SPICE Workshop

May 9th - 10th 2022, Mainz, Germany

ULTRAFAST ANTIFERRO-MAGNETIC WRITING

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ULTRAFAST ANTIFERROMAGNETIC WRITING

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* Due to a general ban on Russian institutions, Dr. Kalashnikova is no longer an active member of the of the oranizer committee as of Feb. 24 2022. This institutional ban is not reflective on individuals.

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Program

Morning Session – Monday, May 9th

08:50 – 09:05	**Registration**
09:05 – 09:15	**Opening Remarks**
09:15 – 09:25	**Aleksei KIMEL, Radboud University** Intro: Pathways to ultrafast switching of antiferromagnets
09:25 – 09:50	**Olena GOMONAY, University of Mainz** Ultrafast dynamics of antiferromagnets: switching vs rotation
09:50 – 10:15	**Kamil OLEJNIK, Czech Academy of Sciences** Quench-switching of antiferromagnetic CuMnAs using ultrashort pulses
10:15 – 10:30	**Coffee Break**
10:30 – 10:40	**Yuriy MOKROUSOV, University of Mainz** Intro: Optically-driven spin excitations in antiferromagnets
10:40 – 11:05	**Christian TZSCHASCHEL, Harvard** Efficient spin excitation via ultrafast damping torques in antiferromagnets
11:05 – 11:30	**Daria GORELOVA, University of Hamburg** Theoretical description of magnetic precessions during ultrafast laser excitation
11:30 – 11:55	**Johan MENTINK, Radboud University** Challenging energy-speed limits in antiferromagnets
12:00 – 13:30	**Lunch & Poster Session**

Afternoon Session – Monday, May 9th

13:30 – 13:40 **Tomáš JUNGWIRTH, Institute of Physics ASCR**
Intro: Switching of antiferromagnetic metals

13:40 – 14:05 **Yoav William WINDSOR, TU Berlin**
Exchange scaling of ultrafast angular momentum transfer in 4f antiferromagnets

14:05 – 14:30 **Sangeeta SHARMA, Max Born Institute**
Ultrafast spin, charge and nuclear dynamics: ab-initio description

14:30 – 15:00 **Coffee Break**

15:00 – 15:25 **Joerg WUNDERLICH, University of Regensburg**
Spin-orbit torque switching between reversed antiferromagnetic state and its electrical detection

15:25 – 15:50 **Peter OPPENEER, Uppsala University**
Ab initio theory for coherent magnetic switching

15:50 – 18:15 **Poster Session**

18:30 **Dinner at Restaurant WASEM**
Edelgasse 15, 55218 Ingelheim am Rhein

Morning Session – Tuesday, May 10th

09:00 – 09:10	**Andrei KIRILYUK, Radboud University** Intro: Switching of antiferromagnetic insulators
09:10 – 09:35	**Ulrich NOWAK, University of Konstanz** Spin dynamics in antiferromagnets: from THz to ultrafast switching
09:35 – 10:00	**Rostislav MIKHAYLOVSKIY, Lancaster University** Terahertz magnons and magnon-polaritons in antiferromagnets
10:00 – 10:30	**Coffee Break**
10:30 – 10:40	**Thomas METZGER, Radboud University** Intro: Phoninic control of antiferromagnets
10:40 – 11:05	**Davide BOSSINI, University of Konstanz** Ultrafast Amplification and Nonlinear Magnetoelastic Coupling of Coherent Magnon Modes in an Antiferromagnet
11:05 – 11:30	**Andrei KIRILYUK, Radboud University** Nonlinear phononics as a universal mechanism for ultrafast switching of spins
11:30 – 11:55	**Ankit DISA, MPSD** Engineering magnetic states with light through nonlinear lattice excitation
12:00 – 13:30	**Lunch & Poster Session**

Afternoon Session – Tuesday, May 10th

13:30 – 13:40 **Davide BOSSINI, University of Konstanz**
Intro: THz excitations in heterostructures and complex spin textures

13:40 – 14:05 **Yannic BEHOVITS, FU Berlin**
Nonlinear magnon dynamics in antiferromagnetic Mn2Au driven by Terahertz Neel spin-orbit torque

14:05 – 14:30 **Dmytro AFANASIEV, Radboud University**
Coherent spin-wave transport in an antiferromagnet

14:30 – 15:00 **Coffee Break**

15:00 – 15:25 **Oksana CHUBYKALO-FESENKO, CSIC**
Modeling of THz phonon-assisted spin dynamics and switching

15:25 – 15:50 **Reinoud LAVRIJSEN, Eindhoven University of Technology**
Using Spin Waves to Probe Ultrafast Spin Current Generation in Rare Earth Ferromagnets

