MA 4: Spin Transport and Orbitronics, Spin-Hall Effects (joint session MA/TT)

Time: Monday 9:30–13:00 Location: HSZ 403

MA 4.1 Mon 9:30 HSZ 403

Topological information device operating at the Landauer limit — •Ahmet Mert Bozkurt[1,2,3], Alexander Brinkman[4], and Inanc Adagideli[3,4] — [1]QuTech, Delft University of Technology, 2600 GA Delft, The Netherlands — [2]Kavli Institute of Nanoscience, Delft University of Technology, 2600 GA Delft, The Netherlands — [3]Faculty of Engineering and Natural Sciences, Sabanci University, Orhanli-Tuzla, Istanbul, Turkey — [4]MESA+ Institute for Nanotechnology, University of Twente, The Netherlands

We propose and theoretically investigate a novel Maxwell's demon implementation based on the spin-momentum locking property of topological matter. We use nuclear spins as a memory resource which provides the advantage of scalability. We show that this topological information device can ideally operate at the Landauer limit; the heat dissipation required to erase one bit of information stored in the demon's memory approaches $k_BT \ln 2$. Furthermore, we demonstrate that all available energy, $k_BT \ln 2$ per one bit of information, can be extracted in the form of electrical work. Finally, we find that the current-voltage characteristics of the topological information device satisfy the conditions of an ideal memristor.

MA 4.2 Mon 9:45 HSZ 403

Controlling 3D spin textures by manipulating sign and amplitude of interlayer DMI with electrical current — •Fabian Kammerbauer[1], Won-Young Choi[1], Freimuth Frank[1,2], Robert Frömter[1], Yuriy Mokrousov[1,2], and Mathias Kläui[1] — [1]Institute of Physics, Joahnnes Gutenberg University, Staudingerweg 7, 55128 Mainz, Germany — [2]Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany

The recently discovered interlayer Dzyaloshinskii-Moriya interaction (IL-DMI) in multilayers with perpendicular magnetic anisotropy favors a canting of spins in the in-plane direction [1]. It could thus stabilize exciting spin textures such as Hopfions. A key requirement for nucleation is to control the IL-DMI and so, we investigate the influence of an electric current on the strength of the IL-DMI, as previously found for FMI. The IL-DMI is quantified using out-of-plane hysteresis loops while applying a static in-plane magnetic field at varied azimuthal angles. We observe a shift in the azimuthal dependence with increasing current, which is concluded to originate from the additional in-plane symmetry breaking introduced by the current flow. Fitting the angular dependence we demonstrate the presence of an additive current-induced term [3]. With this, an easily accessible possibility to manipulate 3D spin textures by current is realized.

[1] Han et al., Nat. Mater. 18, 703-708 (2019)
[2] Karnad et al., Phys. Rev. Lett. 121, 147203 (2018)
[3] Kammerbauer et al, arXiv:2209.01450 (2022)

MA 4.3 Mon 10:00 HSZ 403

Nonequilibrium dynamics in a spin valve with noncollinear magnetization — •Rudolf Smorka[1], Pavel Baláž[2], Michael Thoss[1], and Martin Žonda[3,1] — [1]University of Freiburg, Germany — [2]Institute of Physics of the Czech Academy of Sciences Prague, Czech Republic — [3]Charles University Prague, Czech Republic

Manipulation of magnetization by electric currents enables novel functions for spin-transfer torque devices. We study the nonequilibrium spin dynamics and spin-transfer torques in noncollinear spin-valve heterojunctions using a mixed quantum-classical Ehrenfest approach.

In an isolated valve for short spacer layers and weak spin-electron couplings, magnetization dynamics of the ferromagnetic layers is in agreement with the macrospin approximation. For large spacer layers, our quantum-classical approach predicts electron-induced spin relaxation. For intermediate electron-spin couplings, a change in the localization character of the electronic eigenstates from metallic-like to insulator-like leads to a reduced indirect exchange interaction between spins mediated by the conduction electrons. In a spin valve coupled to leads, spin relaxation times differ by several orders of magnitude depending on whether the DC bias is introduced by shifting the electrochemical potentials of both leads symmetrically about the equilibrium Fermi level of the spin valve (reminiscent of a gate-tunable junction) or by shifting the chemical potential of only one lead (as realized in a scanning tunneling microscope geometry).

[1] R. Smorka, P. Baláž, M. Thoss, M. Žonda, Phys. Rev. B 2022, 106, 144435.

