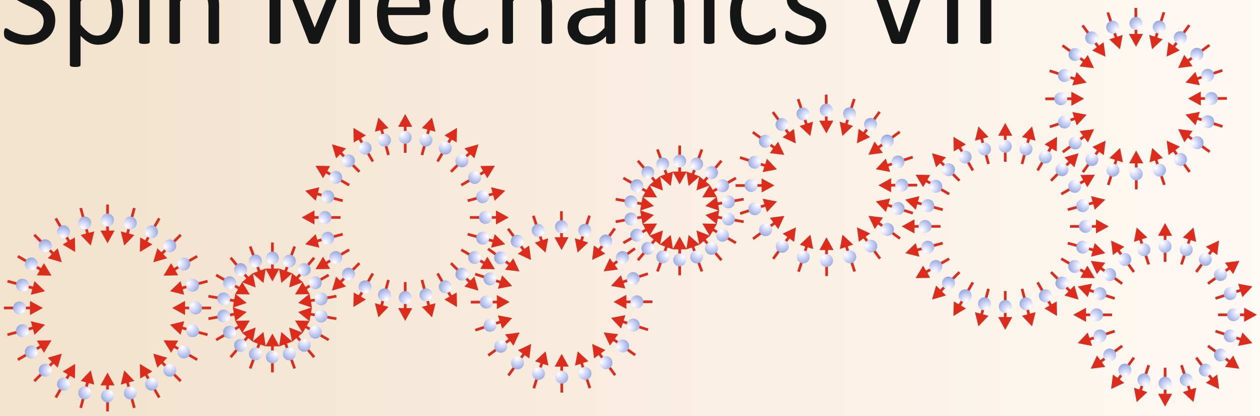
Spin Mechanics VII



August 22 - August 25, 2022
Gerolfingen, Germany

Book of Abstracts

MARTIN-LUTHER-UNIVERSITÄT
HALLE-WITTENBERG

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Welcome

After twice being postponed, Spin Mechanics 7 can now finally take place. Spin Mechanics 7 starts with arrival on the evening of August 21, 2022. Departure will be on August 25.

Goals

The tradition of the spin mechanics is to bring together an interdisciplinary community of scientists, students and engineers interested in the coupling between mechanics, electronic or nuclear spins, or photons. This involves fundamental physics as well as novel techniques to excite or detect spin dynamics.

Topics

- Spin-phonon or magnon-phonon coupling
- Magnetoelasticity and coupling to mechanical oscillations
- Physics of levitated magnetic particles
- Surface acoustic waves
- Resonance force microscopy
- Scanning SQUID or scanning diamond NV-center microscopy

Local organization

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Anti Covid strategy

The pandemic has delayed the conference twice. It is not yet over and we try to keep everyone at the conference safe and healthy. For this purpose, we provide FFP2 masks and quick self-tests for every participant and for every day of the conference with the conference bag at registration.

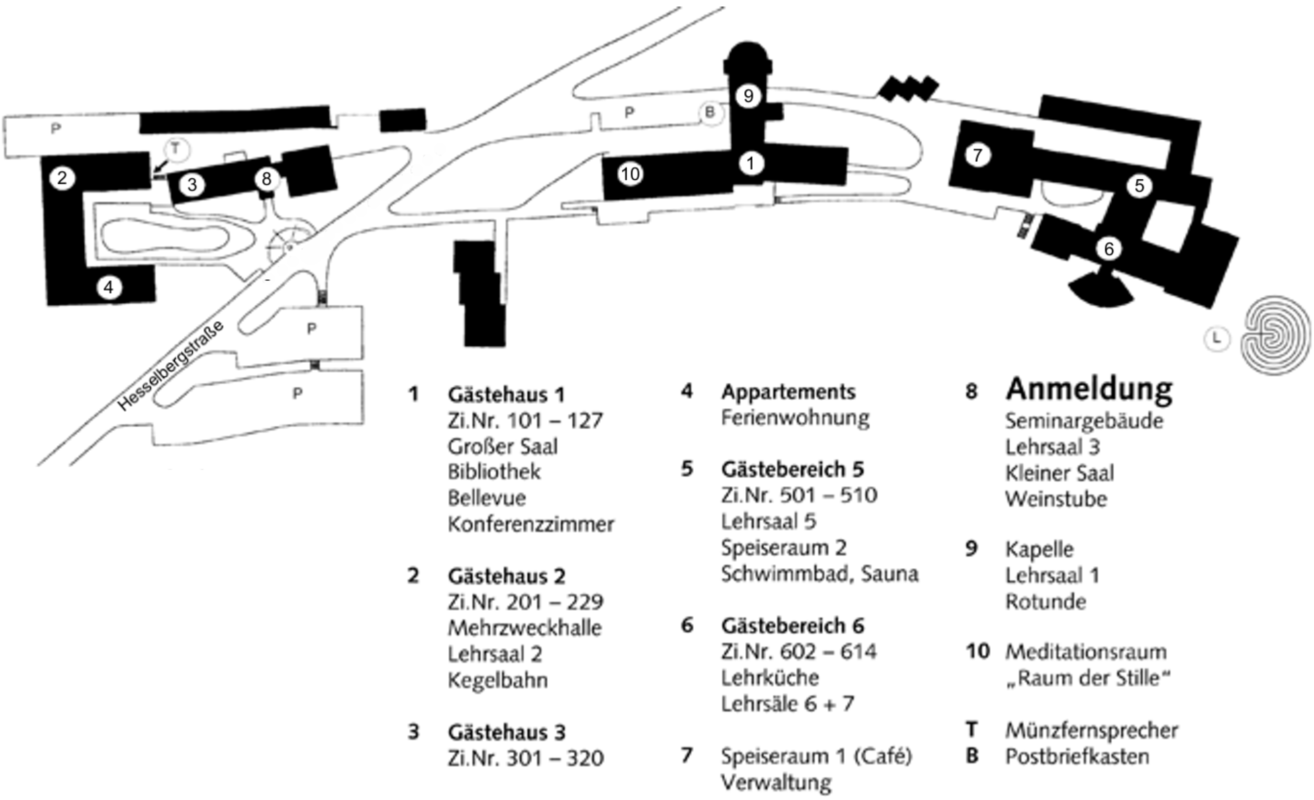
We urge you to do a test every morning and to inform the conference organizers in case of a positive test result.

Wearing the mask is not mandatory but optional. By providing those, we want to make your decision easier. Even if others don't wear a mask don't feel obliged to follow their example if you don't feel like it. But again, it is not mandatory.

We have plenty of space in the auditorium, so you can keep your distance whenever you want during the talks.

Conference location: Bildungszentrum Hesselberg

The Spin Mechanics is held in the Evangelischen Bildungszentrum Hesselberg (Address: Hesselbergstr. 26, 91726 Gerolfingen), located on top of a mountain.



Registration

Participants can register on Sunday evening. Later registration can be done at the conference site during the whole conference.

Housing and meals

All participants will remain at the conference site for the time of their stay so there is ample time to sit together and discuss or just enjoy the August sun. Also all meals will be provided during the conference. We will also have additional coffee breaks during the morning and afternoon sessions.

Drinks and refreshments

While all meals including the barbecue are included in the conference fee, drinks and refreshments are not. You can take what you need and deposit the right amount of cash. This is a matter of trust, so please see that you pay the correct amount for everything you take.

Posters

Posters should be put on the poster boards during the coffee break on Monday morning and can be taken down during the coffee break on Thursday morning. So posters can be visited during all breaks. On Monday and Tuesday evening official poster sessions take place where poster presenters should be available for discussion.

Barbecue

The conference dinner is planned as an outside barbecue that will be held on Wednesday evening after the excursion.

Excursion

The excursion takes place on Wednesday 13:00 and starts with bus transfer to Rothenburg ob der Tauber. It is well known for its well-preserved medieval old town, a destination for tourists from around the world. It is part of the popular Romantic Road through southern Germany. Today it is one of only three towns in Germany that still have completely intact city walls. A guided tour through the historic center is organized.

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Schedule

Sunday, August 21

Registration

Buffet

Monday, August 22

8:00 **Breakfast**

09:00-09:10 Opening remarks
Georg Schmidt

09:10-09:55 A-1: "Long-range Coherent Coupling of Two Magnon Modes using Acoustic Phonons"
Kyongmo An

09:55-10:40 A-2: "Harnessing Magneto-acoustic Coupling to Manipulate Magnetization"
Laura Thevenard

Coffee break

11:00-11:45 A-3: "Multi-mode magnetoelastic coupling in bi- and multi-layer bulk acoustic resonators"
Hans Huebl

11:45-12:30 A-4: "Magnon-Phonon Twist in Metallic Ferromagnets"
Alexey Scherbakov

12:30 **Lunch break**

14:15-15:00 B-1: "Spin Mechanics with trapped diamonds"
Gabriel Hetet

15:00-15:45 B-2: "Precision sensing using spins: measuring materials properties and mechanical degrees of freedom"
Jörg Wrachtrup

Coffee break

16:15-17:00 B-3: "Imaging Berry-curvature magnetism and Chern mosaic in magic-angle graphene"
Eli Zeldov

18:00 **Dinner**

19:15 **Poster session**

Tuesday, August 23

8:00 **Breakfast**

09:00-09:45 C-1: "Cavity Magnomechanics: Harnessing the Magnomechanical Coupling for Applications in the Microwave and Optical Regimes"
Silvia Viola-Kusminskiy

09:45-10:30 C-2: "Phonon Spin in Magnetic Insulators"
Andreas Rückriegel

Coffee break

10:50-11:35 C-3: "Non-linear Magnetomechanics"
Gerhard Kirchmair

11:35-12:20 C-4: "Theory of Kerr enhanced backaction cooling in magnetomechanics"
Anja Metelmann

12:30 **Lunch break**

14:15-15:00 D-1: "Quantum Acoustomechanics with a Micromagnet"
Oriol Romero-Isart

