendicular to its propagation direction via the inverse spin Hall effect when entering an adjacent non-magnetic heavy metal layer. This perpendicular motion of charges in the heavy metal layer along a straight path acts as a Hertzian dipole and emits electromagnetic radiation. The time scale for those current pulses are picoseconds. Therefore, the emitted radiation has THz frequency. The pulses are detected in a pump probe scheme via Auston switch antennas or for a broader frequency range detection up to 30 THz using the electro-optic effect in <110> Zinc Telluride crystals.

The THz spectral range offers various possibilities for imaging applications. The low photon energies allow for non-ionizing structure investigation. Especially biological samples like cells can be scanned for impurities and intoxicants, in the future even the observation of DNA-strands will be possible.

However, refraction limits the resolution capabilities of THz radiation to the range of half of the wavelength, which is in the hundreds of micrometers. Therefore, other approaches are necessary to achieve resolution far below the wavelength. Using near-field imaging in combination with spintronic THz emitters allows to increase imaging resolution to the single digit micrometer range.

The area of THz radiation generation is contained by the size of the laser spot that delivers the femtosecond pulses to excite the electrons in the ferromagnetic layer. Those laser pulses can be focused down to a few micrometers and thus allowing for THz spots at the same magnitude. To make use of this beam confinement, the structure being imaged needs to be positioned in direct vicinity of the THz generation region, closer than the wavelength.

The heterostructures for spintronic THz emitters can be deposited on a large variety of substrates, e.g., thin glass slides, thus bringing THz generation close to imaged structures.

We developed a test structure in 300 nm distance to the point of THz generation and achieve an imaging resolution around 5 micrometers using THz radiation in the near field. This experimental scheme enables near field imaging combined with far field detection increasing the resolution around 60 times below the diffraction limit.

Complex domain structures in the canted antiferromagnet α-Fe_2O_3

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Spintronic devices have proven to be promising candidates for low-dissipation, spin-based computing technologies. Within this field, antiferromagnetic materials have gained significant attention due to their favorable properties such as ultrafast dynamics and no net magnetic moment. The recent observation of topological spin textures in antiferromagnets has sparked particular interest due to their high potential for novel racetrack logic-in-memory devices using solitonic information carriers.
Here, we study the canted antiferromagnet α-Fe_2O_3. We observe a strongly field-dependent domain structure of α-Fe_2O_3 using x-ray magnetic linear dichroism (XMLD) and spin Hall magnetoresistance (SMR) measurements. Combining angle-dependent SMR and XMLD measurements, we can conclude, that the internal destressing fields driving the formation of the multidomain state do not follow the hexagonal crystal symmetry of α-Fe_2O_3 but rather open up a pathway for complex domain structures.

Three-Dimensional Nanoscale Magnetic Imaging by Holographic Vector-Field Electron Tomography

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Holographic vector-field electron tomography (VFET) enables the 3D imaging of magnetic induction *B* with sub-10 nanometer resolution. This is achieved by combining off-axis electron holography (EH) and electron tomography (ET) applied in the transmission electron microscope. EH retrieves the phase shift that an electron wave experiences upon passing through the sample's electrostatic potential and magnetic flux density (*B*-field) of the specimen. ET requires a series of projections (in case of VFET phase images) obtained at different directions, so-called tilt series, to reconstruct the 3D components of the magnetic flux density (B-field) as well as the 3D electrostatic potential using tomographic algorithms. This involves a comprehensive workflow of data processing, including image acquisition, alignment, holographic-tomographic reconstruction and, finally, 3D visualization and analysis. VFET has been successfully applied to reveal the 3D magnetic spin textures in CoNi nanowires with large transversal magnetocrystalline anisotropy [1], and Bloch skyrmion tube lattices in FeGe in which peculiar features such as 3D skyrmion-skyrmion interactions and their coupling to surfaces and interfaces are observed [2] (see Figure 1).

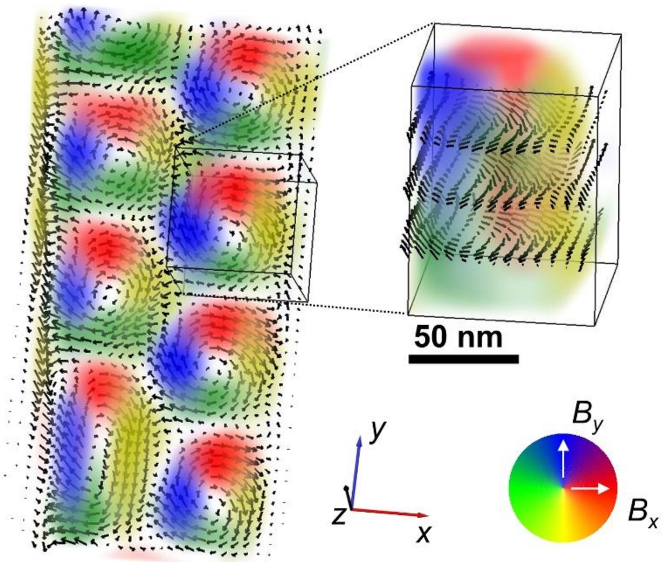

Figure 1. Three-dimensional reconstruction of the magnetic induction ***B*** of a Bloch skyrmion tube lattice in a FeGe needle-shaped sample.

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Abstracts of Posters

(in alphabetical order)

Charge density waves as enablers for chiral magnetism in two-dimensional $CrTe_2$.

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The discovery of two-dimensional (2D) van der Waals magnets opened unprecedented opportunities for the fundamental exploration of magnetism in quantum materials and the realization of next generation spintronic devices. Recently, thin $CrTe_2$ films were demonstrated to be ferromagnetic up to room temperature, with an intriguing dependence of the easy axis on the thickness of the material [1,2]. Here, we demonstrate using first principles that the charge-density waves characterizing a single $CrTe_2$ give rise to chiral magnetism through the emergence of the Dzyaloshinskii-Moriya interaction (DMI). Utilizing atomistic spin dynamics, we perform a detailed investigation of the complex magnetic properties pertaining to this 2D material impacted by the presence of various types of charge density waves.

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Formation of Antiferromagnetic skyrmions on a triangular lattice

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Skyrmions are topologically protected spin textures that are envisioned to be the next generation of bits. However, conventional ferromagnetic (FM) skyrmions are deflected when an electric field is applied, which limits their use in spintronic devices. In contrast, antiferromagnetic (AFM) skyrmions, which consist of two FM solitons coupled antiferromagnetically, are predicted to have zero net magnus force [1], and this makes them promising candidates for spintronic racetrack memories. So far these have been stabilized in synthetic AFM structures [2], i.e. multilayers hosting FM skyrmions, which couple antiferromagnetically through a non-magnetic spacer. Using ab initio calculations in conjunction with atomistic spin dynamics, we investigate systematically and predict the presence of chiral intrinsic AFM structures in specific and realistic combination of thin films deposited on heavy substrates.

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Magnetization dynamics in hybrid ferromagnetic / antiferromagnetic systems

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Ferromagnets and antiferromagnets feature qualitatively different magnetization dynamics. While ferromagnetic magnons are typically gapless at zero external magnetic field, antiferromagnetic magnons have THz frequency. Ferro/antiferromagnetic bilayer systems are thus expected to host excitations of hybrid character.

We study the magnetization dynamics of the Mn_2Au/ $Ni_{80}Fe_{20}$ thin film bilayer system. This system allows us to control the Mn_2Au Néel vector orientation with moderate in-plane external magnetic fields < 500 mT depending on $Ni_{80}Fe_{20}$ layer thickness.

[1]. Mn_2Au furthermore shows strong spin-orbit torque efficiency [2] making this system intriguing for all-electrical control of magnetization direction. We vary the $Ni_{80}Fe_{20}$ thickness to study the effect of the Mn_2Au/ $Ni_{80}Fe_{20}$ interface on $Ni_{80}Fe_{20}$ spin dynamics.

Our Broadband Ferromagnetic resonance (BBFMR) and Brillion light scattering (BLS) experiments reveal that interfacial exchange coupling causes an increase in the resonance frequency of $Ni_{80}Fe_{20}$. This increase is inversely proportional to the thickness of the $Ni_{80}Fe_{20}$ layer.

We furthermore observe a hysteretic behavior of two distinct uniform-mode $Ni_{80}Fe_{20}$ resonances that accompanies the switching of the Mn_2Au Néel vector direction.

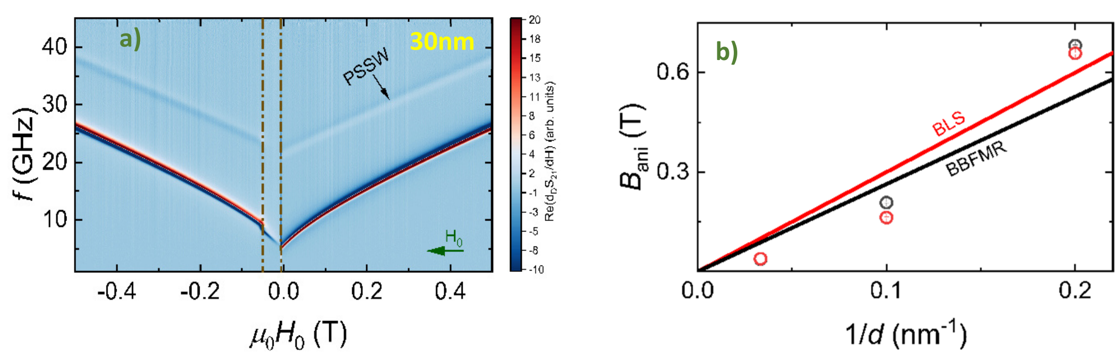

Figure1: a) BBFMR measurement of Mn_2Au/ $Ni_{80}Fe_{20}$ (30 nm). b) Anisotropy field (B_{ani}) vs. ($1/d$), where d is the thickness of $Ni_{80}Fe_{20}$.

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Magnon transport in YIG/Pt nanostructures with reduced effective magnetization

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The transport of information via spin waves (magnons) in magnetically ordered insulators provides novel routes for information processing. For applications based on pure spin current magnetic damping effects resulting in a decrease of the corresponding conductivity have to be minimized. Here, we investigate the magnon transport through an yttrium iron garnet (YIG) thin film with strongly reduced effective magnetization. Utilizing three-terminal Pt strip devices [1], allow us to manipulate the magnon transport between the two outer strips via an additional applied charge current to the center electrode. Most importantly, above a certain threshold current, where damping compensation via spin torque is reached, the effective magnon conductivity can be enhanced by a factor up to six [2]. Another major observation is the linear dependence of the threshold current on the applied magnetic field. We attribute these observations to the reduced effective magnetization in our films and the associated nearly circular magnetization precession.

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Acknowledgement

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Electric field control of chiral magnetic textures in non-centrosymmetric multilayer thin films with perpendicular magnetic anisotropy (PMA)

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Voltage-controlled magnetic anisotropy (VCMA) is a recent technique that can be used in the future spintronic devices, such as magnetic memories, and help developing low-energy consuming technologies. Controlling the magnetic properties with electric field is a relatively new subject in magnetism, especially the magneto-ionic effects where the interface between a magnetic layer and a solid or liquid electrolyte is modified in a non-volatile manner due to the migration of ionic species.

By applying a voltage gate (Vg), the magnetic anisotropy of Pt/Co/MOx (MOx = ZrO2, HfO2) stacks can be modified locally so that the magnetisation easy-axis can be changed from in-plane (IP) to out-of-plane (OOP) in a reversible non-volatile way. This is attributed to a variation of oxidation rate at the interface between Co layer and MOx . The change in the magnetic anisotropy of the system, gives also a variation of properties in the magnetic textures, such as domain walls (DW) stripe domains and skyrmion bubbles.

The first studied system is Pt/Co/TbOx/MOx. In this case we show that the modification of magnetic anisotropy leading to a transition from an from IP to an OOP , going through a in-between state with zero remanence characterized by butterfly (BF) hysteresis loops. Our MFM measurements show that the BF loops correspond to a magnetic stripe domains structure, that can be transformed in skyrmion bubbles in the presence of a weak out-of-plane magnetic field.

In a second set of experiments, we studied the effect of Vg on the velocity of field-driven chiral magnetic DWs. The studied magnetic stack is Pt/Co/Tb, where Tb magnetic moment has an antiparallel orientation to that of Co, covered by a ZrO_2 dielectric layer. By applying the voltage gate, the DW velocity is drastically changed from a state where it can reach only a few m/s to a state where the velocities can reach a few hundred of m/s due to the gradual oxidation of the Tb layer.

