WILHELM UND ELSE HERAEUS-STIFTUNG

658. WE-Heraeus-Seminar

Spins out of equilibrium: Manipulating and detecting quantum magnets

08 - 10 January 2018
Physikzentrum Bad Honnef (Germany)

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation which supports research and education in science, especially in physics. A major activity is the organization of seminars. To German physicists the foundation is recognized as the most important private funding institution in their field. Some activities of the foundation are carried out in cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft).

Aims and Scope of the 658. WE-Heraeus Seminar:

The temporal dynamics of the magnetic order in solids allows for completely novel insights into the elementary interactions of ordered electron spins with their environment. Probing the magnetic order out of equilibrium is of paramount importance both for the storage and processing components of magnetically encoded information, and a fundamental understanding of correlated spins in matter. The time scales relevant for the magnetization dynamics range from the nanosecond regime to the femtosecond range. These magnetic time scales correspond to frequencies of approximately 1 GHz to 100 THz in the electromagnetic spectrum and thus span the range from radio waves to light. Ferromagnetic resonance and spin waves in the GHz domain has a long tradition, and is now applied to single spin manipulation or probing quantum electrodynamics in spin-systems. On the side of THz domain, the interaction of the spin degree of freedom with the femtosecond laser radiation is of key importance for our launching into the field on ultrafast magnetic applications. A particularly exiting aspect is acquiring an ability to shape the required magnetic states for further processing on the ultrafast time scales, which is aided by strongly non-equilibrium processes. On the other hand, the uncovering of the laws which govern the formation of topological states in interacting spin systems, as well as estimating the time-scales and means of influencing their properties in terms of non-equilibrium dynamics require essential leaps in our conceptual understanding of the emergent behavior of ensembles of spins which roots in topological properties. The topological nature of spin ensembles can manifest at various length scales providing thus a large span of phenomena and lead to realization of such promising concepts as 3D memory and topological computing.
In this seminar we will bring together communities working in quantum spin dynamics (aka magnonics), ultrafast spintronics, and topological spins. Our particular focus lies with stimulating the discovery of emergent spin materials suitable for all three areas by introducing new research concepts related to quantum resolved magnon-polariton spectroscopy, advanced cavity-QED, microwave quantum optics technologies, and ultrafast manipulation of spins. The central theme of the seminar is the discovery of novel emergent materials suitable for realization of different ideas for each of the research areas. Ultimately, our goal is to stimulate discoveries of ground-breaking nature, generate novel ideas and extend the research objectives by bringing together the experts in three distinct fields in modern magnetism in order to open up new horizons for quantum, magnon and spin electronics.

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Program

Program

Sunday, January 7th , 2018

17:00 – 21:00	Registration	
From 18:30	*DINNER / Informal get together*	

Monday, January 8th, 2018

07:30	*BREAKFAST*	
08:45 – 09:00	Yuriy Mokrousov Dmitry Turchinovich Martin Weides	**Welcome and opening**
09:00 – 09:45	Jure Demsar	**Néel Spin Orbit Torque driven antiferromagnetic resonance in Mn2Au probed by time-domain THz spectroscopy**
09:45 – 10:30	Mirko Cinchetti	**The vision of optical control of molecular spinterfaces**
10:30 – 11:00	*COFFEE BREAK* ***and discussions***	
11:00 – 11:45	Mathias Kläui	**Topological Spin Structure Dynamics**
11:45 – 12:30	Stefan Mathias	**Ultrafast spin-current induced band-structure evolution and magnon generation in photo-excited Co/Cu**
12:30 – 12:40	**Conference Photo** (in the foyer of the lecture hall)	
12:40	*LUNCH*	

Program

Monday, January 8th, 2018

14:00 – 14:45	Yutaka Tabuchi	**Sensing magnetization oscillation in quantum regime**
14:45 – 15:15	Andrea Eschenlohr	**Femtosecond spin-dependent charge transfer at Co/Cu(001) interfaces**
15:15 – 16:00	Tom Seifert	**Terahertz spintronics: exploiting ultrafast spin currents in magnetic heterostructures**
16:00 – 16:30	Ofer Kfir	**Nanoscale Magnetic Imaging using Circularly Polarized High-Harmonic Radiation**
16:30 – 17:00	*COFFEE BREAK*	
17:00 – 18:30	Shot-gun talks	
18:30	*HERAEUS DINNER* *(cold & warm buffet, free beverages)*	
20:00	**Poster Session (open end)**	

