Hybrid Angular Momentum Transport and Dynamics

820. WE-Heraeus-Seminar

27 – 31 October 2024

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

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

Aims and scope of the 820. WE-Heraeus-Seminar:

In the field of magnetism and spintronics, the transport of spin angular momentum and associated magnetoresistance effects enabled the advent of spintronic applications in modern information technology. At first sight, the fact that spin angular momentum is a non-conserved transport quantity and can be transferred between different (quasi-)particles in a solid state environment seems like an important obstacle for angular momentum based information processing. Over the last years, research showed that the transformation and transfer of angular momentum between different solid-state entities, such as electrons, magnons (quantized excitations of the magnetic lattice), phonons, and photons, unlock coherent and incoherent coupling phenomena between these (quasi-)particles. These coupling phenomena provide access to novel applications reaching from quantum information processing to more efficient classical computing schemes. Especially, they allow the realization of hybrid concepts combining magnetic and non-magnetic materials with the perspective to profit from unique functionalities arising due to coupling phenomena. In this WE-Heraeus seminar, we want to bring together the different scientific communities working on hybrid systems for angular momentum transport and dynamics. We have identified six research areas that we want to represent to facilitate scientific exchange between these different research fields: (i) cavity-mediated magnon coupling, (ii) coherent magnon-phonon transport and dynamics, (iii) magnonics and ferronics, (iv) electron-magnon interactions, (v) orbitronics and (vi) antiferromagnetic spintronics. From our perspective, there is substantial overlap between these separate fields and common themes, which can jumpstart new developments and new research ideas.

Scientific Organizers:

Dr. habil. Matthias Althammer	Bayerische Akademie der Wissenschaften, Germany E-mail: matthias.althammer@wmi.badw.de
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Introduction

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Registration:

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

Program

Program

Sunday, 27 October 2024

17:00 – 21:00	Registration	
18:00	*BUFFET SUPPER and informal get-together*	

Monday, 28 October 2024

07:30	*BREAKFAST*	
08:50	Scientific organizers	**Welcome & Opening Remarks**
09:00 – 09:45	Hans Huebl	**Connecting spins and phonons**
09:45 – 10:30	Akashdeep Kamra	**Unconventional magnetism mediated by spin-phonon-photon coupling**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Silvia Kusminsky	**Harnessing circularly polarized optical photons to probe and control magnons in 2D magnets**
11:45 – 12:30	Bart van Wees	**Magnon transport in the Van der Waals antiferromagnet $CrPS_4$**
12:30	*LUNCH*	

Program

Monday, 28 October 2024

14:30 – 15:15	Rembert A. Duine	**Spin and heat transport in Van der Waals heterostructures**
15:15 – 16:00	Richard Schlitz	**Incoherent angular momentum transport between remote electrodes**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:15	Benedetta Flebus	**Phonon chirality**
17:15 – 17:30	Stefan Jorda	**About the Wilhem and Else Heraeus-Foundation**
17:30 – 18:30	**Impulse talks I -** *Afterwards:* ***Poster Session***	
18:30	*DINNER*	
20:00	**Poster Session & discussions**	

Program

Tuesday, 29 October 2024

08:00	*BREAKFAST*	
09:00 – 09:45	Christian H. Back	**Signatures of magnetism control by flow of angular momentum**
09:45 – 10:30	Mathias Weiler	**Magnetoacoustics**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Satoru Emori	**Probing orbital-spin magnetism in transition metals**
11:45 – 12:30	Katrin Schultheiss	**Floquet magnons in a periodically-driven magnetic vortex**
12:30	*LUNCH*	
14:30 – 14:55	Valentina Errani	**Magnon transistor and magnon entanglement from Klein paradox in antiferromagnets**
14:55 – 15:15	Aakanksha Sud	**Electrically-controlled nonlinear magnon-magnon coupling in synthetic antiferromagnet**
15:15 – 16:00	Ka Shen	**Hybrid magnon transport in rare-earth iron garnets**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:15	Axel Hoffmann	**Hybrid magnon modes**
17:15 – 18:30	**Impulse talks II** - *Afterwards:* ***Poster session***	
18:30	*DINNER*	
20:00	**Poster Session & discussions**	

Program

Wednesday, 30 October 2024

08:00	*BREAKFAST*	
09:00 – 09:45	Mathias Kläui	**From spin-orbitronics to orbitronics: Novel Torques and Magnetoresistance Effects**
09:45 – 10:30	Dongwook Go	**Spintronics and orbitronics: How to distinguish spin and orbital angular momenta**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Tom S. Seifert	**Driving, transporting and sensing orbital currents at terahertz rates**
11:45 – 12:30	Yuriy Mokrousov	**Orbital Magnetism By Light**
12:30	*LUNCH*	

Program

Wednesday, 30 October 2024

14:30 – 14:55	José Solano	**Unraveling the temperature dependent spin-polarized transport in epitaxial Fe films via spin wave Doppler shift**
14:55 – 15:15	Daegeun Jo	**Unconventional torque in altermagnets induced by the magnetic octupole Hall effect**
15:15 – 16:00	Helena Reichlova	**Magneto-thermal transport in Altermagnets**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:15	Romain Lebrun	**GHz and sub-THz magnonics in antiferromagnetic insulating oxides**
17:15 – 18:00	Olena Gomonay	**Nonlinear magnetic dynamics of hematite probed by spin-rectification effect: Suhl instability and beyond**
18:00	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	
20:00	**Evening talk**	**Horror in research**

Program

Thursday, 31 October 2024

08:00	*BREAKFAST*	
09:00 – 09:45	Markus Münzenberg	**Ultrafast spintronics on attosecond time scales**
09:45 – 10:30	Takashi Kikkawa	**Current-induced nuclear- and electron-spin dynamics in a metallic ferromagnet**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Sebastian T.B. Gönnenwein	**Phonon pumping in ferromagnet/single crystal heterostructures**
11:45 – 12:30	Gerrit E. Bauer	**Hybrid quasi-particles that carry magnetic or electric dipoles**
12:30 – 12:45	Scientific organizers	**Closing remarks & Awards**
12:45	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Friday; however, a self-service breakfast will be provided on Friday morning

Posters

Posters

Theodoros Adamantopoulos	**Spin and orbital magnetism by light in rutile altermagnets**
Sanaz Alikhah	**Ab-initio studies of magnetoelectric responses in rutile RuO2**
Aisha Aqeel	**Study of the chiral magnets using resonant X-ray elastic scattering**
Thomas Bornhake	**Towards phonons in magnetic systems by means of density functional perturbation theory implemented in FLAPW**
Yelyzaveta (Liza) Borysenko	**Coupled magnon-phonon dispersion relations from linearized equations of motion**
Davide Bossini	**Dynamical renormalization of the magnon spectrum via nonlinear coherent spin dynamics**
Banhi Chatterjee	**Search for chiral phonons in $MnPS_3$**
Lin Chen	**Control of magnetism by flow of angular momentum**
Mikhail Cherkasskii	**Theory of birefringence in magnon-phonon coupling in ferromagnetic acoustic bilayer structure**
Andi Cong	**Soft magnons in van der Waals multiferroic NiI_2**
Héloïse Damas	**Phononic manipulation of magnetic domains in Co-YIG : from a labyrinth to stripes and bubbles**
Silvia Damerio	**Probing spin and orbital torques in Cu-based magnetic heterostructures**
Rob den Teuling	**Spin waves in the bilayer van der Waals magnet CrSBr**

Posters

Shilei Ding	**Optimization of orbital torques in ferrimagnets and their relationship with Gilbert damping**
Yihang Duan	**Theoretical model for anomalous magnon transport in double umbrella-structured $Tb_3Fe_5O_{12}$**
Chi Fang	**Proximity-induced anomalous Hall effect in $PtSe_2$/YIG at zero field**
Stefano Fedel	**Evidence of long-range Dzyaloshinskii-Moriya interaction at ferrimagnetic insulator/nonmagnetic metal interfaces**
Matteo Fettizio	**Surface magnetoelectric effects in cobalt detected by second harmonic hall measurements**
Oliver Franke	**Theory of ac magnetoelectric transport in normal-metal – magnetic-insulator heterostructures**
Edgar Galíndez-Ruales	**Altermagnetism in the hopping regime**
Holger Grisk	**Investigation of ultrafast magnetism**
Pieter Gunnink	**Surface acoustic wave (SAW) driven acoustic spin splitter in d-wave altermagnetic thin films**
Rahul Gupta	**Harnessing orbital hall effect in spin-orbit torque MRAM**
Guihyun Han	**Magnetic structure effect of magneto-optical Kerr effect, anomalous Hall effect, and spin-splitting on altermagnetic RuO_2**
Berkay Kilic	**Universal symmetry-protected persistent spin textures in nonmagnetic solids**
Durgesh Kumar	**Orbitronics for next-generation memory devices**

Posters

Michaela Lammel	**Lateral solid phase epitaxy of yttrium iron garnet**
Miina Leiviskä	**Spin Hall magnetoresistance at the altermagnetic insulator/Pt interface**
Wardah Mahmood	**Quantum weak measurement of magneto-optic and spintronic effects**
Sergiy Mankovskyy	**Spin and orbital Hall effect in non-magnetic transition metals: extrinsic vs. intrinsic contributions**
Hugo Merbouche	**True amplification of propagating spin-waves using spin orbit torque**
Linda Nesterov	**Setting up current induced spin-wave Doppler shift experiments**
Peter Oppeneer	**Direct observation of current-induced orbital angular momentum in a light 3d metal**
Tahereh Parvini	**Cavity-enhanced optical manipulation of antiferromagnetic magnon-pairs**
Sebastian Sailler	**Competing ordinary and Hanle magnetoresistance in Pt and Ti thin films**
Daniel Schick	**Spin-spin interaction mediated by chiral phonons**
Utkarsh Shashank	**Energy-efficient spin Hall nano-oscillators using PtBi alloys**
Mawgan Alan Smith	**Exchange magnon-photon coupling in metallic thin films**
Vitaliy Vasyuchka	**Temperature-tunable coupling of ferromagnetic and antiferromagnetic spin dynamics in hybrid bilayer systems**

Posters

Johannes Weber	**Magnon-phonon coupling in polycrystalline metallic thin films**
Markus Weißenhofer	**Magnon-phonon hybridization and chiral phonons in bcc Fe**
Jonas Wiemeler	**Misfit dislocations and spin pumping in epitaxial Fe/Rh bilayers**
Misbah Yaqoob	**Spin-orbit torques in ferromagnetic heterostructures**
Mahmoud Zeer	**Orbital torques and orbital pumping in two-dimensional rare-earth dichalcogenides**

Abstracts of Talks

(in alphabetical order)

Signatures of magnetism control by flow of angular momentum

L. Chen[1], Y. Sun[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]

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[4]Munich Center for Quantum Science and Technology, Munich, Germany
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[6]Department of Chemistry, Technical University of Munich, Munich, Germany
[7]TUMint.Energy Research GmbH, Department of Chemistry, Technical University of Munich, Munich, Germany

Exploring novel strategies to manipulate the order parameter of magnetic materials through electrical means is of great significance, not only for advancing our understanding of fundamental magnetism but also for unlocking potential practical applications. The well-established concept of employing gate voltages to control magnetic properties involves adjusting key parameters, such as saturation magnetization, magnetic anisotropies, coercive field, Curie temperature and Gilbert damping, by modulating the charge-carrier population within a capacitor structure through the application of an electric field. This approach holds promise for spintronic devices due to its relatively low energy consumption for substantial modifications. Notably, the induced carriers are non-spin-polarized, making electric-field control independent of the direction of the magnetization. Here, we demonstrate that the magneto-crystalline anisotropy (MCA) of ultrathin Fe films can be reversibly modified by a spin current generated in Pt through the spin Hall effect. The effect decreases as the Fe thickness increases, which indicates that the origin of modification roots in the interface. Uniquely, the change of MCA due to the spin current depends not only on the polarity of the charge current, but also on the magnetization direction, i.e., the change in MCA has opposite signs when the magnetization directions are antiparallel. The control of magnetism by the spin current is distinctly different from the conventional manipulation by electric-fields through a capacitor structure or by mechanical strain.

Hybrid Quasi-Particles that Carry Magnetic or Electric Dipoles

Gerrit E.W. Bauer[1,2]

[1]WPI-AIMR,IMR,CSIS, Tohoku University, Sendai, Japan
[2]Kavli Institute for Theoretical Sciences, UCAS, Beijing, China

Lattice and spin dynamics in magnetic materials are coupled by magnetic anisotropies and magnetoelastic interactions to give rise to hybrid excitations called magnon polarons (not to be confused with spin polarons, who are entirely different animals). They can be interpreted as lattice waves (or phonons) endowed with a spin angular momentum or as spin waves (or magons) that share their spin with phonons. Since the coupling is relatively weak, magnon polarons exist only in small regions of reciprocal space centered at mode crossings that can be mapped by the magnetic field dependence of the spin Seebeck effect.
On the other hand, the electric dipolar order in displacive ferroelectrics is associated with a structural phase transition that is triggered by a soft optical phonon. Polarization waves (or ferrons) are the elementary excitations of the ferroelectric order. Compare to the magnon polarons they are strongly hybridized with and inseparable from the soft optical phonon modes.
In this talk I will discuss the analogies and differences of magnons, phonons, and ferrons and review recent results.

References

[1] G.E.W. Bauer, P. Tang, R. Iguchi, J. Xiao, K. Shen, Z. Zhong, T. Yu, S.M. Rezende, J.P. Heremans, and K. Uchida, Phys. Rev. Applied **20**, 050501 (2023).

Spin and heat transport in Van der Waals heterostructures

R.A. Duine

Institute for Theoretical Physics, Utrecht University, Utrecht, The Netherlands

In this talk, I will discuss spin and heat transport through heterostructures consisting of ferromagnetic insulators and Van der Waals materials. In particular, I will discuss how interfacial effects affect the spin transport, relative to bulk properties.

