Engineered Quantum Materials

US-German WE-Heraeus-Seminar

07 – 11 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 US-German WE-Heraeus-Seminar:

The US-German WE-Heraeus Workshop on "Engineered Quantum Materials" will take place at the Physikzentrum Bad Honnef from January 7-11, 2024.

This workshop, funded by the WE-Heraeus and the Gordon and Betty Moore Foundations, will bring together leading scientists in the quantum materials communities in Germany and the USA to discuss recent developments and future prospects in the synthesis and emergent properties of engineered quantum materials. Engineered quantum materials are the foundation and are essential to the modern world in which we all live.

The workshop will focus on transformative questions framed around cutting-edge challenges for quantum materials synthesis and fabrication and their characterization as well as their novel properties. New synthesis techniques for bulk materials, thin films and heterostructures as well as applications of advanced characterization probes will be included in the workshop.
The physical and electronic properties of topological and chiral materials as well as means of manipulating and controlling their topology and chirality, both in bulk and thin film forms will be discussed. Indeed, new classes of quantum materials are found in insulators and semimetals that exhibit non-trivial topologies: they display a plethora of novel phenomena including: topological surface states; new Fermions such as Weyl, Dirac or Majorana; and non-collinear spin textures such as skyrmions.

Another entirely distinct approach to engineering quantum materials is via thin film growth techniques that allows for the formation of atomically engineered interfaces between distinct materials that can thereby give rise to remarkable properties not presented by the component materials themselves.
The emergent properties of such manufactured quantum interfaces will be extensively discussed.

Finally, one of the goals for the workshop is to establish an innovative and strongly collaborative network between premier research institutes in the USA and Germany involved in leading edge quantum materials research.

Introduction

Scientific Organizers:

Prof. Dr. Stuart Parkin	MPI Halle, Germany E-mail: stuart.parkin@mpi-halle.mpg.de
Prof. Jak Chakhalian	Rutgers University, USA E-mail: jak.chakhalian@rutgers.edu
Dr. Annika Johansson	MPI Halle, Germany E-mail: annika.johansson@mpi-halle.mpg.de
Prof. Leslie Schoop	Princeton University, USA E-mail: lschoop@princeton.edu

Administrative Organization:

Dr. Stefan Jorda
Elisabeth Nowotka

Wilhelm und Else Heraeus-Stiftung
Kurt-Blaum-Platz 1
63450 Hanau, Germany

Phone +49 6181 92325-12
Fax +49 6181 92325-15
E-mail nowotka@we-heraeus-stiftung.de
Internet: www.we-heraeus-stiftung.de

Venue:

Physikzentrum
Hauptstrasse 5
53604 Bad Honnef, Germany

Conference Phone +49 2224 9010-120

Phone +49 2224 9010-113 or -114 or -117
Fax +49 2224 9010-130
E-mail gomer@pbh.de
Internetwww.pbh.de

Taxi Phone +49 2224 2222

Registration:

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

Program

Program

Sunday, 07 January 2024

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

Monday, 08 January 2024

08:00	*BREAKFAST*	
09:00	Scientific organizers	**Welcome words**
09:15 – 10:00	B. Andrei Bernevig	**Flat bands in kagome materials, laves phases, and heavy fermion compounds**
10:00– 10:45	Eva Andrei	**Moiré Crystals and Quasicrystals in Heterostructures of Twisted Bilayer Graphene and hBN**
10:45 – 11:15	*COFFEE BREAK*	
11:15 – 12:00	Titus Neupert	**Realizing higher-order topology**
12:00 – 12:15	**Conference Photo** (in the front of the lecture hall)	
12:15	*LUNCH*	

Program

Monday, 08 January 2024

14:15 – 15:00	Claudia Felser	**Chirality and topology**
15:00 – 15:45	Harold Hwang	**Topochemical transformations of transition metal oxides**
15:45 – 16:30	Ron Naaman	**Why it is so difficult to model the CISS effect?**
16:30 – 17:00	*COFFEE BREAK*	
17:00 – 17:45	**Poster flash talks I**	
17:45 – 18:00	Stefan Jorda	**About the Wilhelm and Else Heraeus-Foundation**
18:00	*DINNER*	

Program

Tuesday, 09 January 2024

08:00	*BREAKFAST*	
09:00 – 09:45	Christian Pfleiderer	**Mesoscale quantum textures**
09:45 – 10:30	Judy Cha	**1D topological systems for next-generation electronics**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Thomas Heine	**Magnetic Carbon**
11:45 – 12:30	Ingrid Mertig	**Origin of orbital hall effect in static and ultrafast regime**
12:30	*LUNCH*	

Program

Tuesday, 09 January 2024

13:45 – 14:30	Chang-Beom Eom	**Electronic-grade epitaxial (111) $KTaO_3$ heterostructures**
14:30 – 15:15	Emilia Morosan	**Real- and reciprocal-space topology in the square net series Eu(Ga1-xAlx)4**
15:15– 16:00	Dmitri Efetov	**tba**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:15	**Poster flash talks II**	
17:15 – 18:00	Jairo Sinova	**Unconventional magnetism in spintronics: The emergence of altermagnetism and its new variants**
18:00	*DINNER*	
19:00	**Postersession**	

Program

Wednesday, 10 January 2024

08:00	*BREAKFAST*	
09:00 – 09:45	Katharina Franke	**Diode effect in Josephson junctions with a single magnetic atom**
09:45 – 10:30	Silke Paschen	**Designing strongly correlated topological semimetals**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Joseph Checkelsky	**Natural superlattice design of modulated superconductors**
11:45 – 12:30	Felix Lüpke	**Engineered quantum states in assembled van der Waals heterostructures studied by scanning tunneling microscopy**
12:30	*LUNCH*	
13:45 – 14:30	Pablo Jarillo-Herrero	**Next generation Moiré quantum matter**
14:30 – 15:15	Leslie Schoop	**From structure to bonds to properties**
15:15 – 16:00	Hengxin Tan	**Charge density waves in emergent Kagome metals**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 18:30	**Postersession**	
19:00	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Thursday, 11 January 2024

08:00	*BREAKFAST*	
09:00 – 09:45	Satoru Nakatsuji	**Manipulation of Weyl semimetallic states in the chiral antiferromagnet Mn3Sn**
09:45 – 10:30	Vidya Madhavan	**Optical and magnetic field manipulation of the charge density wave in RbV_3Sb_5**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Sang-Wook Cheong	**Chirality and Kinetomagnetism**
11:45 – 12:30	Julia Mundy	**Antiferromagnetic metal phase in an electron-doped rare-earth nickelate**
12:30 – 13:00	Scientific organizers	**Poster award & closing words**
13:00	*LUNCH*	

End of the seminar and departure

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

Posters

Poster list

Kevin Allen	**Unusual magnetization plateaus in square-net lattice $EuRhAl_4Si_2$**
Mihiro Asakura	**Effect of interfacial interaction on the magnetic property of the chiral antiferromagnet Mn_3Sn**
Seokjin Bae	**Design and construction of laser scanning tunneling microscopy for investigating light-matter interaction at atomic scale**
Dumitru Călugăru	**Signatures of heavy-fermion physics in the thermoelectric effect of twisted bilayer graphene**
Lucas Caretta	**Non-volatile electric-field control of inversion symmetry**
Tianzhe Chen	**Observation of nonreciprocal Hall effect in superconductor-multiferroics heterostructure**
Andrea Kouta Dagnino	**The landscape of tight-binding models**
Tapan Kumar Das	**Angle dependent magnetoresistance and spin-elective electron transmission in oligopeptides**
Anvesh Dixit	**Phase coherent electrical transport in chiral topological metals**
Nghiep Khoan Duong	**Thermomechanical nanomolding for 1D Topological Materials**
Xiaolong Feng	**MT_6Z_6 kagome candidates with flat bands, magnetism, phonon instability, and charge density waves**
Ke Gu	**Racetrack memory devices based on freestanding multilayers**

Poster list

Hyeon Han	**Electrical formation of all-oxide metamaterials via synchronized local ionic gating**
Moritz Hirschmann	**Fundamental laws of chiral band crossings**
Haoyu Hu	**Heavy-fermion physics in twisted bilayer graphene**
Jingrong Ji	**Two dimensional monochalcogenides lateral superlattices**
Yi Jiang	**Kagome Materials II: SG 191: FeGe as a LEGO Building Block for the Entire 1:6:6 series: hidden d-orbital decoupling of flat band sectors, effective models and interaction Hamiltonians**
Ajin Joy	**Swift skyrmions as a true random number generator**
Dongchang Kim	**Revealing ion dynamics in epitaxial T-Nb_2O_5 thin films during Li-ionic gating**
Amina Kimouche	**Van der Waals epitaxy of a magnetic transition metal dihalide**
Michael Lampl	**Transverse-field susceptibility of spin freezing at themesoscale quantum phase transitions in $LiHoF_4$**
Sergio Leiva	**Spin and orbital Edelstein effect in a bilayer system with Rashba interaction**
Bharti Mahendru	**Chiral hybridization of Yu-Shiba-Rusinov states in Fe clusters on Pb(111)**
Mostafa Marzouk	**Atomic engineered oxide heterostructure interfaces for spintronics applications**
Wenhui Niu	**Quantum chiral nanocarbons with unique chiroptical properties and spin polarization**

Poster list

Naupada Preeyanka	**Deciphering the effect of chiral induced spin selectivity in the catalytic activity of D-glucose oxidase through spin polarized charge reorganization**
Mingqun Qi	**Manipulation of the ground state in altermagnetic RuO_2 thin films induced by octahedral symmetry**
Daniel Rothhardt	**Electronic structure of monolayer MnI_2 islands studied by KPFM**
Rohit Sharma	**Electrical and thermal Hall transport in compensated topological insulators**
Pranava Keerthi Sivakumar	**Helical spin-momentum locking and second order φ_0-Josephson effect in the Dirac semimetal 1T-$PtTe_2$**
Grigorii Skorupskii	**Unconventional anomalous Hall effect and complex magnetism in rare-earth stannides**
Jiang Tingting	**In-situ observation of magnetic structures in twisted stacks of LSMO bilayer**
Victor Ukleev	**Competing anisotropies in a cubic chiral magnet unveiled by resonant x-ray magnetic scattering**
Peng Wang	**Giant spin Hall effect and spin-orbit torques from 5d transition metal - aluminum alloys for energy efficient synthetic antiferromagnetic racetrack memories**
Ke Xiao	**In-plane electric-field-induced orbital hybridization of excitonic states**
Yishen Xie	**Molecular intercalation induced unconventional superconductivity**
Qun Yang	**Monopole-like orbital-momentum locking and the induced orbital transport in topological chiral semimetals**

Poster list

Changjiang Yi	**Quantum oscillations revealing topological band in kagome metal ScV_6Sn_6**
Zihan Yin	**Engineering of Néel-type skyrmions in novel freestanding heterostructures**
Wenjie Zhang	**Current-induced domain wall motion in a van der Waals ferromagnet Fe_3GeTe_2**

Abstracts of Talks

(in alphabetical order)

Moiré Crystals and Quasicrystals in Heterostructures of Twisted Bilayer Graphene and hBN

Xinyuan Lai,[1] Daniele Guerci,[2] Guohong Li,[1] Kenji Watanabe,[3] TakashiTaniguchi,[3] Justin Wilson, [4] Jedediah H. Pixley,[1,2,5] Eva Y. Andrei[1]

[1]Department of Physics and Astronomy, Rutgers University, 136 Frelinghuysen Road, Piscataway, NJ 08854, USA

[2]Center for Computational Quantum Physics, Flatiron Institute, 162 Fifth Avenue, New York, NY 10010, USA

[3]Research Center for Functional Materials, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan

[4]Department of Physics and Astronomy, and Center for Computation and Technology, Louisiana State University, Baton Rouge, LA 70803, USA

[5]Center for Materials Theory, Rutgers University, 136 Frelinghuysen Road, Piscataway, NJ 08854, USA

Using scanning tunneling microscopy on heterostructures of twisted bilayer graphene on hexagonal Boron-Nitride we find Matryoshka-doll like moiré geometric structures with multiple underlying periodicities. The emergent super-moiré structures reveal a phase-diagram where lines of commensurate moiré-crystals are embedded in swaths of moiré quasicrystals. Surprisingly, we find that the commensurate crystals exist over a much wider than predicted range providing evidence of an unexpected self-alignment mechanism, which is explained in terms of an elastic network model.[1]

References:

[1] Xinyuan Lai, Daniele Guerci, Guohong Li, Kenji Watanabe, Takashi Taniguchi, Justin Wilson, Jedediah H. Pixley, Eva Y. Andrei, arXiv:2311.07819 (2023)

Flat Bands in Kagome Materials, Laves Phases, and Heavy Fermion Compounds

B. Andrei Bernevig

Princeton Unversity, USA

We provide faithful electronic tight-binding models for the electronic flat bands on Kagome metals, and analyze their instabilities. We show that generically, flat bands at the fermi level ferromagnetic in plane and antiferromagnetize out of plane. When not at the Fermi level, flat bands leave behind van-hove singularities that lead to a large set of phonon instabilities, which we classify. This predicts large classes of CDW states, some of which have been experimentally verified.

We then provide theoretical and experimental analysis of a new d-f orbital Heavy fermion compound. This remarkable material is unique, in the sense that it is the only heavy fermion compound where the non-heavy (Co d) orbitals magnetically order due to flat bands magnetism at high temperature, while the heavy f-orbitals do not. However, even though it exhibits magnetic ordering, the material also shows a kondo effect below the ordering temperature, which begs the question: “what forms the kondo singlet”. We show that the presence of a new symmetry allows for the formation of a non-local Kongo singlet, and that the coherent f-electron band showing up at the fermi level forms a nodal line with the other dispersive bands.

