X-tronics with Emerging Magnetic Materials

825. WE-Heraeus-Seminar

06 Jan – 09 Jan 2025
at the Physikzentrum Bad Honnef/Germany

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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 825. WE-Heraeus-Seminar:

Elementary excitations and quasi-particles within condensed matter exhibit a diverse array of physical attributes, encompassing spin and orbital angular momenta, electric dipole moments, and their respective higher-order multipoles. Over recent decades, investigations into the generation, detection, manipulation, and transportation of these quantities have developed into the interdisciplinary field known as "X-tronics", where 'X' embodies a degree of freedom or informational carrier inherent to quasi-particles, such as spin, orbital, phonon, magnon, or photon.

They not only enrich our comprehension of fundamentals properties of materials but also underpins pivotal advancements in device functionalities. Within magnetism research, diverse branches of X-tronics — spanning spintronics, orbitronics, magnonics, magneto-acoustics, and magneto-optics — stand as focal points. Yet, despite their individual significance, these domains often remain separated, lacking a unified perspective. The primary object of the seminar is to explore the synergies between various facets of X-tronics and the latest breakthroughs in emerging magnetic materials, such as topological magnetic textures, frustrated magnets, altermagnets, emergent oxide interfaces, superconductors, and novel interfaces with molecules, in which various orders and excitations are often entangled each other. This exploration is anticipated to catalyze a paradigm shift in the applications and functionalities of electronics in the platform of magnetic materials. Internationally renowned experts on X-tronics and emergent manifestations of magnetism in various platforms of materials will present the state-of-the-art in each respective area in a broader and unified context. We cordially invite participants from around the globe to showcase their research through poster presentations and engage in collective discussions aimed at fostering interdisciplinary dialogue and collaboration.

Scientific Organizers:

Dr. Aisha Aqeel	University of Augsburg, Germany E-mail: aishagcu@gmail.com
Dr. Dongwook Go	Forschungszentrum Jülich, Germany E-mail: d.go@fz-juelich.de

Introduction

Administrative Organization:

Dr. Stefan Jorda Martina Albert	Wilhelm und Else Heraeus-Stiftung Kurt-Blaum-Platz 1 63450 Hanau, Germany Phone +49 6181 92325-14 Fax +49 6181 92325-15 E-mail albert@we-heraeus-stiftung.de Internet: www.we-heraeus-stiftung.de

Venue:	Physikzentrum Hauptstrasse 5 53604 Bad Honnef, Germany Conference Phone +49 2224 9010-120 Phone +49 2224 9010-113 or -114 or -117 Fax +49 2224 9010-130 E-mail gomer@pbh.de Internetwww.pbh.de Taxi Phone +49 2224 2222
Registration:	Martina Albert (WE Heraeus Foundation) at the Physikzentrum, reception office Monday (16:00 h – 20:00 h) and Tuesday morning

Program

Program

Monday, January 6, 2025

16:00 – 20:00	Registration	
18:00	*BUFFET SUPPER and informal get-together*	
19:15 – 19:30	Aisha Aqeel Dongwook Go	**Welcome and opening remarks**
19:30 – 19:45	Video contribution	**About the Wilhelm and Else Heraeus Foundation**
19:45 – 20:30	Christian Back	**Tuning magnetic properties by spin currents**
20:30 – 20:45	Lucas Caretta CT	**Stabilizing Multiferroic Order and Topology in Ultrathin $BiFeO_3$**

Program

Tuesday, January 7, 2025

08:00 – 09:00	*BREAKFAST*	
09:00 – 09:45	Felix Büttner	**Topological magnetic switching in 2D and 3D**
09:45 – 10:30	Karin Everschor-Sitte	**"2D + 1D = 3D", sometimes!?**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Sopheak Sorn	**Topological dipoles of quantum skyrmions**
11:45 – 12:30	Alexander Mook	**Interacting Magnons in Ferromagnets, Antiferromagnets and Altermagnets**
12:30 – 14:00	*LUNCH*	
14:00 – 14:45	Mathias Weiler	**Coupling ferromagnetic and antiferromagnetic spin dynamics in hybrid bilayer systems**
14:45 – 15:30	Libor Smejkal	**Altermagnetism and spin group theory**

Program

Tuesday, January 7, 2025

15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	Aurélien Manchon	**Theory of orbital diffusion, pumping, and detection**
16:45 – 17:30	Kyung-Whan Kim	**Exploring Orbital Dynamics Distinct From Spin Dynamics**
17:30 – 18:15	Tom S. Seifert	**Driving and probing terahertz spin and orbital currents**
18:15 – 19:30	*HERAEUS DINNER at the Physikzentrum* *(cold and warm buffet, with complimentary drinks)*	
19:30	**Posters**	

Program

Wednesday, January 8, 2025

08:00 – 09:00	*BREAKFAST*	
09:00 – 09:45	Tatjana G. Rappoport	**Disorder-Driven Effects in Orbital Transport: From Bulk OHE to Mesoscopic Devices**
09:45 – 10:30	Börge Göbel	**Orbital Hall effect accompanying quantum and topological Hall effects**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Yuriy Mokrousov	**Unified topological viewpoint at spin textures**
11:45 – 12:30	NN	
12:30 – 14:00	*LUNCH*	
14:00 – 15:30	**Posters**	
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	Philipp Pirro	**Auto-oscillating magnons leading to magnetic switching- dynamic stability by spin torques**
16:45 – 17:30	Dirk Grundler	**Non-reciprocal magnons in natural and artificial chiral magnets**

Program

Wednesday, January 8, 2025

17:30 – 17:45	Florian Dirnberger CT	**Excitons, magnons & photons in 2D magnetic insulators**
17:45 – 18:00	Hye-Won Ko CT	**Magnetic octupole Hall effect in d-wave altermagnets**
18:00 – 19:30	*DINNER*	
19:30 – 19:45	**Poster Awards**	
19:45 – 20:00	Jing Wu CT	**Manipulation of Spin Ordering in 2D Magnets**
20:00 – 20:15	Robin R. Neumann CT	**Electrical Activity of Topological Magnons**

Program

Thursday, January 9, 2025

08:00 – 09:00	*BREAKFAST*	
09:00 – 09:45	Mario Cuoco	**Spin-orbital chiral metal**
09:45 – 10:30	Katharina J. Franke	**Single atoms and magnetic nanostructures on superconductors: Hybridization of Yu-Shiba-Rusinov states and Josephson-diode effect**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Matthias Althammer	**All-electrical angular momentum transport experiments in antiferromagnetic insulators and isolated ferromagnetic metals**
11:45 – 12:30	Angela Wittmann	**Chiral-induced unidirectional spin-to-charge conversion**
12:30 – 12:45	Scientific organizers	**Concluding remarks**
12:45 – 14:00	*LUNCH*	

End of the seminar and departure

Posters

Posters

Maria Azhar	**Continuous topological transitions — Hopfion slider**
Mona Bhukta	**Dynamic imaging of Spin-orbit-torque driven nanosecond dynamics of antiferromagnetic skyrmions and skyrmion lattices**
Marco Biagi & Corrado Capriata	**Material Exploration for Spin-to-Orbital Conversion for SOT-MTJ**
Davide Bossini	**Dynamical renormalization of the magnon spectrum via nonlinear coherent spin dynamics**
Oksana Busel	**Nonlinear spin dynamics across Néel phase transition in F/AF multilayers**
Avinash Kumar Chaurasiya	**Ultra-low current spin Hall nano-oscillators and their mutual synchronization in large networks**
Dimos Chatzichrysafis	**Thermal Hall Effect of Magnons from Many-Body Skew Scattering**
Lukas Cvitkovich	**Magnetic Tunneling Junctions from First Principles**
Kiranjot Dhaliwal	**Current driven magnetization reversal in CoFeTaB/Pt probed by X-ray magnetic reflectivity**
Claire Donnelly	**Advances in X-ray Imaging of magnetic vector and orientation fields**
Luciano Jacopo D'Onofrio	**Orbital angular momentum polarization effects in centrosymmetric systems**
Anna Duvakina	**Optically induced magnons from a metallic nanodisk**
Hans-Joachim Elmers	**Orbital Magnetic Moments in the Kagome Metal CsV_3Sb_5**

Posters

Matteo Fettizio	**Large Spin-Orbit Torques in the Sb_2Te_3/Au/Co Topological heterostructures**
Robert Frömter	**Merons and anti-merons in synthetic antiferromagnets**
Gyungchoon Go	**Scalar Spin Chirality Hall effect**
Soumyajyoti Haldar	**Ab initio study of all-electrical skyrmion detection in van der Waals tunnel junctions**
Moritz Hirschmann	**Transport Characteristics of Topological Nodal Planes**
Christian Holzmann	**Lateral crystallization of single-crystalline garnet thin films**
Chanyong Hwang	**Skyrmionics**
Jae-Chun Jeon	**Ultrahigh resolution anomalous Hall microscopy for pure electrical detection of magnetic domain wall dynamics**
Akilan K	**Spin charge interconversion in synthetic ferrimagnetic Co/Gd bilayers**
Bomin Kim	**Comparison between Fe_3GaTe_2 and Fe_3GeTe_2: Magnetic exchange interaction and anomalous Hall conductivity**
Sanghoon Kim	**Bulk-type inverse spin Hall effect with helical spin structure in 2D ferromagnet**
Volodymyr Kravchuk	**Fluctuation-induced piezomagnetism and temperature spin conductivity in local moment altermagnets**
Soogil Lee	**Perpendicular magnetization switching through orbital current**
Sergio Leiva Montecinos	**Orbital Edelstein contribution to the spin-charge conversion in Germanium Telluride**

Posters

Miina Leiviskä	**Spin Hall magnetoresistance at the altermagnetic insulator/Pt interface**
Kai Litzius	**Real-Space Investigation of Reversible and Multidirectional Laser-Driven Motion of Chiral Spin Textures**
Justin Llandro	**Thin-film growth of Type-II multiferroic Y-type hexaferrite**
Mehak Loyal	**Near-Room-Temperature Compensation Temperature In Terbium Iron Garnet Thin Films**
Andrea Migliorini	**Interface engineering of spin-orbit torque multilayers for efficient current-induced domain wall motion**
Junais Habeeb Mokkath	**Magnetic skyrmions in MXene flakes**
Ankita Nayak	**Electrical Detection of spin currents in magnetic insulators**
Quynh Anh Thi Nguyen	**β-W Spintronics: Spin Hall Conductivity Engineering in W-X Alloys**
Darius Pohl	**Disentangling the magnetic properties of ferrimagnets using atomic-scale vortex-EMCD**
Vibhuti Narayan Rai	**Spatial coherent phonon spectroscopy on 2H-$MoTe_2$ using THz-STM**
Sonny H. Rhim	**Orbital Hall conductivity of series of Transition Metal: First-principles symmetry analysis**
Carlos Rosário	**Interfacing topological insulators with ferromagnets for spin-orbitronics**
Christin Schmitt	**Orbital magnetoresistance in insulating antiferromagnets**

Posters

Sebastian Schneider	**In-situ correlation of the Hall effect with the occurrence of topological magnetic phases**
Marius Weber	**Ultrafast electron dynamics in altermagnetic materials**
Emily Wedde	**Uncovering the Property Correlations of Two-Dimensional Transition Metal Carbides by Magneto-Optical Spectroscopy**
Jean-Eric Wegrowe	**Unified approach of Hall, thermal Hall, and spin Hall effects in the light of Onsager reciprocity relations**
Yongbing Xu	**Manipulation of Spin Ordering in 2D Magnets**
Manuel Zahn	**Domain walls with 90° magnetization rotation in the topological kagome magnet $TbMn_6Sn_6$**

Abstracts of Lectures

(in alphabetical order)

All-electrical angular momentum transport experiments in antiferromagnetic insulators and isolated ferromagnetic metals

M. Althammer[1,2]

[1] Walther-Meißner-Institut, Bavarian Academy of Sciences and Humanities, Garching, Germany
[2] TUM School of Natural Sciences, Physics Department, Technical University of Munich, Garching, Germany

Pure spin currents, i.e., the flow of angular momentum without an accompanying charge current, represent a new paradigm in spintronics. Here, I present our recent progress in probing angular momentum transport via all-electrical measurements in antiferromagnetic insulators [1,2,3,4] and isolated metallic ferromagnet strips [5].

In the first part, I will show that the quantized spin excitations of an ordered antiferromagnet with opposite chirality represent pairs of spin-up and -down magnons. A magnonic pseudospin can characterize this two-level nature. Over the last few years, we have studied the associated dynamics of antiferromagnetic pseudospin and observed the magnon Hanle effect in hematite thin films [1,2,3,4]. Its realization via electrically injected and detected spin transport in an antiferromagnetic insulator demonstrates its high potential for devices and as a convenient probe for magnon eigenmodes and the underlying spin interactions in the antiferromagnet [2,3].

The second part will present our recent progress toward separating electronic and magnonic contributions to angular momentum transport in metallic ferromagnets [5]. To this end, we electrically excite and detect spin transport between two parallel and electrically insulated ferromagnetic metal strips on top of a diamagnetic substrate. We observe a finite angular momentum flow to the second ferromagnetic strip across a diamagnetic substrate over micron distances. We discuss phononic and dipolar interactions as the likely cause of angular momentum transfer between the two strips.

References

[1] T. Wimmer et al., Phys. Rev. Lett. **125**, 247204 (2020).
[2] A. Kamra et al., Phys. Rev. B **102**, 174445 (2020).
[3] J. Gückelhorn et al., Phys. Rev. B **105**, 094440 (2022).
[4] J. Gückelhorn et al., Phys. Rev. Lett. **130**, 247204 (2023).
[5] R. Schlitz et al., Phys. Rev. Lett. **132**, 256701 (2024)

L. Chen[1], Y. Sun[1], Jianping Guo[1], S. Mankovsky[2], T. N. G. Meier[1], M. Kronseder[3], C. Sun[6,7], A. Orekhov[6], H. Ebert[2], D. Weiss[3] and C. H. Back[1,4,5]

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

[2]*Department of Chemistry, Ludwig Maximilian University, Munich, Germany*

[3]*Institute of Experimental and Applied Physics, University of Regensburg, Regensburg, Germany*

[4]*Munich Center for Quantum Science and Technology, Munich, Germany*

[5]*Center for Quantum Engineering, Technical University of Munich, Munich, Germany*

[6]*Department of Chemistry, Technical University of Munich, Munich, Germany*

[7]*TUMint.Energy Research GmbH, Department of Chemistry, Technical University of Munich, Munich, Germany*

Spin currents, which involve the flow of electron spin rather than charge, are technologically interesting because they enable new functionalities and more efficient devices in spintronics. Typical arguments are reduced energy dissipation, high speed, and advantageous scalability. Here, we will demonstrate more basic effects arising from the application of spin currents. We demonstrate that the magneto-crystalline anisotropy and the magnetization can be controlled by the application of spin currents in traditional materials as well magnetic 2D materials.

Topological magnetic switching in 2D and 3D

Felix Büttner[1,2,*]
[1]*Experimental Physics V, Center for Electronic Correlations and Magnetism, University of Augsburg, 86159 Augsburg, Germany*
[2]*Helmholtz-Zentrum Berlin, 14109 Berlin, Germany*
**felix.buettner@uni-a.de*

In ferromagnetic multilayers, magnetic skyrmion can be created at picosecond timescales by optical stimuli [1]. The nucleation of these topological features is well explained by mediation through a transient fluctuation state. However, the fluctuation model predicts homogenous nucleation across the sample, irrespective of small variations in the energy landscape (pinning). It appears that the fluctuation model is challenged by a recent study that reports the possibility of highly selective laser-induced skyrmion production in artificial, focus-ion-beam (FIB) made pinning sites, at least at some values of the external magnetic field [2]. The contradiction of these observations calls for further studies to reveal the mechanism and timescale of skyrmion nucleation and localization after transient heating of the material.
In this talk, I will first present such a real-time study of the skyrmion localization dynamics, conducted via time resolved small-angle x-ray scattering at the EuXFEL. A periodic grid of focus-ion-beam made nucleation sites allowed us to distinguish in the reciprocal space technique between the time evolution at localization centers and evolution of homogeneous fluctuations. The results show that the physics of skyrmion localization during ultrafast topological switching can explained by an intuitive model of homogeneous skyrmion nucleation and spatially varying skyrmion decay.
In the second part of the talk, I will discuss our most recent study on heat-induced nucleation of magnetic cocoons – a 3D skyrmion texture that penetrates only some of the magnetic layers of the multilayer [3]. Using comprehensive experimental data and matching micromagnetic simulations, we identify a transient spin reorientation transition combined with strong chiral interactions due to flux closure stray field contributions as an alternative driver for ultrafast topological switching.

References

1. Büttner, F., Pfau, B., Böttcher, M., Schneider, M., Mercurio, G., Günther, C. M., Hessing, P., Eisebitt, S., *et al.* Observation of fluctuation-mediated picosecond nucleation of a topological phase. Nature Materials **20**, 30–37 (2021).
2. Kern, L.-M., Pfau, B., Deinhart, V., Schneider, M., Klose, C., Gerlinger, K., Wittrock, S., Engel, D., Will, I., Günther, C. M., Liefferink, R., Mentink, J. H., Wintz, S., Weigand, M., Huang, M.-J., Battistelli, R., Metternich, D., Büttner, F., Höflich, K. and Eisebitt, S. Deterministic Generation and Guided Motion of Magnetic Skyrmions by Focused He^+-Ion Irradiation. Nano Lett. **22**, 4028–4035 (2022).
3. Grelier, M., Godel, F., Vecchiola, A., Collin, S., Bouzehouane, K., Fert, A., Cros, V. and Reyren, N. Three-dimensional skyrmionic cocoons in magnetic multilayers. Nat. Commun. **13**, 6843 (2022).