Revealing 3D magnetic textures in $[Pt/Co/Cu]_{15}$ multilayers by coherent X-ray imaging with 5 nm resolution

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Abstract

In the fields of magnetism and spintronics, magnetic multilayers continue to thrive as pivotal structures to functionalize magnetic interactions, including the interfacial Dzyaloshinskii-Moriya interaction (DMI), and to engineer complex non-trivial spin textures.[1,2,3] However, previous research has focused almost exclusively on 2D structures. The challenge in studying 3D textures is in obtaining the necessary spatial resolution and sensitivity to resolve them. Here we show that this challenge can be met by reference-aided coherent diffractive x-ray imaging combined with a modulated reference beam which amplifies the magnetic signal at large scattering angles.[4] Based on this amplified wide-angle scattering, we achieve 5 nm spatial resolution for spin textures in Pt/Co/Cu magnetic multilayers. Surprisingly, while conventional low-resolution images only show the well-known stripe domain state characteristic of such multilayers, our high-resolution images additionally reveal several small, mostly circular features of much weaker contrast. Since the features are larger than our spatial resolution, their weaker contrast identifies them as textures that penetrate only some of the magnetic layers. Interestingly, while these features are clearly magnetic in nature, and interact with the domain walls, they do not annihilate at the largest fields available in our system (220 mT).

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Magneto-thermal transport in non-collinear antiferromagnetic thin films

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Understanding the interplay between topological properties and transport phenomena in non-collinear antiferromagnets is important for exploiting their unconventional characteristics in spintronics. In particular, non-collinear antiferromagnets can exhibit phenomena previously known to be exclusive to ferromagnets, such as the anomalous Hall Effect (AHE) or the anomalous Nernst effect (ANE).

We experimentally study magneto-thermal transport in unconventional antiferromagnetic thin magnetic films with complex band structure, namely Mn_3Sn [1] and Mn_3NiN [2]. We show that Mn_3Sn epitaxial films exhibit an ANE comparable to ferromagnetic films. However, in the Mn_3Sn films, all spins are arranged in the sample plane. Therefore, AHE and ANE cannot simply be measured in a standard Hall bar geometry and a direct comparison of AHE and ANE is also not straightforward. (001)-oriented Mn_3NiN thin films have their spins arranged in the (111) plane and, therefore, a component of the Hall vector in both out-of plane and in-plane direction. This makes Mn_3NiN an ideal candidate for a systematic study of magneto-thermal transport phenomena and their anisotropy. We will present measurements of ANE, AHE, magnetoresistance and Seebeck effect in a single device. Based on careful thermal gradient calibration, we can compare the measured amplitudes of the magneto-thermal transport coefficients and discuss them in context of the Mott relation [3].

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THz spin dynamics in antiferromagnetic Mn2Au reaching the non-linear regime

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In antiferromagnets, the strong exchange coupling leads to intrinsic terahertz (THz) magnon resonances, which can enable pathways to high-speed spin information processing. In antiferromagnetic CuMnAs and Mn2Au, switching of the Néel vector has been demonstrated by using pulsed electrical currents and free-space THz pulses [1-3]. The switching was attributed to the Néel spin-orbit torque (NSOT), which is proportional to the current [4]. However, the underlying spin dynamics have not been observed on ultrafast timescales.
Here, we employ a THz-pump optical-probe setup to investigate ultrafast dynamics of antiferromagnetic order induced by NSOT in Mn2Au. The direction of the Néel vector was prealigned via spin-flop transition in a high magnetic field (60 T). We observe a signal proportional to the driving THz, which and is consistent with NSOT-driven spin dynamics both in frequency and symmetry. The recorded spin motion corresponds to a strongly damped magnon mode with frequency of 0.6 THz.
Upon increasing the THz field strength, non-linear dynamics emerge, which can be related to a substantial deflection of the Néel vector from its equilibrium position. Based on our results, we can estimate important material-specific parameters and calculate THz pulse field strengths that one needs to switch the antiferromagnetic order of Mn2Au on picosecond timescale.

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A Hybrid Magnon-Quantum System: Magnetic Vortices and Spin Centers in Silicon Carbide

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We report on a hybrid quantum system composed of a ferromagnetic disk and V_{Si} spin centers in a 4H silicon carbide substrate. In the passive regime, the spin centers behave as a room temperature sensor of static stray fields generated by the permalloy disk. We utilize optically detected magnetic resonance (ODMR) to measure the impact of the stray fields on the intrinsic V_{Si} resonance frequencies. Additionally, we use a mixed approach of micromagnetic simulations and analytical calculations to study the active regime in which the dynamic dipolar fields stemming from the modes inside the disk couple with the spin centers in SiC. Our results point toward magnon-driven coherent control of spin centers for quantum applications. This work was supported in part by the German Research Foundation under Grants SCHU 2922/4-1 and AS 310/5-1.

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Research Field **Poster**
Magnetism/Superconductivity

*X*FeAs (*X*=Cu, Fe, Au) - Micromagnetic simulation, comparison with experiments and improvement perspectives

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Predicting magnetic properties of iron-based layered compounds is an interesting and challenging task because magnetic properties in these material are simultaneously related to spin, lattice and orbital degrees of freedom. Small differences between lattice parameters *a* and *b* and large differences between J^{NN} and J^{NNN} render a non negligible $\Delta J/\Delta r$, which entangle the lattice to magnetism[1]. Herein we present simulation done with vampire – an atomistic simulation that bridges the gap between micromagnetics approaches and electronic structure[2].
Simulation of *X*FeAs was done by considering and manipulating NaFeAs (P4/nmm) unit cell parameters taken from Materials Project. Orbital hybridization from As and Fe weren't considered, instead a random spin direction was attributed to As with the goal of introducing a certain magnetic influence on Fe checkboard layer.

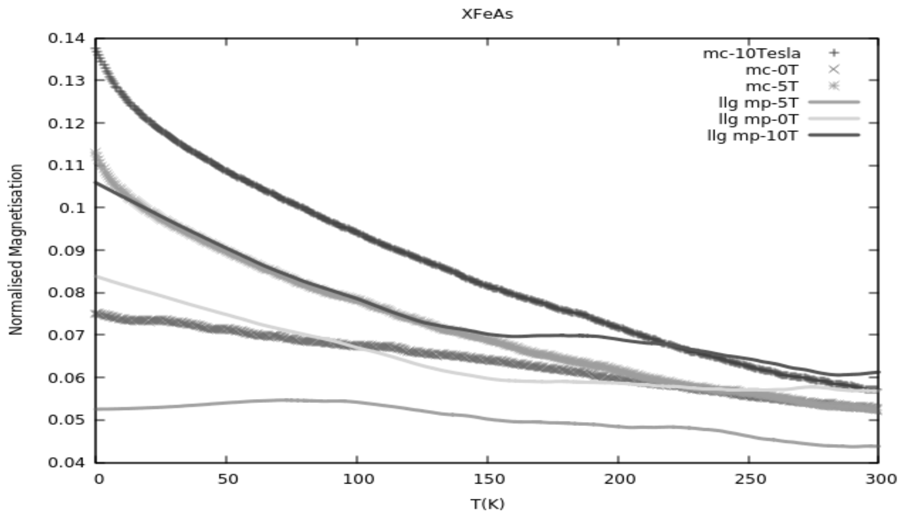

Figure 1: Magnetisation calculated for different field values for two different methods, Monte-Carlo and stochastic Landau-Lifshitz-Gilbert spin model.

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Investigation of Interlayer DMI interactions in Synthetic Anti-Ferromagnets

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Interlayer DMI (IL-DMI) has been recently predicted and observed in two-dimensional multilayer thin film structures [1-3]. This interaction couples two neighboring magnetic films via a non-magnetic interlayer in a chiral fashion. IL-DMI could be utilized to obtain complex chiral magnetic states in one layer, controlled by the magnetic configuration of a neighboring layer, something attractive for spintronic applications.

Previous work using magnetometry techniques indicates the existence of non-zero IL-DMI in Synthetic Antiferromagnetic (SAF) bilayers with highly asymmetric properties, with one layer close to the spin reorientation transition, and the other fully out-of-plane. In these systems, IL-DMI is manifested as a chiral exchange bias under in-plane magnetic fields. In this work, an extension on these results is performed by investigating in detail the type of magnetic states present in the SAFs under in-plane magnetic fields that give rise to this chiral bias. X-ray Resonant Magnetic Scattering (XRMS) measurements have been performed for an in-plane demagnetized state in one layer, with the other layer in a fully out-of-plane configuration. We observe an asymmetric XRMS signal that indicate the presence of Neel domain walls with a well-defined in-plane chirality. Importantly, the sign of this chirality can be controlled by the orientation of the layer underneath.

Complementary X-ray Magnetic Circular Dichroism Photo Electron Emission Microscopy (XMCD-PEEM) measurements have been performed to visualize the domain structure of the demagnetized state and validate the scattering measurements. These results demonstrate how the magnetic chirality in this type of complex SAFs can be indirectly tuned by the relative direction of a neighboring layer, opening exciting applications for 3D nanomagnetism.

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Modeling and Characterization of Racetrack Memories with VCMA Synchronization

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The control of the motion of magnetic domains is of crucial interest for the development of several spintronic applications, such as high-density racetrack memories and domain wall logic [1]. In these devices, the domain wall manipulation can be achieved via pulsed currents or applying an external field. However, real-world applications require accurate signal synchronization systems, keeping limited the power budget. Up to now, geometrical restrictions in the magnetic wire, known as notches, were used to confine domain walls at the expense of a higher current to depin the blocked information. The solution based on the Voltage Controlled Magnetic Anisotropy (VCMA) effect appears more promising because it has already been shown that this technology is able to effectively confine different magnetic textures, avoiding the need for strong depinning currents, and simplifying the fabrication process [2]. The anisotropy variation induced by the VCMA can create barriers or wells that can be used to limit the movement of domain walls and obtain an effective synchronization. In our study, we propose a system-level evaluation of the effectiveness of the proposed VCMA synchronization methods [Fig. 1(a)]. Our analysis is referred to a stack of CoFeB/MgO [Fig. 1(b)]. Starting from a two-coordinates model, the motion of domain walls, the performance and the efficiency of the approach is evaluated. The VCMA proved to be comparable with respect to the notch synchronization approach in terms of energetic performance with a clear advantage in the control and the realization at the system level.

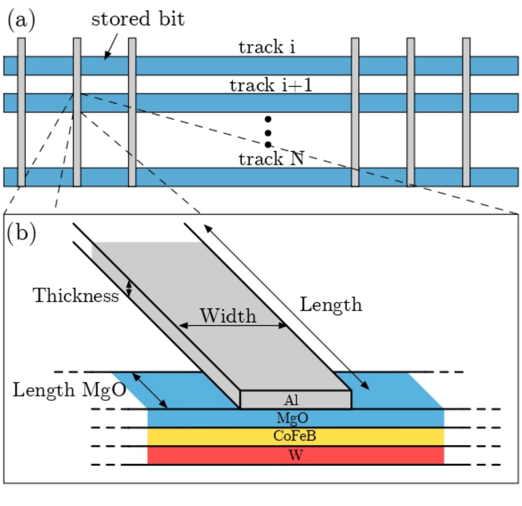

Figure 1: (a) System-level representation of the racetrack memory; (b) Schematic structure of the VCMA gate

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Imaging and phase-locking of non-linear spin waves

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Non-linear processes are a key feature in the emerging field of spin-wave based information processing. Non-linear phenomena allow converting uniform spin-wave excitations into propagating modes at different frequencies. Recently, the existence of non-linear magnons at odd half-integer multiples of the driving frequency (such as 3/2 f_{rf}, 5/2 f_{rf}, etc.) has been predicted for $Ni_{80}Fe_{20}$ at low bias fields [1]. However, it is an open question under which conditions such non-linear spin waves emerge coherently and how to manipulate them in device structures. Here, we demonstrate a modified time-resolved microscopy approach for coherent imaging of the parametrically generated non-linear spin waves [2]. The spatially-resolved observation of parametrically generated magnons in $Ni_{80}Fe_{20}$ elements allows to directly visualize their wave vectors. In addition, we demonstrate phase-locking of the generated non-linear magnons. These results provide unprecedented insight into non-linear spin-wave processes and open new possibilities for applications such as spin wave sources and amplifiers.