Probing Orbital-Spin Magnetism in Transition Metals

S. Emori[1]

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The orbital component of magnetization dynamics, e.g., excited by ferromagnetic resonance (FMR), may generate “orbitronic” effects in nanomagnets [1]. Yet, distinguishing orbital dynamics from spin dynamics remains a challenge. In this presentation, I will present an application of x-ray magnetic circular dichroism, which quantifies the ratio between the orbital and spin components of FMR-induced dynamics [2]. This method provides important insights into resonantly driven orbital moments in transition-metal ferromagnets.

If time permits, I will also showcase a new ferrimagnetic alloy with unusual magnetism, which may be rooted in orbital moments of topological origin. The identity of this “topological orbital” ferrimagnet may come as a surprise. This material may open broader applications, as it is remarkably easy to grow by sputtering.

References

[1] H. Hayashi *et al.* Nature Electronics **7**, 646 (2024); D. Go *et al.* arXiv:2309.14817; S. Han *et al.* arXiv:2311.00362

[2] S. Emori *et al.* Applied Physics Letters **124**, 122404 (2024).

Phonon chirality

B. Flebus

[1]Department of Physics, Boston College, 140 Commonwealth Avenue, Chestnut Hill, Massachusetts 02467, USA

In recent years, a rapidly increasing number of studies has reported novel physical phenomena arising from lattice vibrations that carry angular momentum, leading to the emergence of the field of 'chiral phonons.' In magnetic systems, the coupling between lattice vibrations and magnetic degrees of freedom has been identified as a key mechanism behind phonon chirality and the ensuing thermal Hall effects. However, recent observations of giant thermal Hall signals in a range of compounds suggest that additional mechanisms, such as impurity scattering and coupling to out-of-phase ionic motion [1,2], play a significant role. In this talk, I will present an overview of these sources of phonon chirality and discuss their implications for the interpretation of recent experimental findings.

References

1. B. Flebus, and A. H. MacDonald, Phys. Rev. B **105**, L220301 (2022).
2. B. Flebus, and A. H. MacDonald, Phys. Rev. Lett. **131**, 236301 (2023).

Spintronics and Orbitronics:
How to Distinguish Spin and Orbital Angular Momenta

Dongwook Go

Institute of Physics, Johannes Gutenberg University Mainz, Germany

The community of magnetism research has witnessed rapid development of *orbitronics* with the discovery of orbital currents and manifestations of non-equilibrium orbital angular momentum in various magneto-transport phenomena in the last few years [1,2]. These findings have profound impact on spintronics, in which interaction between local moments and orbital angular momentum can be exploited, for example, to manipulate the magnetization in spintronic devices [3-5]. Although the spin and orbital angular momenta share many common features such as symmetry properties, they are different in their microscopic origins. Distinguishing the spin and orbital angular momenta is one of the most important problems in spintronics and orbitronics in both fundamental and applied research.

In this talk, I will discuss how to distinguish the spin and orbital angular momenta from two concrete cases in which the spin and orbital angular momenta behave differently at both quantitative and qualitative levels; the first on the dephasing of angular momentum in ferromagnets [6], and the second on their reciprocal transport with charge current [7]. I will discuss not only implications from recent experiments [8-11] but also general experimental strategies and candidate materials for further verifications.

References

[1] D. Go *et al*. Europhys. Lett. **135**, 37001 (2021).
[2] Y.-G. Choi, D. Go *et al*. Nature **619**, 52 (2023).
[3] D. Jo, D. Go *et al*. npj Spintronics **2**, 19 (2024).
[4] D. Go and H.-W. Lee, Phys. Rev. Res. **2**, 013177 (2020)
[5] D. Go, Y. Mokrousov *et al*. Phys. Rev. Res. **2**, 033401 (2020).
[6] D. Go, Y. Mokrousov *et al*. Phys. Rev. Lett. **130**, 246701 (2023)
[7] D. Go, Y. Mokrousov *et al*. arXiv:2407.00517
[8] T.-S. Seifert, D. Go, T. Kampfrath *et al*. Nat. Nanotechnol. **18**, 1132 (2023).
[9] H. Hayashi, D. Go, Y. Mokrousov, K. Ando *et al*. Commun. Phys. **6**, 32 (2023).
[10] H. Hayashi, D. Go, Y. Mokrousov, K. Ando *et al*. Nat. Electron. **7**, 646 (2024).
[11] T. Gao, D. Go, Y. Mokrousov, K. Ando *et al*. Nat. Phys. In Press.

Nonlinear magnetic dynamics of hematite probed by spin-rectification effect: Suhl instability and beyond

O. Gomonay[1] and R. Lebrun[2]

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[2] CNRS, Thales, Université Paris-Saclay, France

The advantages of antiferromagnetic materials, such as fast magnetic dynamics and weak coupling to the external magnetic field, make the control and direct observation of antiferromagnetic dynamics challenging. One of the ways to overcome this difficulty is to use the spin rectification effect, which provides information about the magnetic oscillations induced by alternating current. In this talk we will discuss the antiferromagnetic dynamics in hematite, which can be probed by the spin rectification effect at large pumping power, in a nonlinear regime.

Starting from the LLG equations, we analyze the dynamics of uniform and nonuniform magnon modes induced by the different Fourier components of the inhomogeneous Oersted field. The nonlinearity causes the eigenfrequencies of the uniform and nonuniform modes to decrease. Since the amplitude dependence of the frequencies is different, at some critical value, the uniform and one of the nonuniform modes became degenerate. This causes resonant growth of the nonuniform mode and a decrease in the effective Oersted field driving the uniform mode. We compare this effect to the Suhl spin wave instability, which manifests itself as an exponential growth of non-uniform magnon modes in the presence of uniform drive and thermal fluctuations of nonuniform modes.

We next discuss the role of DMI in inducing magnetic dynamics by comparing the current-induced spin torques in hematite (weak ferromagnet) and NiO (antiferromagnet). The DMI-mediated driving force depends on the angle between the N\'eel vector and the Oersted field and can be modified by excitation of non-uniform modes via nonlinear coupling. This results in saturation of the oscillation amplitude and peak-to-peak voltage, and nontrivial angular dependence of the spin rectified signal.

Finally, we discuss the relationship between sample geometry and size and the efficiency of different current-induced spin torques. We believe that our results open a way for reliable control and manipulation of fast magnetic dynamics in antiferromagnets and weak ferromagnets.

Phonon Pumping in Ferromagnet/Single Crystal Heterostructures

Sebastian T. B. Goennenwein

Department of Physics, University of Konstanz, Konstanz, Germany

The properties of magnons (the quanta of spin excitations in magnetically ordered systems) can be widely tuned via the applied magnetic field strength and orientation. Phonons (the quanta of elastic lattice excitations) can feature ultralow damping in high-quality crystal lattices. Combining these properties in magnon-phonon-polaron quasiparticles opens intriguing perspectives, e.g., for magneto-mechanical transducers or spintronic devices. However, in order to tailor the properties of such magnon-phonon-polarons, a detailed understanding of magnon-phonon coupling is mandatory. In 2018, Streib et al. [1] predicted that in magnetic layer/non-magnetic crystal heterostructures, so-called phonon pumping would result in an additional contribution to the magnetization damping. Phonon pumping hereby refers to the emission of phonons from a resonantly driven magnetization into the adjacent nonmagnetic crystal.

In the talk, I will discuss our recent phonon pumping experiments in different magnet/crystal heterostructures [2-4]. We use high-resolution broadband ferromagnetic resonance measurements to study both the high cooperativity regime, where magnons and phonons hybridize to magnon-phonon-polarons, and the incoherent regime, where the pumped phonons can be seen as a dissipative energy outflow from the magnetic system, modifying the magnetization damping. We find that the magnon-phonon coupling can be straightforwardly understood by considering the overlap integral of the magnon and phonon amplitude profile across the film thickness. Phonon pumping measurements in different magnet/crystal heterostructures and for different experimental parameters reveal a subtle interplay of magnon and phonon properties at hand. The approach allows to infer phonon properties over a broad range of frequencies and temperatures, and opens a pathway towards quasiparticle-mediated state transfer.

References

[1] S. Streib, H. Keshtgar, G. E. W. Bauer, Phys. Rev. Lett. **121**, 027202 (2018).

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[3] M. Müller, J. Weber, F. Engelhardt, V. A. S. V. Bittencourt, T. Luschmann, M. Cherkasskii, M. Opel, S. T. B. Goennenwein, S. V. Kusminskiy, S. Geprägs, R. Gross, M. Althammer, H. Huebl, Phys. Rev. B **109**, 024430 (2024).

[4] M. Müller, J. Weber, S. T. B. Goennenwein, S. V. Kusminskiy, R. Gross, M. Althammer, H. Huebl, Phys. Rev. Appl. **21**, 034032 (2024).

Hybrid Magnon Modes

Axel Hoffmann[1]

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Magnons readily interact with a wide variety of different excitations, including microwave and optical photons, phonons, and other magnons. Such hybrid magnon dynamic excitations have recently gained increased interest due to their potential impact on coherent information processing [1]. This in turn opens new pathways for hybrid quantum information systems [2–4]. Although quantum operations of magnons have been demonstrated in bulk magnets, the quantum property of propagating magnons in magnetic films remains a fundamental challenge in both physics and materials science and is key for building magnon-based quantum information devices.

I will discuss specific examples and strategies, where we developed fully integrated devices that form the essential building blocks for more complex integrated quantum systems. Towards this end, we demonstrated strong magnon-photon coupling in scalable coplanar devices using coplanar superconducting microwave photon resonators [5]. Based on this concept we have shown how two magnon resonators can be coupled over macroscopic distances, and using local time-resolved detection, we demonstrate coherent, Rabi-like, energy exchange between them [6]. Lastly, I will show how we demonstrated strongly nonreciprocal magnon transduction using nano-scale microwave antennae [7]. By matching the lateral dimensions of the antenna to the thickness of the ferromagnetic film, we can obtain isolation ratios in excess of 30 dB with a single transmission band in a broad frequency range. This provides a practical way for implementing high performance magnon isolation in magnetic thin-film devices for technological applications.

This work was supported by the U.S. Department of Energy, Office of Science, Materials Sciences and Engineering Division under Contract No. DE-SC0022060.

References

[1] Y. Li,,*et al.*, J. Appl. Phys. **128**, 130902 (2020).
[2] D. D. Awschalom, *et al.*, IEEE Quantum Engin. **2**, 5500836 (2021).
[3] Y. Li, *et al.*, 2022 IEEE Intern. Electr. Dev. Meeting, 14.6.1 (2022).
[4] Z. Jiang, *et al.*, “Appl. Phys. Lett. **123**, 130501 (2023).
[5] Y. Li, *et al.*, Phys. Rev. Lett. **123**, 107701 (2019).
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Connecting spins and phonons

Hans Huebl
Walther-Meißner-Institut, Walther-Meißner-Str. 8, 85748 Garching

Magnons - the quantized excitations of a magnetic system - are not only pivotal for spintronics applications, but also probe the fundamental properties of magnetic systems. For example, the field of magnetization dynamics deduces from the dynamic response of the spin system the type of magnetic order and relevant magnetic anisotropy parameters. In extreme cases, solid-state properties and excitations can also substantially alter the magnetization dynamics. One example, which I will discuss in my presentation is the interplay between magnons and phonons, specifically in the form of elastic excitations of bulk acoustic wave resonators.

I will present an example of a magnon-phonon hybrid system constructed from a magnetic thin-film deposited on a non-magnetic crystalline substrate [1,2]. Here, broadband magnetic resonance spectroscopy reveals the interaction between the Kittel-mode of the magnetic thin film and the acoustic modes of the elastic resonator via the magneto-elastic interaction. While this phenomenon is of interest from the perspective of mode hybridization, it also links the sense of precession or handedness of the magnetic subsystem to the elastic one. I will detail the underlying concepts in view of our findings.

I will conclude the presentation with an outlook on future opportunities for the field of quantum science and, in particular, for sensing and transduction applications [2,3].

[1] Müller *et al.*, *Phys. Rev. Appl.* **21**, 034032 (2024).
[2] Müller *et al., Phys. Rev. B* **109**, 024430 (2024).
[3] Engelhardt *et al., Phys Rev Appl* **18**, 044059 (2022).

Unconventional torque in altermagnets induced by the magnetic octupole Hall effect

D. Jo[1,2], S. Han[3], I. Baek[3], P. M. Oppeneer[1,2], and H.-W. Lee[3]

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Altermagnets have recently emerged as a new class of magnetic materials, exhibiting nonrelativistic spin-split bands with antiferromagnetic spin ordering. Notably, magnetic octupoles have been proposed as the order parameter in *d*-wave altermagnets. In this study, we theoretically show that a non-equilibrium magnetic octupole can induce torque on the spin moment of *d*-wave altermagnets. In a nonmagnetic metal/altermagnetic metal bilayer structure, the non-equilibrium magnetic octupople can be generated in a nonmagnetic metal via the magnetic octupole Hall effect and injected into the altermagnet. This magnetic octupole Hall effect, a phenomenon where the transverse flow of magnetic octupoles is driven by an external electric bias, occurs even in common heavy metals such as Pt. Our findings open new avenues for utilizing magnetic octupoles, beyond the magnetic dipoles, to electrically manipulate the magnetic configurations of altermagnets.

Manipulating Cavity Magnon-Polaritons using Polarisation States of the Excitation Vector Fields

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The field of cavity magnonics offers a unique platform for manipulating the interaction between magnons (quanta of spin waves) and confined microwave photons. This study introduces a novel approach to controlling cavity magnon-polaritons through the precise manipulation of excitation vector fields within a microwave cavity.

