MA 8: Ultrafast Magnetization Effects I

Time: Monday 15:00–18:00 Location: HSZ 04

Invited Talk MA 8.1 Mon 15:00 HSZ 04

Optical control of antiferromagnetism — •Christian Tzschaschel — Department of Chemistry and Chemical Biology, Harvard University, USA

Antiferromagnets are a promising class of materials for novel spintronic applications. The absence of a net magnetization not only leads to a robustness of the magnetic state against magnetic fields but may also enable faster and potentially more energy efficient switching dynamics compared to their ferromagnetic counterparts. However, probing and controlling an antiferromagnetic state, in particular on ultrafast timescales, is a major challenge of antiferromagnetic spintronics.

Here, we will exploit magneto-optical and inverse magneto-optical effects to control antiferromagnetism. For example, the inverse Faraday effect, whereby circularly polarized light acts as a magnetic field in a material, allows us to selectively excite specific magnon modes in fully compensated antiferromagnets. The excitation mechanism can be based on a rotation of the antiferromagnetic vector or the generation of a net magnetization in the material. We will show that excitation mechanisms that induce a net magnetization exhibit a significantly higher efficiency. Moreover, we uncover a new inverse magneto-optical effect that allows us to deterministically induce an antiferromagnetic state in a magneto-electric antiferromagnet.

Our results demonstrate a high degree of optical control of antiferromagnetism, where we use light as both a probe and a handle to act on an antiferromagnetic state. We thus move closer to achieving a fundamental requirement for future ultrafast opto-spintronic devices.

MA 8.2 Mon 15:30 HSZ 04

Accelerating write/erase cycles in all-optical magnetization switching — •Felix Steinbach[1], Nele Stetzuhn[1], Daniel Schick[1], Dieter Engel[1], Unai Atxitia[2], Clemens von Korff Schmising[1], and Stefan Eisebitt[1,3] — [1]Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy — [2]Dahlem Center for Complex Quantum Systems and Fachbereich Physik — [3]Institut für Optik und Atomare Physik, Technische Universität Berlin

All-optical switching of magnetic order presents a promising route toward faster and more energy efficient data storage. However, a realization in future devices is ultimately dependent on the maximum repetition rates of optically induced write/erase cycles. Here, we present two strategies to minimize the temporal separation of two consecutive femtosecond laser pulses to toggle the out-of-plane direction of the magnetization of ferrimagnetic rare-earth transition metal alloys. First, by systematically changing the heat transfer rates using either amorphous glass, crystalline silicon, or polycrystalline diamond substrates, we show that efficient cooling rates of the magnetic system present a prerequisite to accelerate the sequence of double pulse toggle switching. Second, we demonstrate that replacing the transition metal iron by cobalt leads to a significantly faster recovery of the magnetization after optical excitation allowing us to approach terahertz frequency of write/erase cycles with a minimum pulse-to-pulse separation of 7 ps [1].

[1] F. Steinbach et al., Appl. Phys. Lett. 120, 112406 (2022)

MA 8.3 Mon 15:45 HSZ 04

Variation of magnetic model parameters during ultrafast demagnetisation — •S. Polesya, S. Mankovsky, and H. Ebert — Department Chemie, Ludwig Maximilian University, Munich, Germany

Recent developments in time-dependent density functional theory (TD-DFT) paved the way towards investigating the ultrafast demagnetisation caused by a strong laser pulse on an *ab initio* level. However, the relaxation processes after a pump pulse still require to use phenomenological models that allow to account for different types of relaxation mechanisms on the basis of model parameters, that can be calculated from first principles. A stumbling block for such schemes is that the electronic structure is strongly out of equilibrium after the laser pulse and changes with time due to the relaxation. In the present work, we explore whether the parameters which determine the magnetization dynamics in this time regime can indeed be described on a first-principles level. This concerns first of all the exchange coupling, magnetic anisotropy and the Gilbert damping parameters that have been calculated for several transition metals using the spin-polarized relativistic Korringa-Kohn-Rostoker method. To account for the time evolution of the system, the calculations have been performed employing the TD-DFT potentials and occupation numbers generated by the Elk code [http://elk.sourceforge.net] for different time steps during the laser pulse and shortly after it, i.e. in the non-relaxed situation. In all cases a strong modification of the parameters compared to the equilibrium situation is found.