Program

Tuesday, January 9th, 2018

08:00	*BREAKFAST*	
09:00 – 09:45	Silvia Viola Kusminkiy	**Non-linear dynamics and magnetic textures in cavity optomagnonics**
09:45 – 10:30	Can-Ming Hu	**Cavity Spintronics**
10:30 – 11:00	*COFFEE BREAK* ***and discussion***	
11:00 – 11:45	Mathias Weiler	**Spin dynamics in a chiral magnonic crystal**
11:45 – 12:30	Markus Münzenberg	**Manipulating magnetism with light: From FePt to spin structures and vortex patterns**
12:30	*LUNCH*	
14:00 – 14:45	Stuart Parkin	**Spinorbitronics in complex spin systems**
14:45 – 15:15	Isabelle Boventer	**Temperature dependence of YIG magnon-photon polaritons down to milliKelvin temperatures**
15:15 – 15:45	Hans Huebl	**Controlling the Collective Coupling in Spin-Photon Hybrids**
15:45 – 16:30	Roser Valenti	**Engineering spin-orbit-coupled materials**
16:30 – 17:00	*COFFEE BREAK*	
17:00	**Poster Session**	
18:30	*DINNER*	
20:00	Frank Wilhelm	**Solid-state quantum computing: Where are we, where do we go?**

Program

Wednesday, January 10th, 2018

08:00	*BREAKFAST*	
09:00 – 09:45	Stefan Blügel	**Chiral Magnetic Skyrmions and Bobbers at Interfaces**
09:45 – 10:30	Jakub Zelezny	**Spin-polarized current and magnetic spin Hall effect in non-collinear antiferromagnets**
10:30 – 11:00	*COFFEE BREAK* ***and discussion***	
11:00 – 11:45	Timo Kuschel	**Experimental determination of the magnon spin diffusion length by the nonlocal and local spin Seebeck effect**
11:45 – 12:30	Yuriy Mokrousov Dmitry Turchinovich Martin Weides	**Poster award** **Impulse talk award** **and Closing Remarks**
12:30	*LUNCH*	

End of the seminar and Farewell Coffee / Departure

Breakfast for those leaving on Thursday

Posters

Posters

01	Sanjay Ashok	**Ultrafast demagnetization dynamics including spin and charge transport**
02	Lorenzo Baldrati	**Electrical read-out of antiferromagnets using spin Hall magnetoresistance in epitaxial NiO(001)/Pt thin films**
03	Christine Dörflinger	**Introducing a phase shift into driven coupled magnon photon circuit**
04	Stefan Eisebitt + Felix Willems	**Multi-color probing of ultrafast magnetization dynamics in thin magnetic films**
05	Stefan Eisele	**Development of a magnetic on-chip field bias for magnon resonator experiments**
06	Alexander Fernández Scarioni	**A tool for detecting complex magnetic configurations**
07	Frank Freimuth	**Laser-excitation of photocurrents and spin photocurrents in magnetic bilayer systems**
08	Rashid Gareev	**Synthetic antiferromagnet tunneling heterostructures for terahertz controlled magnetization switching and spin precession**
09	Jacob Gayles	**Anomalous and Topological Hall effects in epitaxial B20 Fe1-yCoyGe films**
10	Olena Gomonay	**Femtosecond dynamics of antiferromagnets and entangled magnon states**
11	Sergii Grytsiuk	**Giant structural response of Dzyaloshinskii-Moriya interaction in MnGe B20 compounds**
12	Jan-Philipp Hanke	**Topology for Magetization Control in Complex Magnets**

Posters

13	Daniel Heinze	**Thermally excited skyrmion motion near the spin reorientation transition**
14	Abdur Rehman Jalil	**In-Situ Fabricated Low-Dimensional Topological Insulator - Superconductor Hybrid Junctions: A Platform for Majorana Fermions**
15	Stefan Klingler	**Spin waves in coupled YIG/Co heterostructures**
16	Lukas Liensberger	**Phase-sensitive Detection of Inverse Spin-Orbit Torques in Normal Metal/Ferromagnet Bilayers at Microwave Frequencies**
17	Fabian Lux	**Chiral and Topological Orbital Magnetism of Spin Textures**
18	Aleksandr Makarov	**Multicanonical Sampling of the Space of States of H(2, n)-Vector Models**
19	Franziska Martin	**Spin-orbit torques and DMI in optimized multilayer stacks**
20	Marcel Möller	**Ultrafast magnetization dynamics probed by Lorentz microscopy**
21	Evangelos Papaioannou	**Efficient Spintronic Terahertz Emitters Based on Epitaxial Grown Fe/Pt bilayers**
22	Marco Pfirrmann	**Magnon linewidth in hybrid quantum systems at milliKelvin temperatures**
23	Tomislav Piskor	**Hybrid quantum circuits of superconducting resonators and ferromagnetic magnons**
24	Ulrike Ritzmann	**Current-driven skyrmion dynamics in ultra-thin ferromagnetic films**

