MA 47: Spin Hall Effects and Skyrmions I

Time: Thursday 9:30–13:15 Location: HSZ 04

MA 47.1 Thu 9:30 HSZ 04

Topological orbital ferromagnets — •Jan-Philipp Hanke, Frank Freimuth, Stefan Blügel, and Yuriy Mokrousov — Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany

Spontaneous orbital magnetism in ferromagnets is conventionally explained as a key manifestation of the spin-orbit interaction lifting partially the orbital moment quenching. While such an interpretation applies to most condensed-matter systems, it fails to describe orbital magnetism in crystals exhibiting a finite *topological* orbital magnetization (TOM) without any reference to spin-orbit coupling. In these systems an emergent magnetic field rooting in the noncoplanarity of neighboring spins replaces the spin-orbit interaction as the main mechanism lifting the orbital degeneracy by coupling to the orbital degrees of freedom. The nontrivial topology of this spin texture further gives rise to the topological Hall effect, which is closely related to the TOM both from microscopic and symmetry considerations. Here, we predict from first principles a sizable magnitude of TOM and topological Hall effect (i) in the spin-compensated thin film Mn/Cu(111) and (ii) in the antiferromagnetic bulk material γ-FeMn, both of which reveal noncoplanar spin textures in real space. We demonstrate that these systems are prototypical topological orbital ferromagnets [1,2] for which the macroscopic magnetization is completely dominated by orbital magnetism prominent even in absence of spin-orbit interaction.

[1] J.-P. Hanke *et al.*, Phys. Rev. B **94**, 121114(R) (2016).

[2] J.-P. Hanke *et al.*, Sci. Rep. (submitted, 2016).

MA 47.2 Thu 9:45 HSZ 04

Crossover between mechanisms of skyrmion annihilation in a racetrack — •Pavel Bessarab[1], Igor Lobanov[2], Gideon Müller[3], Filipp Rybakov[4], Nikolai Kiselev[3], Stefan Blügel[3], Lars Bergqvist[5], and Anna Delin[5] — [1]University of Iceland, Reykjavík, Iceland — [2]ITMO University, St. Petersburg, Russia — [3]Forschungszentrum Jülich, Jülich, Germany — [4]Institute of Metal Physics, Ekaterinburg, Russia — [5]KTH Royal Institute of Technology, Kista, Sweden

Theoretical calculations of thermal stability of skyrmions in a PdFe bilayer strip on an Ir(111) substrate are presented. The lifetime of a skyrmion at a given temperature is identified using harmonic transition state theory for spins [1]. The energy barriers are obtained from minimum energy paths (MEPs) for skyrmion annihilation and pre-exponential factors are estimated from the curvature of the energy surface. The MEP calculations [2] revealed two mechanisms of skyrmion annihilation in the strip: escape through the boundary and radial collapse at the interior. At low external fields, the escape mechanism prevails, but a crossover field exists, above which the collapse mechanism becomes dominant, defining the skyrmion stability. This analysis provides a deeper understanding of skyrmion formation and stability and helps develop ways to control magnetic skyrmions in novel devices.

[1] P.F. Bessarab, V.M. Uzdin, H. Jónsson, *Phys. Rev. B*, **85**, 184409 (2012).

[2] P.F. Bessarab, V.M. Uzdin, H. Jónsson, *Comput. Phys. Commun.*, **196**, 335 (2015).

MA 47.3 Thu 10:00 HSZ 04

Magnetic phase transitions in skyrmion host GaV_4Se_8 established by magnetocurrent measurements — Adam Butykai[1,2], •Sandor Bordács[1,2], Miklos Csontos[1], Vladimir Tsurkan[3], and Istvan Kezsmarki[1,2] — [1]Department of Physics, Budapest University of Technology and Economics, Budafoki út 8., Budapest, Hungary — [2]MTA-BME Lendület Magneto-optical Spectroscopy Research Group — [3]Experimental Physics V, Center for Electronic Correlations and Magnetism, University of Augsburg, 86135 Augsburg, Germany

GaV_4Se_8 (GVSe) is a member of the lacunar spinel family, a sister compound to GaV_4S_8 (GVS), wherein the emergence of a Néel-type skyrmion lattice phase has been reported [1]. The supposedly lower magnetic anisotropy in GVSe is expected to stabilize the modulated magnetic structures down to lower temperatures against the uniform ferromagnetic phase.

