Towards Functional van der Waals magnets by Unlocking Synergies with Orbitronics, Magnonics, Altermagnetism, and Optics

803. WE-Heraeus-Seminar

02 - 05 January 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 803. WE-Heraeus-Seminar:

Two dimensional layered van der Waals materials are a new exciting class of materials and one of the central focuses of present condensed matter research. Although intrinsically magnetic layered materials were identified only a few years ago, the magnetic van der Waals materials are already an exceptionally dynamic and growing research field on many fronts.

On the one hand, these materials exhibit novel electronic, optical and topologically protected states in the regime of monolayers, on the other hand, the layer-by-layer coupling to semiconductors, superconductors, charge density waves or even the twisting of the layers enables a variety of potential functionalities that make this class of materials very interesting for applications, for example, in spintronics.

The goal of this workshop is to introduce the broad solid-state magnetism community to this new class of materials and to present their potential, while at the same time connecting to emerging topics in magnonics, orbitronics, altermagnetism, and ultrafast optics to identify novel synergies. International experts in van der Waals systems and the aforementioned topics will present the most recent developments and a lot of space for discussions is offered. Participants of the seminar are invited to present their research at poster sessions.

Scientific Organizers:

Dr. Helena Reichlova	Technical University Dresden, Germany E-mail: helena.reichlov@tu-dresden.de
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Introduction

Venue:

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Registration:

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

Program

Program

Tuesday, 2 January 2024

17:00 – 21:00	Registration	
From 18:00	*BUFFET SUPPER*	
19:30 – 19:45	Scientific organizers	**Opening and Welcome**
19:45 – 20:30	Je-Geun Park	**Birth and future of van der Waals magnetism**

Wednesday, 3 January 2024

08:00 – 09:00	*BREAKFAST*	
09:00 – 09:45	Hidekazu Kurebayashi	**Spin dynamics of $Cr_2Ge_2Te_6$ probed by superconducting resonators and spin-orbit torques in electrostatically gated $Cr_2Ge_2Te_6$**
09:45 – 10:30	Anna Delin	**Magnetism and spin dynamics in low-dimensional materials**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Amilcar Bedoya-Pinto	**Realization of easy-plane magnetism in a van der Waals monolayer**
11:45 – 12:00	Jonah Elias Nitschke	**Unveiling transient dynamics of d-d excitations in the van der Waals antiferromagnet FePS3 via time-resolved ARPES**
12:00 – 12:15	Elina Zhakina	**Curvilinear superconducting vortices in three-dimensional nanoarchitectures**
12:20	*Conference Photo*	
12:30	*LUNCH*	

Program

Wednesday, 3 January 2024

13:45 – 14:30	Sayantika Bhowal	**Electrical control of the orbital degrees of freedom in van der Waals materials**
14:30 – 15:15	Claire Donnelly	**Mapping and controlling three dimensional spin textures**
15:15 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	Dmytro Afanasief	**Shining light on van der Waals antiferromagnets**
16:45 – 17:30	Eva Schmoranzerova	**Effect of Beam Shift on Helicity Dependent Photoresistance Measurement**
17:30 – 18:15	Timo Kuschel	**Cubic magneto-optic Kerr effect in Ni thin films**
18:15	*HERAEUS DINNER* *(social event with cold & warm buffet and complimentary drinks)*	
19:30	**Posters**	

Program

Thursday, 4 January 2024

08:00 – 09:00	*BREAKFAST*	
09:00 – 09:45	Tomas Jungwirth	**Altermagnetism: The third magnetic class**
09:45 – 10:30	Dominik Kriegner	**Altermagnetic properties of MnTe thin films**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Jeroen van den Brink	**Domain wall properties, fluctuation induced piezomagnetism and anomalous hall effects in altermagnets — models and materials**
11:45 – 12:00	Rhea Hoyer	**Zero-Field Crystal Thermal Hall Effect in Insulating Altermagnets**
12:00 – 12:15	Lishu Zhang	**Van der Waals Spin-Orbit Torque Antiferromagnetic Memory**
12:30	*LUNCH*	
13:45 – 15:15	**Posters, Discussions**	
15:15 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	Silvia Viola Kusminskiy	**Light-Matter Interaction in Antiferromagnets: probing and controlling antiferromagnetic magnons**
16:45 – 17:30	Yixi Su	**Topological magnons in van der Waals ferromagnets CrXTe3 (X = Si, Ge)**
17:30 – 18:15	Antonio Costa	**Theory of spin excitations in van der Waals heteroestructures**
18:15	*DINNER*	
19:30 – 19:45	**Poster Awards**	
19:45 – 20:30	Ursula Wurstbauer	**Strong exciton-phonon coupling in 2D magnetic semiconductor CrSBr**

Program

Friday, 5 January 2024

08:00 – 09:00	*BREAKFAST*	
09:00 – 09:45	Dongwook Go	**On the reciprocity between direct and inverse orbital Hall effects**
09:45 – 10:30	Mathias Kläui	**Topological Spin Structures and Spin-Orbitronics in ferromagnets and antiferromagnets: from van der Waals 2D systems to multilayer heterostructures**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Annika Johansson	**Spin and orbital Edelstein effects in topological oxides and Rashba multilayers**
11:45 – 12:30	Pietro Gambardella	**Orbital torques and magnetoresistance in metallic heterostructures**
12:30 – 13:45	*LUNCH*	

End of the seminar and departure

Posters

Posters

Aisha Aqeel	**Spin Dynamics in Complex Magnetic Materials**
Daniel Autrey	**Tuning the Magnetic Properties of Two-Dimensional MXenes by Chemical Etching**
Venkata Krishna Bharadwaj	**Supercell altermagnet MnSe2: A tale of two configurations**
Lucas Caretta	**Out-of-plane spin torques via symmetry engineering in quasi-2D oxides**
Dimos Chatzichrysafis	**Thermal Hall effect from magnon many-body skew scattering**
Hans-Joachim Elmers	**Observation of time-reversal symmetry breaking in the band structure of altermagnetic RuO_2**
Cornelius Gahl	**Electron Dynamics in the Conduction Band of the van-der-Waals Magnet $Cr_2Ge_2Te_6$**
Mateusz Gołębiewski	**Collective Spin-Wave Dynamics in Gyroidal Nanostructures**
Olena Gomonay	**Structure, control and dynamics of altermagnetic textures**
Holger Grisk	**Magnetization manipulation with Terahertz electric currents**
Pieter Gunnink	**Zero-Frequency Chiral Magnonic Edge States Protected by Nonequilibrium Topology**
Rahul Gupta	**Harnessing Orbital Hall Effect Materials for Efficient Magnetization Control with In-plane and Perpendicular Magnetic Anisotropic Ferromagnets**

Posters

Luca Haag	**Theoretical study of optical excitation effects in RuO2**
Sonia Haddad	**Twisted bilayer graphene reveals its flat bands under spin pumping**
Mohammad Hemmati	**Ab inito study of the van der Waals Superconductor NbSe2**
Moritz Hirschmann	**Topological nodal planes in hexagonal space groups**
Matthijs Jansen	**Unraveling light-driven spin transfer and hot carrier dynamics by EUV magneto-optical spectroscopy**
Oleg Janson	**DFT insights into the electronic structure and optical properties of the vdW magnets $FePS_3$ and $NiPS_3$**
Roger Kalvig	**Local magnetic fields in a MnBi2Te4/(Bi2Te3)n topological insulator studied by NMR**
Tamer Karaman	**Exploring Chirality and Topology in Ferrimagnetic Multilayer Systems**
Niklas Kercher	**Spin-Orbit Torque-Driven Magnetisation Switching in a Fe_3GeTe_2-WTe_2 Heterostructure**
Sanghoon Kim	**Anisotropic-Conductivity-Induced Magnetic Phase Transition in the Fe5-xGeTe2 with Current In-Plane Geometry**
Volodymyr Kravchuk	**Thermodynamic properties of the checkerboard model of altermagnet**
Dongzhe Li	**Ab initio study of all-electrical skyrmion detection in van der Waals tunnel junctions**
Eunji Lim	**Memristive behavior of $L1_0$-FePt based granular film for realizing the Neural network**

Posters

Kai Litzius	**Dynamic Investigation of Magnetic Skyrmions in the 2D van der Waals Magnet Fe3GeTe2**
Sina Mehboodi	**Study of the chiral magnet Cu_2OSeO_3 using resonant X-ray elastic scattering**
Valentin Mischke	**Exploring the Electronic Structure of Fe4GeTe2 for Low-Dimensional Spintronic Devices**
Shubhada Prashant Patil	**Low-temperature XPEEM to study functional properties of 2D materials**
Jiri Pospisil	**Large Orbital moment in van der Waals halide VI_3**
Aravind Puthirath Balan	**Exchange bias in fully compensated vdW $Fe_3GeTe_2/MnPS_3$ heterostructures**
Oleksandr Pylypovskyi	**Characterization of domain wall patterns in granular antiferromagnetic Cr_2O_3 films**
Ricarda Reuter	**Detection of Nanoscale Magnetic Fields with Scanning NV Magnetometry**
Javier Rial Rodriguez	**Finite size effect on the Hall response of altermagnetic Mn_5Si_3**
Karl Schiller	**Temperature-resolved photoemission measurements on the antiferromagnetic semiconductor CrSBr**
Daniel Steil	**Photo-induced transient ferromagnetism in lightly doped $LaMnO_3$ thin films**
Tim Titze	**Laser-induced real-space topology control of spin wave resonances**
Luke Alexander Turnbull	**Local control over chiral textures with curvilinear helimagnets**

Posters

Vitaliy Vasyuchka	**Coupling of ferromagnetic and antiferromagnetic spin dynamics in thin film bilayers**
Lucas Vollroth	**Exploring the impact of the inverse Faraday effect on all-optical helicity-dependent magnetization switching**
Jiří Volný	**Sliding ferroelectricity in bulk misfit layer compound $(PbS)_{1.18}VS_2$**
Jakob Walowski	**Crystal structure quality investigations in FePt granular media for all-optical helicity-dependent magnetization switching**
Marius Weber	**Ultrafast electron dynamics in altermagnetic KRu_4O_8**
Angela Wittmann	**Anisotropic Spin-to-charge Conversion in Hybrid Chiral Molecule/ Metal Systems**
Marek Wójcik	**Magnetic interactions in epitaxial films of $Mn_5(Ge_{1-x}Six)_3$ /Ge(111) : ^{55}Mn NMR study**
Stephan Wust	**Altermagnetic signatures in the ultrafast photoconductivity of RuO2**
Zekun Xue	**Magneto-transport Characterization of Pt/Fe_5GeTe_2 Heterostructure**
Mahmoud Zeer	**Promoting p-based Hall effects by p-f hybridization in Gd-based dichalcogenides**

Abstracts of Talks

(in alphabetical order)

Shining light on van der Waals antiferromagnets

D. Afanasiev[1]

[1] *Radboud Universiteit, Nijmegen, The Netherlands*

Van der Waals (vdW) magnets provide excellent opportunities for exploring the fundamentals of low-dimensional magnetism and offer possibilities for ultrathin, highly tunable spin-processing devices. Among various magnetic systems, vdW antiferromagnets (AFMs) are particularly attractive. Not only do they possess these merits, but they also exhibit an unprecedentedly fast spin response within the technologically crucial THz frequency band. However, their ground state lacking net magnetization poses a significant challenge for their practical investigation and manipulation, rendering it a topic of high scientific interest.

During my talk, I will review our recent progress in optically probing and ultrafast control of spins in transition metal phosphorus trisulfides $X\mathrm{PS}_3$ (X = Fe, Mn, Ni, etc.). These vdW AFMs form a unique platform for studies of various types of AFM spin orderings on a honeycomb lattice and have recently attracted a lot of attention due to their spin order down to a single layer 2D limit, strong spin-charge and spin-lattice correlations[1,2], possible magneto-electricity[3,4], signatures of the Berezinskii–Kosterlitz–Thouless (BKT) transition[5], and even piezochromism[6]. I will show how various AFM spin orders in these materials can be probed optically and how large-amplitude THz spin dynamics can be launched via selective optical perturbation of magnetic anisotropy, the parameter crucial for the very stability of magnetism in the 2D limit. Finally, I will present our latest results on optical switching between different macroscopic magnetic phases in the highly tunable bimetallic AFM compounds $\mathrm{Mn}_{1-x}\mathrm{Ni}_x\mathrm{PS}_3$.

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Realization of easy-plane magnetism in a van der Waals monolayer

Amilcar Bedoya-Pinto[1]

[1]*Institute of Molecular Science (ICMol), University of Valencia, Spain*

In this talk, I will present the realization of a nearly-ideal two-dimensional magnet, a $CrCl_3$ monolayer grown on Graphene/6H-SiC(0001) by molecular beam epitaxy. In-situ X-ray magnetic circular dichroism (XMCD) reveals intrinsic ferromagnetic order with easy-plane anisotropy and a 2D-XY universality class [1], indicating the first realization of a Berezinskii-Kosterlitz-Thouless (BKT) phase transition in a quasi-freestanding monolayer magnet. The implications of this discovery will be highlighted, ranging from the emergence of topological spin textures close to the BKT transition, to the possibility of superfluid spin transport across the easy-plane magnet. The important role of the van der Waals substrate interaction and the underlying crystal symmetry for the stabilization of easy-plane magnetism will be discussed, thereby providing routes to control the anisotropy of 2D magnets via growth engineering.

