TT 13: Focus Session: Magnetic Phenomena from Phonon Chirality and Angular Momentum II (joint session MA/TT)

The magnetic moment of the electron lies at the heart of magnetism and spintronics. However, recent research has unveiled the angular momentum and magnetic moment of chiral phonons as fundamental quantities in their own right. These chiral phonons give rise to a plethora of novel lattice phenomena analogous to electronic effects, such as the phonon Hall and phonon Zeeman effects. Moreover, they play a critical role in angular momentum transfer on ultrafast timescales, as seen in the Einstein-de Haas effect. Chiral phonons can also generate effective magnetic fields reaching the tesla scale, inducing magnetization in antiferromagnetic, paramagnetic, and even nonmagnetic materials - a phenomenon reminiscent of the Barnett effect. These advancements showcase phonon chirality and angular momentum as powerful emerging tools for generating and controlling magnetism. This focus session aims to highlight the latest breakthroughs in chiral-phonon magnetism and foster connections between the rapidly evolving field of chiral phononics and the broader magnetism research community.

Coordinators: Dominik M.Juraschek, Eindhoven University of Technology, d.m.juraschek@tue.nl; Martina Basini, ETH Zürich, m.basini@ethz.ch

Time: Tuesday 9:30–12:45 Location: H16

TT 13.1 Tue 9:30 H16

Continuous-wave terahertz spectroscopy on chiral phonons — •Ji Eun Lee, Luca Eisele, Artem Pronin, and Martin Dressel — 1. Physikalisches Institut, Universität Stuttgart, Germany

We apply continuous-wave frequency-domain terahertz spectroscopy to study chiral phonons at low frequencies. As samples, we use thin films of materials with soft phonon modes, such as SrTiO3 and (doped) PbTe. Our experimental method utilizes both, measurements of transmission with circular-polarized light and Faraday-rotation experiments. In the talk, our approach to the measurements and preliminary results will be summarized.

TT 13.2 Tue 9:45 H16

Spin-lattice coupling in multiscale modeling: from angular momentum transfer to chiral phonons — •Markus Weissenhofer[1,2], Philipp Rieger[1], Sergiy Mankovsky[3], Akashdeep Kamra[5], MS Mrudul[1], Hubert Ebert[3], Ulrich Nowak[4], and Peter M. Oppeneer[1] — [1]Uppsala University, Uppsala, Sweden — [2]Freie Universität Berlin, Berlin, Germany — [3]Ludwig Maximilian Universität, München, Germany — [4]Universität Konstanz, Konstanz, Germany — [5]Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau, Kaiserslautern, Germany

Transfer and manipulation of angular momentum is a key aspect in spintronics. Recently, it has been shown that angular momentum transfer between spins and lattice is possible on ultrashort timescales [1]. To contribute to the understanding of this transfer, we have developed a theoretical multiscale framework for spin-lattice coupling, which is linked to ab-initio calculations on the one hand and magnetoelastic continuum theory on the other [2], allowing for the study of a wide range of magnetomechanical phenomena. Here I will discuss how this framework can be used to calculate magnon-phonon coupling parameters, emphasizing the importance of a Dzyaloshinskii-Moriya type interaction for angular momentum transfer [2] and revealing the existence of chiral phonons in iron arising from a chirality-selective coupling [3]. [1] Tauchert al., Nature 602, 73 (2022); Luo et al., Science 382, 698 (2023). [2] Mankovsky et al., PRL 129, 067202 (2022); Weißenhofer et al., PRB 108, L060404 (2023). [3] Weißenhofer et al., arXiv:2411.03879.

TT 13.3 Tue 10:00 H16

Chiral phonon-induced magnetization reversal in 2D ferromagnets — •Daniel Bustamante Lopez[1] and Dominik Juraschek[2] — [1]Department of Physics, Boston University, Boston, Massachusetts 02215, USA — [2]Department of Applied Physics and Science Education, Eindhoven University of Technology, Eindhoven, Netherlands

In our previous work, we explored magnonic rectification, where a coherently excited chiral phonon generates an effective magnetic field capable of inducing quasistatic magnetization in antiferromagnetic materials. In this study, we extend this concept to ferromagnetic materials, demonstrating that phononic magnetic fields can achieve permanent magnetization reversal. We focus on two-dimensional chromium-based ferromagnetic crystals, including CrI3, CrGeTe3, and CrCl3, and investigate reversal mechanisms such as damping switching and precessional switching. Our findings reveal that phononic magnetic fields enable robust and permanent magnetization reversal within nanoseconds, highlighting their potential for ultrafast magnetic control.