Stabilizing Multiferroic Order and Topology in Ultrathin $BiFeO_3$

Lucas Caretta

Brown University, USA

$BiFeO_3$ (BFO) is a room temperature magnetoelectric material demonstrating direct coupling between ferroelectric and magnetic order parameters. While studied extensively in film form, scaling to thinner thickness is required for applications in low power computing. However, scaling ferroelectric and antiferromagnetic order to ultrathin thickness poses significant challenges. Polar order vanishes in nearly all known perovskite ferroelectric materials at thin thickness due to uncompensated bound charges at the ferroelectric surface, causing a “dead layer” formation of a few nanometers. Moreover, dead layers also commonly form in ultrathin oxide antiferromagnets (including BFO) due to off-stoichiometry or reduction in magnetic anisotropy. To overcome these limitations, we explore the polar and magnetic states of ultrathin, sub-5 nm thick BFO under various boundary conditions and epitaxial constraints. We demonstrate that epitaxial compressive strain and short circuit boundary conditions can be used to establish polar and magnetic order in ultrathin BFO via a second order phase transition accompanied by the observation of topological magnetoelectric defects. This work highlights new strategies for designing magnetoelectric materials and topology at the thinnest length scales.

Spin-orbital chiral metal

Mario Cuoco

CNR-SPIN, c/o University of Salerno, Fisciano, Italy

The connection between crystal symmetries, electron interactions, and electronic structure plays a crucial role in the emergence of various unconventional phases of matter. Understanding the intimate nature of these orders and providing robust means for detecting them are key objective in the field of condensed-matter physics. For instance, identifying non-standard types of magnetism with chiral electronic ordering has proven to be quite challenging in experiments. Here, we introduce and discuss symmetry-broken chiral phases which are based on nonstandard orbital and spin-orbital quadrupole currents [1]. We discuss the magnetic character of these phases and their properties. Then, we consider which are the key signatures for their detection when considering circularly polarized, spin-selective, angular-resolved photoelectron spectroscopy. Focusing on the well-known quantum material Sr_2RuO_4, we uncover subtle spectroscopic hallmarks that align with the presence of spin-orbital chiral currents at the material's surface. The uncovered chiral states open new avenues for designing and understanding ordering phenomena with unconventional magnetism.

[1] F. Mazzola, W. Brzezicki, M. T. Mercaldo, et al., Nature 626, 752–758 (2024).

Excitons, magnons & photons in 2D magnetic insulators

Florian Dirnberger*
Technical University of Munich, TUM School of Natural Sciences,
Physics Department, 85748 Garching, Germany

A number of materials from the family of van der Waals magnetic insulators was recently found to support magnetic excitons – a rare type of optical excitation formed by spin-polarized electronic states. With properties that have no analog amongst excitons in conventional band insulators, these optical quasiparticles and their coupling to magnetic order are adding new flavors to the list of magneto-optic effects. In this talk, I will discuss how interactions of magnetic excitons with magnons and photons brings together concepts from semiconductor physics, magnetism, and photonics. The elemental role of strong light-matter coupling and the emergent hybrid light-matter states known as exciton-polaritons will be analyzed in the context of the optical properties of the layered magnetic semiconductor CrSBr [1, 2]. In the second part, I will also present our latest experimental and theoretical advances on unraveling the impact of magnons on the propagation of excitons. Highly non-linear exciton transport features, such as propagation enhanced at the antiferromagnet-to-paramagnet phase transition, will be discussed alongside the anomalous observations of exciton cloud contraction and superdiffusive behavior.

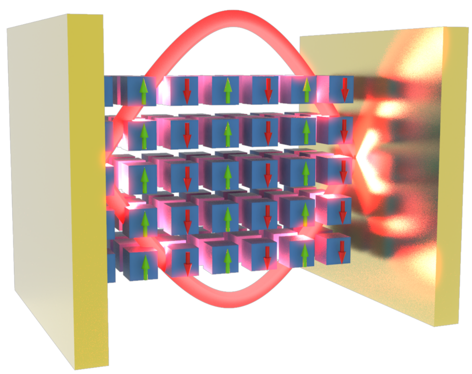

FIG. 1. Confining photons in an optical microcavity can support strong interactions with excitons and magnons in van der Waals magnets.

[1] Dirnberger, F. *et al.* Spin-correlated exciton–polaritons in a van der Waals magnet. *Nature Nanotechnology* **17**, 1060–1064 (2022).

[2] Dirnberger, F. *et al.* Magneto-optics in a van der Waals magnet tuned by self-hybridized polaritons. *Nature* **620**, 533–537 (2023).

* f.dirnberger@tum.de

“2D + 1D = 3D”, sometimes!?

K. Everschor-Sitte[1]

1 Faculty of Physics and Center for Nanointegration Duisburg-Essen (CENIDE), University of Duisburg-Essen, 47057 Duisburg, Germany

Knots and links play a crucial role in understanding topology and discreteness in nature. For classifying topological behavior, the dimensionality of a system is crucial. In magnetic systems, 2D magnetic structures can be classified by the skyrmion winding number within the homotopy group $\Pi_2(S_2) = \boldsymbol{Z}$, while 3D Hopfions are characterized by the Hopf index within $\Pi_3(S_2) = \boldsymbol{Z}$. But what about 3D structures that are effectively “two plus one” dimensional – those composed of 2D structures periodically extending along a third direction? Examples of these include (twisted) skyrmion tubes, screw dislocations [1] and space-time Hopfions [2].
Dirac’s belt trick reveals that in such “two plus one” dimensional systems, the topology reduces to a $\boldsymbol{Z}_2$ invariant. But what implications does this have for magnetic systems? Is there an analogy to the belt trick, and is the Hopf index still a meaningful quantity in these cases? In this talk, we will discuss various two plus one-dimensional textures and propose ways to classify them [3,4]. Using a discrete geometric definition of the Hopf index we show that magnetic textures with arbitrary values of the Hopf index naturally arise and can be interpreted as states of “mixed topology” that are continuously transformable to one of the multiple possible topological sectors [4].

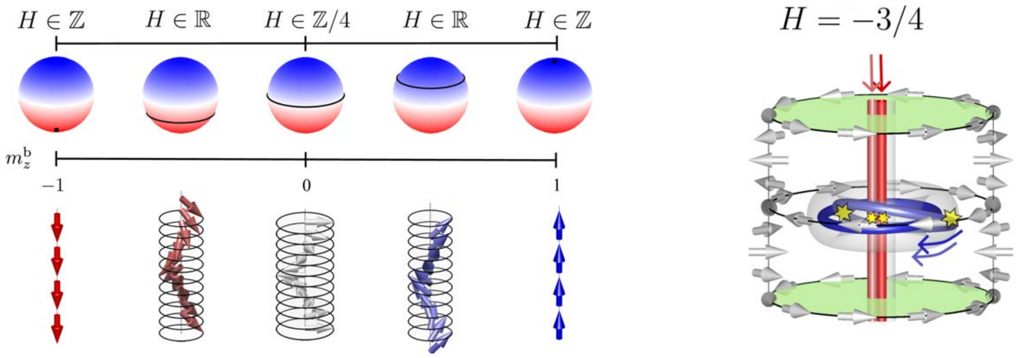

FIG. 1. Left: The Hopf index can take arbitrary and fractional values when the background magnetization is not ferromagnetic. Right: Twiston -- a mixed topology state that can transform into either a hopfion or a skyrmion tube.

References

[1] M. Azhar, V. P. Kravchuk, and M. Garst, Phys. Rev. Lett. 128, 157204 (2022)
[2] R. Knapman, T. Tausendpfund, S. Díaz, KES, Commun. Phys. 7, 151 (2024)
[3] R. Knapman, M. Azhar, A. Pignedoli, L. Gallard, R. Hertel, J. Leliaert, KES, arXiv:2410.22058
[4] M. Azhar, S. C. Shaju, R. Knapman, A. Pignedoli, KES, arXiv:2411.06929

Single atoms and magnetic nanostructures on superconductors:
Hybridization of Yu-Shiba-Rusinov states and Josephson-diode effect

Katharina J. Franke[1]

[1]*Fachbereich Physik, Freie Universität Berlin, Germany*

Exchange-coupled magnetic adatoms on superconductors induce Yu-Shiba-Rusinov (YSR) states within the superconducting energy gap of the substrate. Because the YSR states are located at the interface to the superconductor inside its energy gap, they are protected from interactions with the bulk. Hence, they provide an ideal platform for engineering states with intricate wave-function symmetries or extended bands. Here, we use scanning tunneling microscopy and spectroscopy to explore magnetic adatoms on superconducting Pb and the quasi-two-dimensional superconductor 2H-$NbSe_2$. We further engineer hybridization of YSR states by constructing the nanostructures atom by atom.

By approaching a superconducting STM tip towards the superconducting substrate, we establish atomic-scale Josephson junctions. We show that a single magnetic adatom inside such Josephson junctions induces non-reciprocal behavior. We ascribe this diode-like effect to broken electron-hole symmetry by the YSR states.

Orbital Hall effect accompanying quantum and topological Hall effects

Börge Göbel – Martin-Luther-Universität Halle-Wittenberg

The quantum Hall effect emerges when two-dimensional samples are subjected to strong magnetic fields at low temperatures: Topologically protected edge states cause a quantized Hall conductivity in multiples of e^2/h. As we have recently shown, the quantum Hall effect is accompanied by an orbital Hall effect [1]. Our quantum mechanical calculations fit well the semiclassical interpretation in terms of "skipping orbits." The chiral edge states of a quantum Hall system are orbital polarized akin to an orbital version of the quantum anomalous Hall effect in magnetic systems. The orbital Hall resistivity scales quadratically with the magnetic field, making it the dominant effect at high fields.

In this talk, I will also consider topologically non-trivial magnetic textures, such as magnetic skyrmions, that exhibit a topological Hall effect. It quantifies the transverse electric current once an electric field is applied and occurs as a consequence of the emergent magnetic field of the skyrmions. Therefore, it is closely related to the quantum Hall effect described above. Additionally, an orbital magnetization is generated due to the emergent field [2].

As I will demonstrate, the transverse charge currents are orbital polarized even though the conduction electrons couple to the skyrmion texture via their spin (cf. Figure 1). The topological Hall effect is accompanied by a topological orbital Hall effect even for *s* electrons without spin-orbit coupling [3]. Furthermore, antiferromagnetic skyrmions that have a compensated emergent field exhibit a pure topological orbital Hall conductivity that is not accompanied by charge transport and can be orders of magnitude larger than the topological spin Hall conductivity. Other magnetic quasiparticles beyond skyrmions like magnetic bimerons are briefly discussed as well [4].

[1] B. Göbel, I. Mertig, *Orbital Hall effect accompanying quantum Hall effect: Landau levels cause orbital polarized edge currents*, Phys. Rev. Lett. 133, 146301 (2024).

[2] B. Göbel, A. Mook, J. Henk, I. Mertig, *Magnetoelectric effect and orbital magnetization in skyrmion crystals: Detection and characterization of skyrmions*, PRB 99, 060406(R) (2019).

[3] B. Göbel, L. Schimpf, I. Mertig, *Topological orbital Hall effect caused by skyrmions and antiferromagnetic skyrmions,* arXiv: 2410.00820 (2024).

[4] B. Göbel, I. Mertig, O. Tretiakov, *Beyond skyrmions: Review and perspectives of alternative magnetic quasiparticles*, Physics Reports 895, 1 (2021).

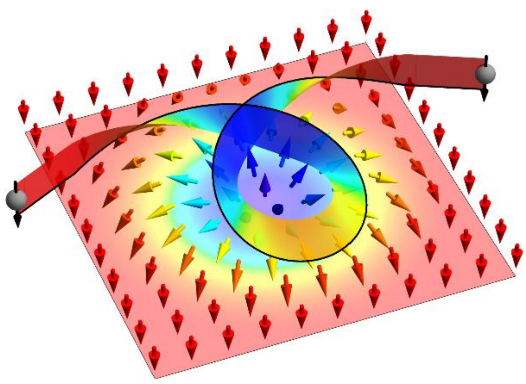

Figure 1: Topological orbital Hall effect.

The spin of the conduction electron (black) aligns with the skyrmion texture (colored arrows; the color resembles the out-of-plane orientation). While moving through the skyrmion, the electron accumulates a Berry phase and is deflected (topological Hall effect). Due to the cycloid trajectory (black), an orbital angular momentum is generated and transported as an orbital current (topological orbital Hall effect).

Non-reciprocal magnons in natural and artificial chiral magnets

Dirk Grundler[1],[2]

[1] Institute of Materials, Laboratory of Nanoscale Magnetic Materials and Magnonics (LMGN),
École Polytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland
[2] Institute of Electrical and Micro Engineering, EPFL, 1015 Lausanne

Interest in spin waves (magnons) has recently grown in view of novel schemes for computation such as hardware-implementations of neural networks and on-chip information transmission and processing which avoid Joule heating (1). Non-reciprocity in magnon frequencies and amplitudes is particularly relevant for uni-directional information flow and optimized energy efficiency. Chiral magnets with bulk Dzyaloshinskii–Moriya interaction and specifically engineered mulitlayers are known to provide such characteristics. Often there are drawbacks, however, in that a low critical temperature and additional magnon damping, respectively, limit their functionality. Alternative approaches allowing for e.g. magnon diodes operating at room temperature are urgently needed. In my talk I will first present our inelastic light scattering studies on non-reciprocal magnons in a low-damping chiral magnet such as Cu_2OSeO_3. Here, I will discuss particularly the magnons observed in the magnetic skyrmion lattice phase near 10 K (2). Then I will present our recent work in which we designed and fabricated Ni microtubes such that they exhibited non-reciprocal magnon characteristics at room temperature. Depositing a single-layered Ni shell on three-dimensional (3D) templates (3) which incorporated left or right-handed screws on the surface we achieved reprogrammable characteristics in zero magnetic field (4). Our experiments and findings fuel the perspective of 3D magnon diodes in 3D magnonic device architectures. Support by P. Che, R. Ciola, M. Garst, V. Kravchuk, P.R. Baral, A. Magrez, H. Berger, T. Schönenberger, H. M. Rønnow, M. Xu, A.J.M. Deenen, H. Guo, P. Morales-Fernández, S. Wintz, and C. Donnelly is gratefully acknowledged. Our work was supported by SNSF via projects 171003 and 197360.

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Exploring Orbital Dynamics Distinct From Spin Dynamics

Seungyun Han[1], Hye-Won Ko[2], Jung Hyun Oh[2], Hyun-Woo Lee[1], Kyung-Jin Lee[2], Kyoung-Whan Kim[3]

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

[2]Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon 34141, Korea

[3]Department of Physics, Yonsei University, Seoul 03722, Korea

Roles of orbital angular momentum of electrons in solids have been ignored for a long time because of the orbital quenching. However, recent theoretical and experimental reports imply that orbital angular momentum is not quenched in nonequilibrium. Furthermore, it is claimed that the orbital degree of freedom is crucial for anomalous spin transport phenomena such as the spin Hall effect. Therefore, understanding the dynamics of orbital angular momentum has become important in the aspect of both fundamental science and spintronic applications. However, it has been believed that the dynamics of orbital angular momentum and that of spin angular momentum are qualitatively similar, so the experimental characterization of orbital dynamics requires quantitative analysis, which is difficult in general.

In this talk, I would like to point out a qualitative difference between the orbital and spin angular momenta by revealing a hidden degree of freedom of the orbital angular momentum, which is named the orbital angular position. It mediates the oscillation of the orbital angular momentum even without breaking time-reversal or spatial-inversion symmetry, which is impossible for spin. Our quantum Boltzmann approach indicates that considering the orbital angular position is essential for the theoretical description of orbital transport. Also, I would like to propose several experimental methods to measure the distinct dynamics of orbital angular momentum.

Magnetic octupole Hall effect in *d*-wave altermagnets

Hye-Won Ko[1] and Kyung-Jin Lee[1]

[1]Korea Advanced Institute of Science and Technology, Daejeon, Korea

An order parameter describes symmetry-broken equilibrium phases and plays a crucial role in identifying nonequilibrium responses. Altermagnets, a class of magnetic systems with multipolar order as the order parameter [1,2], serve as a promising platform to explore multipolar magnetism. In this work, we demonstrate the multipole Hall effect — the transverse flow of multipole moments driven by an external electric field — in *d*-wave altermagnets. Through symmetry analysis of multipole conductivity tensors and linear response calculations, we reveal the emergence of magnetic octupole (MO) Hall effect in *d*-wave altermagnets. We find that MO Hall currents are distinct from spin-splitter based spin current, as they persist even in symmetries where the spin splitter effect is forbidden, providing a clear signature to identify the MO Hall effect. We also show the occurrence of electric quadrupole Hall effect, which has previously been studied in the context of orbitronics. Our work expands the family of Hall effects to encompass higher-order multipole responses and suggests the potential versatility of altermagnets beyond spintronics.

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Theory of orbital diffusion, pumping, and detection

A. Manchon[1], X. Ning[1], A. Pezo[1], D. Ovalle[1]

1 Aix-Marseille Univ, CNRS, CINaM, Marseille, France

*aurelien.manchon@univ-amu.fr

Recent progress in the physics of spin-charge interconversion mediated by spin-orbit coupling has shed new light on the orbital angular momentum degree of freedom. Indeed, while the orbital ordering driven by the crystal-field potential governs the interplay between crystal structure and electronic properties of strongly correlated materials such as Mott insulators, the possibility of transporting the orbital information in these materials has remained an open question so far. In the context of metallic spintronics though, it has been progressively realized that the orbital angular momentum can be generated out of equilibrium, transported, and detected, rather similarly to the spin angular momentum.

In this presentation, I intend to discuss the theoretical aspects of orbital generation, transport, and detection. After introducing general ideas about orbital ordering and orbital angular momentum, I will first present a quantum theory of orbital diffusion and uncover several mechanisms governing orbital torque and magnetoresistance phenomena, including orbital diffusivity, spin-orbit polarization, orbital swapping, and orbital mixing conductance [2,3]. These new concepts are crucial to the understanding of experimental results and can be computed from first principles. Then, I will discuss our recent results on orbital pumping in realistic magnetic bilayers [3]. Finally, I will discuss the possibility of detecting orbital densities optically using the orbital Kerr effect [4]. I will particularly emphasize the central role played by the second-order Hall effect, a companion of the orbital Edelstein effect.