Posters

25	Andre Schneider	**Decoherence of superconducting qubits in large in-plane magnetic fields**
26	Helmut Schultheiss	**Magnon scattering and Magnon angular momentum conservation in a magnetic vortex**
27	Yuriy Shevchenko	**Entropy of diluted antiferromagnetic Ising models on frustrated lattices using the Wang-Landau method**
28	Nynke Vlietstra	**Comparison of the Spin-Hall Magnetoresistance in Magnetic Insulators with different magnetic properties**
29	Jakob Walowski	**Anomalous Nernst effect in magnetic tunnel junctions: Exploring three-dimensional temperature gradients on the nanometer to micrometer scales**
30	Sebastian Weber	**Electron dynamics driving ultrafast de- and remagnetization in itinerant ferromagnets and alloys**
31	Hongbin Zhang	**First-principles study of topological transport in noncollinear magnets**
32	Bernd Zimmermann	**Bridging the scales: Dzyaloshinskii-Moriya interaction at disordered interfaces and new properties by symmetry breaking**

Contributed Talks

(in chronological order)

Contributed Talks

01	Isabella Boventer	**Temperature dependence of YIG magnon-photon polaritons down to milliKelvin temperatures**
02	Andrea Eschenlohr	**Femtosecond spin-dependent charge transfer at Co/Cu(001) interfaces**
03	Hans Huebl	**Controlling the Collective Coupling in Spin-Photon Hybrids**
04	Ofer Kfir	**Nanoscale Magnetic Imaging using Circularly Polarized High-Harmonic Radiation**
05	Timo Kuschel	**Experimental determination of the magnon spin diffusion length by the nonlocal and local spin Seebeck effect**

Abstracts of Lectures

(in chronological order)

Néel Spin Orbit Torque driven antiferromagnetic resonance in Mn2Au probed by time-domain THz spectroscopy

N. Bhattacharjee[1], V. Yu. Grigorev[1,2], A. Sapozhnik[1,2], S. Bodnar[1], S. Y. Agustsson[1], J. Cao[1], D. Dominko[1], M. Obergfell[1], O. Gommonay[1], J. Sinova[1,2], M. Kläui[1,2], H.-J. Elmers[1,2], M. Jourdan[1,2], and J. Demsar[1,2]

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Antiferromagnetic (AFM) materials are attracting a lot of interest in the field of spintronics due to their insensitivity to external magnetic fields and potentially ultrafast switching. Among them Mn_2Au is of special interest due to its high Néel temperature (~1300K), strong spin-orbit coupling and high conductivity [1,2]. One of the central questions for potential ultrafast manipulation/switching of the AFM order for novel spintronic memory devices is to determine characteristic time scales (collective mode frequencies). To shed light on these, we performed linear time-domain THz spectroscopy, where the temperature dependent optical conductivity reveals the presence of a 1 THz mode, which softens upon increasing temperature. This mode can be attributed to an in-plane antiferromagnetic resonance (AFMR), driven by the Néel spin-orbit torque.

To investigate the Néel vector and/or its dynamics we follow a recently demonstrated approach, where a weak birefringence induced by symmetry breaking due to AFM ordering can be resolved in a pump-probe configuration, thereby determining the Néel vector direction [3]. Using this method we were able to determine the Néel vector direction, which is found in agreement with previous theoretical [1] and experimental results [4,5]. Furthermore, the time resolved character of this technique allowed us to observe a shift of its direction on a picosecond time scale, which we attribute to the ps strain induced by photoexcitation.