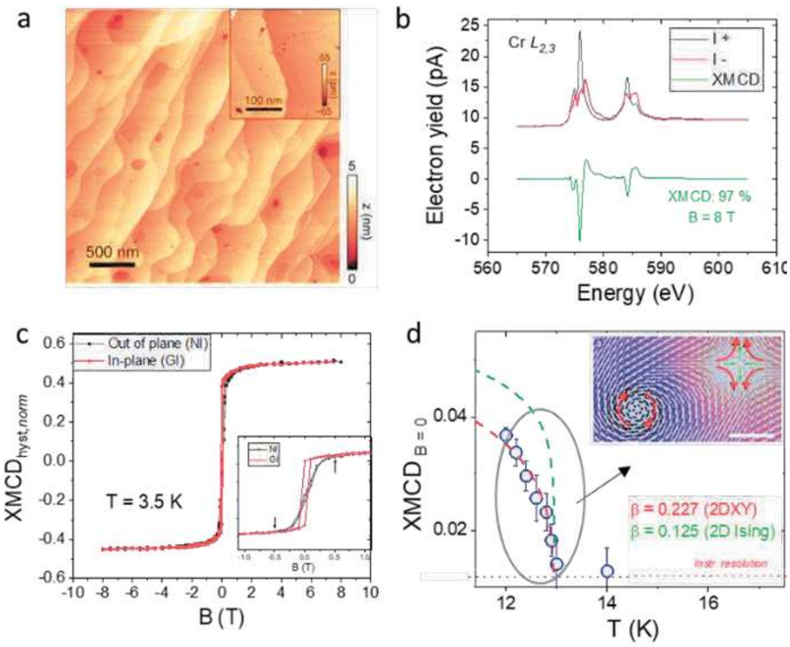

Figure 1. a) Scanning tunneling microscopy image of a monolayer $CrCl_3$ on Graphene/SiC (0001). b) XMCD spectra at the Cr $L_{2,3}$ edge, showing a large intrinsic magnetic moment at the Cr-site. c) Field-dependent XMCD intensity, denoting ferromagnetic behaviour with anisotropy fields of 0.5T (inset). d) Critical exponents at the phase transition corresponding to the 2DXY magnetic universality. The emergence of topological spin textures is expected in this regime.

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Electrical control of the orbital degrees of freedom in van der Waals materials

Sayantika Bhowal

Materials Theory, ETH Zurich, Wolfgang-Pauli-Strasse 27, 8093 Zurich, Switzerland

Electrical manipulation of the spin moments, e.g., the spin Hall effect, is at the heart of the spintronic devices with the advantage of faster processing, higher information density, and low power consumption. An analogous orbital-degrees-driven effect is the orbital Hall effect, in which an applied electric field generates a transverse orbital current. The fundamental nature of the orbital Hall effect, its large magnitude, and no dependence on the spin-orbit interaction have piqued interest in this field. These also vastly increase the potential pool of materials for orbitronic applications compared to spintronics for encoding information. Of particular interest is the van der Waals materials with or without the inversion symmetry, where intrinsic orbital moments, crucial to the desired effects, are present in the Brillouin zone of the system even in the presence of time-reversal symmetry. In my talk, I will discuss the origin of the orbital Hall effect[1,2,3], its connection to the well-known “valley Hall effect”[4], and “spin Hall effect”[1,2], and the electric current induced orbital magnetization[5] in mono-layer and bi-layers of transition metal dichalcogenides, gapped graphene, and also discuss the implications in polar metals[6,7].

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Theory of spin excitations in van der Waals heteroestructures

António T. Costa

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Spin excitations dominate the magnetic response of ferromagnetic two-dimensional crystals. The interplay between low dimensionality, reduced symmetry and spin-orbit coupling endows spin excitations in those materials with intriguing properties, such as non-trivial topology [1] and non-reciprocity [2]. Moreover, spin-orbit coupling connects spin and charge degrees of freedom, opening up paths to electrical control and detection of magnetic states. I will present a microscopic description of the spin response of nanostructured materials based on Hamiltonians for itinerant fermions [3], derived from DFT calculations. This approach incorporates spin-orbit coupling, does not rely on postulated spin models, and can be applied to insulating or conducting 2D heterostructures, with any kind of magnetic order. As specific examples, I will discuss the properties od magnons in an insulating 2D ferromagnet and in a metallic 2D ferromagnet. I will also discuss the proximity effect in a heterostructure formed by a 2D ferromagnet and graphene.

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Magnetism and spin dynamics in low-dimensional materials

A. Delin

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The conventional wisdom for a long time was that fluctuations would kill any long-range magnetic order in materials of lower dimensions than three, since continuous symmetries cannot be spontaneously broken at finite temperature in systems with sufficiently short-range interactions in dimensions $d \leq 2$. It was also thought that two-dimensional materials themselves could not be realized, since they would inevitebly spontaneously roll up into a three-dimensional configuration with lower energy. However, by introducing sufficiently high energy barriers, such low-dimensional states can indeed be created. As we all now know, the structure of two-dimensional materials like graphene can be stabilized with the help of thermal ondulations, and in low-dimensional magnetic systems, the spin-orbit coupling is an important origin of barriers protecting the long-range ordered magnetic state. This leads to a range fascinating phenomena.

In this talk, I will give an overview of our work on spin textures and dynamics in low-dimensional systems. Specifically, I will focus on our recent results on spin-lattice couplings in two-dimensional CrI_3, and our efforts to develop methods to identify both local and global minima in highly convoluted spin-Hamiltonian potential energy surfaces.

Mapping and controlling three dimensional spin textures

Claire Donnelly[1]

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Three dimensional magnetic systems promise significant opportunities for applications, for example providing higher density devices and new functionalities associated with complex topology and greater degrees of freedom [1,2]. Extending to three dimensions allows for the formation of new topologies of spin textures, for example containing defects in 3D such as Bloch point singularities, or truly three-dimensional topological structures such as magnetic hopfions.

In this talk, I will address two main questions: first, can we observe and understand such three-dimensional topological magnetic textures, and second, can we control them?

For the observation and understanding of these three-dimensional textures, we have developed magnetic X-ray tomographic techniques, that open the possibility to map both the three-dimensional magnetic structure [3], and its dynamical response to external excitations [4,5]. In this way, we observe 3D magnetic solitons which we identify as nanoscale magnetic vortex rings, as well as torons that contain Bloch point singularities [6,7].

As well as naturally existing within the bulk, 3D spin textures can be introduced and controlled via the patterning of 3D curvilinear geometries [8]. In this way, not only can new states be realized [9], but the energy landscape of topological defects can be designed through the local patterning of curvature induced chirality [11].

This new understanding and control of topological textures in 3D magnetic systems paves the way not only for enhanced understanding of these systems, but also towards the next generation of technological devices.

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Orbital torques and magnetoresistance in metallic heterostructures

<u>P. Gambardella</u>[1]

[1]*Department of Materials, ETH Zurich, Switzerland*

In transition metals the orbital degree of freedom is normally quenched due to band structure and crystal field effects. However, recent theoretical and experimental work shows that an applied electric field can induce a net flow of orbital angular momentum in topologically-trivial metals, even in the absence of a net magnetization and strong spin-orbit-coupling (SOC) [1-5]. In particular, electric currents in 3d elements can generate a substantial non-equilibrium orbital accumulation that is comparable to or even larger than the spin accumulation caused by the spin Hall effect and the Rashba-Edelstein effect in 4d and 5d elements [6,7]. In this talk I will discuss these phenomena focusing on the crucial role of orbital-to-spin conversion in the generation of spin-orbit torques [8] and orbital magnetoresistances in metallic heterostructures [9,10]. Eventually, the orbital degree of freedom provides a new means to actively generate and detect currents of angular momentum in a broad variety of materials and devices, including 2D materials.

References

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On the reciprocity between direct and inverse orbital Hall effects

Dongwook Go[1,2], Hyun-Woo Lee[3], Stefan Blügel[2], and Yuriy Mokrousov[1,2]

[1]Peter Grünberg Institute and Institute for Advanced Simulation, Forschungszentrum Jülich, Germany
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[2]Department of Physics, Pohang University of Science and Technology, Korea

The reciprocal relation is a fundamental manifestation of the fluctuation-dissipation theorem for near-equilibrium transport phenomena, which constraints the transport coefficients of coupled variables. In orbitronics, the orbital Hall effect plays a pivotal role as it can be used to generate orbital currents. Its reciprocal counterpart, the inverse orbital Hall effect refers to a generation of charge current by gradient of orbital-dependent chemical potential, namely "orbital voltage", which can serve as a mechanism to electrically detect orbital currents in orbitronic devices. The orbital-to-charge conversion has been measured in recent experiments [1-5]. However, theoretical description of the reciprocity between the direct and inverse orbital Hall effects is far from trivial because orbital currents are ill-defined and the orbital angular momentum is not conserved. We show that the reciprocal relation between charge and orbital transport can be rigorously established by adopting the definition of "proper" current proposed by Shi et al. [6], in which the non-conserving effect is considered. Based on the implementation in our first-principles codes, we present a detailed analysis of the direct and inverse orbital Hall effects in Pt(111) and W(110) thin films, prototypical systems used in experiments. We demonstrate that the reciprocal relation is satisfied exactly as the Onsager's theorem dictates for the "total" responses. However, we find interesting features in "local" responses, especially near the surface, where the direct and inverse effects can significantly deviate from each other. We find its origin in the orbital Rashba coupling at the surface, in which the angular momentum transfer between the lattice and orbital degrees of freedom is strongly pronounced. We believe this explains the large inverse orbital Rashba-Edelstein effect measured in a recent THz spectroscopy experiment [1]. We discuss further implications of our finding and its relevance in various experimental setups.

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Zero-Field Crystal Thermal Hall Effect in Insulating Altermagnets

R. Hoyer[1], **L. Šmejkal**[1] **and A. Mook**[1]

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The thermal Hall effect is an emerging probe of charge-neutral collective excitations in insulating quantum matter. Here we address the question of whether thermal Hall effects can occur in compensated collinear magnets at zero magnetic field. Following the recently developed concept of altermagnetism [1,2,3], we provide an affirmative answer by developing a minimal model that exhibits a crystal thermal Hall effect.

Specifically, we present a Heisenberg-type spin model on the rutile lattice. The presence of nonmagnetic atoms causes altermagnetic spin-splitting of magnons [4,5] and gives rise to Dzyaloshinskii-Moriya interaction.
As microscopic heat carriers, we consider magnons, whose Berry curvature causes an intrinsic contribution to the thermal Hall conductivity [6]. We show how the Hall conductivity changes as a function of the Néel vector direction, highlighting the influence of magnetic point group symmetries. The role of symmetry is further emphasized by studying fluctuation induced piezomagnetism and strain engineering of the Hall conductivity. Finally, the thermal Hall response is contrasted with a spin-Nernst response to explore the potential for heat-to-spin conversion in altermagnetic insulators.

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Spin and orbital Edelstein effects in topological oxides and Rashba multilayers

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The (spin) Edelstein effect, also known as current-induced spin polarization, provides charge-spin interconversion in nonmagnetic systems with broken inversion symmetry [1,2]: An external electric field generates a charge current as well as a homogeneous spin density. Thus, a finite magnetization can be generated and tuned exclusively electrically. In addition to this conventionally discussed spin Edelstein effect, the electrons' orbital moments are also expected to provide a current-induced magnetization, which is called orbital Edelstein effect [3-6]. Thus, the magnetization induced electrically by the Edelstein effect can comprise contributions from both the electrons' spins and orbital moments.
In this talk the spin and orbital Edelstein effects are discussed within a semiclassical Boltzmann approach. The theory is applied to the topologically nontrivial two-dimensional electron gas at $SrTiO_3$ interfaces [7]. In this particular system the orbital Edelstein effect is predicted to exceed its spin counterpart by one order of magnitude. Further, the spin and orbital Edelstein effects are discussed for a Rashba multilayer system, using the modern theory of orbital magnetization [8].

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Altermagnetism: The third magnetic class

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Magnetically ordered crystals are traditionally divided into two basic classes – ferromagnetism and antiferromagnetism. In the first part of the talk, we will recall that the ferromagnetic order offers a range of phenomena for energy efficient IT, while the vanishing net magnetization in antiferromagnets opens a possibility of combining ultra-high energy efficiency, capacity and speed of future IT [1-4]. In the main part of the talk we will move on to our recent predictions of instances of strong time-reversal symmetry breaking and spin splitting in electronic bands, typical of ferromagnetism, in crystals with antiparallel compensated magnetic order, typical of antiferromagnetism [5-8]. We resolved this apparent fundamental conflict in magnetism by symmetry considerations that allowed us to classify and describe a third basic magnetic class [6,7]. Its alternating spin polarizations in both crystal-structure real space and electronic-structure momentum space suggested a term altermagnetism. We will discuss predictions and initial experimental verifications [9,10] in which altermagnets combine merits of ferromagnets and antiferromagnets, that were regarded as principally incompatible, and have merits unparalleled in either of the two traditional basic magnetic classes. We will introduce the broad materials landscape of altermagnetism and show how its unconventional nature enriches fundamental concepts in condensed matter physics, such as the Kramers theorem [10]. We will show that this underpins a development of a new avenue in spintronics, elusive within the two traditional magnetic classes, based on strong and conserving spin phenomena, without magnetization imposed scalability limitations.