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Unified topological viewpoint at spin textures

Yuriy Mokrousov[1,2]

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

Magnetic skyrmions are fascinating particle-like objects, whose key properties are governed by their non-trivial real-space topology. We show that the powerful language of non-commutative geometry is the most suitable tool for understanding the properties of spin textures as entangled objects living in a complex non-commutative phase space [1]. As the length scale of a two-dimensional skyrmion crystal approaches the lattice constant of its host material, topological gaps may form in the associated electronic system. However, the smooth texture approximation for the usual geometric approach of emergent magnetic fields is no longer satisfied. Instead, we demonstrate that by adopting a fully algebraic view one can apply noncommutative *K*-theory to compute all admissible Chern numbers, thereby providing a full topological description of electronic states in generic multi-*q* spin textures [2]. As a central application, we tune the texture parameters, creating discontinuous jumps in the real-space winding number for which we observe the relation with different flavors of Chern numbers in the electronic spectrum [3]. We also show that noncommutative framework also provides an easy access to the calculation of orbital magnetization in spin textures of various nature. The power of the non-commutative approach lies in an ability to categorize emergent topological states without referring to smooth real- or reciprocal-space quantities. This opens a way to an educated design of topological phases in aperiodic, disordered, or non-smooth textures of spins and charges containing topological defects. This work has been done together with Fabian Lux, Pascal Praß, Sumit Ghosh, Emil Prodan, Stefan Blügel and Duco van Straten.

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Interacting Magnons in Ferromagnets, Antiferromagnets, and Altermagnets

Alexander Mook

Institute of Physics, Johannes Gutenberg University Mainz, Germany

Magnetically ordered materials host collective excitations, known as spin waves or magnons, which not only provide insight into the quantum many-body physics of magnetic systems but also enable spin and information transport. Crucially, magnons are not free particles—they interact with one another, leading to a renormalization of their quasiparticle properties. These interactions, driven either by thermal fluctuations at finite temperatures or quantum fluctuations at absolute zero, result in a finite magnon lifetime, observable as a spectral linewidth in techniques like inelastic neutron or Raman scattering.

In this talk, I will introduce the theory of magnon-magnon interactions and present two case studies illustrating their implications.

First, I explore the stability of magnons in ferromagnets, antiferromagnets, and the recently discovered altermagnets [1]. While all three phases support Goldstone modes in the nonrelativistic limit, altermagnets stand out due to spin-split magnon bands [2]. I will demonstrate that the low-energy magnon branch in altermagnets is universally stable, whereas the high-energy branch exhibits finite lifetimes driven by quantum many-body fluctuations. This result underscores the unique many-body physics of altermagnets and their deviation from conventional quantum magnetism paradigms.

Second, I analyze the van der Waals ferromagnets CrBr3 and CrI3, known for hosting topological Dirac magnons [3,4]. Recent inelastic neutron scattering experiments on CrBr3 revealed discrepancies with theoretical predictions, suggesting an incomplete understanding of magnon interactions [4]. I will present a revised theoretical framework that achieves excellent agreement with experimental magnon lifetimes and energies. Extending this analysis to CrI3, I will argue that the topological gap in its Dirac magnons remains robust against interactions, highlighting the resilience of topological magnons to thermal fluctuations.

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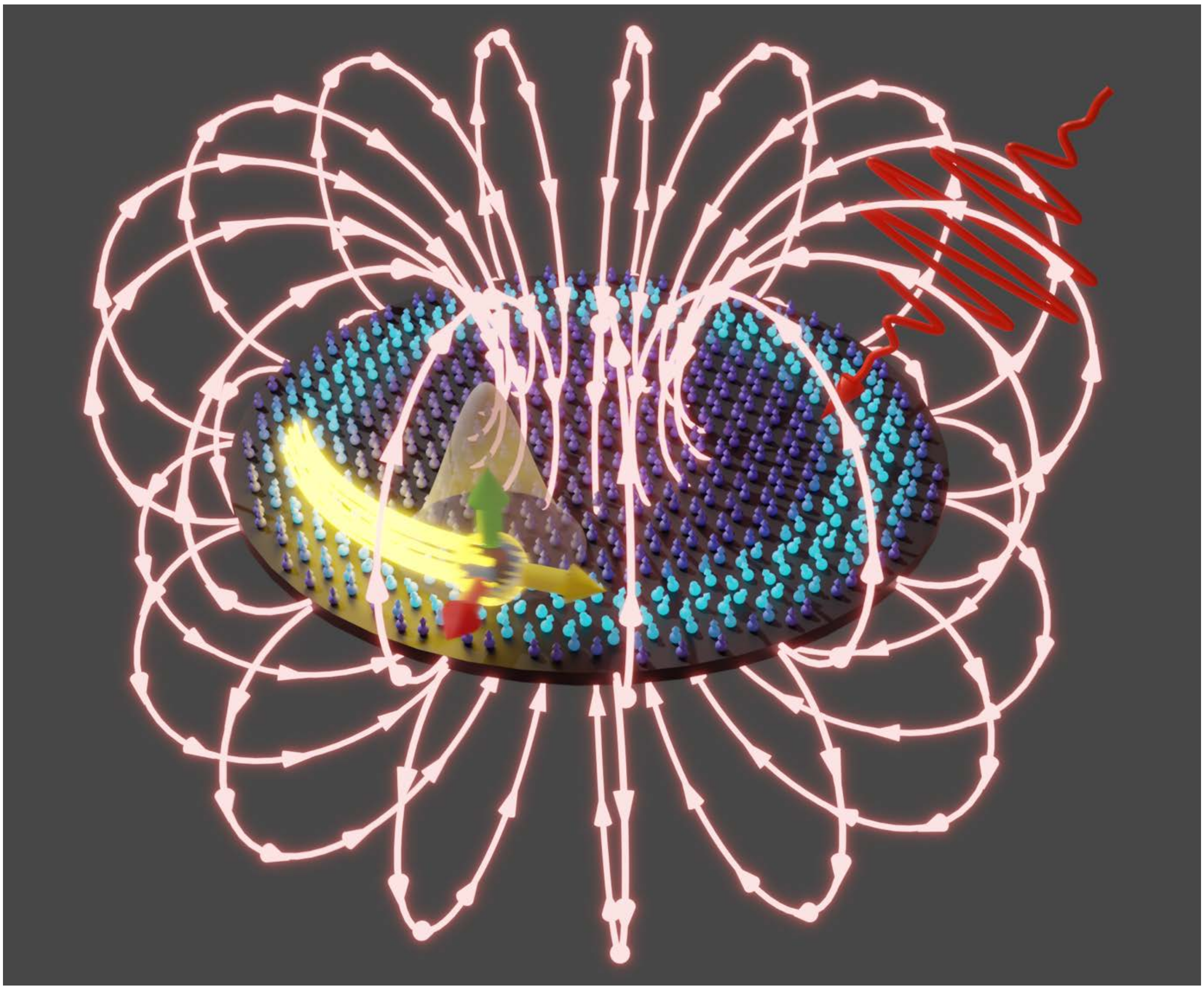
Electrical Activity of Topological Magnons

Robin R. Neumann,[1,2] Jürgen Henk,[2] Ingrid Mertig,[2] and Alexander Mook[1]

[1]Insitute of Physics, Johannes Gutenberg University Mainz, Mainz, Germany
[2]Insitute of Physics, Martin Luther University Halle-Wittenberg, Halle (Saale), Germany

Magnons, the bosonic quasiparticles of collective spin excitations, hold potential as information and energy carriers in spintronic devices. Although the magnonic counterpart of the electronic quantum Hall states was predicted over a decade ago, experimental evidence remains absent.

Herein, I present a specific proposal for using *electrical* probes to detect topological magnons. Despite their charge neutrality, magnetoelectric effects grant magnons an electrical dipole moment, whose direction depends on the chirality of the topological magnons. Consequently, the edge magnons give rise to an electric polarization at the edges driven by thermal spin fluctuations. Furthermore, magnons are predicted to interact with alternating electric fields, opening up the possibility of resonantly exciting topological magnons. The resulting absorption spectrum encodes footprints of topological magnons that might assist in their detection.



Auto-oscillating magnons leading to magnetic switching- dynamic stability by spin torques

Philipp Pirro

RPTU Kaiserslautern-Landau and Landesforschungszentrum OPTIMAS
Kaiserslautern, Germany

Magnetic auto-oscillations driven by spin transfer torques are often considered as magnons with compensated damping. They can be created by injecting a spin current (either by spin transfer or spin orbit torques) whose spin is directed anti-parallel to the spin moments in the magnetic material (“anti-damping spin torque”). If the injected spin current is above a certain threshold value, it can lead to permanent magnetic switching in remanence, as used, e.g., in MRAM technology. Large spin currents can even stabilize the magnetic moments of the material antiparallel to the external bias field. In this case, the fluctuations around this unstable equilibrium are sometimes referred to as “antimagnons” [1] which might help to build novel types of magnon amplifiers [2].

I will present time-resolved micro-focused Brillouin light scattering measurements of the magnon intensity in ultrathin W/CoFeB/MgO layers. The almost compensated effective saturation magnetization in this stack leads to very low threshold currents for magnonic auto-oscillations. In the experiment, anti-damping-like spin current pulses are injected into the magnetic material via the spin Hall effect in W. We show that the magnon intensity grows with the injected current for low currents. For higher currents, the magnetization is switching antiparallel to the bias field after a certain time and the magnon spectrum is changing. By comparing with analytical theory and micromagnetic modelling, I will discuss the challenges to experimentally identify “antimagnons” in the spectra and to distinguish them from nonlinear or heating effects.

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"Disorder-Driven Effects in Orbital Transport: From Bulk OHE to Mesoscopic Devices"

Tatiana G. Rappoport

Physics Center of Minho and Porto Universities (CF-UM-UP),Campus of Gualtar, 4710-057, Braga, Portugal

I will present recent insights into the impact of disorder on orbital transport phenomena, with a focus on the orbital Hall effect (OHE) and orbital relaxation mechanisms in two-dimensional (2D) materials. First I will provide an overview of extrinsic effects in the spin Hall effect (SHE), including skew scattering and side-jump mechanisms, to draw a parallel with the disorder-driven mechanisms influencing the OHE. This comparison offers a foundation for understanding how impurities and short-range defects can create or enhance transverse currents of orbital angular momentum through similar extrinsic processes in the OHE. The core of the presentation will discuss recent theoretical work on disorder-enhanced OHE, detailing how extrinsic contributions such as skew scattering and side-jump effects influence orbital transport in 2D systems, and how these effects can even dominate over intrinsic contributions in certain regimes [1]. In parallel, I will present ongoing numerical work with mesoscopic devices, where disorder plays a crucial role in both enhancing the OHE and providing direct insights into orbital relaxation processes.

[1] "Extrinsic Orbital Hall Effect: Interplay Between Diffusive and Intrinsic Transport"

Authors: Alessandro Veneri, Tatiana G. Rappoport, Aires Ferreira,
arXiv:2408.04492

Driving and probing terahertz spin and orbital currents

Tom S. Seifert

Freie Universität Berlin, Berlin, Germany

The field of spinorbitronics exploits the electron orbital momentum L and its spin S for future data-processing applications [1]. Terahertz (THz) time-domain spectroscopy is a powerful tool to reveal spinorbitronic phenomena with femtosecond time resolution [2]. Here, I will present two complimentary approaches: Studying spinorbitronic dynamics using THz emission spectroscopy (TES) as well as by driving with strong THz pulses.

In TES, we optically trigger ultrafast angular-momentum transport in thin-film stacks [3,4]. Varying the thin-film materials allows us to focus on either S or L-dominated ultrafast transport and distinguish different S/L-to-charge-current conversion mechanisms.

In a second approach, we use these strong THz driving fields to establish spinorbitronic THz detectors by sensing the THz-induced spin accumulation in a bilayer sample. Eventually, I will show how we initiate nonlinear THz magnetization dynamics in the antiferromagnet Mn_2Au by driving Néel spin-orbit torques through the strong THz electric fields [6].

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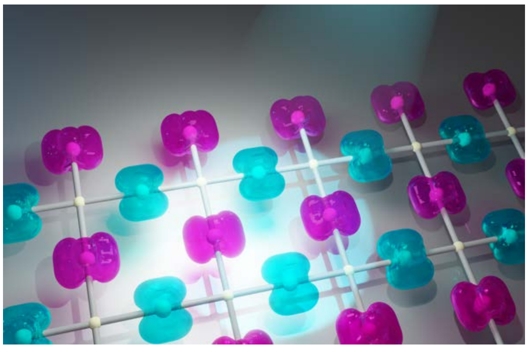
Altermagnetism and spin group theory

Libor Šmejkal[1,2,3]
[1]Max Planck Institute for the Physics of Complex Systems, Nöthinzer Str.38, 01187 Dresden, Germany
[2]Max Planck Institute for Chemical Physics of Solids, Nöthnitzer Str. 40, 01187 Dresden, German
[3]Institute of Physics, Czech Academy of Sciences, Cukrovarnická 10, 162 00, Praha 6, Czech Republic

lsmejkal@pks.mpg.de | https://www.pks.mpg.de/de/fqm | https://www.linkedin.com/in/libor-smejkal/ | https://x.com/LiborPhysics

Symmetry classification is systematically studied using group theory across various areas of physics, such as high-energy physics, superfluidity, and superconductivity. In this talk, we will demonstrate that spin groups enable the analogous systematic exploration of spontaneous exchange symmetry breaking in magnetic crystals [1]. This approach has recently led to the discovery of collinear altermagnets (see an example of d-wave altermagnetic spin density in the inset Figure) [1] and noncollinear p-wave magnets featuring compensated even and odd-partial-wave spin orders, respectively [2]. These unconventional magnetic phases are new additions to a magnetic family tree that was since the 1930s divided into two main branches – ferromagnets and antiferromagnets[3,4].



In the first part of the talk, we will recall our prediction of unconventional time-reversal symmetry-breaking electronic structures similar to ferromagnets in a class of compensated collinear magnets similar to antiferromagnets[5]. We will then show how the ferromagnetic-antiferromagnetic dichotomy[3-7] of these unconventional systems led to the prediction of altermagnetism. Altermagnetism was delimited as a symmetry class genuinely distinct from antiferromagnets and ferromagnets by our systematic spin group theory classification[1]. We will also present our recent identification of unconventional odd-parity p- and f-wave magnets and discuss analogies and differences with classifying superfluids and superconductors[1,2].

In the second part of the talk, we will summarize experimental confirmations of altermagnetic symmetries and effects[8-10]. We will highlight photoemission spectroscopy observation of altermagnetic spin splitting[9] and nanoscale mapping of altermagnetic time-reversal symmetry breaking via x-ray magnetic circular and linear dichroism [10].

Finally, we will overview the more than 300 proposed material candidates and the active and newly emerging research directions in spin symmetries and altermagnetism. Beyond dissipationless Hall currents attractive for nanoelectronics [5,8], we will discuss giant and tunneling magnetoresistance enabling ultrafast and energy-efficient spintronics[7], altermagnetic multiferroics[11], and two-dimensional topological altermagnets [12].

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Topological dipoles of quantum skyrmions

Sopheak Sorn[1] and Jörg Schmalian[1,2] and Markus Garst[1,3]

[1]Institute of Quantum Materials and Technology, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

[2]Institute of Theoretical Condensed Matter Physics, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

[3]Institute of Theoretical Solid State Physics, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

We demonstrate that the quantum dynamics of magnetic skyrmions is governed by a dipole conservation law, akin to that in fracton theories of excitations with constrained mobility. The associated dipole moment enables the definition of a natural collective coordinate that specifies the skyrmion's position. Using this coordinate, we find that the often-debated skyrmion mass actually vanishes. The quasi-classical spin configuration's motion is precisely counterbalanced by a cloud of quantum fluctuations in the form of spin waves. Given this quenched kinetic energy of quantum skyrmions, excitations of the system are shown to be governed by the Girvin-MacDonald-Platzman algebra that was introduced to describe neutral modes of the lowest Landau level in the fractional quantum Hall problem. Consequently, the conservation of the topological dipole suggests that magnetic skyrmion materials offer a promising platform for exploring fractonic phenomena with close analogies to fractional quantum Hall states.

Coupling ferromagnetic and antiferromagnetic spin dynamics in hybrid bilayer systems

Mathias Weiler

Fachbereich Physik and Landesforschungszentrum OPTIMAS, Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau, 67663 Kaiserslautern, Germany

Ferromagnetic and antiferromagnet spin dynamics exhibit qualitatively different properties. While ferromagnets typically support GHz spin dynamics, antiferromagnetic spin dynamics can reach the THz regime. Despite having vastly different resonance frequencies, antiferromagnetic and ferromagnetic spin dynamics can become coupled in ferromagnetic/antiferromagnetic heterostructures with interfacial exchange coupling.
We experimentally and theoretically studied the ferromagnetic – antiferromagnetic spin dynamics coupling in two different hybrid bilayer systems.

First, I will demonstrate that the ferromagnetic magnons in Mn_2Au/NiFe bilayers can couple to their antiferromagnetic counterparts in an evanescent manner, resulting in additional magnon modes and elevated ferromagnetic resonance frequencies [1].

Second, I will demonstrate that similar ferromagnetic-antiferromagnetic spin-dynamics can be controlled in-situ in α-Fe_2O_3 / NiFe bilayers. To this end, we change the system temperature across the α-Fe_2O_3 Morin transition temperature $T_M \approx 260$ K. The interfacial exchange coupling between α-Fe_2O_3 and NiFe is found to be highly sensitive to both temperature and the crystal orientation of α-Fe_2O_3. Specifically, near T_M, the coupling strength varies considerably depending on the α-Fe_2O_3 crystal orientation, either increasing or decreasing sharply. Our theoretical model suggests that the presence of interfacial exchange coupling is influenced by the relative alignment of the Néel vector in α-Fe_2O_3 and the magnetization vector of NiFe.

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Chiral-induced unidirectional spin-to-charge conversion

A. Wittmann

Johannes Gutenberg University Mainz, Germany

The observation of spin-dependent transmission of electrons through chiral molecules has led to the discovery of chiral-induced spin selectivity (CISS). The remarkably high efficiency of the spin polarizing effect has recently gained substantial interest due to the high potential for future sustainable hybrid chiral molecule magnetic applications. However, the fundamental mechanisms underlying the chiral-induced phenomena remain to be understood fully. In our recent work, we explore the impact of chirality on spin angular momentum in hybrid metal/ chiral molecule thin film heterostructures [1]. For this, we inject a pure spin current via spin pumping and investigate the spin-to-charge conversion at the hybrid chiral interface. Notably, we observe a chiral-induced unidirectionality in the conversion. Furthermore, angle-dependent measurements reveal that the spin selectivity is maximum when the spin angular momentum is aligned with the molecular chiral axis. Our findings validate the central role of spin angular momentum for the CISS effect, paving the path toward three-dimensional functionalization of hybrid molecule-metal devices via chirality.