MA 4.4 Mon 10:15 HSZ 403

Nonrelativistic spin currents in altermagnets — •Rodrigo Jaeschke-Ubiergo, Jairo Sinova, and Libor Šmeijkal — Institut für Physik, Johannes Gutenberg Universität Mainz, D-55099 Mainz, Germany

Altermagnetism has emerged recently as a third basic collinear magnetic phase [1], in addition to ferromagnets and antiferromagnets. Conventional antiferromagnets exhibit two sublattices with opposite magnetic moment related by translation or inversion. In altermagnets the magnetic sublattices are connected by a rotation or a mirror operation. The particular symmetry causes that altermagnets display time-reversal (T) symmetry breaking and spin split band structure even in absence of spin-orbit coupling [2]. In this work, we study the spin conductivity tensor in altermagnets by using spin group theory formalism [1]. We also use Kubo's linear response to calculate the spin conductivity tensor in all the altermagnetic spin point groups models. Additionally, we identify and sort 200 altermagnetic candidates into spin conductivity tensor classes. We will discuss some spin point groups that allow for a transverse spin current in detail. This is the case of spin splitter current in RuO2 [3,4], which is a nonrelativistic effect that conserves spin unlike in general magnetic spin Hall effect in noncollinear magnets. Moreover, the spin conductivity tensor is symmetric and T-odd, which makes it different from the conventional spin Hall effect. [1] Šmejkal et al., PRX, 12, 031042 (2022). [2] Šmejkal, et al. Sci.Adv 2020. [3] Gonzalez- Hernandez, et al. PRL 2021. [4] Šmejkal, et al. PRX 12, 011028 (2022).

MA 4.5 Mon 10:30 HSZ 403

Quantification and modulation of intrinsic spin transport in 5d transition metals — •Akash Bajaj, Reena Gupta, Andrea Droghetti, and Stefano Sanvito — School of Physics and CRANN, Trinity College Dublin, Dublin 2, Ireland

Spin-Hall effect (SHE) enables charge-to-spin conversion in heavy transition metals, such as Ta and Pt, with strong spin-orbit coupling (SOC) strengths. It has been extensively studied as a viable mechanism for the development of next-generation spintronics-based non-volatile memory devices. Numerous experimental and first-principles approaches have been devised to quantify the charge-to-spin conversion efficiency i.e., the spin-Hall angle (SHA), for the SHE. However, such approaches unavoidably involve interface contributions and, in general, extrinsic effects such as disorder and impurities, which are known to be less dominant than the bandstructure-only intrinsic contribution in such heavy metals. In this work, we use density functional theory combined with a bond-current-based non-equilibrium Green's functions approach to quantify the intrinsic SHAs of bulk elemental and thin-film models of 5d transition metals. We then computationally demonstrate a strategy for modulating the SHA within the same device, using Pt and Au as contrasting examples. Our computational work not only provides a quantitative estimation of the intrinsic SHAs for these materials, but also enables its theoretical understanding aimed towards the development of higher performance and power-efficient spintronics-based non-volatile memory devices.

MA 4.6 Mon 10:45 HSZ 403

Influence of Disorder at Insulator-Metal Interface on Spin Transport — Mahsa Alsadat Seyed Heydari, Wolfgang Belzig, and •Niklas Rohling — Department of Physics, University of Konstanz

Motivated by experimental work showing enhancement of spin transport between yttrium iron garnet and platinum by the thin antiferromagnetic insulator NiO [1] between them, we consider spin transport trough the interface of a non-magnetic metal and a ferro- or antiferromagnetically ordered insulator. The spin transport is carried by spin-polarized electrons in the metal and by magnons in the insulator. Spin current can be generated by a spin accumulation in the metal due to the inverse spin Hall effect, a microwave field exciting magnons in the insulator, or by a thermal gradient (spin Seebeck effect). The spin current can be computed using Fermi's Golden Rule [2]. For a perfectly clean interface, the in-plane momentum is conserved for

the electron-magnon scattering events which govern the spin transport through the interface. We calculate how disorder-induced broadening of the scatting matrix elements with respect to the in-plane momentum influences the spin current. As a general result, we observe that for many experimental setups, one should expect a rather small effect of interface disorder on the measured spin current.