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Chemically modulated Fe-Ni cylindrical nanowires with asymmetric magnetic response

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Cylindrical nanowires (NWs) are promising nanostructures for the development of a new generation of 3D recording devices like race-track memories [1], designed to allow a higher data storage, a faster access to data and lower energy consumption compared to the 2D hard disks. Their application in devices rely on efficiently controlling the movement of magnetic domain walls (DW) for example by means of electric currents. In recent studies, we have demonstrated that local changes in composition along the axis of permalloy (Py) nanowires can pin the DW and this DW can be move in a reliable way under the application of magnetic field [2]. Following the same concept, in this work we propose a gradual change in Fe/Ni ratio along the axial direction of the NWs to create an asymmetrical energy landscape that may induce asymmetric domain wall motion (ratchet effect).

Nanowire's composition was continuously changed along the NWs between $Fe_{80}Ni_{20}$ and $Fe_{20}Ni_{80}$. The magnetic characterization of single nanowires was carried out using X-ray Photo Emission Electron Microscopy (XPEEM). With this technique we correlate the chemical structure of single NWs with their magnetic configuration. In addition, by applying pulses of magnetic field along the nanowire axis we study the magnetic state depending on the direction of the applied magnetic field. First Ordered Reversal Curves (FORC) were measured in arrays of nanowires to study the magnetic interactions between the nanostructures. Results also point out that Py NW FORC distribution is highly symmetric with respect to the interaction field (Hu), while in the case of modulated NWs, an asymmetry arises evidencing the changes of the interaction fields within the array.

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Into the Fourth Dimension: Time-Resolved Soft X-ray Magnetic Laminography

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Until recently, most of the experimental research into magneto-dynamical systems has been focused on two-dimensional systems. Such systems exhibit a variety of phenomena that include, but are not limited to, magnetic vortex dynamics, domain wall motion, switching processes, skyrmion dynamics, and magnonic processes. The extension to the experimental investigation of fully three-dimensional dynamical processes has up to now only been possible through indirect methods and through comparison of two-dimensional data with micromagnetic simulations. One of the main reasons for this is that microscopy techniques that combine three-dimensional magnetic imaging with nanometric resolutions with the possibility to perform time-resolved investigations with sub-ns temporal resolutions are not widely available.

A first demonstration of time-resolved three-dimensional imaging was performed with hard X-ray magnetic laminography. However, the technique exhibits limitations both in the sensitivity and in the selection of accessible frequencies, which has limited its applicability.

Here, we present first time-resolved measurements of magnetic vortex and spinwave dynamics fully resolved in all three spatial dimensions performed at soft X-ray energies, enabling us to obtain strong magnetic contrast at the 3d ferromagnetic elements. By combining the laminography imaging technique with time-resolved scanning transmission X-ray microscopy to acquire the angular projections, time-resolved three-dimensional imaging with free selection of the frequency of the excitation signals is made possible. Here, we show the full three-dimensional characterization of two magneto-dynamical modes in a microstructured CoFeB element, namely a vortex gyration mode, where the vortex core displays a three-dimensional motion, and a domain wall motion mode, where variations of the motion along the thickness of the CoFeB element can be observed.

Micromagnetics of chemical modulation in magnetic cylindrical nanowires

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Due to their geometry, cylindrical nanowires can host a domain walls (DWs) with curling magnetization that were predicted to reach velocities over 1 km/s, known as Bloch-Point wall, avoiding the Walker breakdown limitation. It is desirable to achieve some control of the DW position along the wire's axis, both to conduct fundamental investigation such as time-resolved, or to develop digital DW-based memories. For this purpose, we investigate wires with Permalloy segments, separated by chemical modulations of $Fe_{80}Ni_{20}$, of length a few tens of nm. We combine micromagnetic simulations and theory, and X-ray magnetic circular dichroism (XMCD) coupled to Photoemission electron microscopy (PEEM), Scanning transmission X-ray microscopy (STXM) and X-ray ptychography with <15nm spatial resolution.

The mismatch of magnetization at the materials interface gives rise to magnetic charges, and thus dipolar energy. This energy cost is reduced by the occurrence of peripheral curling, while magnetization remains longitudinal on the axis. Curling is demonstrated experimentally. The curling angle is determined by a quantitative model simulating the magnetic contrast for a specific three dimensional magnetization texture. The strength of curling increases with both modulation length and wire diameter, with a clear analogy with the vortex state in flat magnetic disks. The chirality of curling is random at rest, however can be switched deterministically by means of the Oersted field of nanosecond pulses of current, with again a clear correlation with the strength of curling depending on the geometry of the modulations. These results pave the way for the physics of DWs interacting with the modulations.

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Non-Linear Magnetic Textures in Strongly Coupled Cylindrical Nanowires

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In the past, nanomagnetic states have been mostly confined to two dimensions, but recent advances in nanofabrication techniques, such as focused electron beam induced deposition (FEBID), have made the experimental realisation of three dimensional nanomagnetism possible [1]. 3D magnetic states can possess novel and exciting spintronic properties that can be controlled by altering the geometry of the system [2], providing a new route to high density, low power data storage devices [3].

In this contribution, I will first present a computational investigation into a variety of magnetic states that form during the growth of pairs of strongly overlapped nanowires through micromagnetic simulations. The separation of the wires was varied in order to determine how the interplay between exchange and magnetostatic energy affected the magnetisation. Following on from this computational work, X-ray magnetic dichroism measurements of strongly coupled nanowire pairs, fabricated by FEBID, will be presented. Showing how the three-dimensional geometry of magnetic nanostructures can stabilise non-linear spin textures.

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Quadratic and third-order magneto-optic Kerr effect in Ni(111) thin films with and without twinning

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The linear magneto-optic Kerr effect (MOKE) as well as higher order MOKE contributions, such as quadratic MOKE, are fascinating magneto-optic effects of fundamental physics but also powerful tools for sample characterization, e.g. to sense the crystallographic ordering in Heusler compounds [1]. To separate and study the dependencies of linear and quadratic MOKE on the crystallographic direction, the so-called eight-directional method can be used [2]. So far, this method or similar ones have been used to characterize (001)- and (011)-oriented thin films of cubic crystal structure [3,4].
Here, we apply the eight-directional method to Ni(111) thin films and report on a strong three-fold anisotropy in longitudinal MOKE (LMOKE). We show that this anisotropy can be attributed to cubic MOKE, i.e. MOKE of third order in $\boldsymbol{M}$ which can be described using the permittivity tensor of third order in $\boldsymbol{M}$ as well as an additional optical interplay of elements in the permittivity tensor of first and second order. Furthermore, we observe that in a Ni(111) thin film with twinning (two structural (111) phases with 60 deg. in-plane rotation), those oscillations are substantially reduced compared to a thin film with almost no twinning. This indicates that the LMOKE anisotropy truly is of crystallographic origin in the ferromagnetic layer.

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Time-resolved measurements of a topological phase transition

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Magnetic skyrmions are topological nanometer-scale spin textures that can be stabilized in magnetic multilayers with perpendicular anisotropy by Dzyaloshinskii-Moriya interaction and dipolar fields. It has been demonstrated recently that single femtosecond IR laser pulses can create skyrmions in these materials in the presence of a symmetry-breaking applied magnetic field [1,2]. The laser pulse drives the ferromagnetic multilayer system into a high-temperature fluctuation phase where large-scale topological switching leads to the formation of a skyrmion phase. This topological phase transition proceeds on a time scale of a few hundreds of picoseconds.
Here, we investigate the influence of the strength of the symmetry-breaking, applied magnetic field on the dynamics of the topological switching. To this end, we performed time-resolved experiments at the free-electron laser FERMI in Italy, which we combine with atomistic simulations. In the experiments, the sample is excited from a field-polarized state into the fluctuation phase by a femtosecond IR laser pulse and probed by resonant x-ray scattering to detect emerging magnetic order. In accordance with previous static imaging experiments [3], we observe a clear reduction of the skyrmion phase' density with increasing applied fields. Above a certain field threshold, a stable skyrmion phase cannot be formed anymore and the material returns to a homogeneously magnetized state. Surprisingly, however, we find that the transient fluctuation phase is hardly influenced by the applied field for early times up to ~100 ps after the laser excitation, even for fields above the threshold for stable skyrmions. Only in the subsequent coarsening phase, the skyrmion nuclei grow to their equilibrium size and distribution promoted by the applied field. Our results provide further insights into the dynamics of the topological phase transition and the nature of the high-temperature fluctuation phase.

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Optical generation of antiferromagnetic spin-spiral and underlying emergent interactions

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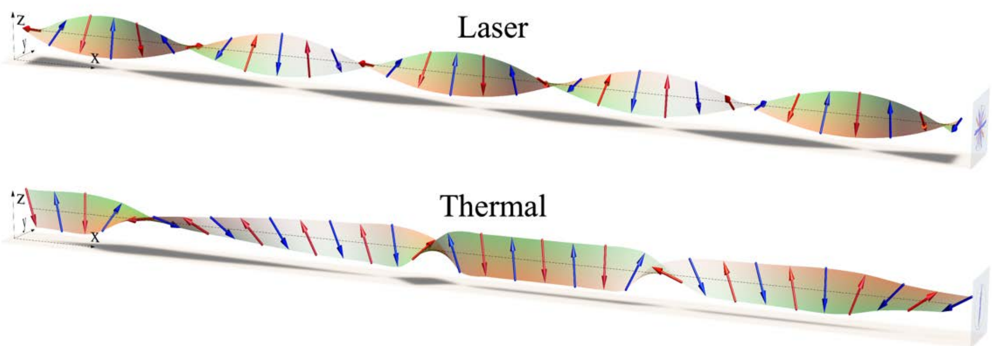
Recent experimental demonstration of skyrmion nucleation with ultrafast laser [1] is a distinguished landmark in the field of optical manipulation of magnetic order. The theoretical understanding of the underlying physics, however, is still under mist and mostly based on phenomenological arguments. Most of the numerical studies are based on the magnetization dynamics which completely ignores the electronic interactions and miss the crucial channels of energy transfer from laser to the magnetic system. In this presentation we present a unified approach which creates a bridge between the two approaches [2]. By combining quantum evolution of states with classical magnetization dynamics we are able to capture the fast electronic interactions playing governing role in the sub-picosecond regime as well as the slow magnetization process that survives for several picoseconds leading to a steady chiral formation. We are able to identify the emergent chiral interaction behind the chiral formation and also able to estimate the lifetime. We show how the final chiral formation can be controlled by tuning the laser parameter as well as by material parameters which shows good qualitative agreement with the experimental finding. Our results shows that this chiral formation is intrinsically different from the thermally excited magnetization dynamics which is widely used to explain ultrafast demagnetisation.



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Orbital current: Why it matters in spintronics

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A recent discovery of the orbital current opens a new possibility to control magnetism via the orbital degree of freedom [1]. Transfer of the orbital angular momentum to the local magnetic moment leads to excitation of the magnetization dynamics, which is now called "orbital torque" [2]. Using the orbital current instead of the spin current in spintronic devices has several advantages. For instance, the efficiency of the orbital Hall effect is much higher than that of the spin Hall effect [3]. Moreover, since the mechanism of the orbital Hall effect does not rely on the relativistic spin-orbit interaction, a wide variety of materials, which are not limited to compounds having heavy elements, can be used [4].

In this poster, I present state-of-the-art results on the orbital current effects in spintronics. I will explain why an electrical generation of the orbital current does not require spin-orbit interaction and discuss which materials are promising candidates with a strong orbital Hall effect. Then I explain the mechanism of angular momentum transfer in the presence of the orbital current and comment on recent experimental demonstrations in various types of thin films and heterostructures [5,6,7,8]. Finally, I discuss how the orbital current may be relevant in chiral magnets and nonlinear magnetism.

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Current induced spin-orbit torque for switching and detection of reversed antiferromagnetic order in a synthetic antiferromagnet

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Synthetic antiferromagnets (SAFs) offer the possibility to achieve spintronic devices with zero net magnetic moment, high stability, and fast operational speed, all relevant sought-after properties for memory applications. Additionally, these systems are an ideal model to study antiferromagnetic spintronics. The main advantage originates from the high tunability of parameters, such as magnetic anisotropies and exchange, by choosing the composition and thickness of the individual layers. Here, we report the detection of Néel order reversal induced either by an external magnetic field or an electrical current pulse. In perpendicularly magnetized SAF structures, the detection of the magnetic order has so far relied on the linear response of the anomalous Hall effect (AHE) resulting from a non-vanishing magnetization. Here, we use the current dependent non-linear magneto-transport response, which does not require a net magnetization to identify reversed antiferromagnetic states. Using a homodyne detection method, we show that the higher-order AMR response can distinguish the reversal of the Néel order by comparing it with the net linear AHE response of a non-compensated SAF sample. Secondly, we study the dependence of the non-linear signal as a function of an applied field. Fitting macrospin simulations to the field sweep data, we identify the presence of an antidamping field and estimate a lower limit to its magnitude of 80 mT/A. Moreover, from the macrospin simulations, we reveal that the higher-order AMR response differentiates the direction of the Néel vector even in symmetric structures.