15:00-15:45 D-2: "Magnetic Membranes in Motion"
Herre van der Zant

Coffee break

16:15-17:00 D-3: "Quantum imaging of nanoscale magnetic textures"
Christian Degen

18:00 **Dinner**

19:15 **Poster session**

Wednesday, August 24

8:00 **Breakfast**

09:00-09:45 E-1: "Antiferromagnets and Strain"
Mathias Kläui

09:45-10:30 E-2: "Spin-current Induced Magnetostriction in a Ferromagnet Tb0.3Dy0.7Fe2"
Hiroki Arisawa

Coffee break

10:50-11:10 E 3: "Three-axis Torque Investigation of Interfacial Exchange Coupling in a NiFe/CoO Bilayer Magnetic Disk"
Michael Dunsmore

11:10-11:30 E 4: "Strain Tuning of Ferromagnetic Resonance in the Low-Loss Organic-Based Ferrimagnet V[TCNE]x~2"
Seth W. Kurfman

12:00 **Lunch break**

13:00 **Excursion**
Bus transfer to Rothenburg ob der Tauber, guided tour through the historic center

18:00 **Barbecue**

Thursday, August 25

8:00 **Breakfast**

09:00-09:45 F-1: "Parametric Pumping of Spin Waves by Surface Acoustic Waves"
Albrecht Jander

09:45-10:30 F-2: "Frequency-resolved Imaging of magneto-elastically driven Spin-Waves"
Rouven Dreyer

Coffee break

10:50-11:35 F-3: "Nonreciprocity in surface acoustic waves driven magnon-phonon coupling"
Mingran Xu

11:35 Closing remarks

12:20 **Lunch break**

Departure

List of posters

P-1: "Magnetic field-dependent ultrafast control of an antiferromagnet"
Abeer Arora

P-2: "Coupled Oscillators with Classical and Quantum Flavours"
Lorenzo Bernazzani

P-3: "Magnon Phonon quantum correlation thermometry"
Victor Bittencourt

P-4: "Dominant Higher-Order Gyromodes in Dome-Shaped Nanodots"
Artem Bondarenko

P-5: "Investigation of THz electromagnetic response in nanopatterned magnetic heterostructures by current confinement"
Bikash Das Mohapatra

P-6: "Optimal Broad-Band Frequency Conversion via a Magnomechanical Transducer"
Fabian Engelhardt

P-7: "Micromagnetic Simulations for Mechanical Studies of Magnetic Dynamics"
Katryna Fast

P-8: "Shape Anisotropy of NiO/Pt thin films"
Felix Fuhrmann

P-9: "Strong photon-magnon-coupling between niobium lumped-element-resonators and micron sized permalloy stripes"
Philipp Geyer

P-10: "Magnon Contributions to the Heat Conductivity of Insulating Antiferromagnets"
Gerhard Jakob

P-11: "Development of Co2FeSn Heusler alloy films and nanocrystals for magnetic and magneto-optical applications"
Md Rejaul Karim

P-12: "Spin-Wave Physics At Ultralow Temperatures"
Sebastian Knauer

P-13: "Optimizing Spin Wave Lenses to Amplify Spin Wave Intensity"
Stephanie Lake

P-14: "Optical Detection of Antiferromagnetic Resonance In Van Der Waals Antiferromagnet"
Alex Melendez

P-15: "High-Sensitivity Magnetic Field Imaging of AC and DC Currents in Bilayer Graphene"
Marius Palm

P-16: "Advances in 3D Magnetic Resonance Force Microscopy"
Nils Prumbaum

P-17: "Strong Suppression of the Spin Seebeck Effect in a Nearly Compensated Ferrimagnet"
Rafael Ramos

P-18: "Generating Arbitrary Quantum States of Magnetization"
Sanchar Sharma

P-19: "Conservation Laws for Adiabatic Spin-Lattice Dynamics"
Simon Streib

Notes

Abstracts

Long-range Coherent Coupling of Two Magnon Modes using Acoustic Phonons

K. An[1,2,*], R. Kohno[1], A.N. Litvinenko[1], R. Lopes Seeger[1], V. V. Naletov[1], L. Vila[1], G. de Loubens[3], J. Ben Youssef[4], N. Vukadinovic[5], G.E.W. Bauer[6,7], A. N. Slavin[8], V. S. Tiberkevich[8], and O. Klein[1],

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We study the coupled dynamics of two magnets on both sides of a thick crystal spacer. The magnets communicate by acting as "speakers" as well as "microphones" for sound waves. We previously demonstrated the coherent mediation of angular momentum by circularly polarized phonons through a nonmagnetic material over 0.5 mm [1]. The system can be brought into tripartite hybridization by carefully tuning the two ferromagnetic resonance frequencies to a degenerate acoustic resonance of the crystal. Being in a regime where the interaction strength between the magnetic excitations is larger than their decay rate, the system is in the strong coupling regime in which the entire system of magnetization and lattice can only oscillate coherently. We show there that illumination of the bright and dark collective modes by a uniform microwave field depends on the parity of the phonon mode, which decides if the lattice displacement at the position of the two magnets is out-of-phase or in-phase. Depending on the parity of intermediate standing lattice waves, the interference is constructive or destructive, giving rise to the bright and dark collective modes [2].

References

[1] K. An & O. Klein et al., Physical Review B 101, 060407 (2020)
[2] K. An & O. Klein et al., Physical Review X 12, 011060 (2022)

Harnessing Magneto-acoustic Coupling to Manipulate Magnetization

A. Vythelingum[1], D. Nguyen[1], A. Mougin[2], J. Sampaio[2], V. Uhlíř[3], J.A. Arregi[3], J-Y. Duquesne[1], C. Gourdon[1] , L Thevenard[1]

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Magnetization precession may be triggered by a variety of stimuli, such as radio-frequency (rf) fields, currents or acoustic waves. In the latter case, an effective field is indeed generated through magneto-elasticity. These dynamics can then be implemented in systems encoding magnetically information, such as the free layer of magnetic tunnel junctions, or the phase of spin-waves in magnonic devices.

In the linear regime of a forced excitation, the magnetization rotates with an amplitude (frequency) proportional (equal) to that of the excitation. Here, we demonstrate how one can reach the non-linear dynamics regime using large amplitude surface acoustic waves (SAW) travelling on a thin layer of (Ga,Mn)As [1]. The resonance frequency of this magnetic semiconductor can easily be tuned to typical SAW frequencies, excited piezoelectrically by interdigitated transducers. We will first show signatures of the non-linear magnetoacoustic response on the magnetic dynamics, then a full resonant magnetic switching strictly induced by a SAW. We will explicit the conditions on magnetic field and SAW power to obtain these effects, and show they are equally efficient on in-plane and out-of-plane magnetized ferromagnets [2], [3]. We will describe in detail the experimental techniques implemented, the pros and cons of this approach compared to other magneto-acoustic excitations, and conclude on how these results could be relevant to other magnetic systems, such as antiferro- or ferri-magnets.

References

1. M. Kraimia *et al.*, Phys. Rev. B, **101**, 144425 (2020).
2. P. Kuszewski *et al.*, J. Phys. Condens. Matter, **30**, 244003 (2018)
3. L. Thevenard *et al.*, Phys. Rev. B, **93** 134430 (2016.)

Multi-mode magnetoelastic coupling in bi- and multi-layer bulk acoustic resonators

H. Huebl[1,2,3]

[1] *Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany*

[2] *Physik-Department, Technische Universität München, Garching, Germany*

[3] *Munich Center for Quantum Science and Technology (MCQST), München, Germany*

Magnetoelastic coupling between wave-like excitations of the spin system (spin waves) and the lattice (elastic excitations) is of interest from a fundamental perspective of mode hybridization as well as for wavelengths transduction applications. In my presentation, I will focus on magnetic thin films on bulk substrates. The resulting structures host a magnetic resonance as well as elastic resonances in the form of a standing stress field of a bulk acoustic resonator. The magnetoelastic interaction then allows to couple these modes. We observe the characteristic signature of the resonances of a bulk acoustic resonator in the ferromagnetic resonance spectroscopy of the Kittel mode which allows to deduce the magnetic and the elastic properties as well as their coupling. Temperature depended experiments reveal a change in the acoustic quality factor which allows to observe an additional substructure of the elastic modes. This data gives further insight to the modes at play as well as their mode-structure. On the long run, we expect that these results contribute to the development of a better understanding of magneto-elastic hybrids and hereby paves the way to frequency conversion applications.

Magnon-Phonon Twist in Metallic Ferromagnets

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The interaction of lattice vibrations (phonons) and precessing spins (magnons) in magnetic materials has a long history of research. It was widely investigated by classical acoustic methods in ferromagnetic insulators [1] but did not find its way to practical applications. The recent development of nanoscale and quantum communications has revived interest in the magnon-phonon interaction as a basis for coherent information processing [2]. Phonons exhibit long lifetimes in various materials, and the localization or propagation of specific phonon modes can be set by nanostructure design. Magnons have excellent tunability through an external magnetic field. Generalizing these properties in a hybridized excitation is attractive but not easy to implement: the weak magnon-phonon interaction and short magnon lifetimes jeopardize magnon-phonon coupling in technologically friendly ferromagnetic metals. The talk will show the approaches to overcome these limitations and observe the manifestations of the magnon-phonon interaction, which recently seemed unattainable.

I will present an overview of the experiments with metallic $Fe_{0.81}Ga_{0.19}$ (Galfenol) nanostructures [3-4]. By combining surface periodic nanopatterning and planar phononic Bragg mirrors, we control the lifetimes and localization of the phonons modes and their spatial matching with the magnon modes. In the pump-probe experiment, we detect the coherent response of the lattice and the spin system on the ultrafast optical excitation. When the frequencies of the selected magnon and phonon modes coincide, their interaction determines the transient signals. Depending on the structure design, we observe the strong coupling of the localized phonon and magnon modes with the formation of a hybridized state or, in contrast, the driving of magnons with a multimode phonon wavepacket propagating beneath the surface. Simple theoretical models and numerical visualization will support the experimental observations. We will also discuss the experimentally observed benefits of the coupled state formation as well as the paths to exploit it in future applications.