15:50 – 16:00 **Closing Remarks**

Speaker Abstracts

Monday, May 9th, 09:25

Ultrafast dynamics of antiferromagnets: switching vs rotation

Olena GOMONAY
University of Mainz

Antiferromagnets show ultrafast magnetic dynamics that can be effectively induced by optical or current pulses. Among plethora of materials the insulating antiferromagnets are of special interest due to low magnetic damping and reduced energy losses. However, optically generated spin torques induce precession of the Néel vector rather than switching into desirable final state.
Here we discuss different scenario of ultrafast switching in noncollinear [1] and collinear [2] antiferromagnets focusing on tailoring of the pulse shapes and combination of different torques. We show that in antiferromagnets the femtosecond optical pulses generate simultaneously two types of spin torques: one scaling with spin current and one scaling with time derivative. Competition between these two opens a way to combine fast rotation of the Néel vector with the effective dynamical damping that enables effective switching into the desired final state. We further discuss the role of magnetoelastic interactions in switching which are relevant for antiferromagnets with strong magnetoelastic coupling like NiO and CoO [3]. We show that optical pulses can induce oscillations of the domain walls pinned by spontaneous strains. Strong enough pulses depin the domain walls and thus induce switching via domain wall motion. Moreover, magnetoelastic domain walls work as convertors between the different magnon modes. This opens a way of a coherent switching using the magnon modes that are most suitable for optical excitations. To conclude, we consider different ultrafast switching mechanisms that could be realised in NiO and Mn3Si antiferromagnets.

[1] O. V. Gomonay and V. M. Loktev. Low Temperature Physics, 41, 698 (2015)

[2] Th. Chirac, J.-Y. Chauleau, P. Thibaudeau, O. Gomonay, and M. Viret. Phys. Rev. B 102, 134415 (2020)

[3] O. Gomonay and D. Bossini. J. Phys. D, 54, 374004 (2021)

Monday, May 9th, 09:50

Quench-switching of antiferromagnetic CuMnAs using ultrashort pulses

Kamil OLEJNIK
Czech Academy of Sciences

The promise of ultrafast dynamics of antiferromagnets motivates a broad effort to develop new materials and techniques suitable for the study and manipulation of the magnetic state of antiferromagnets. As a result of this activity and thanks to the spintronic perspective, many new interesting phenomena and properties of antiferromagnets were discovered recently [1].

The research of CuMnAs antiferromagnet was initiated by theoretical prediction and experimental demonstration of manipulation of the L-vector using staggered spin-orbit field [2]. Besides this effect, a new type of switching was discovered in CuMnAs which is based on the quenching of nanometer-scale multi-domain state. This effect is accompanied by a significant change of resistivity (reaching 100% at low temperatures) making it interesting for magnetic memory applications [3].

The functional characteristics of the quench-switching of CuMnAs will be discussed in detail. The dynamics of the effect will be assessed from the comparison of switching induced by electrical, THz radiation, and optical pulses with lengths ranging from milliseconds to 100 femtoseconds [4], and from analysis of temperature dependent relaxation [3], both indicating its ultrafast antiferromagnetic nature.

[1] Jungwirth, T. et. al, Nature Physics 14,200–203 (2018)
[2] Wadley, P. et al., Science 351, 587-590 (2016)
[3] Kašpar, Z. et al., Nature Electronics 4, 30–37 (2021)
[4] Olejník, K. et al., Science Advances 4, eaar3566 (2018)

Monday, May 9th, 10:40

Efficient spin excitation via ultrafast damping torques in antiferromagnets

Christian TZSCHASCHEL
Harvard

Spin damping effects form the core of many emerging concepts for high-speed spintronic applications. Important characteristics such as device switching times and magnetic domain-wall velocities depend critically on the damping rate. Although the implications of spin damping for relaxation processes are intensively studied, damping effects during impulsive spin excitations are assumed to be negligible because of the shortness of the excitation process. Herein we show that, unlike in ferromagnets, ultrafast damping plays a crucial role in antiferromagnetic dynamics because of their strongly elliptical spin precession. In time-resolved measurements, we find that ultrafast damping results in an immediate spin canting along the short precession axis. The interplay between antiferromagnetic exchange and magnetic anisotropy amplifies this canting by several orders of magnitude towards large-amplitude modulations of the antiferromagnetic order parameter. This leverage effect discloses a highly efficient route towards ultrafast manipulation of magnetism in antiferromagnetic spintronics.

Monday, May 9th, 11:05

Theoretical description of magnetic precessions during ultrafast laser excitation

Daria GORELOVA
University of Hamburg

We developed a quantum-mechanical approach to derive equations of motion for magnetic vectors under the influence of an ultrashort light pulse [1]. Within our approach, the opto-magnetic effect caused by a light pulse on a magnetic system is described by a time-dependent magnetic operator that separates the effect of the laser pulse on the magnetic system from other magnetic interactions. We model and compare laser-induced precessions of magnetic sublattices of easy-plane and easy-axis antiferromagnetic systems. Using these models, we show how the ultrafast inverse Faraday effect induces a net magnetic moment in antiferromagnets and demonstrate that a crystal field environment and the exchange interaction play essential roles for laser-induced magnetization dynamics even during the action of a pump pulse. Suprisingly, light-induced precessions can start even during the action of the pump pulse with a duration several tens times shorter than the period of induced precessions and affect the position of magnetic vectors after the action of the pump pulse.