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Topological Spin Structures and Spin-Orbitronics in ferromagnets and antiferromagnets: from van der Waals 2D systems to multilayer heterostructures

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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 that are stable in multilayers [1] but also in 2D van der Waals systems [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. Going towards 2D van der Waals systems, we explore bulk spin – orbit torques resulting from the particular symmetry [7].

We use skyrmion dynamics for non-conventional stochastic computing applications, where we developed skyrmion reshuffler devices [8] based on skyrmion diffusion, which also reveals the origin of skyrmion pinning [8]. Such diffusion can furthermore be used for Token-based Brownian Computing and Reservoir Computing [9].

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 [10].

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Altermagnetic properties of MnTe thin films

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Altermagnets are a novel type of compensated collinear magnets that complement the conventional classes of ferro- and antiferromagnets [1]. In contrast to antiferromagnets, for which the opposite sublattices are connected by simple lattice translation or inversion, in altermagnets, they are connected by a lattice rotational symmetry (symmorphic/non-symmoprhic, proper/improper) [1]. This causes time reversal symmetry breaking in the band structure and – in contrast to ferromagnets – a spin splitting that alternates in sign within the Brillouin zone suggesting the term altermagnetism. The magnetization, however, integrates to zero over the entire Brillouin zone. Here we show experimental verification of the spin-splitting by angle resolved photo emission spectroscopy investigations in MnTe [3]. The characteristic spin splitting further enables linear responses such as the anomalous Hall effect [4], and X-ray magnetic circular dichroism [5] which will be also discussed.

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Spin dynamics of $Cr_2Ge_2Te_6$ probed by superconducting resonators and spin-orbit torques in electrostatically gated $Cr_2Ge_2Te_6$

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Two dimensional (2D) layered van der Waals (vdW) materials can offer their unique physical properties due to their chemical bonding as well as low crystalline symmetry. The weak vdW bonding allows to mechanically exfoliate individual layers, down to one monolayer in many cases while maintaining thermodynamically stable layers [1]. When it comes to magnetism, this is a perfect material class to study the two dimensionality of magnetic ground states [2-3] and their dynamics. So far, the ground states of 2D magnets have been studied by theory of thermodynamics but these are very simplified cases (e.g. the Mermin Wagner theorem for isotropic magnets [4]) and the microscopic nature of them has been largely unexplored due to the inaccessibility of real experiments at such a limit.

To study spin dynamics and magnetic fluctuations in the monolayer limit for vdW magnets, we are developing a microwave technique to efficiently couple magnons and photons down to that limit. To this end, we use on-chip superconducting resonators with a high quality-factor and small mode-volume to match nano-meter thick vdW flakes. By transferring $Cr_2Ge_2Te_6$ flakes on superconducting lumped element NbN resonators, we achieve the collective coupling strength (rate) of 13 MHz to 18 nm thick $Cr_2Ge_2Te_6$ [5]. The linewidth of the photon-magnon hybrid mode is used to analyse the magnetic properties of $Cr_2Ge_2Te_6$. I will discuss more technical details as well as our strategy of how to achieve sensitive measurements of monolayer vdW magnets.

In the second part of my talk, I will show our experiments of spin-orbit torques in electrostatically gated $Cr_2Ge_2Te_6$. Previously, we demonstrated electron doping of ~10^{14} cm^{-2} in $Cr_2Ge_2Te_6$ by electrolytes, which is accompanied by Curie temperature enhancement by ~140 K and the switching of magnetic easy-hard axis in the out-of-plane direction [6]. Since the gated $Cr_2Ge_2Te_6$ is now an electric conductor, it is possible to study spin transport in the previously insulating material system. We apply second-harmonic voltage techniques and observed characteristic voltages generated in the devices. We use the crystalline symmetry of $Cr_2Ge_2Te_6$ to predict possible spin torques in our experiments and compare between theory and experiment to understand the fundamental nature of the spin torques generated. I will show our interpretation of the results for discussions.

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Cubic magneto-optic Kerr effect in Ni thin films

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The magneto-optic Kerr effect (MOKE) describes the change of polarization state apon reflection of polarized light from a magnetized sample [1]. Initially this effect has been assumed to be proportional to the magnetization M of the investigated sample and, thus, became a standard tool to study magnetic thin-film systems [2]. However, in the last two decades contributions of second order in M have been explored [3]. The so-called quadratic MOKE (QMOKE) is proportional to M^2 and has been investigated, e.g., in Fe [4] and Heusler compound thin films [5]. Furthermore, QMOKE has been utilized to study antiferromagnetic materials [6] since MOKE linear in M (LinMOKE) usually vanishes here.
We have now explored the third-order MOKE called cubic MOKE (CMOKE) being proportional to M^3 in Ni(111) thin films [7]. We found a strong dependence of the CMOKE on the strutural domain twinning of the Ni thin films characterized by off-specular x-ray diffraction mappings. Thus, this effect could be of future use in MOKE microscopy and time-resolved MOKE to determine the creation and manipulation of structural domain twins in space and time.

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Light-Matter Interaction in Antiferromagnets: probing and controlling antiferromagnetic magnons

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In this talk I will go over different examples on how the coupling of antiferromagnets 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]. I will further discuss how dynamical backaction introduced by a cavity can be used e.g. for magnon cooling and squeezing [3,4].

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Unveiling transient dynamics of d-d excitations in the van der Waals antiferromagnet FePS3 via time-resolved ARPES

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Recent discoveries have spotlighted localized d-d excitations between crystal-field split 3d states of transition metal ions in van der Waals magnets as a potential avenue for manipulating magnetic order in two-dimensional systems[1–3]. However, the dipole-forbidden nature of these transitions renders them elusive to optical spectroscopies, leaving a significant portion of their properties, including their excitation and relaxation dynamics, largely uncharted.

With this contribution, I will present first insights into the manifestation of d-d excitations in the van der Waals antiferromagnet $FePS_3$ by a distinct signature in time- and angle-resolved photoelectron spectroscopy (trARPES) when employing an advanced detector capable of capturing the photoelectron signal across the entire surface Brillouin zone in a single measurement. We examine the spin-allowed $^5T_{2g} \rightarrow {}^5E_g$ and the spin-forbidden $^5T_{2g} \rightarrow {}^3T_{1g}$ transitions of the Fe^{2+} multiplet, determine their lifetimes, and introduce a theoretical model to explain the observed complex dynamics. These findings introduce the application of ARPES in exploring the dynamics of d-d transitions across a broad spectrum of solid-state systems and could enable us to study their interplay with other quasiparticles such as phonons or excitons.

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Birth and future of van der Waals magnetism

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Magnetism, in particular two-dimensional magnetism, has a special place in the history of physics. It has been a fertile playground where new concepts and insights have been discovered: the prime examples include the Onsager solution [1] for the Ising model and the Berezinskii–Kosterlitz–Thouless transition [2] for the XY model.

Unsurprisingly, numerous experimental efforts have been made to address those theoretical discoveries using real magnetic systems over the past few decades. However impressive the past progress was, there has been a nagging question of whether and how to tackle the problem head-on with real two-dimensional magnets.

With hindsight, this question and the actions to be followed seem very straightforward, but it was not when I harboured this question for some years in mid-2000. With years-long efforts, my group reported the first realization of several antiferromagnetic van der Waals monolayers using TMPS3 TM=Mn, Fe, Ni [3]. Our works were followed by two reports by the US group using CrI3 [4] and Cr2Ge2Te6 [5].

The field has since been expanding at a fast pace, and one cannot cover all the developments within one's talk. So, I want to focus on two vdW magnets and present what I believe to be important for two reasons: intellectual curiosity and technical potential. One is antiferromagnetic NiPS3, which displays an extremely narrow magnetic exciton peak whose true origin is still elusive [6]. The other is ferromagnetic Fe3GeTe2, whose peculiar symmetry allows unusual control of the magnetic ground states by external variables, offering hope for potential applications [7]. I will end with a personal view of how the field will develop in future [8].

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Effect of Beam Shift on Helicity Dependent Photoresistance Measurement

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Optical methods for generating spin currents are orders of magnitude faster than the conventional electronics while simultaneously providing a high spatial resolution, a combination particularly favourable for studying prototype spintronic devices. The prominent experiments in this field are based on a dependence of the generated photocurrent/photovoltage on the helicity of the exciting light.

A coupling between light polarization and spin current/accumulation has been observed in many systems and is often associated with topologically non-trivial spin structures [1]. Experimentally, a periodical modulation of the light helicity is typically achieved by polarization components such as photoelastic modulator or mechanically-rotated $\lambda/4$ waveplate that rely on a (periodical) change of complex index of refraction. As such, they are extremely sensitive to any imperfection, which limits the laser pointing stability and leads to a periodical beam shift during the measurement.

In this contribution, we show how the effective motion of beam during the helicity modulation can generate artificial signals in the electro-optical experiment via periodically-generated heat gradients [2][3]. The “beam-shift” signals are indistinguishable from the real spin-related photoresistance in the conventional Hall-bar devices without further analysis. We propose a ring-shape device structure that allows for separation of the parasitic signals directly. Furthermore, we present a symmetry a symmetry-based analysis that separates the artefact signals even in the conventional Hall-bars.

From our extensive set of experiments, it follows that the “beam-shift” signals dominate the experimental data in many different systems. This leads us to a conclusion that this artefact should be estimated and corrected in all experiments where the circularly polarized laser beam is used to locally influence the electrical properties.

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Topological magnons in van der Waals ferromagnets Cr*X*Te_3 (*X* = Si, Ge)

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Recently, two-dimensional van der Waals (2D-vdW) honeycomb ferromagnets have emerged as a new platform for topological spin excitations. In this talk, we present a comprehensive inelastic neutron scattering study and theoretical analysis of the spin-wave excitations in 2D-vdW honeycomb ferromagnets Cr*X*Te3 (*X* = Si, Ge) [1-2]. Our inelastic neutron scattering experiments show clear dispersive magnonic bands and a well-resolved bandgap opening at the high-symmetry band-crossing Dirac K points in the Brillouin zone. Based on the fitting to experimental data within the linear spin wave theory, the observed bandgap opening was ascribed to the antisymmetric exchange Dzyaloshinskii-Moriya interactions (DMI), and a spin Hamiltonian model including the second nearest-neighbor DMI could provide a very good description of the magnonic dispersion in Cr*X*Te3. The size of the topological magnonic gap was found to be strongly dependent on the strength of the DMI that intrinsically originates from spin-orbit coupling in this system. Furthermore, the Chern numbers of the magnonic bands were found to be nonzero, thus indicating that the bandgap opening is indeed topologically nontrivial and corresponding edge states could emerge inside the gap. On the basis of the compelling evidence obtained in our studies, we thus conclude that the exotic topological magnon insulator, which is intrinsically gap tunable, can be ideally realized in the family of 2D vdW honeycomb ferromagnets Cr*X*Te3. We hope that this discovery will stimulate further investigations on potential technological applications in the domain of magnonics and topological spintronics.

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Domain wall properties, fluctuation induced piezomagnetism and anomalous hall effects in altermagnets — models and materials

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From a theoretical point of view we will discuss several physical properties that render altermagnets different from canonical antiferro-, ferro- and ferri-magnets. These include static and dynamic properties of domain wall structures, certain heat transport features and the effects of fluctuations on piezomagnetic responses. In a toy model we demonstrate the presence of a switchable anomalous Halls response in a fully compensated altermagnetic state, which is combined with material-specific ab initio investigations.

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Strong exciton-phonon coupling in 2D magnetic semiconductor CrSBr

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The van der Waals (vdW) material CrSBr is an optically active, environmental rather stable 2D magnetic semiconductor with ferromagnetic ordering within each layer. Adjacent layers are coupled antiferromagnetically. Due to highly anisotropic electronic bands, electronic and excitonic states at the fundamental band-gap behav quasi-one-dimensional [1]. Strong light-matter coupling together with the layered nature of the bulk vdW magnet results in self-hybridization of exciton and photons and hence in the formation of polaritons [2]. Consequently, the light matter coupling of the direct band gap material is dominated by strong anisotropic polaritonic resonances making it an interesting material not only from a fundamental point of view but also for opto-spintronic applications.

In this presentation, we combine magnetic field-dependent photoluminescence and resonant Raman experiments at cryogenic temperatures (~3K) well below the Néel temperature to study the impact of magnetic order and magnetization direction on excitonic interband transitions, exciton-phonon coupling, polariton-phonon coupling as well as further collective excitations. We observe distinct differences in the excitonic signatures for anti-ferromagnetic and ferromagnetic order. Strong magnetic anisotropies are identified by the different critical fields along different crystal orientations. The occurrence of new and well resolved sharp modes in the Raman spectra that do not result from Raman-allowed phonon modes indicate strong exciton-phonon or polariton-phonon coupling. The emergence of highly resonant broader signatures in light scattering spectra is discussed in the framework of collective excitations of the charge and spin degree of freedom.