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Ultrafast magnetization enhancement via the dynamic spin-filter effect of type-II Weyl nodes in Co3Sn2S2

Xianyang Lu [1,2,3], Zhiyong Lin [4,5], Hanqi Pi [6,7,8], Tan Zhang [9], Guanqi Li [10], Yuting Gong [2,3], Yu Yan [2,3], Xuezhong Ruan [2,3], Yao Li [2,3], Hui Zhang [4,5], Lin Li [4,5], Liang He [2,3], Jing Wu [10,11] , Rong Zhang [3], Hongming Weng [6,7,8] , Changgan Zeng [4,5] & Yongbing Xu [1,2,3,11]

1. School of Integrated Circuits, Nanjing University, Suzhou 215163, China. 2. State Key Laboratory of Spintronics Devices and Technologies, Nanjing University, Suzhou 215163, China. 3. Jiangsu Provincial Key Laboratory of Advanced Photonic and Electronic Materials, School of Electronic Science and Engineering, Nanjing University, Nanjing 210093, China. 4. International Centre for Quantum Design of Functional Materials (ICQD), Hefei National Laboratory for Physical Sciences at the Microscale, and Synergetic Innovation Centre of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China. 5. CAS Key Laboratory of Strongly-Coupled Quantum Matter Physics, and Department of Physics, University of Science and Technology of China, Hefei, Anhui 230026, China. 6. Beijing National Research Centre for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China. 7. School of Physical Science, University of Chinese Academy of Sciences, Beijing 100049, China. 8. Songshan Lake Materials Laboratory, Dongguan, Guangdong 523808, China. 9. Department of Chemistry, University of Pennsylvania, Philadelphia, PA 19104-6323, USA. 10. School of Integrated Circuits, Guangdong University of Technology, Guangzhou 510006, China. 11. York-Nanjing International Joint Centre in Spintronics, School of Physics, Engineering and Technology, University of York, York YO10 5DD, UK.

The magnetic type-II Weyl semimetal (MWSM) Co3Sn2S2 has recently been found to host a variety of remarkable phenomena including surface Fermi- arcs, giant anomalous Hall effect, and negative flat band magnetism. However, the dynamic magnetic properties remain relatively unexplored. Here, we investigate the ultrafast spin dynamics of Co3Sn2S2 crystal using time-resolved magneto-optical Kerr effect and reflectivity spectroscopies. We observe a transient magnetization behavior, consisting of spin-flipping dominated fast demagnetization, slow demagnetization due to overall half-metallic electronic structures, and an unexpected ultrafast magnetization enhancement lasting hundreds of picoseconds upon femtosecond laser excitation. By combining temperature-, pump fluence-, and pump polarization-dependent measure- ments, we unambiguously demonstrate the correlation between the ultrafast magnetization enhancement and the Weyl nodes. Our theoretical modelling suggests that the excited electrons are spin-polarized when relaxing, leading to the enhanced spin-up density of states near the Fermi level and the con- sequently unusual magnetization enhancement. Our results reveal the unique role of the Weyl properties of Co3Sn2S2 in femtosecond laser-induced spin dynamics.

Reference: Nat Commun 15, 2410 (2024). https://doi.org/10.1038/s41467-024-46604-1

Abstracts of Posters

(in alphabetical order)

Continuous topological transitions — Hopfion slider

Maria Azhar, Sandra C. Shaju, Ross Knapman, Alessandro Pignedoli, and Karin Everschor-Sitte
Faculty of Physics and Center for Nanointegration Duisburg-Essen (CENIDE), University of Duisburg-Essen, 47057 Duisburg, Germany

For three-dimensional spin textures, the Hopf index H provides a quantitative measure of the topological nature of the system. Other quantities relevant for topological characterisation include the Skyrmion charge N_{sk}, the Burgers vector, and linking numbers. Both N_{sk} and H are calculated from the emergent magnetic field $\boldsymbol{F}$ of the texture. We introduce and apply a new formula for H [1] based on the flux-weighted average of the linking numbers of the field lines of $\boldsymbol{F}$:

$$H = \sum_i L_{ii}\Phi_i^2 + 2\sum_{i\neq j} L_{ij}\Phi_i\Phi_j \qquad \text{where} \quad L_{ij} = -\frac{1}{4\pi}\oint_{C_i}\oint_{C_j}\frac{\boldsymbol{r}_i-\boldsymbol{r}_j}{|\boldsymbol{r}_i-\boldsymbol{r}_j|^3}\cdot\left(d\boldsymbol{r}_i\times d\boldsymbol{r}_j\right).$$

Here Φ_i is the (positive definite) flux of $\boldsymbol{F}$ through the flux tube labelled by the index i, and L_{ii} and L_{ij} are respectively the self-linking of flux tube i, and inter-linking between flux tubes i and j. This formalism allows analytical calculation of H and offers insight into the interpretation of H as a measure of the linkage and topology of the system, while surpassing the pitfalls and limitations associated with applying the conventional Whitehead integral formula in finite volumes [2].

We calculate H for many examples of magnetic textures in ferromagnetic, spiral, or screw dislocation backgrounds [3], such as self-linked and inter-linked Skyrmions, meron tubes and Hopfions. We show that magnetic textures with different topological indices can be smoothly transformed into each other and intermediate states along these pathways possess "mixed topology", representing local energy minima. This framework naturally explains the occurrence of textures with non-integer Hopf index values or fractional Hopfions.

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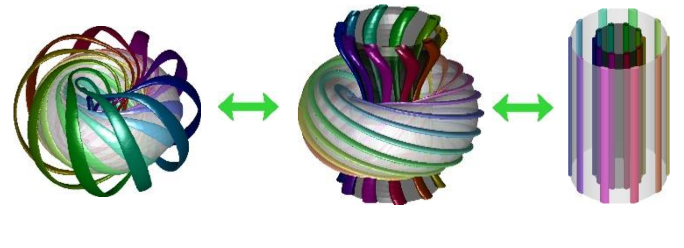
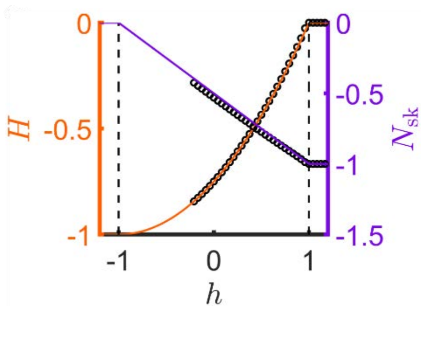


$(H, N_{\mathrm{sk}}) = (-1,0)$ Hopfion — $(-3/4, -1/2)$ Twiston — $(0,-1)$ Skyrmion



Dynamic imaging of Spin-orbit-torque driven nanosecond dynamics of antiferromagnetic skyrmions and skyrmion lattices

Mona Bhukta[1], Takaaki Dohi[1,2], Maria-Andromachi Syskaki[1], Duc Minh Tran [1], Markus Weigand[3], Sebastian Wintz[3], Robert Frömter[1], and Mathias Kläui[1]

[1]Institute of Physics, Johannes Gutenberg-University Mainz, 55099 Mainz, Germany
[2]Laboratory for Nanoelectronics and Spintronics, Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aoba, Sendai 980-8577, Japan
[3]Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, 14109 Berlin, Germany

Topological spin textures, such as skyrmions and merons, are garnering significant interest in antiferromagnets (AFM) as potential platforms for unconventional memory and computing technologies, primarily due to their intrinsic ultrafast dynamics [1,2]. Here, we investigate the dynamics of isolated AFM skyrmion tubes and AFM skyrmion lattices in synthetic antiferromagnetic (SyAFM) multilayers composed of 30–50 ferromagnetic (FM) layers, antiferromagnetically coupled via the interlayer exchange interaction. Using element-specific time-resolved scanning transmission X-ray microscopy (STXM), we demonstrate the current-induced dynamics of the resulting AFM skyrmions. In uncompensated SyAFM, we observe a current-polarity-dependent, non-reciprocal skyrmion Hall effect of individual AFM skyrmions, arising from the unique intrinsic properties of the hybrid chiral skyrmion tubes in the flow regime. This nonreciprocity can be tuned by the degree of magnetic compensation and vanishes in highly compensated SyAFM [3]. In fully compensated SyAFM systems, we employ nanoscale pump–probe imaging to resolve the nanosecond, layer-resolved dynamics of a SyAFM skyrmion lattice in both the depinning and flow regimes, while imaging both ferromagnetic (FM) layers. Our time-resolved dynamics measurements shows that the AFM skyrmion lattice moves directly along the applied current, indicating the absence of the skyrmion Hall effect due to the cancellation of gyrotropic forces [4]. Additionally, we observe a significant deformation of the skyrmion lattice in the depinning/creep regime while in the flow regime a purely homogeneous translation of the SyAFM skyrmion lattice occurs [4].

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Material study for orbital-to-spin conversion for SOT-MTJ

M.Biagi[1], C.C.M.Capriata[1], R.Sousa[1], K.Garello[1]

marco.biagi@cea.fr, corrado-carlomaria.capriata@cea.fr

[1] Université Grenoble Alpes, CEA, SPINTEC, Grenoble, France

Spin-orbit torques (SOT) have emerged as a credible next-generation mechanism for MRAM technology that allows for faster and more efficient magnetisation writing [1]. However, important technology requirements that must be met are poorly addressed so far: the device manufacturing yield must be close to 100%, and the write error rate has to be less than 1x10^{6}. Yield is challenging to achieve due to "top-pinned" MTJ configuration where the etching of the MTJ pillar must precisely stop on the SOT metal, resulting in nano-shorts due to metal re-deposition on the tunnel barrier sidewalls, limiting also the density [1]. On the other hand, write error rate (WER) is poorly reported, but shown to be impacted by SOT field like term [2]. SOT are generated in heavy metal non-magnetic materials with strong spin-orbit coupling such as W, Pt or Ta. It relies on spin-orbit coupling (SOC) effects, spin Hall effect (SHE) and Rashba-Edelstein effect (REE), for converting charge currents into spin currents which is then transferred to an adjacent ferromagnetic layer, e.g. the free layer (FL) of an MTJ. Recently, it has been predicted that SHE and REE arise from more fundamental effects [3], namely Orbital Hall effect (OHE) and Orbital Rashba-Edelstein Effect (OREE), featuring a larger diffusion length and magnitude with respect to the spin counterpart. These orbital currents do not interact directly with the magnetic moment but must be converted into spin current via SOC [4]. To address these issues, we engineer the SOT/FL interface with the insertion of a spacer layer between the FL and the SOT track that can provide several benefits: widening the etching error margin in the fabrication process, enabling precise control of the Γ_{FL}/Γ_{AD} torque ratio lowering writing errors, and exploiting orbital currents to increase the SOT efficiency. In this poster, we explore systems based on OHE source material (Ru), and a HM spacer layer (Pt, Ta, W) for orbital-to-spin current conversion, and identify their contribution and possible limitations for 3-terminal device implementation. We quantify the SOT efficiency components (damping-, and field-like) in Hall bars, via harmonic Hall voltage method, as a function of the thickness of the different layers, and compare the results with reference stacks without the orbital material.

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Dynamical renormalization of the magnon spectrum via nonlinear coherent spin dynamics

C. Schönfeld,[1] L. Feuerer[1], J. Bär[1], L. Dörfelt[1], M. Kerstingskötter[1], T. Danneger[1], D. Wuhrer[1], W.Belzig[1], U. Nowak[1], A. Leitenstorfer[1], D. Juraschek[2] and D. Bossini[1]

[1]University of Konstanz, Konstanz, Germany
[2] School of Physics and Astronomy, Tel Aviv, Israel

A major research trend of modern condensed matter physics aims at optically manipulating magnetic materials at fundamental timescale, i.e. the inherent timescales of the eigenfrequencies and lifetimes of collective vibrational, electronic and magnetic excitations in solids. The full dynamical response of a magnetic solid, at all possible time- and length-scales, is encoded in the dispersion relation of magnons. The optical activation of coherent magnons, which enables to imprint a well-defined phase on a macroscopic ensemble without requiring any laser-induced heating, has been widely reported. Coherent collective excitations have been driven into nonlinear regimes, displaying coupling among different modes and between light and collective modes not allowed in a linear dynamical regime. Despite the massive volume of research in this direction, an arbitrary optical control of the spectrum (frequency, amplitude and lifetime) of the eigenmodes appearing in the dispersion relation of magnets is lacking. In my contribution, I will discuss an approach to this open problem, based on a resonant drive of high-energy magnons, with wavevectors near the edges of the Brillouin zone. The transient spin dynamics reveals the activation and a surprising amplification of coherent low-energy zone-centre magnons, which are not directly driven. Strikingly, the spectrum of these low-energy magnons differs from the one observed in thermal equilibrium. The light-spin interaction thus results in a room-temperature renormalisation of the magnon spectra, as five-fold and three-fold increases of the amplitudes and 4% frequency shifts of their ground-state values were measured. We rationalise the observation in terms of a novel resonant scattering mechanism, in which zone-edge magnons couple nonlinearly to the zone-centre modes. A quantum mechanical model and numerical simulations (atomistic spin dynamics) reveal that the observed corrections to the spectrum are due to both the photoinduced magnon population and the subsequently triggered channels of magnon-magnon scattering channels. Our results present a milestone on the path towards an arbitrary tuning of the quasiparticles eigenfrequencies.

Nonlinear spin dynamics across Néel phase transition in F/AF multilayers

Oksana Busel, Dmytro M. Polishchuk, Milton Persson, Stefen Petersen, Mykola M. Kulyk, Anatolii Kravets, and Vladislav Korenivski

Nanostructure Physics, Royal Institute of Technology, 10691 Stockholm, Sweden

We demonstrate two types of ferromagnetic resonance (FMR) modes in F/AF multilayers of [Py(6)/FeMn(6)]$_{(N-1)}$/Py(6)/Al(5) with a variable number of F layers in the range N_F = 2, 4, …, 8, with each AF layer, sandwiched between two F layers (layer thicknesses in parentheses are in nm). We specifically chose the thicknesses of the layers to avoid suppressing the AF order by the ferromagnetic proximity-induced exchange while simultaneously mediating coupling between the ferromagnetic layers via the AF spacers [1-3]. The first two modes are assigned to the main uniform FMR when each F layer resonates individually. The second mode exhibits enhanced FMR frequencies and is attributed to higher-order FMR excitations akin to standing SW in uniform F films [4]. Our micromagnetic simulations using Mumax3 for the model F/AF system recreate the observed uniform and SW modes and the variation of their intensity throughout the multilayer, thus supporting the experimental findings. We further find that the F-F coupling via the AF spacers is strongly temperature-dependent. Well above Néel temperature, the F layers become decoupled as the AF layers become paramagnetic; as a result, we observe only the main uniform FMR mode from nominally identical, individual F layers. At low temperatures, the interlayer coupling does not propagate through the AF spacers because of their strong AF ordering, and the higher-order SW modes vanish, like in the high-temperature limit. Thus, the SW modes in F/AF multilayers are observed only in a narrow temperature range of just about Néel temperature of AF, where F-F magnon exchange via thermally softened AF spacer can occur. Their intensity can be thermally gated, showcasing a giant nonlinearity higher than 90 percent with a tendency to further growth—potentially useful for novel thermos-magnetic devices.

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Ultra-low current spin Hall nano-oscillators and their mutual synchronization in large networks

Nilamani Behera[1,*], Avinash Kumar Chaurasiya[1,*], Akash Kumar[1,2,*], Roman Khymyn[1], Artem Litvinenko[1], Lakhan Bainsla[1], Ahmad A. Awad[1,2], Johan Åkerman[1,2]

[1] *Department of Physics, University of Gothenburg, Gothenburg 412 96, Sweden.*
[2] *Research Institute of Electrical Communication (RIEC), Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan.*
**Authors with equal contribution*

Recently, spin Hall nano-oscillators (SHNOs) have emerged as a new versatile class of spintronic devices for generating propagating spin waves over long distances [1] which could be potential for Ising machines, spectrum analysis, unconvetional computing [2]. Thanks to their easy fabrication [3], direct control using voltage gating [4], and tendency towards mutual synchronization in one [5] and two [6] dimensions. Power consumption during auto-oscillation is primarily governed by the threshold current, is an important figure of merit that needs to be minimized. While the first SHNOs required several mA of current [3], with optimizing the high SOT efficiency, inclusion of perpendicular magnetic anisotropy, reduction of lateral dimensions and inserting better electrical insulation with good thermal conductivity substrate/seed layers, i.e. HiR-Si/Al_2O_3(3 nm)/$W_{88}Ta_{12}$(5 nm)/CoFeB(1.4 nm)/MgO(2 nm) material stack, the threshold current is dramatically reduced by a factor of 15 (400 μA to 28 μA) of ultra-low 10 nm SHNO device [7] as compared to previous work.

Further, mutual synchronizations have been studied by fabricating in large network of SHNO arrays. The measurement of electrical microwave power spectral density, and scanning micro Brillouin light scattering experiment confirm the robust mutual synchronization with single frequency, positive non linearity, follow the theoretical prediction of linewidth and microwave output power with number of SHNOs [8]. Our results represent a significant step towards viable SHNO network applications in wireless communication and unconventional computing.

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Thermal Hall Effect of Magnons from Many-Body Skew Scattering

Dimos Chatzichrysafis and **Alexander Mook**

Johannes Gutenberg-Universität, Mainz, Germany

The thermal Hall effect is an important probe of insulating quantum matter, providing a window into the charge-neutral emergent excitations such as magnons. Existing theories relate the thermal Hall conductivity, as measured e.g. in van der Waals magnets, to the magnonic Berry curvature, which can only exist in non-Bravais lattices. Here, we develop a theory for a magnon Hall effect driven by many-body skew scattering. To exclude intrinsic effects, we consider a chiral ferromagnet with a single magnon band. The Dzyaloshinskii–Moriya interaction gives rise to many-body interactions that break time-reversal symmetry. Within the framework of the semi-classical Boltzmann equation, we show that a transverse magnon current arises from the skew scattering caused by the interference of three-magnon and four-magnon scattering channels. This novel contribution to the thermal Hall effect is neither intrinsic (Berry curvature induced) nor extrinsic (defect induced), which makes it an independent source of transverse currents. Thus, we believe that our work will help better explain related experimental results.