[1] Daria Popova-Gorelova, Andreas Bringer, and Stefan Blügel, Phys. Rev. B 104, 224418 (2021)

Monday, May 9th, 11:30

Challenging energy-speed limits in antiferromagnets

Johan MENTINK
Radboud University

Antiferromagnets host the fastest and smallest magnetic waves of all magnets. With their additional intrinsically small dissipation antiferromagnets are ideal candidates to challenge the limits for energy and speed in data storage and processing technologies. However, understanding the magnon spectrum at short wavelengths and high oscillation periods has been challenging even for the simplest model: the antiferromagnetic Heisenberg model in 2D [1]. Furthermore, studying the space-time dynamics of this model defines an intricate quantum many-body problem out of equilibrium, for which until recently no accurate methods were available.

Beyond the limitations of existing methods, we adopt a machine learning inspired ansatz [2] to simulate the dynamics of the 2D Heisenberg model [3-4]. By sudden perturbations of the exchange interaction, we directly trigger dynamics of short-range spin correlations that is often described as the dynamics of magnon-pairs. Interestingly, although the anisotropic pattern can be indeed qualitatively understood with magnon theory, the spreading at the smallest length and time scales is up to 40% faster than expected from the highest magnon velocity. We explain the enhanced propagation speed by magnon-magnon interactions, which become exceptionally strong in the two dimensions and in the deep quantum limit (S=1/2).

Beyond sudden perturbations of the exchange interaction, we consider parametric driving of magnon pairs and explore the potential for switching between two stable oscillation states [5]. Using a semi-classical theory, we predict that switching can occur at the femtosecond timescale with an energy dissipation down to a few zepto Joule. This result touches the thermodynamical bound of the Landauer principle and approaches the quantum speed limit up to 5 orders of magnitude closer than demonstrated with magnetic systems so far.

[1] H. Shao et al, Phys. Rev. X 7, 041072 (2017)
[2] G. Carleo and M. Troyer, Science 355, 602 (2017)
[3] G. Fabiani & J.H. Mentink, SciPost Phys 7, 004(2019)
[4] G. Fabiani, M.D. Bouman and J.H. Mentink, Phys. Rev. Lett. 127, 097202 (2021)
[5] G. Fabiani & J.H. Mentink, Appl. Phys. Lett. 120, 152402 (2022)

Monday, May 9th, 13:40

Exchange scaling of ultrafast angular momentum transfer in 4f antiferromagnets

Yoav William WINDSOR
TU Berlin

Ultrafast manipulation of magnetism bears great potential for future information technologies. While demagnetization in ferromagnets is governed by the dissipation of angular momentum, materials with multiple spin sublattices, for example antiferromagnets, can allow direct angular momentum transfer between opposing spins, promising faster functionality. In lanthanides, 4f magnetic exchange is mediated indirectly through the conduction electrons (the Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction), and the effect of such conditions on direct spin transfer processes is largely unexplored. Here, we investigate ultrafast magnetization dynamics in 4f antiferromagnets and systematically vary the 4f occupation, thereby altering the magnitude of the RKKY coupling energy. By combining time-resolved soft X-ray diffraction with ab initio calculations, we find that the rate of direct transfer between opposing moments is directly determined by this coupling. Given the high sensitivity of RKKY to the conduction electrons, our results offer a useful approach for fine tuning the speed of magnetic devices. If time permits, we will further discuss results on deterministic ultrafast light-induced rotation of the antiferromagnetic spin arrangement by means of a coherent displacive excitation of the 4f moments' local magnetic anisotropy.

[1] Windsor et al., Communications Physics 3, 139 (2020) https://doi.org/10.1038/s42005-020-00407-0
[2] Windsor et al., Nat. Mater. (2022). https://doi.org/10.1038/s41563-022-01206-4

Monday, May 9th, 14:05

Ultrafast spin, charge and nuclear dynamics: ab-initio description

Sangeeta SHARMA
Max Born Institute

Laser induced ultrafast dynamics is a burgeoning field of condensed matter physics promising the ultimate short time control of light over matter. From the outset of research into femtomagnetism, the field in which spins are manipulated by light on femtosecond or faster time scales, several questions have arisen and remain highly debated: How does the light interact with spin moments? How is the angular momentum conserved between the nuclei, spin, and angular momentum degrees of freedom during this interaction? What causes the ultrafast optical switching of magnetic structures from anti-ferromagnetic to ferromagnetic and back again? What is the ultimate time limit on the speed of spin manipulation? What is the impact of nuclear dynamics on the light-spin interaction?

In my talk I will advocate a parameter free ab-initio approach to treating ultrafast light-matter interactions, and discuss how this approach has led both to new answers to these old questions but also to the uncovering of novel and hitherto unsuspected early time spin dynamics phenomena. In particular I will demonstrate OISTR (optical inter-site spin transfer)[1,2] to be one of the fastest means of spin manipulation via light [4,7,8,9], with changes in magnetic structure occurring on attosecond time scales [8]. I will also discuss the impact of nuclear dynamics on laser induced spin dynamics and demonstrate how selective phonon modes can be used to enhance the OISTR effect.

The ability to measure and calculate the same physical quantity forms the cornerstone of the vital collaboration between theory and experiment, and I will discuss recent work where we have ab-initio calculated the real time response functions of L-edge and M-edge semi-core states during spin dynamics, demonstrating both good quantitative agreement with experiment [5,6] but also showing how theory can actually predict new phenomena and guide new experiments.