TT 13.4 Tue 10:15 H16

Chiral phonons in coupled magnon-phonon band structure — •Yelyzaveta Borysenko, Daniel Schick, and Ulrich Nowak — University of Konstanz, Konstanz, Germany

Coupling of spin and lattice degrees of freedom in magnetic materials is a key aspect for angular momentum based information processing. During ultrafast demagnetization, spin angular momentum can be transferred into the lattice creating chiral phonons even in simple centrosymmetric materials [1]. Spin-lattice coupling mechanisms involved in such processes can be approached using first principles calculations, which allow to determine leading energy terms for angular momentum exchange for different materials [2, 3]. Coupled spin-lattice dynamics is then described constructing angular momentum-conserving Hamiltonian linked to ab initio calculated model parameters [4].

Here, we linearize the equations of motion and calculate coupled magnon-phonon dispersions. We discuss how different coupling terms, e.g., of anisotropy or Dzyaloshiskii-Moriya type, can modify magnon and phonon dispersions, open up energy gaps, lift the degeneracy of modes, and lead to avoided crossings in the band structure.

[1] S. R. Tauchert et al., Nature 602, 73 (2022); [2] S. Mankovsky et. al., Phys. Rev. Lett. 129, 067202 (2022); [3] J. Hellsvik et al., Phys. Rev. B 99, 104302 (2019); [4] M. Weißenhofer et al., Phys. Rev. B 108, L060404 (2023)

TT 13.5 Tue 10:30 H16

Phonon Inverse Faraday effect from electron-phonon coupling — •Natalia Shabala and Matthias Geilhufe — Department of Physics, Chalmers University of Technology, 412 96 Gothenburg, Sweden

The phonon inverse Faraday effect describes the emergence of a DC magnetization due to circularly polarized phonons. From time-dependent second order perturbation theory and electron-phonon coupling we develop a microscopic formalism for phonon inverse Faraday effect. We arrive at a general and material-independent equation [1]. Using this equation for ferroelectric soft mode in $SrTiO_3$ gives an estimate of effective magnetic field which is consistent with recent experiments [2]. Hence, our approach is promising for shedding light into the microscopic mechanism of angular momentum transfer between ionic and electronic angular momentum, which is expected to play a central role in the phononic manipulation of magnetism.

[1] N. Shabala and R. M. Geilhufe, Accepted to PRL, arXiv:2405.09538, 2024

[2] M. Basini et al., Nature 628, 534 (2024)

TT 13.6 Tue 10:45 H16

Temperature dependent magnon-phonon coupling in YIG/GGG heterostructures — •J. Weber[1,2], M. Cherkasskii[3], F. Engelhardt[3,4,5], S.T.B. Goennenwein[6], S.Viola Kusminskiy[3,5], S. Geprägs[1], R. Gross[1,2,7], M. Althammer[1,2], and H. Huebl[1,2,7] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany — [2]School of Natural Sciences, Technical University of Munich, Munich, Germany — [3]Institute for Theoretical Solid State Physics, RWTH Aachen University, Aachen, Germany — [4]Department of Physics, University Erlangen-Nuremberg, Erlangen, Germany — [5]Max Planck Institute for the Science of Light, Erlangen, Germany — [6]Department of Physics, University of Konstanz, Konstanz, Germany — [7]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany

Magnon-phonon coupling in heterostructures has recently gained interest in the context of angular momentum conversion and angular momentum transport via phonons. A typical experimental setting is a bilayer system, where the magnetization dynamics of a magnetic thin film interacts with the elastic standing wave excitations of a non-magnetic bulk crystal. So far, bulk acoustic wave resonators consisting of a ferrimagnetic yttrium iron garnet (YIG) film deposited on a crystalline gadolinium gallium garnet (GGG) substrate have been studied at room temperature due to the favorable magnetic damping properties of YIG [1]. We present a temperature dependent analysis of the magnon-phonon coupling of a YIG/GGG bulk acoustic wave resonator.

[1] K. An et al., Phys. Rev. B **101**, 060407, (2020).