In our work, we engineered a square cavity resonator excited by two ports, enabling the generation of various polarisation states including circular, linear, and elliptical modes. By controlling the input signals to these ports, we can modify the polarisation state of cavity electromagnetic modes on demand. We demonstrate that by using circular polarisation we can enhance coupling strength into the strong coupling regime, or induce complete decoupling, depending on the sense of rotation of the polarised field with respect to the chirality of spin precession. Additionally, we have the ability to engineer an external applied magnetic field non-reciprocity mechanism into cavity-magnon hybridisation, adding another layer of tunability to the system.

The understanding presented here is particularly relevant for technological applications in quantum information processing and spin-based technologies [1, 2]. By enabling precise control over the coupling strength between photons and magnons, our findings open new avenues for facilitating coherent information exchange between cavity magnon-polaritons and other systems such as qubits [3, 4, 5]. This capability allows for the creation of hybrid systems where information exchange can be finely controlled.

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Unconventional magnetism mediated by spin-phonon-photon coupling

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Magnetic order typically emerges due to the short-range exchange interaction between the constituent electronic spins. Recent discoveries have found a crucial role for spin-phonon coupling in various phenomena from optical ultrafast magnetization switching to dynamical control of the magnetic state. Here, we demonstrate theoretically the emergence of a biquadratic long-range interaction between spins mediated by their coupling to phonons hybridized with vacuum photons into polaritons. The resulting ordered state enabled by the exchange of virtual polaritons between spins is reminiscent of superconductivity mediated by the exchange of virtual phonons. The biquadratic nature of the spin-spin interaction promotes ordering without favoring ferro- or antiferromagnetism. It further makes the phase transition to magnetic order a first-order transition, unlike in conventional magnets. Consequently, a large magnetization develops abruptly on lowering the temperature which could enable magnetic memories admitting low-power thermally assisted writing while maintaining a high data stability. The role of photons in the phenomenon further enables an in-situ static control over the magnetism. These unique features make our predicted spin-spin interaction and magnetism highly unconventional, paving the way for novel scientific and technological opportunities.

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Current-induced nuclear- and electron-spin dynamics in a metallic ferromagnet

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Nuclear spins, with their long coherence times, are fundamental to nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI), serving as powerful tools for probing microscopic properties of matter. In addition to having a spin angular-momentum comparable to that of electrons, nuclear spins have unique advantages. For instance, they can maintain high entropy even at extremely low temperatures and strong magnetic fields, where electron spin dynamics are inevitably frozen out. Despite these fascinating properties, the application of nuclear spins in spintronics has been limited. Recently, however, spin-current generation from nuclear spins have been reported [1,2]. These studies utilize an antiferromagnetic insulator $MnCO_3$, in which nuclear and electron spins are coupled by strong hyperfine interaction between them, showing the potential to harness hyperfine coupling for exploring nuclear spintronic phenomena. In this presentation, I will discuss our recent results on current-induced nuclear and electron spin dynamics in a metallic ferromagnet and their electrical detection through hyperfine interactions.

This work has been done in collaboration with J. Numata, T. Makiuchi, E. Saitoh (from University of Tokyo), T. Kubota, T. Seki, K. Takanashi, S. Takahashi (from Tohoku University), and H. Chudo, M. Umeda (from Japan Atomic Energy Agency).

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From spin-orbitronics to orbitronics:
Novel Torques and Magnetoresistance Effects

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Novel spintronic devices can play a role in the quest for GreenIT if they are stable and can transport and manipulate spin with low power. Devices have been proposed, where switching by energy-efficient approaches is used to manipulate topological spin structures [1,2].

We combine ultimate stability of topological states due to chiral interactions [3,4] with ultra-efficient manipulation using novel spin torques [3-5]. In particular orbital torques [6] increase the switching efficiency by more than a factor 10.

We use skyrmion dynamics for non-conventional stochastic computing applications, where we developed skyrmion reshuffler devices [7] based on skyrmion diffusion, which also reveals the origin of skyrmion pinning [7]. Such diffusion can furthermore be used for Token-based Brownian Computing and Reservoir Computing [8].

We go beyond simple ferromagnets and study multilayers with antiferromagnetic coupling termed synthetic antiferromagnets. We find that the diffusion dynamics is drastically enhanced due to the topology and efficient dynamics can be induced by spin torques [9]. Finally, we find novel topological spin structures, such as bi-merons that are stabilized in synthetic antiferromagnets [10].

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Harnessing circularly polarized optical photons to probe and control magnons in 2D magnets

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In this talk I will go over different examples on how the coupling of two dimensional magnets to optical photons can be harnessed to both probe and control magnons. I will show that the magnon circular photogalvanic effect enabled by two-magnon Raman scattering provides an all-optical pathway to the generation of directed magnon currents with circularly polarized light in two-dimensional honeycomb antiferromagnetic insulators [1], and that the circular dichroism corresponding to these processes can be used to probe the magnon topology, in particular the Chern number and the topological gap [2]. Finally, I will discuss recent results on how to probe and detect magnonic topological edge states.

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GHz and sub-THz magnonics in antiferromagnetic insulating oxides

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Spin waves are collective spin excitations in a magnetically ordered material. The research field of magnonics, targets spin-wave based computing relying on their integration as primary information carriers in logic and radiofrequency devices, and potentially for emerging quantum technologies [1]. Conventional magnonic devices uses standard ferromagnetic materials and thus operates only at GHz frequencies. Magnonic devices could thus strongly benefit from the integration of antiferromagnetic materials that brings the prospect of devices operating at THz frequencies. Recent works highlighted how uncoherent magnons can propagate spin-information over long-distances insulating antiferromagnets [2,3]. However, efficiently excitation and detecting coherent magnons remains key challenging tasks to develop antiferromagnetic magnonic.

In this talk, I will first demonstrate that canted antiferromagnetic materials (also belonging to the recently discovered class of altermagnets) can host non-degenerated and non-reciprocal spin-waves with group velocities > 10 km/s which are key functionalities for the development of magnonic devices [4]. I will also highlight that one can efficiently detect antiferromagnetic resonance [5] and propagating spin-waves [4] using inverse spin-Hall effects. Secondly, I will highlight the possibility to achieve optically induced narrow band THz emission in antiferromagnetic materials using ultra-fast spin-currents [6]. These results highlight promising perspectives to develop hybrid antiferromagnetic and altermagnetic magnonic devices.

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Orbital Magnetism By Light

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Orbital degree of freedom in solids is attracting ever increasing attention owing to possible diverse applications in the areas of magnetization control and angular momentum current generation [1,2]. So far, the properties of non-equilibrium orbital magnetism and orbital currents has been explored predominantly in the regime of weak perturbations, while the orbital physics is expected to be particularly rich in the realm of excitations brought by light. From the fundamental point of view, the interaction of light with matter is mediated predominantly by the orbital properties of quantum states. As we shall see, in various materials this gives rise to strong orbital response in terms of orbital magnetization, which imprints a subdominant spin response, discussed and studied intensively in the past. We will show that when structural inversion symmetry is broken either intrinsically, upon deposition, or by magnetism, strong orbital coupling to the electric field of the pulse will give rise to currents of orbital angular momentum, with optical currents of spin dragged by spin-orbit interaction [3]. The currents of angular momentum can be detected in THz emission experiments [4], providing a unique insight into the temporal and spatial properties of charge, spin and orbital interconversion processes [5]. We will demonstrate that among various material platforms, structurally complex antiferromagnets present a unique niche for achieving best orbital performance with direct implications for the magnetic order control [6,7], and will discuss the prospects and repercussions of light-induced orbital magnetism.

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Ultrafast spintronics on attosecond time scales

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Magnetization manipulation is an indispensable tool for both basic and applied research. I will discuss an actual overview on ultrafast magnetism and THz spintronics [1].

The dynamics of the spin response depends on the energy transfer from the laser excited electrons to the spins within the first femtoseconds [1]. Due to the non-equilibrium electron distribution in layered nanoscale spintronic devices, ultrafast spin currents are generated and contribute to the laser driven spin dynamics. Ultrafast laser-driven spin currents can be converted via the spin-Hall effect into a charge current burst [2] that can even compete with state-of-art THz emitters [3]. They allow to map topological spin structures, and their THz dynamics, with potentially with sub micron resolution as we recently demonstrated [4]. We have also recently shown that attosecond lasers are breaking new frontiers and records towards the observation of coherent spin processes on ever shorter time scales, reaching Petaherz light frequency spintronics. Using light wave coherent charge transfer, driven by a few cycle laser pulse, I will report the first coherent attosecond magnetism in layered spintronic devices [5]. These experiments, the fastest spin-dynamics observed experimentally, fit perfectly to the time scales for time resolved DFT, from theoretical sides revealing a coherent electron transfer at interfaces in operado. This opens up applications of coherent spin current processes. We acknowledge funding by SpinAge, Horizon 2020 FET Open and META-ZIK Plasmark-T, BMBF Unternehmen Region.

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Magneto-thermal transport in Altermagnets

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Over the past several decades, substantial progress in spintronics has uncovered a variety of phenomena in magnetically ordered systems with vanishing magnetization [1,2]. Key transverse effects, such as the anomalous Hall effect and the anomalous Nernst effect, have been found in non-collinear antiferromagnets [3,4]. More recently, a new class of compensated magnets has been discovered [5]. This unconventional magnetic phase appears in crystals where opposite-spin sublattices are related by a rotational symmetry transformation. This phase, known as "altermagnetism," features alternating spin polarization in both the real-space crystal structure and the momentum-space electronic structure.

In this talk, I will present the experimental confirmation of the altermagnetic phase in various materials, with a particular emphasis on transport phenomena. The anomalous Hall effect, which was once thought to be absent in collinear compensated magnets, has now been detected in collinear systems such as RuO2 [8], MnTe [6,7], and Mn5Si3 [9]. Notably, in MnTe and Mn5Si3, we observe a spontaneous anomalous Hall effect, which occurs even without an applied magnetic field with a particular anisotropy [10]. Furthermore, I will discuss the detection of the anomalous Nernst effect in a compensated collinear magnet Mn5Si3 [11] and provide an overview of our upcoming experimental plans.

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Incoherent angular momentum transport between remote electrodes

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Magnons are quantized excitations of the magnetization texture in ordered magnets, which can be used to transport spin information. In recent years, a new device concept in magnonics has demonstrated that direct current electrical transport can provide access to the transport properties of magnons. These devices leverage the angular momentum conversion from the electrical to the magnonic domain to electrically generate and detect magnon spin currents in heterostructures composed of a magnetic insulator and a heavy metal [1]. Recent studies showed, that in the nonlinear regime the changes of the nonlocal transport allow to also obtain information on the transported magnon manifold [2,3].

In this talk, I will show that when entering the nonlinear regime, local modifications of the magnon dispersion can sensitively affect the nonlocal transport, giving rise to a strong enhancement of the number of specific low energy magnons. Considering the role of nonlinear relaxation processes, the nonlocal transport can be reconciled with the local modification of the magnon dispersion. These results suggest that nonlocal transport measurements, despite averaging over all modes, are a sensitive probe to unravel changes to the magnon manifold.

Finally, I will present results from a recent collaborative effort, revealing nonlocal transport between two ferromagnetic electrodes on a nonmagnetic insulator. In these devices, the magnon path between the two electrodes via the underlying substrate is absent, indicating the presence of another transport mechanism for angular momentum [4].

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Floquet magnons in a periodically-driven magnetic vortex

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Magnetic vortices are prominent examples for topology in magnetism with a rich set of dynamic properties. They exhibit an intricate magnon spectrum and show an eigen-resonance of the vortex texture itself, the gyration of the vortex core. While there have been studies about magnon-assisted reversal of the vortex core polarity [1], the impact of the vortex core gyration on the magnon spectrum has not been addressed so far.

The fundamental modes of both excitation types are clearly separated in their resonance frequencies. While the vortex typically gyrates at a few hundred MHz, the magnon modes typically have frequencies in the lower GHz range. This separation allows for studying the temporal evolution of the magnon spectrum when the gyration of the vortex core is driven by an external drive. Under the influence of such a periodic driving field, Floquet states emerge due to a temporal periodicity imposed on the system's ground state, much like the formation of Bloch states in the periodic potential of a crystal lattice. While Bloch states are shifted in momentum space, Floquet states are shifted in energy by multiples of the drive frequency, facilitating the design of novel properties and functionalities in condensed matter systems.

This talk delivers experimental results and numerical simulations on how the regular magnon modes in a magnetic vortex transform into novel Floquet bands, when the vortex ground state is modulated in time by driving the vortex core gyration simultaneously. The observed magnon Floquet states are both distinct from the well-known regular magnon modes as well as from the vortex gyration and represent truly unique excitations providing new opportunities to study and control nonlinear magnon dynamics.

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Driving, transporting and sensing orbital currents at terahertz rates

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Terahertz emission spectroscopy (TES) is a powerful tool to reveal photocurrent dynamics with femtosecond time resolution [1]. An exciting application for TES arises in the emerging field of orbitronics that exploits the electron orbital momentum L for possible data-processing applications [2]. Compared to spin-polarized electrons, L may allow the transfer of magnetic information with considerably higher density over longer distances in more materials. However, direct experimental observation of L currents, their extended propagation lengths and their conversion into charge currents has remained challenging.

Here, we optically trigger ultrafast angular-momentum transport in Ni|W|SiO2 thin-film stacks [3]. The resulting terahertz charge-current bursts exhibit a marked delay and width that grow linearly with the W thickness. We consistently ascribe these observations to a ballistic-like L current from Ni through W with a giant decay length (~80 nm) and low velocity (~0.1 nm fs−1). At the W/SiO2 interface, the L flow is efficiently converted into a charge current by the inverse orbital Rashba–Edelstein effect, consistent with ab initio calculations.