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The vision of optical control of molecular spinterfaces

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The miniaturization trend in the semiconductor industry has led to the understanding that interfacial properties are crucial for device behaviour. Spintronics has not been alien to this trend, and phenomena such as preferential spin tunnelling, the spin-to-charge conversion due to the Rashba–Edelstein effect and the spin–momentum locking at the surface of topological insulators have arisen mainly from emergent interfacial properties, rather than the bulk of the constituent materials. In this talk I will describe inorganic/molecular interfaces by looking closely at both sides of the interface. I will discuss recent developments in the field and underline how molecular materials have arisen as an ideal platform for creating interfacial spin effects [1]. As an example, I will show that the extreme multi-functionality of organic molecules can be used to functionalize the spin properties of surfaces with a spin-texture induced by strong spin-orbit coupling. I will present our results on the following two-dimensional electronic systems: the surface states of the topological insulator Bi2Se3 [2], and the Rashba-split surface states of a Pb-Ag surface alloy [3]. Finally, I will discuss the key role that molecular interfaces may play in the development of a new generation of spin-based technologies, thanks to their unique capability of being actively tuned to reach as-yet unexplored functionalities. For example, I will show how the nano-scale object that naturally forms when an organic molecule is hybridized on a metallic surface (a nano-scale molecular spinterface) could be used to achieve coherent control — at the molecular scale — of technologically important parameters, such as magnetization, plasmonic resonances, and spin texture.

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Topological Spin Structure Dynamics

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Three key requirements for new application os spintronics are: (i) stable spin structures for long term data retention; (ii) efficient spin manipulation for low power devices and (iii) no susceptibility to stray fields as realized for antiferromagnets.
We explore different materials classes to tackle these challenges and explore the science necessary for a disruptive new technology.
To obtain ultimate stability, topological spin structures that emerge due to the Dzyaloshinskii-Moriya interaction (DMI), such as chiral domain walls and skyrmions are used. These possess a high stability and are of key importance for magnetic memories and logic devices [1,2]. We have investigated in detail the dynamics of topological spin structures, such as chiral domain walls that we can move synchronously with field pulses [3]. We determine in tailored multilayers the DMI [4], which leads to perfectly chiral spin structures.
For ultimately efficient spin manipulation, spin transfer torques are maximized by using highly spin-polarized ferromagnetic materials that we develop and we characterize the spin transport using THz spectroscopy [2]. Furthermore we use spin-orbit torques, that can transfer 10x more angular momentum than conventional spin transfer torques [4-6].
We then combine materials with strong spin-orbit torques and strong DMI where novel topologically stabilized skyrmion spin structure emerge [5]. Using spin-orbit torques we demonstrate in optimized low pinning materials for the first time that we can move a train of skyrmions in a “racetrack”-type device [1] reliably [5,6]. We find that skyrmions exhibit a skyrmion Hall effect leading to a component of the displacement perpendicular to the current flow [6]. We study the field - induced dynamics of skyrmions [7] and find that the trajectory of the skyrmion’s position is accurately described by our quasi particle equation of motion. From a fit we are able to deduce the inertial mass of the skyrmion and find it to be much larger than inertia found in any other magnetic system, which can be attributed to the non-trivial topology [7].
Going beyond ferromagnets, we finally we explore spin-orbit effects in antiferromagnets. In particular we develop Mn_2Au and show that by spin-orbit torques we can switch the Néel vector in this material [8].

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Ultrafast spin-current induced band-structure evolution and magnon generation in photo-excited Co/Cu

Stefan Mathias, University of Göttingen

Ultrashort extreme-ultraviolet pulses from high-harmonic generation (HHG) provide a powerful tool for novel experiments in the area of ultrafast materials science. The short-wavelength nature of these sources provide important information related to all electronic, magnetic, structural, and chemical properties of a solid. In our experiments, we use HHG-based magneto-optical and photoemission experiments to probe ultrafast carrier dynamics and photo-induced phase transitions in materials.
Using element-specific HHG magneto-optical techniques, we elucidate the role of photo-induced ultrafast spin currents in magnetic multilayer stacks [1,2]. With the help of a HHG time-, spin-, and angle-resolved photoemission spectroscopy (spin-resolved trARPES), we map the spin-dependent band structure response in Co to such ultrafast photo-induced spin currents [3]. Here, we observe two distinct processes at work. At energies near the Fermi-level, the spin dynamics are predominantly driven by a redistribution of spin-polarized carriers. At higher binding energies >1 eV, quenching of the spin polarization exhibits transient band dynamics that can be unambiguously traced back to rapid band mirroring of the electronic states. Because band-mirroring is a strong indication of spin fluctuations, we conclude that optically driven femtosecond spin currents induce collective spin excitations on extremely fast timescales.