15 min. break

TT 13.7 Tue 11:15 H16

Modeling of the preparation and conservation of coherent phonon (pseudo) angular momentum — •Olga Minakova[1], Maximilian Frenzel[1], Carolina Paiva[2], Joanna M. Urban[1], Michael S. Spencer[1], Martin Wolf[1], Dominik M. Juraschek[2,3], and Sebastian F. Maehrlein[1,4,5] — [1]FHI Berlin — [2]Tel Aviv University — [3]Eindhoven University of Technology — [4]HZDR — [5]TU Dresden

The angular momentum of lattice vibrations - phonon angular momentum - is an underexplored degree of freedom in solid-state systems. Recent experiments have shown that circularly-polarized THz pulses can coherently excite degenerate phonon modes, enabling the preparation of phonon angular momentum states. THz-Kerr effect spectroscopy provides a means to monitor these states by directly measuring vectorial phonon trajectories. To interpret such experiments, it is essential to understand the symmetry properties of the phonon modes that influence the driving and probing processes, as well as the conservation of angular momentum in the crystal lattice. Here, we model the generation and detection of coherent phonon angular momentum, revealing how crystal symmetry dictates the selection rules in the lattice. We show that the form of the Raman tensors associated with the phonon explains the phonon helicity observed in experiments, linking the discrete rotational symmetry of the material to the conservation of pseudo angular momentum in lattice vibrations.

TT 13.8 Tue 11:30 H16

Spin-spin interaction via chiral phonons — •Daniel Schick[1], Markus Weissenhofer[2,3], Akashdeep Kamra[4], and Ulrich Nowak[1] — [1]University of Konstanz, Konstanz, Germany — [2]Uppsala University, Uppsala, Sweden — [3]Free University of Berlin, Berlin, Germany — [4]University of Kaiserslautern-Landau, Kaiserslautern, Germany

Coupling between the magnetic degrees of freedom and phonons has emerged as a topic of great importance for explaining various magnetic phenomena, like ultrafast demagnetization processes [1], and the possibility to affect magnetization dynamics via phonon pumping [2]. We develop a tool to study spin-lattice coupling in atomistic simulations, which conserves total angular momentum. This allows us to precisely retrace the transfer of angular momentum between the spin and lattice systems. We demonstrate the emergence of an effective spin-spin interaction mediated by chiral phonons. This effect can arise from thermal phonons as follows. A spin may precess after coupling to a phonon, with this precession producing chiral phonons, which in turn, affect other spins. A similar effect can be achieved by driving a spin to induce chiral phonons. We discuss the dependence of this interaction on the temperature and strength of the spin-lattice interaction and discuss our findings within the context of phonon-enhanced magnon transport phenomena.

[1] S. R. Tauchert, et. al., Nature **602**, 73 (2022)
[2] R.Schlitz et. al. Phys. Rev. B **106**, 014407 (2022)

TT 13.9 Tue 11:45 H16

Ultrafast generation of multicolor chiral phonons in magnetic and ferroelectric materials — •Omer Yaniv[1] and Dominik M. Juraschek[2] — [1]Tel Aviv University, Tel Aviv, Israel — [2]Eindhoven University of Technology, Eindhoven, Netherlands

Terahertz pulses are powerful tools capable of initiating coherent vibrational motions in solids. Circularly polarized pulses can further excite chiral phonons. Such phonons carry an angular momentum and are able to generate magnetic moments leading to a varying range of phenomena, including the phonon Hall, phonon Zeeman, and phonon inverse Faraday effects. Our study investigates the coherent driving of phonons using multicolor laser pulses, leading to Lissajous trajectories of the atoms. We demonstrate the generation of such multicolor chiral phonons in BaTiO3, a task that presents significant challenges due to the requirement of an exact 1:2 phonon frequency ratio. Achieving this precise ratio is crucial for the generation of closed atomic Lissajous loops. However, we overcome this challenge by creating phonon polaritons with shifted frequencies through the use of optical cavities. This approach allows us to surpass the limitations imposed by the strict phonon frequency ratio. By carefully tuning the cavity parameters, we demonstrate a new pathway for controlling lattice vibrations at ultrafast timescales. We also explore how multicolor phonons tune magnetic properties in monolayer CrI3, a 2D material with strong spin-orbit coupling and ferromagnetism. By manipulating phonon dynamics, we examine the interaction between lattice vibrations and magnetic order.