1D topological systems for next-generation electronics

Judy J. Cha[1]

[1]Department of Materials Science and Engineering at Cornell University, Ithaca, USA, jc476@cornell.edu

Topological nanowires, topological materials confined in one dimension (1D), hold great promise for robust and scalable quantum computing and low-dissipation interconnect applications [1], which will transform current computing technologies. To do so, research in topological nanowires must continue to improve their synthesis and properties.

In this talk, I will discuss my group's efforts to develop a high throughput and precision synthesis method to fabricate 1D topological systems [2]. I will highlight our studies on topological semimetal nanowires for their potential application as extremely-scaled, low-resistance interconnects. In particular, we demonstrate that the resistivity scaling of topological metal MoP nanowires is superior to those of the state-of-the-art Cu interconnects and Cu alternative metals, presenting MoP as a breakthrough metal for the low-resistance interconnect applications [3].

References

[1] P. Liu, J. R. Williams, J. J. Cha, Nature Review Materials **4**, 479-496 (2019)

[2] N. Liu, Y. Xie, G. Liu, S. Sohn, A. Raj, G. Han, B. Wu, J. J. Cha, Z. Liu, J. Schroers, PRL **124**, 036102 (2020)

[3] H. J. Han, S. Kumar, X. Ji, J. L. Hart, G. Jin, D. J. Hynek, Q. P. Sam, V. Hasse, C. Felser, D. G. Cahill, R. Sundararaman, J. J. Cha, Adv. Mater. **35**, 2208965 (2023)

Natural Superlattice Design of Modulated Superconductors

J. G. Checkelsky

MIT, Cambridge, USA

Connecting theoretical models for exotic quantum states to real materials is a key goal in quantum materials synthesis. Two-dimensional model systems have been proposed to host a wide variety of exotic phases- historically a number of techniques have been used to realize these including thin film growth and mechanical exfoliation. We describe here our recent progress in experimentally realizing 2D model systems using bulk crystal synthesis including modulated superconducting states. We discuss their structures and the new phenomena that they support. We comment on the perspective for realizing further 2D model systems in complex material structures and their connections to other methods for realizing 2D systems.

Chirality and Kinetomagnetism

<u>Sang-Wook Cheong</u>, Xianghan Xu, and Feiting Huang

Rutgers Center for Emergent Materials, USA, sangc@physics.rutgers.edu

Chirality, which arises from the breaking of mirror symmetries combined with any spatial rotations, plays a ubiquitous role in a wide range of phenomena, from the DNA functionality, vine climbing to the piezoelectricity of quartz crystals. It's important to note that chirality does not necessarily involve a screw-like twisting, and magnetic chirality means chirality in spin ordered states or mesoscopic spin textures. Despite being mathematically well-defined, the term "chirality" has been extensively used, often in confusing ways, in recent years. In steady states, chirality ($\mathcal{C}$) does not change with time-reversal operation, while chirality prime ($\mathcal{C}'$) denotes the breaking of time-reversal symmetry in addition to broken all mirror symmetries, combined with any spatial rotations. Various examples of magnetic chirality and chirality prime and their emergent phenomena, such as self-inductance, directional nonreciprocity in magnetic fields, current-induced magnetization, chirality-selective spin-polarized current, Schwinger scattering, magneto-optical Kerr effect, linear magnetoelectricity, and chiral tunneling will be discussed. Many of these phenomena can be understood with one hypothesis on “kinetomagnetism in chiral systems” that I will present. Some of these exotic phenomena have been recently observed, while many others require experimental confirmation in the future.

Electronic-grade epitaxial (111) $KTaO_3$ heterostructures

Chang-Beom Eom

University of Wisconsin-Madison, Madison, WI 53706, USA
eom@engr.wisc.edu

$KTaO_3$, a newly identified superconducting semiconductor [1], combines quantum paraelectricity, strong spin-orbit coupling, and nanoscale reconfigurability, offering new opportunities for quantum materials and quantum information applications. But the high and low vapor pressures of potassium and tantalum present processing challenges to creating interfaces clean enough to reveal the intrinsic quantum mechanisms. We report superconducting heterostructures based on electronic-grade epitaxial (111) $KTaO_3$ thin films synthesized with a new hybrid approach, resulting in a two-dimensional electron gas at a $LaAlO_3/KTaO_3$ thin film heterointerface that exhibits significantly higher electron mobility, superconducting transition temperature and critical current density than in bulk $KTaO_3$-based heterostructures owing to cleaner interfaces [2]. Our hybrid approach also enables investigation of fundamental quantum properties of other alkali metal-based oxides beyond the synthesis capabilities of conventional methods.

References

[1] C. Liu et al. Science **371**, 716 (2021).
[2] Jieun Kim et al. arXiv:2308.13180

Chirality and Topology

Claudia Felser, Dresden, DE

Prof. Dr. Claudia Felser, Max Planck Institute Chemical Physics of Solids, Nöthnitzer Straße 40, 01067 Dresden

Chirality is a very active field of research in organic chemistry, closely linked to the concept of symmetry. Topology, a well-established concept in mathematics, has nowadays become essential to describe condensed matter [1,2]. At its core are chiral electron states on the bulk, surfaces and edges of the condensed matter systems, in which spin and momentum of the electrons are locked parallel or anti-parallel to each other. Magnetic and non-magnetic Weyl semimetals, for example, exhibit chiral bulk states that have enabled the realization of predictions from high energy and astrophysics involving the chiral quantum number, such as the chiral anomaly, the mixed axial-gravitational anomaly and axions [3-5]. Chiral topological crystals exhibit excellent chiral surface states [6,7] and different orbital angular momentum for the enantiomers, which can be advantageous in catalysis. The potential for connecting chirality as a quantum number to other chiral phenomena across different areas of science, including the asymmetry of matter and antimatter and the homochirality of life, brings topological materials to the fore [8].

References:

[1] M. G. Vergniory, B. J. Wieder, L. Elcoro, S. S. P. Parkin, C. Felser, B. A. Bernevig, N. Regnault, Science 2022, 376, 6595.
[2] P. Narang, C. A. C. Gracia and C. Felser, Nat. Mater. 2021, 20, 293.
[3] J. Gooth et al., Nature 2017, 547, 324.
[4] J. Gooth et al., Nature 2019, 575, 315.
[5] D. M. Nenno, et al., Nat Rev Phys 2022, 2, 682.
[6] B. Bradlyn, J. Cano, Z. Wang, M. G. Vergniory, C. Felser, R. J. Cava and B. A. Bernevig, Science 2016, 353, aaf5037.
[7] N. B. M Schröter, et al., Science 2020, 369, 179.
[8] C. Felser, J. Gooth, preprint arXiv:2205.05809

Diode effect in Josephson junctions with a single magnetic atom

Martina Trahms[1], Larissa Melischek[2], Jacob F. Steiner[2], Bharti Mahendru[1], Idan Tamir[1], Nils Bogdanoff[1], Olof Peters[1], Gael Reecht[1], Clemens B. Winkelmann[3], Felix von Oppen[2], Katharina J. Franke[1]

[1]Fachbereich Physik, Freie Universität Berlin, Germany
[2] Fachbereich Physik and Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, Germany
[3] Université Grenoble Alpes, CNRS, Institut Néel, Grenoble, France

Diode behavior in superconducting junctions describes the phenomenon of dissipationless current flow in one direction, while the current in the other direction underlies dissipation. Such non-reciprocal behavior has been found in Josephson junctions where inversion and time-reversal symmetry are broken. So far, most realizations are made of layered structures.

Here, we create atomic-scale Josephson junctions in a scanning tunneling microscope and investigate their transport properties in current biased mode. This allows characterization of the switching and retrapping currents, which separate the dissipationless from the dissipative branch. Plain Pb-Pb junctions show hysteretic and reciprocal behavior. By insertion of single magnetic adatoms the retrapping current adopts nonreciprocity, mimicking diode behavior.
We show that the nonreciprocity of the retrapping current depends on the particle-hole asymmetry of the Yu-Shiba-Rusinov (YSR) states inside the superconducting energy gap [1]. Aided by theoretical modelling, we ascribe the non-reciprocity to quasiparticle currents flowing via Yu-Shiba-Rusinov (YSR) states inside the superconducting energy gap [1,2].

References

[1] M. Trahms, L. Melischek, J. F. Steiner, B. Mahendru, I. Tamir, N. Bogdanoff, O. Peters, G. Reecht, C. B. Winkelmann, F. von Oppen, K. J. Franke, Nature **615**, 628 (2023)

[2] J. F. Steiner, L. Melischek, M. Trahms, K. J. Franke, F. von Oppen, Phys. Rev. Lett. **130**, 177002 (2023)

Magnetic Carbon

H. Yu[1] and T. Heine[1]

[1]*School of Science, TU Dresden, Germany*

It is generally accepted that carbon is the most versatile element of the periodic table, and it offers a plethora of compounds ranging from biology to materials science. While the list of fascinating properties carbon materials offer is long, they are not yet famous for magnetism.

Indeed, most carbon materials are diamagnetic. Defects, dopants and dangling bonds can introduce paramagnetic centers without the potential to generate magnetic ordering. Recently reported magic-angle twisted bilayer graphene may become ferromagnetic due to a half-filled flat band at the fermi level and spin-orbit coupling [1]. A spectacular early report on magnetic carbon in pressurized fullerenes [2] was found to be caused by defects and the paper has been retracted five years later.

We propose an alternative concept to generate carbon materials with strongly coupled magnetic centers. Our materials are based on molecular triangulene and its derivatives, aromatic molecules intrinsically carrying one or two unpaired electrons. Using covalent linkages that preserve electron conjugation, we construct two-dimensional polymers with honeycomb-kagome lattice. The magnetic coupling between the monomers is facilitated by the linker groups. This has been examined in detail for the dimers [3]. When extending this concept to 2D polymers, we predict magnetic carbon materials with intriguing electronic structure that includes orbital ferromagnetism, while it maintains the Dirac and flat bands which are characteristic for the honeycomb-kagome lattice of the underlying 2D polymer.

References

[1] A. A. Sharpe E. J. Fox, A. W. Barnard, J. Finney, K. Watanabe, T. Taniguchi, M. A. Kastner, D. Goldhaber-Gordon, ACS Nano **21**, 4299 (2021).

[2] T. L. Makarova, B. Sundqvist, R. Höhne, P. Esquinazi, Y. Kopelevich, P. Scharff, V. A. Davydov, L. S. Kashevarova, A. V. Rakhmanina, Nature **413,** 716, (2001) (retracted).

[3] H. Yu, T. Heine, J. Am. Chem. Soc. **145,** 19303 (2023).

Topochemical transformations of transition metal oxides

Harold Hwang[1]

[1]Stanford University, Stanford, CA, USA, hyhwang@stanford.edu

We will present recent progress on using oxygen intercalation and de-intercalation to access families of transition metal oxides spanning various oxidation states, for Ni and Co based compounds. A focus of interest is greater understanding and improvement of materials control and crystallinity, and the resulting physical properties. An update on recent measurements of the normal and superconducting state in the nickelates will be given.

Engineered quantum states in assembled van der Waals heterostructures studied by scanning tunneling microscopy

F. Lüpke

Peter Grünberg Institut (PGI-3), Forschungszentrum Jülich, 52425 Jülich, Germany

The assembly of van der Waals (vdW) materials into heterostructures enables the engineering of exotic quantum states by moiré and proximity effects. The resulting properties are typically well accessible on the heterostructure surfaces, such that scanning tunneling microscopy (STM) has become an important tool for their structural and electronic characterization. While the possibilities to combine individual vdW layers are virtually infinite, the fabrication of samples with atomically clean surfaces, as required for high-resolution STM studies, was typically limited to air-stable or epitaxially grown samples. In my talk, I will summarize our developed vdW assembly methods [1], which allow the stacking of air-sensitive vdW materials with atomically clean surfaces and internal interfaces, and will show results of proximity heterostructures [2,3] and twisted bilayers [4].

References

[1] K. Jin, *et al.*, arXiv.2306.10305 (2023)
[2] F. Lüpke *et al.*, Nature Physics **16**, 526 (2020)
[3] J. Martinez-Castro et al., arXiv.2304.08142 (2023)
[4] F. Lüpke *et al.*, Nano Letters **14**, 5674 (2022)

Acknowledgements

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Optical and Magnetic Field Manipulation of the Charge Density Wave in RbV_3Sb_5.

Yuqing Xing[1†], Seokjin Bae[1†], Ethan Ritz[2], Fan Yang[2], Turan Birol[2], Andrea N. Capa Salinas[3], Brenden R. Ortiz[3], Stephen D. Wilson[3], Ziqiang Wang[4], Rafael M. Fernandes[5], Vidya Madhavan[1*]

[1] *Department of Physics and Materials Research Laboratory, University of Illinois Urbana-Champaign, Urbana, IL 61801, USA.*

[2] *Department of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, Minnesota 55455, USA*

[3] *Materials Department, University of California Santa Barbara, Santa Barbara, California 93106, USA*

[4] *Department of Physics, Boston College, Chestnut Hill, Massachusetts 02467, USA*

[5] *School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*

**vm1@illinois.edu*

The recently discovered family of kagome superconductors AV3Sb5 (A = K, Rb, or Cs), with an exotic charge-density wave (CDW) state, has emerged as a strong candidate for hosting an unusual phase involving orbital magnetism or loop currents. This idea however is being intensely debated due to conflicting experimental data**.** In this talk I will describe our laser-coupled scanning tunneling microscopy (STM) studies of RbV3Sb5 [1]. In the absence of any external stimulation, we find that the intensities of the three CDW Fourier peaks are different, indicating that the CDW breaks rotational and mirror symmetries. By applying linearly polarized light along the CDW direction, we can switch the relative intensities of the CDW peaks. This implies a substantial electro-striction response, indicative of strong non-linear electron-phonon coupling. We observe a similar CDW intensity switching with perpendicular magnetic fields, which implies an unusual piezo-magnetic response that, in turn, requires time-reversal symmetry-breaking. We show that the simplest CDW that satisfies these constraints is an out-of-phase combination of bond charge order and loop currents that we dub congruent CDW flux phase. I will discuss how this order parameter reconciles previous seemingly contradictory experimental data. The newly set up laser-STM opens the door to the possibility of dynamic optical control of complex quantum phenomenon in correlated materials.