Our findings establish orbitronic materials with long-distance L transport as possible candidates for future efficient and ultrabroadband orbitronic terahertz emitters, and an approach to discriminate Hall-like and Rashba–Edelstein-like conversion processes.

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Hybrid magnon transport in rare-earth iron garnets

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Spin waves or their quanta, magnons, in magnetic insulators are regarded as potential information carriers for low-consumption devices. As the spin wave properties in the star material, YIG (yttrium iron garnet), have been intensively investigated, other family members of rare-earth iron garnets have recently attracted increasing research interest partially because of the coexistence and the controllability of opposite magnon chiralities. In this talk, I would like to share our recent progresses on hybrid magnon transport in different rare-earth iron garnet systems. In particular, we will discuss the high tunable spin Seebeck anomaly originating from magnon-polarons, hybrid modes of magnon and phonon [1], in representative compensated ferrimagnetic garnets, GdIG (gadolinium iron garnet) [2-3] and TbIG (terbium iron garnet) [4-5] and magnon-magnon coupling in magnetic heterostructure consisting of YIG and GdIG [6] .

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Unraveling the temperature dependent spin-polarized transport in epitaxial Fe films via spin wave Doppler shift

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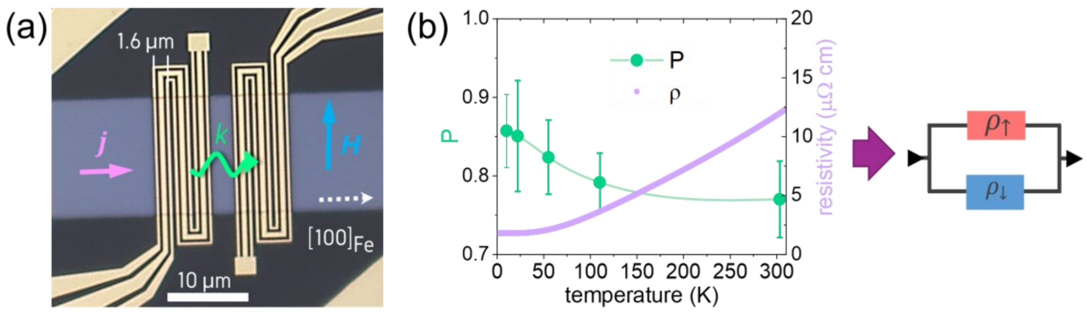
Although central for spintronics, the interplay between magnetism and transport in metallic ferromagnets remains incompletely understood. In particular, the finite temperature resistivity of elemental Fe, Co, Ni could only be modelled until recently using sophisticated ab-initio methods [1]. In this work, we address this interplay experimentally in $MgAl_2O_4$/MgO/Fe/MgO thin films, using the recently developed current-induced spin-wave Doppler shift technique [2] [see Fig.1 (a)]: we measure the shift of the spin wave resonance field due to the spin-transfer torque from the electric current.

Following precisely the shifts for counterpropagating spin waves as a function of the temperature, we extract the temperature dependence of the degree of spin-polarization of the electrical current **P** [see Fig.1 (b)] This is found to increase from 75% up to 85% when cooling the sample from 300K down to 10K. This observation contradicts early considerations, which, based on its global density of states, predict a weak spin-polarization for Fe [3]. On the contrary, we believe there is a majority electron channel that is much less affected by scattering compared to minority electrons. Combining our polarization estimate with resistivity measurements we create a relatively simple two-current resistivity model with contributions from film surfaces, phonons and thermal magnons.



(a) Microscope picture of the device for current-induced Doppler shift: two antennas patterned on top of a 14μm wide and a 20 nm thick Fe (001) strip. (b) Temperature dependence of degree of spin-polarization of the current and resistivity in our devices.

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Electrically-controlled Nonlinear Magnon-Magnon Coupling in Synthetic Antiferromagnet

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The coupling of harmonic oscillators has been extensively studied in both classical and quantum systems, drawing significant interest in spintronics. Synthetic antiferromagnets (SyAFs), with their acoustic (ac) and optical (op) magnon modes, offer a unique platform for exploring nonlinear dynamics. This study investigates the nonlinear coupling between these magnon modes using current-induced resonance spectroscopy. By applying a radio frequency (RF) current at half the resonance frequency of the op mode, we observed distinct spectral splitting in the ac mode, achieved without breaking the system's intrinsic symmetry.

Using in-plane magnetic fields and specific modeling assumptions derived from the Landau-Lifshitz equations, we show that the coupling is facilitated through three-magnon mixing, involving frequency down-conversion (splitting) and up-conversion (confluence). This interaction leads to a Rabi-like splitting of the ac mode without the need for oblique wave excitation, out-of-plane fields, or asymmetric layers.

The observed spectral splitting indicates robust nonlinear interactions. Our findings offer new insights into nonlinear antiferromagnetic dynamics, highlighting SyAFs' potential for coherent spintronic applications and advancing the understanding of complex magnetic phenomena. This research represents a significant step forward in designing advanced spintronic devices and quantum technologies.

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Magnon transport in the Van der Waals antiferromagnet $CrPS_4$

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I will present recent results on electrically and thermally induced magnon spin transport in two magnetic insulator/semiconductor systems. I will introduce the non-local magnon transport geometry, and show how it can be used to obtain magnon spin transport parameters such as magnon spin conductivity and magnon relaxation lengths [1]. For the case of YIG, I will show experimentally that making the YIG layer thinner unexpectedly improves the magnon transport dramatically [2].
I will discuss our recent results on magnon transport in the layered antiferromagnet CrPS4 [3,4]. A strong correlation was observed between the magnetic field dependence of the dynamics of the antiferromagnetic magnon mode, and the observed electrically and thermally induced magnon transport. Above the spin flip magnetic field of around 7T a strong increase of the magnon transport was observed, which is currently not well understood.
If time permits I will also discuss how we studied gate controllable magnon transport in unconventional magnon transistor geometries based on CrPS4 [5].

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Magnetoacoustics

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Spin waves form the basis for the field of magnonics, where they are used for information transport and processing [1]. Acoustic waves, in particular surface acoustic waves (SAWs), are widely employed as frequency filters in mobile communication technology. Spin waves and SAWs have comparable group velocities and wavelengths and are typically operated at microwave frequencies. In magnetic media, spin waves can interact with SAWs which defines the field of magnetoacoustics. Magneto-acoustic devices can be used to excite and detect magnetization dynamics acoustically and control SAW propagation magnetically. Because of the ellipticity of the magneto-acoustic driving fields, as well as the spin-wave non-reciprocity due to dipolar coupling and the Dzyaloshinskii-Moriya interactions [2,3], magneto-acoustic waves are thereby generally chiral and non-reciprocal [4,5].

I will discuss the chirality and non-reciprocity of hybrid magneto-acoustic waves in magnetically ordered thin films and heterostructures. The magnon-phonon coupling is driven not only by magneto-elastic interactions [6] but also by magneto-rotation [7,8]. The coupling of SAWs and spin waves is coherent [9] and can drive non-linear magneto-acoustic dynamics [10]. Non-linear and non-reciprocal coherent magneto-acoustic waves may be useful for the implementation of miniaturized on-chip microwave components.

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Abstracts of Posters

(in alphabetical order)

Spin and Orbital Magnetism by Light in Rutile Altermagnets

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While the understanding of altermagnetism is still at a very early stage, it is expected to play a role in various fields of condensed matter research, for example spintronics, caloritronics and superconductivity [1]. In the field of optical magnetism, it is still unclear whether altermagnets can exhibit magnetisation dynamics effects distinct from ferromagnets and antiferromagnets. Here we choose RuO_2, a prototype metallic altermagnet with a giant spin splitting, and CoF_2, an experimentally known insulating altermagnet, to study the inverse Faraday effect (IFE) in altermagnets from first-principles [2]. We predict large and canted induced spin and orbital moments after the optical excitation which are distinct on each magnetic sublattice. By resorting to microscopic tools, we interpret our results in terms of the altermagnetic spin splittings and of their reciprocal space distribution. Overall, in accordance with our symmetry analysis, we demonstrate that the behavior of altermagnets when exposed to optical pulses incorporates both ferromagnetic and antiferromagnetic features.

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Ab-initio studies of magnetoelectric responses in rutile RuO2

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RuO2, known as an antiferromagnet with an alternating spin-split band structure — referred to as an “altermagnet”— has drawn significant attention in spintronics research. This interest is largely due to its unconventional spin Hall effect (SHE), which has been substantiated through both theoretical predictions and experimental observations. While extensive progress has been made in understanding SHE, other potential spin torque generation mechanisms such as orbital Hall effect (OHE) and spin/orbital Rashba Edelstein effect (SREE/OREE) in this material remain unexplored. This study investigates the SHE, OHE, SREE, and OREE in RuO2 based on a first-principles calculation.

This work offers theoretical insights into these mechanisms using first-principles calculations within the framework of density-functional theory (DFT) with the on-site Hubbard U correction combined with linear response theory. We analyze the response of RuO2 to an applied external electric field in terms of spin and orbital densities, represented as magnetoelectric response tensors.

The atom-resolved tensors show that the responses are predominantly governed by oxygen atoms, which exhibit a response magnitude 2-3 orders higher than ruthenium atoms. Additionally, while oxygen atoms demonstrate the expected antiferromagnetic order in their response tensors, ruthenium atoms only partially reflect this symmetry. These findings provide a deeper understanding of magnetoelectric responses in altermagnets as potential sources of spin torque, highlighting the crucial role of oxygen atoms in the spintronic properties of RuO2.

Study of the chiral magnets using resonant X-ray elastic scattering

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Resonant elastic X-ray scattering (REXS) is an element-specific synchrotron X-ray technique that combines diffraction and spectroscopy. It can be used to study complex magnetic materials and provides a sensitive probe for the spatial modulation of spin configuration. In this study, we investigated the chiral magnet Cu_2OSeO_3 using REXS. Cu_2OSeO_3 is a unique magnetic insulator that exhibits a complex spin configuration, including helices, conical spirals, and skyrmions. Skyrmions are topologically protected magnetic textures that can appear near the Curie temperature [1] and at low temperatures [2]. These magnetization vortices with non-trivial topological properties were first observed using neutron scattering techniques [3], broadband microwave spectroscopy [4], and resonant X-ray scattering techniques [5]. We studied the skyrmion phase and the tilted conical phase of the high-quality single crystal Cu_2OSeO_3 at low temperature [6] using the REXS technique, which occurs when the energy of the incident X-ray photon is matched near the absorption edge of a magnetic element, in this case, Cu. We carried out all the experiments by tuning the photon energy to the L_3 edge of Cu at 931.8 eV. We can directly observe the magnetic diffraction pattern caused by the magnetic arrangement of Cu^{2+} ions in different phases of Cu_2OSeO_3.

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Towards Phonons in magnetic systems by means of Density Functional Perturbation Theory implemented in FLAPW

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The coupling of the spin system or the magnetization to the phonon system describes an important channel for the transfer of angular momentum and is an important research topic in spintronics, orbitronics and spin-dynamics. Therefore, the calculation of phonons in magnetic systems by means of density functional theory (DFT) is a timely topic. All electron full-potential linearized augmented plane wave (FLAPW) DFT methods, as implemented in the FLEUR code [1], proved to be reference methods for the treatment of magnetic systems. We report about the successful implementation for calculating phonon properties by means of our FLAPW code FLEUR using the density functional perturbation theory (DFPT) [2] and we show, how we have overcome the technical challenges inherent in all electron methods related to the displacement of muffin-tin spheres and the respective movement of sphere-centered basis functions. We discuss our first results on magnetic bulk systems, and the impact of the magnetic-configuration on the phonon-dispersion. Additionally, the implementation of the electron-phonon matrix element within the FLAPW method is addressed.

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Coupled magnon-phonon dispersion relations from linearized equations of motion

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Understanding and control of the angular momentum flow in a magnetic material is important for spintronic applications. Recently, the angular momentum transfer from the spin system to the lattice was demonstrated even on ultrashort timescales: in the ultrafast demagnetization process, the spin angular momentum can be absorbed by phonons, only later on resulting in the macroscopic Einstein–de Haas effect [1].

A coupling between spin and lattice degrees of freedom must be based on spin-orbit coupling, because it leads to the modulation of magnetic interactions in consequence of lattice vibration. This was shown to cause coherent oscillations between lattice and magnetic excitations in some materials and phonon to magnon conversion [2, 3].

Including the lattice degrees of freedom in calculations from first principles allows to determine leading energy terms for the angular momentum exchange and to classify spin-lattice effects driven by spin-orbit coupling [4, 5]. Coupled spin-lattice dynamics is described by combinig atomistic spin dynamics and molecular dynamics simulations, expressed through a spin-lattice Hamiltonian. Using rotationally invariant Hamiltonian conserves total angular momentum and allows to link all energy terms to the ab initio calculated model parameters [6].

Here, we linearize the coupled equations of motion and calculate resulting excitations spectra. The two-site anisotropy coupling term is considered, which may be relevant e.g. for FePt. We show how spin-lattice coupling can modify magnon and phonon dispersions, lift the degeneracy of modes and cause avoided crossings in the band structure.

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Dynamical renormalization of the magnon spectrum via nonlinear coherent spin dynamics

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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.