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Curvilinear superconducting vortices in three-dimensional nanoarchitectures

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Three-dimensional nanostructuring offers new possibilities to control the emergent properties of quantum materials via geometric effect. In nanomagnetism, for example, the introduction of curvature can lead to exotic dynamic effects, as well as curvature-induced chirality and anisotropy. In superconductivity, the introduction of three-dimensional geometries offers a route to controlling the emergent properties of the system, with new opportunities for devices. [1]. However, while the fabrication of 3D magnetic nanostructures is well established, there remain challenges in realizing three-dimensional superconducting systems [2].

In this work, we present a new route to gaining control over new emergent properties in superconductors by patterning three-dimensional nano geometries by focused electron-beam-induced-deposition [3], allowing us to implement a prototype direct-write three-dimensional superconducting nanostructure with a critical temperature on the order of 5 K. We confirm the presence and propagation of superconducting vortices through our 3D superconducting nanostructure. Through the development of a three-dimensional time-dependent Ginsburg-Landau model, we determine the superconducting vortices to be curvilinear and exhibit non-trivial field-dependent pinning effects. The curvilinear structure of the vortices, in combination with the 3D nanostructure leads to a shape anisotropy, manifesting in an angular dependence of the upper-critical magnetic field. These experimental and numerical capabilities for 3D nanosuperconductivity open the door to the designing of 3D superconducting devices, that harness dynamics of the superconducting vortices in curved 3D nanoarchitectures.

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Van der Waals Spin-Orbit Torque Antiferromagnetic Memory

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The technique of conventional ferromagnet/heavy-metal spin-orbit torque (SOT) offers significant potential for enhancing the efficiency of magnetic memories. However, it faces fundamental physical limitations, including hunting effects from the metallic layer, broken symmetry for enabling antidamping switching, spin scattering caused by interfacial defects, and sensitivity to stray magnetic fields. To address these issues, we here propose a van der Waals (vdW) field-free SOT antiferromagnetic memory using a vdW bilayer $LaBr_2$ (an antiferromagnet with perpendicular magnetic anisotropy) and a monolayer T_d phase WTe_2 (a Weyl semimetal with broken inversion symmetry). By systematically employing density functional theory in conjunction with non-equilibrium Green's function methods and macrospin simulations, we demonstrate that the proposed vdW SOT devices exhibit remarkably low critical current density approximately 10 MA/cm^2 and rapid field-free magnetization switching in 250 ps. This facilitates excellent write performance with extremely low energy consumption. Furthermore, the device shows a significantly low read error rate, as evidenced by a high tunnel magnetoresistance ratio of up to 4250%. The superior write and read performance originates from the unique strong on-site (insulating phase) and off-site (magnetic phase) Coulomb interactions in electride $LaBr_2$, a large non-zero *z*-component polarization in WTe_2, and the proximity effect between them.

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Abstracts of Posters

(in alphabetical order)

Spin Dynamics in Complex Magnetic Materials

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Magnetic skyrmions show great promise as potential information carriers in future memory applications. These unique entities can be visualized as nanoscale twists or knots within a uniform magnetic material, resembling particle-like topological solitons. Skyrmions are commonly found in chiral magnets lacking inversion symmetry, owing to the presence of finite Dzyaloshinskii-Moriya interaction (DMI). The intricate three-dimensional internal structure of magnetic skyrmions and their interactions with one another are determined by the surrounding magnetic state of the host material [1]. A comprehensive understanding of the dynamic magnetization of skyrmions in chiral magnets is crucial for their practical implementation in devices.

In this study, we investigate the magnetization dynamics within heterostructures composed of a single crystal of the chiral magnet Cu2OSeO3 (CSO) and a polycrystalline ferromagnet NiFe (Py) thin film [2]. Our approach involves employing broadband ferromagnetic resonance (FMR) at cryogenic temperatures. Our observations have identified significant variations in the field dependence of the low-temperature skyrmion (LTS) phase within the CSO/Py sample. An important finding is that depositing Py onto CSO eliminates the need for a specific field cycling protocol to induce the LTS phase [3,4], as it can now be observed in Py/CSO samples without any field cycling. These findings carry substantial implications for future experiments focusing on the surface engineering of skyrmions in bilayer systems.

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Tuning the Magnetic Properties of Two-Dimensional MXenes by Chemical Etching

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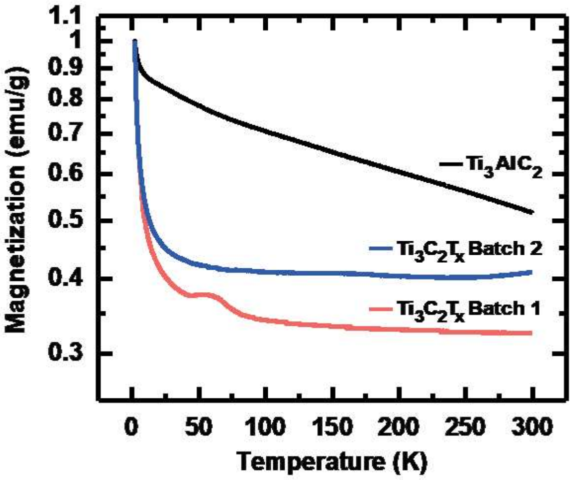

Figure 1. Magnetization versus temperature at 1000 Oe for (a)Ti_3AlC_2, (b) LiF/HCl etched $Ti_3C_2T_x$ Batch 1 and (c) Batch 2 samples.

Two-dimensional materials based on transition metal carbides and nitrides called MXenes, a class of two-dimensional inorganic compounds with the chemical formula $M_{n+1}X_nT_x$, where M denotes an early transition metal, X indicates a carbon, nitrogen or both, and T_x is a surface termination group, have been intensively studied due to their unique properties including metallic conductivity, hydrophilicity, and structural diversity and have shown great potential in several applications, for example, energy storage, sensing, and optoelectronics. While MXenes based on magnetic transition elements show interesting magnetic properties, not much is known about the magnetic properties of titanium-based MXenes. Here, we measured magnetic properties of $Ti_3C_2T_x$ MXenes synthesized by different chemical etching conditions such as etching temperature and time. Our magnetic measurements using superconducting quantum interference device (SQUID) indicate that there is a paramagnetic–antiferromagnetic (PM-AFM) phase transition, and the transition temperature depends on the synthesis procedure of MXenes. Our observation indicates that the magnetic properties of these MXenes can be tuned by the extent of chemical etching which can be beneficial for the design of MXene-based spintronic devices.

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Supercell altermagnet MnSe2: A tale of two configurations

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Altermagnets constitute a novel subclass of magnetic materials, defined as compensated collinear magnets that break time-reversal symmetry, resulting in spin-split band structures [1]. In recent years, there has been a growing emphasis on altermagnetism, with significant efforts directed toward the discovery of new altermagnetic materials. However, all identified altermagnetic candidates thus far have unit cells that are equivalent to their non-magnetic unit cells. In our research, we expand the scope by introducing the concept of supercell altermagnets, where the magnetic unit cell consists of multiples of the paramagnetic primitive unit cell [2]. These materials are distinguished by the presence of a non-zero propagation vector within their magnetic structure. We identify realistic material candidates exhibiting d- and g-wave orders. Furthermore, our study revealed that a d-wave altermagnet, $MnSe_2$, exhibits two distinct orientations of the d-wave order parameter. Ab initio calculations indicate the potential to actively control the spatial orientation of the d-wave order parameter by favoring one configuration, owing to a small energy difference between the two configurations. Such a reorientation could make possible the switch of spin-polarized currents.

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Out-of-plane spin torques via symmetry engineering in quasi-2D oxides.

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The field of spintronics is predicated on the ability to generate spin torques that can manipulate and switch the magnetization of magnetic nanobits for future applications in memory and logic, such as magnetic random access memory (MRAM). Current-induced spin torques generated by materials with large spin-orbit coupling (SOC) are a promising approach. However, a significant challenge is generating spin torques with the correct orientation to deterministically switch perpendicularly oriented magnetic layers by 180 degrees. Unfortunately, the high rotational and reflectional symmetry of commonly used centrosymmetric spin torque metals, such as Pt, Ta, W, and topological insulators (e.g., Bi_2Se_3, Bi_2Te_3), lack the ability to efficiently switch the magnetization of perpendicularly magnetized nanomagnets[1] without the additional assist of an inefficient and unscalable magnetic field or another extrinsic source of symmetry breaking[2–8]. Here, we show that by engineering symmetry via lattice mismatch strain in quasi-2D layered polar oxide metal, we can control the spin torque orientation via intrinsic symmetry engineering. We show that out-of-plane spin torques arise in these systems when the asymmetry is engineered such that Dresselhaus and Rashba band structures are balanced. Our work provides a pathway to symmetry design of spin torques via epitaxy in quasi-2D oxides.

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Thermal Hall effect from magnon many-body skew scattering

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

Observation of time-reversal symmetry breaking in the band structure of altermagnetic RuO_2

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Altermagnets are an emerging elementary class of collinear magnets. Unlike ferromagnets, their distinct crystal symmetries inhibit magnetization while, unlike antiferromagnets, they promote strong spin polarization in the band structure. The corresponding unconventional mechanism of time-reversal symmetry breaking without magnetization in the electronic spectra has been regarded as a primary signature of altermagnetism, but has not been experimentally visualized to date. We directly observe strong time-reversal symmetry breaking in the band structure of altermagnetic RuO2by detecting magnetic circular dichroism in angle-resolved photoemission spectra. Our experimental results, supported by ab initio calculations, establish the microscopic electronic-structure basis for a family of interesting phenomena and functionalities in fields ranging from topological matter to spintronics, that are based on the unconventional time-reversal symmetry breaking in altermagnets.

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Electron Dynamics in the Conduction Band of the van-der-Waals Magnet $Cr_2Ge_2Te_6$

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The electron dynamics in the vicinity of the Brillouin zone center of $Cr_2Ge_2Te_6$ has been investigated by time-resolved ARPES. The optical excitation with a photon energy of 1.55 eV leads to a transient broadening of the valence band. Additionally, an excited electron population is created which is initially concentrated at the energy range of 0.7 to 1.3 eV above the Fermi level and continuously relaxes towards states at 0.5 eV within 1ps. According to their long lifetime of >3 ps we attribute these states to the conduction band minimum which theory predicts to be located close to the K point of the surface Brillouin zone [1,2]. The broad momentum distribution in the conduction band suggests enhanced scattering in the excited material.

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Collective Spin-Wave Dynamics in Gyroidal Nanostructures

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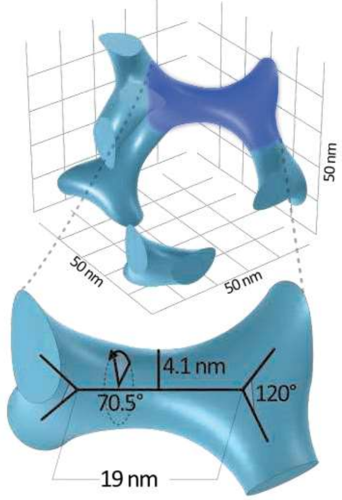

Fig. 1. A geometric model of the gyroid unit cell.

The exploration of three-dimensional networks in magnonics opens new avenues for spin wave manipulation and control, offering major advances in the field. Among these structures, gyroids – characterized by their chiral triple bonds and periodicities in all spatial directions (Fig. 1) – stand out as particularly promising yet underexplored in magnetism research. In our study, we have successfully fabricated nickel gyroid nanostructures through a meticulous process involving thermal annealing of a block copolymer template, selective dissolution, and electrodeposition. The orientation of these gyroid networks relative to the static magnetic field axis proved to be critical, as evidenced by broadband ferromagnetic resonance measurements, which revealed a significant influence of crystallography on spectral signals and their linewidth. To complement these findings, we used a finite element solver [1], *tetmag,* to perform micromagnetic simulations of the gyroid systems. These simulations provided deeper insights into the experimental results and revealed that the gyroid networks have significant metamaterial-like effects on the magnetic properties, such as tunable effective values of M_s and g-factor, and influence on the Gilbert damping parameter [2]. To further research, I have performed new micromagnetic simulations using Comsol Multiphysics software. These simulations focus on the analysis of spin-wave propagation and dispersion relations in gyroid structures over different thicknesses and filling factors. This approach allows us to delve into the intricate dynamics of spin waves within these complex 3D nanostructures, providing a more comprehensive understanding of their behavior and potential applications.

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Structure, control, and dynamics of altermagnetic textures

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We present a phenomenological theory of altermagnets, able to describe their unique magnetization dynamics and to model magnetic textures in this emergent collinear magnetic ordered phase, having zero-net magnetization and alternating spin-polarization in the non-relativistic electronic band structure. Focusing on the prototypical d-wave altermagnets, e.g. RuO_2, we can explain intuitively the unique lifted degeneracy of their magnon spectra, by the emergence of an effective sublattice-dependent anisotropic spin stiffness arising naturally from the phenomenological theory.