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Origin of Orbital Hall Effect in static and ultrafast regime

Oliver Busch[1], Franziska Ziolkowski[1], Börge Göbel[1], Jürgen Henk[1], and Ingrid Mertig[1]
[1]Institute of Physics, Martin Luther University Halle-Wittenberg, 06099 Halle, Germany

Email: ingrid.mertig@physik.uni-halle.de

An orbital current can be generated whenever an object has a translational and rotational degree of freedom. In condensed matter physics, intra-atomic contributions to the transverse orbital transport, labeled orbital Hall effect [1, 2], rely on propagating wave packets that must consist of hybridized atomic orbitals. However, inter-atomic contributions [3] are equally important as they give rise to a new mechanism for generating orbital currents [4]. It is shown, that even wave packets consisting purely of s electrons can transport orbital angular momentum if they move on cycloidal trajectories.

Furtheron, it will be shown, that the orbital Hall effect in a metal can be extended into the femtosecond time domain [5]. We investigate theoretically orbital angular momenta and their currents induced by a femtosecond laser pulse in a Cu nanoribbon. Our numerical simulations provide detailed insights into the laser-driven electron dynamics on ultrashort timescales with atomic resolution. The ultrafast orbital Hall effect established in this work complies with the familiar pictorial representation of the static orbital Hall effect, but we find also pronounced differences between physical quantities that carry orbital angular momentum and those that do not. This study lays the foundations for investigations of ultrafast Hall effects in confined metallic systems.

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Real- and reciprocal-space topology in the square net series $Eu(Ga_{1-x}Al_x)_4$

E. Morosan
Rice University, Houston TX, USA
emorosan@rice.edu

Magnetic topological semimetals allow for an effective control of the topological electronic states by tuning the spin configuration. Among them, Weyl nodal line semimetals are thought to have the greatest tunability, yet they are the least studied experimentally due to the scarcity of material candidates. In this talk, I will discuss our recent results on the series of square-net compounds $Eu(Ga_{1-x}Al_x)_4$. Using a combination of ARPES and quantum oscillation measurements, together with DFT calculations, we identify the end compound $EuGa_4$ as a magnetic Weyl nodal ring semimetal, in which the line nodes form closed rings near the Fermi level [1]. The Weyl nodal ring states show distinct Landau quantization with clear spin splitting in a magnetic field. The transverse magnetoresistance of $EuGa_4$ is non-saturating and exceeds 500,000% at 40 T, which is more than two orders of magnitude larger than that of other known magnetic topological semimetals. Our theoretical model suggests that the non-saturating MR is a direct consequence of the nodal ring state. When Ga and Al are mixed in the $Eu(Ga_{1-x}Al_x)_4$ series, magnetotransport measurements reveal evidence for both reciprocal- and real-space topology [2,3]. For compositions $0.50 \leq x \leq 0.90$, a maximum in the topological Hall effect (THE) points to non-coplanar spin textures (real-space topology), while for smaller x ($0.25 \leq x \leq 0.39$), magnetization measurements reveal an intermediate field state, but no transition in the Hall measurements. These results suggest the $Eu(Ga_{1-x}Al_x)_4$ family is a rare material platform where real- and reciprocal-space topology exist in a single compound.

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Why it is so difficult to model the CISS effect?

Ron Naaman

Weizmann Institute, Rehovot, Israel

The chiral induced spin selectivity (CISS) effect means that electron transport through chiral systems is spin dependent. [1] The effect was found to exist not only on molecular scale but also in crystals when the scale of the spin transport exceeds microns. In addition, in many cases, the effect was found to increase with increasing temperatures. Recent studies on electron transfer (ET) through proteins established that the effect is indeed long range and with extremely high spin selectivity, reaching 100%.[]

Experimental results obtained on long range CISS effect will be presented and the dilemma they present will be discussed. Since the CISS effect involves also charge transfer, its mechanism must reflect the ET process. Experimental results will be presented that indicate that the CISS effect cannot be explained based on a single electron and Born-Oppenheimer based models.

It will be shown that models that are not based on these approximations can provide qualitative understanding of the CISS, although real first principle calculations remain a major challenge.

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Manipulation of Weyl semimetallic states in the chiral antiferromagnet Mn_3Sn

Satoru Nakatsuji[1*,2,3,4]

[1] *Department of Physics, School of Science, The University of Tokyo*
[2] *Institute for Solid State Physics, The University of Tokyo*
[3] *Department of Physics and Astronomy, Johns Hopkins University*
[4] *Trans-Scale Quantum Science Institute, The University of Tokyo*
**satoru@phys.s.u-tokyo.ac.jp*

Antiferromagnetic spintronics has attracted a lot of attention for its potential ultrafast operation and high integration density. Among a variety of antiferromagnets that have been studied, the chiral antiferromagnet Mn_3X systems are unique for its time-reversal breaking magnetic octupole order and the Weyl semimetallic electronic structure, exhibiting the phenomena similar to ferromagnets in the antiferromagnets such as anomalous Hall, Nernst effects and magnetooptical signals [1]. These phenomena further enable design of the devices to write and read the magnetic states electrically. In this presentation, after presenting the review on the properties of the antiferromagnetic Weyl semimetal Mn_3Sn, we show our recent results on the electrical switching of the chiral antiferromagnetic state in its heterostructure using heavy metals [2,3,4] and the magneto tunneling effect using all antiferromagnetic tunnel junctions [5].

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Realizing Higher-Order Topology

T. Neupert[1]

[1]*Department of Physics, University of Zurich, Zurich, Switzerland*

Higher-order topology generalizes the bulk-boundary correspondence of topological phases of matter, by allowing topological modes to be localized at corners and hinges instead of edges and surfaces. I will introduce the theory behind this concept, both for noninteracting as well as interacting systems and consecutively discuss two realizations in rather distinct setups. First, as-grown crystals of bismuth, grey arsenic, as well as bismuth bromide are demonstrated to display the essential physics of higher-order topological insulators. Second, it is shown that lattices of so-called Shiba bound states induced by magnetic adatoms in conventional superconductors can be brought into a higher-order superconducting phase. I will report on experimental progress for both system types based on spanning probe as well as transport measurements.

Designing strongly correlated topological semimetals

Silke Paschen

[1] *TU Wien, Institute of Solid State Physics, Vienna, Austria, paschen@ifp.tuwien.ac.at*

Gapless electronic topology driven by strong correlations is an emerging field of great interest, with heavy fermion compounds at its forefront. I will introduce the first such materials class, Weyl-Kondo semimetals [1-3], and report on the giant signatures of topology observed in $Ce_3Bi_4Pd_3$ [1,3] and the genuine topology control that can be achieved by magnetic field tuning [4,5]. I will also discuss design strategies for further correlation-driven topological phases, and discuss several realizations [6,7].

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Mesoscale quantum textures

Christian Pfleiderer

Physik Department
Technical University of Munich

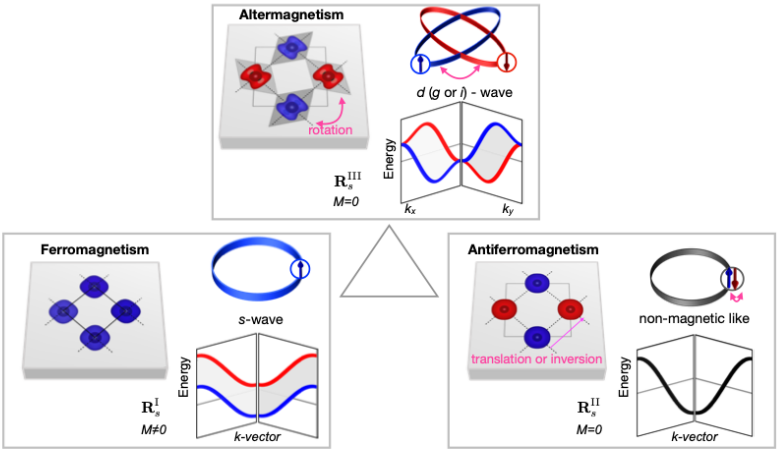
Mesoscale patterns are well-known in ferromagnets, ferroelectrics, superconductors, monomolecular films or block copolymers, where they reflect spatial variations of a pertinent order parameter at length and time scales that may be described classically. In the past thirty years increasing evidence suggests the presence of mesoscale patterns near zero-temperature phase transitions, also known as quantum phase transitions. Focussing on the textbook example of a ferromagnetic transverse-field quantum critical point in carefully selected materials, we identified a new type of phase transition that may be referred to as mesoscale quantum criticality. Our results establish the surroundings of quantum phase transitions as a regime of mesoscale pattern formation, in which non-analytical quantum dynamics and materials properties without classical analogue may be expected.

Unconventional Magnetism in Spintronics: the emergence of Altermagnetism and its new variants

Jairo Sinova

Johannes Gutenberg University Mainz, Germany

The discovery of d-wave magnetic order in momentum space has motivated a closer look at the symmetry classification of collinear magnetic systems. This has emerged as the third basic collinear magnetic ordered phase of altermagnetism, which goes beyond ferromagnets and antiferromagnets. Altermagnets exhibit an unconventional spin-polarized d/g/i-wave band structure in reciprocal space, originating from the local sublattice anisotropies in direct space. This gives properties unique to altermagnets (e.g., the spin-splitter effect), while also having ferromagnetic (e.g., polarized currents) and antiferromagnetic (e.g., THz spin dynamics and zero net magnetization) characteristics useful for spintronics device functionalities. A key consequence of d-wave magnetism is a new ability to manipulate its magnetic textures. 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. Focusing on the prototypical d-wave altermagnets, e.g. RuO_2, we can explain intuitively the unique lifted degeneracy of their magnon spectra, and show that the altermagnetic domain walls, in contrast to antiferromagnets, have a finite gradient of the magnetization projection along the easy axis orientation, with its strength and direction connected to the altermagnetic anisotropy. This gradient generates a ponderomotive force in the domain wall in the presence of an external magnetic field, allowing the possibility to control the domains in a magnetically compensated ordered phase.



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Charge density waves in emergent Kagome metals

Hengxin Tan

Weizmann Institute of Science, Rehovot, Israel
E-mail: hengxin.tan@weizmann.ac.il

Kagome materials with corner-shared triangular sublattices are fascinating because of their unique crystal and electronic structures. This talk focuses on the charge instabilities of kagome materials. I will first introduce our recent theoretical investigations into charge density waves (CDW) and the formation mechanism within kagome metals ScV_6Sn_6. A concise summary outlines the similarities and distinctions between CDWs in ScV_6Sn_6 and the extensively studied AV_3Sb_5 (A=K, Rb, Cs). Then, I will introduce our recent theoretical insights into unexpected surface charge orders in the RV_6Sn_6 series (R = rare earth elements) and the modulation of charge order by magnetism in RMn_6Sn_6. Comparative analyses between the formation mechanisms of these surface charge orders and the CDW in the magnetic kagome metal FeGe are presented. Novel phenomena induced by the competition between surface charge instability and magnetism are discussed.

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Abstracts of Posters

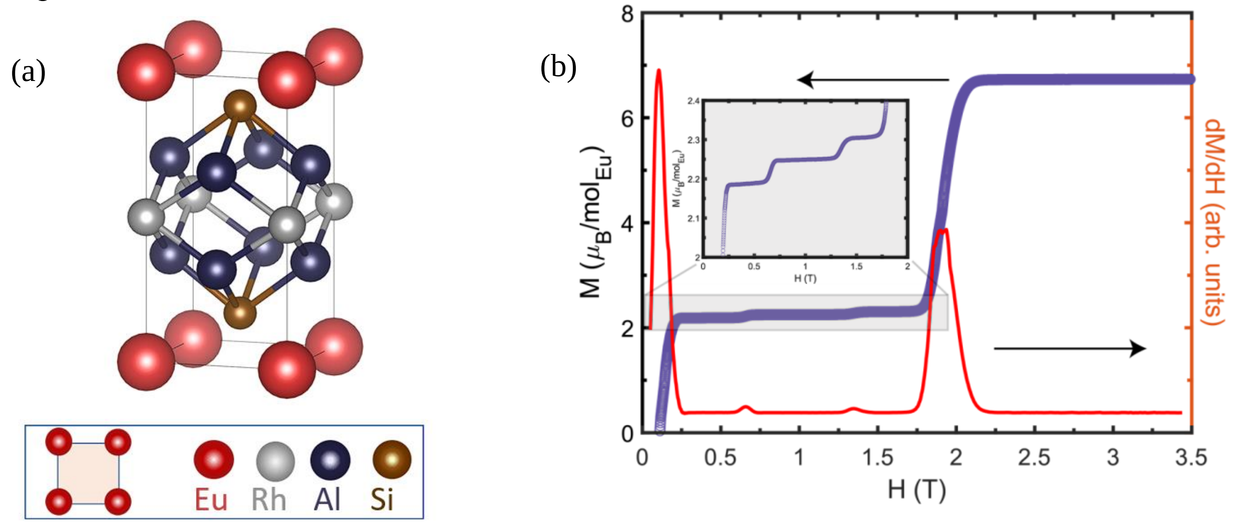
(in alphabetical order)

Unusual Magnetization Plateaus in Square-Net Lattice $EuRhAl_4Si_2$

<u>Kevin James Allen</u> and Emilia Morosan

Department of Physics and Astronomy, Rice University, Houston, TX, 77005, USA
and
Rice Center for Quantum Materials, Rice University, Houston, TX, 77005, USA

Square-net lattice compounds host diverse properties, including real and reciprocal space topology, even in the absence of geometric frustration (as in triangular lattice compounds) or anisotropic interactions (e.g., Dzyaloshinskii-Moriya) etc. Square-net topological materials have garnered a lot of interest due to their unique electronic properties that are protected by certain symmetries. $EuRhAl_4Si_2$ (space group P4/mmm [1] – Fig. 1a) is such a candidate material, which is theoretically predicted to host Dirac crossings. I will present magneto-transport properties, ARPES, and neutron diffraction measurements, together with DFT calculations for $EuRhAl_4Si_2$. Magnetization isotherm M(H) display a plateau at $M = 1/3M_0$, where M_0 is the saturation magnetization. More intriguingly, two smaller steps occur at $M = 1/3M_0 (1 \pm 1/100)$ (Fig. 1b). ARPES experiments reveal that some bands near the Fermi level split across the magnetic transition, as well as a 1/3 nesting condition on the Fermi surface. Furthermore, neutron diffraction indicates an in-plane 1/3 AFM incommensurate to commensurate transition and a possible FM (or higher harmonic) component. DFT calculations confirm the bands observed in ARPES and provide insight into the ground state of $EuRhAl_4Si_2$ and the nature of the steps in magnetization.