MA 8.4 Mon 16:00 HSZ 04

Temperature- and density-dependent spin-resolved coupling parameters in the μT-model — •Christopher Seibel, Sebastian T. Weber, Tobias Held, Sanjay Ashok, Hans Christian Schneider, and Baerbel Rethfeld — Department of Physics and Research Center OPTIMAS, RPTU Kaiserslautern-Landau

Since the first ultrafast demagnetization experiment by Beaurepaire *et al.* in 1996, many models have been developed. They reach from complex kinetic descriptions to simpler temperature-based models. The former consider the microscopic interactions between the individual (quasi-)particles involved and allow to extract coupling parameters of the individual interactions. These parameters can enter temperature-based models and depend on the nonequilibrium distribution, (quasi-)temperature, densities and the spin-dependent density of states [1,2,3]. However, these coupling parameters are often assumed to be constant in temperature-based models.

In this work, we investigate the influence of transient coupling parameters, like the electron-phonon coupling parameter, on the magnetization dynamics. The spin-resolved coupling parameter is calculated using complete Boltzmann collision integrals and depends on the transient temperatures and densities of the individual subsystems.

[1] Lin *et al.*, Phys. Rev. B **77**, 075133
[2] Mueller and Rethfeld, Phys. Rev. B. **87**, 035139
[3] Zahn *et al.*, Phys. Rev. Research **3**, 023032

MA 8.5 Mon 16:15 HSZ 04

Investigating the interplay of local electron correlations and ultrafast spin dynamics in fcc Ni at the European XFEL — •Tobias Lojewski — University of Duisburg-Essen

The interplay between exchange interaction, electron hopping and local Coulomb repulsion is of great interest as it influences the magnetic order in the 3d transition metals. We report the investigation of the electronic structure in fcc Nickel on the time scale of these interactions by combining the femtosecond time-resolved spectroscopic analysis of Nickel X-ray absorption spectra, measured at the SCS instrument of the European XFEL, with *ab initio* TD-DFT. We find a transient broadening and redshift of the $L_{2,3}$-edge absorption spectra, which we relate to electron repopulation and correlation-induced electronic structure modifications, demonstrating a time-dependent interaction between band formation, exchange interaction and Coulomb repulsion.

[1] T. Lojewski, M. F. Elhanoty, L. Le Guyader, O. Grånäs, N. Agarwal, C. Boeglin, R. Carley, A. Castoldi, C. David, C. Deiter, F. Döring, R. Y. Engel, F. Erdinger, H. Fangohr, C. Fiorini, P. Fischer, N. Gerasimova, R. Gort, F. de Groot, K. Hansen, S. Hauf, D. Hickin, M. Izquierdo, B. E. Van Kuiken, Y. Kvashnin, C. H. Lambert, D. Lomidze, S. Maffessanti, L. Mercadier, G. Mercurio, P. S. Miedema, K. Ollefs, M. Pace, M. Porro, J. Rezvani, B. Rösner, N. Rothenbach, A. Samartsev, A. Scherz, J. Schlappa, C. Stamm, M. Teichmann, P. Thunstrom, M. Turcato, A. Yaroslavtsev, J. Zhu, M. Beye, H. Wende, U. Bovensiepen, O. Eriksson and A. Eschenlohr, arXiv:2210.13162.

MA 8.6 Mon 16:30 HSZ 04

Laser-induced spin polarization on ultrafast time scales — •Oliver Busch, Franziska Ziolkowski, Ingrid Mertig, and Jürgen Henk — Institut für Physik, Martin-Luther-Universität, D-06099 Halle

In ultrafast spin dynamics one focuses often on demagnetization. However, the incident laser pulse should produce spin-polarized excited electrons – an effect ubiquitous in spin- and angle-resolved photoemission [1]. This laser-induced spin polarization certainly affects the ultrafast dynamics.