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Sensing magnetization oscillation in quantum regime

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Quanta of magnetization oscillation, i.e., magnons, are essential ingredients in spintronics technology. Although their characteristics have been investigated for a long time, the behavior in the quantum regime, where the number of thermal excited magnons is nearly zero, is still unknown. Here we demonstrate ultra-sensitive sensing of magnons using a superconducting qubit. Superconducting "transmon" qubits, which are formed by two electrodes shunted by Josephson junctions, have dipole antennas in their structures and thus they couple to surrounding electromagnetic fields. Owing to their huge dipole moments which are typically 4th-order-magnitude larger than those of atoms, the transmon qubits can detect a change in microwave signal to a single photon level. We exploit such feature for sensing the magnetization oscillation in a magnet. A transmon qubit interacts with an electric microwave field, whereas the magnetization couples to a magnetic microwave field through ferromagnetic resonance. We use a 50x20x3-mm^3-microwave rectangular cavity to induce an effective coupling between them; both the qubit and the magnetization couple with the same microwave field mode but through different components [1]. With an appropriate detuning between the qubit and magnetization oscillation frequencies, the qubit excitation frequency shifts depending on the number of magnons in the magnetization oscillation mode. The qubit resonance peak shift is discretized in the limit where the qubit linewidth is narrower than the shift for a single magnon, so that we can count magnons in the magnetization oscillation mode to a single magnon level. We experimentally show that the coherently excited magnetization oscillation obeys the Poissonian magnon number distribution [2]. Our ultra-sensitive sensing method provides a powerful tool for magnetization oscillation sensing as well as quantum information processing.

References

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Femtosecond spin-dependent charge transfer at Co/Cu(001) interfaces

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Laser-induced spin transport shows great promise for extending spintronics towards femtosecond (fs) timescales, as ultrafast demagnetization [1], transient magnetization enhancement [2] and spin transfer torque [3] driven by fs spin currents have been demonstrated recently. Here, we focus on the epitaxial model system Co/Cu(001), in which optically excited spin transport from the Co film into the Cu substrate dominates the magnetization dynamics during the first few tens of fs after laser pumping, while the electronic system is in a non-equilibrium state [4,5]. We directly compare interface-sensitive time-resolved magnetization-induced second harmonic generation on 3 and 5 monolayer thin Co/Cu(001) with parameter-free *ab initio* time-dependent density functional theory (TDDFT) [6] calculations on the very same sample system. Our findings show that the initial dynamics in the < 30 fs range are dominated by spin-dependent charge transfer between Co and Cu. Subsequently, while the transient spin-dependent charge current already relaxes, the magnetization is further reduced by spin-orbit coupling mediated spin flips, as recently predicted by TDDFT [6]. These results show the potential of a predictive theoretical description to elucidate spin transfer across ferromagnet-metal interfaces in conjunction with interface-sensitive magneto-optical experiments.

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Terahertz spintronics: exploiting ultrafast spin currents in magnetic heterostructures

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Spin-orbit interaction (SOI) will be of central importance for future spin-based electronics (spintronics) as it permits, for example, the conversion of charge into spin currents and vice versa via the spin Hall effect [1]. It is highly interesting to study spin dynamics at terahertz (THz) frequencies because spintronic devices should eventually operate at THz rates.

In our experiments, we employ femtosecond optical pulses to trigger ultrafast spin transport in magnetic thin-film stacks. Due to SOI, the spin current is partially converted into a transverse charge current which is monitored by detecting the concomitantly emitted THz electromagnetic radiation [2-5].

In particular, we study THz emission from bilayers consisting of a magnetic and a nonmagnetic metallic layer. By varying the magnetic layer material from conducting to insulating and from ferromagnetic to antiferromagnetic, we aim at identifying the different mechanisms that can lead to the ultrafast generation of spin currents across those structures. Such mechanisms include super-diffusive spin transport by conduction-band electrons [6] in metal-metal stacks and magnon-mediated transfer of spin angular momentum in insulator-metal stacks [7,8].

The results shown here were obtained in close collaborations with the research groups of J. Barker, C. Ciccarelli, S.T.B. Gönnenwein, M. Kläui, Y. Mokrousov, M. Münzenberg, P.M. Oppeneer, I. Radu and D. Turchinovich.