[1] Dewhurst et al. Nano Lett. 18, 1842, (2018)
[2] Elliott et al. Scientific Reports 6, 38911 (2016)
[3] Shokeen et al. Phys. Rev. Lett. 119, 107203 (2017)
[4] Chen et al. Phys. Rev. Lett. 122, 067202 (2019)
[5] Willems et al. Nat. Comm. 11, 1 (2020)
[6] Dewhurst et al. Phys. Rev. Lett. 124, 077203 (2020)
[7] Hofherr et al. Sci. Advs. 6, eaay8717 (2020)
[8] Siegrist et al. Nature 571, 240 (2019)
[9] Golias et al. Phys. Rev. Lett. 126, 107202 (2021)

Monday, May 9th, 15:00

Spin-orbit torque switching between reversed antiferromagnetic state and its electrical detection

Joerg WUNDERLICH
University of Regensburg

Magnetic data storage is based on the switching and detection of energetically degenerate ferromagnetic ground states with reversed magnetization separated by a sufficiently high energy barrier to maintain long-term non-volatility of the stored data. Therefore, exploiting the many advantages of zero net moment antiferromagnets for fast and energy-efficient magnetic storage will also rely on the realization of switching and detecting stable antiferromagnetic states with reversed magnetic order.

In this talk, we discuss that switching between nonvolatile stable states with opposite Néel vector orientations and their detection in collinear antiferromagnetic systems with combined spatial inversion and time-reversal (PT) symmetry can be realized by generating relativistic effective spin-orbit fields and by detecting higher-order magneto-transport responses. As a model system, we consider a fully compensated synthetic antiferromagnet (SAF) with engineered PT symmetry and an natural equivalent, the antiferromagnet CuMnAs.

Besides just storing "0"-s or "1"-s corresponding to two fully polarized magnetic states with reversed Néel vectors, we also show that partial switching enables the realization of nonvolatile memristor type of devices.

Monday, May 9th, 15:25

Ab initio theory for coherent magnetic switching

Peter OPPENEER
Uppsala University

Magnetization switching processes in magnetic materials can generally be divided in coherent and incoherent processes. Whereas the latter involve thermal quenching and then rebuilding of the magnetic order, the former are particularly interesting for fast and energy-efficient switching. I will focus on several mechanisms that could provide coherent torques for magnetization switching, in particular, the spin and orbital Hall and Rashba-Edelstein effects and inverse Faraday effect. To understand the possible achievable magnitudes of these mechanisms, we perform ab initio calculations of the current-induced or light-induced magnetizations in selected materials, including ferromagnets and antiferromagnets (AFMs) [1-3].

We show that both the Rashba-Edelstein effect and the inverse Faraday effect can lead to staggered torques in AFM materials [2,3]. Those induced by the inverse Faraday effect are particularly large. For the selected case of AFM CrPt we find, in collaboration with the group of U. Nowak, that coherent ultrafast single-shot switching of the AFM order is possible within less than 200 fs [4]. This is due to the coherent action of the staggered induced moments as well as the speed of exchange enhanced dynamics in AFMs.

[1] M. Berritta et al., Phys. Rev. Lett. 117, 137203 (2016)
[2] L. Salemi et al., Nat. Commun. 10, 5381 (2019)
[3] L. Salemi et al., Phys. Rev. Mater. 5, 074407 (2021)
[4] T. Dannegger et al., Phys. Rev. B 104, L060413 (2021)

Tuesday, May 10th, 09:10

Spin dynamics in antiferromagnets: from THz to ultrafast switching

Ulrich NOWAK
University of Konstanz

On the basis of spin model calculations, the dynamics of antiferromagnets is discussed and compared to that of ferromagnets. The magnetic field component of a THz laser excitation can excite antiferromagnetic magnon modes, for very large fields eventually leading even to switching [1]. Relativistic extensions of the Landau-Lifshitz-Gilbert equation like field-derivative torques [2] and inertial spin dynamics [3] lead to additional dynamic effects which can facilitate switching in the THz regime.

Furthermore, we explore the possibility of ultrafast, coherent all-optical magnetization switching by studying the action of the inverse Faraday effect in CrPt, an easy-plane antiferromagnet. Using a combination of density-functional theory and atomistic spin dynamics simulations, we show how a circularly polarized laser pulse can switch the order parameter of the antiferromagnet within a few hundred femtoseconds. This nonthermal switching takes place on an elliptical path, driven by the staggered magnetic moments induced by the inverse Faraday effect, leading to reliable switching between two perpendicular magnetic states [4].

[1] S. Wienholdt et al., Phys. Rev. Lett. 108, 247207 (2012)
[2] R. Mondal et al., Phys. Rev. B 100, 060409 (R) (2019)
[3] R. Mondal et al., Phys. Rev. B 103, 104404 (2021)
[4] T. Dannegger et al., Phys. Rev. B 104, L060413 (2021)

Tuesday, May 9th, 09:35

Terahertz magnons and magnon-polaritons in antiferromagnets

Rostislav MIKHAYLOVSKIY
Lancaster University

The antiferromagnetic materials appeal to spintronics and magnonics because of their very high terahertz (THz) frequencies of spin dynamics and unique functionalities in comparison to conventional ferromagnets. Due to the strong coupling of the propagating THz magnetic fields with magnons, the hybrid magnon-polariton modes are formed. The physics of the magnon-porations calls for an interdisciplinary approach at the merge of magnetism and photonics.