References

1. O. Yu. Belyaeva et al., Sov. Phys. Uspekhi **35**, 106 (1992).
2. Y. Li et al., APL Materials **9**, 060902 (2021).
3. F. Godejohann et al., Phys. Rev. B **102**, 144438 (2020).
4. D. Yaremkevich et al., ACS Nano **15**, 4802 (2021).

Spin Mechanics with Trapped Diamonds

M. Perdriat, C. Pellet-Mary, P. Huillery, G. Hétet[1]

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Many research groups are investigating platforms for coupling the motion of levitating particles to the spin of individual atoms at the quantum level. The angular degrees of freedom of levitating diamonds coupled to embedded Nitrogen-Vacancy (NV) centers offer bright prospects towards this purpose [1].

I will present our results on coherent manipulations of the spin of NV centers [2] and of the spin-dependent torque and spin-cooling of the angular motion of diamonds levitating in a Paul trap [3]. I will then discuss our recent efforts towards using dipolar interactions between NV centers to control the angular motion of diamonds [4] as well as our observations of spin-diamagnetism mediated by NV centers under magnetic field above a level crossing at ≈ 0.1T (see Figure 1). I will show how the negative magnetic susceptibility enables microwave-free magneto-optical alignment of the diamond main axes along the magnetic field [5], offering prospects towards spin-levitation and angular control of diamonds under viscous environments.

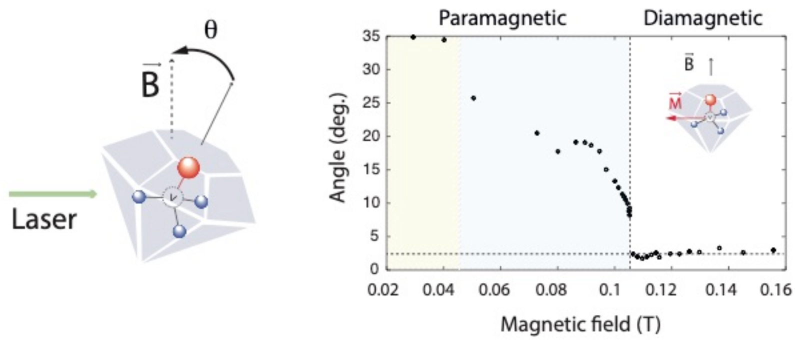

Figure 1: Magnetic torque on a levitating diamond using optically polarized NV centers. Right : Angle of one of the diamond [111] axis versus magnetic field amplitude

References

1- M. Perdriat, C. Pellet-Mary, P. Huillery, L.Rondin, and G. Hétet, Micromachines 12 (2021).
2- T. Delord, P. Huillery, L. Schwab, L. Nicolas, L. Lecordier, and G. Hétet, Phys. Rev. Lett. 121, 053602 (2018).
3- T. Delord, P. Huillery, L. Nicolas, and G. Hétet, Nature 580, 56 (2020).
4- C. Pellet-Mary, P. Huillery, M. Perdriat, and G. Hétet, Phys. Rev. B 104, L100411 (2021).
5- M. Perdriat, P. Huillery, C. Pellet-Mary, and G. Hétet, Phys. Rev. Lett. 128, 117203 (2022)

Precision sensing using spins: measuring materials properties and mechanical degrees of freedom

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2D materials are exciting new platforms for the study of spin physics. Recently magnetic order in those materials have been found. The investigation of magnetic order in 2D materials requires dedicated probes. While conventional probes of magnetism with nanoscale resolution, like Lorenz microscopy or MFM fail for few layer- or monolayer samples, STM requires dedicated sample preparation. NV-based magnetic probes on the other hand are very well suited to provide quantitative data with a few ten nm spatial resolution and sufficient sensitivity, even for monolayer samples. In the talk I will describe experiments on $CrBr_3$ which show the domain structure of the material [1]. Upon imaging material with different number of layers we gained insight into interlayer coupling and it impact on magnetic order. We also measure magnetic order over a wide range of temperatures and derive information on the physics of the phase transition of $CrBr_3$. In addition, I will show measurements on CrI_3 samples of different thickness and relative orientation where we find signatures of Moiré patterns in twisted multilayers [2].

Spins in 2D materials are discussed as interesting platforms for quantum simulations. Nuclear spins in those systems are e.g. capable of mimicking phase transitions in long-range coupled spin systems. In the talk I will show attempts to cool these spin systems to their ground state and manipulate order with external magnetic fields.

References

1 Qi-Chao Sun et al., *Magnetic domains and domain wall pinning in atomically this $CrBr_3$ revealed by nanoscale imaging*, Nature Comm. **12**, 1989 (2021)

2 Qi-Chao Sun et al., *Direct visualization of magnetic domains and moiré magnetism in twisted two-dimensional magnets*, Science **374**, 1140 (2021)

3 Farida Shagieva et al., *Microwave-Assisted Cross-Polarization of Nuclear Spin Ensembles from Optically Pumped Nitrogen-Vacancy Centers in Diamond*, Nano Lett. **18**, 3731 (2018)

4 M. Raghunandan et al., *High-Density Quantum Sensing with Dissipative First Order Transitions*, PRL **120**, 150501 (2018)

Imaging Berry-curvature magnetism and Chern mosaic in magic-angle graphene

Eli Zeldov

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Charge carriers in magic angle graphene come in eight flavors described by a combination of their spin, valley, and sublattice polarizations. When inversion and time reversal symmetries are broken, the flavor degeneracy can be lifted and their corresponding bands can be filled sequentially. Due to their non-trivial band topology and Berry curvature, each of the bands is classified by a topological Chern number C, leading to the quantum anomalous Hall and Chern insulator states. Using scanning superconducting quantum interference device on a tip (SQUID-on-tip), we image the nanoscale Berry-curvature-induced equilibrium orbital magnetization, the polarity of which is governed by C, thus providing the means for resolving the local band topology [1]. At integer filling $\nu = 1$, we observe a zero-field Chern insulator, which rather than being described by a global topologically invariant C, forms a Chern mosaic of microscopic patches of $C = -1$, 0, or 1. Upon further filling, we find a first-order phase transition due to recondensation of electrons from valley K to K', leading to irreversible flips of the local Chern number and magnetization, and to the formation of valley domain walls giving rise to hysteretic anomalous Hall resistance.

References

1 S. Grover, M. Bocarsly, A. Uri, P. Stepanov, G. Di Battista, I. Roy, J. Xiao, A. Y. Meltzer, Y. Myasoedov, K. Pareek, K. Watanabe, T. Taniguchi, B. Yan, A. Stern, E. Berg, D. K. Efetov, and E. Zeldov, arXiv:2201.06901

Cavity Magnomechanics: Harnessing the Magnomechanical Coupling for Applications in the Microwave and Optical Regimes

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[2] *Max Planck Institute for the Science of Light, Erlangen, Germany*

Cavity magnonic systems are ideally suited to explore the range of possibilities opened by tailoring the interactions between photons, phonons, and magnons. In this talk I will discuss the different coupling mechanisms and propose applications ranging from quantum thermometry to wavelength conversion.

Phonon Spin in Magnetic Insulators

Andreas Rückriegel

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Besides the conduction electrons and magnetic quasiparticles like magnons, there is in principle another carrier of angular momentum in every solid state system: the phonon. Similar to photons, phonons can carry an intrinsic angular momentum, often called the "phonon spin", related to microscopic circular shear displacements without a global rotation of the system. I will discuss in what kind of physical systems and situations one can expect this phonon spin to be relevant. The phonon spin can be driven by the magnetization dynamics, which even makes it possible to inject a spin current into nonmagnetic insulators. This current leads to a non-local spin transfer between two magnets that are separated by a nonmagnetic insulator. I will show that for realistic materials, such a phonon spin current decays over millimeter length scales, and can be controlled by the system dimensions and the ferromagnetic resonance frequency of the magnets.

Nonlinear Magneto-Mechanics

D. Zoepfl,[1, 2, *] M. L. Juan,[3] N. Diaz-Naufal,[4] C. M. F. Schneider,[1, 2] L. F. Deeg,[1, 2] A. Sharafiev,[1,2] A. Metelmann,[4, 5, 6] and G. Kirchmair[1, 2,]

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The possibility to operate massive mechanical oscillators in the quantum regime has become central in fundamental sciences. Optomechanics, where photons are coupled to mechanical motion, provides the tools to control mechanical motion near the fundamental quantum limits. Our setup [1] consists of a magnetic field sensitive cavity coupled to a magnetic cantilever, a beam equipped with a magnet on its tip, leading to a position dependent magnetic field. A SQUID embedded in our superconducting cavity provides the sensitivity to magnetic fields. In this magneto-mechanical system, we achieve single photon coupling strength, which are among the highest in the field and more than a factor of ten larger compared to other electro-mechanical systems.

Despite working at cryogenic temperatures, macroscopic mechanical objects (i.e. the cantilever) are in highly excited thermal states and need to be cooled close to the ground state in order to investigate quantum phenomena. We demonstrate a novel cooling scheme [2] by using the intrinsic nonlinearity of the cavity induced by the SQUID. We show, that the non-linearity has to be included in describing the back action and demonstrate a one order of magnitude improvement in the cooling compared to a linear system with comparable parameters. With our system it seems to be possible to overcome the back-action limit, which limits the cooling performance in linear cavities.