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Effect of Interfacial Interaction on the Magnetic Property of the Chiral Antiferromagnet Mn_3Sn

M. Asakura[1], T. Higo[1,2,3], T. Matsuo[1,4], R. Uesugi[2], D. Nishio-Hamane[2], and S. Nakatsuji[1,2,3,4,5]

[1]Department of Physics, The University of Tokyo, Tokyo, Japan
[2]Institute for Solid State Physics, The University of Tokyo town, Chiba, Japan
[3]CREST, Japan Science and Technology Agency, Saitama, Japan
[4]Institute for Quantum Matter and Department of Physics and Astronomy, Johns Hopkins University, Baltimore, USA
[5]Trans-scale Quantum Science Institute, The University of Tokyo, Tokyo, Japan

Interfacial interaction between a magnetic thin film and another material often affects the magnetic properties of the magnetic layer and has been of intense investigation in spintronics. In the research on the interfacial interaction, antiferromagnets (AFMs) have mainly played a supporting role to fix the magnetization of a ferromagnet (FM) for a long time. This is because controlling and detecting the magnetic order of AFMs were thought to be difficult. On the other hand, recent proposal that AFM has several advantages such as ultrafast spin dynamics and negligible stray field [1,2] has led to active research to replace FMs in spintronic device by AFMs. The chiral AFM Mn_3Sn without macroscopic time reversal symmetry is a typical example of AFMs that are expected to act as functional materials [2,3]. It has been shown that the antiferromagnetic order of Mn_3Sn can be controlled and detected by means similar to that used for FMs. For example, current-induced spin orbit torque switching of the magnetic order and detection of the magnetic order through tunneling magnetoresistance, which are essential phenomena in spintronics, have been demonstrated [4,5]. However, the effect of interfacial interaction on this material and its similarity to ferromagnetic systems are still unknown. In this presentation, we report the effect of the interfacial interaction on a polycrystalline chiral AFM Mn_3Sn coupled with another metallic AFM detected through the anomalous Hall and Nernst effect. The observed effect shows properties similar to conventional ferromagnetic systems and unique to our system with a characteristic magnetic anisotropy.

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Design and construction of laser scanning tunneling microscopy for investigating light-matter interaction at atomic scale

Seokjin Bae[1] and **Vidya Madhavan[1]**

[1]*Department of Physics and Frederick Seitz Materials Research Laboratory, University of Illinois Urbana-Champaign, Urbana, Illinois 61801, USA*

Recent progress in ultrafast spectroscopies on condensed matter systems has brought opportunities to explore the physics of nonequilibrium states which have not been accessible with conventional probes. Example of those states includes light-induced superconductivity, Floquet-Chern insulator phase, transient charge density wave, and light-induced topological phase transition. So far, experimental probes for these phenomena have focused on momentum and frequency space characterization. To obtain further insight into these transient and nonequilibrium phenomena from a microscopic level, it is desired to develop a real-space atomic scale time-resolved spectroscopy. In this poster, we present the design and ongoing construction of a laser scanning tunneling microscopy (laser-STM). The first stage version of the laser-STM visualizes a control of the direction of mirror symmetry breaking in a Kagome superconductor RbV_3Sb_5 through laser-induced strain [1]. The ongoing construction for the second stage laser-STM where we aim to realize an atomic scale probe at picosecond time resolution will also be discussed.

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Signatures of Heavy-Fermion Physics in the Thermoelectric Effect of Twisted Bilayer Graphene

D. Călugăru[1], H. Hu[2], D. K. Efetov[3,4], N. Regnault[1,5], B. A. Bernevig[1,2,6]

[1]*Department of Physics, Princeton University, Princeton, New Jersey 08544, USA*
[2]*Donostia International Physics Center, P. Manuel de Lardizabal 4, 20018 Donostia-San Sebastian, Spain*
[3]*Faculty of Physics, Ludwig-Maximilians-University Munich, Munich 80799, Germany*
[4]*Munich Center for Quantum Science and Technology (MCQST), Ludwig-Maximilians-University Munich, Munich 80799, Germany*
[5]*Laboratoire de Physique de l'École normale supérieure, ENS, Université PSL, CNRS, Sorbonne Université, Université Paris-Diderot, Sorbonne Paris Cité, 75005 Paris, France*
[6]*IKERBASQUE, Basque Foundation for Science, Bilbao, Spain*

We study the transport properties of twisted bilayer graphene (TBG) using the topological heavy-fermion (THF) model in an interacting framework [1]. In the THF model, TBG comprises localized, correlated f-electrons and itinerant, dispersive c-electrons [2]. We focus on the Seebeck coefficient, which quantifies the voltage difference arising from a temperature gradient. Microscopically, in the Seebeck effect, an applied thermal gradient causes both the electron- and hole-like carriers to diffuse from high to low temperatures. The predominant type of carrier, either electron or hole, determines the sign of the resulting thermoelectric voltage, with electron-dominated transport yielding a negative Seebeck coefficient. TBG's Seebeck coefficient shows unconventional traits: negative values with sawtooth oscillations at positive fillings, contrasting typical band-theory expectations. This behavior can be attributed to the presence of heavy (correlated, short-lived f-electrons) and light (dispersive, long-lived c-electrons) electronic bands. Their longer lifetime and stronger dispersion lead to a dominant transport contribution from the c-electrons. At positive integer fillings, the correlated TBG insulators feature c- (f-)electron bands on the electron (hole) doping side, leading to an overall negative Seebeck coefficient. Additionally, sawtooth oscillations occur around each integer filling due to gap openings. Our results highlight the importance of electron correlations in understanding the transport properties of TBG and, in particular, of the lifetime asymmetry between the two fermionic species (naturally captured by the THF model). Our findings are corroborated by new experiments in both twisted bilayer [3] and trilayer graphene [4].

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Non-volatile electric-field control of inversion symmetry

Lucas Caretta[1,8], Yu-Tsun Shao[2], Archana Raja[3], Lane W. Martin[1], Long-Qing Chen[4], Manfred Fiebig[5], Keji Lai[6], Nicola A. Spaldin[5], David A. Muller[2], Darrell G. Schlom[7], Ramamoorthy Ramesh[1]

[1]*Department of Materials Science and Eng., University of California, Berkeley, USA*
[2]*School of Applied and Engineering Physics, Cornell University, Ithaca, New York, USA*
[3]*Molecular Foundry, Lawrence Berkeley National Laboratory, Berkeley, California, USA*
[4]*Department of Materials Science and Engineering, The Pennsylvania State University, University Park, Pennsylvania, USA*
[5]*Department of Materials, ETH Zurich, Zurich, Switzerland*
[6]*Department of Physics, University of Texas, Austin, Texas, USA*
[7]*Department of Materials Science and Eng., Cornell University, Ithaca, New York, USA*
[8]*School of Engineering, Brown University, Providence, Rhode Island, USA*

In condensed-matter systems, competition between ground states at phase boundaries can lead to significant changes in material properties under external stimuli[1–4], particularly when these ground states have different crystal symmetries. A key scientific and technological challenge is to stabilize and control coexistence of symmetry-distinct phases with external stimuli. Using $BiFeO_3$ (BFO) layers confined between layers of the dielectric $TbScO_3$ (TSO) as a model system, we stabilize the mixed-phase coexistence of centrosymmetric and non-centrosymmetric BFO phases at room temperature with antipolar, insulating and polar, semiconducting behavior, respectively. Application of orthogonal in-plane electric (polar) fields results in the reversible, nonvolatile interconversion between the two phases, hence removing and introducing centrosymmetry in the system. Counterintuitively, we find that an electric field can 'erase' polarization in the system, resulting from the anisotropy in octahedral tilts introduced by the interweaving TSO layers. Consequently, this interconversion between centrosymmetric and non-centrosymmetric phases coincides with simultaneous changes in the non-linear optical response of over three orders of magnitude, a change in resistivity of over five orders of magnitude, and control of the microscopic polar order. Our work establishes a materials platform allowing for novel cross-functional devices which take advantage of changes in optical, electrical, and ferroic responses, and also demonstrates octahedral tilts as an important order parameter in materials interface design.

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Observation of nonreciprocal Hall effect in superconductor-multiferroics heterostructure

Tianzhe Chen[1], Yufeng Wu[1], Stuart S. P. Parkin[1]

[1] *Max Planck Institute of Microstructure Physics, Weinberg 2, 06120, Halle, Germany*

Heterostructures constructed between superconductors and ferromagnets emerge exotic physical phenomena, including Bogoliubov quasiparticles, superconducting vortex, FFLO states, spin-triplet superconductivity, π-Josephson junctions, Majorana states, topological superconducting states, etc. The aforementioned novel phenomena stem from (inverse) superconducting proximity effects. While in superconductors and ferroelectrics heterostructure, a novel magnetoelectric effect, charge-to-spin magnetization conversion, by applied supercurent has been proposed and theoretically predicted. Here, we have constructed a heterostructure between a conventional superconductor and a room temperature multiferroic, which could realize nonreciprocal Hall effect in DC transport measurements. This is different from what have been exploited in superconductor/ferromagnets heterostructures, where the nonreciprocal transport mediated by spin polarized supercurrents be realized in the nonlinear regime by AC transport measurements.

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The landscape of tight-binding models

A. K. Dagnino[1,2], A. Corticelli[2] and P. A. McClarty[2]

[1]Department of Physics, University of Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland
[2] Max Planck Institute for the Physics of Complex Systems, Nöthnizer Str. 38, 01187 Dresden

Tight-binding models are ubiquitous in condensed matter physics. Fundamental properties of many materials can be understood from simple toy models of electrons hopping between orbitals on a lattice. In particular, crystallographic symmetries are crucial in determining the degeneracies of band structures at high symmetry points in the Brillouin zone. These degeneracies fundamentally affect the properties of the material that is being modelled, ranging from the allowed optical transitions to symmetry-indicated topological invariants. Getting a full list of crystal symmetries of a material is therefore crucial when trying to predict or understand its physical properties. In this poster, we systematically study the symmetries of lattices in 3 dimensions and their implications for the corresponding tight-binding models. We uncover a landscape of tight-binding models related by crystal symmetries and apply these findings to understand the recently uncovered altermagnetic nature of RuO_2 and MnTe.

Angle Dependent Magnetoresistance and Spin-elective Electron Transmission in Oligopeptides

Tapan Kumar Das[1], Jonas Fransson[2] and Ron Naaman[1]*

[1]Department of Chemical and Biological Physics, Weizmann Institute of Science, Rehovot 7610001, Israel
[2]Department of Physics and Astronomy, Uppsala University, Uppsala 75236, Sweden
Email: tapan-kumar.das@weizmann.ac.il
**Corresponding author: ron.naaman@weizmann.ac.il*

Conduction through chiral molecules follows spin-selective electron transmission, which makes chiral molecules an efficient spin-filter.[1,2] Chiral oligopeptides monolayers were adsorbed on ferromagnetic surface and their magnetoresistance was measured as a function of the angle between the magnetization of the ferromagnet and the surface normal. The measurements were conducted as a function of temperature for both enantiomers. The angle dependent was found to follow cosine square function. Quantum simulation revealed that this angle distribution could be obtained only if the monolayer has significant spin orbit coupling (SOC) and that the assuming SOC only of the leads cannot reproduce the observed angle distribution. The simulation had also to include electron-electron and electron-phonons interactions and dissipation in order to reproduce the experiments

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Phase coherent electrical transport in chiral topological metals

A. Dixit[1], **P. K. Sivakumar**[1], **A. Johansson**[1], **S.P.P. Parkin**[1]

[1]*Max Planck Institute of Microstructure Physics, Weinberg 2, 06120, Halle (Saale), Germany*

The recent discoveries of topological phases, such as topological insulators and (semi)metals, have opened up new possibilities for the next generation of electronics. The wave-like nature of massless fermions at the mesoscopic scale in these phases provide new degrees of freedom of charge carriers such as chirality.[1] Understanding and developing strategies to manipulate it is essential to create efficient and low-noise spintronic devices. This poster introduces a new class of topological matter called chiral topological metals (CTM) and their fascinating electromagnetic responses. Its topological nature arises from multifold band crossing near the Fermi level at high symmetry points in the Brillouin zone. The collective behavior of the electrons near these crossings gives rise to chiral fermions. Topological metals can generate spin currents under longitudinal electric and magnetic fields due to the phenomenon known as the chiral anomaly.[2] However, these spin currents are localized, short-lived, and often masked by electrical transport in the trivial bulk bands. The poster aims to identify the charge transport in topological states in chiral topological metals and understand the influence of geometric chirality. It presents experimental strategies based on focused-ion beam crystal micro-sculpting and lateral Josephson junctions to study non-linearity and phase coherence of electrical transport along the low-miller crystal indices.