Magnetoelasticity-driven textures in antiferromagnets

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Possibility of all-electrical switching makes antiferromagnets promising materials for spintronic devices. However, recent experiments question the spin-related mechanisms responsible for the switching and elucidate the role of the domain structure, heat effects and strain. Here we develop a model of switching in antiferromagnets which puts together current-induced temperature gradients, spin-orbit torques, and magnetoelastic effects. Inhomogeneous volume expansion caused by the temperature gradients creates additional stresses whose relaxation induces redistribution of antiferromagnetic domains seen at a macroscopic level as a switching between different states. We calculate the domain patterns and related observable – magnetoresistance, -- as a function of current, and establish equivalence between the values of current and of the magnetic field in switching phenomena. We show that depending on the geometry of electrodes the stress-related mechanism can either compete with or support the switching mediated by spin-orbit torques thus opening new functionalities of spintronic devices. Moreover, high temperature gradient and related stresses can trigger formation of new domain walls and thus substantially change the domain patterns and corresponding macroscopic response. Thus, this study offers a way to optimize efficiency of antiferromagnetic spintronic devices by tailoring of the geometry and proper choice of the constitutive materials.

Magnon Hanle effect in easy-plane antiferromagnets

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Antiferromagnets have drawn much attention due to their unique properties and new opportunities for interesting device applications. In contrast to ferromagnets, in antiferromagnets magnon modes occur in pairs of spin-up and -down magnons. In analogy to the spin-1/2 system of an electron, these magnon pairs can be described in terms of a magnonic pseudospin. Recently, experimental observations of the associated dynamics of antiferromagnetic pseudospin have been demonstrated and, in particular, we reported the first observation of the magnon Hanle effect in thin films of the antiferromagnetic insulator hematite (α-Fe_2O_3) [1]. A similar behavior was found in Zn-doped hematite films [2]. These studies describe their findings using a two-dimensional pseudospin transport model [3, 4]. Here, we expand the description of magnon pseudospin dynamics and discuss the effects of dimensionality on the magnon spin transport. To this end, we study the magnon spin transport in films with varying thickness of hematite utilizing two platinum strips for all-electrical magnon injection and detection. For thin and thick films, we find a distinct signal caused by the magnon Hanle effect. However, the magnonic detector signal exhibits clear differences in both cases. We explain these differences by an extended theoretical model and thereby provide deeper insight into the detailed understanding of magnonic pseudospin dynamics in antiferromagnetic systems.

Financial support from the Deutsche Forschungsgemeinschaft under Germany's Excellence Strategy - EXC-2111 - 390814868 and project AL2110/2-1, and the Spanish Ministry for Science and Innovation - AEI Grant CEX2018-000805-M (through the “Maria de Maeztu" Programme for Units of Excellence in R&D) is gratefully acknowledged.

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Transition of laser-induced terahertz spin currents from torque- to conduction-electron-mediated transport

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Spin Transport of spin angular momentum is a fundamental operation required for future spin-electronic devices. To be competitive with other information carriers, it is required to push the bandwidth of spin transport to the terahertz (THz) frequency range [1]. Here, we use femtosecond laser pulses to excite prototypical F|N bilayers consisting of a ferrimagnetic metal F and a nonmagnetic metal N [2,3]. Following absorption of the pulse, a spin current in F is launched and converted into a transverse charge current in N, giving rise to the emission of a THz electromagnetic pulse [2]. Depending on the conductivity of F, two driving mechanisms of the spin current can occur: (i) the ultrafast spin Seebeck effect [3] generating magnons and (ii) a spin voltage, generating a spin current carried by conduction electrons [4]. Remarkably, in the half-metallic ferrimagnet Fe3O4, we observe the coexistence of these contributions and disentangle them based on their distinctly different ultrafast dynamics. Our results shed new light on the magnetic structure of this mature material.

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Spin Wave Frequency Comb Formation in a Magnetic Vortex

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Due to its intrinsic nonlinear behavior, the magnetic system is an excellent tool for studying a variety of nonlinear phenomena. This ranges from fundamental physical questions to technical applications such as hardware implementations of neural networks. Therefore, it is of great interest to find ways to manipulate and steer nonlinear magnon interaction.
Recently, it has been shown that four magnon scattering can be stimulated into specific frequency channels and a cascade of the stimulation processes leads to a spin wave frequency comb in CoFe stripes [1].
Here, we extend the spin wave frequency comb formation to another confined system, a magnetic vortex. The magnetic vortex shows rich spin wave dynamics like the formation of whispering gallery magnons [2]. Using Brillouin light scattering microscopy, we show that the interaction of GHz spin-waves and MHz vortex core dynamics in a NiFe disk leads to the excitation of evenly spaced discrete spin wave modes. The spacing of the resulting comb is governed by the frequency of the vortex core dynamics, which can be excited either via an in plane magnetic field or by injecting spin transfer torque through electrical contacts.

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Magnon Bose–Einstein condensate-based qubit calculus

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Future computing technologies are expected to use quantum computing, in which the basic unit of computation is a quantum bit, or a qubit for short. In the classical domain, the superposition of two wave states of quasiparticles with different energies or different quasi-momenta can be used to obtain many benefits of qubit computing. Although entanglement is necessary for many quantum computing algorithms, there are examples of problems that can be solved using a qubit calculus without entanglement and still be more efficient than the best possible classical algorithms.

We propose to enable a set of room-temperature qubit computing functionalities using two frequency-degenerate magnon Bose–Einstein condensates (BECs) existing at opposite wavevectors in an Yttrium-Iron-Garnet ferrimagnetic film [1]. The macroscopic wavefunctions of these BECs serve as the two orthonormal basis states that form a qubit.

Using the Gross-Pitaevskii equation and numerical simulations based on the Landau-Lifshitz-Gilbert equation, we first show how to initialize the qubit in one of the basis states: using wavevector-selective parallel parametric pumping enables the formation of only a single magnon BEC in one of the two lowest energy states of the system.

Next, by translating the concept of Rabi-oscillations into the wavevector domain, we demonstrate how to manipulate the qubit state along the polar axis in the Bloch sphere representation. We also discuss the manipulation regarding the azimuthal angle.

Although qubit calculus with classical wave functions is superior to conventional Boolean logic, it does not compete with quantum computing technologies. Nevertheless, it works under ambient conditions, and the properties of scalability and stability are advantageous. Moreover, the magnon qubits can be used in solid-state devices with standard microwave interface technology.

We acknowledge funding by the European Research Council within the Advanced Grant No. 694709 SuperMagnonics and by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) within the Transregional Collaborative Research Center – TRR 173/2 – 268565370 “Spin+X” (Project B04).

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Echo State Property in Spin Torque Oscillator

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We will present on applicability of spin torque oscillator (STO) to reservoir computing (RC) at finite temperature. Among various computing methods used for natural language processing, RC is a fast and energy-efficient algorithm because only weights between reservoir and output layer are trained whereas the weights between neurons are randomly fixed [1]. It was reported that STO can recognize human voice by RC algorithm [2]. To guarantee the computational reproducibility in RC, effects of the initial state of the physical system should fade in time, and the property as such is called echo state property (ESP) [3]. Previously, the ESP in STOs has been studied only at zero temperature [4]. In this work, we studied the existence of the ESP in vortex-type STO at finite temperature by numerically solving the Thiele equation. The ESP is verified by measuring noise-induced synchronization (NIS) [5]. The NIS is a phenomenon where identical oscillators with different initial states show synchronized motions, even in the absence of interaction between them, when common random signals are injected. We repeated to inject common random signal to the STO with different initial states and studied whether the responses from the STO in each trial show synchronization. Without random pulse inputs, we showed that the amplitude of the averaged dynamics is quite small compared to that of one trial because the oscillations with different initial states cancel each other due to their phase differences. On the other hand, in the presence of random pulse inputs, the averaged amplitude remains finite even at finite temperature (Fig. 1). It indicates that the vortex dynamics becomes independent from the initial states and NIS occurs between trials. The results mean the existences of the ESP. We investigated the dependence of the averaged amplitude on the input-pulse strength and temperature, and specified the parameter region that enhances the feasibility of the ESP. This work was supported by NEDO (Grant No. JPNP16007).

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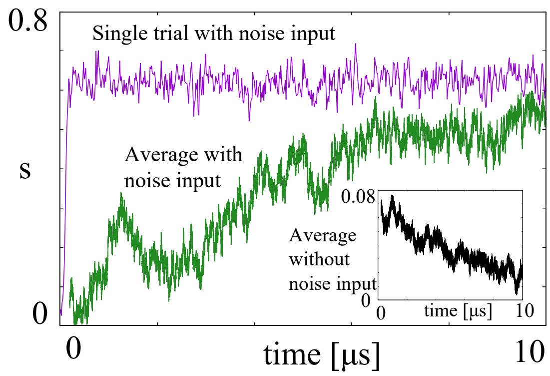

Fig. 1: Time dependence of averaged amplitude with and without noise input, and amplitude of single trial with noise input, of the vortex core position normalized by the radius of the vortex at T = 300 [K].

Magnetic and thermodynamic properties of mixed spin-3/2 and spin-1/2 Ising model on a hexagonal structure: Monte Carlo-Mean Field Treatment

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We apply Mean-Field and Monte Carlo simulations techniques to study the magnetic properties of the hexagonal Ising nanowire, consisting of a ferromagnetic core of spin-3/2 atoms surrounded by a ferromagnetic shell of spin-1/2 atoms. The effect of the exchange interactions (J_S and J_{in}) and crystal field D_C on the magnetic properties, critical and compensation temperatures of the system have been investigated. Depending on different values of the magnetic parameters, we have found various types of magnetization curves. In particular, the compensation behavior has been discovered for certain parameters.

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Revealing the ultrafast domain wall motion in Manganese Gold through Permalloy capping

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Antiferromagnetic (AFM) spintronic devices have the potential to greatly outperform their current ferromagnetic (FM) counterparts. Mn2Au is one of the most promising AFMs due to its ability to generate Néel spin orbit torques (SOTs)[1-4] meaning the magnetisation can be controlled. However, a read-out of the Néel order parameter is still a challenge. One possibility for detecting the magnetisation of MnAu is by coupling the AFM to a thin FM film[5], giving the advantages of the FM and the AFM. The FM will give a measurable magnetisation and the AFM gives the ultrafast controllable dynamics due to the imprinting of the AFM structure onto the FM as found experimentally[6].

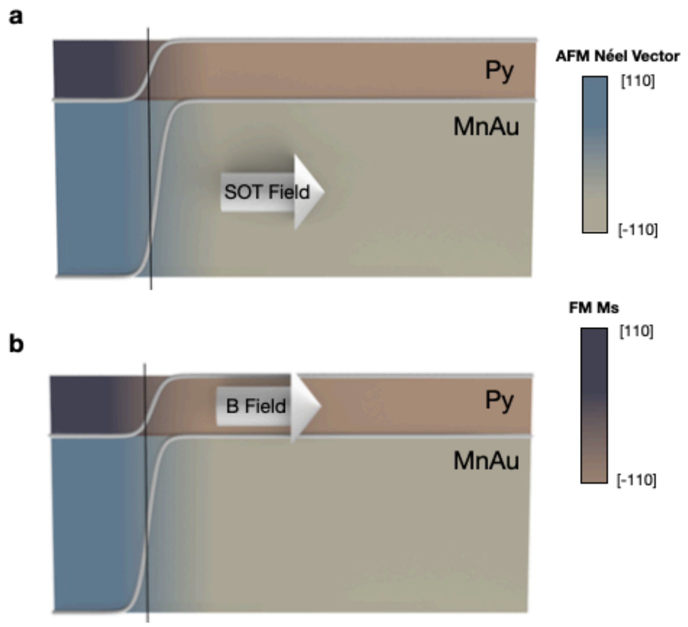

Figure 1. Different mechanisms for controlling the domain wall motion in an MnAu/Py bilayer, using a SOT field the motion is controlled by the AFM. Using a B field the motion is controlled by the FM. The grey lines show the domain wall profile in the FM/AFM respectively and the black line shows the initial position of the domain wall centre.