For instance, magnon-polaritons are shown to play a dominant role in propagation of terahertz (THz) waves through TmFeO3 orthoferrite, if the frequencies of the waves are in vicinity of the quasi-antiferromagnetic mode of spin resonance [1]. This leads to beating between magnon-polaritons due to the energy exchange between the higher and lower polariton branches formed in vicinity of the antiferromagnetic magnon frequency.

Polaritonic nature of spin modes in antiferromagnets has important implications for THz-driven spin control [2]. In DyFeO3 orthoferrite the lattice-mediated coupling of the electric fields produced by otherwise orthogonal magnon modes leads to internal resonance, when the frequencies of the modes are close to each other. This resonance results in a dramatic enhancement of spin oscillations excited by THz magnetic field.

[1] K. Grishunin , T. Huisman, G. Li, E. Mishina, Th. Rasing, A. V. Kimel, K. Zhang, Z. Jin, S. Cao, W. Ren , G.-H. Ma and R. V. Mikhaylovskiy. ACS Photonics 5, 1375 (2018)

[2] S. Baierl, M. Hohenleutner, T. Kampfrath, A. K. Zvezdin, A. V. Kimel, R. Huber, and R. V. Mikhaylovskiy. Nature Photonics 10, 715–718 (2016)

Tuesday, May 10th, 10:40

Ultrafast Amplification and Nonlinear Magnetoelastic Coupling of Coherent Magnon Modes in an Antiferromagnet

Davide BOSSINI
University of Konstanz

The wildly growing field of antiferromagnetic spintronics mainly deals with single-domain states materials, even if generating this configuration requires magnetic fields available only in a handful of dedicated facilities in the world. Optical experiments are usually performed focussing the beams into a single domain, whose size can be increased in several materials by annealing. Domains are thus perceived as a nuisance, occurring in the ground state of antiferromagnets, to be avoided for an efficient control of spins. In my talk paper I will discuss recent results, which experimentally disprove this commonly accepted wisdom. Relying on a spectroscopic opto-magnetic investigation of the femtosecond spin dynamics in the archetypal antiferromagnet NiO in a multidomain state I will demonstrate: i) the excitation and a novel mechanism to arbitrary amplify a THz magnon mode via the exciton-magnon transition[1]; ii) nonlinear femtosecond spin dynamics, in the form of coupling between the different magnon modes, typically orthogonal in a single-domain state; iii) the microscopic nature of the coupling between modes, which is due to the presence of domain walls. This last point was supported by a phenomenological model[2] and, most importantly, by means of a control experiment performed in a single domain of the material. This experiment confirms that the coupling between the modes requires domain walls, as it is not observed in a single domain[3].

[1] Nat. Phys.14, 370 (2018)
[2] J. Phys. D: Appl. Phys. 54, 374004 (2021)
[3] Physical Review Letters 127, 077202 (2021)

Tuesday, May 9th, 11:05

Nonlinear phononics as a universal mechanism for ultrafast switching of spins

Andrei KIRILYUK
Radboud University

Here I will show how an ultrafast resonant excitation of optical phonon modes can switch magnetic order. The mechanism appears to be very universal, and is shown to work in samples with very different magnetic order, including weak ferromagnets and antiferromagnets. Using single-shot time resolved microscopy, we demonstrate that the dynamics of switching proceeds via a strongly inhomogeneous state, related to the spin-wave instabilities that appear due to large amplitude of precessional motion.

Tuesday, May 10th, 11:30

Engineering magnetic states with light through nonlinear lattice excitation

Ankit DISA
MPSD

Optical manipulation of magnetism offers enormous possibilities for enabling energy-efficient data storage and processing with ultrafast switching speeds. These advantages are especially pronounced in antiferromagnets, which are robust to environmental perturbations and whose fundamental magnetic modes typically lie at high frequencies. While absorption can result in heating-induced modifications of magnetic order, it also accompanied by detrimental incoherent effects. Thus, an important research effort has centered around understanding non-thermal coupling pathways of light with the magnetic order parameter in complex magnetic materials.

Recent studies have demonstrated the ability to drive magnetic changes via the coupling between the electromagnetic field of a light pulse and the spins or interaction parameters, which is often mediated through indirect electronic processes. Alternatively, the crystal structure can provide a direct handle on magnetism, dictating both local magnetic states and their interactions through the lattice symmetry and bonding environment.

In this talk, I discuss how one can dynamically control the crystal structure by resonantly exciting optical phonons in the mid-infrared and THz range, and I show how this approach can be applied to induce, enhance, and switch magnetic order. I focus on our recent experiment demonstrating light-induced ferrimagnetism in the prototypical antiferromagnet CoF2. By simultaneously driving degenerate lattice vibrations, we transiently realize a low-symmetry, non-equilibrium crystal structure, which generates a net magnetization via a “dynamical piezomagnetic effect.” The optically created magnetization is switchable by the light polarization, and has a magnitude that can be tuned up to 100 times larger than achievable in equilibrium, offering a potential platform for opto-magnetic applications. I also highlight a new experiment on the correlated magnet YTiO3 in which ferromagnetism is transiently enhanced and stabilized at a temperature well in excess of the equilibrium Tc. In both cases, optically driven symmetry breaking is enabled by selectively exploiting phonon nonlinearities, demonstrating new possibilities for rational designing non-equilibrium magnetism with light.