We demonstrate that alternative magnetic domain walls, unlike their counterparts in antiferromagnets, exhibit a discernible gradient in the magnetization projection along the easy axis orientation. The magnitude and orientation of this gradient are intricately linked to the alternative magnetic anisotropy, persisting even for 180° domain walls. This gradient serves as a valuable means for visualizing the domain walls through detection via NV magnetometry. Furthermore, the presence of this gradient engenders a ponderomotive force within the domain wall when subjected to an external magnetic field gradient.

The motion of these altermagentic domain walls are also characterized by an anisotropic Walker breakdown, with much higher speed limits of propagation than ferromagnets but lower than antiferromagnets. Finally, also in contrast to antiferromagnetic and ferromagnetic domain walls, we demonstrate magnon scattering from unpinned domain walls, which can lead to domain wall manipulation by magnonic currents, polarized along the easy axis orientation for the case of RuO_2.

Magnetization manipulation with Terahertz electric currents

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Operating electronic devices in the Terahertz band is still challenging today. However, the constantly growing demand for faster computation devices increases their complexity. Further, energy consumption reduction in information technology remains a challenging task. The recent development of Spintronic Terahertz Emitters [1,2] demonstrates the possibility of generating current pulses on the sub-picosecond time scale. This evolution proposes an opportunity to investigate the potential for data transfer on this time scale.

Spintronic Terahertz Emitters consist of a ferromagnetic/nonmagnetic metal junction heterostructure. They offer the possibility of electric circuit's integrations. Such short electric pulses, e.g., can be employed to trigger magnetization dynamics. Those effects have been previously investigated with LT-GaAs Auston switches, an older generation of Terahertz Emitters [3]. With Spintronic Terahertz Emitters as a sub-picosecond current pulse source, we can extend these investigations in a simplified way without additional detector layers.

We present an optical lithography mask specially developed using a direct laser writing technique to produce patterns for Spintronic Terahertz Emitter-based electric circuits to generate and detect THz pulses within the magnetic layers of the heterostructures. Within the circuit pattern, an Au line connects two Spintronic Terahertz Emitters and acts as a waveguide for electric THz pulses. We use all-optical pump-probe experiments to generate electric current pulses by pumping the first Spintronic Terahertz Emitter while probing the resulting magnetization dynamics in the second Terahertz Emitter time delayed by the time-resolved magneto-optic Kerr-effect (TR MOKE).

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Zero-Frequency Chiral Magnonic Edge States Protected by Nonequilibrium Topology

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Topological Magnon Insulators (TMIs) are magnonic realizations of topological insulators, where magnons, instead of electrons, are the carriers of information. However, topological bosonic excitations must, in contrast to their fermionic counterparts, appear at finite energies. This is a key challenge for TMIs, as it prevents straightforward excitation and detection of topologically-protected magnonic edge states and their use in magnonic devices.

We propose a general strategy to access the topologically protected edge states in a magnon Chern insulator [1]. We show that the chiral edge states can be tuned in frequency by considering magnon excitations on top of a magnetization that is pointing against the applied external magnetic field [2]. In this non-equilibrium state, stabilized by spin-orbit torques, the topologically-protected chiral edge modes lie at zero frequency, while the bulk modes remain gapped. Using numerical Landau-Lifshitz-Gilbert simulations we show that the chiral edge states can be excited with low-frequency microwave fields. Furthermore, we demonstrate that in a propagating spin wave spectroscopy experiment the edge states can be directly detected, even in the presence of disorder.

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Harnessing Orbital Hall Effect Materials for Efficient Magnetization Control with In-plane and Perpendicular Magnetic Anisotropic Ferromagnets

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The spin Hall effect (SHE) and orbital Hall effect (OHE) are promising mechanisms for magnetization control in spintronic devices [**1-6**]. Ru shows one of the highest orbital Hall conductivities among 3d, 4d, and 5d elements, surpassing Pt's spin Hall conductivity by a factor of four [**7**, **8**].

This presentation discusses differentiating between SHE and OHE and explores OHE's impact on spin-orbit torques and magnetization switching. Preliminary findings reveal a significant orbital Hall torque generated by Nb and Ru, with a strong and long-range dependence on in-plane magnetized ferromagnets [**9, 10**]. Comparing Nb (or Ru)/Ni and Nb (or Ru)/FeCoB heterostructures, a pronounced enhancement in damping-like torque efficiency is observed, along with a sign reversal in Nb/(Ni or FeCoB) samples.

By harnessing the OHE, we have demonstrated enhanced orbital torques and decreased switching current density within the Ru/Pt OHE layer when compared to bare Pt, Cr, Nb attached with Co/Ni multilayers as a perpendicular anisotropic ferromagnet [**11**].

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Theoretical study of optical excitation effects in RuO2

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Recently, altermagnets have gained interest due to their ability to combine ferromagnetic and antiferromagnetic properties. Altermagnetic materials show a momentum-dependent spin polarization in reciprocal space without net magnetization, making them particularly well suited for pronounced spin-dependent transport effects and as a potential building block for faster and more robust spintronic devices [1,2]. Systems with magnetic order tend to also exhibit responses to ultrafast optical fields that are connected to the driven electronic dynamics and as well as scattering processes on ultrashort timescales. Here, we focus on the optical response of altermagnetic materials as a key property. We model the optical excitation of the d-wave altermagnet RuO_2 and investigate how the underlying symmetries affect its optical characteristics. We employ a hybrid approach that combines Density Functional Theory (DFT) and optical transition probabilities in a Fermi's Golden Rule approach [3,4] to simulate the excitation with momentum, spin and band resolution. The band dispersion and momentum matrix elements are computed using ab initio approaches, including spin-orbit coupling [5]. We study the excitation process driven by linearly polarized laser pulses and discuss the characteristics of the driven electronic distributions.

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Twisted bilayer graphene reveals its flat bands under spin pumping

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The salient property of the electronic band structure of twisted bilayer graphene (TBG), at the so-called magicangle (MA), is the emergence of flat bands around the charge neutrality point. These bands are associated with theobserved superconducting phases and the correlated insulating states. Scanning tunneling microscopy combinedwith angle resolved photoemission spectroscopy are usually used to visualize the flatness of the band structureof TBG at the MA. Here, we theoretically argue that spin pumping (SP) provides a direct probe of the flat bandsof TBG and an accurate determination of the MA. We consider a junction separating a ferromagnetic insulatorand a heterostructure of TBG adjacent to a monolayer of a transition metal dichalcogenide. We show that theGilbert damping of the ferromagnetic resonance experiment, through this junction, depends on the twist angleof TBG, and exhibits a sharp drop at the MA. We discuss the experimental realization of our results which openthe way to a twist switchable spintronics in twisted van der Waals heterostructures [1].

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Ab inito study of the van der Waals Superconductor NbSe2

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Abstract: Transition metal dichalcogenides (TMDCs) are a very versatile material class in which many physical phenomena can be found [1]. These phenomena range from a topological electronic structure in Weyl and Dirac semimetals to magnetic, and even superconducting systems and charge-density waves. Different van der Waals (vdW) materials can also be combined easily due to these layered materials. The TMDC NbSe2 is an example of a superconducting TMDC which shows unconventional Ising superconductivity up to T_C=7K that is particularly robust against magnetic fields in certain directions (in-plane vs out-of-plane) [1, 2]. vdW heterostructures combining magnetism and superconductivity are intriguing for probing topological superconductivity or realizing a field-free Josephson diode [3, 4]. In our work, the Coherent Potential Approximation is employed to treat the effects of disorder on the electronic structure. It extends the KKR formalism to include disordered systems assuming an averaged effective medium [5].

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Topological nodal planes in hexagonal space groups

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Nodal planes are the two-dimensional generalization of nodal points/lines, and like them they may carry a topological charge. So far, proposed material realizations of symmetry-enforced topological nodal planes are unsuitable for the study of Fermi arcs and Berry curvature effects. To remedy this, we introduce representation-enforced topological nodal planes as a tool to identify suitable materials, which leads us towards hexagonal space groups.
As an application, we study the hexagonal van der Waals material $CoNb_3S_6$, which exhibits such topological nodal planes. Recently, this compound has gained interest due to its All-in-All-out magnetic order that exhibits a non-trivial spin-space symmetry [1]. We theoretically investigate the emergence of anomalous Hall and Nernst effects in this van der Waals magnet and its relation to the topological nodal planes of the paramagnetic phase.

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Unraveling light-driven spin transfer and hot carrier dynamics by EUV magneto-optical spectroscopy

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The control of spin dynamics by light offers a unique opportunity to control the magnetic state of matter and bring spintronics into the femtosecond regime. Recently, light-driven spin dynamics have been shown to evolve on <10 femtosecond timescale via the process of optical inter-site spin transfer (OISTR) [1,2,3,4]. However, due to nonlinearities and optical artefacts in the ultrafast measurement methods used, a quantitative comparison between experiment and theory has not been possible and doubts have been cast on the main experimental observations.

Here, we address these challenges and present a quantitative measurement of femtosecond light-driven inter-site spin dynamics in FeNi alloys. Starting with incidence angle-resolved EUV T-MOKE measurements, we show how to recover the full femtosecond dynamics of the dielectric tensor, including both the magneto-optical response and the electronic response [5]. Applying this technique to laser-excited nickel, permalloy and iron-nickel alloy [6], we show that the magneto-optical and the electronic responses can be completely disentangled. Moreover, the transient response of the dielectric tensor enables a direct and quantitative comparison with ab-initio theory calculations, so that we clearly verify the OISTR effect. Finally, our data also elucidate how the previously found delayed demagnetization of Ni in FeNi alloys arises as a consequence of the OISTR effect.

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DFT insights into the electronic structure and optical properties of the vdW magnets $FePS_3$ and $NiPS_3$

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Transition-metal phosphorous trisulfides MPS_3 are quasi-two-dimensional van-der-Waals materials with resilient honeycomb-lattice magnetism that remains stable in the ultrathin-film limit down to atomic monolayers. The diverse electronic, magnetic and optical properties of these materials are largely determined by the electronic configuration of the transition-metal atom *M*.

$FePS_3$ is a zigzag antiferromagnet with a high ordering temperature of about 120 K. The d^6 Fe^{2+} atoms are in the high-spin S=2 state, characterized by a strong easy-axis anisotropy. A hallmark of this material is the giant linear dichroism of the optical response within the magnetic planes. Using DFT+*U* calculations and simulations of optical properties, we demonstrate that the dichroism of $FePS_3$ is directly related to electronic correlations that accompany the virtual transfer of minority electrons [1].

$NiPS_3$ also undergoes magnetic ordering into the zigzag antiferromagnetic state, yet the d^8 configuration of its Ni^{2+} atoms gives rise to the nearly isotropic S=1 magnetism. The most prominent feature of $NiPS_3$ is the appearance of an exceptionally sharp excitation in the magnetically ordered state. Using DFT-parameterized multiplet calculations, we demonstrate that this excitation has a predominantly singlet character. By simulating the EELS spectra with DFT+*U* and mimicking the temperature effects using the Boltzmann distribution, we reproduce the experimentally observed difference between the signals of the paramagnetic and the zigzag-ordered state, and in this way prove that the prominent feature at 2.5 eV stems from the magnetic order [2].

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Local magnetic fields in a $MnBi_2Te_4/(Bi_2Te_3)_n$ topological insulator studied by NMR

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Intrinsic magnetic topological insulators have recently attracted a tremendous research interest due to the interesting physical phenomena such as quantum anomalous Hall effect [1]. One of the most promising platforms for exploring this elusive quantum effect is the $MnBi_2Te_4$ system, grown in a self-organized layered structure of the van der Waals type $MnBi_2Te_4/(Bi_2Te_3)_n$. This compound is composed of seven atomic layers: Te-Bi-Te-Mn-Te-Bi-Te bonded by the van der Waals interaction to the quintuple layers composed of the Bi_2Te_3 blocks. Neutron diffraction studies report that the Mn atoms within a single Mn layer are ferromagnetically ordered along the axis perpendicular to the Mn plane, but macroscopically the entire system behaves as an A-type antiferromagnet with $T_N = 24\,K$. Nevertheless, local magnetic properties of this system are still unclear and several contradictory reports give the value of manganese magnetic moment in a broad range of different values $(1.14 - 5)\mu_B$ [2]. To gain new insight into the microscopic spin structure of $MnBi_2Te_4$ we performed Nuclear Magnetic Resonance (NMR) investigation on $Mn_{0.81}Bi_{2.06}Te_{4.13}$ crystal consisting of the $MnBi_2Te_4$ layers incorporated in the Bi_2Te_3 matrix. The NMR experiments have been carried out at 4.2 K in the external magnetic field applied perpendicular to the Mn planes. The ^{55}Mn resonance has been found at 419 MHz, corresponding to a local magnetic field of 40 T. Based on this value, the local magnetic moment of Mn atoms is estimated at 3.33 μB. This is in contrast to the previous theoretical and experimental reports giving the magnetic moment value of around 5 μB and suggesting a corresponding Mn^{2+} valence state. In addition, ^{209}Bi NMR signal has been observed at the frequency of 110 MHz, corresponding to a local magnetic field of 16 T. Its origin is related to a transferred hyperfine field due to polarization of bismuth electronic shells by the uncompensated magnetic moment of manganese atoms.