Here, we simulate the coupled dynamics of a 90 degree domain wall percolating the FM/AFM bilayer using spin dynamics simulations[6]. We study the domain wall dynamics in two cases, i) under the presence of a current to generate SOTs in the AFM and ii) an applied field to generate motion through the FM. In both cases the coupled domain walls of the FM and the AFM remain coupled together throughout the domain wall motion. For SOTs the domain wall moves with THz dynamics predicted from the AFMs natural frequency. Whereas, the applied field drives the domain wall motion from the FM and therefore causes a slower GHz motion. These results pave the way for ultimate control of the AFM with the ability to manipulate the speed of the domain wall by either driving it with the GHz FM motion or THz AFM motion whilst also offering measurability through the coupled FM layer.

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Current-induced interlayer DMI in synthetic antiferromagnets

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The exchange interaction has two counterparts – the symmetric and antisymmetric part. The symmetric term governs the ferro- and antiferromagnetism where the antisymmetric, often called Dzyaloshinskii-Moriya exchange interaction, promotes topologically non-trivial chiral spin textures that promise new magnetic devices. Synthetic antiferromagnets can display an antisymmetric interlayer exchange interaction due to symmetry breaking within the sample plane [1, 2]. This effect provides an additional handle to engineer magnetic structures and could enable three-dimensional topological structures.

Additionally, there have been reports that a current can induce a change in the antisymmetric exchange interaction [3]. Thus, we have observed a current effect on the antisymmetric interlayer exchange interaction by employing anomalous Hall effect measurements with an additional applied in-plane fields. In order to quantify the current dependence of the antisymmetric interlayer exchange interaction, an interlayer DMI field is introduced as a measure of quantification in which a consistent current dependence is observed. Therefore, we have observed the possibility to control the antisymmetric interlayer exchange interaction by current.

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Magnetic Representation Theory and Dzyaloshinskii-Moriya Interaction in α-Fe_2O_3

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Domain-walls, spin-spirals, skyrmions, bobbers and others are currently in the limelight of science. Beyond the conventional Heisenberg interaction between pairs of spins, the on-site magnetic anisotropy and the Zeeman interaction with an external field, the chiral Dzyaloshinskii-Moriya interaction (DMI) [1,2,3], higher-order exchange interactions and higher-order chiral interactions have been discussed. This scenario puts the Dzyaloshinskii-Moriya interaction into a much broader context.
To explain the weak ferromagnetism of α-hematite, the first theoretical explanation of the DMI was given by Dzyaloshinskii phenomenologically based on Landau theory [1]. Later he showed that globally non-zero DMI leads to globally modulated structures [2]. Shortly after the publication of Ref [1], Moriya [3] provided a microscopic description of DMI in terms of an antisymmetric pair interaction by adding the on-site spin-orbit interaction to the Anderson model describing the superexchange interaction in transition-metal oxides and deriving the magnetic pair interaction in second-order perturbation theory. Ref. [3] includes also Moriya's rules, which determine the symmetry conditions under which the prefactor of the DMI interaction, known as the DMI vector, is nonzero. Many other microscopic models lead to the same functional form of antisymmetric pair interactions. In addition to the classical and quantum mechanical description by Dzyaloshinskii and Moriya, respectively, both derivations differ in terms of symmetry: in the derivation by Dzyaloshinskii, the density distribution function is expanded in a basis of magnetic symmetry, whereas, the D-vector that determines Moriya's microscopic DMI term is determined by the crystallographic space group without any reference to the magnetic symmetry. In this presentation, we would like to return to the discovery of DMI and discuss a detailed understanding of the interaction based on magnetic symmetry.

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Chiral response of spin spiral states as the origin of chiral transport fingerprints of spin textures

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There is growing consensus in the solid-state community that 2D materials hosting complex magnetic order will find plenty of applications in information storage and processing. Transport properties of non-trivial spin textures, therefore, are coming under closer inspection as the amount of experimental data and theoretical simulations is increasing. With increasing interest in the properties of skyrmions, domain walls and multi-q states it has become clear that a complete picture of electric transport in these structures has to incorporate the interplay between external fields, fluctuations and electronic structure with magnetic properties [1,2]. To extend the commonly accepted yet simplifying and approximate picture of transport effects taking place in systems with spatially varying magnetization, it is important to understand the transport properties of the homochiral spin-spiral states, which are building blocks for more advanced textures of different nature and dimensionality. In this work [3], by referring to phenomenological symmetry arguments based on the gradient expansion, and explicit calculations within the Kubo framework, we study the transport properties of various types of spin-spirals in a two-dimensional model with strong spin-orbit interaction. Specifically, we focus on the contributions to the magnetoconductivity, planar Hall effect and anomalous Hall effect, which are sensitive to the sense of chirality of the spiral states. In particular, we analyze the emergence, symmetry, and microscopic properties of the resulting chiral magnetoconductivity, chiral planar Hall effect and chiral Hall effect in terms of spin-spiral propagation direction, cone angle, spiral pitch and disorder strength. To visualize the prominent role that chiral magnetotransport signals can play in the detection of non-trivial spin textures, we estimate a sizable chiral conductivity contribution in specific types of skyrmion textures from results for the homochiral spirals.

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Identification and characterization of plastics using THz-spectroscopy

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THz-spectroscopy is an attractive tool for scientific research, especially in life science, offering non-destructive interaction with matter due to its low photon energies [1]. Current research investigates the impact of plastic nanoparticles on cell tissue in several aspects, because those particles are highly abundant in the environment and also enter the human body potentially causing harmful interactions [2]. THz spectroscopy offers the opportunity to discover and study the influence of microplastics in living human cells. Our project aims to identify and characterize different types of plastics in the human body or even in cells. Therefore it is necessary to set up a database with THz-spectra of the most abundant polymers. We analyze transmission spectra of several plastics with a commercial THz spectrometer (bandwidth from 0.1 to 6 THz) and identified specific absorption peaks for the individual studied materials. Furthermore, by determining the refractive index and the absorption coefficient, specific polymers can be characterized and identified.
Funding by BMBF: MetaZik PlasMark-T (FKZ:03Z22C511) is acknowledged.

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Coherent Correlation Imaging: Resolving fluctuating states of matter

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Fluctuations are ubiquitous in magnetically and charge ordered systems spanning orders of magnitude in space and time [1,2]. Real-space access to fluctuating states of matter is impeded by a dilemma between spatial and temporal resolution. Averaging over an extended period of time (or repetitions) is key for the majority of high-resolution imaging experiments due to insufficient signal on timescales faster than the relevant dynamics. If, by lack of better knowledge, averaging is indiscriminate, it leads to a loss of temporal resolution and to motion-blurred images.
We present coherent correlation imaging (CCI) – a high-resolution, full-field imaging technique that realizes multi-shot, time-resolved imaging of stochastic processes. The key of CCI is the classification of camera frames that correspond to the same physical state. This is done by combining a correlation-based similarity metric with powerful classification algorithm developed for nanoparticle tomography and genome research [3]. CCI extends these algorithms to the temporal domain, realizing informed, non-sequential signal averaging while maintaining single frame temporal resolution. To develop and demonstrate CCI, we study the thermal hopping of magnetic domain walls on timescales ranging from sub-seconds to hours under equilibrium conditions. Our material is a Co-based chiral ferromagnetic multilayer with magnetic pinning low enough to exhibit stochastically recurring dynamics that resemble thermally-induced Barkhausen jumps near room temperature.
CCI reconstructs sharp, high-contrast images of all domain states and, unlike previous approaches, also tracks the time when these states occur. The spatiotemporal imaging reveals not only an intrinsic transition network between the states, but further, unprecedented details of the magnetic pinning landscape. These capabilities allow us to explain the complex dynamics by a combination of attractive and repulsive pinning and intrinsic configurational energies.

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Linear and nonlinear spin-wave dynamics in magnetic nanotubes: Beyond the thin-shell approximation

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One of the prospects of magnetic nanotubes in magnetization dynamics is using them as waveguides for spin waves. Recently, we have shown that spin waves in thin-shell nanotubes with a vortex-state equilibrium magnetization exhibit an asymmetric dispersion along the nanotube [1,2]. This asymmetry is of dipolar origin and a consequence of the geometrical magnetic pseudo charges induced by the surface curvature of the nanotube. So far, predictions on the spin-wave dispersion in magnetic nanotubes were only available for tubes with a thin shell (with thicknesses comparable to the exchange length of the material) for which the spatial profile of the spin-wave modes can be assumed to be approximately homogenous in radial direction. With the help of our newly-developed finite-element dynamic-matrix approach for spin waves propagating in waveguides with arbitrary cross section [3], we are now exploring the transition of the spin-wave dispersion and mode profiles as the thickness of the nanotube is increased. To this end, we investigate the emergence of spin-wave modes with a standing-wave character along the nanotube thickness which are strongly hybridized and correspond to the radial modes in vortex-state disks or to the perpendicular-standing spin waves in magnetic thin films. We present that the dispersion changes drastically as the nanotube-shell thickness is increased. In particular, the dispersion asymmetry increases to the point where there is an almost completely unidirectional propagation similar to the spin-wave transport reported for exchange-coupled bilayers [4]. Finally, we are exploring how the non-collinearity of the magnetic equilibrium enables an exchange contribution to the nonlinear three-magnon scattering in thick vortex-state nanotubes, which was previously observed in vortex-state magnetic disks [5].

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Frequency multiplication by collective nanoscale spin wave dynamics

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Frequency multiplication, a process essential for modern electronics, where harmonics of the input frequency are generated, is usually achieved in non-linear electronic circuits. Devices based on the propagation and interaction of spin waves are a promising alternative to conventional electronics.

By studying low frequency magnetic excitations in a heterogeneous ferromagnetic material with two novel experimental techniques, Super-Nyquist-Sampling Magneto-Optic Kerr Effect Microscopy (SNS-MOKE) and Optical Detection of magnetic Resonance in diamond Nitrogen vacancy defect centers (ODMR), we show that the magnetization dynamics leads to high harmonic spin wave emission.
The demonstrated broadband frequency multiplication opens exciting perspectives for spintronic applications, such as mixers or on-chip GHz sources, since the frequency is up-converted from the MHz to the GHz range within the magnetic medium itself.

Magnetic field mapping of 2-dimensional and 3-dimensional frustrated magnets using off-axis electron holography

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Artificial spin ices can be formed from geometrically-frustrated arrangements of two-dimensional magnets. Magnetostatic interactions between the magnets in such an array can lead to rich emergent behavior, including the formation of magnetic monopoles, chiral dynamics and phase transitions. The ability to map magnetic fields with high spatial resolution is essential to gain an understanding of this behavior. When compared with 2-dimensional systems, magnetic frustration in 3-dimensional systems has been studied much less intensively.
Here, we use off-axis electron holography to measure magnetic fields in an artificial two-dimensional spin ice lattice formed from permalloy (Py) nanomagnets and in a three-dimensional Py magnetic gyroid structure. The square lattice of Py elements for chiral ice pattern was prepared on SiN membrane using lift-off lithography. The magnetic gyroid structures were fabricated using block co-polymer templates and electrodeposition of Py. Experiments were recorded both in magnetic-field-free conditions and in magnetic fields up to 1.5 T. The recorded electron optical phase images of the Py islands were analyzed using a model-based iterative reconstruction algorithm, in order to determine maps of projected in-plane magnetization. Magnetostatic interactions between the Py elements and the stray field distribution in chiral ice [2] were studied by applying both in-plane and out-of-plane magnetic fields to the sample. The experimental results were compared with micromagnetic simulations, which were created based on input from TEM images. The experimental results and micromagnetic simulations indicated that the gyroid structure was able to support many different magnetization configurations [3].

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Chaotic Antiferromagnetic Nano-Oscillator driven by Spin-Torque

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We theoretically describe the behavior of a terahertz nano-oscillator based on an anisotropic antiferromagnetic dynamical element driven by spin torque. We consider the situation when the polarization of the spin-current is perpendicular to the external magnetic field applied along the anisotropy easy-axis. We determine the domain of the parametric space (field, current) where the oscillator demonstrates chaotic dynamics. Characteristics of the chaotic regimes are analyzed using conventional techniques such as spectra of the Lyapunov exponents. We show that the threshold current of the chaos appearance is particularly low in the vicinity of the spin-flop transition. In this regime, we consider the mechanism of the chaos appearance in detail when the field is fixed and the current density increases.

We show that the appearance of chaos is preceded by a regime of quasiperiodic dynamics on the surface of a two-frequency torus arising in phase space as a result of the Neimark-Sacker bifurcation.