Tuesday, May 9th, 13:40

Nonlinear magnon dynamics in antiferromagnetic Mn2Au driven by Terahertz Neel spin-orbit torque

Yannic BEHOVITS
FU Berlin

In antiferromagnets, strong exchange coupling leads to intrinsic terahertz (THz) magnon resonances, which have large potential for high-speed spin information processing. For CuMnAs and Mn2Au, switching of the Néel vector has been demonstrated by using pulsed electrical currents and free-space THz pulses [1-3]. The switching was attributed to the Néel spin-orbit torque (NSOT), which is proportional to the current [4]. However, the underlying spin dynamics have not been observed on ultrafast timescales.

Here, we employ a THz-pump magneto-optic-probe setup to investigate ultrafast dynamics of antiferromagnetic order induced by THz electromagnetic fields in Mn2Au. In our samples, the direction of the Néel vector was prealigned via a spin-flop transition in a high magnetic field (60 T) [5]. We observe a strongly damped oscillatory signal at 0.6 THz, whose amplitude is proportional to the driving THz electric field. Our observations are consistent with an NSOT-driven magnon mode.

Upon increasing the THz field strength to 0.65 MV/cm, a non-linear response emerges. By using a simple model, the signal can be related to a substantial deflection of the Néel vector from its equilibrium position. Based on our results, we can estimate important material-specific parameters and calculate THz pulse field strengths at which switching of the antiferromagnetic order of Mn2Au on picosecond timescales is achieved.

[1] Wadley, P., et al., Electrical switching of an antiferromagnet. Science, 2016. 351(6273): p. 587-590.

[2] Olejník, K., et al., Terahertz electrical writing speed in an antiferromagnetic memory. Science Advances, 2018. 4(3): p. eaar3566.

[3] Bodnar, S.Y., et al., Writing and reading antiferromagnetic Mn2Au by Néel spin-orbit torques and large anisotropic magnetoresistance. Nature Communications, 2018. 9(1): p. 348.

[4] Železný, J., et al., Spin-orbit torques in locally and globally noncentrosymmetric crystals: Antiferromagnets and ferromagnets. Physical Review B, 2017. 95(1): p. 014403.

[5] Sapozhnik, A.A., et al., Direct imaging of antiferromagnetic domains in Mn2Au manipulated by high magnetic fields. Physical Review B, 2018. 97(13): p. 134429.

Tuesday, May 10th, 14:05

Coherent spin-wave transport in an antiferromagnet

Dmytro AFANASIEV
Radboud University

Magnonics is a research field complementary to spintronics, in which quanta of spin waves (magnons) replace electrons as information carriers, promising lower dissipation [1,2]. The development of ultrafast nanoscale magnonic logic circuits calls for new tools and materials to generate coherent spin waves with frequencies as high, and wavelengths as short, as possible [3]. Antiferromagnets can host spin waves at terahertz (THz) frequencies and are therefore seen as a future platform for the fastest and the least dissipative transfer of information [4]. However, the generation of short-wavelength coherent propagating magnons in antiferromagnets has so far remained elusive. We report the efficient emission and detection of a nanometer-scale wavepacket of coherent propagating magnons in antiferromagnetic DyFeO3 using ultrashort pulses of light [5]. The subwavelength confinement of the laser field due to large absorption creates a strongly non-uniform spin excitation profile, enabling the propagation of a broadband continuum of coherent THz spin waves (see Fig. 1). The wavepacket features magnons with detected wavelengths down to 125 nm that propagate with supersonic velocities V0 of more than 13 km/s into the material. This long-sought source of coherent short-wavelength spin carriers opens up new prospects for THz antiferromagnetic magnonics and nanoscale coherence-mediated logic devices at THz frequencies.

[1] V.V. Kruglyak et al., J. Phys. D 43, 264001 (2010)
[2] B. Lenk et al., Phys. Rep. 507, 107 (2011)
[3] A.V. Chumak et al. Nat. Phys. 11, 453 (2015)
[4] T. Jungwirth et al. Nat. Nano. 11, 231 (2016)
[5] J.R. Hortensius et al. Nat. Phys. 17, 1001 (2021)

Tuesday, May 9th, 15:00

Modeling of THz phonon-assisted spin dynamics and switching

Oksana CHUBYKALO-FESENKO
CSIC

Novel possibilities for ultrafast magnetisation switching have been presented recently using ultrafast phonon excitations in Terahertz (THz) regime [1]. These results also suggest that at the picosecond timescale and below spin-phonon dynamics occur simultaneously and one system can excite another. Here we investigate the magnetisation dynamics in a spin-lattice model [2]parameterised for Fe under the application of a THz phonon pulse. The modeling is done within the molecular dynamics approach in a self-consistent spin-lattice framework. We demonstrate the possibility of a very energy efficient switching in the conditions when phonons are excited with high k-values and THz frequencies, corresponding to a maximum in the density of states and no possibility of spinwave excitation. The mechanism of switching

is via local magneto-elastic fields created by atom's displacements. In the conditions of the absence of spinwave excitations, practically all phonon angular momentum is transferred to a precessional magnetisation switching. The spin temperature calculated during the switching

process shows a minimum increase (in the order of mK), hence the switching process can be considered non-dissipative. Finally, I will also discuss some very recent results on antiferromagnets.