References:

1. Single-Photon Cooling in Microwave Magnetomechanics
   D. Zöpfl, M. L. Juan, C. Schneider, G. Kirchmair
   Phys. Rev. Lett. 125, 023601 (2020); https://doi.org/10.1103/PhysRevLett.125.023601
2. Kerr nonlinear enhanced backaction cooling in magnetomechanics
   D. Zoepfl, M. L. Juan N. Diaz-Naufal C. M. F. Schneider, L. F. Deeg, A. Sharafiev, A. Metelmann, and G. Kirchmair (2022)
   arxiv:2202.13228

Theory of Kerr enhanced backaction cooling in magnetomechanics

A. Metelmann

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Ground state cooling of a mechanical resonator is the prerequisite to utilize them for quantum information processing, and for ultrasensitive precision measurements at the quantum limit. In the field of cavity optomechanics dynamical backaction cooling and feedback protocols have been successfully used to bring macroscopic mechanical elements into or near the quantum ground state. Cooling in the linear regime of optomechanics has been extensively studied in the literature, and it has been theoretically proposed that utilizing a nonlinear cavity can improve the cooling efficiency. We revisit this nonlinear regime and study the cooling properties of a mechanical resonator coupled to a nonlinear cavity, acting as a high-Q Duffing oscillator. We compare our theory with experimental results obtained in a magnetomechanical platform, which show that the presence of the Duffing-nonlinearity improves the cooling efficiency significantly.

Quantum Acoustomechanics with a Micromagnet

Oriol Romero-Isart and Carlos Gonzalez-Ballestero

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In this talk I will give an introduction the field of levitodynamics [1]: levitation and control of microscopic objects in vacuum. I will then focus on some theoretical results [2,3] that show to strongly couple the center-of-mass motion of a micromagnet in a harmonic potential to one of its acoustic phononic modes. The coupling is induced by a combination of an oscillating magnetic field gradient and a static homogeneous magnetic field. The former parametrically couples the center-of-mass motion to a magnonic mode while the latter tunes the magnonic mode in resonance with a given acoustic phononic mode. The magnetic fields can be adjusted to either cool the center-of-mass motion to the ground state or to enter into the strong quantum coupling regime. The center of mass can thus be used to probe and manipulate an acoustic mode, thereby opening new possibilities for out-of-equilibrium quantum mesoscopic physics. Our results hold for experimentally feasible parameters and apply to levitated micromagnets as well as micromagnets deposited on a clamped nanomechanical oscillator.

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Magnetic Membranes in Motion

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Atomically thin membranes are ideal building blocks for nanoelectromechanical systems (NEMS) because of their unique mechanical properties and their low mass. We make membranes by transferring atomically thin layers on top of silicon oxide substrates that are pre-patterned with circular or rectangular holes. The suspended membranes are characterized by a laser interferometer set-up that gives access to information on the dynamical mechanical properties in the frequency- and time-domain. Recently, it has become clear that nanomechanics can also probe thermodynamic properties such as thermal conductivity, specific heat, and thermal expansion [1]. Specifically, phase transitions are typically accompanied by abrupt changes in the specific heat, resulting in accompanying changes in the strain of the material which can be measured via the mechanical resonance frequency. In this way, we have detected the Néel temperature of antiferromagnetic $FePS_3$ membranes [2], their magnetic anisotropy and studied the nonlinear coupling between magnetic and elastic properties.

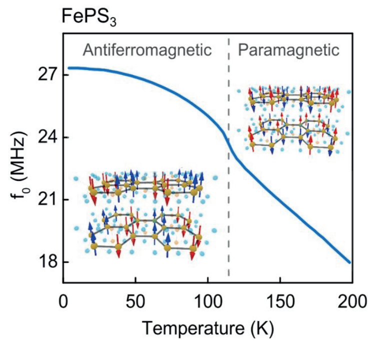

Figure 1: A kink in the resonance frequency vs. temperature curve signals the magnetic phase transition in $FePS_3$.

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Quantum imaging of nanoscale magnetic textures

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Nanoscale magnetic fields contain rich information about the structure, organization and physics of matter. At a close enough look, almost any material or device generates a magnetic stray field, even if often minute: Examples range from magnetically ordered materials, like ferromagnets and antiferromagnets, to superconducting materials, to currents flowing in conductors, to electronic and nuclear spins in molecules and biological matter. Our group is developing new experimental probes for imaging tiny magnetic fields with nanometer spatial resolution.

In this talk, I will discuss our progress with scanning diamond magnetometers in pursuit of this goal. Diamond magnetometers rely on a single spin defect in a probe tip (a nitrogen-vacancy center) and exploit concepts of quantum metrology to reach very high sensitivities. In a first part of the talk I will discuss instrumental challenges in the fabrication of diamond probes and their integration into scanning probe microscopy (SPM) systems. In the second part I will present illustrative examples of applications in nanoscale magnetism, including the imaging of antiferromagnetic domains and domain walls and the flow of currents in graphene devices. I will conclude with an outlook on simultaneous imaging of electric and magnetic fields in multiferroics.

Antiferromagnets and Strain

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While known for a long time, antiferromagnetically ordered systems have previously been considered, as “interesting but useless”. However, since antiferromagnets potentially promises faster operation, enhanced stability and higher integration densities, they could potentially become a game changer for new spintronic devices. Here I will show how antiferromagnets can be used as active spintronics devices by demonstrating the key operations of “reading” [1], “writing” [2], and “transporting information” [3] in antiferromagnets.
A key issue for antiferromagnets is the strong magneto-elastic coupling. This allows one to use even relatively modest strain to manipulate the Néel vector. We have shown that both mechanical strain and piezoelectrically generated strain can be used to manipulate the antiferromagnetic order [4]. Furthermore, the domain configuration in confined geometries is also very dependent on the strain to relaxation and element edges leading to an effective shape anisotropy concept [5].

Finally, we find that strain plays a key role in the current-induced switching of antiferromagnts. To investigate the current-induced switching, we employ different devices and pulsing geometries in which the pulsing along the same current direction $\boldsymbol{j}$ leads to opposite switching directions of the antiferromagnetic order $\boldsymbol{n}$, contrary to an SOT-based switching mechanism. We also observe that a single current pulse can lead to the formation of different domains with opposite final states $\boldsymbol{n} \parallel \boldsymbol{j}$ or $\boldsymbol{n} \perp \boldsymbol{j}$. We can attribute such reversal to thermomagnetoelastic switching processes, as simulated current induced heat and strain profiles in the respective devices favor different switching final states. Combined with electrical measurements of the spin Hall magnetoresistance, we can now reconcile previously conflicting reports of the final state of the switching in different device geometries. We achieve reversible thermomagnetoelastic switching in regions where no current flows in a custom-developed device geometry in the absence of contributions from spin-transfer and spin-orbit torque mechanisms [6]. We demonstrate that strain, in AFMs with strong magnetoelastic coupling, can enable the control and readout of antiferromagnetic ordering. Thus, strain can be a powerful tool to tailor antiferromagnetic devices.

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Spin-current Induced Magnetostriction in a Ferromagnet $Tb_{0.3}Dy_{0.7}Fe_2$

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The interplay between magnetization and strain in a magnet has long been an important issue in magnetism. The typical example is the magneto-volume effect (MVE) [1] in a ferromagnet, the volume change connected to the spin fluctuation modulation. Extensive studies on the MVE have been made by controlling spin fluctuation via magnetic field application or temperature modulation, leading to remarkable progress in the physics of spin fluctuation and electronic correlation. Now, owing to the recent progress of spintronics, spin fluctuation can be directly modulated by using a spin current [2], enabling us to expand the physics of magnetomechanical dynamics in the MVE into a spintronics framework.

We have investigated a spin current volume effect [3], volume manipulation by using a spin current, in a giant magnetostrictive material $Tb_{0.3}Dy_{0.7}Fe_2$. By injecting a spin current into a $Tb_{0.3}Dy_{0.7}Fe_2$ film, we demonstrated that the $Tb_{0.3}Dy_{0.7}Fe$ film thickness changes in response to the spin current injection (Fig. 1). We performed theoretical calculation and found that the spin-current induced modulation of magnetization fluctuation well reproduces the experimental results, which offers a way for magnetomechanical control of mechanical actuators based on spintronics.

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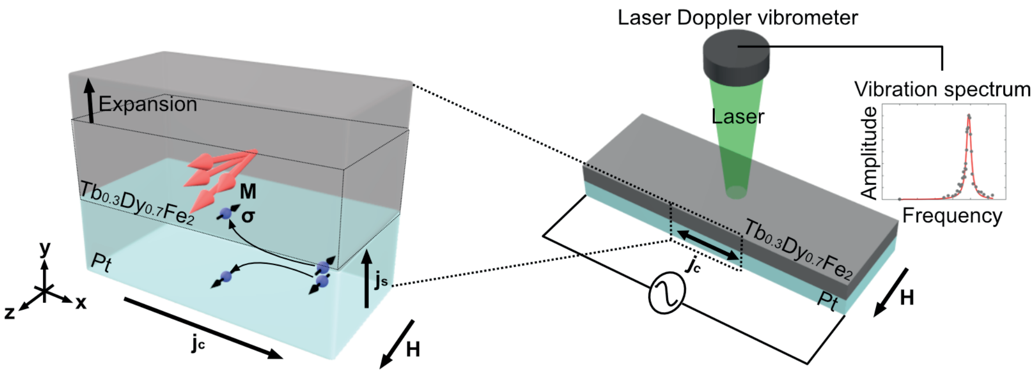

Figure 1: A schematic illustration of a measurement setup.

Three-axis Torque Investigation of Interfacial Exchange Coupling in a NiFe/CoO Bilayer Magnetic Disk

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Effects of interfacial exchange coupling between ferromagnetic permalloy (Py) and antiferromagnetic cobalt oxide (CoO) bilayers have been measured by simultaneous three axis AC torque magnetometry of nanomechanical resonators [1, 2]. An electron micrograph of the resonator is shown in Figure 1, arrows are drawn to serve as a visual aid pertaining to the motion of the paddle when a torque is applied along one of the three principal axes. To improve mechanical compliance of x and z torques, one of the torsion paddle's arms was severed. Measurements of magnetic torque were made throughout a rotation of an in-plane DC magnetic field and were used to investigate anisotropies emerging from exchange coupling at Py/CoO interface. The simultaneous three-axis measurement capability of our experiment permits measurement of the z torque that is uniquely sensitive to effects of exchange coupling at the bilayer interface.