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Nanoscale Magnetic Imaging using Circularly Polarized High-Harmonic Radiation

Ofer Kfir[1,2*], Sergey Zayko[1*], Christina Nolte[3], Murat Sivis[1], Marcel Möller[1], Birgit Hebler[4], Sri Sai Phani Kanth Arekapudi[4], Daniel Steil[3], Sascha Schäfer[1], Manfred Albrecht[4], Oren Cohen[2], Stefan Mathias[3,5] and Claus Ropers[1,5]

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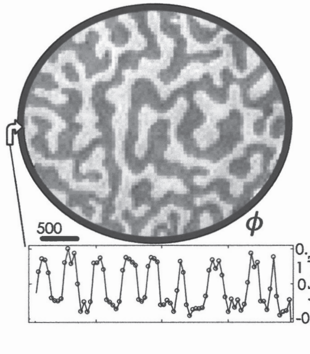
Attractive magnetic phenomena such as skyrmions and all-optical-switching are found in ferrimagnetic materials and structures. [1-3]. Mapping the underlying spin configurations and probing their dynamics is an essential step towards functional nanomagnetic systems. Magneto-optical microscopy with extreme-UV and X-rays offers a unique element-specific probe of the magnetization state (rather than the stray magnetic field), however, it is presently limited to synchrotrons and free electron lasers [4]. This work is the first demonstration of nanoscale magnetic imaging with high-harmonic radiation. Harnessing recent developments in generation of laser-based circularly polarized high-harmonics [5], we probe the M-edge phase- and absorption contrast of cobalt (59 eV), within a ferrimagnetic-like Co/Pd multilayer structure (figure shows phase contrast of the magnetic circular dichroism). Our approach enhances the weakly scattered light from the magnetic features by interfering it with a strong auxiliary wave. By applying an iterative algorithm to recover the real-space pattern from the recorded diffraction intensities [6], we reach a resolution of 49 nm in the retrieved image (see single pixel contrast in the figure's lineout). Our results open the path towards element-specific probing of magnetic dynamics at the nanometer- and femtosecond-scales, even at a ferrimagnetic compensation point.



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Non-linear dynamics and magnetic textures in cavity optomagnonics

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In optomagnonics, light couples coherently to collective magnetic excitations in solid state systems. Recent experiments have demonstrated this coupling for the first time. This topic is of high interest for quantum information processing platforms at the nanoscale. In this talk, I show how to obtain the microscopic optomagnonic Hamiltonian starting from the Faraday effect and discuss the optically-induced classical nonlinear dynamics for a homogeneous magnetic mode. A unique feature of optomagnonic systems is moreover the possibility of coupling light to spin excitations on top of magnetic textures. For the case of a microdisk geometry, I discuss the coupling between magnon modes in the presence of a magnetic vortex, and light confined to whispering gallery modes.

Cavity Spintronics

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Cavity Spintronics [1] (also known as Spin Cavitronics) is a newly developing interdisciplinary field that brings together microwave cavity community with researchers from spintronics. This field started around 2014 when it was found that ferromagnets in cavities hybridize with both microwaves and light via light-matter interaction [2-5]. Since then, the emergence of this field has attracted broad interests. At the center stage of the topic is the physics of a quasi-particle called cavity magnon polariton (CMP) [5,6]. Via the quantum physics of spin-photon entanglement on the one hand, and via classical electrodynamic coupling on the other, CMP connects some of the most exciting modern physics, such as quantum information and quantum optics, with one of the oldest science on the earth, the magnetism.

In this new community, the focus so far is on the development of cavity-mediated coupling and transducing techniques for both spintronic and quantum applications. This stream of research, including our recent demonstration of cavity-mediated distant control of spin current [7], roots on the single-particle hybrid nature of CMP. In this talk, we will present a new feedback-coupled cavity-spintronic technique, which we develop to study the cooperative dynamics of trillions of CMP. Utilizing the coherent dynamics of CMP ensembles, we demonstrate the control of magnon-photon Rabi frequency by changing the photon Fock state occupation, and we discover the evolution of CMP to cavity magnon triplet and cavity magnon quintuplet [8]. Our results may open up new avenues for exploiting the light-matter interactions using cavity spintronic approach.

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Spin dynamics in a chiral magnonic crystal

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As the size of transistors used in conventional semiconductor technology approaches its physical limits, present schemes for information processing will struggle to keep up with our ever-increasing demand for computational power. Hence, alternatives to semiconductor transistor-based computation are vigorously sought after. A promising approach is found in exploiting the electronic spin degree of freedom for information storage, transport and processing in magnonic devices.