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Thermomechanical nanomolding for 1D Topological Materials

Yeryun Cheon[1], Khoan Duong[1], Quynh Sam[2], Mehrdad Kiani[2], Judy J. Cha[2]

[1]Department of Physics, Cornell University, Ithaca, New York 14853, USA
[2]Department of Materials Science and Engineering, Cornell University, Ithaca, New York 14853, USA

Topological materials possess symmetry-protected surface states with unique electronic properties potentially useful in micro-electronics, spintronics, and quantum computing. The large number of both theoretically predicted and experimentally discovered topological materials necessitates the rapid screening of these materials, to fully characterize the nature of their topological states, as well as to identify among these materials those with the most useful properties for practical applications.

To address this challenge, we employ thermomechanical nanomolding, a novel synthesis technique capable of rapidly and scalably fabricating nanowires of controlled sizes and morphologies[1]. By hot-pressing bulk crystalline materials into nanoporous molds, we have been successful at synthesizing single-crystalline nanowires of a wide variety of materials, ranging from topological Weyl semimetals, to topological insulator, as well as Weyl semiconductor. The wire diameter can be controlled down to the 10-nm range, allowing us to enhance the surface-to-bulk ratio, thus exposing and exploiting the properties of the surface states for potential applications in low-dimensional interconnects.

In addition, we have also been able realize some metastable phases of materials using the nanomolding technique[2]. This opens up exciting possibilities for exploring little-known corners of the materials' phase diagrams, as well as potentially studying novel phases of matter. The ability to control the dimensions of the wires allows us to examine the possible roles of surface stress and surface energy in stabilizing different structures and phases of materials under 1D confinement, thus providing a versatile tuning knob for engineering material properties.

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MT_6Z_6 kagome candidates with flat bands, magnetism, phonon instability, and charge density waves

Xiaolong Feng[1], **Yi Jiang**[2], **Haoyu Hu**[2], **Dumitru Călugăru**[3], **M. G. Vergniory**[1,2], **C. Felser**[1], **S. Blanco-Canosa**[2], **and B. Andrei Bernevig**[2,3,4]

[1]*Max Planck Institute for Chemical Physics of Solids, 01187 Dresden, Germany*
[2] *Donostia International Physics Center(DIPC), Paseo Manuel de Lardizábal. 20018, San Sebastián, Spain*
[3]*Department of Physics, Princeton University, Princeton, NJ 08544, USA*
[4]*IKERBASQUE, Basque Foundation for Science, 48013 Bilbao, Spain*

Kagome materials manifest rich physical properties due to the emergence of abundant electronic phases at different fillings. Here, we carry out a high-throughput first-principles study of the MT_6Z_6 kagome materials, regarding their electronic flat bands and lattice instability. The diverse MT_6Z_6 kagome candidates reveal the remarkable tunability of kagome flat bands from unfilled and fully filled states. Notably, Mn/Fe-166 compounds exhibit partially filled flat bands with a pronounced sharp DOS peak near the Fermi level, suggesting the presence of magnetic orderings, which split the sharp DOS peak and stabilize the phonon. When the flat bands are located away from the Fermi level, the instabilities can be classified into three types, regarding their vibration modes. Type-I instabilities involve the in-plane distortion of kagome nets, while type-II and type-III present out-of-plane distortion of trigonal M and Z atoms. We take $MgNi_6Ge_6$ and $HfNi_6In_6$ as examples to illustrate the possible CDW structures derived from the emergent type-I and type-III instabilities. Our prediction suggests a vast kagome family for the exploration of rich properties induced by the flat bands, possible CDW transitions, and their interactions with magnetism.

Racetrack memory devices based on freestanding multilayers

K. Gu[1], BK. Hazra[1], Y. Guan[1], P. Wang[1], H. Deniz[1] and S. Parkin[1]

[1]Max Planck Institute of Microstructure Physics, Halle (Saale), Germany
E-mail: guke@mpi-halle.mpg.de

Magnetic racetrack memory (RTM) devices encode data in a series of magnetic domain walls (DWs) that are manipulated by current pulses within a single racetrack element. Due to the small width of the DWs and the fast motion of the DWs that can be realized in racetracks, RTM goes beyond conventional magnetic memory devices and shows a promising future as next-generation spintronic devices. RTM devices have recently been developed into highly efficient synthetic antiferromagnetic two-dimensional (2D) racetracks [1]. However, most studies to date have focused on 2D racetracks. Here, we show that by using a water membrane based lift-off and transfer technique, 3D RTM devices can be fabricated from freestanding magnetic heterostructures, bypassing the limitations of sputtering. Efficient 3D RTM devices based on freestanding multilayers show similar performance to those fabricated from as-deposited samples can be realized (Fig. 1) [2]. We further show that the freestanding multilayers can act as a good platform for creating novel coupling effects that can be further applied in DW logic [2]. Our experimental results open up a new route for designing future spintronic devices with high data capacity, low power consumption and novel functionality.

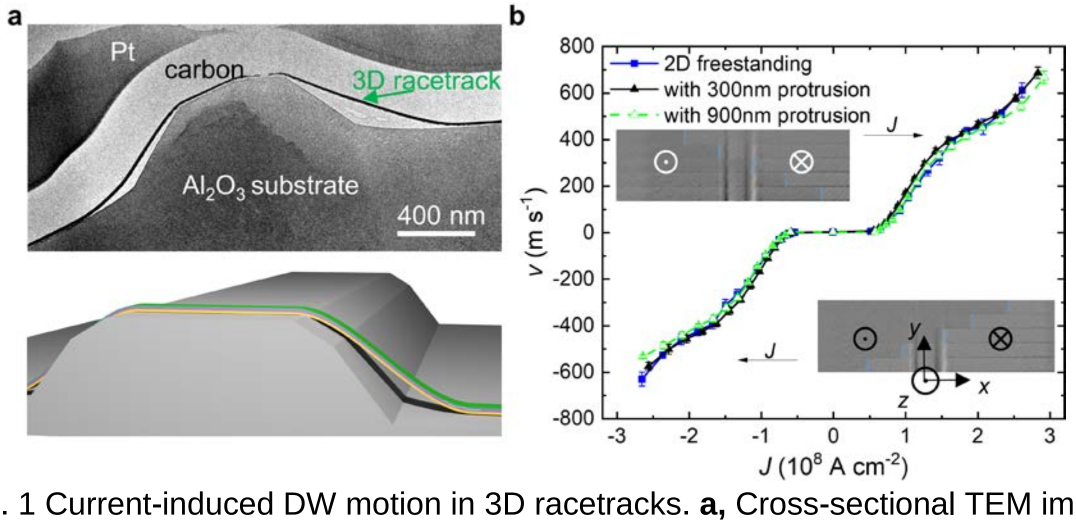

Fig. 1 Current-induced DW motion in 3D racetracks. **a,** Cross-sectional TEM image (top) and schematic (bottom) of a 3D racetrack formed on the protrusion. **b,** DW velocity versus current density in racetracks formed from freestanding heterostructures with or without protrusions.

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Electrical formation of all-oxide metamaterials via synchronized local ionic gating

Hyeon Han[1] and Stuart S. P. Parkin[1]

[1]Max Planck Institute of Microstructure Physics, 06120 Halle (Saale), Germany.

E-mail: hyeon.han@mpi-halle.mpg.de

Ionic gating (IG) of thin oxide layers has emerged as a novel way of engendering phase transitions between insulating and metallic phases or between distinct magnetic phases [1-5]. Most studies to date have been carried out on single devices with a three-terminal configuration [2]. However, by exploring the electrokinetics of the gating process, we reveal that such a configuration leads to a highly non-uniform gating response for initially insulating oxide layers. Here, we show, by the use of a conducting underlayer, that synchronized IG allows for the creation of large numbers of equally gated nano-regions in a large area of a single continuous oxide layer, leading to collective phenomena that are not inherently present in the single regions. This allows for the creation of oxide metamaterials with designed electrical, magnetic, and/or optical textures. Designer metamaterials formed in this way from a single oxide layer display anomalous optical reflection that can be reversibly and repeatedly controlled by electric-fields. Moreover, synchronized IG enables the electrical creation of magnetic metamaterials in a non-destructive way, namely, artificial spin ices revealing collective interactions in ferromagnetic nano-islands. Our findings provide a new concept to locally and simultaneously manipulate the physical properties of numerous nano-regions and thus to electrically create and control complex nanostructures.

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Fundamental laws of chiral band crossings

K. Alpin,[1] M. M. Hirschmann,[1,2] N. Heinsdorf,[1,3] A. Leonhardt,[1]
W. Y. Yau,[1,4] X. Wu,[1,5] and A. P. Schnyder[1]

[1] Max Planck Institute for Solid State Research, Stuttgart, Germany
[2] RIKEN Center for Emergent Matter Science, Wako, Japan
[3] Department of Physics and Astronomy & Stewart Blusson Quantum Matter Institute, University of British Columbia, Vancouver BC, Canada
[4] Max Planck Institute of Molecular Cell Biology and Genetics, Dresden, Germany
[5] Institute for Theoretical Physics, Chinese Academy of Sciences, Beijing, China

The number of surface states as well as the electric response of Weyl semimetals is determined to a large extent by the Chern number of the Weyl points, a property also referred to as their chirality. It is known [1,2] that rotation eigenvalues affect the value of the chirality.

We show that the previous works are applications of a local constraint [3], relating the Chern number with the exchange of rotation eigenvalues. We find that it holds for arbitrary combinations of symmetries as well as for chiral crossings comprising more than two bands. Using this constraint, we explain the chiralities of quadruple Weyl points, double Weyl points on two-fold rotation axes, and discuss the emergence of a Chern number 5 band within certain fourfold point crossings. Furthermore, with a global constraint, stemming from the periodicity of the Brillouin zone, we can identify space groups with enforced topological nodal planes.

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Kondo nodal-line semimetal in the antiferromagnetic phase

Haoyu Hu[1] , Yi Jiang[1], Defa Liu[2], Yulin Chen[3], Yuanfeng Xu[4], and B. Andrei Bernevig[5,1]

[1]Donostia International Physics Center, P. Manuel de Lardizabal 4, 20018 Donostia-San Sebastian, Spain

[2]Department of Physics, Beijing Normal University, Beijing 100875, China

[3]Department of Physics,University of Oxford,Oxford,OX13PU,United Kingdom

[4]Zhejiang University, Hangzhou 310058, China

[5]Department of Physics, Princeton University, Princeton, NJ 08544, USA

The interplay among topology, magnetism, and the Kondo effect has the potential to give rise to various exotic quantum phenomena in the heavy-fermion systems, including the emergence of quantum critical points and the formation of topological Kondo insulators. Here, we report the discovery and understanding of a novel heavy-fermion material wherein magnetism, Kondo effect, and non-trivial topology coexist. We demonstrate that, at high temperatures, due to the existence of the relatively flat bands, the system develops a type-A antiferromagnetic (AFM) order. The remaining symmetry of the AFM phase leads to two-fold degenerate Kramer-doublet bands favoring the formation of Kondo singlet in the AFM phase. The onset of the Kondo effect then creates additional single-particle excitation and produces a symmetry-protected Dirac nodal line. Our findings not only illuminate the connections between electronic correlations and topology, but also underscore the important role of lattice symmetry in the development of the Kondo effect.

Two dimensional monochalcogenides lateral superlattices

Jingrong Ji[1], Zi-Ang Gao[2], Shiva Prasad Poudel[3], Salvador Barraza-Lopez[3], Kai Chang[2], Stuart S. P. Parkin[1]

[1] Max-Planck Institute of Microstructure Physics, Halle 06120, Germany
[2] Beijing Academy of Quantum Information Sciences, Beijing 100193, China
[3] Department of Physics and MonArk NSF Quantum Foundry, University of Arkansas, Fayetteville, AR 72701, USA

Two-dimensional heterostructures and superlattices have been focused on since the huge potential applications for developing the electronics and optoelectronic devices. However, the fabrication of the high-quality heterostructures is still the main challenge, especially for the lateral heterostructures. Until now, the most explored lateral heterostructures are still limited in the transition metal chalcogenides (TMDC). Thus, the fabrications of high quality and reproducible lateral heterostructures are essential. Here, I report the work on the molecular beam epitaxial growth and scanning tunneling microscopy characterization on the two-dimensional monolayer SnTe/PbTe lateral superlattices. The ultra-narrow periods and atomically clean interfaces are realized. Except this, the surficial diffusion mechanism for 2D materials is put forwards depending on the asymmetric diffusion existed in the SnTe/PbTe interfaces. Owing to the ferroelectricity in the monolayer SnTe and paraelectricity in the monolayer PbTe, this work provides the opportunity for the potential applications such as ferroelectric tunneling junctions.

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Kagome Materials II: SG 191: FeGe as a LEGO Building Block for the Entire 1:6:6 series: hidden d-orbital decoupling of flat band sectors, effective models and interaction Hamiltonians

Yi Jiang[1,2], Haoyu Hu[1], Dumitru Calugaru[5], Claudia Felser[3], Santiago Blanco-Canosa[1], Hongming Weng[2], Yuanfeng Xu[4], and

B. Andrei Bernevig[5,1,6]

[1] Donostia International Physics Center (DIPC), San Sebastián 20018, Spain
[2]Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China
[3] Max Planck Institute for Chemical Physics of Solids, 01187 Dresden, Germany
[4]Zhejiang University, Hangzhou 310058, China
[5]Department of Physics, Princeton University, Princeton, NJ 08544, USA
[6]IKERBASQUE, Basque Foundation for Science, 48013 Bilbao, Spain

The electronic structure and interactions of kagome materials such as 1:1 (FeGe class) and 1:6:6 (MgFe6Ge6 class) are complicated and involve many orbitals and bands at the Fermi level. Current theoretical models usually treat the systems in an s-orbital kagome representation, unsuited and incorrect both quantitatively and qualitatively to the material realities. In this work, we lay the basis of a faithful framework of the electronic model for this large class of materials. We show that the complicated ``spaghetti" of electronic bands near the Fermi level can be decomposed into three groups of d-Fe orbitals coupled to specific Ge orbitals. Such decomposition allows for a clear analytical understanding (leading to different results than the simple s-orbital kagome models) of the flat bands in the system based on the S-matrix formalism of generalized bipartite lattices. Our three minimal Hamiltonians can reproduce the quasi-flat bands, van Hove singularities, topology, and Dirac points close to the Fermi level, which we prove by extensive ab initio studies. We also obtain the interacting Hamiltonian of d orbitals in FeGe using the constraint random phase approximation (cRPA) method. We then use this as a fundamental ``LEGO"-like building block for a large family of 1:6:6 kagome materials, which can be obtained by doubling and perturbing the FeGe Hamiltonian. We applied the model to its kagome siblings FeSn and CoSn, and also MgFe6Ge6. Our work serves as the first complete framework for the study of the interacting phase diagram of kagome compounds.