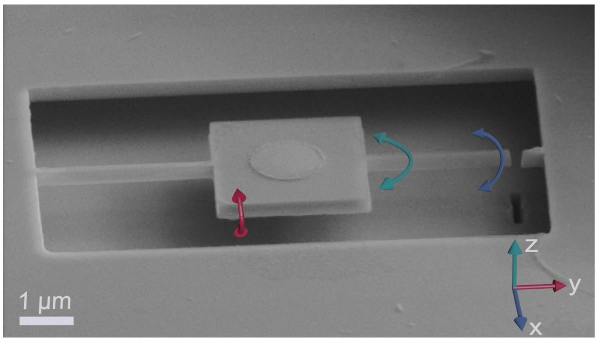

Figure 1: Electron micrograph of the nanomechanical resonator with Cartesian axes indicating principal axes along which torques are applied.

Macrospin simulations of the Landau-Lifshitz-Gilbert equation were used to simulate the three axes of torque and serve as a method to fit to experimental results. There are three effects of exchange coupling [3] that are required to explain features of our data: unidirectional anisotropy, rotatable anisotropy, and spin flop anisotropy. Each anisotropic contribution corresponds to unique features of our observations. Study of other effects of interfacial exchange coupling such as the training effect will also be discussed.

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Strain Tuning of Ferromagnetic Resonance in the Low-Loss Organic-Based Ferrimagnet V[TCNE]$_{x\sim2}$

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We demonstrate strain-based tuning of ferromagnetic resonance (FMR) in devices that integrate the low-loss ($\alpha \sim 4 \times 10^{-5}$), molecule-based, room-temperature ferrimagnet vanadium tetracyanoethylene (V[TCNE]$_{x\sim2}$) mechanically coupled to PMN-PT piezoelectric transducers. Upon straining the V[TCNE]$_x$ films, we demonstrate shifts of the FMR frequency by more than 6 times the resonant linewidth with no change in damping. This tuning effect is due to a strain-dependent magnetic anisotropy in the films via magnetostriction effects, and demonstrates a platform for voltage-tuned devices and applications utilizing V[TCNE]$_x$. These experimental results are backed by density functional theory (DFT) calculations of the magnetostriction. This combination of ultra-narrow linewidth and magnetostriction in a flexible, organic-molecule-based magnet promises unprecedented functionality for electric-field tuned microwave devices ranging from low-power, compact filters and circulators to emerging applications in quantum information science and technology.

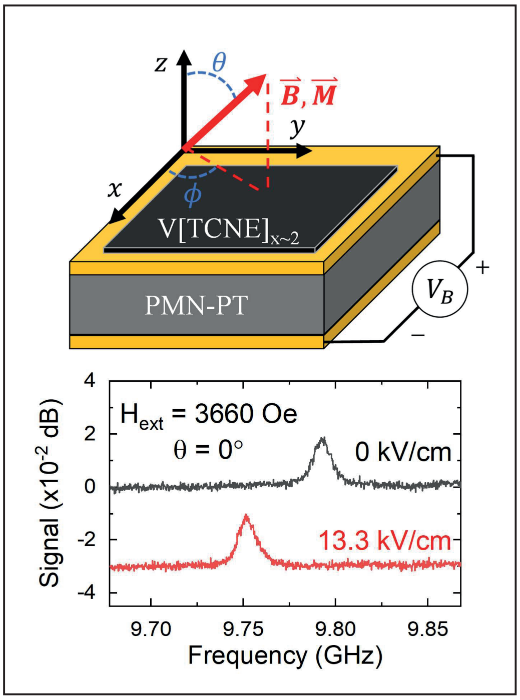

Figure 1: Device diagram and frequency-swept FMR without (0 kV/cm) and with (13.3 kV/cm) applied strain.

Parametric Pumping of Spin Waves by Surface Acoustic Waves in Thin-Film YIG

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We consider the conditions for effective parametric pumping of forward volume spin waves by surface acoustic waves in thin-film YIG through micromagnetic simulation and experiment. With positive dispersion and isotropic in-plane propagation, forward volume waves are convenient for implementation of magnonic devices. However, due to the nearly circular precession, they are not efficiently pumped by magnetic fields. We show that forward volume waves can be pumped by anisotropy modulation via magneto-elastic coupling to acoustic waves [1]. For effective pumping, the acoustic pumping wave, the incoming signal spin wave and the resulting idler spin wave must meet conditions of energy and momentum conservation respectively: $\omega_p = \omega_s + \omega_i$, $\vec{\boldsymbol{k}}_p = \vec{\boldsymbol{k}}_s + \vec{\boldsymbol{k}}_i$. The pumping efficiency is further dependent on the relative orientations of the magnetization and strain vectors relative to the magneto-elastic tensor components. Micromagnetic simulation confirms the vector relationship between the signal, pump and generated idler wave (Fig. 1).

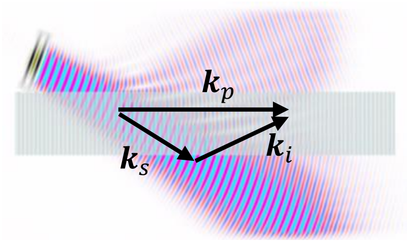

Figure 1: Micromagnetic simulation of a beam of forward volume spin waves parametrically pumped by a surface acoustic wave.

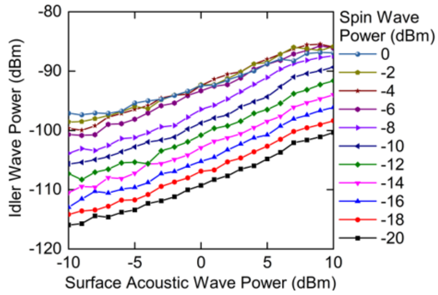

Figure 2: Idler wave power versus signal and pump power for a forward volume spin wave pumped by a standing surface acoustic wave.

With a perpendicular orientation between the acoustic and spin wave vectors, pumping can occur only with a standing acoustic wave. For this case, we have shown experimentally the generation of an idler with an amplitude proportional to the product of the signal and pump amplitudes (Fig. 2) [2]. Parametric pumping by acoustic waves is thus a promising way to amplify spin waves in YIG and other magnetostrictive materials. Further, the interaction can be used for non-linear signal processing, such as frequency conversion and microwave signal correlation.

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Frequency-Resolved Imaging Of Magneto-Elastically Excited Spin Waves

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In recent years, surface acoustic waves (SAWs) have proven to be an alternative excitation mechanism for magnetization dynamics which may pave the way towards novel magnonic applications. So far, most studies on SAW driven magnetization dynamics rely on integrating vector network analyzer techniques [1]. However, this approach yields only limited information about the local properties of the elastically excited spin waves. In contrast, optical detection approaches help to identify these properties on a diffraction limited scale. Thus, we utilize Super-Nyquist-Sampling magneto-optical Kerr microscopy (SNS-MOKE) [2] to reveal the elastically driven dynamics in a local fashion. In addition to these local phase-resolved measurements, SNS-MOKE allows to separate magnetic and non-magnetic signal contributions. Using this technique, we directly image the elastically driven dynamics in lithographically patterned micron-sized Nickel elements as well as in transferred monocrystalline YIG microstructures [3] as a function of various experimental parameters. In doing so, we reveal the wave vectors of the spin waves excited by the SAW and compare it with micromagnetic simulations.

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Nonreciprocity in surface acoustic waves driven magnon-phonon coupling

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In 1963, J. R. Eshbach experimentally demonstrated the magnetoelastic waves excitation in YIG (Yttrium iron garnet) [1]. In the presence of magnon-phonon coupling (MPC), dispersions of the magnons and phonons are no longer independent.

In recent years, surface acoustic waves driven MPC has attracted enormous attention due to the emergence of the nonreciprocity [2]. As shown in Fig. 1., depending on the propagation direction, surface acoustic waves rotate the lattice in opposite direction. This rotational motion can couple with the magnetization via magneto-rotation coupling [2, 3], giving rise to a circularly polarized effective field, which either suppresses or enhances the magnetization precession (purple cone in Fig. 1.), and in turn induces a nonreciprocal attenuation on the surface acoustic waves [4].

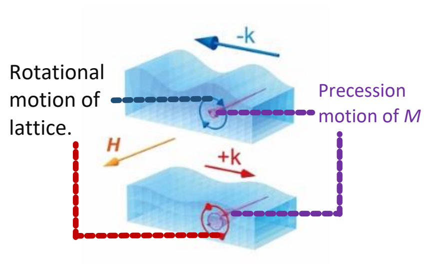

Figure 1: Schematics of the magneto-rotation coupling.

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Posters

Magnetic Field-Dependent Ultrafast Control of an Antiferromagnet

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Antiferromagnets, due to their zero net magnetization, offer faster manipulation of spins and more robust devices. But this also makes the interaction with magnetic order challenging. One way to manipulate the spin arrangement is to utilize the magnetic anisotropy (MA) which we demonstrated recently using ultrafast optical excitation [1]. External magnetic fields, as regularly used in ferromagnetic materials, can also have strong influence on the MA, providing an addition control knob on the magnetic order. Therefore, understanding the interaction of this effect with external magnetic fields is of strong interest. To this end, we performed time-resolved resonant soft X-ray diffraction in the prototypical A-type antiferromagnet $GdRh_2Si_2$ as shown in figure 1. Consistent with our previous study, we observe a coherent rotation of the antiferromagnetic (AF) arrangement of Gd 4f spins followed by oscillations of the AF order as a consequence of a light-induced change in the MA potential. Surprisingly, upon increasing magnetic field, the frequency of the oscillations as well as the extent of demagnetization upon photoexcitation increases. These observations indicate a change in the MA potential and may offer a new way towards deterministic control of spin order using combined electromagnetic and magnetic fields.