Magnetic Tunneling Junctions from First Principles

Lukas Cvitkovich[1] and Jaroslav Fabian[1]

[1] Institute for Theoretical Physics, University of Regensburg, 93040 Regensburg, Germany

Spin-dependent tunneling (SDT) in magnetic tunnel junctions (MTJs) represents a key mechanism underpinning the functionality of spintronic devices, such as magnetic random-access memory (MRAM) and magnetic sensors. This work investigates the SDT phenomenon by calculating the tunneling density of states (TDOS) from first-principles, providing a fundamental understanding of the spin-resolved electronic states that contribute to tunneling across diverse materials. We use density functional theory (DFT) to obtain accurate electronic structures and interface properties, essential for characterizing the TDOS. By examining a range of ferromagnetic and insulating materials in MTJs, we assess the influence of material composition, interface quality, and layer thickness on the spin polarization of the tunneling current. Our results reveal distinct trends in TDOS contributions and spin polarization, demonstrating that optimal selection of magnetic and insulating layers can enhance SDT and lead to improved tunneling magnetoresistance (TMR) ratios. This work offers critical insights into material design for next-generation spintronic devices and supports the ongoing development of high-performance MTJs through tailored material selection and interface engineering.

Current driven magnetization reversal in CoFeTaB/Pt probed by X-ray magnetic reflectivity

Kiranjot,[1] Raymond Fan,[1] David M. Burn,[1] Kalel Alsaeed,[2] Oto-obong Inyang,[2] Laurence Bouchenoire,[3,4] Aidan T. Hindmarch,[2] Paul Steadman[1]

[1]Diamond Light Source, Harwell Science and Innovation Campus, Didcot OX11 0DE, United Kingdom [2]Department of Physics, Durham University, South Road, Durham DH1 3LE, United Kingdom [3]XMaS, The UK-CRG Beamline, ESRF, 71 Avenue des Martyrs, CS 40220, F-38043 Grenoble, France [4]Department of Physics, University of Liverpool, Liverpool L69 7ZE, United Kingdom

The increasing demand for energy-efficient data storage has resulted in the quest for alternative magnetization manipulation methods beyond conventional external magnetic fields. Electrical magnetization control has emerged as a promising avenue. In this work, the current driven magnetization reversal in CoFeTaB/Pt is investigated taking advantage of the magnetisation direction and the polarisation dependence of the X-ray scattering cross-section [1]. The magnetic fields and current are applied orthogonal to each other to a CoFeTaB/Pt heterostructure to induce magnetization reorientation in the scattering plane (formed by incoming and outgoing X-rays) [2]. The circularly polarized X-ray magnetic reflectivity (XRMR) is the most sensitive to the magnetization direction in this case. Measurements during field- and current-driven hysteresis cycles reveal transitions between two magnetic states. XRMR asymmetries, measured at Fe-L_3 resonance with both helicities, vary slightly between saturation states and differ between current and field-driven cases, despite the same intended magnetization reorientation direction. Since the linearly polarized XRMR is more sensitive to the out-of-scattering plane magnetization components, XRMR measurements were performed with linear polarization. The measurements in this case show significant asymmetries, suggesting a substantial perpendicular magnetization component in the current-driven states and hence, incomplete magnetization switching with applied current. To probe the interfacial magnetism, proximity-induced magnetism in the Pt layer is measured by tuning the incident energy to Pt-L_3 resonance and perform XRMR measurements with circular polarization. The measurements confirm that the Pt magnetic moments follow the CoFeTaB magnetization. Temperature-dependent studies (100-290K) reveal a decrease in the current-driven coercivity of CoFeTaB with increasing temperature, which follows the same trend as the magnetic field driven coercivity (probed using vibrating sample magnetometry). The critical reversal current is found to be relatively insensitive to the change in temperature.

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Advances in X-ray Imaging of magnetic vector and orientation fields

Jeffrey Neethirajan, Andreas Apseros, Valerio Scagnoli, Benedikt J. Daurer, Marisel Di Pietro Martínez, Aleš Hrabec, Luke Turnbull, Rikako Yamamoto, Marina Raboni Ferreira, Aleš Štefančič, Daniel Alexander Mayoh, Geetha Balakrishnan, Zhaowen Pei, Pengfei Xue, Liao Chang, Emilie Ringe, Richard Harrison, Sergio Valencia, Majid Kazemian, Burkhard Kaulich, Johannes Ihli and Claire Donnelly

Nanoscale mapping of a magnetic configuration is key to understanding - and ultimately controlling - emergent textures in the magnetisation. In recent years, we have developed X-ray magnetic tomography, that allows to map 3D magnetic configurations, and their GHz dynamics. With 3D imaging capabilities well established for ferromagnets, we have now been developing new imaging capabilities for a wider range of materials. First, by harnessing coherent X-rays, we exploit phase dichroism to open up the study of previously inaccessible ferromagnetic systems [1]. Second, we have gone beyond ferromagnets by establishing linear dichroic tomography, gaining access to 3D orientation fields: from crystallographic defects in catalysts [2], to 3D antiferromagnets.

These advances in imaging capabilities pave the way to map complex configurations in a wide variety of materials, ultimately allowing us to understand - and, in the future, control - them.

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Orbital Angular Momentum Polarization Effects in Centrosymmetric Systems

Luciano Jacopo D'Onofrio[1], Maria Teresa Mercaldo[2], Federico Mazzola[3], Wojciech Brzezicki[4,5], Adam Kłosiński[6], Carmine Ortix[2], and Mario Cuoco[1]

[1]CNR-SPIN, c/o Università di Salerno, IT-84084 Fisciano (SA), Italy

[2]Dipartimento di Fisica "E. R. Caianiello", Università di Salerno, IT-84084 Fisciano (SA), Italy

[3]CNR-SPIN, c/o Complesso di Monte S. Angelo, IT-80126 Napoli, Italy

[4]Institute of Theoretical Physics, Jagiellonian University, ulic, S. Łojasiewicza 11, PL-30348 Kraków, Poland

[5]International Research Centre MagTop, Institute of Physics, Polish Academy of Sciences, Aleja Lotników 32/46, PL-02668 Warsaw, Poland

[6]Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, Pasteura 5, PL-02093 Warsaw, Poland

Spintronics and orbitronics are cutting-edge fields focused on the control and manipulation of both the spin and orbital angular momentum (OAM) of electrons across various materials. OAM is a key attribute of electrons in solids and plays a substantial role within orbitronics. Traditionally, it has been thought that the crystalline field potential reduces OAM, leading to its limited presence primarily through spin-orbit coupling (SOC) or in materials without inversion symmetry. Furthermore, spin selectivity is expected to be obtained through electron transfer processes in chiral media. In this study, we explore the mechanisms of electron transfer and the symmetry conditions required for effective OAM filtering. Here, we demonstrate that in electronic systems exhibiting both time-reversal and inversion symmetry, orbital moment polarization filtering effects can be obtained. Additionally, we outline the key symmetry conditions necessary for achieving OAM filtering in the presence of spin-orbit coupling and how it can lead to spin filtering with high efficiency.

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Optically induced magnons from a metallic nanodisk

Anna Duvakina[1], Mingran Xu[1], Vage Karakhanyan[2], Miguel Suarez[2], Axel J. M. Deenen[1], Andrea Mucchietto[1], Thierry Grosjean[2] and Dirk Grundler[1],[3]

[1] Institute of Materials, Laboratory of Nanoscale Magnetic Materials and Magnonics (LMGN),
École Polytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland
[2] Optique department, Nano-Optique team, Centre national de la recherche scientifique (CNRS), 25030 Besançon, France
[3] Institute of Electrical and Micro Engineering, EPFL, 1015 Lausanne

Recent interest in spin waves (magnons) for information transmission and computation shows their potential to complement CMOS technology in energy efficiency and to support new architectures like logic-in-memory. However, the tunable excitation of spin waves with a nanometer scale source remains a significant challenge. Here, we present tunable nanoscale emission of spin waves by coupling microwave-modulated laser light to an individual plasmonic nanoantenna. A modulated circularly polarized light is focused onto a gold nanodisk. We detect the excitation of short-wavelength spin waves at a frequency matching the modulation frequency of the incident laser light. The frequency of these optically induced spin waves is controlled by tuning the modulation frequency of the light over a wide spectral range. We discuss the excitation process in terms of a confined, modulated magnetic field. Our results show the potential of plasmonic nanoantennas as a nanoscale magnon emitter capable of tunably transduce a microwave signal carried by laser light into short-wavelength spin waves. This work was supported by SNSF via project 197360.

Orbital Magnetic Moments in the Kagome Metal CsV_3Sb_5

H.J. Elmers[1], O. Tkach[1, 2], Y. Lytvynenko[1,3], P. Yogi[1], M. Schmitt[4,5], D. Biswas[4], J. Liu[4], S.V. Chernov[6], Q. Nguyen[7], M. Hoesch[6], D. Kutnyakhov[6], N. Wind[6,8], L. Wenthaus[6], M. Scholz[6], K. Rossnagel[8,9], A. Gloskovskii[6], C. Schlueter[6], A. Winkelmann[10], A.-A. Haghighirad[11], T.-L. Lee[4], M. Sing[5], R. Claessen[5], M. Le Tacon[11], J. Demsar[1], G. Schönhense[1] and O. Fedchenko[1]

[1]Institut für Physik, Johannes Gutenberg-Universität, Mainz, Germany, [2]Sumy State University, Kharkivska 116, 40007 Sumy, Ukraine, [3]Institute of Magnetism of the NAS and MES of Ukraine, 03142 Kyiv, Ukraine, [4]Diamond Light Source Ltd., Didcot OX11 0DE, United Kingdom, [5]Physikalisches Institut, Julius-Maximilians-Universität, Würzburg, Germany, [6]Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany, [7]Linac Coherent Light Source, Menlo Park, CA 94025, USA, [8]Institut für Experimentelle und Angewandte Physik, CAU Kiel, Germany, [9]Ruprecht Haensel Laboratory, Hamburg, Germany, [10]Academic Centre for Materials and Nanotechnology, Krakow, Poland, [11]Institute for Quantum Materials and Technologies, KIT Karlsruhe, Germany

Using x-ray photoelectron diffraction (XPD) and angle-resolved photoemission spectroscopy, we study photoemission intensity changes related to changes in the geometric and electronic structure in the kagome metal CsV_3Sb_5 upon transition to an unconventional charge density wave (CDW) state. The XPD patterns reveal the presence of a chiral atomic structure in the CDW phase. Furthermore, using circularly polarized x-rays, we have found a pronounced non-trivial circular dichroism in the angular distribution of the valence band photoemission in the CDW phase, indicating a chirality of the electronic structure. This observation is consistent with the proposed orbital loop current order. In view of a negligible spontaneous Kerr signal in recent magneto-optical studies, the results suggest an antiferromagnetic coupling of the orbital magnetic moments along the c-axis. While the inherent structural chirality may also induce circular dichroism, the observed asymmetry values seem to be too large in the case of the weak structural distortions caused by the CDW.

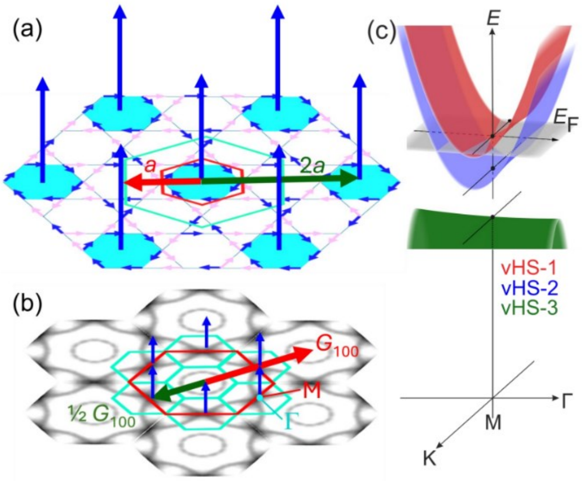

Figure 1 (a) V-Sb plane constituting the kagome lattice. Small arrows indicate the loop current order forming a 2×2 superstructure of orbital moments. (b) Fermi surface in reciprocal space. Hexagons indicate the Brillouin zones. The blue arrows indicate the expected orbital moments near the M-points where the Fermi wave vector and the Γ points of the 2×2 superstructure coincide. (c) Sketch of the first three vHSs near E_F.

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Large Spin-Orbit Torques in the Sb_2Te_3/Au/Co Topological heterostructures

Matteo Fettizio[1], Can Onur Avci[1], Roberto Mantovan [2],Emanuele Longo[1]**

[1]**Institut de Ciència de Materials de Barcelona (ICMAB-CSIC), 08193 Bellaterra, Spain*
[2]*Institute of Microelectronics and Microsystems (CNR-IMM), 20864 Agrate Brianza, Italy*
*mfettizio@icmab.es *elongo@icmab.es

Topological insulators (TIs) exhibit a unique electronic structure characterized by insulating bulk and conductive surface states with spin-momentum locking, enabling efficient spin-charge conversion (SCC) [1]. In this context, chalcogenide-based TIs (i.e. Bi_2Te_3, Bi_2Se_3, Sb_2Te_3) are gaining remarkable attention owing to their compatibility with wafer-scale growth technique. [2] Recently, high-quality 30 nm-thick Sb_2Te_3 films grown by metal-organic chemical vapor deposition are demonstrated to be TIs, evidenced by angle resolved photoemission spectroscopy and magnetotransport measurements [9,12]. Accordingly, high SCC efficiency is shown in Sb_2Te_3/Au/Co heterostructures by spin-pumping ferromagnetic resonance spectroscopy [3,4]. Nevertheless, to fully assess the potential of Sb_2Te_3 for devices applications, SCC efficiency needs to be evaluated also under charge current injection in the TI layer and quantifying the resulting spin currents. [10]

In this study, we investigate SCC in Sb_2Te_3(30)/Au(5)/Co(5)/Au(5) heterostructures by measuring spin-orbit torques (SOT) [5] induced by a charge current in Sb_2Te_3. Harmonic Hall measurements [6] conducted on multiple devices allow to estimate an average spin Hall angle (θSH) of 56.2 ± 3.8 and an average spin Hall conductivity (σSH) of (3.41 ± 0.2) × 10^6 (2e/ℏ $m^{-1}\Omega^{-1}$), among the highest reported for TI-based systems thus far [7]. To further substantiate our finding, we estimate the inverse Edelstein effect length (λIEE) associated with (θSH), quantifying the SCC between the 2D charge current flowing in the Sb_2Te_3 and the generated 3D spin current [8]. As a result, we find λIEE = 0.53 nm, which in agreement with the previously reported once varying between 0.28-0.61 nm [3]. These findings underscore the potential of Sb_2Te_3 for TI-based efficient spintronics.

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Merons and anti-merons in synthetic antiferromagnets

M. Bhukta[1], T. Dohi[1,2], R. Frömter[1], V.K. Bharadwaj[1], R. Zarzuela[1], M-A. Syskaki[1,3], M. Foerster[4], M.A. Niño[4], J. Sinova[1], and M. Kläui[1]

[1]*Institute of Physics, Johannes Gutenberg-University Mainz, 55099 Mainz, Germany*
[2]*Laboratory for Nanoelectronics and Spintronics, Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aoba, Sendai 980-8577, Japan*
[3]*Singulus Technologies AG, Hanauer Landstraße 107, 63796 Kahl am Main, Germany*
[4]*ALBA Synchrotron Light Facility, 08290 Cerdanyola del Vallès, Barcelona, Spain*

Recent investigations have elucidated topological spin textures within in-plane magnetized systems, encompassing merons, antimerons, and bimerons [1,2]. These spin textures demonstrate a more intricate current-induced dynamical behavior compared to skyrmions [3]. Specifically, bimerons are robust topological entities that are homeomorphic to skyrmions and can be conceptualized as the superposition of two merons (half-skyrmions). We demonstrate the realization of chiral in-plane topological antiferromagnetic spin textures, including merons, antimerons, and bimerons, in synthetic antiferromagnets by simultaneously engineering the effective perpendicular magnetic anisotropy, interlayer exchange coupling, and magnetic compensation ratio. By combining different magnetic imaging techniques such as magnetic force microscopy (MFM), scanning electron microscopy with polarization analysis (SEMPA), and X-ray magnetic circular dichroism photoemission electron microscopy (XMCD-PEEM) we image the local three-dimensional (3D) vectorial magnetization orientation of antiferromagnetic merons and antimerons in Pt/CoFeB/Ir-based SyAFM stacks with interfacial Dzyaloshinskii–Moriya interaction [4]. We observe that near the spin-reorientation transition, where the effective anisotropy approaches zero, the synthetic antiferromagnetic (SyAFM) system supports homochiral antiferromagnetic (AFM) merons, as identified by their helicity and core polarity. Moreover, their helicity can be readily adjusted by varying the magnetic compensation of the synthetic antiferromagnet, suggesting that interlayer dipolar interactions significantly contribute to the stabilization of these spin textures. Our micromagnetic simulations and analytical calculations provide a comprehensive explanation of the experimental findings, elucidate the stabilization mechanism of AFM topological textures in synthetic antiferromagnets, and present the corresponding phase diagram for their stability [4]. Furthermore, by varying the temperature, we observed the transition from meron to out-of-plane stripe domains.

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Scalar Spin Chirality Hall effect

Gyungchoon Go[1] and Durga Prasad Goli[2], Nanse Esaki[2,3], Yaroslav Tserkovnyak[4], Se Kwon Kim[1]

[1]Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon 34141, Korea.
[2]Department of Physics, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, Japan.
[3]Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan.
[4]Department of Physics and Astronomy and Bhaumik Institute for Theoretical Physics, University of California, Los Angeles, Los Angeles, CA, 90095, USA.

The scalar spin chirality, which characterizes the fundamental unit of noncoplanar spin structures, plays an important role in rich chiral physics of magnetic materials. In particular, the intensive research efforts over the past two decades have demonstrated that the scalar spin chirality is the source of various novel Hall transports in solid-state systems, offering a primary route to bring about chiral phenomena in condensed matter physics. However, in previous studies, scalar spin chirality has been treated as a stationary background, playing only a passive role in the transport properties of materials. Whether scalar spin chirality itself can exhibit Hall-type transport remains an open question. In this talk, I will show that the answer is yes: scalar spin chirality can indeed exhibit Hall transport in Kagome ferromagnets and antiferromagnets under an external bias, leading to what we term the scalar spin chirality Hall effect. Remarkably, this effect arises even in the absence of spin-orbit coupling. Additionally, I will present atomistic spin simulation results that substantiate the existence of the scalar spin chirality Hall effect.