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Abstract

Swift Skyrmions as a True Random Number Generator

Ajin JOY[1], Soubhik KAYAL[2], P.S. ANIL KUMAR[2]

Ajin.joy@mpi-halle.mpg.de

Skyrmions, with high speed, have the potential to revolutionize data storage technology. Racetrack memories, where Skyrmions move as data storage bits, work by moving them through perpendicularly magnetized nanowires, which are connected to metal layers that have high spin-orbit coupling and DMI. Skyrmions are tiny spin structures that can be controlled with current pulses and have multiple uses. While Skyrmions have been observed at both low and room temperatures, their speed has been limited by factors such as higher hall angle deviations and greater anisotropy. In this study, we used the dusting effect in Pt/Co/Pt systems to stabilize Skyrmions by systematically tuning the anisotropy value to be comparable to the DMI value. This resulted in Skyrmions that could move at speeds of 260 m/s. These fast-moving Skyrmions can be used as random number generators, as they are destroyed every time a new current pulse with higher strength and pulse width is applied. In today's world of data encryption and cryptocurrency, high-efficiency true random number generation is crucial. Our skyrmion-based random number generator can produce ten million random numbers per second and passed randomness tests with a very low p-value of 0.00894, which is more efficient than current methods.

In-Plane Electric-Field-Induced Orbital Hybridization of Excitonic States

<u>Ke Xiao</u>[1], Bairen Zhu[2] and Xiaodong Cui[3]

[1]Max-Planck Institute of Microstructure physics, Halle, Germany
[2] Zhejiang University of Technology, Hangzhou, China
[3] The University of Hong Kong, Hong Kong, HKSAR

The giant exciton binding energy and the richness of degrees of freedom make monolayer transition metal dichalcogenide an unprecedented playground for exploring exciton physics in 2D systems. Thanks to the well-energetically separated excitonic states, the response of the discrete excitonic states to the electric field could be precisely examined.

Here we utilize the photocurrent spectroscopy to probe excitonic states under a static in-plane electric field. Combined with numerical simulation, we demonstrate that the in-plane electric field leads to a significant orbital hybridization of Rydberg excitonic states with different angular momentum (especially orbital hybridization of 2s and 2p) and, consequently, optically actives 2p-state exciton. [1] Besides, the electric-field controlled mixing of the high lying exciton state and continuum band enhances the oscillator strength of the discrete excited exciton states. This electric field modulation of the excitonic states in monolayer TMDs provides a paradigm of the manipulation of 2D excitons for potential applications of the electro-optical modulation in 2D semiconductors.

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Revealing ion dynamics in epitaxial T-Nb_2O_5 thin films during Li-ionic gating

Dongchang Kim[1†], Hyeon Han[1†], Farheen N[2]. Sayed, George Phillips[2], Alice Merryweather[2], Clare P. Grey[2] and Stuart S.P. Parkin[1]

[1]Max Planck Institute of Microstructure Physics, Halle (Saale), Germany.
[2] Yusuf Hamied Department of Chemistry, University of Cambridge, Cambridge, UK.
Email : Dongchang.Kim@mpi-halle.mpg.de

Ionic gating has garnered considerable attention due to emergent physical phenomena such as insulator-metal transitions, emergent superconductivity and magnetism via ion migrations into or out of films. However, its electrochemically driven responses are sluggish compared to conventional field-effect transistors, which hinders the diverse potential applications. Therefore, a profound understanding of the kinetics and dynamics of ion intercalation into materials is crucial for advancing fast ionic gating devices. We previously reported rapid and colossal insulator-metal transitions in epitaxial T-Nb2O5 thin films, featuring vertical ionic transport channels that promote fast Li ion migration [1] Here, we elucidate defect-accelerated ion dynamics in epitaxial T-Nb2O5 thin films during ionic gating using optical interferometric scattering microscopy (iSCAT) [2]. By employing iSCAT [3], we observe that the optical contrast of the thin film changes into rectangular-shaped domains in the early stage of Li ion insertion. Scanning transmission electron microscopy (STEM) revealed the formation of vertical anti-phase boundaries in the T-Nb2O5 thin films, likely accelerating the Li ion migration along the vertical pathways. These defect-driven fast ion migrations may open new avenues for designing and developing fast ion gating devices.

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Van der Waals epitaxy of a magnetic transition metal dihalide

D. Rothhardt[1,2,3], Z. Ahmed[2,3], C. Penschke[4], H. Liu[2,3], R. Hoffmann-Vogel[1], P. Saalfrank[4], H. J. Hug[2,3], and A. Kimouche[1]

[1] *Institute of Physics and Astronomy, University of Potsdam, 14476 Potsdam-Golm, Germany*
[2] *Swiss Federal Laboratories for Materials Science and Technology, CH-8600 Dübendorf, Switzerland*
[3] *Department of Physics, University of Basel, CH-4056 Basel, Switzerland*
[4] *Institute of Chemistry, 14476 Potsdam-Golm, Germany*

Email address of corresponding author: amina.kimouche@uni-potsdam.de

The field of quantum materials has developed into an active playground of competing interactions for testing novel ideas and protocols for future devices. Such competitions lead to a great variety of ordered states and huge efforts are put into the realization of reliable building blocks for quantum technologies. In recent years, the introduction of a new class of two-dimensional (2D) materials like transition metal dihalides (TMHs) is expected to open a wide range of possibilities for quantum applications [1]. These materials have emerged as a new platform to not only study 2D magnetism where spin fluctuations are expected to be strongly enhanced but also to investigate the growth mechanism in these magnetic crystals. Up to now only few publications show the growth of monolayer transition metal dihalides however, their local magnetic visualization is still lacking. Here, low temperature Multimodal Scanning Probe Microscopy (SPM) imaging combined with Kelvin Probe Force Microscopy (KPFM) and Magnetic Force Microscopy (MFM) revealed a ferromagnetic ground state persisting even in the monolayer regime. Various phases have been formed giving rise to a reach variety of electronic structures as revealed by KPFM. Our results are corroborated with DFT calculations which display similar surface morphology.

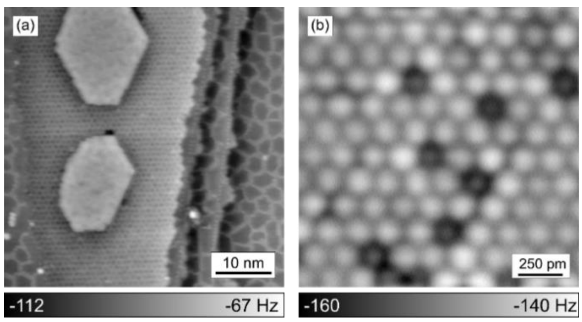

Fig: First flexural mode resonance frequency shift data recorded at constant tunnelling current (a) Overview (I_t = 10 pA, V_{bias} = 1000 mV) and (b) atomic resolution of the $NiBr_2$ (I_t = 50 pA, V_{bias} = 20 mV). (a) and (b): A_{1st} = 3 nm, f_{res} = 294.46 kHz, Q = 30000, c = 40 N/m, T = 6.3 K.

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Transverse-field susceptibility of spin freezing at the mesoscale quantum phase transitions in $LiHoF_4$

M. Lampl[1], A. Wendl[1] and C. Pfleiderer[1]

[1]Physik-Department, Technical University of Munich, 85748 Garching, Germany

The perhaps best understood example of a quantum critical point is the response of the dipolar Ising ferromagnet $LiHoF_4$ under a transverse field [1-3]. When tilting the magnetic field away from the hard axis such that the Ising symmetry is always broken, a line of well-defined phase transitions emerges from the transverse-field quantum critical point, characteristic of further symmetry breaking, and in stark contrast to a crossover expected microscopically [4]. Detailed theoretical modelling in excellent agreement with experiment identifies this line of phase transitions as mesoscale quantum criticality. We report an experimental study of the transverse-field susceptibility of this mesoscale quantum criticality into a regime of spin freezing under large field tilting angles. Our observations will be compared with the characteristics of spin freezing, kinetic arrest, and quantum annealing observed in heavily diluted $LiY_{1-x}Ho_xF_4$.

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Spin and orbital Edelstein effect in a bilayer system with Rashba interaction

S. Leiva[1], J. Henk[1], I. Mertig[1], and A. Johansson[2]

[1]Institut für Physik, Martin-Luther-Universität Halle-Wittenberg, D-06099 Halle (Saale), Germany.

[2] Max Planck Institute of Microstructure Physics, 06120 Halle (Saale), Germany

The spin Edelstein effect has proven to be a promising phenomenon to generate spin polarization from a charge current in systems without inversion symmetry. In recent years, current-induced orbital magnetization, also called the orbital Edelstein effect, has also been predicted for several systems with broken inversion symmetry [1-5].

In the present work, we calculate the current-induced spin and orbital magnetization for a bilayer system with Rashba interaction for the interface configuration. We use the modern theory of orbital magnetization [6] and the Boltzmann transport theory. We found a significantly larger spin than orbital effect, with a strong dependence on the model parameters such as effective mass and spin-orbit coupling per layer. This dependence allows us to enhance and even revert the sign of the orbital effect.

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Chiral hybridization of Yu-Shiba-Rusinov states in Fe clusters on Pb(111)

Bharti Mahendru[1], **Léa Meynier**[1], **Lisa M. Rütten**[1], **Harald Schmid**[1], **Felix von Oppen**[1,2] **and Katharina J. Franke**[1]

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

[2]*Dahlem Center for Complex Quantum Systems and Fachbereich Physik, Freie Universität Berlin, Berlin, Germany*

Unpaired electron spins exchange coupled to a superconductor give rise to bound states inside the superconducting energy gap, so-called Yu-Shiba-Rusinov (YSR) states [1-3]. Scanning tunneling microscopy and spectroscopy (STM/STS) are powerful tools to probe the excited state around the Fermi level of such systems at the atomic scale. Previously, it has been shown that the crystal field splits the d-levels of Mn atoms on Pb surfaces, which lead to distinct YSR states inheriting the symmetry of the spin-carrying orbital [4]. Engineered YSR systems have attracted a lot of attention in the context of investigating hybridization [5] and topological superconductivity [6,7].

Here, we investigate self-assembled clusters of Fe on Pb(111) using STM/STS. Single Fe atoms, although having four unpaired electrons in the d-levels in the gas phase, do not show YSR states on a superconducting Pb(111) surface. Two possible reasons for the absence of YSR states could be the weak coupling between the magnetic impurity and the superconductor or the energy of YSR state is close to the superconducting gap energy. In contrast, we observe different clusters that are most likely dimers and trimers, all showing in-gap states. These YSR states exhibit different symmetries that are related to the structure of the cluster on the Pb(111) surface. Interestingly, one type of the cluster exhibits spatially chiral YSR wavefunctions in differential conductance (dI/dV) maps. Using a simple model, we find that the origin of this chirality results from the adsorption of Fe atoms in the three-fold symmetric hollow sites of the substrate and the extent of the YSR wavefunctions.

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Probing the Disordered Superconductivity in TiN Films grown by Molecular Beam Epitaxy

Mostafa Marzouk[1], Malli Tangi[1], Banabir Pal[1], Stuart Parkin[1]

[1]*Max-Planck Institute of Microstructure Physics, Halle (Saale), Germany, Mostafa.marzouk@mpi-halle.mpg.de*

Cooper pairing, a fundamental physical phenomenon integral to elucidating the genesis of conventional superconductivity, describes the formation of electron pairs confined within a bound state below the critical zero-resistance transition temperature (T_c), as illustrated by the Bardeen-Cooper-Schrieffer (BCS) theory [1]. Titanium nitride (TiN) falls within the category of conventional superconductors, implying an anticipated manifestation of Cooper pairing below its transition temperature. However, recent investigations by Bastiaans *et al*., utilizing scanning tunneling microscopy, have demonstrated Cooper pairs even above the critical transition temperature in TiN [2-3]. Our study aims to understand the causative factors instigating the formation of Cooper pairs above T_c in TiN. Using state-of-the-art molecular beam epitaxy, we have grown high quality TiN thin films along 100 and 111 crystallographic directions. Subsequently, structural and transport assessments are conducted to probe the origins of disorder-induced superconductivity and its association with the occurrence of Cooper pairing above T_c in this specific system. This inquiry lays the groundwork for a deeper comprehension of the behaviors exhibited by disordered superconducting materials.