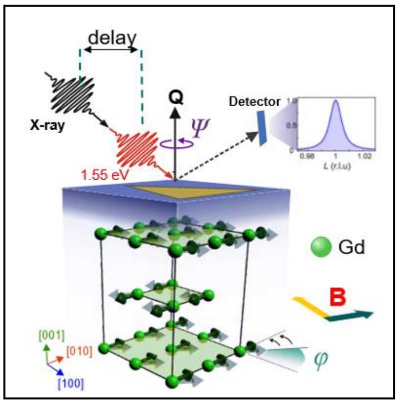

Figure 1: Schematic depicting time resolved RXRD on GdR_2hSi_2. The intensity of Bragg peak is studied as a function of delay under varying magnetic field (B) and pump fluence.

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Coupled Oscillators With Classical And Quantum Flavours

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It is quite well established that the dynamics of a quantum two-level systems described by Schrödinger's equation can be simulated by classical systems, e.g. coupled classical harmonic oscillators. A few papers [1-2] have outlined that this similarity between the dynamics leads to the observation of purely quantum mechanical effects in classical systems, e.g. Rabi oscillations [3-7], Landau-Zener transitions [8], Stueckelberg interferometry [9] and Fano resonances [10]. At the present time our project deals with the description of such classical systems with the addition of noise. The goal would be to mimic further elusive features of quantum mechanics in the same framework established by the aforementioned literature. For instance, it is well known that the Bloch vector dynamics arising from the classical coupled oscillator problem leads to the same relaxation time for all the components of the Bloch vector [2,9], whether in the quantum mechanical analogy two relaxation times are present, i.e. $T_1 \neq T_2$. A better understanding of such fundamental features of quantum-classical analogy in these kinds of systems could lead to further proposals for hybrid mechanical systems as simulators of quantum systems made of coupled spins.

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Magnon-Phonon Quantum Correlation Thermometry

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A large fraction of quantum science and technology requires low-temperature environments such as those afforded by dilution refrigerators. In these cryogenic environments, accurate thermometry can be difficult to implement, expensive, and often requires calibration to an external reference. Here, we theoretically propose a primary thermometer based on measurement of a hybrid system consisting of phonons coupled via a magnetostrictive interaction to magnons. Thermometry is based on a cross-correlation measurement in which the spectrum of back-action driven motion is used to scale the thermomechanical motion, providing a direct measurement of the phonon temperature independent of experimental parameters. Combined with a simple low-temperature compatible microwave cavity readout, this primary thermometer is expected to become a promising alternative for thermometry below 1 K.

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Dominant Higher-Order Gyromodes in Dome-Shaped Nanodots

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Magnetic vortices present a unique system for study of magnetic dynamics owing to their non-trivial and stable magnetic texture. However the low speed of their intristic mechanics limits the potential scope of their application.

One way to reach for the higher frequencies has been exploring the scaling of the G_0, homogenous vortex gyration mode with the particle thickness, predicting the monotonous increase in this mode frequency.[1] However previous studies[2] severely limited themselves in the explored thickness range.

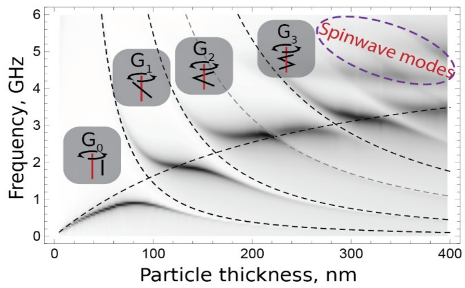

Figure 1: Simulated frequency response of 500 nm wide cylindrical nanodots versus the nanodot thickness. Darker color coresponds to more intense response. Dashed lines are analytically-predicted non-interacting modes.

By extending the range much further both experimentally and numerically we are able to observe the picture which is much easier to explain systematically. We observe that the various order gyrotropic modes couple strongly with eachother, and with spin wave modes confined in the nanodot. Inversion of mode amplitudes is now a consequence of coupling to homogeneous mode, and observed frequency fall is just switch of the oscillation character at the point of anti-crossing. Explicit spatial distributions were used to confirm the inferred connections, and non-trivial axially symmetric geometries from experiment were simulated.

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Investigation of THz Electromagnetic Response in Nanopatterned Magnetic Heterostructures by Current Confinement

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STEs (Spintronic Terahertz Emitters) are novel THz radiation sources. Many studies have demonstrated that the STEs when illuminated with fs-laser pulse, ultrafast spin current is produced which leads to ultrafast transverse charge current by Inverse Spin Hall Effect, resulting in THz electromagnetic pulses. We were able to fabricate THz emitters into arrays of various squares and rectangles of micron or sub-micron size, using Sputter deposition and e-beam lithography. These emitters generate a different emission spectrum than large area reference emitters when irradiated with a fs laser. We propose that the confinement due to small size induces local charge buildup, which leads to additional currents that counterbalance the original charge current due to the Inverse Spin Hall Effect.

Optimal Broad-Band Frequency Conversion via a Magnomechanical Transducer

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Developing schemes for efficient and broad-band frequency conversion of quantum signals is an ongoing challenge in the field of modern quantum information. Especially the coherent conversion between microwave and optical signals is an important milestone towards long-distance quantum communication. In this work, we propose a two-stage conversion protocol, employing a resonant interaction between magnetic and mechanical excitations as a mediator between microwave and optical photons. Based on estimates for the coupling strengths under optimized conditions for yttrium iron garnet, we predict close to unity conversion efficiency without the requirement of matching cooperativities. We predict a conversion bandwidth in the regions of largest efficiency on the order of magnitude of the coupling strengths which can be further increased at the expense of reduced conversion efficiency.

Micromagnetic Simulations for Mechanical Studies of Magnetic Dynamics

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Micromagnetic simulation using time-dependent solutions to the Landau-Lifshitz-Gilbert (LLG) equation is a powerful tool for the study of magnetization dynamics. In applications to nanomechanical measurements of magnetic torque, direct comparison between model predictions and experimental results can be used for determination of measurables such as the magnetomechanical ratio *g'* [1], vector torques [2], and anisotropy energies [3]. More generally, inspecting the output of LLG simulations allows connecting AC magnetic drive torques to several avenues of generation for AC mechanical reaction torques via cross-products with anisotropy fields, via magnetic damping, and via the Einstein-de Haas (EdH) effect. The EdH effect results from angular momentum conservation between magnetic spins and the lattice and resulting torques are linearly dependent on frequency. Simulations of EdH torques show qualitative agreement in frequency dependence and phase relative to the driving field. However, an ad hoc inclusion of g' prevents the LLG equation from fully capturing the physical mechanisms responsible for such torques.

For simulations of AC magnetic torque in equilibrium, a magnetic relaxation for each time step is required. In such a model, AC fields can be mimicked by discrete offsets of field magnitude; linear variation of magnetization with offset field strength can be used to estimate EdH torques [1]. In a non-equilibrium model, the simplest version of which is a macrospin approximation, the relaxed state is not required. This model allows application of a sinusoidal AC driving field and direct calculation of resulting AC field-driven mechanical torques. Within this model, field geometries such as presented in [4] can be applied, wherein two perpendicular driving fields yield a mixing torque. This particular field geometry is useful for concurrent study of magnetic resonance and direct torque where simulation is useful for elucidating the origin of mixing torque. Comparison of the macrospin model with experiment has had early success and indicates several promising avenues for experimental design and model development.

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Shape Anisotropy of NiO/Pt thin films

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We demonstrate that for insulating antiferromagnets (iAFMs) with large magnetostriction, such as NiO, the magnetic order is strongly affected by strain in the structure. Considering the potential of antiferromagnets as active elements in spintronic devices [1] it is important to investigate these effects. We show, that a compressive out-of-plane strain induced during the epitaxial growth of NiO on an MgO(001) substrate leads to a canting of the Néel vector in NiO compared to the bulk orientation [2]. For nano-scale elements, shape-induced strain due to pattering of rectangular elements on NiO/Pt thin films can be used to control the AFM ordering. We observe different domain structures for rectangular elements of NiO patterned along the easy and hard magnetocrystalline anisotropy axes of our film and can identify magnetoelastic interactions of the different domain configurations [3]. Further, we demonstrate how the variation of the aspect ratio of rectangular shapes can be used to control the antiferromagnetic ground state (Fig. 1). Thus, shape-induced strain does not only need to be considered in the design of antiferromagnetic devices, but can potentially be used to tailor their properties, providing an additional handle to control AFMs.

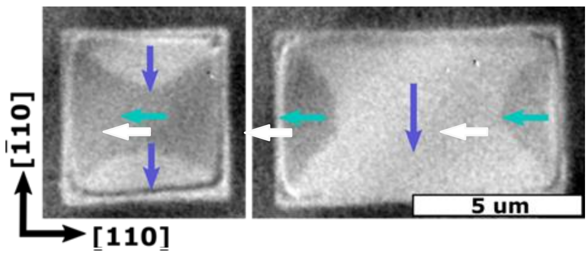

Figure 1: XMLD-PEEM image of shape-induced NiO domains inside rectangular shaped elements, with edges oriented along the in-plane projection of the easy axis.

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Strong photon-magnon-coupling between niobium lumped-element-resonators and micron sized permalloy stripes

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Since quantum computing plays a more and more important role in information technology hybrid quantum magnonics emerge as promising research field. Here, the coupling between different quantum states like microwave photons and magnons at cryonic temperatures is in focus [1].

We investigate the coupling between superconducting niobium Lumped-Element-Resonators and thin micron-sized permalloy stripes. Resonator and magnet were structured by optical lithography and grown by argon-ion sputtering at room-temperature.