Search for chiral phonons in $MnPS_3$

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Chiral phonons can be observed in two-dimensional transition metal dichalcogenide (TMDC) materials when the inversion symmetry is broken in the non-equilibrium state triggered by optical excitations using circularly polarized light. In order to avoid any debate about chirality in two dimensions, chiral phonons are henceforth referred to as circular phonons. A detailed theoretical calculation of the circular phonons production rate has already been done for the TMDC MOS_2 [1]. We investigate the antiferromagnetic semiconductor $MnPS_3$ with a similar band-structure like MOS_2 as a novel candidate material that may allow for excitation of circular phonons. In this material, although the total magnetic moment is zero in the ground state, exciting the system using circularly polarized light induces a net magnetic moment [2]. The damping of the magnetic moment observed experimentally points to the transfer of orbital angular moment to combined phonon-magnon excitations. We use DFT+U and density functional perturbation theory (DFPT) to search for circular phonon modes at the valley-points of a monolayer $MnPS_3$ and we obtain initial promising signatures for the same. We further perform calculations of the excited electronic states carrying orbital angular momentum with the help of the DFT+U and study the matrix elements for electron-phonon coupling in these states using DFPT, similar to the methodology recently employed for studying phonons in the 2D ferromagnet CrI_3 [3]. Our theoretical calculations could be used to design and benchmark experiments on creation and detection of circular phonons using electronic and optical spectroscopy of valley polarization, time-resolved diffraction etc.

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Control of magnetism by flow of angular momentum

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We report that the magnetocrystalline anisotropy (MCA) of ultrathin Fe films can be reversibly modified by a spin current generated in Pt by the spin Hall effect. The effect decreases with increasing Fe thickness, indicating that the origin of the modification can be traced back to the interface. Uniquely, the change in MCA due to the spin current depends not only on the polarity of the charge current but also on the direction of magnetization, i.e. the change in MCA has opposite sign when the direction of magnetization is reversed. The control of magnetism by the spin current results from the modified exchange splitting of majority- and minority-spin bands, providing a functionality that was previously unavailable and could be useful in advanced spintronic devices.

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Theory of birefringence in magnon-phonon coupling in ferromagnetic acoustic bilayer structure

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In a recent study [1], the effect of crystal symmetry on magnon-phonon coupling was observed in magnetoelastic bilayers. We present a theoretical framework that shows quantitative agreement with these measurements. The theory reveals the effects of phonon pumping and the polarization of eigenmodes on magnon-phonon coupling. Our findings indicate that hybridization with magnons imparts magnetic properties to non-magnetic phonons. We also demonstrate that the circularly polarized Kittel mode acquires linear polarization from the phonons. These results have potential applications in magnomechanical systems.

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Soft magnons in van der Waals multiferroic NiI_2

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The ferroelectric polarization in van der Waals multiferroic NiI_2 is believed to be induced by the helimagnetic spin order [1]. Recently, the multiferroic order were found persist down to bilayer [2] and monolayer [3] NiI_2. However, the formation of the helimagnetic ground spin configuration and the properties of its spin excitation are yet to be clarified theoretically. Based on the magnetic parameters from first-principles study [4], we explore the proper magnetic ground states with well-defined magnon spectra in a single layer of few-layer NiI_2 [5]. While the spin frustration in triangular lattice due to competition between the nearest-neighbor ferromagnetic and the third-nearest-neighbor antiferromagnetic exchange terms stabilizes a helimagnetic phase, the anisotropic Kitaev interaction introduces a canting of the spin rotation plane. The modulation vector of the helimagnetic structure can be continuously oriented within the atomic plane by the competition between the third-nearest-neighbor exchange and the Kitaev interaction. In addition, the calculation of magnon spectrum reveals anomalous features with soft magnons at finite wave vectors, which is found to be related with the vibration of the canting plane. From the finite-temperature calculation of the magnon spectra, we predict a magnetic phase transition driven by soft magnons, which cause a spatial modulation of the canting plane. Furthermore, a sign change is predicted in the temperature dependence of the transverse magnon thermal conductivity.

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Phononic manipulation of magnetic domains in Co-YIG : from a labyrinth to stripes and bubbles

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Due to the conservation of total angular momentum in a system, the macroscopic magnetic state of a solid can be influenced by the transfer of angular momentum from reservoirs to the magnetization. One of these reservoirs is the crystal lattice, where the angular momentum transfer is mediated by phonons. The universal presence of phonons in materials makes them an interesting medium for a universal way to control magnetization.

Our work shows that the magnetic state can be controlled by mid-infrared optical pulses emitted from a free-electron laser at the FELIX laboratory, when their frequency is tuned to the optical phonon modes of magnetic materials. This phononic switching has been demonstrated in ferrimagnetic yttrium iron garnet (YIG) [1-2] and antiferromagnetic iron borate [3]. The peculiar patterns of the switched domains could be qualitatively explained and reproduced by micromagnetic simulations considering a light-induced elastic strain [1-3]. However, the microscopic mechanisms explaining the magnetization control - from the generation of the crystal strain to its transformation into magnetoelastic interactions and the subsequent effective field distribution - are not fully understood.

In this poster, we present the study of a Co-doped YIG exhibiting labyrinth magnetic domains. Upon illuminating the film with narrow-band infrared pulses targeting optical phonon modes at resonance, we observe new permanent stripes and magnetic bubble domains. Since the shape of these magnetic patterns after irradiation directly reflects the underlying magnetoelastic interactions, we aim to quantitatively characterize the magnetoelastic interactions and effective fields that drive the dynamics leading to these peculiar magnetic domains and to further understand the mechanisms leading to phononic switching.

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Probing spin and orbital torques in Cu-based magnetic heterostructures

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The interconversion between charge and spin currents is an essential in spin-based technologies, playing a central role in the manipulation of the magnetization by means of spin-orbit torques (SOTs) [1]. So far, the generation of SOTs has mostly relied on the spin-Hall effect (SHE) in the presence of strong spin–orbit interaction, but recently, the discovery of a orbital counterpart to the SHE, the orbital Hall effect (OHE) has drawn increasing attention as an alternative route for the generation of SOTs [2-3]. In this study, we examine the SOTs induced in different ferromagnetic materials (FM), specifically Co and Permalloy (Py), by an adjacent normal metal (NM) layer by means of harmonic Hall measurements. Comparing the results between different NM and analyzing the FM thickness dependence of the effect, we conclude that the SOTs originate from the SHE in Pt and from the OHE in naturally oxidized CuO_x. Owning to the large orbital-to-spin conversion coefficient in Py, the SOT in Py/CuO_x above 5 nm is comparable in magnitude to the reference Py/Pt bilayer. This confirms that the OHE in this material is large and can be harnessed in spin orbitronics devices based on light metals. Moreover, due to the negative sign of the orbital conductivity in our CuO_x layer, the damping-like torque efficiency changes sign based on the oxidation state of Cu. We exploit this to demonstrate reversible tuning of the SOT in Co(5)/CuO_x(3) via voltage-driven ion migration in solid-state gated devices. Our findings [4], consistent with previous reports, support the potential for using light metals to achieve efficient electrical control of magnetization, thereby encouraging further exploration of spin-orbitronic devices based on more economical and sustainable light elements.

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Spin waves in the bilayer van der Waals magnet CrSBr

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Analytical expressions for spin wave frequencies and relative precession magnitudes are presented for monolayer and antiferromagnetically coupled bilayer CrSBr with in-plane external magnetic fields. The antiferromagnetic, spin-flip and canted phases are discussed. We show that the effect of dipolar interactions in the two-dimensional limit effectively switches the intermediate and hard anisotropy axes in the monolayer, in accordance with the literature. The spin wave frequencies of all phases are tunable by an external magnetic field. The effects of intra- and interlayer exchange, triaxial anisotropy, and intralayer dipolar fields on the frequency and relative precession magnitudes are included.

Optimization of orbital torques in ferrimagnets and their relationship with Gilbert damping

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The orbital magnetic moment of metals is usually quenched by electron delocalization and crystal field effects. However, the application of an electric field can induce a non-equilibrium current of orbital angular momentum in conductive materials whose electronic bands have a k-dependent orbital character [1,2]. This phenomenon can lead to the current-induced accumulation of orbital momenta in nonmagnetic layers, which can then diffuse into neighboring magnetic layers and interact with the local spin magnetization through spin-orbit coupling, giving rise to so-called orbital torques [3]. Conversely, the excitation of spin precession in a magnetic layer can give rise to an orbital current, resulting in orbital pumping and dissipation of angular momentum in the nonmagnetic layer. In the first part, I will present the efficacy of converting orbital to spin momenta in ferrimagnetic materials, specifically in the RE-TM ferrimagnet Gd_yCo_{100-y} [4]. This work underscores the mechanisms that facilitate orbital-to-spin conversion within a magnetic layer at the atomic level. In the second part, I will discuss how the Gilbert damping parameter correlates to spin and orbital torques in magnetic layers adjacent to Pt and CuO_x layers, respectively. [5]. I will show that CoFe/CuO_x bilayers exhibit a favorable combination of efficient orbital torque and minimal increase in Gilbert damping, which is promising for the implementation of orbital torque oscillators with reduced damping compared to spin torque oscillators.

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Theoretical Model for Anomalous Magnon Transport in Double Umbrella-Structured $Tb_3Fe_5O_{12}$

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Rare earth garnets such as $Y_3Fe_5O_{12}$ and $Gd_3Fe_5O_{12}$ with collinear spin structures have attracted many attentions due to low damping, adjustable magnon chirality, etc. Garnets composed of rare earth ions such as Tb^{3+}, Dy^{3+}, Ho^{3+} can exhibit complex and interesting noncollinear magnetic structures, which is related to the on-site anisotropy caused by their large orbital angular momenta[1]. Neutron diffraction demonstrate that $Tb_3Fe_5O_{12}$ (TbIG) forms a zero-field “double umbrella” magnetic structure at low temperatures, and exhibits rich *M-H* behaviors, for example high-field hysteresis loops[2]. Recently, experiments about spin Seebeck effect in TbIG/Pt bilayers have also found similar high-field anomalous hysteresis, and the spin Seebeck coefficient (SSC) exhibits peculiar phenomena such as sign changes and significant enhancement near the anomalous loops. However, these phenomena lack reliable theoretical interpretation. Here, we introduce a theoretical model that combines on-site anisotropy with exchange interactions between magnetic ions[3], which not only successfully constructs a zero-field double umbrella magnetic structure but also reproduces the experimentally observed *M-H* curves. Our model reveals the origin of the magnetic structure in high-field hysteresis loops, where the magnetic moment orientation of one of the Tb sublattices undergoes a sudden change. Based on this model, anomalous SSC phenomena are interpreted through the evolution of magnon spectra during the magnetic structure transition. More interestingly, we also found that the magnon dispersion near the transition is almost tangential to the phonon dispersion, which suggests that magnon polarons (magnon-phonon hybrid modes) may significantly contribute to the increase of SSC near the loop.

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Proximity-induced anomalous Hall effect in $PtSe_2$/YIG at zero field

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The proximity effect at material interfaces can induce novel properties, such as unconventional magnetism and superconductivity, particularly in 2D materials where surface-to-volume ratios dominate. Recent advancements in spintronics have been greatly driven by the fascinating phenomena emerging at the interfaces and within heterostructures composed of various van der Waals (vdW) materials.

In this work, we report an advancement in the field of spintronics by demonstrating a proximity-induced anomalous Hall effect in a $PtSe_2$/Y_3Fe5O_{12} (YIG) heterostructure at zero external magnetic field. By leveraging the magnetic proximity effect, we have engineered a heterostructure comprising $PtSe_2$, a high-mobility but non-magnetic 2D material, and YIG, a magnetic insulator. YIG films were deposited with magnetron sputtering system sputtering system and underwent a high-temperature annealing process in an oxygen atmosphere to enhance both the crystalline quality and the epitaxial relationship between the film and the substrate. Thin flakes of $PtSe_2$ were mechanically exfoliated and then transferred the 10 nm YIG films. As the spin Hall magnetoresistance could be eliminated, this combination is thought to induce out-of-plane magnetization in $PtSe_2$ with the additional advantage of stability at higher temperatures, which further gives the anomalous Hall effect at zero field.

Our findings contribute to both materials science and applied physics by addressing the demand for novel magnetic vdW structures with high critical temperatures, while demonstrating the potential of interfacial engineering for spintronic applications.

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Evidence of Long-Range Dzyaloshinskii-Moriya Interaction at Ferrimagnetic Insulator/Nonmagnetic Metal Interfaces

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The Dzyaloshinskii-Moriya interaction (DMI) is a chiral magnetic exchange interaction promoting the perpendicular alignment of neighboring spins. The DMI typically occurs in materials characterized by inversion asymmetry and strong spin-orbit coupling [1, 2], such as ferromagnetic/nonmagnetic metal (FM/NM) interfaces. The microscopic origin of this interfacial DMI is commonly described by the three-site Levy-Fert model [3], where neighboring atomic moments interact through the vicinal non-magnetic atoms. Here, we extend this viewpoint and show evidence of substantial DMI arising from long-range interactions with a nonlocal interface. We measured the interfacial DMI in a ferrimagnetic insulator, $Tb_3Fe_5O_{12}$ (TbIG), as a function of thickness and interfaced with various NMs. By correlating the DMI with the interfacial spin transport and element-resolved transmission electron microscopy analysis, we demonstrate that the TbIG/NM interface is the dominant source of the DMI in our structures. We find that using Cu as a spacer modifies the interfacial DMI substantially due to a long-range interaction of TbIG with the Cu/NM interface. Density Functional Theory calculations on similar structures support the experiments and consolidate our interpretation. These results provide new insights into the fundamental understanding and engineering of interfacial DMI and will stimulate research in other materials with overarching implications for domain wall and skyrmion-based devices.

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Surface Magnetoelectric effects in cobalt detected by Second Harmonic Hall measurements

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The electric manipulation of magnetic information is crucial for advancing spintronic devices, and magnetoelectric (ME) effects have recently gained attention as a promising way to enhance their efficiency [1]. Several physical mechanisms have been explored, such as ionic migration [2,6], magnetoelastic coupling via piezoelectric substrates [3], and modulation of interfacial magnetism through electrostatic charge accumulation [4,6,8]. The latter approach is particularly beneficial due to its versatility and speed, as it avoids slow ionic diffusion and does not depend on specific substrates.