We found that chiral magnets can provide an intriguing platform for magnonics as they act as natural magnonic crystals. Magnonic crystals are typically created in a top-down approach by introducing an artificial, extrinsic periodic modulation of a magnetic property. In contrast, chiral magnets feature an intrinsic modulation of the equilibrium spin direction with periodicity of about 10nm to 100nm – most prominently visible in the formation of a magnetic skyrmion lattice. Hence, chiral magnets form natural magnonic crystals and thus provide a bottom-up approach for magnonics. In our experiments, we study spin dynamics in the chiral magnetic insulator Cu_2OSeO_3 using broadband magnetic resonance spectroscopy [1]. We discover GHz-frequency magnon bands in the chiral magnetic phases and low spin wave damping at low temperatures. Our findings reveal the excellent quality of the natural magnonic crystal formed in a chiral magnet and unite aspects from the fields of skyrmionics and magnonics.

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Manipulating magnetism with light: From FePt to spin structures and vortex patterns

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Ultrafast magnetism concentrated on the understanding of out-of-equilibrium spins for the last 20 years, which is known now in many of its fundamental aspects [1]. Meanwhile many ways have been found to control spin structures by light on ultrafast time scales, which are connected with the variety of mechanism polarized light can act on a magnetic media. One possibility of control, is to shape the properties of the electronic system and thereby the THz dynamics. A special material of interest for magnetic storage development are FePt nanoparticles storage media. At high fluence, the electron temperature shoots to higher values above the Curie temperature, demagnetizing the system - a precondition for all-optical writing in metallic ferromagnets. Writing experiments by single laser spots point to an asymmetric writing per each shot. Different groups consistently observe this. I will review the current understanding of the interaction of ultrafast excitation and heating, influence of magnetic dichroism and the presence of the inverse Faraday effect for different wavelength into the infrared. Ab-initio calculations of the optically induced magnetization and the thermal modeling together, allow to calculate the switching rates of the individual FePt nanoparticles and to understand the out-of-equilibrium dynamics that finally results in deterministic switching with multiple pulses. Not only magnetic nanoparticles can be reversibly written by light, also vortex, antivortex networks can be written in standard thin Fe films, and also skyrmions. I will review these recent developments that may lead to address an individual nanosized magnetic element in the far future all optically, for writing magnetic memory and memory storage.

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Temperature dependence of YIG magnon-photon polaritons down to milliKelvin temperatures

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In information technology research, the spin wave-based approach using magnons, the quasiparticles associated to a spin wave, as information carrier, is a promising candidate for a new generation of applications for information transfer and logic.
A spin wave represents the collective excitation of a magnetically ordered spin ensemble out of the equilibrium state by a microwave probe signal.
Experimentally, we interface magnons with microwave cavities to investigate dynamics within the magnetic system. To this end, magnonic elements are strongly coupled to a photonic microwave resonator, resulting in hybridized magnon - resonator states, i.e. cavity magnon-photon polaritons.
These polaritons are key components for information processing technologies, because they merge the individual advantages of each of its constituents [1].
We have set up an experimental apparatus for the resonant coupling of spin waves in a magnetic bulk or thin film to either a microwave cavity or a coplanar waveguide (CPW) in the strong coupling regime [2,3]. This enables both readout at a fixed frequency or broadband measurements employing ferromagnetic resonance and input-output theory for temperatures from 10 mK to 290 K.
We present temperature dependent spectroscopic measurements of magnon – polariton states. The sample is a millimeter-sized YIG sphere (⌀ 0.5 mm), placed in the 6.5 GHz bright mode of a re - entrant cavity [4].
Specifically, we discuss features of the strongly coupled systems such as the coupling strength g, and linewidth of Kittel mode, that is the mode of a uniform excitation [5].
Regarding the coupling strength g, we observe for temperatures $T > 100$ K a temperature dependence which is proportional to the square root of the saturation magnetization's temperature dependence, following Bloch's $T^{3/2}$ law.
Due to conservation of the total spin number, an increased probability for a coupling of cavity photons to other magnetostatic modes in our specimen, results in the observed decrease of the coupling strength for temperatures below 100 K.
The temperature dependence of the Kittel magnon linewidth is possibly governed by rare earth impurity scattering caused by impurities in form of other rare earth elements in our sample.
As a next step, control of the coupling strength as a function of the phase of our applied microwave probe will help us to steer the flow of information in our hybridized magnonic-photonic system.