Our findings can be useful for concepts of neuromorphic computing that rely on stochastic (chaotic) oscillator behavior, e.g. reservoir computing or spike-based encoding. For details see Ref. 1.

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Nonlinear dynamics of skyrmion strings

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Skyrmion string is a topological line formed by a skyrmion core penetrating through a 3D chiral magnet. Using the effective field-theoretical description based on the collective variables method, we found a number of nonlinear excitations propagating along the string: helical waves and solitary waves. The latter are characterized by two independent parameters: velocity of motion along the string and frequency of rotation [1]. In the low-energy limit we obtain the form of the solitary wave solution and determine the existence domain in the parametric space.

Application of the spin-polarized current directed along the skyrmion string results in the string instability with respect to the generation of the helical waves. In an ideal (free of defects) magnet, this instability mechanism is thresholdless and it takes place for single strings, as well as for skyrmion lattices.

Our analytical results are confirmed with micromagnetic simulations for parameters appropriate for FeGe.

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Audio Recognition with Skyrmion Mixture Reservoirs

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Physical reservoir computing is a computational architecture that enables temporal pattern recognition to be performed directly in physical matter. By exciting dynamical systems with temporal input data, we can create nonlinear mappings from the original input to a high dimensional latent space allowing for classification and regression. The use of physical matter leads the way towards energy-efficient devices capable of solving machine learning problems without building a modular system from millions of interconnected synapses. We propose a 'skyrmion mixture reservoir' that implements the reservoir computing model for multi-dimensional inputs. Through micro-magnetic simulations, we show that our implementation can solve audio classification tasks at the nanosecond timescale to a high degree of accuracy. Due to the quality of the results shown and the low power properties of magnetic texture reservoirs we argue that skyrmion magnetic textures are a competitive substrate for reservoir computing.

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Nonlinear band structure effects induced by noncollinear magnetic order

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While nonlinear magnetic interactions in the Landau free energy functional can induce noncollinear magnetism, noncollinear magnetic order can induce nonlinear effects in the electronic structure with nontrivial topological properties [1]. On this poster, we show how this phenomenon can be understood within the framework of noncommutative geometry by interpreting the noncollinear magnetic state via a generalized notion of emergent magnetic fields [2]. The power of our approach lies in an ability to categorize topological states algebraically without referring to smooth real- or reciprocal-space quantities. This opens a way towards an educated design of topological phases in aperiodic, disordered, or non-smooth textures of spins and charges containing topological defects.

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Ab-initio studies of chiral crystals

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Materials with a chiral atomic arrangement exhibit specific electronic structure features [1]. The clock-wise or anti-clock-wise winding of sublattices has been associated with an enhanced band-splitting from spin-orbit coupling, and with a radial spin texture in reciprocal space, with spin polarization pointing toward the Brillouin zone origin or away from it at every k-point [2]. In the context of x-ray absorption spectroscopy, this scenario can give rise to x-ray natural circular dichroism (XNCD) cross-sections [3]. From the point of view of electronic transport, the above features provide interesting consequences for the response [4] to e.g. an applied electric field, for instance in terms of Edelstein effect [5] and particularly its dependence on the sign of the perturbation. We report about ab-initio calculations of transport properties and predictions about robustness of the effect with respect to substitutional disorder and finite temperature effects from first-principles studies within the frameworks of a spin-polarized relativistic Korringa, Kohn, Rostoker / linear muffin tin orbitals Green's function treatments [6].

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Strain-controlled Domain Wall injection into nanowires for sensor applications

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In this study, we address a well-known challenge in magnetic sensor development, which is the effect of packaging-induced strain on the sensor properties[1]. While previously the field operation window has only been studied in idealized operation conditions, in real devices further external factors such as strain play a role.

In this experimental work, we investigate the injection of a 180° domain wall from a nucleation pad into a nanowire, as typically used for domain wall-based sensors, while straining the device along selected directions. Combining our experimental measurements by Kerr microscopy with micromagnetic simulations, we find that strain, regardless of its direction, increases the domain wall injection field due to the magnetoelastic coupling of the magnetic material. The above-described observations can be explained by an effective strain-induced anisotropy in the device [2].

We find additionally that a careful material preparation, comprising of an annealing step, can reduce the effective anisotropy caused by the strain in the magnetic layer. With this we show that a device free of magnetostrictive behavior can be achieved [3].

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THz-light driven spin-lattice coupling in cobalt difluoride

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Understanding spin-lattice coupling is among the key challenges in modern condensed matter physics [1,2]. The efficiency of angular momentum and energy transfer between spins and lattice imposes fundamental limits on the speed to control spins in spintronics, magnonics and magnetic data storage. At the same time, it has been long believed that a coherent transfer of energy from spins to lattice requires their linear coupling.

Recently we have discovered a new nonlinear mechanism for THz-light driven spin-lattice coupling in CoF_2 [3]. High-intense THz pulse resonantly interacts with a coherent magnonic state in CoF_2 and excites the Raman-active THz phonon. In our experiments the magnon amplitude scales linear on THz magnetic field strength which is typical for the conventional Zeeman torque excitation mechanism [4]. In contrast, the phonon amplitude scales quadratically with the THz field strength clearly evidencing the nonlinear excitation mechanism [5]. The phonon amplitude reaches maximum near a special temperature at which the magnon frequency matches half of the phonon frequency. Above the Néel temperature, the phonon practically is not excited, thus clearly indicating strong spin-lattice coupling.

Moreover, we have performed unique measurements combining high-intense THz pulses and high static magnetic fields (up to 10 T) in TELBE facility (Dresden, Germany). The phonon excitation shows resonance behaviour while tuning the frequency of the magnon with the help of external magnetic field. Interestingly that the magnon frequency at this resonance fulfils earlier mentioned frequency matching condition: the magnon frequency matches half of the phonon frequency. The results are especially appealing for ultrafast and coherent control of complex order, multiferroics, 2D magnets, non-collinear antiferromagnets, where the spin-lattice interaction plays the decisive role.

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Photocurrents of charge and spin in single-layer Fe3GeTe2

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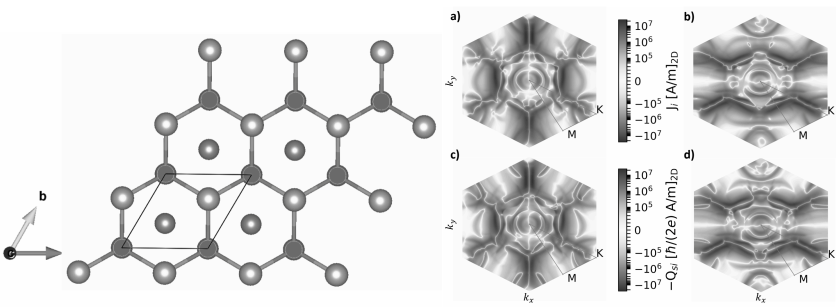
In the realm of two-dimensional materials magnetic and transport properties of a unique representative−Fe3GeTe2−attract ever increasing attention [1]. Here, we use a developed first-principles method for calculating laser-induced response [2] to study the emergence of photo-induced currents of charge and spin in single-layerFe3GeTe2, which are of second order in the electric field. We provide a symmetry analysis of the emergent photocurrents in the system finding it to be in excellent agreement with ab-initio calculations. We analyse the magnitude and behavior of the charge photocurrents with respect to disorder strength, frequency and band filling. Remarkably, not only do we find a large charge current response, but also predict that Fe3GeTe2 can serve as a source of significant laser-induced spin-currents, which makes this material as a promising platform for various applications in optospintronics [0].
We acknowledge funding from Deutsche Forschungsgemeinschaft (DFG) through SFB/TRR 173/2 and 288. Simulations were performed with computing resources granted by JARA-HPC from RWTH Aachen University and Forschungszentrum Jülich under projects jara0062, jiff40 and jias1a [3].



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Peculiar behavior of sputter-grown DyCo near its compensation temperature

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Rare earth – transition metal alloys have gained interest as a potential host for chiral magnetic structures due to recently discovered bulk Dzyaloshinskii–Moriya interaction (DMI) in GdFeCo films [1]. This effect opens up the possibility of stable ultra-small DMI-stabilized skyrmions, which would be difficult to stabilize in sample systems that only exhibit interfacial DMI. Due to the strong spin-orbit coupling of Dy, a DyCo-alloy is expected to exhibit even stronger bulk DMI compared to GdFeCo, making it an ideal candidate for further investigations.

We present a study of the bulk characteristics of sputter-grown 50 nm thick DyCo thin film samples, for which we performed temperature dependent SQUID magnetometry measurements. Near the compensation temperature we observe two step hysteresis loops, indicating a two phase system similar to a synthetic antiferromagnet. We explain this phenomenon with a gradient in the Dy concentration along the layer normal, which leads to a spatially varying compensation temperature in the material. This effect is considered to be paramount for emergence of bulk DMI by breaking the otherwise present inversion symmetry of the amorphous alloy.

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Theory of electrically-induced spin and orbital accumulation in transition-metal thin films

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Electrical control of magnetization is of crucial importance for integrated spintronics devices. Spin-orbit torques (SOT) in heavy-metal/ferromagnetic heterostructures have emerged as a promising tool to achieve efficiently current-induced magnetization reversal. However, the microscopic origin of the SOT is being debated, with the spin Hall effect (SHE) due to nonlocal spin currents and the spin Rashba-Edelstein effect (SREE) due to local spin polarization at the interface being the primary candidates.

Here, we investigate computationally the electrically induced out-of-equilibrium spin and orbital polarizations in pure Pt films and in Pt/3*d*-metal (Co, Ni, Cu) bilayer films using *ab initio* electronic structure methods and linear-response theory [1]. We compute atom-resolved response quantities that allow us to identify the induced spin-polarization contributions that lead to fieldlike (FL) SOTs, mostly associated with the SREE, and dampinglike (DL) SOTs, mostly associated with the SHE, and compare their relative magnitude, dependence on the magnetization direction, as well as their Pt-layer thickness dependence. We find that both the FL and DL components contribute to the resulting SOT at the Pt/Co and Pt/Ni interfaces, with the former contributions being larger at the Pt interface layer and the latter larger in the Co or Ni layers [2]. Our calculations show that the electrically induced transverse orbital polarization is exceedingly larger than the induced spin polarization and present even without spin-orbit coupling, in contrast to the spin polarization. Moreover, we find that there exists in fact sizable induced longitudinal spin and orbital polarizations along the applied electric field in magnetic bilayers, giving rise to a DL torque. Lastly, the electrically induced orbital polarization is shown to have a distinctly different profile across the film than the induced spin polarization.

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Effect of Iron and Excitation Frequency on nonlinear magnetic Signal of Synomag® Nanoparticles

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Magnetic nanoparticles (MNPs) are used to facilitate magnetic particle imaging (MPI) which has the potential to become the leading diagnostic instrument for biomedical imaging. This comparative study assesses the effects of changing iron content and excitation frequency on point-spread function (PSF) representing the effect of magnetization reversal. PSF is quantified by features of interest for MPI: i.e., drive field amplitude and full-width-at-half-maximum (FWHM). A superparamagnetic quantifier (SPaQ) is used to assess the non linear magnetic signal of two commercially available MNPs: Synomag®-D50 and Synomag®-D70. For both MNPs, the signal output depends on increase in drive field frequency and amount of iron-oxide, which might be hampering the sensitivity of MPI systems that perform on higher frequencies. Nevertheless, there is a clear potential of Synomag®-D for a stable MPI resolution, especially in case of 70 nm version, that is independent of either drive field frequency or amount of iron-oxide.

Exploiting nonlinear dynamics of topological textures

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Novel remarkable applications arise from exploiting the nonlinear dynamics of topological textures. We show that it allows for the proposal of in materio frequency multipliers [1], and the bi-directional control of antiferromagnetic domain wall motion by spin waves [2]. The first application largely increases the range of controllably accessible frequencies by performing the frequency conversion between input and output frequencies. We show that this may be achieved by exciting eigenmodes of topological structures with fractions of the corresponding eigenfrequencies. The second application is a key component towards next-generation of Joule-heating-free antiferromagnetic insulator devices. We provide a highly tunable control of the motion of domain walls in Kagome antiferromagnets by manipulating the frequency of applied linearly polarized spin waves. The two proposals were verified via numerical simulations and yield means for experimental realization.