In this study, we introduce an alternative method to detect and quantify voltage-controlled modulation of saturation magnetization and magnetic anisotropy (VCMA) in in-plane magnetized thin films using the second harmonic Hall technique. We applied this method to Co/Al_2O_3-based heterostructures. Magnetization was measured through the anomalous Hall effect (AHE) in Hall bars with a top gate structure. Unlike typical gating experiments, where a second voltage source applies a DC gate during the AHE measurement [5], in our design, both the gate and current contacts are connected to the same AC source. This setup modulates the gate at the same frequency as the sinusoidal input current, producing a second harmonic signal whose amplitude reflects the strength of the ME coupling. Since ionic diffusion is much slower than the gating frequency, this method probes only electrostatic effects, excluding ionic migration. To demonstrate the interfacial nature of the ME effect, we introduced a spacer layer between the Co layer and the gate oxide, and we studied the ME efficiency as a function of Co thickness. The extracted VCMA efficiencies, around 40 fJ/Vm, are consistent with values found in the literature [1], while the changes in saturation magnetization match predictions from spin-dependent screening models [7,8]. This method provides a precise and efficient approach for studying electrostatic modulation of magnetic properties in spintronic devices.

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Theory of ac magnetoelectric transport in normal-metal – magnetic-insulator heterostructures

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Electron-magnon coupling at the interface between a normal metal and a magnetically ordered insulator modifies the electrical conductivity of the normal metal, an effect known as spin-Hall magnetoresistance [1, 2]. It can also facilitate magnon-mediated current drag [3, 4], the nonlocal electric current response of two normal metal layers separated by a magnetic insulator. In this contribution, we present a theory of these two spintronic effects and their nonlinear counterparts for time-dependent applied electric fields E(ω), with driving frequencies ω up to the THz regime [5]. We compare various mechanisms leading to a quadratic-in-E response — Joule heating, spin-torque diode effect [6], and magnonic unidirectional spin-Hall magnetoresistance [7] — and show how these can be disentangled by their characteristic dependences on ω and the magnetization direction.

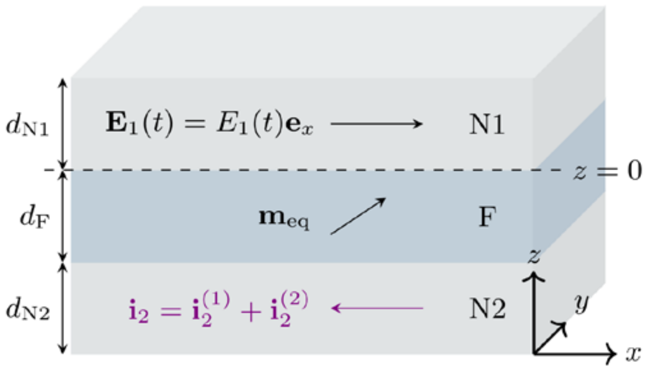

FIG. Geometry of an N|F|N trilayer consisting of two normal metals N1 and N2 and a magnetically ordered insulator F. An in-plane electric field E(ω) in one of the N layers gives rise to charge currents in both layers. We calculate the charge currents linear as well as quadratic in E(ω) from the dc limit to THz frequencies [5].

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Altermagnetism in the hopping regime

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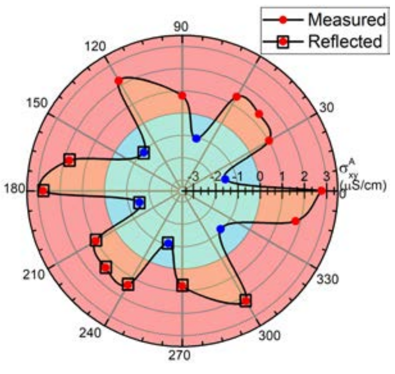
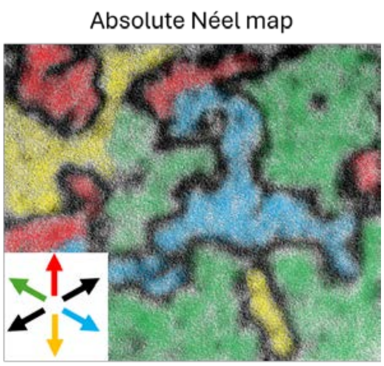
Conventional antiferromagnets are characterized by time-reversal symmetry, resulting in a zero anomalous Hall effect (AHE). However, altermagnets—a newly discovered class of materials—exhibit nonzero AHE and non-dissipative transversal currents [1]. Unlike high-symmetry systems with isotropic Hall effects, low-symmetry materials such as Ti-doped hematite show remarkable anisotropic magnetotransport behavior. We investigated the magnetotransport properties of Ti-doped hematite, revealing an unconventional symmetry dependence strongly influenced by crystal orientation [2]. These results establish a clear link between our experimental findings and the classification of hematite as an altermagnet with anisotropic AHE.

We explored the Hall effect in hematite across various Hall bar orientations through advanced transport measurements, identifying unusual Hall conductivity contributions (Fig 1.a). These contributions deviate from typical antiferromagnetic symmetries and arise from crystal symmetry and the magnetic order parameter, which agree with theoretical predictions. A key discovery is the 60° sign inversion in the Hall effect, marking the first observation of Hall signal inversion in an altermagnetic material in the hopping regime.

We further confirmed these altermagnetic properties using X-ray magnetic circular dichroism (XMCD) imaging (Fig.1.b). Correlating XMCD with magnetic linear dichroism (XMLD) and first-principle simulations allowed us to distinguish between 180° Néel domains in hematite. This direct imaging, combined with our transport measurements, provides the first experimental evidence of altermagnetism in the hopping regime, advancing the understanding of this phenomenon and paving the way for future applications in spintronics.





a) Polar plot of the amplitude σ_{xy}(H=11 T) as a function of the angle α of the Hall bar. Red (blue) points represent a positive (negative) amplitude. b) Full Neel vector orientation map (XMCD + XMLD combination) of hematite.

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Investigation of ultrafast magnetism

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In 1996, Beaurepaire and Bigot published the first ultrafast demagnetization of a ferromagnet after excitation with a femtosecond laser pulse. This seminal experiment revolutionized the view on the mechanisms, energy, and time scales in magnets. The research field of ultrafast magnetism was born, resulting in countless studies exploring the dynamics of numerous magnetic materials. Gathering information on magnetization dynamics, which are at least two orders of magnitude faster than conventional electronics, requires the deployment of femtosecond pulses. The two main tabletop diagnostics tools for this task are the time-resolved magneto-optic Kerr effect (TR MOKE) and the measurement of Terahertz Emission Spectroscopy after femtosecond laser excitation of ferromagnetic/nonmagnetic metallic heterostructures.

Both methods provide insight into the magnetic response of materials to ultrashort laser pulse excitation. TRMOKE is purely an analytical tool for tracking the magnetization dynamics processes after heating, while Spintronic Terahertz emitters are one of the first applications to utilize spin currents generated by ultrashort laser pulses in metallic ferromagnets. Currently, their functionality is expanded for further tasks, e.g., to analyze orbital currents generated at interfaces to layers attached to the emitters. New material systems like topological insulators or altermagnets are under investigation as further Terahertz radiation sources.

In this case we study the behavior of a biquadratic exchange coupled Ta(5)/CoFeB(5)/Ru(0-1)/CoFeB(5)/Ta(5) in nm heterostructure. We observe a strong anisotropic hysteresis in MOKE measurement at 0.5 nm ruthenium thickness where along the easy axis of magnetization the Kerr ellipticity dips and along the hard axis of magnetization the Kerr ellipticity as a strong peak.

Surface Acoustic Wave (SAW) driven acoustic spin splitter in d-Wave Altermagnetic thin films

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The generation of spin currents is essential to the field of spintronics. In this work, we propose that a surface acoustic wave (SAW) [1] can be used to generate spin currents in altermagnetic thin films, realizing an acoustic spin splitter. In an altermagnet, both electrons and magnons are spin polarized [2], and we show that a SAW can be used to drive a spin current carried by both electrons and magnons. The acoustic spin splitter we propose can therefore be implemented in both metallic and insulating altermagnetic thin films.

We study a realistic setup, and propose to use a heavy metal layer to convert the spin current in a directly measurable charge current. For representative parameters, we calculate the expected spin current and inverse spin Hall voltage in a Platinum layer. Finally, we show how choosing different SAW frequencies can be used to further tune the generated spin current, showcasing the versatility of the acoustic spin splitter for spintronics applications.

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Harnessing Orbital Hall Effect in Spin-Orbit Torque MRAM

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The spin Hall effect (SHE) and orbital Hall effect (OHE) are promising mechanisms for magnetization control in spintronic devices [**1-3**]. Ru exhibits one of the highest orbital Hall conductivities, surpassing Pt's spin Hall conductivity by a factor of four [**4**]. In my poster, we address two key questions: 1) How can the experimental differentiation between SHE and OHE be achieved? 2) To what extent does a large OHE contribute to torque enhancement and reduced switching current density in orbital-assisted spin-orbit torque (SOT) MRAM devices?

To investigate this, we first examine and quantify the significant orbital Hall torque in ferromagnet (FM)/non-ferromagnet (NFM) heterostructures, particularly in low spin-orbit coupling (SOC) NFMs. We distinguish between the orbital Hall effect and spin Hall effect mechanisms by analyzing the sign of the measured torque. Our results show that Ru, as an orbital layer, exhibits higher torque efficiency compared to Nb [**5**].

We then utilize the enhanced OHE in various OHE layers to extract torque and switching current densities for Co/Ni multilayers with perpendicular magnetic anisotropy. Results show a 30% torque enhancement in the Ru/Pt OHE layer, reducing switching current density by 20% compared to pure Pt, highlighting the potential of leveraging OHE for improved SOT MRAM performance [**6**]. Additionally, we found a thermal stability factor exceeding 60 kBT, ensuring over 10 years of data retention, while maintaining the perpendicular magnetic anisotropy (500 mT) [**6**].

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Magnetic structure effect of magneto-optical Kerr effect, anomalous Hall effect, and spin-splitting on altermagnetic RuO_2

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RuO_2 is one of prototype for recently suggested altermagnetic material [1, 2] although the exact magnetic structure is still in debate [3-5]. Here first-principles study on altermagnetic RuO_2 is presented. First, three possible magnetic structures, magnetization along [001], [010], and [110], are analyzed with magnetic space group. Then, the magneto-optical Kerr effect (MOKE) and the anomalous Hall effect (AHE) are calculated. When magnetization is along [001], MOKE and AHE vanish identically. On the other hand, MOKE and AHE of other magnetic structures are nonzero. Robust spin-splitting is demonstrated with group of k analysis.

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Universal symmetry-protected persistent spin textures in nonmagnetic solids

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The significance of Mendeleev's periodic table extends beyond the classification of elements; it lies in its remarkable predictive power for discovering new elements and properties, revealing the underlying symmetrical patterns of nature that were only fully understood with the advent of quantum mechanics. Fundamental material properties, such as electron transport and magnetism, are also governed by crystal symmetry. In particular, spin transport depends on the spin polarization of electronic states, and recently discovered materials where the electron spin polarization is independent of momentum - a property known as a persistent spin texture (PST) - promise extended spin lifetime and efficient spin accumulation. In this work, we establish the general conditions for the existence of symmetry-protected PST in bulk crystals. By systematically analyzing all 230 crystallographic space groups, similar to elements in the periodic table, we demonstrate that PST is universally present in all nonmagnetic solids lacking inversion symmetry. Using group theory, we identify the regions within the Brillouin zone that host PST and determine the corresponding directions of spin polarization. Our findings, supported by first-principles calculations of representative materials, open the route for discovering robust spintronic materials based on PST.

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Orbitronics for next-generation memory devices

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Recently, it has been theoretically predicted that analogous to the spin Hall effect and interfacial Rashba Edelstein effect, their orbital counterparts, namely, the orbital Hall effect (OHE) and orbital Rashba Edelstein effect (OREE), may also exist[1]. These effects utilize the orbital degree of freedom of the electrons and are predicted to be more efficient at least by an order of magnitude than their spin counterparts[2]. More importantly, one does not require a nonmagnetic metal (NM) with a large spin-orbit coupling (SOC) to host these effects. The orbital effects can efficiently convert the charge current (I_C) into orbital current (I_L). When a ferromagnetic (FM) layer is deposited in the vicinity of NM, the I_L can exert torque on the magnetization through I_L-I_S conversion either inside the FM[3] or in an additional convertor layer[4].

Here, we will present our recent results, demonstrating an unambiguous generation of torque on FM due to I_L generation at NM layer in NM/FM bilayers[5]. We studied Ru (Nb)/Ni (CoFeB) bilayers and observed a large damping-like torque (DLT) in Ru (Nb)/Ni bilayers. In contrast, the same was found to be very small in Ru (Nb)/CoFeB bilayers. Such a dependence of DLT on the FM layer indicates that the origin of observed torque is OHE, generated in the Ru (Nb) layer. Furthermore, we studied the Ni thickness dependence of DLT and observed a long-range action of the DLT originating from the OHE of studied NMs. Our results also indicate that Ni is a better I_L-I_S convertor. However, CoFeB is highly compatible with applications. Therefore, we strategically inserted a Pt layer between the NM and FM materials. This configuration successfully demonstrated an efficient I_L-I_S conversion inside Pt and resulted in efficient torques on the FM. In conclusion, our findings not only uncover the origin of the OHE in NMs with relatively low SOC but also represent a step forward in the development of energy-efficient magnetic random access memory devices for green technologies.