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Ab initio study of all-electrical skyrmion detection in van der Waals tunnel junctions

D. Li[1] , S. Haldar[2] and S. Heinze[2]

[1] CEMES, Universite de Toulouse, CNRS, France
[2] Institute of Theoretical Physics and Astrophysics, University of Kiel, Germany

Magnetic skyrmions in atomically thin van der Waals (vdW) materials provide an ideal playground to push skyrmion technology to the single-layer limit with high tunability [1]. A major challenge for this is establishing reliable electrical detection. In this talk, based on first-principles calculations, we show that all-electrical detection of skyrmions in 2D vdW magnets is feasible via scanning tunnelling microscopy (STM) and in planar tunnel junctions with straightforward implementation into device architectures. We use the nonequilibrium Green's function method for quantum transport in planar junctions, including self-energy due to electrodes and working conditions, going beyond the standard Tersoff-Hamann approximation. We obtain a very large tunneling anisotropic magnetoresistance (TAMR) around the Fermi energy for a graphite/Fe_3GeTe_2/germanene/graphite vdW tunnel junction. An extremely large non-collinear magnetoresistance (NCMR) is observed for atomic scale skyrmions in a vdW tunnel junction based on the graphite/Fe_3GeTe_2/germanene/graphite vdW tunnel junction [2]. The NCMR can be orders of magnitude higher than that reported for conventional transition-metal interfaces. We trace the origin of the NCMR to spin-mixing between spin-up and -down states of p_z and d_{z^2} character at the surface atoms and the orbital matching effect at the interface. Our work paves the way to promote the electrical detection of magnetic skyrmions in 2D vdW tunnel junctions.

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Transport Characteristics of Topological Nodal Planes

M. M. Hirschmann,[1,2] **K. Alpin**,[1] **R. Wiedmann**,[1] **N. Heinsdorf**,[1,3] **W. Y. Yau**,[1,4] **A. Leonhardt**,[1] **D.H. Fabini**,[5] **J. Mitscherling**,[1,6,7] **and A. P. Schnyder**[1]

[1] Max Planck Institute for Solid State Research, Stuttgart, Germany
[2] RIKEN Center for Emergent Matter Science, Wako, Japan
[3] Department of Physics and Astronomy & Stewart Blusson Quantum Matter Institute, University of British Columbia, Vancouver BC, Canada
[4] Max Planck Institute of Molecular Cell Biology and Genetics, Dresden, Germany
[5] Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, United States
[6] Department of Physics, University of California, Berkeley, California 94720, USA
[7] Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Str. 38, 01187 Dresden, Germany

Nodal planes are the two-dimensional generalization of nodal points/lines [1,2], and like them, they may carry a topological charge. In the case of one and two joined topological nodal planes, Fermi arcs on the surface connect the pockets of Weyl points and nodal planes. Yet, this raises the question of how nodal planes differ from Weyl points.
We thus study their transport properties and find that the large degeneracy of nodal planes is susceptible to a time-reversal breaking that contributes to the anomalous Hall effect. Further, we see a generically strong contribution to the quantum metric at a nodal plane, which affects the interband part of the optical conductivity.
As an application, we study the hexagonal van der Waals material $CoNb_3S_6$, which exhibits such topological nodal planes. Recently, this compound has gained interest due to its All-in-All-out magnetic order that exhibits a non-trivial spin-space symmetry [3]. We show that anomalous Hall and Nernst effects in this van der Waals magnet are dominated by the topological nodal plane contribution.

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Lateral crystallization of single-crystalline garnet thin films

Christian Holzmann[1], Stephan Glamsch[1], David Stein[1], Aladin Ullrich[1], Maximilian Mihm[1], Richard Schlitz[2], Sebastian Sailler[2], Michaela Lammel[2], Johannes Boneberg[2], Manfred Albrecht[1]

[1] Institute of Physics, University of Augsburg, 86159 Augsburg, Germany

[2] Department of Physics, University of Konstanz, 78457 Konstanz, Germany

Garnet thin films are insulators with an ultra-low Gilbert damping and high spin diffusion length, next to tunable magnetic properties allowing for perpendicular magnetic anisotropy or a magnetic compensation point, and a strong magneto-optical coupling. Interfacing a garnet thin film with other functional materials offers a unique platform to combine low damping magnonics and other "x-tronics" branches. While high quality, single-crystalline garnet films are readily grown, e.g. by pulsed laser deposition (PLD), typically a specific substrate is required as crystal seed, limiting their applications [1]. As a means to counteract these restrictions we employ the concept of lateral crystallization [2]. Hereby, an "interlayer" is deposited on the substrate prior to the garnet growth, where contact areas with the substrate act as crystal seed for the garnet layer. We use sputtered Pt as interlayer, which is widely used for garnet spintronics [3], and a PLD-grown thulium iron garnet film. A hole pattern in the Pt interlayer is created by partial thermal dewetting or artificial patterning by laser interference. During post-deposition annealing the created holes act as crystal seeds, enabling lateral, single-crystalline garnet growth on top of the Pt layer. We trace this lateral growth by x-ray diffraction, electron backscatter diffraction, and cross-sectional transmission electron microscopy, showing a high crystal quality comparable to epitaxially grown films without an interlayer. The hole pattern used as seeds allows to crystallize large film areas in reasonable timeframes, e.g. a 5x5 mm² area within few hours, while annealing at 700 °C in ambient atmosphere. Further, SQUID magnetometry and ferromagnetic resonance reveal a similar coercivity (about 2.6 mT) and Gilbert damping (about 1.5 x 10^{-2}) at room temperature as films without interlayer [3]. Therefore, lateral crystallization is an attractive way to study the unique magnetic properties of garnet films interfaced with non-garnet layers, expanding research opportunities for "x-tronics".

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Skyrmionics

C. Hwang

Quantum Tech. Institute, Korea Research Institute of Standards and Science, Daejoen, South Korea

A magnetic skyrmion is a particle-like topological spin texture, where the forming knots are key parameters that define its topology. It has garnered significant attention due to its potential use in spintronic devices. From memory to logic devices, the ability to manipulate skyrmions (including their creation, deletion, and movement) using purely electric external variables is highly sought after. Recently, we have demonstrated several unique methods for generating and manipulating magnetic skyrmions, based on a detailed understanding of the skyrmion formation process. Using these methods, we have shown various skyrmion-based devices, such as skyrmion racetrack memory, skyrmion transistors, and skyrmion neuromorphic devices. Recently, we have focused on p-bits with magnetic skyrmion and stripe phases and quantum skyrmionics, and some of our ongoing projects will be introduced

Ultrahigh resolution anomalous Hall microscopy for pure electrical detection of magnetic domain wall dynamics

J.-C. Jeon[1], A. Migliorini[1], J. Yoon[1], J. Jeong[2], S. S. P. Parkin[1]
[1]Max Planck Institute for Microstructure Physics, Halle, Germany
[2]Samsung Semiconductor, San Jose, CA 95134, USA

Domain wall dynamics in (anti-)ferromagnetic systems reveal spin-related physics behind the magnetic materials and interfaces, e.g., Dzyaloshinskii–Moriya interaction. The most technologically relevant feature is the manipulation of spin texture, i.e., domain wall and skyrmion or magnetization reversal, by injecting spin current. The current-induced manipulation of mobile domain walls in nanoscopic magnetic wires and their electrical detection are keys to the development of domain-wall-based memory and logic devices (racetrack) that go beyond today's binary technologies [1, 2]. Thus far, optical techniques, e.g., magneto-optical Kerr microscope, are preliminarily used to investigate the physical properties of domain wall dynamics in magnetic materials. However, optical microscopy technology suffers from the resolution – which is typically of ~ 1 um. Here we show how multiple mobile domain walls can be effectively traced with superior resolution (spatial resolution of better than 40 nm) using a set of specially engineered anomalous Hall detectors integrated into the racetracks [3]. In order to visualize the complex dynamic signal from nanoscopic racetrack devices, we use Poincaré plots and suggest static and dynamic phase space analyses for interpreting the dynamics of domain walls. Technologically, a racetrack device with a single domain wall is functionally equivalent to a memristor in which the output signal is proportional to the position of the boundary core. In such device, analogue-like output can be achieved upon the current-induced motion of the domain wall, which can be a platform for unconventional computing schemes such as neuromorphic computing [4-5]. Racetrack devices can possess multiple mobile domain walls in a single racetrack cell, in contrast to conventional memristors. As a result, the racetrack with multiple domain walls can generate highly complex time-signal outputs upon operation. In order to describe the complex dynamics of domain walls from the racetrack, we introduce a multi-core memristor model. We strongly believe this work will serve as an important platform for unconventional computing schemes.

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Spin charge interconversion in synthetic ferrimagnetic Co/Gd bilayers

Akilan K[1], Sébastien Petit-Watelot[1], Jose Luis Ampuero Torres[3], Melissa Yactayo[1], Laurent Badie[1], Stephane Mangin[1], Michel Hehn[1], Andrew D. Kent[2] and Juan-Carlos Rojas-Sánchez[1]

[1]Institute Jean Lamour Université Lorraine - CNRS (UMR 7198) Campus Artem, F-54011 Nancy Cedex, France. [2]Center for Quantum Phenomena, Department of Physics, New York University, New York, 10003, USA. [3]Instituto Balseiro, Department of Physics, Universidad Nacional de Cuyo, Bariloche, Provincia de Río Negro, Argentina

Spin-orbitronics in ferrimagnets have gained a lot of traction in the field of Nanomagnetism for efficient memory and logic applications. In particular, rare-earth (RE)-transition metal (TM) ferrimagnetic alloys facilitate current-driven operations while exhibiting exciting phenomena such as self-torques, fast current-driven domain wall motion, and single pulse all-optical switching (AOS) [1,2]. Moving towards RE-TM synthetic ferrimagnets (SFiM) enables easier tunability via thickness and interface engineering. In recent years, wide-range single-shot AOS, and spin-orbit torques (SOT) have been reported in SFiM such as Co/Gd multilayers [3,4]. To understand the SOT and the role of interface effects in a bilayer RE-TM SFiM system, we fabricated bilayers of Co/Gd on SiO_2 substrate with different capping layers such as Al, Pt, and Ta along with reversal of the bilayer stacking order. Moreover, in another series, we inserted Pt or Cu in between Co and Gd. We mainly use the harmonic Hall technique to quantify the SOT. Whereas for spin-to-charge conversion (SCC), we perform spin-pumping ferromagnetic resonance and spin Seebeck experiments. We report a systematic study on magnetic anisotropy and SCC efficiency in these SFiM systems. This ultimately helps us engineer multilayer systems with high SCC efficiency and host favourable static and dynamic properties of spin textures such as skyrmions.

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Comparison between Fe_3GaTe_2 and Fe_3GeTe_2: Magnetic exchange interaction and anomalous Hall conductivity

Bomin Kim[1], Tumentsereg Ochirkhuyag[2], Dorj Odkhuu[2] and S.H. Rhim[1]

[1]Department of Physics, University of Ulsan, Ulsan 44610, Republic of Korea.
[2]Department of Physics, Incheon National University, Incheon 22012, Republic of Korea.

Among van der Waals ferromagnets [1-3], Fe_3GaTe_2 has drawn significant attention due to room temperature Curie temperature (T_c). Fe_3GeTe_2 has T_c of 220 K [4], while the isostructural Fe_3GaTe_2 exhibits much higher T_c of 380 K [5]. The exchange coefficients and anomalous Hall conductivity of both Fe_3GaTe_2 and Fe_3GeTe_2 are compared and investigated using first-principles calculations. The exchange coefficients are calculated in the framework of the magnetic force theorem [6, 7]. While for the first and the second nearest neighbor interactions, J_1 and J_2, Fe_3GeTe_2 has larger values than Fe_3GaTe_2, the contributions of the third and higher-order nearest neighbors, J_n (n≥3) in Fe_3GaTe_2 are larger than in Fe_3GeTe_2. Moreover, the summation of J_n (n≥3) over all neighbors in Fe_3GaTe_2 is larger than that in Fe_3GeTe_2 which accounts for higher T_c of Fe_3GaTe_2 than Fe_3GeTe_2. Using Monte Carlo simulations [8] based on these J values, the T_c of Fe_3GaTe_2 and Fe_3GeTe_2 are estimated to be 454 K and 213 K, respectively. In addition, the anomalous Hall conductivity is investigated with k-resolved Berry curvature.

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Bulk-type inverse spin Hall effect with helical spin structure in 2D ferromagnet

Jungmin Park and Sanghoon Kim

University of Ulsan

Two dimensional (2D) magnetic material is very important for the future spintronics because it efficiently offers a new opportunity to control a spin, or to manipulate the spin device. Among the 2D magnetic van del Waals materials, the Fe_5GeTe_2, which has non-centrosymmetric structure, has been focused due to high magnetic ordering temperature (Tc ~ 320K). Recently, the various spin texture, such as helical state and skyrmion, was observed in Fe_5GeTe_2. These spin structures make the Fe_5GeTe_2 as a new topological 2D magnet. Here, we report the magnetic dynamics and self-induced inverse spin Hall effect (ISHE) of Fe_5GeTe_2 on the ferromagnetic state and chiral soliton lattice (CSL). In ferromagnetic state, a magnon corresponding to the Kittel mode with k=0 is observed. The various magnons are disclosed in the CSL sate. Self-induced ISHE in ferromagnetic state is not nearly observed at 8GHz, while it in the CSL state reaches about 1.3 μV at that point. And we observed that the sign of the self- induced ISHE in CSL state is changed depending on resonance state.

Fluctuation-induced piezomagnetism and temperature spin conductivity in local moment altermagnets

K. Yershov[1,2], V. Kravchuk[1,2], M. Daghofer[3], J. van den Brink[1]

[1]Leibniz-Institut für Festkörper- und Werkstoffforschung, IFW Dresden, 01171 Dresden, Germany
[2]Bogolyubov Institute for Theoretical Physics of the National Academy of Sciences of Ukraine, 03143 Kyiv, Ukraine
[3]Institut für Funktionelle Materie und Quantentechnologien, Universität Stuttgart, 70550 Stuttgart, Germany

It was recently discovered that, depending on their symmetries, collinear antiferromagnets may break spin degeneracy in momentum space, even in the absence of spin-orbit coupling. Such systems, dubbed altermagnets, have electronic bands with a spin-momentum texture set mainly by the combined crystal-magnetic symmetry. This discovery motivates the question of which novel physical properties derive from altermagnetic order. Here we show that one consequence of altermagnetic order is a fluctuation-driven piezomagnetic response. Using two Heisenberg models of *d*-wave altermagnets, a checkerboard one and one for rutiles, we determine the fluctuation-induced piezomagnetic coefficient η considering temperature-induced transversal spin fluctuations. In the limit of low temperatures, neglecting magnon-magnon interactions, we considered the thermally induced magnons as an ideal Bose gas and computed magnetization M as a thermodynamic quantity. We obtain finite M perpendicular to the magnetic film beyond the altermagnetic limit, when the altermagnetic Heisenberd terms in our models become not equivalent, e.g. due to the applied mechanical stress. Direction of M (up or down) is determined by direction of the stress application relative to the crystallographic axes. In the linear regime (small stress) we obtained the temperature dependence of *η*. For temperatures larger than the gap temperature, η is linear in temperature, while it is exponentially suppressed for small temperatures. The obtained temperature dependence of η for large temperatures was reproduced by spin-lattice simulations with thermal fluctuations.

We establish in addition that magnetic fluctuations induce an anisotropic thermal spin conductivity [1]. Computing the spin capacity per magnon, and using the relaxation-time approximation, we obtain nonvanishing components of the tensor of thermal spin conductivity $\sigma_{\alpha\beta}$. For small temperatures, $\sigma_{\alpha\beta}$ is linear in strength of the altermagnetic terms. The latter indicates the altermagnetic origin of the effect.

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Perpendicular magnetization switching through orbital current

Soogil Lee[1,2], Min-Gu Kang[3], Soyoung Shin[4], and Byong-Guk Park[4]

[1]Department of Electronic Engineering, Gachon University, Seongnam, 13120, Korea
[2]Department of Semiconductor Engineering, Gachon University, Seongnam, 13120, Korea
[3]Department of Materials, ETH Zürich, Zürich, 8093, Switzerland
[4]Department of Materials Science and Engineering, KAIST, Daejeon, 34141, Korea

Spin-orbit torque (SOT), arising from spin currents induced by the spin Hall effect, provides an efficient way to control magnetization direction. However, further enhancement of SOT efficiency is necessary for its practical application in spintronic devices. Recent theoretical studies have shown that the orbital Hall conductivity is much larger than the spin Hall conductivity in various transition metals, prompting investigating into exploiting orbital currents to enhance the SOT efficiency. In this presentation, we investigate the role of orbital-to-spin conversion and associated orbital torque in light-metal (Cr or Ti)/heavy-metal (Ta or Pt)/ferromagnetic metal (CoFeB) structures, where light-metals and heavy-metals serve as sources for orbital current and orbital-to-spin conversion, respectively [1]. We demonstrate perpendicular magnetization switching in these structures. Furthermore, the switching current in Ti/Ta/CoFeB is reduced compared to the Ta/CoFeB reference, where Ta is a well-known spin Hall material and source for the conventional SOT. These findings pave the way for utilizing orbital currents in the development of energy-efficient spintronic devices.

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Orbital Edelstein contribution to the spin-charge conversion in Germanium Telluride.

Sergio Leiva-Montecinos,[1] Libor Vojáek,[2] Jing Li,[2] Mairbek Chshiev,[2] Ingrid Mertig,[1] and Annika Johansson[3]

[1] Institute of Physics, Martin Luther University Halle-Wittenberg, Halle (Saale), Germany
[2] Univ. Grenoble Alpes, CEA, Leti, F-38000 Grenoble, France
[3] Max Planck Institute of Microstructure Physics, Halle (Saale), Germany

The Edelstein effect (EE) is a promising mechanism for generating spin and orbital polarization from charge currents in systems without inversion symmetry. In ferroelectric materials, such as Germanium Telluride (GeTe), the combination of bulk Rashba splitting and voltage-controlled ferroelectric polarization provides a pathway for reversible spin-charge interconversion [1, 2].