Similarly to GVS, the Selenide compound is also a magnetoelectric multiferroic (with a Curie-temperature of T_C=19K), therefore the cycloidal spirals and the magnetic skyrmions are expected to carry magnetoelectric polarization, as demonstrated for GVS [2].

Magnetcurrent and pyrocurrent measurements were performed to detect the magnetic phase transitions in GVSe in two principal directions of the external magnetic field. A tentative magnetic phase diagram has been established, indicating an extended cycloidal and skyrmion lattice phase.

[1] Kezsmarki, I. et al. Nature materials 14, (2015) [2] Ruff, E. et al. Science advances 1, (2015)

MA 47.4 Thu 10:15 HSZ 04

Annihilation of magnetic skyrmions by quantum tunneling — •Sergei Vlasov[1,2], Pavel F. Bessarab[1,2], Igor S. Lobanov[2], Maria Potkina[3], Valery M. Uzdin[2,3], and Hannes Jónsson[1] — [1]University of Iceland, Reykjavík, Iceland — [2]University ITMO, St. Petersburg, Russia — [3]St. Petersburg State University, St. Petersburg, Russia

Magnetic skyrmions are localized, noncollinear spin configurations which are topological solitons. In discrete systems, a skyrmion state is separated from the ferromagnetic state by a finite energy barrier and transitions between these states can occur by jumps over the barrier or by quantum mechanical tunnelling. The rate of such transitions is an important consideration when the stability of skyrmions is assessed for data storage devices.

As the temperature is lowered, quantum tunneling becomes the dominant transition mechanism. The shift from thermally activated jumps to tunnelling is analysed and a general expression derived for the crossover temperature in terms of the second derivatives of the energy with respect to the orientations of the spin vectors at the saddle point. The expression is an extension of the theory for single spin onset temperature [S. Vlasov et al., Faraday Discussions DOI: 10.1039/c6fd00136j]. Skyrmion onset temperature is evaluated for an extened Heisenberg Hamiltonian representing a Co monolayer on Pt(111) for which the thermal jump rate has recently been calculated using a harmonic approximation to transition state theory [I.S. Lobanov et al., Phys. Rev. B 94, 174418 (2016)] and found to be 3 K.

MA 47.5 Thu 10:30 HSZ 04

Relaxation dynamics between the modulated magnetic phases of GaV_4S_8 investigated by ac-susceptibility measurements — •Bertalan György Szigeti[1], Ádám Butykai[1], Sándor Bordács[1,2], László Ferenc Kiss[3], and István Kézsmárki[1,2] — [1]Department of Physics, Budapest University of Technology and Economics, Budafoki út 8., Budapest, Hungary — [2]MTA-BME Lendület Magneto-optical Spectroscopy Research Group — [3]Wigner Research Centre for Physics, Budapest, Hungary

GaV_4S_8 is a multiferroic semiconductor, known to be the first bulk material with a non-chiral crystal structure to host (Néel-type) magnetic skyrmions [1]. Below its Curie-temperature, T_C=13 K, the compound features cycloidal spin spirals, a skyrmion lattice phase and a uniform ferromagnetic phase in increasing magnetic fields. The field-induced phase transitions involve the rearrangement of large magnetic structures, therefore the magnetic relaxation occurs on enhanced, often macroscopically large timescales. Here, a systematic study of the frequency-dependent ac-susceptibility of the material is presented, also discussing the temperature dependence of the relaxation time at the phase boundaries.

[1] I. Kézsmárki et al., Nat. Mater.14, 1116 (2015)

MA 47.6 Thu 10:45 HSZ 04

Topological Spin Hall Effect in Antiferromagnetic Skyrmions — •Patrick M. Buhl, Frank Freimuth, Stefan Blügel, and Yuriy Mokrousov — Peter Grünberg Institut and Institute of Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany

We report on our recent methodological developments designed to describe the transport properties of large-scale chiral magnetic structures on the basis of a Boltzmann-like semiclassical formalism. Density-functional theory is used to supply an accurate initial collinear description of our antiferromagnetic example systems such as Fe/Cu/Fe trilayer. On top, skyrmionic long-range chiral magnetic texture is artificially imposed on the level of degenerate, and thus non-abelian, equations of motion, in which the topological non-triviality manifests as the emergent magnetic field. Within this framework, we iteratively find the wave-packet semiclassical trajectories for the states at the Fermi surface in order to estimate the conductivity tensor. Thereby we gain an important insight into the macroscopic transport properties of two-dimensional chiral magnetic structures and can quantify their sizeable topological spin Hall effect. This work is supported by SFB1238.