TT 13.10 Tue 12:00 H16

Chiral Phonons induced by Magnon-Phonon Coupling — •Hannah Bendin[1], Alexander Mook[2], Ingrid Mertig[1], and Robin R. Neumann[1,2] — [1]Martin Luther University Halle-Wittenberg, Halle (Saale), Germany — [2]Johannes Gutenberg University, Mainz, Germany

Chiral phonons, the quasiparticles of circularly polarized lattice vibrations, have recently been investigated due to a range of emerging phenomena. Notably, chiral phonons carry nonzero angular momentum. However, the systems in which they occur still require extensive research. Chiral phonons may, for example, be found in lattices with broken inversion symmetry. Alternatively, they can be induced by the coupling to magnons, the quasiparticles of spin excitations, thereby lifting time-reversal symmetry.

Here, we analyze how magnetoelastic coupling gives rise to magnon-phonon hybridization, which, in turn, generates phonon angular momentum. Conversely, we show how the phonon angular momentum and the spin of the magnons affects their coupling strength. This interplay between magnons and chiral phonons allows for the tunability of the phonon angular momentum.

TT 13.11 Tue 12:15 H16

Ultrafast laser-induced carrier and magnetization dynamics in $SrTiO_3$ from real-time time-dependent DFT — •Andri Darmawan, Markus E. Gruner, and Rossitza Pentcheva — Department of Physics, University of Duisburg-Essen

Recent experimental studies indicate electric-field-driven ferroelectricity [1] and multiferroicity [2] in the paradigmatic nonmagnetic band insulator $SrTiO_3$ in the terahertz regime. Following a comprehensive study of the optical [3] and x-ray absorption [4] spectra including quasiparticle and excitonic effects, here we explore the response of $SrTiO_3$ to laser excitation. Using real-time time-dependent density functional theory (RT-TDDFT) as implemented in the Elk code, we investigate both linear and circular polarized laser pulses. A complex site- and orbital-dependent temporal dynamics is observed with opposite sign of fluctuations at O and Ti sites and charge transfer from O $2p$ to Ti $3d$ states for linearly polarized light, that breaks dynamically inversion symmetry. Notably, circularly polarized pulses induce a finite transient magnetic moment which is absent for linearly polarized pulses. Funding by DFG within CRC1242 (project C02) and computational time at magnitUDE, amplitUDE and the Leibniz Supercomputer Center (project pr87ro) are gratefully acknowledged.

[1] T.F. Nova et al., Science 364, 1075 (2019)
[2] M. Basini et al., Nature 628, 534 (2024)
[3] V. Begum, M.E. Gruner and R. Pentcheva, Phys. Rev. Mater. 3, 065004 (2019)
[4] V. Begum-Hudde et al., Phys. Rev. Res. 5, 013199 (2023)

TT 13.12 Tue 12:30 H16

Phonon pumping in ferromagnet/nonmagnetic insulator hybrid systems — •Richard Schlitz[1], Luise Holder[1], Johannes

Weber[2,3], Mikhail Cherkasskii[4], Fabian Engelhardt[4], Julie Střihavková[5], Matthias Althammer[2,3], Silvia V. Kusminskiy[4,6], Hans Huebl[2,3,7], and Sebastian T. B. Goennenwein[1] — [1]Department of Physics, University of Konstanz, Konstanz, Germany — [2]Walther-Meißner-Institut, BAdW, Garching, Germany — [3]School of Natural Sciences, TUM, Garching, Germany — [4]Institute for Theoretical Solid State Physics, RWTH Aachen University, Aachen, Germany — [5]Faculty of Mathematics and Physics, Charles University, Prague — [6]Max Planck Institute for the Science of Light, Erlangen, Germany — [7]Munich Center for Quantum Science and Technology, München, Germany

In ferromagnetic thin films, magnetization dynamics, e.g., driven by ferromagnetic resonance, can coherently couple to phonons. If a ferromagnetic film is deposited on a crystalline substrate with polished parallel faces, the sample stack forms a bulk acoustic resonator, leading to characteristic modifications of the magnetic resonance signal.

In this work, we show that the magnetoelastic coupling can mediate the hybridization of the coherent magnetization dynamics with longitudinal and transverse phonons, with a particular dependence on the orientation of the magnetic field. We extract the magnetoelastic coupling parameters and compare them with theoretical expectations. Our results show that both longitudinal and transverse phonons can be efficiently excited, depending on the magnetic field orientation.