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Spatially Resolved Terahertz Spectroscopy using Spintronic-Terahertz-Emitter

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In the last years terahertz (THz) spectroscopy was shown to be a promising tool for investigation of various magnetic effects at terahertz frequencies. On one hand, new efficient laser-driven sources provide high THz fields suitable for observation of non-linear spin dynamics in various materials [1][2]. On the other hand, infrared and THz cameras also known as focal plane arrays (FPA) allow real-time imaging of THz beams [3]. FPAs are often used to characterize the THz beam size at the focus and to estimate the electric field strength. However, the result of such characterization strongly depends on how much each frequency component contributes to the FPA signal. Therefore, it is often important to know the sensitivity of a given FPA in the corresponding THz range. Determining the sensitivity is quite challenging and usually relies on either narrow-band THz sources or black body radiators.
Here, we develop a table-top technique, which allows one to separate spectral contributions to the FPA image in the THz range. The method is based on Fourier analysis of the images obtained by the FPA excited by two consecutive broadband THz pulses with a variable delay. This technique allows us to measure the FPA sensitivity in the THz range and map the distribution of different frequencies in the focus of the THz pulse. Using a spintronic THz emitter as a source of the pump pulses, we push the bandwidth of our setup from 1 up to 12 THz and perform measurements for two industrial FPAs. Our results indicate that the FPA sensitivity can be quite resonant at different frequencies, meaning that one cannot extract the beam size from the FPA image if the source has significant bandwidth.

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Nutation dynamics in antiferromagnets

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The dynamics of spin systems is conventionally described by the phenomenological Landau-Lifshitz-Gilbert equation, explaining the precession of the magnetic moments around an effective magnetic field and their relaxation towards it. It has been suggested that on very short time scales the Landau-Lifshitz-Gilbert equation has to be extended by an inertial term [1]. This term gives rise to nutation, corresponding to the precession of the magnetic moment around the angular momentum direction. Recent experiments indicated that such inertial effects can be observed in ferromagnetic resonance experiments in the THz range [2].

Here, the effect of the inertial term on the dynamics of antiferromagnets is examined using analytical methods and numerical simulations. It is demonstrated that the interplay between nutation and precession dynamics is more pronounced in antiferromagnets than in ferromagnets due to the exchange enhancement [3]. Going beyond the linear-response regime, it is shown how switching the direction of the staggered magnetization in antiferromagnets may be achieved via exciting the inertial dynamics using oscillating magnetic fields with THz frequencies. These results predict that antiferromagnets are especially well suited for detecting experimental signatures of the nutation dynamics.

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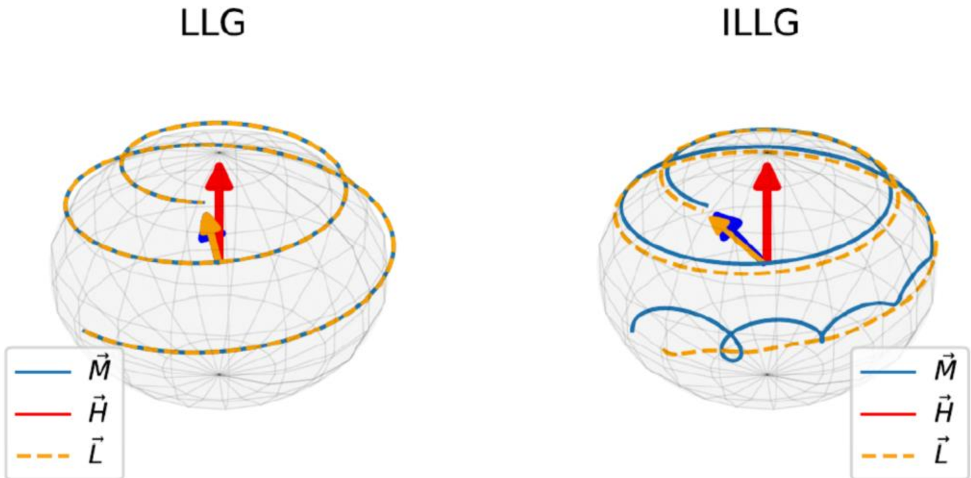

Figure 1 Time evolution of the angular momentum $\vec{L}$ and the magnetic moment $\vec{M}$ under the Landau-Lifshitz-Gilbert (LLG, left) and Inertial Landau-Lifshitz-Gilbert (ILLG, right) equations.

Magnetization in cylindrical nanowires: the role of chirality

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The magnetization dynamics in low-dimensional structures is one of the most studied topics in the last years in both fundamental and applied magnetism. In particular, the control of the movement of magnetic domain walls (DW) along nanostructures by means of magnetic fields or electric currents is a key aspect in the design of novel devices. Although most of the studies up to now have been focused on nanostripes—elongated structures with rectangular cross section, cylindrical electrodeposited nanowires are starting to play a key role in this field of nanomagnetism and spintronics.
The passage from flat structures to cylindrical electrodeposited nanowires (NWs) brings the emergence of novel DW structures directly linked to the cylindrical geometries,such as Bloch points, which interact with a spin-polarized current in a very different way than in 2D geometries, and also other structures with chiralily. In addition, the possibility of tailoring the nanowires or the templates used for their fabrication introduces additional degrees of freedom, producing magnetic tridimensional structures and enabling the appearance of new physics to exploit. These advances in the growth of 3D structures should be also accompanied by strategies and methodologies to map the tridimensional spin textures associated.

Here, I will present an overview of our recent results in the control of the magnetic configuration of cylindrical nanowires as well as the approach followed to unravel the spin texture in these structures using x-ray microscopy[1,2]. On one hand, I will show the role of chirality in the stabilization of topologically non-trivial domain wall in permalloy nanowires when local changes in composition along the wire are introduced. On the other hand, I will introduce novel strategies to introduce additional 3D magnetic textures in the nanowires (compositional axial gradients and radial modulations of composition) and their impact in the magnetization processes.

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Intrinsic stability and size tunability of magnetic antiskyrmions in tetragonal inverse Heuslers

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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] that has distinct topological features from that of Bloch and Néel skyrmions, was discovered in tetragonal inverse Heuslers [2]. Anti-skyrmions have boundaries 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. This causes the magnetic structure of the anti-skyrmion to be aligned with the crystal lattice that leads to an enormous stability of anti-skyrmions over a wide range of temperature, magnetic field and thickness of the lamella in which they are formed [3,4]. In this presentation, I will discuss our recent studies on the nucleation, stabilization and size manipulation of anti-skyrmions in Heuslers for example, in $Mn_{1.4}PtSn$ using Lorentz transmission electron microscopy and magnetic force microscopy.

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Uncovering the hidden Rashba spin and orbital textures present in bulk Fe3GeTe2 from first-principles

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Within the field of spintronics, the two dimensional (2D) van der Waals (vdW) material Fe3GeTe2 has been in the spotlight in the last few years for displaying exciting characteristics such as being a potential nodal line semimetal [1] and a material for highly efficient spin orbit torque switching [2]. The exotic underlying electronic structure has also given rise to nonlinear magnetic effects such as chiral spin spirals [3] and skyrmion formation [4]. Using first principles methods, we investigated the spin and orbital textures present on the Fermi surface and uncover local sub-layer resolved Rashba splitting present within the material, hidden due to its overall global inversion symmetry. Despite the global inversion symmetry, in a recent collaboration [5] we found that spin orbit torques (SOTs) were observed in bulk Fe3GeTe2. By investigating the layer resolved spin and orbital current-induced torkance its overall magnitude was nonzero and of comparable magnitude to the experimental signal. Here in this work [6] we aim to discuss in more detail the microscopic origins of the layer resolved 'hidden' torkance by investigating the contributions from the 'hidden' Rashba-split spin and orbital textures present on the Fermi surface and making a connection to the rich valley physics present within this material. From these considerations we aim to provide insights into how, in combination with other mechanisms, the hidden current-induced SOT could give rise to a tangible signal in experiment, and how the hidden Rashba splitting plays a role. Looking forward, our findings could provide the key information we need to craft these complex non-liner magnetic systems into low power devices for a new age of computation and data storage.

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Chiral logic computing with twisted antiferromagnetic magnon modes

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Antiferromagnetic (AFM) materials are demonstrated to offer a new exciting platform for ultrafast information processing with low cross talks and good compatibility with existing technology[1]. Particularly interesting for energy-saving computing are low-energy AFM excitations: magnons. For an AFM waveguide we prove the existence of chiral magnonic eigenmodes. Similar to the case of ferromagnetic waveguides[2] these eigenmodes possess a well-defined projection of the angular momentum (OAM) along the wave propagation direction. The OAM is an unbounded integer determined by the spatial topology of the respective mode and is shown to be exploitable for multiplex AFM magnonic computing. We demonstrate how a variety of symmetry and topology protected logic gates can be realized and operated without Joule heating. Our findings uncover a new aspect of AFM spintronics and point to a novel route to communicating and handling data swiftly, with high fidelity and at low energy cost.

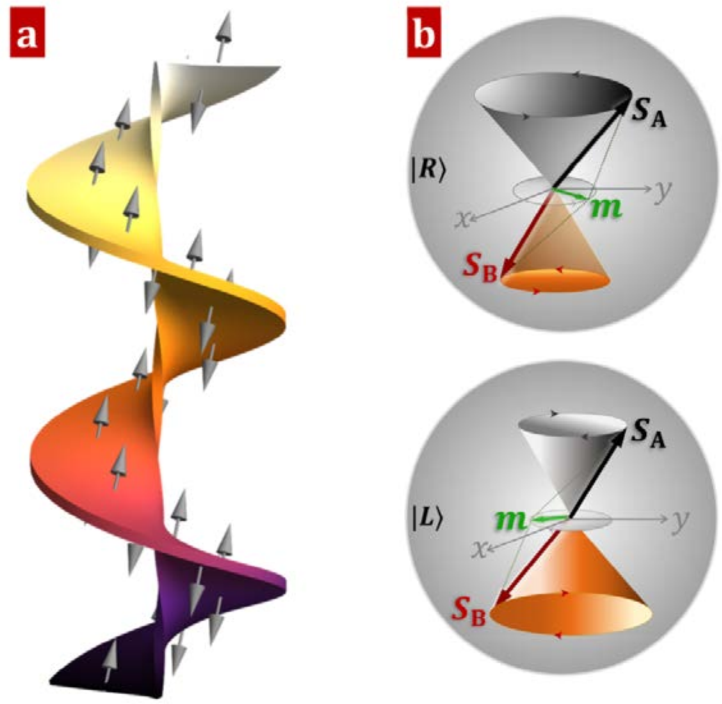

Figure 1 Schematic representation of twisted magnon beams in AFM waveguide. a) Twisted magnon beams propagating along a cylindrical AFM waveguide with two magnetic sublattices A (up arrows) and B (down arrows). b) Degenerate right- and left-handed spin wave modes, |L> and |R> dominated by the sublattice A and B, respectively. The small magnetization is defined as $\mathbf{m}=(\mathbf{S}_A+\mathbf{S}_B)/2S$.

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Terahertz spin and charge dynamics in magnetic systems: From ferro- and ferri- towards antiferromagnets.

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Understanding nonlinear effects in magnetic systems at the ultrafast time scale is a prerequisite for future high-speed spintronic devices. To this end, we employ femtosecond optical laser pulses to drive ultrafast spin and charge currents in magnetic heterostructures with different magnetic ordering. Inside these samples, a nonlinear conversion leads to the emission of a terahertz pulse that allows to calculate back to the current dynamics [1,2]. In a second approach, we employ strong terahertz electric field pulses to drive the highly-nonlinear process of switching in antiferromagnetic CuMnAs memory cells [3]. Eventually, we use the inverse principle of heat-assisted magnetic recording in these terahertz switching experiments by employing additional optical laser pulses [4].

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Angular dependence of the spin-torque diode effect on the external magnetic field

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Spintronics is a rapidly developing promising area of nanoelectronics. Spintronic devices use not only the electrons' charge but also their spins for information processing and communication, which provides new functional opportunities. One of the most interesting spintronic devices is the spin-torque diode, which is based on the magnetic tunnel junction (MTJ) and the spin transfer torque effect (STT). Spin-torque diode is a potential candidate for the next generation of RF (radio frequency) detectors and of the electromagnetic energy harvesting systems [1]. A key advantage of such devices is a high microwave sensitivity, which is equal to the ratio of the rectified voltage to the incident power of the RF signal. The maximum sensitivity of MTJ is achieved at the resonance when the frequency of the input signal coincides with the frequency of its ferromagnetic resonance. In this case, the response of MTJ to an RF signal is the appearance of intrinsic dynamic excitations of MTJ magnetization, both in the bulk and at the edges of the free layer, which can be controlled by varying the magnitude of the external magnetic field. The dynamics of the magnetization in such devices is realized as a multimode process, and the interaction of the spin-wave modes is of great interest.
In this work, we used the ST-FMR experimental technique combined with micromagnetic modeling to study the dependence of the magnetization resonance frequency on the change in the direction and the magnitude of the external magnetic field. The influence of the spin-wave modes and the inter-mode interaction on the electrical and microwave properties of the MTJ is investigated. This research will help to optimize MTJ-based microwave spintronic devices.