[1] A. Stupakiewicz et al Nat. Phys. 17 (2021) 489
[2] M.Strungary et al Phys Rev B 103 (2021) 024429

Tuesday, May 10th, 15:25

Using Spin Waves to Probe Ultrafast Spin Current Generation in Rare Earth Ferromagnets

Reinoud LAVRIJSEN
Eindhoven University of Technology

All-optical switching (AOS) of ferrimagnetic rare earth-transition metal compounds with femtosecond laser pulses shows great promise for technological applications [1]. However, the possibly essential role of spin transport has scarcely been addressed. While it has been claimed that Gd can produce large spin currents [2], these are notoriously difficult to probe, impeding a full understanding of the physics at play. We demonstrate the use of spin waves to probe spin currents generated by ferromagnetic rare earth films. Upon fs laser pulse excitation, spin waves are excited in an in-plane Co layer via an out-of-plane spin current [3, 4] originating from a ferrimagnetic Co/Gd bilayer. Here, Co stabilizes the antiparallel Gd magnetization, and provides a spin current to compare the effect of Gd to. For increasing Gd thickness, the spin current is expected to shift from Coto Gd-dominated, reversing its polarization. Using time-resolved MOKE, we find that the homogeneous (FMR) mode experiences a phase rotation of nearly 180° over a small Gd thickness range, which confirms a large contribution of Gd to the overall spin current. Qualitative modeling supports this interpretation, with efforts underway to better quantify the Gd contribution. Substituting Tb for Gd strongly decreases the amplitude of the FMR mode, implying weaker spin current generation. This might also partly explain the apparent difficulty in achieving AOS in Tb-containing systems. The same spin currents can excite THz frequency standing spin waves in the in-plane layer [5, 6], which appear to be strongly suppressed with increasing rare earth thickness. This is consistent with the relatively slow magnetization dynamics in these materials [7] leading to longer lasting spin currents, which excite high frequency modes less efficiently. This approach for probing optically generated spin currents can elucidate the processes at work in AOS, giving valuable insight for implementation in data storage devices of the future.

[1] A. Kimel and M. Li, Nature Reviews Materials, 4, p189-200 (2019)
[2] S. Iihama et al., Advanced Materials, 30.51, 1804004 (2018)
[3] A. Schellekens et al., Nature Communications, 5, 4333 (2014)
[4] G-M. Choi et al., Nature Communications 5, 4334 (2014)
[5] I. Razdolski et al., Nature Communications 8, 15007 (2016)
[6] M. Lalieu et al., Physical Review B, 99.18, 184439 (2019)
[7] B. Frietsch et al., Science Advances, 6.39, eabb1601 (2020)

List of Contributions - Talks

Surname	Name	Talk Title
Afanasiev	Dmytro	Coherent spin-wave transport in an antiferromagnet
Behovits	Yannic	Nonlinear magnon dynamics in antiferromagnetic Mn2Au driven by Terahertz Neel spin-orbit torque
Bossini	Davide	Ultrafast Amplification and Nonlinear Magnetoelastic Coupling of Coherent Magnon Modes in an Antiferromagnet
Chubykalo-Fesenko	Oksana	Modeling of THz phonon-assisted spin dynamics and switching
Disa	Ankit	Engineering magnetic states with light through nonlinear lattice excitation
Gomonay	Olena	Ultrafast dynamics of antiferromagnets: switching vs rotation
Gorelova	Daria	Theoretical description of magnetic precessions during ultrafast laser excitation
Kirilyuk	Andrey	Nonlinear phononics as a universal mechanism for ultrafast switching of spins
Lavrijsen	Reinoud	Using Spin Waves to Probe Ultrafast Spin Current Generation in Rare Earth Ferromagnets
Mentink	Johan	Challenging energy-speed limits in antiferromagnets
Mikhaylovskiy	Rostislav	Terahertz magnons and magnon-polaritons in antiferromagnets
Nowak	Uli	Spin dynamics in antiferromagnets: from THz to ultrafast switching
Olejnik	Kamil	Quench-switching of antiferromagnetic CuMnAs using ultrashort pulses
Oppeneer	Peter	Ab initio theory for coherent magnetic switching
Sharma	Sangeeta	Ultrafast spin, charge and nuclear dynamics: ab-initio description
Tzschaschel	Christian	Efficient spin excitation via ultrafast damping torques in antiferromagnets
Windsor	Yoav William	Exchange scaling of ultrafast angular momentum transfer in 4f antiferromagnets
Wunderlich	Joerg	Spin-orbit torque switching between reversed antiferro-magnetic state and its electrical detection