We detect strong coupling as avoided crossing in the transmission related S-Parameter measured by a vector-network-analyzer.

Due to the shape anisotropy, we can observe strong coupling in a non-saturated magnetization regime of the permalloy stripe. In that regime a reversed splitting of the anticrossing occur which implies a magnon-dispersion with a negative slope regarding the external magnetic field strength [2].

For validation of our experimental results, we perform electromagnetic simulations with *CST Studio Suite* and micromagnetic simulations with MuMax3.

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Magnon Contributions to the Heat Conductivity of Insulating Antiferromagnets

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Heat conductivity κ of insulators is dominated by phonons. In magnetic materials, however, magnons are another set of quasiparticles that can facilitate spin and energy transport. The flow of magnons that is induced by a temperature gradient in insulators can be detected by the longitudinal spin Seebeck effect (SSE) [1]. In ferrimagnet yttrium iron garnet (YIG), where magnon propagation length is exceptionally large, the formation of magnon polarons was demonstrated [2] and the magnon contribution to κ is evident in the magnetic field dependence of $\kappa(B)$ [3]. Since we could demonstrate long distance spin transport in antiferromagnets [4] we look for the contribution of antiferromagnetic magnons to the heat conductivity using the 3ω method.

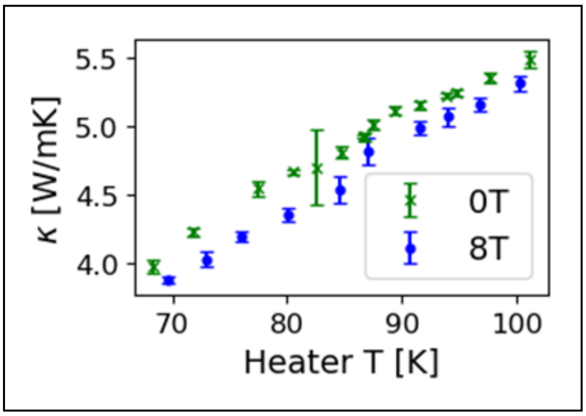

Figure 1: κ(T) for the orthoferrite $TmFeO_3$

In orthoferrite $TmFeO_3$ crystals, a spin reorientation transition is evident in measurements of the spin Hall magnetoresistance. Measurements of $\kappa(B,T)$ do not show signatures of the spin reorientation transition, while an opening of a magnon gap in a magnetic field of 8 T leads to a nearly temperature independent reduction of κ by 3% near the spin reorientation temperature. We compare our experimental results to simulations for the heat transport based on magnon dispersion relations.

For hematite single crystals, we can detect the Morin transition directly in temperature dependence of $\kappa(T)$ measurements. Magnetic field dependence $\kappa(B)$ in hematite is weak and detailed measurements are in progress.

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Development of Co_2FeSn Heusler alloy films and nanocrystals for magnetic and magneto-optical applications

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Heusler alloy (HA) materials are expected to have a wide range of spintronics such as, in magnetic recording medium, in thermoelectricity, magneto-optical device applications, etc. We have developed a modified three step electrochemical growth method for thin film deposition. Using this scheme we have successfully grown Co_2FeSn thin films on copper and Si substrate. The deposited films show a large degree of magneto-optical Kerr rotation (MOKE) as well as high saturation magnetization at room temperature. The Kerr measurements show rotation reaching up-to a maximum value of ~0.3° [1] on a polycrystalline copper substrate and ~0.8° [2] on a single crystalline substrate which is comparable with the films grown by conventional techniques. The static MOKE measurements also reveal that electrodeposited samples possess strong uniaxial magneto-crystalline anisotropy. For Co_2FeSn [3] nanoparticles specific absorption rate (SAR) value of about 112 W/gm was obtained at moderate strength of alternating magnetic field.

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Spin-Wave Physics At Ultralow Temperatures

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Modern quantum technologies rely on low temperatures for large-scale quantum computation [1], quantum simulation [2], for integrated quantum circuits [3], or quantum transducers [4]. In particular the latter ones are of great interest, as they vow to bridge the gap between different quantum systems coherently. A robust and highly integratable system to transfer quantum information between terahertz to gigahertz photons are spin waves, and their single quanta magnons [5]. To interconnect with individual quantum systems, such as photons [6], phonons [7] or fluxons [8], and to remove thermally excited magnons, these magnons also have to operate at ultralow temperatures. A system of choice is Yttrium-Iron-Garnet (YIG), with its remarkable properties, such as a low damping at room-temperature. In this work we present our latest results on spin-wave propagation at ultralow temperatures. An example is given in Fig.1. Here we show a measured propagating spin-wave signal ($|S_{12}|$) through a 70x2mm (thickness: 5.65µm) YIG sample on a 500µm thick Gadolinium-Gallium-Garnet substrate, at a temperature of 30mK in the Damon-Echbach configuration.

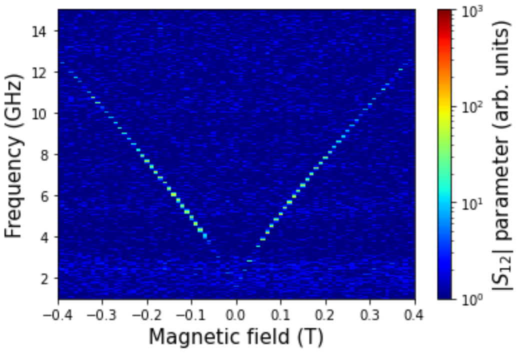

Figure 1: Spin-wave propagation ($|S_{12}|$) through a 70x2mm (thickness: 5.65µm) Yttrium-Iron-Garnet sample on a 500µm Gadolinium-Gallium-Garnet substrate at 30mK.

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Optimizing Spin Wave Lenses to Amplify Spin Wave Intensity

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One way to amplify magnons is to concentrate many toward a localized point. This would provide a high-intensity source of magnons and could facilitate magnonic applications [1]. This “spin-wave (SW) lens” is a magnon counterpart to the nonimaging Fresnel lens concentrator. By relying on an understanding of SW dispersion, we are able to create robust SW lenses.

Our SW lenses are comprised of funnel structures patterned in yttrium iron garnet (YIG) [2]. Due to their geometry, the structures’ demagnetization vary and deflect magnons from their original path. Now propagating off-axis, multiple magnons intersect at a focal point outside of the structure.

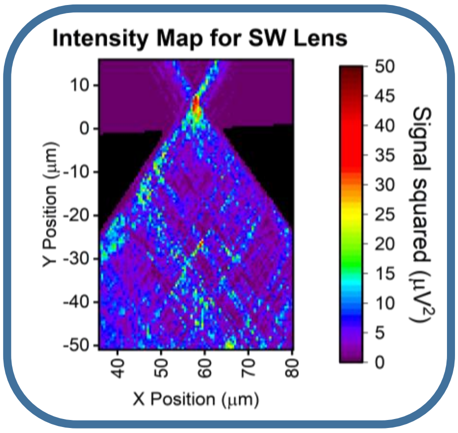

Figure 1: Example of a spin-wave lens.

SW lens behavior was simulated with Mumax, where one of the most promising simulations showed up to a 384-fold increase in SW intensity at a frequency of 3.25 GHz and magnetic field of 51.62 mT, relative to the structure’s start.

However, preliminary magneto-optical Kerr effect (MOKE) measurements for a similar geometry exhibited a mere 7-fold increase. To approach the simulation’s upper limit, we conduct several parameter sweeps. We highlight the best performing SW lens, which focuses magnons about 7 μm beyond the lens and increases SW intensity by 51-fold.

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Optical Detection of Antiferromagnetic Resonance In Van Der Waals Antiferromagnet

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In recent years, antiferromagnets have been shown to be advantageous as components in high frequency and robust spintronic devices[1-2]. However, detection and characterization of antiferromagnetic dynamics is challenging due to high resonant frequencies and lack of net magnetization. One method to detect antiferromagnetic dynamics is the use of atomic-scale color centers, which are optically active point defects in crystals. Color centers constitute sensitive noninvasive probes with the ability to detect local fields and fluctuations emanating from dynamics in magnetic systems[3]. In addition to nitrogen-vacancy (NV) centers in diamond, recently discovered color centers in hexagonal boron nitride (h-BN) hold promise for achieving close proximity to a sample surface which aids in sensing the short-range magnetic field fluctuations produced by antiferromagnetic dynamics[4]. Moreover, dynamics at frequencies well above the color center resonance frequency can be indirectly detected through magnon scattering that produces local magnetic noise at the color center resonance frequency[3,5]. Here we present the first optical detection of antiferromagnetic resonance in the van der Waals material $CrCl_3$. This measurement allows inferences to be made about the parameters that govern the dynamics in thin samples that would otherwise be challenging to measure using conventional FMR. This technique provides a powerful tool for studying dynamics driven at the interface between thin antiferromagnets and neighboring systems that couple to the antiferromagnetic state.

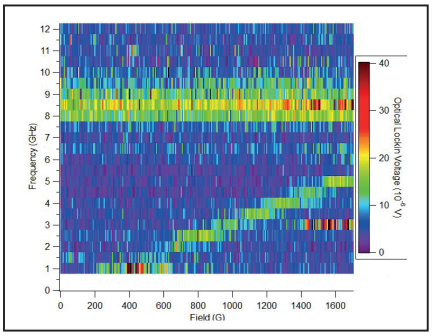

Figure 1: Optical detection of antiferromagnetic resonance (AFMR) in ~10μm $CrCl_3$ using NV centers as a function of field and frequency, showing acoustic (lower) and optical (upper) AFMR modes. Dynamics were excited by a microwave stripline at 9K with field applied in plane.