In this work, we investigate current-induced spin and orbital magnetization in bulk GeTe using Wannier-based tight-binding models derived from DFT calculations and semiclassical Boltzmann theory. Employing the modern theory of orbital magnetization (MTOM), we demonstrate that the orbital Edelstein effect (OEE) entirely dominates its spin counterpart (SEE) with opposing signs. This difference is visualized through the textures at the Fermi surfaces, where the orbital texture surpasses the spin texture by one order of magnitude. Moreover, the OEE remains largely unaffected when we suppress the spin-orbit coupling, highlighting its distinct physical origin compared to the SEE.

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Spin Hall magnetoresistance at the altermagnetic insulator/Pt interface

M. Leiviskä[1], R. Firouzmandi[2], K. Ahn[1], P. Kubaščik[3], Z. Soban[1], S.P. Bommanaboyena[1], C. Müller[1], D. Kriegner[1], S. Sailler[4], M. Lammel[4], K. K. Bestha[2,5] L. Šmejkal[6], J. Zelezny[1], A. U. B. Wolter[5], M. Opel[7], S. Geprägs[7], M. Althammer[7], B. Büchner[2], T. Jungwirth[1], L. Nadvornik[3], S. T. B. Goennenwein[4], V. Kocsis[2], and H. Reichlova[1]

[1]Institute of Physics, Czech Academy of Sciences, Prague, Czechia
[2]Institute of Solid State and Materials Physics, TU Dresden, Dresden, Germany
[3]Department of Chemical Physics and Optics, Faculty of Mathematics and Physics, Charles University, Prague, Czechia
[4]Department of Physics, University of Konstanz, Konstanz, Germany
[5]Leibniz IFW Dresden, Institute of Solid State Research, Dresden, Germany
[6]Institute for Physics, Johannes Gutenberg University Mainz, Mainz, Germany
[7]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany

The resistance of a normal heavy metal can be modulated by an adjacent magnetic material through the concerted action of spin Hall, inverse spin Hall effect, and the dissipation of spin accumulation at the interface. This is referred to as the spin Hall magnetoresistance (SMR) [1,2]. The spin accumulation dissipation can occur through various channels, spin-transfer torque being the most extensively studied one [2]. However, the properties of SMR signals at the interfaces of normal metals and altermagnets, in particular their magnitude and anisotropy, call for an examination of contributions beyond spin-transfer torque, such as the magnonic contributions [3-5].

In this talk, we will first review the existing models of SMR and discuss the various contributions to it. We will also explore the possible role of altermagnetism in SMR in terms of anisotropy and magnitude. We will then compare these theoretical models with our experimental SMR data measured at the interfaces of Pt and two different altermagnetic insulators: α-Fe_2O_3 and $Ba_2CoGe_2O_7$. We will recall that the SMR in α-Fe_2O_3/Pt exhibits a record-high amplitude and then show that the previously not reported SMR in $Ba_2CoGe_2O_7$/Pt has a relatively large amplitude that is anisotropic with respect to the crystal orientation. Finally, we will discuss the possible origins of this anisotropy and highlight its consistency with the anisotropic magnon dispersion of the altermagnetic $Ba_2CoGe_2O_7$.

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Real-Space Investigation of Reversible and Multidirectional Laser-Driven Motion of Chiral Spin Textures

Kai Litzius[1], Lisa-Marie Kern[2], Shiyu Zhou[3], Victor Deinhart[2,4], Michael Schneider[2], Christopher Klose[2], Clemens von Korff Schmising[2], Stefan Eisebitt[2,5], Geoffrey Beach[6], Felix Büttner[1,7], Bastian Pfau[2], and Lucas Caretta[3]

[1]*University of Augsburg, Augsburg, Germany*
[2]*Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Berlin, Germany*
[3]*Brown University, Providence, USA*
[4]*Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, 12489 Berlin, Germany*
[5]*Technische Universität Berlin, Berlin, Germany*
[6]*Massachusetts Institute of Technology, Cambridge, USA*
[7]*Helmholtz-Zentrum Berlin, Berlin, Germany*

In the pursuit of advancing applications in memory and logic, the investigation into noncolinear spin textures, specifically chiral magnetic solitons such as domain walls and skyrmions, has emerged as a promising research direction. While current-driven devices show potential, practical implementation in one- and two-dimensional systems remains challenging, calling for a deeper understanding of spin texture dynamics under both current and optical influences in multidimensional space. This talk will discuss our recent advances toward achieving precise control of chiral magnetic textures in two dimensions on ultrafast timescales via optical excitation.

We address the challenge of manipulating skyrmions and chiral domain walls freely in two dimensions through an exploration of the displacement of chiral solitons in ferrimagnetic films, employing ultrafast laser pulses to enable motion over arbitrary distances and directions with high reproducibility. A key focus is understanding the role of the Dzyaloshinskii-Moriya interaction (DMI) and ferrimagnetic compensation temperature in stabilizing and driving ultra-fast domain wall motion. In essence, our findings contribute to a deeper understanding of spin texture dynamics in multidimensional space, opening new avenues for the advancement of spintronics.

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Thin-film growth of Type-II multiferroic Y-type hexaferrite

J. Llandro[1,2,3], H. Arisawa[3,4], Z. Liu[1,3], D. Nakamura[3], A. Kikkawa[3], M. Nakamura[3], E. Saitoh[3,4], Y. Tokura[3,4,5], Y. Taguchi[1,3], S. Okamoto[1,2]

[1]*Correlated-Materials Based Ecological Device Laboratory, RIKEN, Wako, Japan*
[2]*Sumitomo Chemical Co., Ltd., Tokyo, Japan*
[3]*RIKEN Center for Emergent Matter Science (CEMS), Wako, Japan*
[4]*Department of Applied Physics, University of Tokyo, Tokyo, Japan*
[5]*Tokyo College, University of Tokyo, Tokyo, Japan*

The strong coupling between polarization and magnetization in Type-II multiferroics offers an attractive prospect not only for ultra-low-power memory, but also for sensing of optical and magnetic fields. In particular, Y-type hexaferrites with generic composition $Ba_{2-y}Sr_yCo_2Fe_{12-x}Al_xO_{22}$ exhibit not only robust direct and converse magnetoelectric effects [1], but also permit the electric field component of EM radiation to excite spin waves, leading to giant electromagnon resonance in the THz regime near room temperature [2]. However, to achieve scalability and on-chip integration for applications, thin-film growth is required. Key challenges for realizing well-ordered Y-type hexaferrite thin films include balancing high temperatures needed for crystallization against diffusion and re-evaporation of lighter elements.

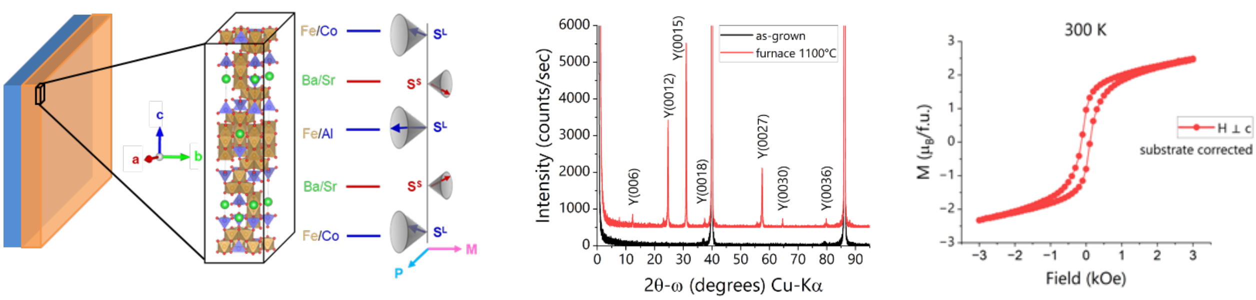

Figure 1: Schematic of Y-type hexaferrite thin film, with measured XRD and M-H data.

Here, we present the growth and characterization of epitaxial thin films of Y-type hexaferrite $BaSrCo_2Fe_{11.1}Al_{0.9}O_{22}$ fabricated by RF sputtering on STO(111) substrates. In this presentation we will report on control of the orientation of the coupled polarization and magnetization vectors with respect to the substrate.

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Near-Room-Temperature Compensation Temperature In Terbium Iron Garnet Thin Films

M. Loyal[1], A. Akashdeep[1], M. Kläui[1], and Gerhard Jakob[1]

1Institute of Physics, Johannes Gutenberg University Mainz, Staudingerweg 7, 55128 Mainz, Germany

Rare-earth iron garnets (REIGs) with perpendicular magnetic anisotropy (PMA) have emerged as promising materials for spintronic applications. The compensation temperature (T_{comp}), where the net magnetization for the ferrimagnet becomes zero, plays a crucial role in determining potential application. While bulk REIGs have a T_{comp} well below room temperature, researchers have shown that it can be tuned in thin films[1]. $Tb_3Fe_5O_{12}$ (TbIG) with bulk compensation temperature ~240 K, in particular has gained interest as recent report shows a near-room-temperature T_{comp} for TbIG thin films[2].

We investigate the factors that tune the compensation temperature (T_{comp}) of TbIG thin films to near-room-temperature. This would have significant implications for the development of spintronics applications, potentially enabling more efficient and stable operation at ambient conditions. PMA TbIG thin films are deposited on (111)-oriented $Gd_3Ga_5O_{12}$ (GGG) substrates using pulsed laser deposition (PLD). The magnetization reversal of TbIG thin films at different temperatures are probed using transverse magneto-resistance measurement. The study contributes to the broader understanding of REIGs and paves the way for integration into practical spintronic applications.

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Interface engineering of spin-orbit torque multilayers for efficient current-induced domain wall motion

A. Migliorini[1], Y. Mala[1], K. Akin[1], J.-C. Jeon[1], A. Styervoyedov[1] and S. S. P. Parkin[1]

Max Planck Institute for Microstructure Physics, Halle (Saale), Germany

Recent developments in spintronic devices based on current-induced domain wall motion [1-3], have provided a significant contribution toward the implementation of magnetic racetrack applications, in which chiral domain walls can be efficiently manipulated using spin currents generated by materials with strong spin-orbit coupling. In this regard, introducing novel classes of materials that can generate large spin-orbit torques (SOT) has considerably reduced the current density needed to move domain walls, thus enabling highly efficient operation of magnetic racetrack devices [4].

In this study, we demonstrate that sophisticated interface engineering of the SOT layer can significantly enhance the efficiency of current-induced domain wall motion (CIDWM) in magnetic nanowires. First, we show that engineered SOT multilayers not only facilitate the growth of films with perpendicular magnetic anisotropy (PMA) but also boost the generated spin current, leading to highly efficient motion of chiral domain walls. Second, we investigate the impact of altering the interface between the magnetic film and the SOT multilayer, which plays a crucial role as it contributes to the Dzyaloshinskii–Moriya interaction, the magnetic anisotropy, and the interface transparency to the spin current injection. Our findings indicate that engineering this interface allows for extensive tunability of the film properties, further reducing the threshold current density and leading to device performances up to five times more efficient than conventional SOT materials. Lastly, we evaluate the potential performance of a nanoscopic domain-wall memory device with an engineered SOT multilayer. We observe significant improvements in writing energy and latency, potentially leading to sub-10-fJ and sub-1-ns device operations.

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Magnetic skyrmions in MXene flakes

Junais Habeeb Mokkath

College of Integrative Studies, Abdullah Al Salem University (AASU), Block 3, Khaldiya, Kuwait.

junais.mokkath@aasu.edu.kw

Comprehending spin dynamics within magnetic materials is essential for advancements in information processing and storage technologies. In this presentation, I will examine the influence of magnetic fields ranging from 0 T to 8 T on the spin configurations of an MXene monolayer flake, utilizing atomistic spin dynamics simulations. Significant alterations in spin configurations were identified under varying magnetic fields. At 0 T, spin spiral states are observed. As the field increases from 0.50 to 2.50 T, the system undergoes a transition from spiral states to skyrmion lattices. Further augmentation of the magnetic field from 3.0 T to 5.0 T results in a distinct skyrmion [2] lattice, with both its geometry and the skyrmion count being modulated by the field strength. At elevated fields (6.0 T to 8.0 T), the system progresses toward a ferromagnetic state, with the skyrmion count reducing to zero at 8.0 T. Moreover, I will discuss ultrafast laser-induced heating utilizing a two-temperature model.

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Nonlinear Spin-Wave Theory in Altermagnets:
Spontaneous Magnon Decays from Nonrelativistic Band Splitting

Rintaro Eto[1,2], Matthias Gohlke[3], Masahito Mochizuki[2], Alexander L. Chernyshev[4], and Alexander Mook[1]

[1] Insitute for Physics, Johannes Gutenberg University Mainz, Germany
[2] Department of Applied Physics, Waseda University, Japan
[3] Okinawa Institute of Science and Technology, Japan
[4] Department of Physics and Astronomy, University of California, Irvine, US

Collinear magnets, including ferromagnets, antiferromagnets, and the recently discovered altermagnets [1], present a diverse landscape of spin phenomena. Altermagnets are distinguished by their nonrelativistic spin splitting in electronic and magnonic bands [2], offering a novel platform to explore spin dynamics beyond traditional paradigms. In insulating altermagnets, magnons—the fundamental spin excitations—are key spin carriers, yet their stability under quantum fluctuations remains an open question.

Here, we examine magnon stability in a two-dimensional nonrelativistic Heisenberg model with d-wave spin splitting. Employing nonlinear spin-wave theory, we demonstrate that the splitting opens spontaneous decay channels for the higher-energy magnon branch, while the lower-energy branch remains robust. These theoretical results are validated by time-evolution simulations using matrix product states, showcasing excellent agreement. Our findings reveal that quantum fluctuations set a fundamental limit on magnon lifetimes in altermagnets, advancing the understanding of many-body effects in this new class of quantum magnets.

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ELECTRICAL DETECTION OF SPIN CURRENTS IN MAGNETIC INSULATORS

Ankita Nayak[1], Matthias Kronseder[2], Nynke Vlietstra[3], Hans Huebl[3,4,5], Jeroen A. Heuver[6], Beatriz Noheda[6], Maxim Mostovoy[6], and Christian Back[3,4] and Aisha Aqeel[1,3,4]

[1]University of Augsburg, 86135Augsburg, Germany
2Department of Physics, Regensburg University, 93053 Regensburg, Germany
3Department of Physics, Technical University Munich, 85748 Garching b. Munich, Germany.
4Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 M¨unchen.
5Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany

Spin transport employing magnetic insulators has recently attracted considerable attention, exploring new functionalities in the field of spintronics. To understand the spin transport at the normal metal (NM) - ferromagnetic insulator (FMI) interface, several different experiments have been performed including the spin Seebeck effect (SSE) and the spin Hall magnetoresistance (SMR). However, these effects are mostly studied in collinear magnetic insulators like prototype Yttrium Iron Garnet (YIG). The sensitivity and response of these effects in non-collinear magnetic insulators are rather unknown. Here, we report the simultaneous detection of the SMR and the SSE in the $CoCr_2O_4$ non-collinear magnetic insulator, by a lock-in detection technique [1,2].
For the SMR detection, an AC-current is sent through the Pt Hall-bar, creating a spin accumulation at the Pt/FMI interface, due to the spin Hall effect in Pt. The spin accumulation at the interface will be either absorbed or reflected, depending on the direction of the magnetization M of the FMI. When a charge current I is sent through the Pt Hall bar, it produces joule heating, resulting in a thermal gradient across the Pt/FMI interface. This thermal gradient can create thermal magnons in the CCO magnetic insulator, resulting in a spin current, which will be pumped into Pt and can be detected electrically by the ISHE.
$CoCr_2O_4$ (CCO) is a spinel with a collinear ferrimagnetic state below T_c = 94 K and non-collinear magnetic phases at lower temperatures. We investigated the SMR and the SSE at different temperatures (5K-300K). We observe a large enhancement in the SMR and the SSE in the non-collinear phase of the CCO with a large sensitivity to noncollinear phases of the CCO [2].

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β-W Spintronics: Spin Hall Conductivity Engineering in W-X Alloys

Quynh Anh T. Nguyen and Sonny H. Rhim*

Department of Physics and Energy Harvest Storage Research Center,
University of Ulsan, Ulsan 44610, Republic of Korea.

Tungsten (W) has attracted in recent spintronics with desirable properties, including low price, excellent CMOS-compatibility, and high melting temperature [1]. Particularly, β-W based alloys in A15 structure are receiving significant attention in spintronics due to remarkable spin Hall conductivity (SHC) and spin Hall angle [2-4]. Inspired by recent works [5-7], SHC of W-X alloys (X = N, Si, and Ti) are investigated using first-principles calculations. For all, we calculate formation energy to check structural stability. Additionally, we performed the Berry curvature and the symmetry analysis to explain the SHC features. Without doping, pure β-W has SHC of -818 S/cm. For X = N, W_2N exhibits a significant SHC of -966 S/cm, attributed to a large negative spin Berry curvature (Ω<0) from the anti-crossing point near the Fermi level (EF). For X = Si, W-Si alloys show a large SHC of -1306 S/cm at 3.13% Si. For X = Ti, W-Ti alloys reach the largest SHC of -1461 S/cm at 12.5% Ti among W-X alloys, 78.61% increase over β-W. For W-Si and W-Ti alloys, band structure is engineered upon doping effect, including tuning EF and band degeneracy lifting, resulting in an enhancement of Ω<0 and SHC.

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Disentangling the magnetic properties of ferrimagnets using atomic-scale vortex-EMCD

D. Pohl[1], H. Makino[1], R. Erni[2], A. Ernst[3], J. Rusz[4], D. Negi[5], and B. Rellinghaus[1]

[1]Dresden Center for Nanoanalysis (DCN), TU Dresden, Dresden, Germany; [2]Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland; [3]Johannes Kepler University, Linz, Austria; [4]Uppsala University, Uppsala, Sweden; [5]Indian Institute of Technology, Jodhpur, India

Electron magnetic circular dichroism (EMCD), the electron wave analog of X-ray magnetic circular dichroism (XMCD), allows the element specific measurement of spin and orbital magnetic moments with up to nanometer resolution in transmission electron microscopy [1]. Recently discovered electron vortex beams (EVBs), which carry quantized orbital angular momentum (OAM), are envisioned to be used in combination with EMCD measurements to determine the magnetic properties of a material in transmission electron microscopes [2]. Since EVBs can be easily focused down to sub-nanometer diameters [3], this novel technique has enormous potential for quantifying spin and orbital magnetic moments with unrivaled lateral resolution. We use specially designed condenser apertures to generate isolated atomic-sized EVBs with user-selectable OAM. As a proof-of-concept experiment, we present "classical" and vortex EMCD measurements on ferrimagnetic barium hexaferrite samples. Classical EMCD allows us to disentangle the contribution of Ti doping to the magnetic moment configuration and to determine the oxidation state of individual Fe atomic sites. For the first time, EVB-EMCD achieves the necessary resolution to resolve the local ferrimagnetic order. Surprisingly, we find a deviation from the expected ferrimagnetic moment arrangement that correlates with the Ti doped atomic sites. The experimental results are further supported by inelastic scattering simulations and density functional theory (DFT) calculations.