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Exploring Chirality and Topology in Ferrimagnetic Multilayer Systems

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The potential of strong chiral interactions in thin magnetic films is the basis of promising applications, including in-memory and neuromorphic computing technologies[1]. To achieve this goal, however, new materials are required in which information-carrying topological magnetic spin textures can be small and fast at the same time[2,3]. Chiral rare-earth transition metal ferrimagnets hold promise for fulfilling this objective, exhibiting a dual nature that combines characteristics of both ferromagnets and antiferromagnets with adjustable material properties, including bulk Néel-type Dzyaloshinskii-Moriya interaction (DMI), adjustable anisotropy, and minimal stray fields. An ongoing challenge lies in the absence of a volume-sensitive method for quantifying the strength of bulk DMI in the material where the thickness is a crucial parameter. Here we utilize Fresnel Lorentz Transmission Electron Microscopy (L-TEM) imaging to resolve the chirality and topology of spin textures in thick ferrimagnetic Dy/Co multilayer films and to quantify the strength of Néel-type bulk DMI. Interestingly, depending on the magnetic field and tilt angle in the L-TEM microscope, we find both skyrmions and topologically trivial bubbles within the material, indicating an intricate balance of micromagnetic interactions. The study signifies the importance of local real-space probes of chirality for the understanding of bulk DMI ferrimagnets and opens the door for further extensive exploration and exploitation.

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Spin-Orbit Torque-Driven Magnetisation Switching in a Fe_3GeTe_2-WTe_2 Heterostructure

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Current-induced spin-orbit torques (SOTs) allow the efficient electrical manipulation of magnetisation. Typically, they require a symmetry-breaking in-plane magnetic field to deterministically switch magnets with out-of-plane anisotropy [1]. However, in materials that merge structural symmetry-breaking with strong spin-orbit coupling, additional out-of-plane spin directions can be induced, enabling field-free deterministic switching [2,3]. In this context, van der Waals materials stand out as an essential platform for exploring these unconventional SOTs. Stacking exfoliated magnetic materials with low structural compounds facilitate the fabrication of devices that possess high crystal quality and atomically sharp interfaces [3].

In this poster, we characterise the current and field dependent magnetic properties within a heterostructure comprising a 5 nm ferromagnetic Fe_3GeTe_2 (FGT) and a 4 nm thick semi metallic WTe_2 flake, pictured in Fig 1. Using a cryogenic magneto-optical Kerr effect (MOKE) setup, we conducted a detailed investigation of the current-induced magnetisation switching and extract the SOTs following a technique proposed by Montazeri *et al.* [4]. At 150 K, the critical direct current for field-free switching of the FGT flake is approximately $5\cdot10^6$ A$\cdot$cm^{-2} at 150 K.

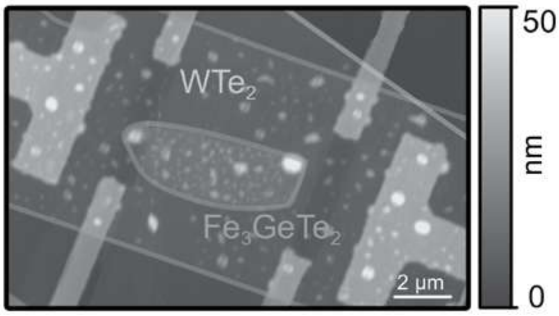

Fig. 1 AFM image of the FGT-WTe_2 heterostructure.

Our findings enhance the understanding of field-free switching through unconventional SOTs and the switching behaviours and dynamics of two-dimensional magnetic systems.

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Anisotropic-Conductivity-Induced Magnetic Phase Transition in the Fe5-xGeTe2 with Current In-Plane Geometry

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In this presentation, microscopic structures and magnetic properties of the $Fe_{5-x}GeTe_2$ single crystal, recently discovered as a promising van der Waals (vdW) ferromagnet, are introduced. Our study demonstrates a new way of the magnetization control of the vdW magnets via the electrical control of the interlayer coupling from ferromagnetic (FM)-to-antiferromagnetic (AFM). The current-induced phase transition results in drastically enhanced magnetoresistance from 5% to 170% with current in-plane geometry. This observation is fundamentally different from other conventional ways such as spin torque effects and gate voltage effects.

This study will provide essential information to understand the complex magnetic properties and the origin of the new vdW ferromagnet, $Fe_{5-x}GeTe_2$ for future topology-based spin devices.

Thermodynamic properties of the checkerboard model of altermagnet

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Using the checkerboard Hubbard hamiltonian as a model for two-dimensional altermagnet, we demonstrated that the temperature-induced fluctuations can lead to several new effects, namely the fluctuation induced piezomagnetism and thermal spin conductivity.

First, computing the dispersion relation for magnons, we demonstrated that the model under consideration breaks the spin degeneracy in the momentum space leading to the anisotropic (in k-space) splitting of magnon branches typical for the altermagnets. The obtained dispersion relation was completely reproduced by our spin-lattice simulations. Next, in the limit of low temperatures, neglecting magnon-magnon interactions, we considered the thermally induced magnons as an ideal Bose gas and computed the thermodynamic potential accordingly. Using the thermodynamic potential, we computed magnetization M as a thermodynamic quantity, and demonstrated that M vanishes for vanishing magnetic field. However, M is finite beyond the altermagnetic limit, when the diagonal terms in the checkerboard model becomes not equivalent, e.g. due to the applied mechanical stress. In the linear regime (small stress) we obtained the dependence of the *fluctuation induced piezomagnetic constant η* on temperature. For temperatures larger than the gap temperature, η is linear in temperature, while it is exponentially suppressed for small temperatures. The obtained temperature dependence of η for large temperatures was reproduced by spin-lattice simulations with thermal fluctuations.

In addition, we predict generation of the spin-current in response тo the applied temperature gradients. Computing the spin capacity per magnon, and using the relaxation-time approximation, we obtained nonvanishing components of the tensor of thermal spin conductivity $\sigma_{\alpha\beta}$. For small temperatures, $\sigma_{\alpha\beta}$ is linear in strength of the diagonal terms of the checkerboard model. The latter indicates the altermagnetic origin of the effect.

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

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Magnetic skyrmions in atomically thin van der Waals (vdW) materials provide an ideal playground to push skyrmion technology to the single-layer limit [1–4]. However, a major challenge is reliable skyrmion detection. In this talk, based on rigorous *ab initio* calculations, we will show that all-electrical detection of skyrmions in 2D vdW magnets is feasible via scanning tunneling microscopy (STM) and in planar tunnel junctions with straightforward implementation into device architectures (see Fig. 1). We use the nonequilibrium Green's function method for quantum transport in planar junctions, including self-energy due to electrodes and working conditions, going beyond the Tersoff-Hamann approximation applicable to STM and mostly used to date. We propose the graphite/FGT/Ge/graphite tunnel junction, an experimentally feasible system, as an ideal platform for reliable all-electrical skyrmion detection. An extremely large NCMR of beyond 10,000 % is observed, which is more than two orders of magnitude higher than the NCMR obtained for conventional transition-metal interfaces [5]. We trace the origin of the NCMR to spin-mixing between spin-up and -down states of p_z and d_{z^2} character at the surface atoms and the orbital matching effect at the interface. Our proposal opens a new route to realize skyrmion racetrack memories based on atomically thin vdW materials with full-electrical writing and reading.

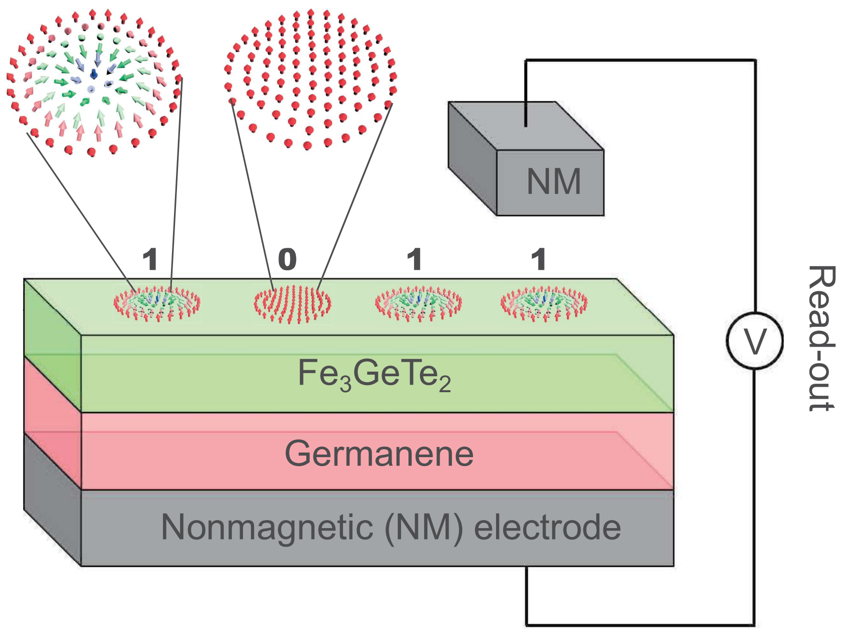

Figure 1: The proposed vertical tunnel junctions with nonmagnetic electrodes for electrical read-out of skyrmions in 2D vdW magnets, e.g., in racetrack memory. The skyrmions are stabilized at the Fe_3GeTe_2/germanene vdW heterostructure. Reading data from the skyrmion pattern is accomplished all electrically based on the noncollinear magnetoresistance effect.

Acknowledgments

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Memristive behavior of $L1_0$-FePt based granular film for realizing the Neural network

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The spintronic device has been considered a promising candidate for neuromorphic computing because of its non-volatility, switching speed(~ns), retention and scalability. In spintronic device, domain wall (DW) nucleation followed by DW propagation is one of the dominant mechanisms of magnetization switching. Advantage of DW driven switching is that multi-level switching can be realized by controlling the position of the DW across a nanostructure. However, difficulties in the precise control of the DW limit realization of the synaptic applications.
In this presentation, we discuss about synaptic characteristics with L10-FePt based granular film. Since a granular film is composed of nm-sized grains embedded in highly resistive non-magnetic medium with strong perpendicular magnetic anisotropy, control of each grain is ideally possible. This is a promising platform for realizing synaptic spin devices. We observed the multi-level state along the pulse amplitude and good retention property. Our device presents the possibility of performing gradual switching behaviors to construct spin synapses and spin neurons for neuromorphic computing.

Dynamic Investigation of Magnetic Skyrmions in the 2D van der Waals Magnet Fe3GeTe2

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The vast versatility of 2-dimensional (2D) magnetic van der Waals materials has attracted immense interest within recent years. The biggest advantage of this material class is its ability to form versatile heterostructures that can be tailored towards a broad spectrum of properties, ranging from spintronic to optomagnetic and electrical applications. It is also capable of hosting chiral topological spin textures, such as skyrmions, interesting, e.g., for spintronic data storage applications. Unique to this class of materials is their mechanical flexibility and the option to exfoliate perfectly crystalline sheets on pre-pattered substrates. This offers the prospect of highly efficient low-dimensional devices and extreme ease to fabricate versatile heterostructures by stacking separate individual layers.

In this work, we utilize real-space imaging of the magnetic texture in thin flakes of the 2D van der Waals magnet Fe3GeTe2 (FGT) to characterize the dynamics of skyrmions in trilayer devices consisting of an FGT sheet capped by hexagonal boron nitride (hBN) and a graphite electrode to inject currents through a vertical nanocontact. With this device we realize the local injection of skyrmions and investigate dynamical effects of the generation process. Moreover, we investigate the effects of temperature and pinning on skyrmion dynamics in FGT. Ultimately, the choice of composition, nucleation mechanism und temperature result in a selective stabilization of individual skyrmions that can then be manipulated by targeted current pulses. Our findings thus open novel perspectives and strategies for designing van der Waals heterostructure-based devices.

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Study of the chiral magnet Cu_2OSeO_3 using resonant X-ray elastic scattering

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Cubic chiral magnets like Cu_2OSeO_3 can exhibit complex spin textures, encompassing conical, helical, and skyrmion phases. Skyrmions are topologically protected magnetic textures that can occur in the vicinity of the Curie temperature [1] and at low-temperatures [2]. These magnetization swirls with nontrivial topological properties were initially observed in MnSi using neutron scattering techniques [3]. A low-temperature skyrmion phase and tilted conical states have been observed using broadband microwave spectroscopy [4] and resonant x-ray scattering techniques while exciting the sample with magnetic fields at gigahertz frequencies [5]. We studied the skyrmion phase and the tilted conical phase of high-quality single crystal Cu_2OSeO_3 at low temperatures [6] using the resonant x-ray elastic scattering technique while adjusting the energy of photons to match the Cu L_3 edge at 931.8 eV. We directly witness the magnetic diffraction pattern produced by the magnetic arrangement of Cu^{2+} ions in different phases.