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Resonant control of phase of spin-wave reflected from subwavelength Gires-Tournois interferometer

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The introduction of metasurfaces was an innovatory concept in photonics. It allowed designing a new class of photonic devices such as flat lenses. However, the concept of metasurfaces has not yet been widely investigated in magnonics, even though metasurfaces can alter the properties of waves in minuscule distances, which is of great importance in spin-wave devices.

Our study explores new ways of controlling the spin-wave phase using metasurfaces built by ferromagnetic nanoresonators [1,2]. By employing micromagnetic simulations, we show that the phase of spin waves reflected from an interface between a ferromagnetic layer and a bilayer can be changed by manipulating the geometrical properties of the bilayer. This bilayer, built of a resonator placed above the edge of the layer, is a realisation of the magnonic Gires-Tournois interferometer [1]. With an increase of bilayer's width, the phase shift of the reflected spin-wave also increases. Moreover, for specific widths, abrupt phase changes of full angle are observed. To explain this behaviour, we use mode analysis. The analysis shows that long-wavelength modes in the bilayer provide a steady accumulation of the phase in the bilayer. On the other hand, short wavelengths modes give significant input to the phase accumulation only for specific widths of the bilayer. We also found that the geometry of the bilayer heavily influences the phase shift [2]—the shape of the phase shift function changes for different layer thicknesses. Dependency is almost linear for thin layers, whereas for thick layers, subsequent abrupt phase changes are separated by distinctive plateaus.

In summary, our research reveals new spin-wave phase control methods by employing metasurfaces made of nanoresonators. In this case, the phase of spin waves reflected from an interferometer can be changed in a controlled manner by manipulating the system's geometrical properties. Presented interferometers may be used as one of the building blocks of magnonic devices such as spin-wave flat lenses, phase shifters, multiplexers.

Acknowledgments—The research leading to these results has received funding from the National Science Centre of Poland, project no. 2019/35/D/ST3/03729.

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THz-2D Scanning Spectroscopy

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THz-spectroscopy offers attractive imaging capabilities for scientific research, especially in life science. Its low photon energies lead to non-destructive interaction with matter [1,2]. However, wavelengths above $100\,\mu m$ principally limit its spatial resolution by diffraction. Near-field-imaging using spintronic emitters offers the most feasible approach to overcome this restriction.

In our study, we investigate THz-pulses generated by fs-laser-excitations in CoFeB/Pt heterostructures, based on spin currents together with a LT-GaAs Auston switch as detector. The spatial resolution is tested by applying a 2D scanning technique with motorized stages allowing scanning steps in the sub-micrometer range. For this purpose, the spintronic emitter is directly evaporated on a gold-test pattern separated by a several hundred nanometer thick insulating spacer layer. Moving these structures with respect to the THz wave generation spot allows for resolution determination using the knife-edge method. We observe a THz beam FWHM of $4.86 \pm 0.37\,\mu m$ at 1 THz by using near-field imaging, which are in the dimension of the laser spot. Due to its simplicity, our technical approach offers a large potential for wide-ranging applications.

Funding by: MetaZIK PlasMark-T (FKZ:03Z22C511), BMBF

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Coulomb and exchange interaction in antiferromagnetic $LaCrO_3$

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The Rare earth orthochromites $ReCrO_3$ with orthorhombic crystal structure Pnma (#62) have interesting magnetic and electrical properties and the interplay between them[1-5]. Electronic band structure calculation using density functional theory carried out for $LaCrO_3$ with on-site columb intraction (DFT+U) and exchange interaction (DFT+U+J). Optimised lattice parameters, magnetic states, magnetic moments and band gap values for ground state $LaCrO_3$ are calculated. $LaCrO_3$ is succesfully synthesised and two enegy gaps in the system is recreated by applying on-site columb interaction and exchange interaction. The result shows that the band gap is increasing with increasing U. Magnetic properties of $LaCrO_3$ is also discussed. The Cr-O hybridization is described with the help of density of states and molecular orbital picture. How the splitting happened in 3d orbitals of Cr is explained by partial density of states.

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Non-equilibrium self-assembly of spin-wave solitons in FePt nanoparticles

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Spin wave solitons are localized high amplitude spin precessions in which the nonlinear effects balance with the dispersion of the medium. Up to now the nonlinear precession has been achieved through spin transfer torque with a nanocontact injecting a polarized spin current into the magnetic medium, but with this generation mechanism achievable soliton sizes are bound by size limits of nanocontact fabrication. Here an alternative generation mechanism has been achieved. We have created solitons of sub 10-nm size in self assembled L10-FePt nanoparticles with an average diameter of 16nm. High precession of the magnetic moment is driven by demagnetizing the samples with an ultrafast laser pulse. Soliton existence is first predicted with micromagnetic simulations and then confirmed by performing time resolved x-ray scattering. High spin precession frequency is observed at 0.1 THz, 10 times higher than other spin wave solitons reported in the literature. Their Frequency close to the THz range positions this system as a platform to develop miniature devices capable of filling the THz gap.

All optical switching on the nanometer scale excited and probed with femtosecond extreme ultraviolet pulses

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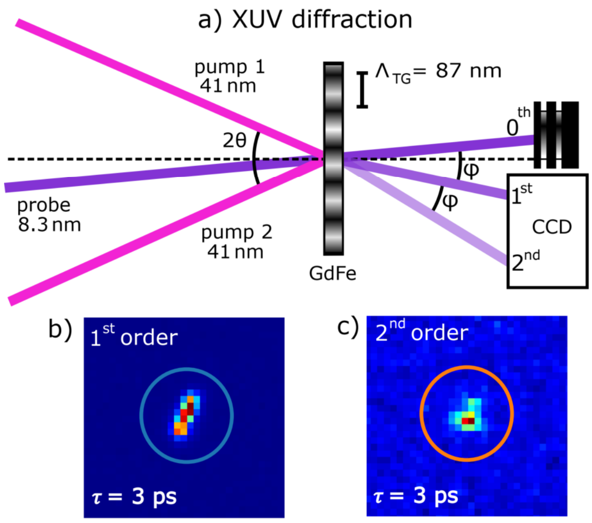
Ultrafast control of magnetization on the nanometer length scale, in particular all optical switching, is key to putting ultrafast magnetism on the path towards future technological application in data storage technology. However, magnetization manipulation with light on this length scale is challenging due to the wavelength limitations of optical radiation. Here, we excite transient magnetic gratings in a GdFe alloy with periodicites of 87, 41 and 17 nm by interference of two coherent femtosecond light pulses in the extreme ultraviolet spectral range at the FERMI free electron laser facility FERMI. The subsequent ultrafast evolution of the magnetization pattern is probed by diffraction of a third, time-delayed pulse tuned to the Gd N-edge at a wavelength of 8.3 nm. By examining the simultaneously recorded first and second diffraction orders and by performing reference real-space measurements with a wide-field magneto-optical microscope with femtosecond time resolution, we demonstrate the ultrafast emergence of all-optical switching on the nanometer length scale.



a) Diffraction experiment at the free electron laser (FEL) facilities FERMI in Trieste, Italy. The interference of two XUV pump pulses generates a transient magnetic grating with periodicities of Λ_{TG} = 87, 41 and 17 nm. The first b) and second c) order diffraction of a time-delayed, resonant XUV probe pulse at 8.3 nm are recorded simultaneously.

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Continuous illumination picosecond imaging of magnetisation dynamics in a transmission electron microscope

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Studies of chiral effects in magnetism often require high-spatial and temporal resolution magnetic imaging using transmission electron microscopy (TEM) methods. In fact, while achieving sub-nanometre spatial resolution in modern TEMs is straightforward, the temporal resolution is, in general, limited to the microsecond range. Here, we present the possibility to access magnetisation dynamics in the picosecond range applying a fast delay line detector (DLD) at an aberration-corrected transmission electron microscope, maintaining its excellent imaging properties.

DLDs measure the arrival time of every electron which was assigned to a specific phase based on the synchronisation with the microwave magnetic excitation. Latter was introduced using a custom-made holder. The limits of the setup were probed with low angle diffraction experiments where the electron beam was deflected by microwave magnetic fields. There, an intrinsic temporal resolution of 122 ps was achieved in a frequency range from 0.1 to 2.3 GHz.

As a proof of concept, the magnetic vortex core gyration excited by microwave magnetic fields was imaged employing Lorentz microscopy. There, the deflection of the electron beam due to the Lorentz force was used to visualise the position of the vortex core. The magnetic vortex was stabilised in a permalloy disk with 1.6 µm in diameter and 130 nm in thickness, which was patterned using lift-off lithography. The resonance frequency was found to be around 420 MHz and the radius of the gyration was in the range of a few tens of nanometers for the applied microwave excitation.

This work is supported by the DFG through CRC/TRR 270 (Project ID 405553726), the European Union's Horizon 2020 Research and Innovation Programme (Grant No. 856538 and 823717) and ETH Zurich.

Exceptional points controlling oscillation death in coupled spintronic nano-oscillators

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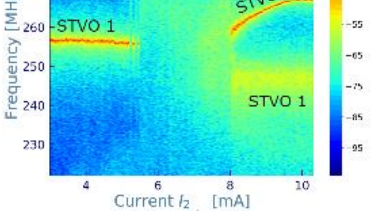
Non-hermitian physics was initially considered rather a mathematical-physics concept compared to the dominant paradigm of hermiticity in most physical systems. However, in the past two decades, there has been a growing interest in such systems since PT symmetry was proved a sufficient condition in order to describe meaningful physical quantities. Only recently, the field gained attention due to recent experimental advances particularly in photonics, where the controlled realization of so-called Exceptional points (EPs) could be demonstrated. Exceptional points describe singularities in the parameter space of a >2D system corresponding to the coalescence of two or more eigenvalues and the associated eigenvectors and are a peculiar feature of non-Hermitian physics. EPs are of interest not only from the fundamental viewpoint but also for the design of a new generation of sensors with unprecedented sensitivity.

In magnetic systems that naturally have largely discussed implications for future applications and beyond-CMOS technologies, the emergence of EPs is a very recent phenomenon in theory and as well in experiment. They occur under certain specific conditions in coupled systems and provide novel phenomena, such as topological features in the parameter space and even more complex dynamics that leverages new perspectives in several branches of physics. This includes non-hermiticity in general, non-hermiticity in strongly nonlinear regimes that is anticipated to provide stochastic or chaotic phenomena or complex bifurcations and the potentialities for applications, such as ultra-sensitive sensors or neuromorphic computing schemes.

Here, we experimentally show the emergence of EPs in mutually coupled spintronic oscillators [Wittrock et al., arXiv:2108.04804] which are intrinsically strongly nonlinear. We demonstrate the occurrence of complex dynamics, such as oscillation death due to the EP, and discuss topological operations and stochastic features in its vicinity.



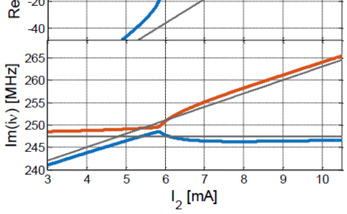


Figure: Death of oscillations in the vicinity of the EP and corresponding complex eigenvalues.

Spontaneous curvature-induced drift of magnetic skyrmions in curved films

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Here we propose a comprehensive theory of the curvature-induced drift of ferro- and antiferromagnetic skyrmions along cylindrical surfaces with non-zero curvature gradients [1], i.e skyrmion moves without any external stimuli. The strength of the curvature-induced driving is determined by the skyrmion type, while the trajectory is determined by the type of magnetic ordering. Using rigid particle-like assumption, we show that for the case of Neel skyrmion the driving force is linear with respect to the gradient of the curvature, while for Bloch skyrmion the driving is proportional to the product of mean curvature and its gradient. During the motion along the surface, skyrmion experiences deformation which depends on the skyrmion type. Equations of motion for Neel and Bloch magnetic skyrmions in curved ferromagnetic and antiferromagnetic materials are obtained in terms of collective variables. All analytical predictions are confirmed by numerical simulations.

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