List of Contributions - Poster

Surname	Name	Talk Title
Adamantopoulos	Theodoros	Laser-induced charge and spin photocurrents in BiAg2 surface from first-principles
Besbas	Jean	Understanding all-optical switching in Mn2RuGa
Blank	Thomas	Linear and Nonlinear Channels for THz Control of Ferrimagnetism
Dannegger	Tobias	Investigating the ultrafast dynamics of antiferromagnets with ab initio-parameterised spin models
Dolgikh	Alexander	Ultrafast imaging of heat assisted magnetization dynamics in ferrimagnetic iron garnet
Dolgikh	Irina	Ultrafast emergence of ferromagnetism in antiferromagnetic FeRh in high magnetic fields
Gareev	Timur	Laser-induced Magnetization Dynamics of Dy ions in DyFeO3
Ghosh	Sumit	Ultrafast laser induced chirality in collinear antiferromagnets
Hellenes	Anna Birk	Giant and tunneling magnetoresistance in unconventional collinear antiferromagnets with nonrelativistic spin-momentum coupling
Herrgen	Paul	Ultrafast manipulation of antiferromagnets by optical excitation
Jourdan	Martin	Spin-orbit torque vs. thermomagnetoelastic switching of Mn2Au thin films
Leenders	Ruben	Optical generation and detection of propagating magnons in an antiferromagnet
Lu	Zhiwei	Influence of non-local damping on magnon properties

List of Contributions - Poster

Surname	Name	Talk Title
Mankovskyy	Sergiy	Spin-lattice interaction from first principles
Metzger	Thomas	Propagation of nearly single cycle THz pulse through antiferromagnetic CoF2
Nussle	Thomas	Quantum dynamical atomistic simulations of antiferromagnets
Polesya	Svitlana	Spin-lattice interaction from first principles
Reimers	Sonka	Spin-orbit torque vs. thermomagnetoelastic switching of Mn2Au thin films
Rezende	Sergio	Collective spin dynamics in the noncollinear antiferromagnet IrMn3
Schick	Daniel	Probing spin and lattice dynamics in elemental and artificial antiferromagnets by resonant magnetic X-ray scattering
Stremoukhov	Pavel	Phononic manipulation of antiferromagnetic domains in NiO
Taylor	James	Manipulating the chiral spin texture of noncollinear antiferromagnets – from current-driven switching towards ultrafast excitation
van Gerven	Lucas	Excitation of ultrafast spin precession in a 2D magnet by THz light
Wust	Stephan	Ultrafast manipulation of antiferromagnets by optical excitation
Zelezny	Jakub	Spin-transfer torque in non-collinear antiferromagnetic junctions

	Monday, May 9th	Tuesday, May 10th
08:50	**Registration**	
09:00		**Intro Andrei Kirilyuk**
	Opening Remarks	
09:10		**Ulrich NOWAK** Spin dynamics in antiferromagnets: from THz to ultrafast switching
	Intro Aleksei KIMEL	
09:20		
	Olena GOMONAY Ultrafast dynamics of antiferromagnets: switching vs rotation	
09:30		
		Rostislav MIKHAYLOVSKIY Terahertz magnons and magnon-polaritons in antiferromagnets
09:40		
09:50	**Kamil OLEJNIK** Quench-switching of antiferromagnetic CuMnAs using ultrashort pulses	
10:00		**Coffee Break**
10:10		
	Coffee Break	
10:20		
10:30	**Intro Yuriy MOKROUSOV**	**Intro Thomas METZGER**
10:40	**Christian TZSCHASCHEL** Efficient spin excitation via ultrafast damping torques in antiferromagnets	**Davide BOSSINI** Ultrafast Amplification and Nonlinear Magnetoelastic Coupling of Coherent Magnon Modes in an Antiferromagnet
10:50		
11:00		
	Daria GORELOVA Theoretical description of magnetic precessions during ultrafast laser excitation	**Andrei KIRILYUK** Nonlinear phononics as a universal mechanism for ultrafast switching of spins
11:10		
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11:30	**Johan MENTINK** Challenging energy-speed limits in antiferromagnets	**Ankit DISA** Engineering magnetic states with light through nonlinear lattice excitation
11:40		
11:50		
12:00	**Lunch & Poster Session**	**Lunch & Poster Session**
13:30	**Intro Tomáš JUNGWIRTH**	**Intro Davide Bossini**
13:40	**Yoav William WINDSOR** Exchange scaling of ultrafast angular momentum transfer in 4f antiferromagnets	**Yannic BEHOVITS** Nonlinear magnon dynamics in antiferromagnetic Mn2Au driven by Terahertz Neel spin-orbit torque
13:50		
14:00		
	Sangeeta SHARMA Ultrafast spin, charge and nuclear dynamics: ab-initio description	**Dmytro AFANASIEV** Coherent spin-wave transport in an antiferromagnet
14:10		
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14:30	**Coffee Break**	**Coffee Break**
14:40		
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15:00	**Joerg WUNDERLICH** Spin-orbit torque switching between reversed antiferromagnetic state and its electrical detection	**Oksana CHUBYKALO-FESENKO** Modeling of THz phonon-assisted spin dynamics and switching
15:10		
15:20		
	Peter OPPENEER Ab initio theory for coherent magnetic switching	**Reinoud LAVRIJSEN** Using Spin Waves to Probe Ultrafast Spin Current Generation in Rare Earth Ferromagnets
15:30		
15:40		
15:50	**Poster Session**	**Closing Remarks**
18:30	**Dinner at Restaurant WASEM** Edelgasse 15, 55218 Ingelheim am Rhein	