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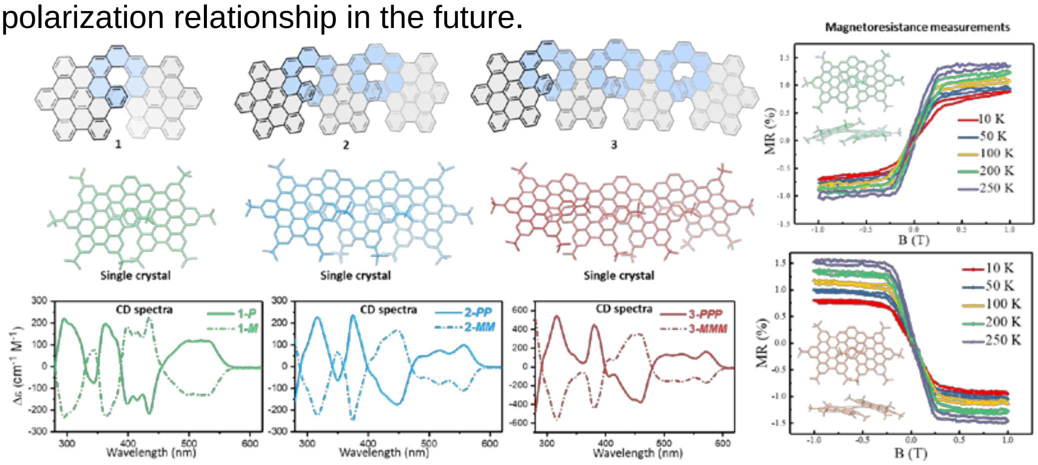
Quantum Chiral Nanocarbons with Unique Chiroptical Properties and Spin Polarization

Wenhui Niu[1], Tapan Kumar Das[2], Ron Naaman[2], and Xinliang Feng[1]

[1]*Max Planck Institute of Microstructure Physics, Halle, Germany*
[2]*Weizmann Institute of Science, Rehovot, Israel*

Chiral nanocarbons have attracted growing attention due to their exotic 3D structure, inherent chirality, and intriguing optoelectronic properties, in particular, their unique chiral-induced spin selectivity (CISS) effect. Due to the unique structural tunability and the specificity of quantum sensing, chiral nanocarbons have the potential to be a transformative tool in the next generation of quantum applications. Among them, Helical nanographenes (NGs) featuring multi-layer topology have been considered as promising candidates for understanding the intricate interplay between the chiral structure and chiroptical properties/spin polarization. In this study, we demonstrate a modular synthetic strategy to construct a series of novel helical NGs (1-3) with bilayer, trilayer, and tetralayer structures.[1] The resultant NGs exhibit excellent circular dichroism (CD) and circularly polarized luminescence (CPL) response with unprecedented high CPL brightness up to 168 M^{-1} cm^{-1}, rendering them promising candidates for CPL emitters. More interestingly, the helical NGs hold great potential for chiral-induced spin selectivity (CISS) effect, which describes the ability of spin polarization over the chiral skeletons. With the cooperation with Prof. Ron Naaman's group, the magnetoresistance (MR) measurements were performed to investigate the spin polarization of our chiral molecules (1-P and 1-M). As shown in following figure, the magnetoresistance (MR%) varies when the magnetic field was changed, which proves the clear CISS effect of helical NGs. Further MR investigations for other helical NGs (2 and 3) are going on, which enable the investigation of chiral structure-spin polarization relationship in the future.



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Deciphering the effect of Chiral Induced Spin Selectivity in the Catalytic Activity of D-Glucose Oxidase through Spin Polarized Charge Reorganization

Naupada Preeyanka,[1] Qirong Zhu[1], Tapan Kumar Das[1], and Ron Naaman[1]*
[1]Weizmann Institute of Science, Rehovot, Israel
E-mail: naupada.preeyanka@weizmann.ac.il

The electron transport through chiral molecules is spin-dependent with preference in their spin orientation, is well established through chiral induced spin selectivity (CISS) effect.[1,2] The present work is a manifestation of CISS effect through electron transport in self-assembled monolayer (SAM) of D-glucose oxidase (GOx), during the formation of gluconic acid from glucose, using confocal fluorescence microscopy and Hall voltage measurements. The charge rearrangement resulting in concomitant change in the spin orientation, dictates the catalytic activity of SAM of GOx from fluorescence studies and comprehended their structure-function correlation in presence of D-glucose and L-glucose from the symmetrical arrangement of Hall potentials. These spin exchange interactions can govern the charge transport kinetics in bioorganic molecules as well as initiates the spadework for new solid-state devices based on Hall effect, operating without any external magnet.

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Manipulation of the ground state in altermagnetic RuO_2 thin films induced by octahedral symmetry

Mingqun Qi[1], Tianzhe Chen[1], Chi Fang[1], Yufeng Wu[1] and Stuart S. P. Parkin[1]

[1] Max Planck Institute of Microstructure Physics, Halle (Saale), Germany

The investigation into ruthenates has consistently captivated substantial interest as an eminent category of strongly correlated physical systems [1,2]. In comparison to the 3d transition metals, ruthenium possesses a higher atomic mass and its 4d electrons exhibit an increased real space radius, thereby resulting in enhanced spin-orbit coupling and a diverse range of properties [3,4]. The recent discovery of altermagnetic and strain-induced superconductivity in collinear antiferromagnetic RuO_2, which is closely associated with its crystal structure and momentum-space band structure, has garnered considerable interest [5-8]. In this work, we employed pulsed laser deposition (PLD) to epitaxially grow RuO_2 films with varying thicknesses on TiO_2 substrates. The Laue oscillation observed in XRD and the reciprocal space map (RSM) both indicate excellent crystallinity and coherent epitaxial growth. The intriguing discovery revealed a thickness-dependent enhancement of Hall anomalous behavior and field-induced magnetization observed in magneto-transport measurements. The distinctive experimental phenomenon observed can be primarily ascribed to modifications in the electronic ground state caused by a high-pressure oxygen atmosphere during growth and transformations in ruthenium-oxygen octahedral symmetry induced by epitaxial strain. Our findings provide an interpretation of how the crystal structure of ruthenate governs its magnetic ground state and sheds light on the underlying mechanism behind the occurrence of altermagnetism in RuO_2.

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Electronic structure of monolayer MnI_2 islands studied by KPFM

D. Rothhardt[1,2,3], **R. Hoffmann-Vogel**[1], **H. J. Hug**[2,3], **and A. Kimouche**[1]

[1] Institute of Physics and Astronomy, University of Potsdam, 14476 Potsdam-Golm, Germany

[2] Swiss Federal Laboratories for Materials Science and Technology, CH-8600 Dübendorf, Switzerland

[3] Department of Physics, University of Basel, CH-4056 Basel, Switzerland

There has been a growing interest in exploring two-dimensional (2D) materials beyond graphene. Starting from 2017, new platforms have been discovered with which magnetism at low dimensions is explored. The introduction of a variety of atomically thin magnetic crystals has inspired efforts to not only understand the nature of magnetism but also to investigate the growth mechanism in these crystals. Here, we study the epitaxial growth of manganese iodide (MnI_2) on metallic substrates. Two dimensional MnI_2 islands tend to grow on a specific buffer layer giving rise to the formation of twin domains rotated by 60°. The surface morphology undergoes a significant change under different evaporation condition, which lead to an island shape transition and a more homogenous growth mode. Here we employ frequency-modulated scanning force microscopy in the non-contact mode, combined with Kelvin probe microscopy and scanning tunnelling microscopy to investigate the electronic and topographic fingerprints of MnI_2 on different metal substrates.

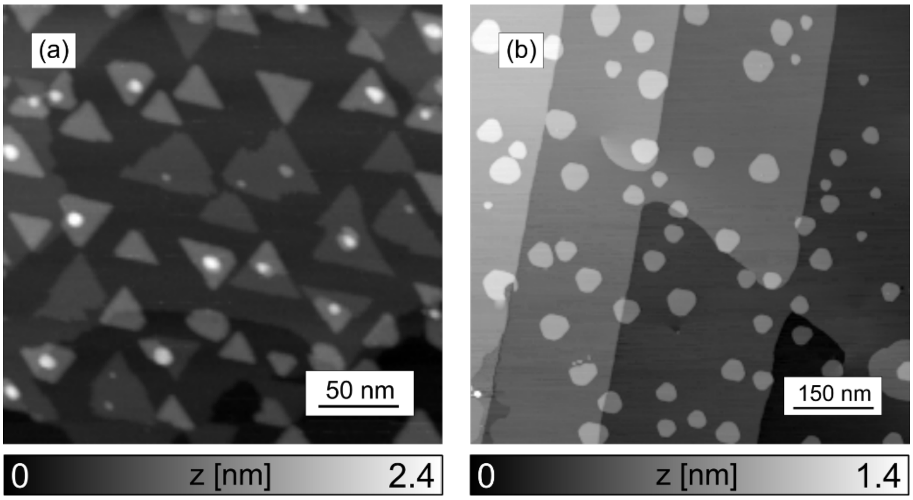

Figure 1Scanning Force Microscopy (SFM) topography (a) MnI_2 grown on Au(111) (Δf_{1st} = -31 Hz, A_{1st} = 4.3 nm, Q_{1st} = 24500, f_{1st} = 192.13 kHz, V_{bias} = 352 mV) and Scanning Tunnelling Microscopy (STM) topography (b) MnI_2 on Ag(111) (I_t = 66 pA, V_{bias} = 88 mV).

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Electrical and thermal Hall transport in compensated topological insulators

Rohit Sharma [1], Mahasweta Bagchi [1], Yongjian Wang [1], Yoichi Ando [1], and Thomas Lorenz [1]

[1] II. Physikalisches Institut, Universität zu Köln, Zülpicher Str. 77, 50937 Köln, Germany

E-mail: sharma@ph2.uni-koeln.de

The emergence of a substantial thermal Hall effect driven by phonons across a spectrum of quantum materials, from cuprate superconductors [1] to spin liquids [2] and titanates [3], is a surprising revelation. Despite phonons lacking charge and being common low-energy solid-state excitations, the source of the handedness inducing a phonon Hall effect under a magnetic field remains a puzzling mystery. From a systematic study of thermal and charge transport in various single crystals of compensated topological insulators we identify the evolution of a large low-temperature thermal Hall effect as a characteristic common feature. To disentangle phononic and electronic contributions, we evaluated the electronic contributions through electrical measurements on corresponding samples, employing the Wiedemann-Franz law. The longitudinal thermal conductivity κ_{xx} is phonon dominated in all samples. The transverse thermal conductivity κ_{xy} exhibits a large negative signal, followed by a peak around the similar temperature, where a peak in κ_{xx} is observed. The coincidence of peaks position in κ_{xx} and κ_{xy} indicates an underlying phononic mechanism driving the thermal Hall effect in compensated topological insulators. Possible reasons for the occurrence of phononic thermal Hall effect in compensated topological insulators will be discussed.

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Helical spin-momentum locking and second order φ_0-Josephson effect in the Dirac semimetal 1T-$PtTe_2$

Pranava K. Sivakumar[1], Mostafa T. Ahari[2], Jae-Keun Kim[1], Yufeng Wu[1], Anvesh Dixit[1], George J. de Coster[3], Avanindra K. Pandeya[1], Matthew J. Gilbert[2,4] and Stuart S. P. Parkin[1].

1. Max Planck Institute of Microstructure Physics, 06120 Halle (Saale), Germany
2. Materials Research Laboratory, The Grainger College of Engineering, University of Illinois, Urbana-Champaign, Illinois 61801, USA
3. DEVCOM Army Research Laboratory, 2800 Powder Mill Rd, Adelphi, Maryland 20783, USA
4. Department of Electrical Engineering, University of Illinois, Urbana-Champaign, Illinois 61801, USA

email: sivakumar@mpi-halle.mpg.de

The Josephson diode effect (JDE) has attracted a lot of recent attention for its potential application in superconducting circuits as a logic element. However, it can also serve as a potent tool in probing the spin-momentum locking and time-reversal symmetry breaking in the superconducting state. In this work, we establish the presence of a large JDE in a van der Waals transition metal dichalcogenide and type-II Dirac semimetal 1T-$PtTe_2$ and distinguish between intrinsic and extrinsic mechanisms contributing to the effect in lateral Josephson junctions (JJs). A large second-harmonic component in the Josephson supercurrent is shown to exist through analysis of the current-phase relationship that also serves as an essential ingredient for the existence of an intrinsic JDE, thus making it also a useful probe of second-order Josephson supercurrents in a junction. We refer to junctions with such current-phase relationships as 'second order φ_0- junctions', discuss their properties, and differentiate them in terms of the diode effect from junctions with other well-known current-phase relationships. The presence of a large second harmonic component in $PtTe_2$ JJs is attributed to the long-range phase-coherent transport facilitated by the Dirac-like spin-momentum locking in the system. The high chemical stability, high transparency, and large spin-orbit coupling along with large critical currents provided by $PtTe_2$, make it an interesting platform to further investigate the Josephson diode effect.

Unconventional anomalous Hall effect and complex magnetism in rare-earth stannides

G. Skorupskii,[1] F. Orlandi,[2] I. Robredo,[3] M. Jovanovic,[1] R. Yamada,[4] P. Manuel,[2] M. G. Vergniory,[3] M. Hirschberger,[4] and L. M. Schoop[1]

[1]Princeton University, Princeton, NJ, USA
[2]ISIS Neutron and Muon Source, Didcot, UK
[3]Max Planck Institute for Chemical Physics of Solids, Dresden, Germany
[4]The University of Tokyo, Tokyo, Japan

Non-collinear spin textures are often proposed as information carriers for future data storage devices.[1] Particularly interesting are materials where the magnetic structure elicits a strong response in electrical transport, allowing for simple interfacing with the data. Electrical Hall effect of magnetic materials can display anomalous behavior,[2] and serve as one such signature. Prominently, strong and sharp Hall anomalies are hallmarks of magnetic skyrmions,[3,4] commonly invoked in prospective computer memories.

Here, we present a family of rare-earth tin intermetallic compounds, which host a complex array of magnetic phases at cryogenic temperatures. We demonstrate that several of those phases display an extremely strong and sharply localized Hall response. We discuss the potential origins of this Hall anomaly, and propose chemical design approaches that may allow future discovery of similar magnetic phases.

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In-situ observation of magnetic structures in twisted stacks of LSMO bilayer

T.-T Jiang[1] **and S. Parkin**[2]

[1]*Max Plank Institute of Microstructure Physics, Halle(Saale), Germany*

The design and fabrication of novel quantum devices in which exotic phenomena arise from magnetic physics have sparked a new race of conceptualization and creation of artificial lattice structures. A platform for assembling freestanding LSMO thin films with different orientations into artificial stacks with heterointerfaces is developed, showing high-quality twisted bilayer and interesting magnetic evolution in STEM mapping and LTEM recording. This study paves the way to the construction of higher-order artificial oxide heterostructures based on different symmetries and provides the foundation for investigating magnetic effects in an expanded selection of twisted oxide thin films.