[1] Wang et al., Phys. Rev. Lett. 113, 097202 (2014), Phys. Rev. B 91, 220410(R) (2015); Lin et al. Phys. Rev. Lett. 116, 186601 (2016)
[2] Bender et al., Phys. Rev. Lett. 108, 246601 (2012)

MA 4.7 Mon 11:00 HSZ 403

Long-range orbital-Hall torques in Nb(or Ru)/Ni Heterostructures — Arnab Bose[1], Fabian Kammerbauer[1], •Rahul Gupta[1], Dongwook Go[2], Yuriy Mokrousov[1,2], Gerhard Jakob[1], and Mathias Kläui[1,3] — [1]Institute of Physics, Johannes Gutenberg University Mainz, Staudingerweg 7, 55128 Mainz, Germany — [2]Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany — [3]Center for Quantum Spintronics, Department of Physics, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway

We report a large orbital Hall torque (OHT) generated by Nb and Ru via strong dependence of torques on the ferromagnets, Ni, in Nb(Ru)/Ni heterostructures. We found the sign reversal of the damping-like torque in Nb/Ni. Moreover, the long-range orbital transport in the ferromagnet was revealed by the thickness dependences of Ni in Ni/Nb(or Ru) heterostructure, which are markedly different from the regular spin absorption in the ferromagnet that takes place within a few angstroms and thus it uniquely distinguishes OHT from the spin Hall torque. The experimentally measured effective orbital-Hall conductivities are found to be 6.1×10^4 $\frac{\hbar}{2e}$ $(\Omega\text{m})^{-1}$ and 5.86×10^4 $\frac{\hbar}{2e}$ $(\Omega\text{m})^{-1}$ for Nb and Ru, respectively, which is an order of magnitude higher than their measured spin Hall conductivities, as also confirmed by the density functional theory. This study opens a plethora of possibilities to further engineering the torques, utilizing the orbital degree of freedom.

MA 4.8 Mon 11:15 HSZ 403

Layer-resolved spin-orbit torque assisted magnetization dynamics in Pt/Co heterostructure — •Harshita Devda[1], András Deák[2], Leandro Salemi[3], Levente Rózsa[1], László Szunyogh[2], Peter M. Oppeneer[3], and Ulrich Nowak[1] — [1]Universität Konstanz, Konstanz, Germany — [2]Budapest University of Technology and Economics, Budapest, Hungary — [3]Uppsala University, Uppsala, Sweden

It is well known that the spin-orbit torque (SOT) mechanism is more reliable for current induced magnetization dynamics than the spin-transfer torque. The key phenomenon behind the SOT in heavy metal/ferromagnet (HM/FM) bilayers is attributed to the spin Hall effect (SHE) and the spin Rashba-Edelstein effect (SREE). However, the exact mechanism is still under debate. So far various works have studied the SOT-driven magnetic behavior in different magnetic systems, but the layer-resolved understanding of the SOT effect in the HM/FM bilayer due to spin-orbit coupling (SOC) in heavy metal is still lacking. We focus on current-induced magnetization dynamics in a Pt/Co bilayer assisted by the SOC in Pt. We use a multiscale model which links ab initio calculations with atomistic spin dynamics simulations. We implement a linear-response formalism to compute the electrically induced magnetic moments, caused by SHE in bulk and SREE at the interface, and utilize these in atomistic spin dynamics simulations. We analyse the layer-resolved behavior of both field-like and damping-like torques in FM and determine how they affect magnetization dynamics in ferromagnets.

MA 4.9 Mon 11:30 HSZ 403

Spin and orbital Edelstein effect in a bi- and trilayer system with Rashba interaction — •Sergio Leiva[1], Jürgen Henk[1], Ingrid Mertig[1], and Annika Johansson[2] — [1]Martin Luther University Halle-Wittenberg, Halle, Germany — [2]Max Planck Institute of Microstructure Physics, Halle, Germany

The spin Edelstein effect has proved 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 [1-6].

In the present work, we calculate the current-induced spin and orbital magnetization for a bilayer and a trilayer system with Rashba interaction for the interface and the free-standing slab configurations. We use the modern theory of orbital magnetization [7] and the Boltzmann transport theory. We found a significantly larger orbital than spin 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.

[1] T. Yoda *et al.*, Sci. Rep., **5**, 12024 (2015).
[2] D. Go *et al.*, Sci. Rep. **7**, 46742 (2017)
[3] T. Yoda *et al.*, Nano Lett., **18**, 916 (2018).
[4] L. Salemi *et al.*, Nat. Commun. **10**, 5381 (2019)
[5] D. Hara *et al.*, Phys. Rev. B, **102**, 184404 (2020).
[6] A. Johansson *et al.*, Phys. Rev. Research, **3**, 013275 (2021).
[7] T. Thonhauser *et al.* Phys. Rev Lett. **95**, 137205 (2005).