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POSTER TITLE and ABSTRACT

Exploring the Electronic Structure of Fe4GeTe2 for Low-Dimensional Spintronic Devices

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The foundation of spintronics lies in the generation of highly spin-polarized currents using spin-polarized current sources [1]. Magnetic 2D van der Waals (vdW) materials have emerged as pivotal in advancing spintronic devices. Hence, the current research spotlight is on magnetic two-dimensional vdW materials as potential spin-polarized current sources.
This study delves into the electronic structure of the ferromagnetic metal, Fe4GeTe2. Characterized by its low magnetic anisotropy, exceptional conductivity, and high magnetic moment (~1.8 μ_B), Fe4GeTe2 emerges as a candidate for spin source in low-dimensional spintronics devices [2]. The material's Curie temperature, which is close to room temperature (approximately 270 K), further underscores its suitability. We present the experimental band structure of Fe4GeTe2 derived from photoemission spectroscopy in the UPS range. These experiments were performed using a momentum microscope [3] coupled with a He lamp, enabling comprehensive measurements of the valence band structure across the entire Brillouin zone. Through temperature-dependent studies, we successfully extracted data on the band-resolved electron-phonon coupling.

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Low-temperature XPEEM to study functional properties of 2D materials

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Two-dimensional (2D) magnetic van der Waals materials are particularly promising for electronic and spintronic devices [1]. 2D layers often exhibit novel electronic and magnetic properties that are ideal for investigation with surface-sensitive X-ray photoemission electron microscopy (X- or XMCD-PEEM). We have developed a dedicated sample environment for PEEM to study functional properties of 2D materials such as the response to electric and magnetic fields or optical excitations at low temperatures down to 20 K. In the poster we will explain in more detail the experimental possibilities of the measurement setup which will also become available for external groups.

In addition to examples and results of previous projects, we will also discuss our current goals and first steps to fabricate and pre-characterize mono- and heterostructures from 2D materials under an inert gas atmosphere.

Our work focuses on studies of 2D magnetic heterostructures prepared by mechanical exfoliation of Fe_3GeTe_2 crystal onto gold-coated Si/SiO_2 substrates in inert atmosphere with a use of polydimethlyl siloxane (PDMS) as a support polymer. The exfoliated Fe_3GeTe_2 flakes with the macroscopical lateral dimensions and thicknesses up to a few monolayers are protected from oxidation with a use of h-BN capping layer. Mechanically exfoliated graphene sheets adjacent to the Fe_3GeTe_2 layers can further serve as electrodes in the prototype of devices for spin valve applications. Element-specific X-ray photoemission electron microscopy (XPEEM) will be employed to study the peculiarities of magnetic domain formation along with their time resolved responses to the optical excitation by fs laser pulses to explore the ultrafast magnetization dynamics in the prepared 2D heterostructures. The transport, optical, magneto-optical and magnetic properties of these heterostructures will be thoroughly studied as well.

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Large Orbital moment in van der Waals halide VI_3

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Van der Waals (vdW) magnets are currently intensively investigated due to their magnetic order in low dimension. VI_3 is a vdW material with semiconductor properties and ferromagnetic order below 50K. In this system, layers composed of edge-sharing VI6 octahedra arranged in a honeycomb lattice are bound by vdW forces. The van-der-Waals halides are fascinating group of materials, where ferromagnetic order can be preserved down to the single layer limit. VI_3 with complex magnetic and structural phase diagrams is the last discovered member[1].

VI_3 presents a large magnetic anisotropy[2] and the measured total magnetic moment shows discrepancies to the expected spin-only value. These experimental results together with a few theoretical works about the V ground state lead to the suggestion of a large unquenched orbital moment (OM). Below ~ 36K different experimental techniques evidence a qualitatively different ferromagnetic phase, and the co-existence of two different V sites was proposed. In this work, we have used x-ray magnetic circular dichroism at the V $L_{3,2}$ edges in VI_3 to quantify the V OM. Using sum rule analysis of the XMCD spectrum we confirm a large unquenched OM. With the help of density functional theory and ligand field multiplet simulations we propose a model for the V ground state where there is a co-existence of two V sites with different orbital occupation[3].

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Exchange bias in fully compensated vdW $Fe_3GeTe_2/MnPS_3$ heterostructures

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The phenomenon of exchange bias, observed in systems with exchange-coupled ferromagnetic (FM) and antiferromagnetic (AFM) materials, has intrigued researchers for over six decades. This study focuses on exchange bias in van der Waals (vdW) heterostructures, specifically examining the $MnPS_3/Fe_3GeTe_2$ system. This system consists of an Ising-type FM layer [1] paired with a compensated AFM layer [2] at the interface, allowing for a detailed exploration of exchange bias in compensated AFM/FM heterostructures. Magneto-transport measurements reveal significant exchange bias at the fully compensated $MnPS_3/Fe_3GeTe_2$ interface, along with a dynamic evolution of exchange bias at low temperatures due to thermal cycling-induced van der Waals gap modification, confirmed by cross-sectional STEM measurements. Interestingly, the observed exchange bias is attributed to the anomalous ferromagnetic ordering that emerges in $MnPS_3$ at low temperatures, as confirmed by bulk SQUID Magnetometry and surface-sensitive NV Magnetometry measurements [3]. This research highlights the potential of vdW materials in advancing our understanding of exchange bias and provides insights into the intricate interplay of exchange interactions at interfaces.

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Characterization of domain wall patterns in granular antiferromagnetic Cr_2O_3 films

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Cr_2O_3 is an exceptional antiferromagnet with an easy axis of anisotropy that exhibits a magnetoelectric effect at room temperature [1]. Although there are technological challenges to use it for applications because of the relatively low bulk Neel temperature of T_N = 308 K, there are demonstrations that T_N can be substantially enhanced by strain in thin films. The morphology and growth procedure of such samples allow the appearance of flexomagnetic effects and pinning of domain walls at grain boundaries [2,3].

Here, we propose a material model of granular antiferromagnetic films and apply it to maze-like domain patterns in thin Cr_2O_3 samples [4]. The domain pattern is obtained by means of the nitrogen vacancy magnetometry and compared with spin-lattice simulations. We analyze the statistics of the size and self-similarity of the domain wall patterns to correlate the experimental measurements with the parameters of the theoretical model and compare the domain wall patterns with predictions made by a machine learning approach. The estimated inter-grain coupling is characterized by a substantial reduction of the effective exchange coupling to about 10% of the bulk value, with a wide standard deviation. Based on the material model, we provide design rules for the granular AFM recording media.

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Detection of Nanoscale Magnetic Fields with Scanning NV Magnetometry

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For most magnetic field sensors, there seems to be a trade-off between magnetic field sensitivity and spatial resolution. Furthermore, some measurement techniques require special conditions such as cryogenic temperatures or ultra-high vacuum to achieve the best results.

Scanning nitrogen-vacancy (NV) measurements are generally conducted at room temperature and under ambient conditions. The key part of the Scanning NV is the NV center, a point defect in a diamond host lattice. Due to its unique electronic structure, the NV center can be utilized to detect magnetic fields with sensitivities up to several nT/√Hz, which are read out optically. Scanning NV setups therefore combine an optical excitation/detection path with an Atomic Force Microscope (AFM), ideally providing nanoscale magnetic and spatial resolution at the same time. In conclusion, Scanning NV magnetometry is a convenient tool to characterize magnetization processes and local properties of 2D materials like van der Waals magnets.

However, the actual magnetic resolution of Scanning NV depends on several factors, including the distance between NV center and sample surface, the shape of the nanodiamond tip, and the measurement time. Parameters like the coherence time and optically detected magnetic resonance (ODMR) contrast of the respective NV center have to be considered as well. We discuss the impact of these factors on magnetic measurements of typical nanoscale magnetic structures with different characteristic dimensions. Finally, we compare our results to vacuum Magnetic Force Microscope (MFM) measurements.

Finite size effect on the Hall response of altermagnetic Mn_5Si_3

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Epitaxial thin film of Mn5Si3 [1,2] is a candidate to the recently predicted class of magnetic materials called ‘alter’magnet [3], and more specifically to the anisotropic d-wave magnetic phases that features an unconventional combination of strong time reversal symmetry breaking responses and a vanishing net magnetization. The Mn5Si3 compound displays a large spontaneous anomalous Hall (AHE) response of a few S.cm-1 below its Néel temperature of about 200 K, to which adds a topological-like (THE-like) signal below about 90 K, wherein some twisting of the magnetic moments is expected to occur, as opposed to a collinear arrangement above [1,2]. What is the anisotropic response of the AHE signal and what is the exact origin of the THE-like signal are some questions which are still pending and that we will present here. To address the first point, measurements were taken for a current and/or an external magnetic field applied along several crystallographic directions. For the second point a systematic study of the finite size effects was performed so as to understand whether the THE-like signal is the result of an actual topological effect related to the electrons picking up a Berry phase on interaction with the non-collinear spin structure of Mn5Si3 below 90 K or whether it is the bare summation of several AHE signals of opposite sign, in an inhomogeneous médium [4].

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Temperature-resolved photoemission measurements on the antiferromagnetic semiconductor CrSBr

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The combination of a semiconductor with tunable electrical transport properties and a magnet with tunable spin configuration represents a highly interesting platform for next-generation spintronic devices [1]. One candidate is the van der Waals antiferromagnet CrSBr, which not only possesses a high Néel temperature of 132 K and air stability for bulk crystals but also exhibits a strong correlation between magnetic order, charge transport [2] and quasiparticle excitations [3].

Fundamental to these properties is the electronic band structure, which has been determined in the paramagnetic phase by previous photoemission studies [4]. However, the antiferromagnetic structure and temperature-related changes have remained elusive. Here we present temperature-resolved photoemission measurements on bulk CrSBr from room to Néel temperature. Although we did not observe abrupt changes in the electronic structure at the phase transition, an energy band-dependent broadening was detected, which will be discussed in this contribution.

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Photo-induced transient ferromagnetism in lightly doped $LaMnO_3$ thin films

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The ground state of perovskite manganites is well-known to be tunable by chemical doping, e.g., from insulating phases with differing magnetic order to ferromagnetic (FM) metallic behavior in the prototypical correlated manganite $La_{1-x}Sr_xMnO_3$ (LSMO). Ultrashort light pulses possibly provide another avenue for optical doping of such materials, making them promising candidates to observe photo-induced phase transitions.

We report transiently enhanced ferromagnetic and weakened insulating behavior within the overall FM ($T<T_C$) insulating and the paramagnetic ($T>T_C$) insulating phase of underdoped LSMO ($x\approx0.1$ – 0.15) and self-doped LayMnO3+δ ($y\approx0.9$) LMO thin films epitaxially grown on $SrTiO_3$(100) substrates.

The non-thermal transient phase in the lightly doped LMO films manifests itself in a transient magnetization of the system. Furthermore, we observe an initially negative and then continually reduced transient reflectivity signal indicating a more conductive state as derived from comparison with temperature-dependent static data. In comparison, optimally doped metallic LSMO ($x\approx0.3$ – 0.35) film, does not show such an unconventional photo-response, rather exhibiting only thermally-driven dynamics.

We interpret our experimental results as a transient increase of the effective hole doping, i.e., the Mn^{4+}/Mn^{3+} ratio, which corresponds to a scenario in which the material is transiently pushed towards an equilibrium phase boundary.

Laser-induced real-space topology control of spin wave resonances

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Materials exhibiting tunable magnetic spin textures in the ground state promise advanced magnetic control via the generation of ultrafast and non-equilibrium spin dynamics upon femtosecond laser excitation. In this regard, systems hosting magnetic bubble/skyrmion lattices are of particular interest. In this study, we focus on ferrimagnetic Fe/Gd multilayers exhibiting a rich diversity of magnetic spin textures at ambient temperature [1,2]. Stripe domains appear at low magnetic fields, a dense bubble/skyrmion lattice at intermediate fields, and a single domain state at high fields at magnetic saturation. We demonstrate that these distinct magnetic ground states can be unambiguously identified by their coherent spin dynamics in response to a weak laser excitation. Furthermore, we show that non-equilibrium and ultrafast modification of these ground states is achieved via strong laser excitation, as it is possible to both annihilate, but also create bubbles/skyrmions from stripe domains.
We corroborate these findings by micromagnetic simulations and by Lorentz transmission electron microscopy with in-situ optical excitation. Our results showcase how ultrafast excitations can be used to gain versatile control of magnetic spin textures via non-equilibrium excitation pathways.

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Local control over chiral textures with curvilinear helimagnets

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Broken inversion symmetry in the crystal structure of systems characterized by strong spin-orbit coupling gives rise to the Dzyaloshinskii-Moriya interaction (DMI), an intrinsic antisymmetric exchange interaction with the capacity to stabilize topological magnetization textures[1]. In curvilinear geometries, where patterned curvature, chirality, or torsion are present, inversion symmetry is also broken, leading to new effective magnetic interactions and emergent anisotropic effects[2,3]. The interplay between such intrinsic and extrinsic interactions offers the prospect of tailoring and locally tuning the magnetic energy landscape of systems, potentially yielding new three-dimensional textures with designed properties.