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Competing anisotropies in a cubic chiral magnet unveiled by resonant x-ray magnetic scattering

V. Ukleev,[1] O. Utesov,[2] C. Luo,[1] F. Radu,[1] M. Winter,[3,4] A. Than,[4] B. Rellinghaus,[4] K. Karube,[5] Y. Tokura,[5] Y. Taguchi,[5] and J. S. White[6]

[1]*Helmholtz-Zentrum Berlin für Materialien und Energie, Germany*
[2]*Institute for Basic Science, Daejeon, Republic of Korea*
[3]*Max Planck Institute for Chemical Physics of Solids, Dresden, Germany*
[4]*Technical University Dresden, Dresden, Germany*
[5]*RIKEN Center for Emergent Matter Science, Wako, Japan*
[6]*Paul Scherrer Institute, Villigen, Switzerland*

Resonant elastic small-angle soft x-ray scattering (REXS) is the unique tool that allows to study long-periodic spin textures in noncentrosymmetric magnets with unprecedented reciprocal-space resolution. Moreover, the unique sample environment allows one to investigate hitherto unexplored pathways of spin texture transformations and extract small parameters that are inaccessible with other real or reciprocal-space methods. Here we will focus on a recent study of a chiral room-temperature skyrmion host $Co_8Zn_8Mn_4$ using REXS. The cubic β-Mn-type alloy $Co_8Zn_8Mn_4$ is a chiral helimagnet that exhibits a peculiar temperature-dependent behavior in the spiral pitch, which decreases from 130 nm at 300 K to 70 nm at 20 K. Notably, this shortening is accompanied by a structural transition of the metastable skyrmion texture, transforming from a hexagonal to a square lattice of elongated skyrmions [1-3]. The underlying cause of this transformation remains unknown, with potential interactions responsible for the change that includes temperature-dependent Dzyaloshinskii-Moriya interaction, magnetocrystalline, and exchange anisotropies (AEI) [3,4]. In this study, we employed REXS in vectorial magnetic fields to investigate the temperature dependence of the anisotropic properties of $Co_8Zn_8Mn_4$. Our results reveal that in this complex material, the AEI gradually increases towards lower temperatures, leading to a 5% variation in the helical pitch within the (001) plane at 20 K. The negative AEI constant throughout the temperature range below T_C indicates a competition between the exchange and cubic magnetocrystalline anisotropies. Theoretical model, incorporating both AEI and uniaxial strain-induced anisotropy contributions [5], allows for the quantitative extraction of the AEI parameter.

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Giant spin Hall effect and spin-orbit torques from 5d transition metal - aluminum alloys for energy efficient synthetic antiferromagnetic racetrack memories

Peng Wang[1], Stuart S.P. Parkin[1]
[1] Max Planck Institute of Microstructure Physics, Weinberg 2, Germany

Synthetic antiferromagnetic thin film stacks are an essential component for racetrack memory and magnetic tunnel junction devices. The magnetic layers in these devices must display perpendicular magnetic anisotropy (PMA) that is typically derived from interfaces between [111] crystallographically textured layers of Co and Ni. Here, we show that 5d transition metal-Al alloy sputtered thin films that display an $L1_0$ structure even for room temperature deposition both show large PMA as well as giant spin Hall effects that give rise to giant spin orbit torques. Using the $L1_0$ compound RuAl as a AF spacer layer we demonstrate novel synthetic antiferromagnets with an entire $L1_0$ structure that are, moreover, crystallographically ordered along the [001] orientation and yet demonstrate high PMA. We demonstrate state-of-the-art racetrack memory devices that exhibit a several-fold increased efficiency for current induced domain wall motion as compared to prior-art materials. These structures are formed on thin Ir_xAl_{100-x} underlayers with an $L1_0$ structure and are composed of ultra-thin layers of cubic Co and Ni with the $L1_0$ RuAl as the antiferromagnetic coupling spacer layer. These structures exhibit chiral Néel -type domain walls so that all the domain walls move synchronously along the racetracks at very high speeds under the influence of nano-second long current pulses. Moreover, the domain walls show very high thermal stability after repeated motion backwards and forwards along the racetracks. These novel materials based on $L1_0$ compounds provide a new route for the multifunctional use of racetrack memories that are compatible with complementary metal-oxide semiconductor technologies.

Molecular intercalation induced unconventional superconductivity

Y. XIE[1], P.K. Sivakumar[1], Y. Wu[1], R. Naaman[2], and S.S.P. Parkin[1]

[1] Max Planck Institute of Microstructure Physics, Halle(Saale), 06120, Germany
[2] Department of Chemical Physics, Weizmann Institute of Science, Rehovot, 76100, Israel

Chiral molecules have a handedness that distinguishes them from their mirror image. The interplay between chirality of the molecule and the spin of each electron passing through the chiral molecule determines the transmission probability of the electron through the molecule. This effect is known as chirality induced spin selectivity (CISS) and it opens the possibility of using chiral molecules for spintronics applications [1]. Recently it was reported that chiral molecules (such as R-α-methylbenzylamine and S-α-methylbenzylamine) can be intercalated in two dimensional superconductors such as TaS_2 and TiS_2 to create a superlattice that displays CISS in the non-superconducting state[2]. Furthermore, a robust half-flux quantum phase shift in Little-Parks experiment that can be considered as a signature of unconventional superconductivity was also observed[3]. In our work, we would like to further explore this chiral molecule intercalated superlattices in the superconducting state and look for signatures of spin-polarized supercurrents. We are also interesting in exploring chiral molecules whose chirality can be switched by light to generate CISS-based opto-electronic switches[4].

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Monopole-like orbital-momentum locking and the induced orbital transport in topological chiral semimetals

Qun Yang[a,b], Jiewen Xiao[b], Iñigo Robredo[a,c], Maia G. Vergniory[a,c], Binghai Yan[b], and Claudia Felser[a*]

[a]Max Planck Institute for Chemical Physics of Solids, 01187 Dresden, Germany
[b]Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 7610001, Israel
[c]Donostia International Physics Center, 20018 Donostia-San Sebastian, Spain

The interplay between chirality and topology nurtures many exotic electronic properties. For instance, topological chiral semimetals display multifold chiral fermions which manifest nontrivial topological charge and spin texture [1-2]. They are an ideal playground for exploring chirality-driven exotic physical phenomena. In this work, we reveal a monopole-like orbital-momentum locking texture on the three-dimensional Fermi surfaces of topological chiral semimetals with B20 structures (e.g., RhSi and PdGa). This orbital texture enables a large orbital Hall effect (OHE) and a giant orbital magnetoelectric (OME) effect in the presence of current flow. Different enantiomers exhibit the same OHE which can be converted to the spin Hall effect by spin-orbit coupling in materials. In contrast, the OME effect is chirality dependent and much larger than its spin counterpart. Our work reveals the crucial role of orbital texture for understanding OHE and OME effect in topological chiral semimetals and paves the path for applications in orbitronics, spintronics and enantiomer recognition.

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Quantum oscillations revealing topological band in kagome metal ScV_6Sn_6

Changjiang Yi[1], Xiaolong Feng[1], Ning Mao[1], Premakumar Yanda[1], Subhajit Roychowdhury[1], Yang Zhang[2,3], Claudia Felser[1], and Chandra Shekhar[*,1]

[1]Max Planck Institute for Chemical Physics of Solids, 01187 Dresden, Germany
[2]Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA
[3]Min H. Kao Department of Electrical Engineering and Computer Science, University of Tennessee, Knoxville, TN 37996, USA
*Chandra.Shekhar@cpfs.mpg.de

Compounds with kagome lattice structure are known to exhibit Dirac cones, flat bands, and van Hove singularities, which host numerous versatile quantum phenomena. Inspired by these intriguing properties, we investigate the temperature and magnetic field dependent electrical transports along with the theoretical calculations of ScV_6Sn_6, a non-magnetic charge density wave (CDW) compound. At low temperatures, the compound exhibits Shubnikov–de Haas quantum oscillations, which help to design the Fermi surface (FS) topology. This analysis reveals the existence of several small FSs in the Brillouin zone, combined with a large FS. Among them, the FS possessing Dirac band is a non-trivial and generates a non-zero Berry phase. In addition, the compound also shows the anomalous Hall-like behaviour up to the CDW phase transition, and they might be correlated. Combining these interesting physical properties with the CDW phase, ScV_6Sn_6 presents a unique material example of the versatile $HfFe_6Ge_6$ family and provides various promising opportunities to explore the series further.

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Engineering of Néel-type Skyrmions in Novel Freestanding Heterostructures

Z. Yin[1] , P. Wang[1], K. Gu[1], A. K. Srivastava[1], S. Parkin[1]

[1]*Max Planck Institute of Microstructure Physics, Halle, Germany*

Skyrmions are spatially inhomogeneous spin textures with nanoscale size. Néel-type skyrmions can be induced by interfacial symmetry broken [1]. They are regarded as novel information carriers for use in high-density, low-power, and multi-functional spintronic devices. In this project, we use freestanding technology to tune the strain effects in ferromagnets. The phase of spin textures can be observed through Lorentz Transmission Electron Microscope (LTEM).

Shown in the figure below, the wrinkles on the freestanding heterostructure thin film (a) can result in various types of magnetic textures (b) due to the varying strain. And with applied field, we can observe difference in density for both strip and skyrmion phase.

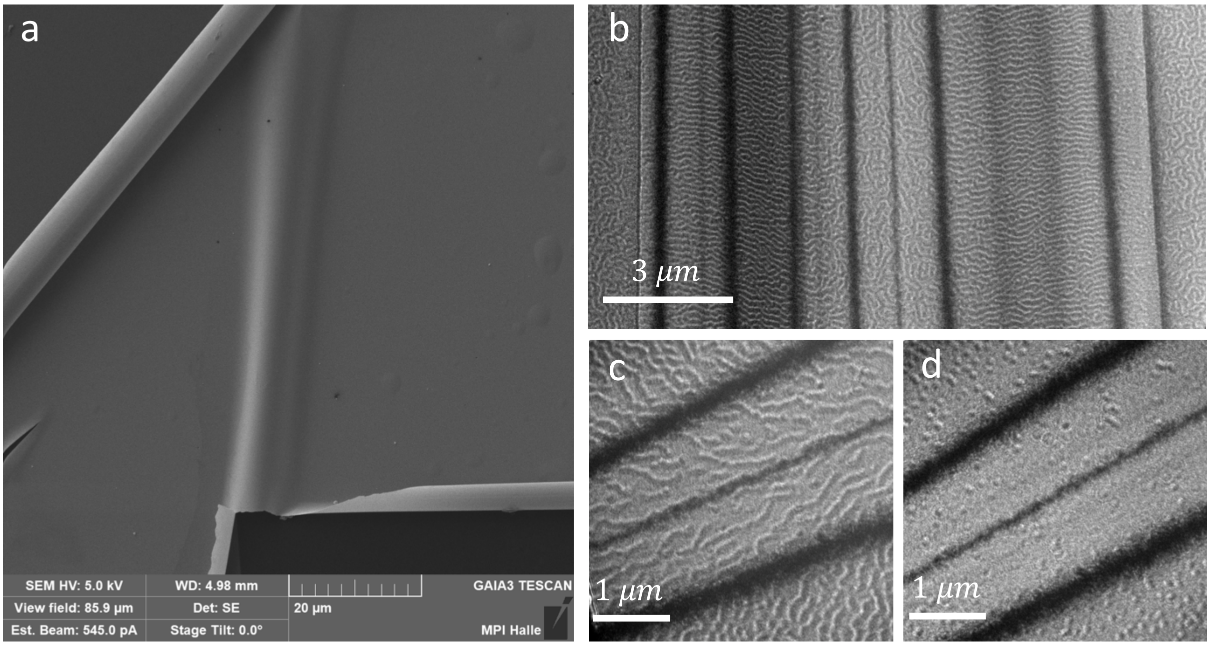

Fig. 1. (a) Scanning electron microscope (SEM) image of the freestanding thin film with wrinkles. (b)-(d) LTEM image at the wrinkles with underfocus 1.5mm, tilting along a axis 20º and at room temperature. Applied fields are 0 mT (b), 130 mT (c) and 290 mT (d). Magnification is at 2000 (b) and 8000 (c) & (d).

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Current-induced domain wall motion in a van der Waals ferromagnet Fe_3GeTe_2

Wenjie Zhang[1], Tianping Ma[1], Binoy Krishna Hazra[1], Holger Meyerheim[1], Prajwal Rigvedi Madhusudan Rao[1], Zihan Yin[1], Abhay Kant Srivastava[1], Zhong Wang[1], Ke Gu[1], See-Hun Yang[1], Yicheng Guan[1], Stuart S. P. Parkin[1]

[1]*Max Planck Institute of Microstructure Physics, Weinberg 2, 06120 Halle, Germany*

The manipulation of spin textures in magnetic systems by spin currents derived from charge currents is of fundamental and technological interest. A particularly interesting system is the 2D van der Waals ferromagnet Fe_3GeTe_2 (FGT) in which Néel type skyrmions have recently been observed. The origin of these chiral spin textures in a nominally centrosymmetric system is of considerable interest. Recently it was proposed that these derive from defects in the structure that lowers the symmetry and allows for a vector Dzyaloshinsky-Moriya interaction (DMI). Here we demonstrate the current-induced domain wall motion (CIDWM) in FGT flakes, whose maximum DW velocity is an order of magnitude higher than those reported in previous studies. In heterostructures where Pt and W layers are deposited on top of the FGT flakes, we show that domain walls can be moved in both systems from a coexistence of spin transfer torques and spin-orbit torques. The competition between these torques leads to a change in the direction of domain wall motion with increasing magnitude of injected current. The existence of bulk DMI in nanometer thick FGT flakes is also proven by a Néel type wall configuration revealed from a magnetic field dependence of domain wall velocity.

References

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