We study systematically the laser-induced spin polarization and its effect on the electron dynamics in Co/Cu heterostructures, modeled within our theoretical framework EVOLVE [2]. The spin polarization depends strongly on polarization and angle of incidence of the femtosecond laser pulse, similar to photoemission [3]. Moreover, we find a significant spatial dependence, which underlines the importance of inhomogeneities in ultrafast spin dynamics.

[1] W. Schattke and M. A. Van Hove (eds.), *Solid-State Photoemission and Related Methods: Theory and Experiment* (Wiley-VCH, Weinheim, 2003)

[2] F. Töpler *et al.*, New J. Phys. **23** 033042 (2021)

[3] J. Henk *et al.*, J. Phys.: Condens. Matter **8** 47 (1996)

MA 8.7 Mon 16:45 HSZ 04

Finite-size effects in [Fe/MgO]n heterostructures on ultrafast timescales — •MOUMITA KUNDU[1], NICO ROTHENBACH[2], TOBIAS LOJEWSKI[2], ANDREA ESCHENLOHR[2], MARKUS GRUNER[2], KATHARINA OLLEFS[2], CAROLIN SCHMITZ-ANTONIAK[3], KLAUS SOKOLOWSKI-TINTEN[2], WILLIAM WINDSOR[4], LAURENZ RETTIG[4], ROSSITZA PENTCHEVA[2], HEIKO WENDE[2], ULRICH NOWAK[1], and UWE BOVENSIEPEN[2] — [1]University of Konstanz, Konstanz, Germany — [2]University of Duisburg-Essen, Duisburg, Germany — [3]TH Wildau, Wildau, Germany — [4]FHI Berlin, Berlin, Germany

The analysis of magnetization dynamics on ultrafast timescales provides insight into microscopic interactions of magnetic moments with the charge and lattice degrees of freedom in solids. Here we analyze the finite size effect of ferromagnets on ultrafast timescales for $[Fe/MgO]_n$ heterostructures. Using femtosecond time-resolved XMCD, measured at the Femtoslicing facility, BESSY II, we observe an increasing laser-induced demagnetization at time delays > 0.5ps as the Fe layers get thinner, and it can be clearly distinguished from the primary ultrafast demagnetization occurring at < 0.5ps. Atomistic spin simulations are used to investigate the thickness dependence of the ultrafast magnetization dynamics in iron thin films, modeled using an extended Heisenberg-type Hamiltonian in the stochastic Landau-Lifshitz-Gilbert equation, coupled with the 2-temperature model. Comparing with our measurements, we conclude that finite size effects are the dominating factor for the different demagnetization rates due to a reduced spin-spin coordination at the interfaces.

MA 8.8 Mon 17:00 HSZ 04

A real-space tight-binding approach to ultrafast spin dynamics in inhomogeneous systems — •FRANZISKA ZIOLKOWSKI, OLIVER BUSCH, INGRID MERTIG, and JÜRGEN HENK — Martin Luther University Halle-Wittenberg, Halle, Germany

In laser-induced ultrafast spin dynamics a spin current is generated at a magnetic-nonmagnetic interface, whose orgin and properties are still under debate. To better understand the microscopic processes and the role of the interface we are developing the theoretical framework *evolve* [1].

In a real-space tight-binding model the electron system is optically excited by a femtosecond laser pulse and coupled to a bosonic bath. The time evolution of the density operator yields occupation numbers, demagnetization profiles as well as spin- and orbital-resolved occupation flows.

Our simulations confirm the importance of interfaces for ultrafast transport phenomena and demagnetization processes. We identify a reflow from Cu d orbitals across the interface into Co d orbitals as an important contribution to demagnetization. This refilling manifests itself as a minority-spin current proceeding several layers into the Cu region.

Moreover, we investigate the influence of pulse parameters such as polarization and photon energy.