15 min. break.

MA 47.7 Thu 11:15 HSZ 04

Absence of detectable current-induced magneto-optical Kerr effects in Pt, Ta and W — •Patricia Riego[1], Saül Vélez[1], Juan M. Gomez-Perez[1], Jon Ander Arregi[1], Luis E. Hueso[1,2], Fèlix Casanova[1,2], and Andreas Berger[1] — [1]CIC nanoGUNE, San Sebastian (Spain) — [2]Ikerbasque, Bilbao (Spain)

The direct detection of spin accumulation arising from the spin Hall effect (SHE) in metals via the magneto-optical Kerr effect (MOKE) would enable an easily accessible methodology for spintronics phenomena. Prior works have performed such measurements and have reported a successful outcome [1]. Here, we explore such possibility by means of generalized magneto-optical ellipsometry (GME), a MOKE-based method that, in contrast to conventional MOKE measurement schemes, allows for a clear identification of the magneto-optical (MO) nature of the signal. We have performed measurements for three different materials: Pt, W, and Ta, and we observe a current-induced change in the light intensity in all of them. However, our complete GME analysis shows that such current-induced effects are not MO in nature, and therefore do not arise from a SHE-induced light polarization signal in any of the materials. Instead, they constitute a purely optical signal that arises from a heating-induced change in reflectivity. Based on the sensitivity achieved in our experiments, we conclude that state-of-the-art MO methods utilizing linear optics are not sufficiently sensitive to detect SHE-induced spin accumulation in these metals [2].

[1] O. M. J. van't Erve et al., Appl. Phys. Lett. 104, 172402 (2014).
[2] P. Riego et al., Appl. Phys. Lett. 109, 172402 (2016).

MA 47.8 Thu 11:30 HSZ 04

Current induced manipulation of the staggered magnetization of an antiferromagnet — •Stanislav Bodnar, Martin Jourdan, Hans-Joachim Elmers, and Mathias Kläui — Institute of Physics, Johannes Gutenberg University Mainz, 55099 Mainz, Germany

Novel concepts for ultrafast spintronics rely on antiferromagnets (AFMs), e.g. by employing the direction of their staggered magnetization for data storage. Thus, new approaches for the manipulation of the AFM spin-orientation beyond magnetic fields need to be established. Considering the tetragonal AFM compound Mn2Au, current densities of 108-109 A/cm2 were estimated to reorient the spin-axis via spin-orbit torques [Zel14]. We prepared epitaxial thin films of Mn2Au [Jou15] and investigated the possibility to reorient the antiferromagnetic domains by the application of short current pulses. Our measurements of the planar Hall effect and longitudinal resistance of these sample show clear dependencies on the direction of previously applied current pulses, thus provided strong evidence for current induced manipulation of the Néel vector.

[Zel14]*J. Železný, H. Gao, K. Výborný, J. Zemen, J. Mašek, A. Manchon, J. Wunderlich, J. Sinova, T. Jungwirth, Phys. Rev. Lett. 113, 157201 (2014). [Jou15] M. Jourdan, H. Bräuning, A. Sapozhnik, H.-J. Elmers, H. Zabel and M. Kläui, J. Phys. D: Appl. Phys. 48, 385001 (2015).

MA 47.9 Thu 11:45 HSZ 04

Temperature dependence of the spin Hall angle and switching current in the nc-W(O)/CoFeB/MgO system with perpendicular magnetic anisotropy — Lukas Neumann, Daniel Meier, Jan Schmalhorst, Karsten Rott, Günter Reiss, and •Markus Meinert — Center for Spinelectronic Materials and Devices, Bielefeld University, Bielefeld, Germany

We investigated the temperature dependence of the switching current for a perpendicularly magnetized CoFeB film deposited on a nanocrystalline tungsten film with large oxygen content: nc-W(O). The effective spin Hall angle $|\Theta_{\mathrm{SH}}^{\mathrm{eff}}| \approx 0.22$ is independent of temperature, whereas the switching current increases strongly at low temperature. The increase can not be explained by the increased coercive field, but rather indicates that the current induced switching itself is thermally activated, in agreement with a recent theoretical prediction. The dependence of the switching current on the in-plane assist field suggests the presence of an interfacial Dzyaloshinskii-Moriya interaction with $D \approx 0.23\,\mathrm{mJ/m^2}$, intermediate between the Pt / CoFe and Ta / CoFe systems. We show that the nc-W(O) is insensitive to annealing, which makes this system a good choice for the integration into magnetic memory or logic devices that require a high-temperature annealing process during fabrication.