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Lateral Solid Phase Epitaxy of Yttrium Iron Garnet

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Lateral solid phase epitaxy of yttrium iron garnet (YIG) enables the fabrication of single crystalline YIG on top of non-lattice matched carrier materials and therefore the realization of single crystalline, nonplanar YIG structures. We demonstrate the lateral solid phase epitaxy of YIG over an artificial edge, such that the crystallization direction is perpendicular to the initial seed. We use micropatterned SiO_x mesas on top of single crystalline garnet seed substrates to study the lateral crystallization across and on top of the SiO_x. We find that YIG retains the crystal orientation of the substrate not only when in direct contact with the seed garnet, but also across the edge on top of the SiO_x mesa. By controlling the crystallization parameters, it is possible to almost completely suppress the formation of polycrystals and to enable epitaxial growth of single crystalline YIG on top of SiO_x. From a series of annealing experiments, we extract the activation energy and the velocity prefactor for the lateral crystallization of YIG. Our results pave the way to engineer single crystalline non-planar yttrium iron garnet structures with controlled crystal orientation.

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Spin Hall magnetoresistance at the altermagnetic insulator/Pt interface

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Spin Hall magnetoresistance (SMR) occurs in heterostructures typically comprising of an insulating magnet and a heavy metal, and relies on the concerted action of spin Hall (SHE) and inverse spin Hall effects (ISHE) [1, 2]. The flow of spins across the interface depends on the relative orientations of polarization of the conduction electrons in Pt and the magnetization direction in the magnetic insulator [2]. In the minimalistic model, SMR is attributed to the spin-transfer torque being active or inactive [2] while recent models take into account also the effect of the ISHE induced magnon excitations [3, 4, 5].

In this poster, we will show results on SMR signal in Pt interfaced with an altermagnetic insulator, $Ba_2CoGe_2O_7$. We have fabricated Pt Hall bars with orientations along different high-symmetry axes on polished single crystals of BCGO in order to study the anisotropy of the SMR. We observe a surprisingly high SMR ratio considering a non-optimized *ex situ* interface between Pt and BCGO and a relatively thick Pt layer. The SMR ratio we observe is already comparable to that of heterostructures comprising of conventional antiferromagnets with *in situ* grown Pt. Moreover, we observe a systematic dependence of the SMR ratio on the orientation of the Hall bar. We will discuss our results in the context of altermagnetic magnon excitations contributing to the SMR signal.

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Quantum weak measurement of magneto-optic and spintronic effects

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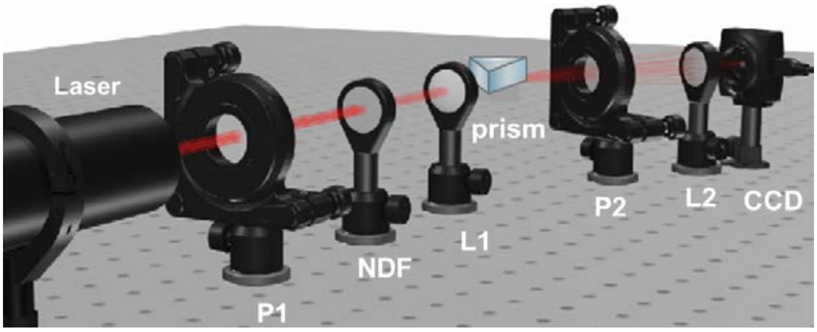
The furthering of scientific research and the emergence of new technologies relies on our capability to measure physical quantities with ultrahigh precision. Quantum weak measurements have emerged as a highly sensitive technique for probing magneto-optic and spintronic effects. By leveraging weak value amplification, these measurements allow for ultra-precise detection of light matter interactions in thin films, where traditional methods tend to fail due to low signal intensity. The experimental setup combines quantum weak value amplification with Spin Hall Effect of Light (SHEL) and Magneto-Optic Kerr Effect (MOKE) to measure magnetic and optical responses from materials like ferromagnetic heterostructures and 2D transition metal dichalcogenides. We intend to probe, theoretically and experimentally, weak spin-optical effects like spin hall effect, spin Hall effect of light, beam deflections, hysteresis and other polarization effects in an optical network. Moreover, this approach provides a versatile platform for investigating the fundamental quantum behaviors of nanomaterials, helping to unlock new functionalities in next-generation materials.



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Spin and orbital Hall effect in non-magnetic transition metals: extrinsic vs. intrinsic contributionsS. Mankovsky and H. Ebert

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Kubo's linear response formalism has been used to study the orbital Hall effect (OHE) for non-magnetic undoped and doped transition metal systems, focusing on the impact of different types of disorder. Corresponding first-principles calculations of the orbital Hall conductivity (OHC) were performed making use of the KKR Green function method that allows in particular to monitor the impact of the vertex corrections on the OHC. The doping- and temperature-dependence of the OHC have been investigated and compared with corresponding results for the spin Hall conductivity (SHC). The temperature dependent properties of the OHC and SHC determined by thermally induced lattice vibrations have been accounted for making use of the alloy analogy model. A strong difference has been found between the results for undoped and doped metallic systems. For elemental systems at finite temperature a dominating role of the intrinsic contribution to the temperature-dependent OH and SH conductivities is found (Fig. 1). Furthermore, the electron-phonon skew scattering has a negligible contribution to the extrinsic OHC and SHC in pure metal systems. The different temperature dependent behavior of the intrinsic SOC-independent OHC and SOC-driven SCH indicates a non-trivial relationship between these quantities. It is shown, that in contrast to the intrinsic part of the OH and SH conductivities, the extrinsic contributions in doped systems (Fig. 2) are determined by spin-orbit coupling for both of them. It is dominating at low temperature but strongly decreases at higher temperatures due to the increasing impact of the electron-phonon scattering (Fig. 3).

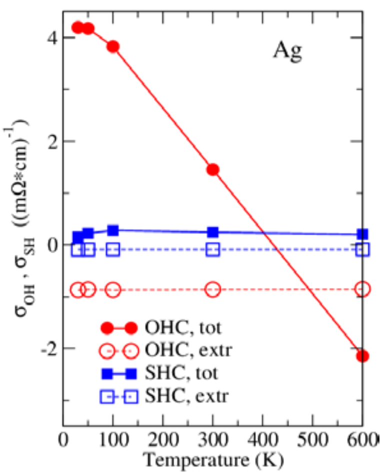

Fig. 1

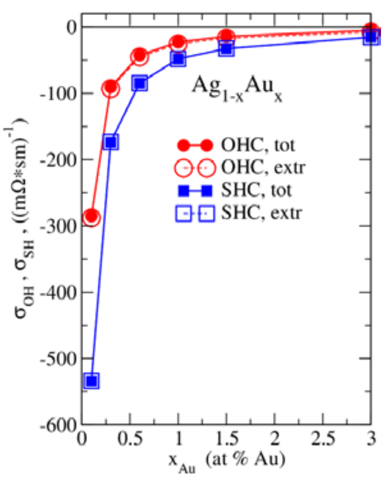

Fig. 2

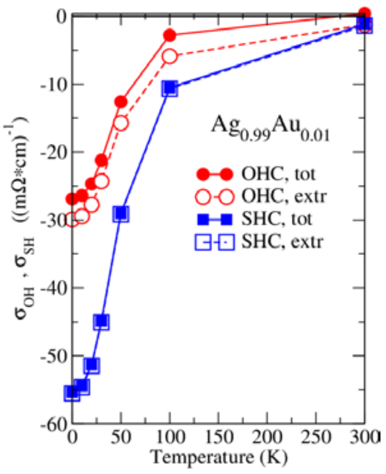

Fig. 3

True amplification of propagating spin-waves using spin orbit torque

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Spin-waves can carry information at the nanoscale at extremely low power, a promising property that makes them a prime candidate for low-energy computing. However, the spin-waves couple to their environment and their intensity decays exponentially during their propagation, before any meaningful computation can be done. The recent discovery of spin-orbit torque provided an elegant mechanism to apply an anti-damping torque to spin-waves in extended magnonic structures. This torque acts on the spin-waves a bit like the wind on the sea, amplifying all the incoherent, thermally excited, spin-waves. In early experiments this would create a “stormy sea” of incoherent spin-waves that strongly scatters rf-excited coherent spin-waves, preventing their amplification [1].

In this work [2] (fig.1a), we tackle this long-standing problem by engineering the material magnetic properties to control the amplified incoherent magnons and their detrimental non-linear interactions. We use a favorable time window (the “calm before the storm”) to reach the elusive amplification regime for the first time, where the rf-excited coherent SW amplitude grows exponentially as it propagates (fig.1b).

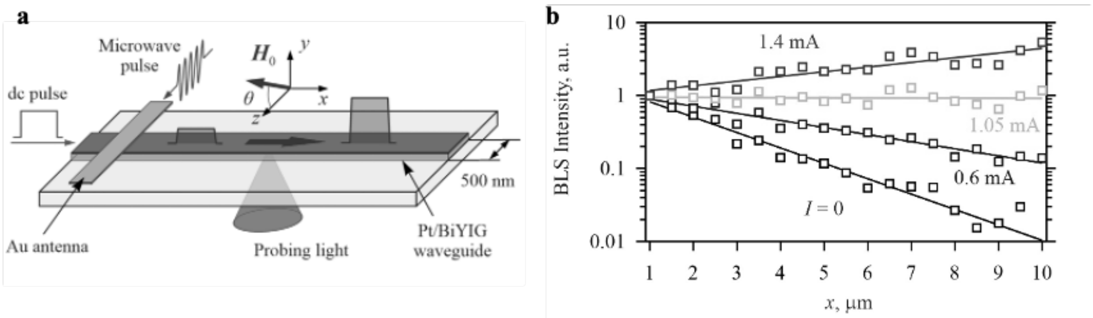

Figure 1: (a) Schematics of the experiment. Spin-wave pulses are excited by an Au antenna and propagate in a BiYIG(20 nm)/Pt(6 nm) waveguide. In-plane dc current flowing in the Pt layer exerts anti-damping torque on the magnetization. (b) Spin-wave amplitude measured by µ-BLS at different dc currents, as labelled. Symbols show the experimental data. Data obtained at f = 5.025 GHz and H_0 = 1.8 kOe applied at 30°.

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Setting up current induced spin-wave Doppler shift experiments

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The coupling of coherent spin waves with incoherent spin transport, e.g. spin-polarized electrons, leads to transfer of angular momentum via spintransfer-toque enabling the so-called spin-wave Doppler shift. Our research aims to deepen the insight into this fundamental process, which has a notable influence for the development of next-generation memory devices and other spintronic applications. The propagating spin wave spectroscopy is used to detect a possible Doppler shift in spin waves generated by charge currents in a 20 nm thick Ni81Fe19 strip. The experiments are conducted using a vector network analyser with an in- and out-of-plane magnetic field, applied perpendicular to the direction of the propagating spin wave, which is excited with the use of a coplanar waveguide design. In contrast to published works in the literature, this study uses Ta2O5 as an insulating material, chosen for its high permittivity, which could significantly contribute to a better impedance matching of the system. First optimization steps regarding impedance matching, antenna design, and performance analysis will be discussed in this contribution.

Direct observation of current-induced orbital angular momentum in a light 3d metal

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Conversion of charge to orbital angular momentum through the orbital Hall effect (OHE) holds transformative potential for the development of orbital-based electronics, the so-called emerging field of *orbitronics* [1]. Although first-principles calculations have predicted very large OHE conductivities in light 3d metals [2,3], it is very challenging to directly observe the electrically generated orbital accumulation caused by the OHE. Here we employ two methods to detect the orbital accumulation in light 3d metals: the magneto-optical Kerr effect (MOKE, see [4,5]) and the electron magnetic circular dichroism (EMCD) in a transmission electron microscope [6]. Using MOKE detection on a thin Cr film, we measure an orbital polarization consistent with all signatures of OHE and estimate an orbital diffusion length l_o ~ 6.6 nm. Employing the EMCD *in operando* on a thin Ti film, we measure with nanometer scale resolution the samples' outer perimeter. Employing the EMCD sum rules, we detect a sizable orbital accumulation and determine an orbital diffusion length l_o ~ 7.3 nm. Our measurements reveal a surprising dependence of the orbital diffusion length on the nano-structural morphology.

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Cavity-Enhanced Optical Manipulation of Antiferromagnetic Magnon-Pairs

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The optical manipulation of magnon states in antiferromagnets (AFMs) holds significant potential for advancing AFM-based computing devices [1-3]. In particular, two-magnon Raman scattering processes are known to generate entangled magnon-pairs with opposite momenta [4]. We propose to harness the dynamical backaction of a driven optical cavity coupled to these processes, to obtain steady states of squeezed magnon-pairs, represented by squeezed Perelomov coherent states. The system's dynamics can be controlled by the strength and detuning of the optical drive and by the cavity losses. In the limit of a fast (or lossy) cavity, we obtain an effective equation of motion in the Perelomov representation, in terms of a light-induced frequency shift and a collective induced dissipation which sign can be controlled by the detuning of the drive. In the red-detuned regime, a critical power threshold defines a region where magnon-pair operators exhibit squeezing—a resource for quantum information— marked by distinct attractor points. Beyond this threshold, the system evolves to limit cycles of magnon-pairs. In contrast, for resonant and blue detuning regimes, the magnon-pair dynamics exhibit limit cycles and chaotic phases, respectively, for low and high pump powers. Observing strongly squeezed states, auto-oscillating limit cycles, and chaos in this platform presents promising opportunities for future quantum information processing, communication developments, and materials studies [5].