[1] Töpler *et al* 2021 *New J. Phys.* **23** 033042

MA 8.9 Mon 17:15 HSZ 04

MEASURING THE SPIN-FLIP SCATTERING RATES IN THE DEMAGNETIZATION TRANSIENT STATE OF FERROMAGNETS — •RÉGIS DECKER[1], ARTUR BORN[1,2], KARI RUOTSALAINEN[1], KARL BAUER[1], ROBBY BÜCHNER[1,2], ROBERT HAVERKAMP[1,2], ANNETTE PIETZSCH[1], and ALEXANDER FÖHLISCH[1,2] — [1]Institute Methods and Instrumentation for Synchrotron Radiation Research PS-ISRR, Helmholtz-Zentrum Berlin für Materialien und Energie Albert-Einstein-Strasse 15, 12489, Berlin, Germany. — [2]Institut für Physik und Astronomie, Universität Potsdam, Karl-Liebknecht-Strasse 24-25, 14476, Potsdam, Germany

In crystalline ferromagnets, one of the main microscopic mechanisms of spin relaxation is the electron-phonon driven (Elliott-Yafet) spin-flip scattering. To deduce the spin-flip scattering rate, we exploit the stringent atomic symmetry selection rules of X-ray Emission Spectroscopy (XES) and observe the quantifiable change in the decay peak intensities in static XES spectra when changing the temperature, *i.e.* the phonon population. We deduce the temperature-dependent spin-flip scattering rate for Ni [1]. In FeNi alloys, we evidence a thresholding the Elliott-Yafet mechanism linked to the intra- and intersublattice exchange energies [2]. In Gd, we show an Elliott-Yafet mechanism for the itinerant 5d electrons and its absence for the localized 4f electrons [3].

[1] R. Decker *et al.*, Sci. Rep. **9**, 8977 (2019). [2] A. Born *et al.*, Sci. Rep. **11**, 1883 (2021). [3] R. Decker *et al.*, Appl. Phys. Lett. **119**, 152403 (2021).

MA 8.10 Mon 17:30 HSZ 04

Electron-magnon interactions and Elliot-Yafet Spin Flips in a Two Band Stoner Model — •FELIX DUSABIRANE, KAI LECKRON, BÄRBEL RETHFELD, and HANS CHRISTIAN SCHNEIDER — Physics Department & Research Center OPTIMAS, RPTU Kaiserslautern, Germany

We study electronic scattering dynamics in ferromagnets due to electron-magnon and electron-electron scattering. We also include an electron-electron spin-flip process, i.e., an electronic Elliott-Yafet mechanism and study the dynamics due to the interplay of the different scattering processes on the magnetization on ultrafast timescales. For the ferromagnetic band structure, we employ a model system consisting of two Stoner-exchange split bands and electron-magnon interaction, as can be obtained using a Heisenberg model where magnons (and electrons) are treated as bosons (and fermions). Electron-electron and electron-magnon scattering dynamics are studied with Boltzmann scattering integrals. We show that the spin-flip electron-electron scattering together with electron-magnon scattering generates non-equilibrium magnons, leading to a pronounced magnetization change that is mostly due to magnon generation and only to a very limited extent to a change in the spin polarization of the electrons. The effect of electron spin-flips and time dependent spin splitting will also be discussed.

MA 8.11 Mon 17:45 HSZ 04

Nonequilibrium Magnons from Hot Electrons in Antiferromagnetic Systems — MARION BARBEAU[1], MIKHAIL TITOV[2], MIKHAIL KATSNELSON[2], and •ALIREZA QAIUMZADEH[1] — [1]Center for Quantum Spintronics, Department of Physics, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway — [2]Radboud University, Institute for Molecules and Materials, 6525 AJ Nijmegen, The Netherlands

We describe a *nonthermal* magnon activation mechanism in antiferromagnetic (AFM) systems via locally equilibrated *spin-unpolarized* hot electrons excited by an ultrafast intense laser pulse. We employ a quantum kinetic equation that takes into account a direct electron-magnon scattering channel in either bulk AFM metal or at the interface of the AFM/normal-metal heterostructure. The mechanism is responsible for the nonequilibrium population of AFM magnon modes on a subnanosecond timescale, which are formed shortly after the local thermalization of hot electrons by Coulomb interactions. Nonequilibrium magnon populations can be additionally manipulated by applying an external magnetic field. Our work paves the way toward spin dynamics control in AFM systems via the ultrafast manipulation of out-of-equilibrium magnon excitations [1].

[1] M. M. S. Barbeau, M. Titov, M. I. Katsnelson, A. Qaiumzadeh, arXiv:2209.03469v1