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Spatial coherent phonon spectroscopy on 2H-$MoTe_2$ using THz-STM

Vibhuti Rai, Junyoung Sim, Florian Faaber, Sergey Trishin, Nils Bogdanoff, Tom Seifert, Tobias Kampfrath, Christian Lotze, and Katharina J. Franke
Freie Universität Berlin, Department of Physics, Arnimallee 14,14195 Berlin, Germany

Scanning tunneling microscopy (STM) enables probing features on conducting surfaces down to the atomic scale, however, lacks the time resolution to capture the ultrafast dynamics of different carrier excitations such as phonons. Integrating STM with a well-established pump-probe scheme employing ultrashort laser pulses facilitates time resolutions down to picosecond, along with sub-nanometer spatial resolution [1,2]. In this work, we utilize our custom-built terahertz (THz) setup, combined with an STM operating at 5K in ultra-high vacuum, to study phonon dynamics in a bulk 2H-$MoTe_2$. THz pump-probe measurements reveal a temporally decaying oscillatory signal that is sensitive to the surface defects [3,4]. Fourier analysis identifies two prominent excitation modes, which we associate with coherent phonon modes. Spatial mapping of coherent phonon spectroscopy shows that surface defects enhance one of these two excitation modes.

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Orbital Hall conductivity of series of Transition Metal: First-principles symmetry analysis

Thi H Ho[1,2,3], Quynh Anh T. Nguyen[1], Minkyu Park[1,4], Kenji Nawa[5,6], and Sonny H. Rhim[1]

[1] *Department of Physics and Energy Harvest-Storage Research Center, University of Ulsan, Ulsan 44610, Republic of Korea*

[2] *Laboratory for Computational Physics, Institute for Computational Science and Artificial Intelligence, Van Lang University, Ho Chi Minh City, Vietnam*

[3] *Faculty of Mechanical -Electrical and Computer Engineering, School of Technology, Van Lang University, Ho Chi Minh City, Vietnam*

[4] *Quantum Spin Team, Korea Research Institute of Standards and Science, 267 Gajeong-ro, Yuseong-gu, Daejeon 34113, Republic of Korea*

[5] *Mie University, Tsu 514-8507, Japan*

[6] *National Institute for Materials Science (NIMS), Tsukuba 305-0047, Japan*

Orbital Hall conductivity (OHC) of transition metals (TMs) of 3d, 4d, and 5d are investigated using density functional calculations. TMs are classified into crystal structure, bcc, fcc, and hcp.Overall, bcc and hcp metals exhibit larger OHC than fcc, which is discussed in terms of atomic numbers (or occupation) and symmetry associated with structure. Berry curvature responsible for orbital Hall effect is analyzed in the framework of group theory invoking group of k and related irreducible representations. Furthermore, OHC of magnetic Fe, Co, Ni are compared with their nonmagnetic phases.

Interfacing topological insulators with ferromagnets for spin-orbitronics

Carlos M. M. Rosário[1], Luana Benetti[1], Tim Böhnert[1], Daniel Brito[1], Marco Biagi[2], Kevin Garello[2], Ricardo Ferreira[1], Sascha Sadewasser[1]

[1]INL – International Iberian Nanotechnology Laboratory, Braga, Portugal

[2]University of Grenoble Alpes, CEA, CNRS, Grenoble INP, SPINTEC, Grenoble, France

Topological insulators (TIs) enable new directions in (quantum) electronics, but their research has been mostly restricted to cryogenic temperatures that enable exploring the combinations of topology and superconductivity or intrinsic magnetism, for example. This could hinder the full realisation of the potential of TIs for novel electronics. With this in mind, the EU-funded TopRooT project (MSCA ERA Fellowship) targets the application of TIs for room-temperature electronic devices, with the objective of establishing a clear path for creating and designing such devices. To this end, a crucial technology is the integration of TIs with topologically-trivial materials, such as ferromagnets (FM), enabling applications in spin-orbitronics and other emerging magnetic X-tronics concepts. Therefore, the project focuses on optimising TI/FM heterostructures, which play a pivotal role in enabling upcoming novel technologies like SOT-MRAM. SOT-MRAM is at the forefront of the emerging technologies that enable a new generation of brain-inspired and energy-efficient computing, extremely relevant to drastically decrease the energy consumption of information and communication technologies, especially of artificial intelligence. TIs promise even higher energy efficiency than that obtained with conventional SOT materials [1].

State-of-the-art implementation of SOT in TI/FM heterostructures is achieved at the microscale, which is not enough to achieve the needed high density of devices. Therefore, the project will target the fabrication of nanoscale TI/FM heterostructures and address the integration and SOT efficiency challenges that arise. Bi_2Se_3 (the chosen topologically insulating system) is grown by molecular beam epitaxy and the FM layers are sputter deposited. Nanoscale fabrication will be achieved by electron beam lithography and auxiliary techniques. The efficiency of the SOT in TI/FM heterostructures will be accurately quantified via Harmonic Hall Voltage and spin-torque ferromagnetic resonance measurements at room temperature [2].

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Orbital magnetoresistance in insulating antiferromagnets

Christin Schmitt[1,*], Sachin Krishnia[1], Edgar Galíndez-Ruales[1], Takashi Kikkawa[2], Duc Tran[1], Timo Kuschel[1], Eiji Saitoh[2,3], Yuriy Mokrousov[1,4], and Mathias Kläui[1,5]

[1]Institute of Physics, Johannes Gutenberg-University Mainz, 55128 Mainz, Germany
[2]Department of Applied Physics, The University of Tokyo, Tokyo 113-8656, Japan
[3]WPI-Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
[4]Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany
[5]Center for Quantum Spintronics, Norwegian University of Science and Technology, 7491 Trondheim, Norway
*christin.schmitt@uni-mainz.de

Antiferromagnets (AFMs) are promising candidates as active elements in spintronic devices due to their intrinsic properties such as dynamics in the THz range and the absence of stray fields. Insulating ferrimagnets and antiferromagnetic materials are of particular interest for the development of low power devices, as their low damping allows for the transport of pure spin currents over long distances [1,2]. Recently, orbital angular momentum (OAM), the spin counterpart of the electron, has emerged as a crucial concept in modern condensed-matter physics, especially in electronic transport phenomena [3] and magnetism [4]. Both theoretical and experimental studies have highlighted that the orbital Hall effect (OHE) can enable charge-to-OAM conversion (and orbital current) with efficiency orders of magnitude higher than that of spin Hall effects [3,5].

In this study, we investigate magneto-resistance effects in magnetic insulators [3,6]. We find that in the magnetic insulator TmIG the transverse magnetoresistance signal is increased significantly upon replacing Pt, a spin-current generator, by Cu*, which serves as a pure orbital-current generator [3]. In Py/CuOx we find that the orbital Rashba Edelstein effect can reveal the length scales for the conversion between spin and orbital. And we explore antiferromagnets with orbital magnetoresistance effects as pure orbital current is crucial for next generation pure orbitronics devices using abundant, cheap and environmentally friendly materials.

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In-situ correlation of the Hall effect with the occurrence of topological magnetic phases

Sebastian Schneider[1,2], Vijay Bhatia[2], Apurv Yadav[2], Steven Waddy[2], Daniel A. Mayoh[3], Geetha Balakrishnan[3], Takanori Sato[2], Yevheniy Pivak[4], Darius Pohl[1], Andy Thomas[5], David J. Reilly[2], Julie M. Cairney[2], Magnus Garbrecht[2] and Bernd Rellinghaus[1]

[1]Dresden Center for Nanoanalysis (DCN), TU Dresden, Dresden, Germany; [2]The University of Sydney, Sydney, Australia; [3]University of Warwick, Coventry, United Kingdom; [4]DENSsolutions, Delft, Netherlands; [5]IFW Dresden, Dresden, Germany

In search for the since long debated topological Hall effect we have investigated the impact of (anti-)skyrmions on the anomalous Hall effect in two materials, which host (anti-)skyrmions at room temperature.

Magnetic imaging in a transmission electron microscope (TEM) has proven extremely valuable for unveiling the details of these magnetic solitons [1, 2]. Hall effect measurements on such textures are usually conducted on samples that differ substantially in size and morphology from those investigated in a TEM. However, since the stability of (anti-)skyrmions may be highly sensitive to the sample geometry, the correlation of magneto-transport and TEM data is often problematic if not obtained from identical samples.

We have therefore devised an in-situ measurement platform that bridges this gap and allows for magneto-transport measurements in-situ in a TEM [3]. We correlate the Hall effect in $Mn_{1.4}PtSn$ and $Co_8Zn_9Mn_3$ with the occurrence of topologically protected magnetic phases such as stripe/helical phases and (anti-)skyrmions.

The observed field dependencies of the Hall effect can be fully attributed to the magnetization of the simultaneously monitored magnetic textures, and *no* evidence of a topological Hall effect was found [4]. [5]

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Ultrafast electron dynamics in altermagnetic materials

M. Weber[1,2], K. Leckron[1], L. Haag[1], R. Jaeschke-Ubiergo[2], L. Šmejkal[2],J. Sinova[2], and H. C. Schneider[1]

[1]Department of Physics and Research Center OPTIMAS, University of Kaiserslautern-Landau ,67633 Kaiserslautern, Germany

[2] Institut für Physik, Johannes Gutenberg University Mainz, 55099 Mainz, Germany

Altermagnetic materials [1,2] exhibit anisotropic band-structures with a characteristic alternating spin arrangement. This contribution explores the impact of such a spin structure on the electronic dynamics as it is driven by ultrashort optical pulses. We present a numerical investigation of the optical excitation process and subsequent electronic scattering dynamics in a prototypical altermagnetic band structure. We determine the optical excitation by time dependent transition rates for the ab-initio calculated band structure of Kru_4O_8 [3]. For these optical excitation conditions, we calculate the microscopic momentum-dependent scattering dynamics throughout the Brillouin zone for a minimal tight-binding model with a two-dimensional k-space with optimized parameters, which captures the essential momentum-space characteristics of the altermagnetic phase. Using an efficient implementation of the Boltzmann scattering integrals for electron-phonon and electron-electron interactions, we determine the dynamics of the band and k-resolved electronic distribution functions. We characterize the influence on charge and spin dynamics throughout the entire Brillouin zone and highlight the importance of Elliot-Yafet spin flips. Our results reveal fingerprints of altermagnetic features on the ultrafast timescales [3]. First experiments indicate that optical pulses can indeed be used to tune the spin polarization of altermagnets on these timescales [4].

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Uncovering the Property Correlations of Two-Dimensional Transition Metal Carbides by Magneto-Optical Spectroscopy

E. S. Wedde[1], A. Kenny-Wilby[2], and P. V. Radovanovic[3]

[1]University of Waterloo, Waterloo, Canada, [2]University of Waterloo, Waterloo, Canada, [3]University of Waterloo, Waterloo, Canada

As the information technology industry strives for the continuous miniaturization of electronic devices in conjunction with enhancing their speed, computational power, and functionality, traditional semiconductor materials are approaching their natural performance limits. To achieve the next generation of electronic devices, it is essential to develop technologies based on new operating principles. One promising approach is to use multifunctional materials to create novel information-coding methods analogous to the "0" and '1' binary states in conventional charge-based electronics. This is achieved in spintronics by the simultaneous control of electron and spin degrees of freedom, while the recently developed concept of plasmontronics relies on controlling the collective motion of free charge carriers, called plasmons, as another degree of freedom.[1,2] These emerging technologies require the development of new materials with strongly correlated properties, which can be achieved in low-dimensional materials. Magneto-optical spectroscopy is a powerful tool for gaining insight into the electronic structure, optical, magnetic, and magneto-optical properties.[3,4] Due to the specificity of this technique, it can also be used to examine property correlations. In this work, we utilize magneto-optical spectroscopy to examine the electronic structure, fundamental properties, and property correlations of two-dimensional transition metal carbides known as MXenes, including novel reports of their magneto-optical properties. This work provides foundational insight into the origin of material properties in MXenes that can be extended into emerging magnetic phases. Through this work, we aim to evaluate the potential of transition metal carbide MXenes as a new class of multifunctional two-dimensional materials for next-generation technologies based on new principles.

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Unified approach of Hall, thermal Hall, and spin Hall effects in the light of Onsager reciprocity relations

Jean-Eric Wegrowe

LSI, Ecole Polytechnique, CNRS, CEA, IP Paris, Palaiseau, France

In the context of the classical Hall effect, two different phenomena are occurring in magnetic materials: the Anomalous Hall effect (AHE) and the Planar Hall effect (PHE). The former is analogous to the usual Hall effect due to an external magnetic field, and is defined by an antisymmetric conductivity matrix, while the latter is defined by the anisotropic magnetoresistance with a symmetric conductivity matrix [1].

The same dichotomy occurs in the case of the thermal Hall effect, and the corresponding thermoelectric effect (the Nernst effect) [2], because the thermal conductivities matrix obeys the same symmetries as for electric conductivity [3].

All these transport effects can be described in an unified way as long as the phenomenological transport equations are derived from the Onsager reciprocity relations and the symmetry of the material. The case of the spin-Hall effect can also be described within this approach (for the two-channel model) [4].

One of the main interest of this approach is the possibility to derive the *efficiency* of the device, i.e. the electric power that can be extracted from the edges of the Hall bar and injected into a load circuit[1,5]. This derivation is based on the principle of minimum power dissipation. The specificity of *altermagnetism*, and of *orbital Hall effect* can then be investigated at the phenomenological level within this approach.

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Manipulation of Spin Ordering in 2D Magnets

X. Q. Zhang[1], B. Liu[1], L. He[1], X. Z. Ruan[1], J. Wu[2], Yongbing Xu[1,2*]
[1]*National Key Laboratory of Spintronics, Nanjing University, Nanjing 210093, China*
[2]*York-Nanjing Joint Center of Spintronics, The University of York, YO10 3DD, United Kingdom*
*(*email: ybxu@nju.edu.cn)*

The discovery of two-dimensional (2D) magnets opens the door for fundamental physics and next-generation spintronics. Here, we report our recent studies of the manipulation of the spin ordering in two prototype systems Fe_3GeTe_2 (FGT) and $CrTe_2$, focusing on the enhancement of spin-ordering temperatures and new spin structures. We have found that the femtosecond pulsed laser can drive the emergence of ferromagnetism at room temperature in a few monolayers of FGT [1]. Both the saturation magnetization and the coercivity is strongly modulated by the excitation intensity of the femtosecond pulsed laser. In $CrTe_2$, we have found that the bilayer graphene substrate can lead to room temperature intrinsic ferromagnetism with a Curie temperature (T_C) above 300 K and perpendicular magnetic anisotropy (PMA) constant of 4.89×10^5 erg/cm^3 at room temperature in these few-monolayer films grown by MBE [2]. The FM order is preserved with the film thickness down to a monolayer, benefiting from the strong PMA and weak interlayer coupling. With spin-resoved ARPES, the atomic-layer-dependent spin-resolved EDCs measurements reveal a significantly enhanced spin polarization in an atomically thin CrTe2 film [3]. This finding contrasts with the typical decrease in magnetic order observed in well-known ferromagnets as they approach the 2D limit. With the strong spin-orbit coupling in Bi_2Te_3, we have obtained a giant THE signal in the van der Waals heterostructures of $CrTe_2/Bi_2Te_3$, a prototype of two-dimensional (2D) ferromagnet (FM)/topological insulator (TI) [4]. Moreover, the engineering of the antiferromagnetic (AFM) interlayer exchange coupling between atomically thin FM $CrTe_2$ layers in the 2D magnetic crystal, Cr_5Te_8 is realized [5]. By self-introducing interstitial Cr atoms in the vdW gaps, the emergent AFM ordering and the resultant giant magnetoresistance effect are induced. A large negative magnetoresistance with a plateau-like feature is revealed, which is consistent with the AFM interlayer coupling between the

adjacent $CrTe_2$ main layers in a temperature window of 30 K below the Néel temperature. In the ultra-thin $CrTe_2$ Field Effect Transistor (FET), we have found that the application of gate voltage ranging tunes its coercivity (H_C) and Curie temperature [6]. The rapid development of 2D magnetic materials has opened new possibilities in the field of spintronics, and our work lays some foundations for these exciting opportunities.

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Domain walls with 90° magnetization rotation in the topological kagome magnet $TbMn_6Sn_6$

Manuel Zahn[1,2], Ralph Rajamathi[1], Kai Litzius[1], Dennis Meier[2], Sándor Bordács[3], and István Kézsmárki[1]

[1]Center for Electronic Correlations and Magnetism, University of Augsburg, Augsburg, Germany
[2]Department of Materials Science and Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
[3]Department of Physics, Budapest University of Technology and Economics, Budapest, Hungary

The layered Kagome ferrimagnet, TbMn6Sn6, attracts much attention due to its topologically non-trivial features. The bulk electronic band structure realizes a Chern insulating state and in the real space, skyrmion bubbles have been observed in thin lamellae of this compound. $TbMn_6Sn_6$ exhibits a zero-field first-order spin reorientation transition at T_{SR} = 315 K, below/above which the magnetic moment points perpendicular/parallel to the Kagome plane. Here, using magnetic force microscopy, we reveal peculiar domain textures in the vicinity of T_{SR} on the surface of bulk $TbMn_6Sn_6$ crystals. Upon approaching T_{SR} from lower temperatures, we observed a broadening of the domain walls separating regions oppositely magnetized perpendicular to the Kagome plane, and the emergence of a strictly in-plane magnetized region at the center of the walls. We compared these results with analytical calculations based on a continuum magnetic model and found that the π/2 stepwise rotation of the magnetization is a universal effect at the spin reorientation transition.