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Controlling the Collective Coupling in Spin-Photon Hybrids

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Solid-state based quantum systems (e.g. single spin systems like NV centers in diamond or phosphor donors in silicon, superconducting qubits, nanomagnets, and nanomechanical elements) are building blocks for devices exploiting quantum physics phenomena. With different quantum systems available, schemes allowing to couple them move into focus. In particular, coupling enables information transfer between the sub systems.

We will focus on the magnon-photon interaction between spin ensembles and microwave resonators and aspects of controlling this interaction. Hereby we will explore the different coupling regimes from weak to strong coupling. We will discuss the ferrimagnetic insulator Yittrium Iron Garnet as well as the compensated ferrimagnet Gadolinium Iron Garnet. In compensating magnetic systems the net-magnetization becomes tunable via the polarization and compensation of their sub-lattice magnetizations. We will show that the net magnetization of Gadolinium Iron Garnet can be tuned drastically around its compensation temperature and discuss its impact on the collective magnon-photon coupling rate.

Engineering spin-orbit-coupled materials

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In the search for novel materials' properties, the generation and manipulation of highly entangled quantum states is a grand challenge of solid state research. Amongst the most entangled proposed states are quantum spin liquids. In this context, the exactly solvable Kitaev Z2 spin-liquid model, for which finely tuned anisotropic interactions exactly fractionalize spins into fermionic Majorana spinons and gauge fluxes has activated an enormous amount of interest. Most specially since possible realizations may be achieved in octahedral coordinated spin-orbit-coupled
4d5 and 5d5 insulators. However, the low symmetry environment of the known Kitaev materials also allows interactions beyond the Kitaev model that open possible new routes for further exotic excitations.
Based on ab initio and many-body simulations and comparison to experimental observations, we will discuss in this talk, the challenges and opportunities that one faces in designing such materials and in identifying the origin of their excitations[1,2,3,4].

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Solid-state quantum computing: Where are we, where do we go?

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Quantum computing is becoming serious. After an extended period of basic research, quantum computing finds industrial adoption, use cases, and claims of outperforming classical supercomputers in certain applications. I will describe the three paradigms of uncorrected quantum advantage, fault-tolerant quantum computing, and quantum annealing with their requirements and perspectives. I will review solid-state platforms in the context of these paradigms and describe their potential.

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Chiral Magnetic Skyrmions, Antiskyrmions and Bobbers at Interfaces

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The spin-orbit interaction is a small but extremely important interaction in the context of magnetism and spintronics giving rise to important static, dynamical and transport properties. In this talk I focus on the role of the spin-orbit interaction for the formation of non-collinear spin-structures with emphasis on the chiral symmetry breaking Dzyaloshinskii-Moriya interaction [1], whose competition to the exchange interaction may lead to the formation of chiral magnetic skyrmions [2] and bobbers [3] at the interfaces and surfaces. I propose an experimental challenge to observe the topological orbital moments in skyrmions. I publicize a three-scale approach, which relates the microscopic theory of magnetic interactions as obtained by density functional theory, via a spin-lattice model to a micromagnetic models. I report on a recently introduced micromagnetic classification scheme [4] partitioning chiral magnets into *isotropic* rank-three DM bulk and rank-two DM film magnets, and *anisotropic rank-two* and *rank-one* DMI film magnets, where skyrmions and antiskyrmions can coexist even of the same energy. I provide examples of designing interactions to get skyrmions ready for technology and provide an outlook of an race track memory design based on the coexistence of different particles.
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Experimental determination of the magnon spin diffusion length by the nonlocal and local spin Seebeck effect

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The magnon spin diffusion length λ is a key parameter in spintronics and magnonics. It has recently been determined experimentally by the spin Seebeck effect (SSE) in magnetic insulators [1-4]. In the nonlocal SSE geometry, the injector-detector distance has to be varied to obtain λ from the exponentially decaying nonlocal SSE signal [1,5-7], while for the local SSE measurements, the increase and saturation of the local SSE response with increasing sample thickness is used to extract λ [3,4]. The determined values vary over decades from hundreds of nm to tens or even hundreds of µm depending on the geometry used and on the material under investigation.

Here, we present both techniques to obtain λ by the SSE in magnetic insulators and discuss advantages and disadvantages. We further present the pitfalls in the nonlocal SSE analysis that can lead to incorrect λ values [8]. Finally, we discuss the impact of using either the temperature gradient or heat flux normalization on the local SSE analysis [9-12].

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