MA 47.10 Thu 12:00 HSZ 04

Novel spin currents in non-collinear antiferromagnets — •Jakub Zelezny[1], Yang Zhang[1,2], Claudia Felser[1], and Binghai Yan[1,3] — [1]Max Planck Institute for Chemical Physics of Solids, Dresden, Germany — [2]Leibniz Institute for Solid State and Materials Research, Dresden, Germany — [3]Max Planck Institute for the Physics of Complex Systems, Dresden, Germany

Many key spintronics phenomana are caused by spin currents. Here we study spin currents in non-collinear antiferromagnets Mn3Sn and Mn3Ir. It was recently demonstrated that a large spin Hall effect exists in these materials. We show by symmetry analysis and microscopic ab-initio calculations that in these antiferromagnets, also a different type of spin currents occur, which have an origin and symmetry distinct from the spin Hall effect. These spin currents are similar to spin-polarized currents in ferromagnets, however, unlike in ferromagnets, they also contain a transversal contribution (i.e., a spin current flowing in the direction transversal to the charge current). Our calculations reveal that both the spin-polarized currents and the transversal spin currents are large in the studied materials. These spin currents could have important applications since the effects that originate from the spin-polarized current in ferromagnets, like the tunneling magnetoresistance or the spin-transfer torque, will also be present in the non-collinear antiferromagnets. Furthermore, the transversal spin currents will contribute to the spin-orbit torque generated by the spin Hall effect.

MA 47.11 Thu 12:15 HSZ 04

Optimizing the spin Hall angle above 100% — •Christian Herschbach[1], Dmitry Fedorov[2,1], Martin Gradhand[3], and Ingrid Mertig[1,2] — [1]Martin Luther University Halle-Wittenberg, Halle, Germany — [2]Max Planck Institute of Microstructure Physics, Halle, Germany — [3]University of Bristol, Bristol, United Kingdom

The spin Hall effect (SHE) is one of the key effects in modern spintronics creating pure spin currents directly in nonmagnetic materials. The effect's strength is usually quantified with the so-called spin Hall angle (SHA), which is the ratio of the transverse spin conductivity to the longitudinal charge conductivity. Reported values based on both experimental and theoretical investigations increased during the last years. Measurements on Pt-doped Au samples yielded a SHA of about 10% introduced as giant SHE [1] while a SHA of 24% was published for thin-film Cu(Bi) alloys [2]. The large effect caused by Bi impurities in Cu was theoretically predicted for bulk samples [4]. Further theoretical investigations on Bi-doped ultrathin noble-metal films forecast *colossal* SHAs slightly below 100% [5].

In this work we further investigate the possibility to optimize the SHE. We identify systems with a strong anisotropy of the in-plane transport properties that lead to SHAs above 100%.

[1] Seki *et al.*, Nat. Mater. **7**, 125 (2008)
[2] Niimi *et al.*, Phys. Rev. Lett. **109**, 156602 (2012)
[3] Pai *et al.*, Appl. Phys. Lett. **101**, 122404 (2012)
[4] Gradhand *et al.*, Phys. Rev. Lett. **104**, 186403 (2010)
[5] Herschbach *et al.*, Phys. Rev. B **90**, 180406(R) (2014)

MA 47.12 Thu 12:30 HSZ 04

Tuning spin Hall angles by alloying — •S. Wimmer[1], K. Chadova[1], D. Ködderitzsch[1], M. Obstbaum[2], M. Decker[2], A. K. Greitner[2], M. Härtinger[2], T. N. G. Meier[2], M. Kronseder[2], C. H. Back[2], and H. Ebert[1] — [1]Department Chemie, Ludwig-Maximilians-Universität München — [2]Institut für Experimentelle und Angewandte Physik, Universität Regensburg