MA 4.10 Mon 11:45 HSZ 403

Optical detection of the orbital Hall effect in a light metal Ti — •Young-Gwan Choi[1,2], Daegeun Jo[3], Kyung-Hun Ko[1], Dongwook Go[4,5], Kyung-Han Kim[3], Hee Gyum Park[6], Changyoung Kim[7,8], Byoung-Chul Min[6], Uri Vool[2], Gyung-Min Choi[1,9], and Hyun-Woo Lee[3,10] — [1]DOES, SKKU, Suwon, Korea — [2]MPI-CPfS, Dresden, Germany — [3]Physics, POSTECH, Pohang, Korea — [4]PGI and IAS, FZJ and JARA, Julich, Germany — [5]GSE Mainz, Mainz, Germany — [6]Center for Spintronics, KIST, Seoul, Korea — [7]Physics, SNU, Seoul, Korea — [8]CCES, IBS, Seoul, Korea — [9]CINAP, IBS, Suwon, Korea — [10]APCTP, Pohang, Korea

Electrical generation of the angular momentum current enables the development of novel memory devices, similar to spin current generation. Recently, it has been theoretically proposed that the orbital angular momentum (OAM) current can be driven by a charge current, called as the orbital Hall effect (OHE). Here we report evidence of the OHE, measured by magneto-optical Kerr effect microscopy. We detect large Kerr signals in one of the 3d transition metals, Ti, in which the high orbital Hall conductivity is predicted. We also find that the large OAM is accumulated by the OHE with a relaxation length ~70 nm. Moreover, we present the torque results in Ti/Ni. The high torque efficiency shows that the OAM injection allows for the electrical control of the magnetization. We also propose magnetic imaging using a nitrogen-vacancy scanning probe to measure OAM accumulation directly. Our results can pave the way for a deep understanding and provide techniques for generating and detecting orbital transport.

MA 4.11 Mon 12:00 HSZ 403

Spin and orbital Edelstein effects at oxide interfaces — •Annika Johansson[1], Börge Göbel[2], Sara Varotto[3], Srijani Mallik[3], Ingrid Mertig[2], and Manuel Bibes[3] — [1]Max Planck Institute of Microstructure Physics, Halle, Germany — [2]Martin Luther University Halle-Wittenberg, Halle, Germany — [3]Unité Mixte de Physique, CNRS, Thales, Université Paris-Saclay, Palaiseau, France

The spin Edelstein effect (SEE) provides charge-spin interconversion in nonmagnetic systems with broken inversion symmetry [1,2]: An external electric field generates a charge current as well as a homogeneous spin density. Further, a finite current-induced magnetization originating from the electrons' orbital moments can be generated, which is called orbital Edelstein effect (OEE) [3-5]. In this talk, the SEE and OEE at $SrTiO_3$- and $KTaO_3$-based two-dimensional electron gases are discussed within a semiclassical Boltzmann approach [6-8]. The OEE is predicted to exceed its spin counterpart by one order of magnitude, which can be understood by a band-resolved analysis of the SEE and OEE. Further, we suggest design rules for Rashba-like systems to enhance spin-charge interconversion efficiencies.

[1] A. G. Aronov, Y. B. Lyanda-Geller, JETP Lett. **50**, 431 (1989) [2] V. M. Edelstein, Solid State Commun. **73**, 233 (1990) [3] T. Yoda *et al.*, Sci. Rep. **5**, 12024 (2015). [4] T. Yoda *et al.*, Nano Lett. **18**, 916 (2018). [5] L. Salemi *et al.*, Nat. Commun. **10**, 5381 (2019) [6] D. Vaz *et al.*, Nat. Materials **18**, 1187 (2019) [7] A. Johansson *et al.*, Phys. Rev. Research **3**, 013275 (2021) [8] S. Varotto *et al.*, Nat. Commun. **13**, 6165 (2022)

MA 4.12 Mon 12:15 HSZ 403

Anisotropic anomalous Hall effect in altermagnetic Mn_5Si_3 — •Miina Leiviskä[1], Rafael Lopes Seeger[1], Helena Reichlová[2,3], Ismaïla Kounta[4], Libor Šmejkal[5,3], Javier Rial[1], Sebastian Beckert[2], Antonín Badura[6,7], Isabelle Joumard[1], Dominik Kriegner[2,3], Eva Schmoranzerová[6], Jairo Sinova[5], Tomáš Jungwirth[3], Sebastian Goennenwein[7], Lisa Michez[4], and Vincent Baltz[1] — [1]Univ. Grenoble Alpes, CNRS, CEA, Grenoble INP, IRIG-SPINTEC, F-38000 Grenoble — [2]Institute of Solid State and Materials Physics, TU Dresden, Dresden, Germany —