Fig7.pNG

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Competing Ordinary and Hanle Magnetoresistance in Pt and Ti Thin Films

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One of the key elements in spintronics research is the spin Hall effect, allowing to generate spin currents from charge currents. A large spin Hall effect is observed in materials with strong spin orbit coupling, e.g., Pt [1]. Recent research suggests the existence of an orbital Hall effect [2], the orbital analogue to the spin Hall effect, which also arises in weakly spin orbit coupled materials like Ti, Mn or Cr. In Pt both effects are predicted to coexist [3].
In any of these materials, a magnetic field perpendicular to the spin or orbital accumulation leads to additional Hanle dephasing and thereby the Hanle magnetoresistance (MR) [4,5]. Aiming to reveal the MR behavior of a material with both spin and orbital Hall effect, we have studied the MR of Pt thin films over a wide range of thicknesses. Careful evaluation shows that the MR of our textured samples is dominated by the so-called ordinary MR, while the Hanle effect does not play a significant role. Analyzing the intrinsic properties of Pt films deposited by different groups, we find that next to the resistivity, also the structural properties of the film influence which MR dominates. We further show that this correlation can be found in both spin Hall active materials like Pt and orbital Hall active materials, like Ti [6]. We find that for both materials, crystalline samples show a MR consistent with the ordinary MR, whereas a large Hanle MR is present in samples without apparent structural order. We conclude that in all materials exhibiting a spin or orbital Hall effect, the Hanle MR and the ordinary MR coexist, and that the sample's purity and crystallinity determines which MR dominates.

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Spin-spin interaction mediated by chiral phonons

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The interaction between spin and lattice degrees of freedom is a key aspect in the explanation of several well-known physical effects, such as the Einstein-de Haas effect[1,2], demagnetization on an ultrafast timescale[3,4], and avoided crossing in combined phonon-magnon spectra[5]. In this work, we specifically investigate the role of chiral phonons in the propagation of a long-ranged effective spin-spin interaction by a combined molecular dynamics and atomistic spin dynamics approach[6].
In pure spin dynamics simulations, some terms, such as the on-site anisotropy do not conserve angular momentum, which in our model, taking into account the lattice degrees of freedom, causes a transfer thereof into the lattice, and thus the emergence of chiral phonons. Therefore, a precessing spin can excite a phonon carrying angular momentum, and such a phonon can cause a spin to precess in turn, creating an effective spin-spin interaction. As this interaction is mediated by phonons, it can propagate event through non-magnetic domains. We investigate and quantify this interaction in terms of temperature dependent spin-spin correlation functions and coupled magnon-phonon dispersion relations.

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Energy-efficient spin Hall nano-oscillators using PtBi alloys

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Damping-like torque efficiency (θ_{DL}) emanating from the bulk spin Hall effect (SHE) [1], can drive auto-oscillations (AO) in nano-constriction based spin Hall nano-oscillators (SHNOs) [2]. For robust, energy-efficient, and sustained oscillation, a reduction in the threshold current (I_{th}) is of paramount importance, which can be achieved in materials with a high θ_{DL}. However, achieving a higher θ_{DL} from bulk SHE often comes at the expense of a higher longitudinal resistivity, ρ_{xx}. Therefore, Pt based alloys have emerged as a viable alternative to supplant the traditional 5*d* transition materials [3]. In this work, we study the SHE and AO by fabricating SHNOs on Pt, $Pt_{94}Bi_6$ and CoFeB based heterostructures. We find the θ_{DL} to increase from 0.096 (Pt) to 0.216 ($Pt_{94}Bi_6$) in exchange of a lower increase in ρ_{xx} from 88 μΩ-cm (Pt) to 155 μΩ-cm ($Pt_{94}Bi_6$) using DC-bias spin-torque ferromagnetic resonance (ST-FMR) measurements. Subsequently, we perform the AO measurements at a fixed in-plane angle, θ=20° and out-of plane angle, φ=84° in the presence of an external magnetic field, H_{ext}, and a varying DC-bias, I_{dc} from ≈0.4 to 1.6 mA for 180 nm width, w based SHNO. We demonstrate a ≈31% reduction in I_{th} from 1.1 mA (Pt) to 0.75 mA ($Pt_{94}Bi_6$). Our findings of a high θ_{DL}, a reduced I_{th}, along with a better trade-off in ρ_{xx}, provides an alternative path to design energy-efficient SHNOs using Pt-based alloys, beyond the archetypal 5*d* transition materials such as Pt.

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Exchange magnon-photon coupling in metallic thin films

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Cavity magnonics has become an intriguing field of research due to its potential to enable next-generation technologies centered around controlling information exchange in hybrid resonant systems. Investigating the tunable nature of magnon-photon coupling, and the critical effects of dissipation, are key to advancing the field. Study of variation in the dissipation of different magnon modes is rare in the context of cavity dynamics, where works have so far only addressed the effect of milli-Kelvin temperatures on magnetic spheres [1]. Here we report on the observation of coupling between the first-order exchange magnon mode in metallic thin film Permalloy (Py) with a cavity photon mode at room temperature. In contrast to widespread magnetic insulators such as Yttrium Iron Garnet (YIG), in metals like Py at 100nm and above, the first-order magnon mode exhibits lower dissipation than the Kittel mode, something which has been observed in previous studies in isolated Py systems [2]. At the same time, this exchange mode maintains similar levels of coupling strength to that of the Kittel mode, meaning higher cooperativity is possible. This finding may also have future implications for the dynamic tuning of cavity magnonic systems between different coupling regimes, such as the so called Purcell and strong-coupling regimes.

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Temperature-tunable coupling of ferromagnetic and antiferromagnetic spin dynamics in hybrid bilayer systems

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We investigate the temperature-dependent spin dynamics in α-Fe_2O_3/Py ($Ni_{80}Fe_{20}$) heterostructures using Cryogenic Ferromagnetic Resonance (Cryo-FMR) Spectroscopy. Our study encompasses a broad temperature range, including both above and below the Morin transition temperature ($T_M \approx 260$ K). Obtained results reveal that the resonance frequency of ferromagnetic uniform mode significantly enhances up to 12 GHz at 40 K. The interfacial exchange coupling between α-Fe_2O_3 and Py 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 Py. These findings highlight the potential for temperature-tunable spin dynamics in AFM/FM heterostructures and offer insights into the design of advanced magneto-electronic devices with controlled resonance frequencies.

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Magnon-Phonon Coupling in Polycrystalline Metallic Thin Films

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The coupling between the quantized excitations of the spin system (magnons) and the lattice (phonons) regained interest due to potential applications in quantum devices. We report the coherent excitation of elastic waves in a metallic ferromagnetic Co25Fe75 thin film by driving its Kittel modes, leading to the excitation of transverse acoustic phonons in the substrate forming a bulk acoustic wave resonator. Our results agree well with model calculations for the effective coupling strength.

Magnon-phonon hybridization and chiral phonons in bcc Fe

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Over the last couple of years, an ever increasing amount of research has focused on the role of the angular momentum of phonons, particularly in the field in ultrafast magnetization dynamics [1][2]. Phonon angular momentum arises from circular (or elliptical) orbital motions of atoms around their equilibrium lattice positions and the emerging collective motion is called a chiral phonon mode. The emergence of chiral phonon modes is fundamentally linked to a breaking of combined inversion (P) and time-reversal (T) symmetry. While it is well established that a structural P-symmetry breaking, e.g. in the crystal structure, can give rise to chiral phonon modes, their emergence in P-symmetric systems as a result of T-symmetry breaking by coupling to electronic angular momentum has only recently gained attention [3].

Here, we investigate magnon-phonon coupling in bcc Fe from first principles based on a recently developed framework [4].
We report the hybridization between magnon and phonon modes to magnon-polarons, leading to the formation of a gap (or "avoided crossing") in the associated dispersion relation.
Along certain high-symmetry lines we find that, as a result of the coupling with magnons, otherwise degenerate transverse phonon modes are transformed into chiral phonons modes with an energy splitting between left- and right-handed phonon modes.

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Misfit dislocations and spin pumping in epitaxial Fe/Rh bilayers

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We investigate the growth and epitaxy of Rh on Fe(001)/GaAs(001)-4x6 ultrathin bilayer deposited using molecular beam epitaxy in ultrahigh vacuum (5E-10 mbar). Between Fe and Rh exists a lattice mismatch of ≈6%. We use in situ low-energy electron diffraction (LEED) and Auger electron spectroscopy (AES) during growth, as well as cross-sectional transmission electron microscopy (TEM), X-ray diffraction (XRD) and x-ray circular magnetic dichroism (XMCD) to show, that the Fe/Rh interface is atomically sharp and Rh is not spin polarised. The fcc-Rh layers grow 45° rotated with respect to the bcc-Fe lattice, that is Rh(001)[110] || Fe(001)[100] to minimise the lattice mismatch. Cross-section HRTEM reveals high crystallinity with a misfit dislocation defect density of 0.2 defects/nm at the interface with Fe. Rh grows in a layer-like Stranski-Krastanov mode on the Fe substrate [1]. Using broadband ferromagnetic resonance, we determine a high spin pumping efficiency with a spin-mixing conductance $g_{\uparrow\downarrow}$ =(2.5 $\pm$0.2)10^{19} m^{-2} at room temperature comparable to that of Fe/Pt bilayers [2, 3].

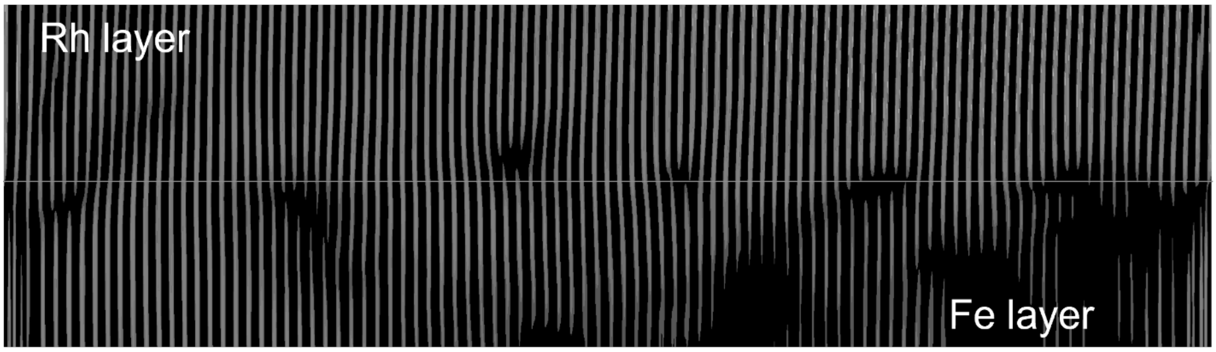

Figure 1: FFT filtered STEM image of the Fe/Rh interface, only the Rh[020] and Fe[011] diffraction peaks were used for iFFT filtering. The horizontal line is a guide to the eye indicating the interface. Each vertical line represents a column of atoms. The splitting at the interface shows edge dislocation defects (dark areas of missing colour information), which allow Rh to relax its lattice.

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Spin-orbit torques in ferromagnetic heterostructures

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Spin-orbit torques (SOTs) are an emerging phenomenon that enables the efficient manipulation of spintronic devices. Typically, SOTs are generated in bilayers of ferromagnets and heavy metals such as Pt, Ta or W. Instead, our ferromagnetic heterostructures are based on perpendicular magnetic anisotropy (PMA) multilayers of [Co/Ni] and [Co/Pt] that generate SOTs of even and odd symmetry in adjacent CoFeB thin films with in-plane magnetic anisotropy (IMA) as shown in Fig.1(a).

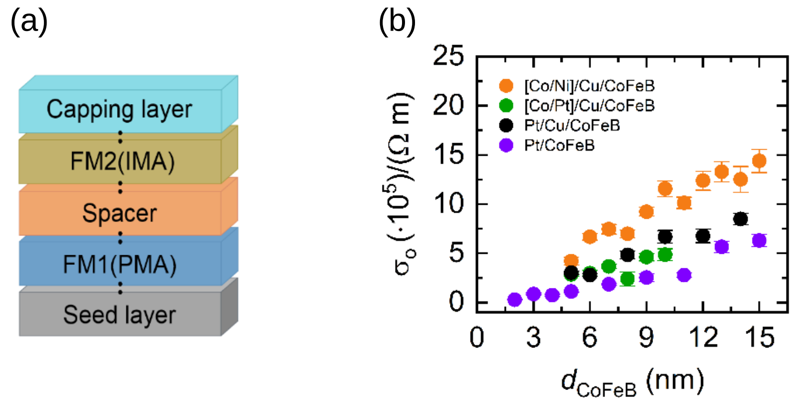

Figure 1. (a) Schematic view of PMA/IMA hybrid thin film stack. (b) SOTs of odd symmetry σ_o for [Co/Ni], [Co/Pt], Pt/Cu and Pt based heterostructures.

We investigate the SOTs in these heterostructures using vector network analyser ferromagnetic resonance spectroscopy (VNA-FMR). In our experiments [1], we excite spin dynamics in the CoFeB layer and inductively detect the generated electrical currents in the PMA layers [2]. In our experiments, we found that our multilayers generate SOTs comparable in magnitude to Pt (see Fig.1(b)), in agreement with first-principles calculations. Additionally, we observed a pronounced dependence of the SOTs on the CoFeB layer thickness due to the self-induced torque [3] generated in CoFeB. We acknowledge financial support by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) via TRR 173 “Spin+X” 268565370.

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Orbital torques and orbital pumping in two-dimensional rare-earth dichalcogenides

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The design of two-dimensional (2D) materials presents exciting opportunities in modern spintronics. In this context, GdX_2 and EuX_2 [1,2] monolayers exhibit pronounced charge, spin, and orbital Hall effects while also demonstrating robust magnetism. Rare-earth-based dichalcogenides, which possess strong spin-orbit interactions and pronounced orbital polarization, could hold significant potential for spin-orbit torque (SOT) applications. This study investigates ferromagnetic Janus H-phase monolayers of rare-earth dichalcogenides, demonstrating that their colossal orbital response, driven by *f*-electrons, leads to substantial SOT. Additionally, orbital torques can drive strong in-plane orbital currents, making *f*-based 2D materials a promising platform for future orbitronic and spintronic technologies.

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