Within a combined experimental and theoretical study it could be shown that the spin Hall angle of a substitutional alloy system can be continuously varied via its composition [1]. For Au_xPt_{1-x} a substantial increase of the maximum spin Hall angle compared to the pure alloy partners could be achieved. The experimental findings for longitudinal charge conductivity σ_{xx}, transverse spin Hall conductivity σ_{xy}^{z}, and spin Hall angle α_{SH} could be confirmed by calculations based on the Kubo-Bastin formula [2] implemented in a KKR-CPA framework. Calculations of these response quantities for different temperatures using the so-called Alloy-Analogy Model [3] show that the divergent behavior of σ_{xx} and σ_{xy}^z is rapidly suppressed with increasing temperature T. As a consequence, σ_{xy}^z is dominated at higher T by its intrinsic contribution that has only a rather weak temperature dependence. Detailed analysis of the scaling behavior of $\sigma_{xy}^z(x,T)$ w.r.t. $\sigma_{xx}(x,T)$ moreover reveals that the extrinsic contribution changes sign as a function of T in the dilute limit $x \to 0$.

[1] M. Obstbaum *et al.*, *Phys. Rev. Lett.* **117**, 167204 (2016). [2] A. Bastin *et al.*, *J. Phys. Chem. Solids* **32**, 1811 (1971). [3] H. Ebert *et al.*, *Phys. Rev. B* **91**, 165132 (2015).

MA 47.13 Thu 12:45 HSZ 04

Skyrmions with attractive interactions in an ultrathin magnetic film — •Levente Rózsa[1], András Deák[2], Eszter Simon[2], Rocio Yanes[3], László Udvardi[2], László Szunyogh[2], and Ulrich Nowak[3] — [1]Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary — [2]Budapest University of Technology and Economics, Budapest, Hungary — [3]Universität Konstanz, Konstanz, Germany

Magnetic skyrmions in ultrathin films, corresponding to localized noncollinear spin structures, hold promising aspects in future data storage and spintronics applications[1]. Besides chiral skyrmions stabilized by the Dzyaloshinsky–Moriya interaction, the frustration of the isotropic exchange interactions may also lead to the formation of skyrmions[2]. We performed *ab initio* electronic structure calculations to determine the parameters in a classical spin Hamiltonian describing an Fe monolayer on Pd(111) surface with a $Pt_{1-x}Ir_x$ alloy overlayer. We demonstrate that increasing the Ir concentration x transforms the ground state from ferromagnetic into a spin spiral state, primarily due to the increased frustration of the isotropic exchange interactions. Using spin dynamics simulations, we show that the isolated skyrmions observed in the collinear phase form clusters due to the short-range attractive interaction between them, and that these clusters remain stable against thermal fluctuations[3].

[1] A. Fert *et al.*, Nat. Nanotech. **8**, 152 (2013).
[2] A. O. Leonov *et al.*, Nat. Commun. **6**, 8275 (2015).
[3] L. Rózsa *et al.*, Phys. Rev. Lett. **117**, 157205 (2016).

MA 47.14 Thu 13:00 HSZ 04

Spin-torque and fluctuation-dissipation at FM-AFM tunnelling junctions — •Kei Yamamoto[1,2], Georg Schwiete[3,1], Olena Gomonay[1,4], and Jairo Sinova[1,5] — [1]Institut für Physik, Johannes Gutenberg Universität, 55128 Mainz, Germany — [2]Institute for Material Research, Tohoku University, Sendai 980-8577, Japan — [3]Department of Physics and Astronomy and Center for Materials for Information Technology, The University of Alabama, Tuscaloosa, AL 35487 — [4]National Technical University of Ukraine "KPI", 03056, Kyiv, Ukraine — [5]Institute of Physics, Academy of Sciences of the Czech Republic, Cukrovarnicka 10, 162 00 Praha 6, Czech Republic

Antiferromagnetic materials (AFM) are emerging as a promising candidate to be a fundamental building block of next generation spintronic devices. One of the highlights from recent experimental findings is their peculiar spin transport characteristics. In ferromagnetic-antiferromagnetic heterostructures, spin pumping measurements revealed a strong temperature dependence of AFM spin conductivity, while their spin-Hall magnetoresistance indicates that AFM can be as good a sink of spin as ferromagnetic materials (FM).

In this talk, I present a microscopic description of non-equilibrium spin transport through FM-AFM tunneling junctions. Employing path integral formulation of quantum statistical mechanics, one can derive formulas for spin torque, spin pumping and the power spectrum of spin current fluctuations at the junction in a single unified framework. As an application, the AFM magnetic moment fluctuation induced by a steady voltage/temperature bias is computed.