Here we combine intrinsic and extrinsic interactions in patterned toroidal helimagnets, resulting in a locally varying DMI. Specifically, by patterning nanoscopic tori of single crystal helimagnets using focused ion beam patterning and imaging their magnetic configuration using resonant soft x-ray ptychographic imaging, we observe the presence of a radial curvature-induced helical texture, that we confirm with finite element micromagnetic simulations. This combination of intrinsic and extrinsic DMI not only stabilizes non-trivial remanent states, but also leads to local control of field-induced textures such as skyrmions and chiral bobbers[4]. Our work highlights the impact of curvature on chiral helimagnetism, offering opportunities to tailor chiral magnetic textures within curvilinear geometries[5].

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Coupling of ferromagnetic and antiferromagnetic spin dynamics in thin film bilayers

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Ferromagnets have a net magnetic moment and uniform spin dynamics in the GHz range. In contrast, collinear antiferromagnets have two equal but opposite sublattice magnetizations with vanishing net magnetic moment and spin dynamics that can reach the THz range. The difference in the magnetization dynamics of ferromagnetic (FM) and antiferromagnetic (AFM) materials could potentially be exploited in applications that integrate AFM materials in high-frequency spintronic devices. A promising approach to enhance the FM spin dynamics frequencies and control FM spin-wave dispersions might be the combination of FM and AFM thin-film layers with interfacial exchange coupling.

We investigate magnetization dynamics of Mn_2Au/Py thin film bilayers using broadband ferromagnetic resonance (FMR) and Brillouin light scattering spectroscopy [1]. Our bilayers exhibit two resonant modes with zero-field frequencies up to almost 40 GHz, far above the single-layer Py FMR. Our model calculations attribute these modes to the coupling of the Py FMR and the two antiferromagnetic resonance modes of Mn_2Au. The coupling strength is in the order of 1.6 T·nm at room temperature for nm-thick Py. Our model reveals the dependence of the hybrid modes on the antiferromagnetic resonance frequencies and interfacial coupling as well as the evanescent character of the spin waves that extend across the Mn_2Au/Py interface.

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Exploring the impact of the inverse Faraday effect on all-optical helicity-dependent magnetization switching

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All-optical helicity-dependent magnetization switching (AO-HDS) is a fast deterministic technique for data storage applications using solely ultrashort laser pulses. Granular high data density magnetic storage media developed for heat-assisted magnetic recording (HAMR) provide the perfect playground to investigate the interplay of effects leading to magnetization switching. In the latest perception, we identify two effects, the magnetic circular dichroism (MCD) and the inverse Faraday effect (IFE), as the forces driving the switching process. During photon absorption, which leads to a rapid temperature rise and thus to magnetization quenching, the MCD ensures two distinct electron temperatures due to helicity-dependent absorption. This effect already holds a nonvanishing probability for magnetization switching. At the same time, the IFE induces a magnetic moment within the material, enhancing the switching probability. We present AO-HDS experiments using ultrashort laser pulses (≤ 200 fs) in the near-infrared range from 800 nm to 1500 nm.

The experiments demonstrate a strong dependence of the switching efficiency on the absorbed energy density, bringing the electron temperature close to the Curie Temperature, allowing for the IFE to take full effect, inducing a magnetic moment for deterministic switching in the quenched magnetization state. We conclude that the magnetic moment induced by the IFE is crucial for the switching efficiency and the distinct deterministic character of the switching process. Laser pulses with a higher absorption induce a higher magnetic moment and switch magnetization at lower fluences.

Sliding ferroelectricity in bulk misfit layer compound $(PbS)_{1.18}VS_2$

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The recent theoretical prediction [1] and experimental [2,3] confirmation of sliding ferroelectricity has significantly expanded the group of two-dimensional (2D) ferroelectrics. Due to the weak van der Waals interactions in layered van der Waals multilayers, an out-of-plane polarization can be created in many of those systems via in-plane interlayer sliding of a layer and thereby breaking the inversion symmetry.

Here, the sliding ferroelectric properties of bulk $(PbS)_{1.18}VS_2$ misfit layer compound (MLC) crystals have been investigated. MLCs are thermodynamically stable, bulk, materials with a natural superlattice, consisting of the alternating stacking of two different 2D layers, here PbS and VS_2. The superlattice's formation and stability are still under debate, but it is suggested that charge transfer between the individual layers creating a strong electrostatic bond might stabilize these compounds.

Using single crystal X-ray diffraction and a combination of imaging techniques, the sliding ferroelectric properties of $(PbS)_{1.18}VS_2$ were explored. The interaction between the two subsystems is derived from the presence of satellite reflections in the diffraction pattern of the composite. We find that the subtle interaction between the two subsystems causes the presence of twins, where two of the majority twins have a twist angle below one degree, the necessary condition for sliding ferroelectricity. The presence of ferroelectric domains, with a triangular shape and size from tens of nanometers to tens of micrometres, and their surface electrical potential from the induced sliding ferroelectricity can be observed using scanning electron microscopy, photoemission electron microscopy, imaging x-ray photoelectron spectroscopy and scanning probe microscopy imaging.

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Crystal structure quality investigations in FePt granular media for all-optical helicity-dependent magnetization switching

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Developed for heat-assisted magnetic recording, granular high-density magnetic storage media are ideal for investigating magnetization switching effects. In combination with all-optical helicity-dependent magnetization switching (AO-HDS) as a fast and deterministic technique for data storage applications using solely ultrashort laser pulses this opens a new ultrafast data storage technique. We identify two effects, the magnetic circular dichroism (MCD) and the inverse Faraday effect (IFE), as the forces driving the switching process. During photon absorption, the magnetization quenching is caused by a rapid temperature rise due to helicity-dependent absorption, which ensures two distinct electron temperatures. This effect already holds a non-vanishing probability for magnetization switching. Simultaneously, the IFE induces a magnetic moment within the material, enhancing the switching probability. We present AO-HDS experiments using ultrashort 800 nm laser pulses using FePt granular media with 6 nm sized grains in a carbon matrix and reduced magnetic anisotropy on various NiTa heat sink layers.
The experiments demonstrate a dependence of the switching efficiency on the crystalline structure quality and saturation magnetization combined with the ability to transport heat away from the grains by providing enough heat capacity by the NiTa heat sink layer.

Ultrafast electron dynamics in altermagnetic KRu_4O_8

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Altermagnetic materials [1,2] exhibit, among other intriguing properties, unique anistropic band-structure landscape with an alternating spin order. Spin-dependent electronic dynamics on ultrashort timescales should be strongly influenced by their band-structure features, and we numerically explore the features of electronic dynamics in the altermagnetic KRu_4O_8,, using as ab-initio input the band structure and the corresponding dipole matrix elements. Optically excited carrier distributions are determined using a Fermi's Golden Rule approach[4], and these then form the basis for our dynamical calculations. In order to resolve the main altermagnetic features, it is imperative to calculate the microscopic momentum dependent scattering dynamics in the whole Brillioun zone. To make these demanding calculations feasible, the number of bands and k-space dimensions have to be reduced. We therefore employ a tight-binding model with a two-dimensional k-space by fitting the model parameters fit to the DFT band structure. This allows us to numerically calculate the electron dynamics due to electron-phonon [4,5] and electron-electron interactions including the key momentum-space properties of KRu_4O_8. Already the excited carrier distribution exhibits a strong anisotropy and k-dependent spin polarization. Subsequently we find rich electronic dynamics in the whole Brillioun zone, for which Elliot-Yafet spin flips play an important role. Furthermore, we show that the interplay between the spin-split band structure and the corresponding spin character may lead to ultrafast spin relaxation.

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Anisotropic Spin-to-charge Conversion in Hybrid Chiral Molecule/ Metal Systems

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The observation of spin-dependent transmission of electrons through chiral molecules has led to the discovery of chiral-induced spin selectivity (CISS). The CISS effect has recently gained significant interest for novel hybrid molecule magnetic spintronics applications due to the high efficiency of spin filtering in chiral molecules. In our work, we explore spintronic phenomena at hybrid chiral molecule magnetic interfaces to elucidate the underlying mechanisms of the chiral-induced spin selectivity effect. For this, we investigate the spin-dependent spin-to-charge conversion in chiral molecule/metal thin film heterostructures. Quantifying the impact of the adsorption as a function of the structure of the chiral molecules will reveal the role of the structural design in the spin filtering effect paving the path toward three-dimensional engineering of hybrid chiral interfaces.

Magnetic interactions in epitaxial films of $Mn_5(Ge_{1-x}Si_x)_3$ /Ge(111) : ^{55}Mn NMR study

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Mn_5Ge_3 and Mn_5Si_3 are two isostructural compounds crystallizing in the hexagonal $D8_8$ structure (space-group $P6_3/mcm$) that can be mutually alloyed over the entire concentration range [1]. The two end compositions of the $Mn_5(Ge_{1-x}Si_x)_3$ series exhibit very different magnetic behavior: Mn_5Ge_3 is a metallic ferromagnet with a Curie temperature of 296 K whereas Mn_5Si_3 reveals a complex antiferromagnetic order at low temperatures: a chiral spin structure below 65 K and a collinear spin arrangement between 65 K and 100 K. Their unit cell contains two formula units, with the manganese atoms in two Wyckoff crystallographic positions: 4*(d)* and 6*(g)* (here denoted as Mn_I and Mn_{II} sites, respectively). It was shown that the $Mn_5(Ge_{1-x}Si_x)_3$ films can be grown epitaxially on Ge(111) substrates[2]. With the aim to understand local magnetic properties in each of the two manganese sites as a function of Si content we have undertaken a ^{55}Mn NMR study in a series of the $Mn_5(Ge_{1-x}Si_x)_3$ epitaxial films with silicon concentration ($0 \le x \le 0.5$).The thorough analysis of NMR data shows that substitution of Ge atoms by Si significantly modifies the exchange interactions involving the 6*(g)* manganese sites, leading to a drop of the magnetic moment of those Mn_{II} atoms that have Si neighbour instead of Ge. The effect on the Mn_I sites is secondary and consists in a smaller contribution of the transferred hyperfine field due to the reduced magnetic moment of the Mn_{II} neighbors and a loss of the quadrupolar structure due to the inhomogeneity brought by Ge/Si replacement. Relative intensity of the MnII satellite line coincides with a probability of finding 2 Si nearest neighbors. Those MnII atoms that have 2 Si neighbours instead of Ge experience the modified exchange interactions, leading to a significant drop of the magnetic moment. Anisotropy of the orbital moment in all mangenese sites of $Mn_5(GeSi)_3$ is practically the same as in Mn_5Ge_3, for all studied concentrations.

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Altermagnetic signatures in the ultrafast photoconductivity of RuO_2

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The discovery of altermagnets as a new class of magnets opens new avenues to exploit spin-polarized electron conductivity in materials with compensated spin structures [1]. This is possible due to the spin-split band structure of altermagnets and the corresponding non-relativistic spin polarization. These features distinguish altermagnets from antiferromagnets and can, for example, lead to spin-splitter currents [2] in compensated magnets. However, the exotic properties and functionalities of altermagnets are not limited to electric currents. Here, we demonstrate the existence of characteristic altermagnetic signatures in the photoconductivity of the prototypical altermagnet RuO_2 after optical excitation using fs light pulses. This is achieved by combining all optical pump-probe methods with ab-initio calculations, which together provide insight into the spin polarization of the optically excited carriers in RuO_2 for different excitation geometries. Our results constitute a first crucial step in the exploration of light-driven spin functionalities in altermagnetic materials.

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Magneto-transport Characterization of Pt/Fe_5GeTe_2 Heterostructure

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Spintronics is an area of study focused on the manipulation and control of electron spin degrees of freedom in solid-state systems. Over the past few decades, 2D van der Waals materials and their heterostructures have garnered significant interest in the research community. This interest is largely due to their remarkable properties, which include a Curie temperature close to room temperature, as well as stable electronic and magnetic behaviors.

This poster firstly illustrates a review of spintronics in the context of 2D van der Waals materials. Then, we will particularly focus on the investigation and quantification of current-induced spin orbit torque in a Pt/Fe5GeTe2 bilayer device. The poster will detail the methodologies employed in this study, including the exfoliation of materials, transfer of flakes, and the experimental procedures followed. Additionally, the results of these experiments will be thoroughly discussed, highlighting their significance in the field of spintronics.

Promoting p-based Hall effects by p-f hybridization in Gd-based dichalcogenides

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We conduct a first-principles study of Hall effects in rare-earth dichalcogenides, focusing on monolayers of the H-phase EuX_2 and GdX_2 where X = S, Se, and Te. Our predictions reveal that all H-phase monolayers of EuX_2 and GdX_2 exhibit high magnetic moments and wide bandgaps. Furthermore, we consider the effect of the Coulomb repulsion (U) parameter and observe that a large value of U leads to strong hybridization of the p-f-d orbitals in the case of EuX_2 while a large value of U causes the minority/majority density of states (DOS) of the p-state to shift down/up when the f- state of Gd is shifted in energy. Notably, these systems display significant anomalous, spin, and orbital Hall conductivity. Moreover, we find that the application of strain can significantly modify the electronic structure of these systems, resulting in changes in the magnitude of the anomalous, spin, and orbital Hall conductivity. Furthermore, strain induces quantized values of AHC and quantized plateaus of SHC and OHC in close proximity to the Fermi energy. Our findings suggest that rare-earth dichalcogenides hold promise as a platform for topological spintronics and orbitronics.