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High-Sensitivity Magnetic Field Imaging of AC and DC Currents in Bilayer Graphene

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We employ nitrogen-vacancy centers in diamond as sensitive magnetic field sensors to image current flow in mono- and bilayer graphene device. Spatially resolving the current distribution in these nanostructures enables us to obtain insights on transport phenomena which cannot be obtained easily with conventional transport measurements. We report on the implementation of high-sensitivity quantum measurement schemes for AC [1] and DC [2] current detection, with magnetic field sensitivities reaching down to 4.6 nT at a spatial resolution of 50-100 nm. We demonstrate our imaging capabilities by mapping current flow in a bilayer graphene device at room temperature by AC modulating the source-drain current [1] or by locally oscillating the sensor [2]. Specifically, we resolve minute variations in the current flow profile due to changes in the potential landscape and find that the current flow is uniform through a narrow channel close to charge neutrality (in contrast to monolayer graphene [3]). We further illustrate how the dynamic range of the quantum sensing protocols can be extended through a set of phase unwrapping schemes.

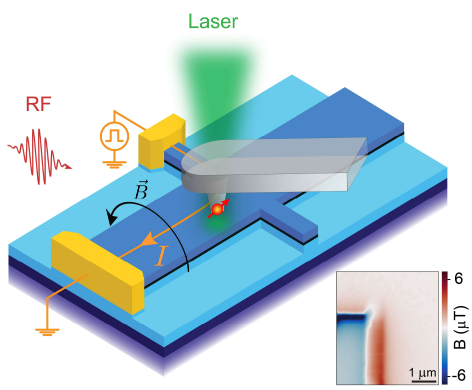

Figure 1: Schematic of the scanning diamond magnetometer: The inset shows the magnetic field recorded above the Hall bar structure. Figure adapted from [1].

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Advances in 3D Magnetic Resonance Force Microscopy

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The goal of nanoscale magnetic resonance imaging (NanoMRI) is the 3D visualization of nuclear spin densities inside objects with near-atomic spatial resolution. One promising candidate for NanoMRI is magnetic resonance force microscopy (MRFM), a scanning probe technique used to image objects at a nanometer-scale resolution. In MRFM, nuclear spins are periodically inverted by magnetic resonance pulses in a magnetic field gradient and the resulting magnetic forces acting on an ultra-sensitive nanomechanical force transducer are measured [1].

We will present recent improvements achieved in our measurement setup. On the one hand, we strive to reduce the impact of strong cantilever-surface interactions, which lead to detrimental bending effects. By employing novel microstrip designs with embedded microstrips, we managed to minimize these effects. On the other hand, we are able to increase the speed and robustness of our measurements through the use of compressed sensing techniques [2]. This results in improved image reconstruction when applied to our latest 3D MRFM datasets.

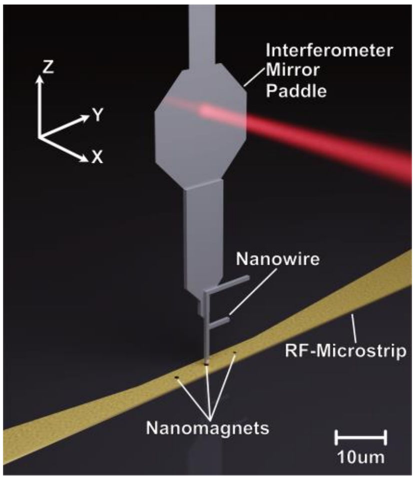

Figure 1: Configuration of the MRFM Experiment

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Strong Suppression of the Spin Seebeck Effect in a Nearly Compensated Ferrimagnet

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It is known that the spin Seebeck effect (SSE) can be suppressed by application of large magnetic fields as a result of the Zeeman-induced energy shift of the magnon dispersion [1].

Here, we will show that the SSE suppression increases with an increasing level of magnetic compensation. We investigate three different iron garnets and observed that the films with the higher level of compensation [2] show a stronger SSE suppression which is at least 3 times larger than in YIG. By evaluation of the magnon-polaron SSE we can estimate the magnon dispersions and discuss the results in terms of possible contributions from opposite polarization magnons, and the effect of an increased magnon relaxation.

These results highlight the capability of the SSE as an efficient tool to study the spin dynamics and, particularly, the magnon-polaron SSE to obtain information of the magnon dispersion characteristics in magnetic systems.

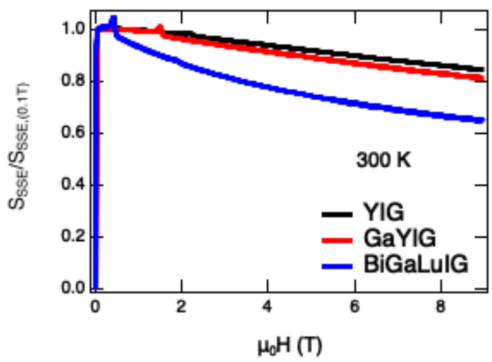

Figure 1: Detail of the SSE suppression for 3 garnets with different level of non-magnetic doping (Ga).

References

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Generating Arbitrary Quantum States of Magnetization [1]

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Magnets are known for commercial memory storage and have potential as low energy computing devices. Recently, interest has developed in using magnet for quantum applications such as quantum sensing or microwave-to-optical conversion owing partially to it being a high coherence solid state bosonic system. An important step towards "quantum magnonics" is to be able to deterministically create and detect arbitrary quantum states. Magnon detection was experimentally demonstrated at an accuracy of single magnon by coupling the magnet to a superconducting qubit [2]. While some progress was made in quantum state generation [3], there is no known method to deterministically create arbitrary quantum states.

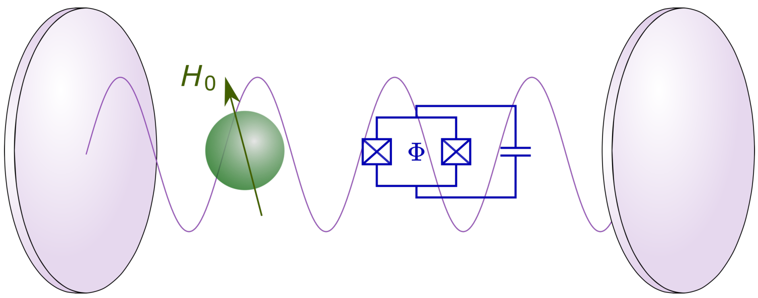

Figure 1: A magnet and a superconducting transmon kept inside a microwave cavity.

We propose to use the same system as in [2], see Fig. 1, for state generation. We repeatedly excite the transmon and transfer a part of the excitation to magnons. To mitigate the effect of magnon dissipation, we ought to shorten the time of the protocol. Simply shortening the excitation pulses leads to non-resonant excitation of higher transmon levels susceptible to higher decoherence. Thus, we apply counter-pulses to ensure that higher levels are lesser occupied. We find that we can faithfully produce magnon states with maximum occupation of ≤9 magnons and average ≤4 magnons.

References

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[2] Lachance-Quirion et al., Sci. Adv. 3:e1603150 (2017); Science 367, 425-428 (2020).

[3] Bittencourt et al. PRA 100, 013810 (2019); Elyasi et al. PRB 101, 054402 (2020); Sharma et al. PRB 103, L100403 (2021)

Conservation Laws for Adiabatic Spin-Lattice Dynamics

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The transfer of energy and angular momentum between magnetization and lattice is a crucial aspect of the ultrafast demagnetization of a magnet by a femtosecond laser pulse and also determines the damping of magnetic excitations. Furthermore, the transfer of angular momentum between magnetization and phonons [1] could enable a long-range transfer of spin angular momentum [2,3]. For theoretical models of spin-lattice dynamics, it is therefore important to understand when and how they conserve energy and angular momentum.

We consider the conservation laws for adiabatic spin-lattice dynamics, which is based on the adiabatic approximation for spin and lattice degrees of freedom. In this approach the lattice forces and effective magnetic fields that drive the dynamics are obtained directly from the electronic structure, which is assumed to be in a quasi-equilibrium state. We show that adiabatic spin-lattice dynamics conserves the energy only at zero electronic temperature and the angular momentum only if the magnetic moment lengths are held constant [4].

The adiabatic spin-lattice simulations are implemented within the computer code CAHMD [5], where the electronic structure is based on a parametrized tight-binding model. First results for adiabatic spin dynamics (without lattice dynamics) are available in Ref. [4].

References

1. S. Streib *et al.*, Phys. Rev. Lett. **121**, 027202 (2018).
2. A. Rückriegel *et al.*, Phys. Rev. Lett. **124**, 117201 (2020).
3. K. An *et al.*, Phys. Rev. B **101**, 060407(R) (2020).
4. S. Streib *et al.*, e-print arXiv:2203.11759 (2022).
5. Computer code CAHMD, classical atomistic hybrid multi-degree dynamics. (Danny Thonig, danny.thonig@oru.se, 2013) (unpublished, https://cahmd.gitlab.io/cahmdweb/).

	Monday	Tuesday	Wednesday	Thursday
08:00	Breakfast	Breakfast	Breakfast	Breakfast
09:00	Opening remarks	C 1 - Viola-Kusminskiy	E 1 - Kläui	F 1 - Jander
09:10	A 1 - An			
09:45		C 2 - Rückriegel	E 2 - Arisawa	F 2 - Dreyer
09:55	A 2 - Thevenard			
10:30		Break	Break	Break
10:40	Break			
10:50		C 3 - Kirchmair	E 3 - Dunsmore E 4 - Kurfman	F 3 - Xu
11:00	A 3 - Huebl			
11:10				
11:35		C 4 - Metelmann		Closing remarks
11:45	A 4 - Scherbakov			
12:00			Lunch break	
12:20				Lunch break
12:30	Lunch break	Lunch break		
13:00			Excursion	Departure
14:15	B 1 - Hetet	D 1 - Romero-Isart		
15:00	B 2 - Wrachtrup	D 2 - van der Zant		
15:45	Break	Break		
16:15	B 3 - Zeldov	D 3 - Degen		
17:00				
18:00	Dinner	Dinner	Barbecue	
19:15	Posters	Posters		