[3]Institute of Physics, Czech Academy of Sciences, Prague, Czechia — [4]Aix-Marseille University, CNRS, CINaM, Marseille, France — [5]Institute for Physics, Johannes Gutenberg University Mainz, Mainz, Germany — [6]Department of Chemical Physics and Optics, Faculty of Mathematics and Physics, Charles University, Prague, Czechia — [7]Department of Physics, University of Konstanz, Konstanz, Germany

The altermagnetic epitaxial films of Mn_5Si_3 exhibit anomalous Hall effect (AHE) despite the vanishing net magnetization [1]. This can be explained by non-relativistic time-reversal symmetry breaking, which allows for momentum-locked alternating spin-splitting of the bands [2]. Here, we investigate the anisotropy of the AHE by varying both the external field and the current channel orientations. In both cases, we observe unconventional, anisotropic behaviour that deviates from the typical behaviour of ferromagnets.

[1] H. Reichlova et al. arXiv:2012.15651, (2020)
[2] L. Šmejkal et al. Phys Rev X 12, 031042 (2022)

MA 4.13 Mon 12:30 HSZ 403

Observation of nonreciprocal magnon Hanle effect — •Janine Gückelhorn[1,2], Sebastián de-la-Peña[3], Matthias Grammer[1,2], Monika Scheufele[1,2], Matthias Opel[1], Stephan Geprägs[1], Juan Carlos Cuevas[3], Rudolf Gross[1,2,4], Hans Huebl[1,2,4], Akashdeep Kamra[3], and Matthias Althammer[1,2] — [1]Walther-Meißner-Institut, BAdW, Garching, Germany — [2]Physik-Department, School of Natural Sciences, TUM, Garching, Germany — [3]IFIMAC and Departamento de Física Teórica de la Materia Condensada, Universidad Autónoma de Madrid, Madrid, Spain — [4]Munich Center for Quantum Science and Technology, München, Germany

The realization of the magnon Hanle effect, which is based on the precession of magnon pseudospin about the equilibrium pseudofield, via electrically injected and detected spin transport in an antiferromagnetic insulator demonstrates its high potential for devices and as a convenient probe for the underlying spin interactions in antiferromagnets. Here, we observe a nonreciprocity in the magnon Hanle signal measured in hematite (α-Fe_2O_3) using two spatially separated platinum electrodes as spin injector/detector [1]. Interchanging their roles was found to alter the detected magnon spin signal. The recorded difference depends on the applied magnetic field and reverses sign when the signal passes its nominal maximum at the so-called compensation field. We explain these observations in terms of a spin transport direction-dependent pseudofield. The latter leads to a nonreciprocity, which is found to be controllable via the applied magnetic field.

[1] J. Gückelhorn *et al.*, arXiv:2209.09040 (2022).

MA 4.14 Mon 12:45 HSZ 403

Spontaneous anomalous Hall effect arising from an unconventional compensated magnetic phase in a semiconductor — •Dominik Kriegner[1,2], Ruben Dario Gonzalez Betancourt[1,2,3,4], Jan Zubáč[1,3], Rafael Julian Gonzalez Hernandez[5], Kevin Geishendorf[4], Gunther Springholz[6], Kamil Olejník[1], Jakub Železný[1], Libor Šmejkal[7], Andy Thomas[2,4], Helena Reichlová[1,2], Sebastian Tobias Benedikt Goennenwein[8], and Tomas Jungwirth[1,9] — [1]Institute of Physics, AV ČR, Prague, Czech Republic — [2]IFMP, TU Dresden — [3]Charles University, Prague — [4]IFW Dresden — [5]Universidad del Norte, Barranquilla, Colombia — [6]JKU Linz, Austria — [7]JGU, Mainz — [8]University of Konstanz — [9]University of Nottingham, United Kingdom

The anomalous Hall effect, commonly observed in metallic magnets, has been established to originate from the time-reversal symmetry breaking by an internal macroscopic magnetization in ferromagnets or by a non-collinear magnetic order. Here we observe a spontaneous anomalous Hall signal in the absence of an external magnetic field in an epitaxial film of MnTe, which is a semiconductor with a collinear antiparallel magnetic ordering of Mn moments and a vanishing net magnetization. The anomalous Hall effect arises from an unconventional phase with strong time-reversal symmetry breaking and alternating spin polarization in real-space crystal structure and momentum-space electronic structure.

R. D. Gonzalez Betancourt et al., arXiv:2112.06805