ICC-IMR / 20th REIMEI International Workshop on

Spin Mechanics 2

June 21 - 24, 2014

Institute for Materials Research

Tohoku University

Lecture Hall [1st floor, 2nd bldg]

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ABSTRACTS

June 21 – 24, 2014
IMR Lecture Hall

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Spin Mechanics 2

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ICC-IMR / 20th REIMEI International Workshop on

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Scientific program

21st (Sat)

09:00~09:30	Takanashi	Opening
09:30~11:00	Heremans	Thermal properties of magnons, and magnetic properties of phonons
	Coffee	
11:30~13:00	Gross	Exploring the Quantum with Solid State Systems
	Lunch	
14:30~16:00	Yamaguchi	Nonlinear phonon dynamics in electromechanical resonators
	Coffee	
16:30~18:00	Saitoh	Spin currents

Posters up all time

22nd (Sun)

09:00~09:30	Hillebrands	Phonon Mediated Magnon Condensate
09:30~10:00	Chudnovsky	Nanomechanics with Spin
10:00~10:30	Ziman	Correlation effects in skew scattering
	Coffee	
11:00~11:30	Gonnenwein	Spin current generation in F/N heterostructures
11:30~12:00	Carman	Strain Mediated Nanoscale Multiferroics - Analysis and Experiments
12:00~12:30	Balestro	Coupling magnetism and mechanics on a molecular level
	Lunch	
14:30~15:00	Nakamura	Toward quantum magnonics: hybfidizing magnon mode in ferromagnet with superconducting qubit
15:00~15:30	Blanter	Mechanical systems as transducers
15:30~16:00	Klein	Mechanical-FMR spectroscopy of YIG|Pt nanodisks
	Coffee	
16:30~17:00	Uchihashi	Mechanical Rotation of Chiral Molecular Dimers Induced by Scanning Tunneling Mircoscope
17:00~17:30	Otani	Non-local Spin Injection into a Superconducting Niobium with Strong SO interaction
17:30~18:00	Mizuguchi	Anomalous Nernst effects in ferromagnetic metallic thin films and their thermoelectric application
		Poster up all time

23rd (Mon)

09:00~09:30	Freeman	Nanomechanical AC Susceptometry and Spectroscopy of Individual Mesoscopic Magnets
09:30~10:00	Jander	Interactions of Spin Wawves and Acoustic Waves in Yttrium Iron Garnet Films
10:00~10:30	Matsuo	Spin transport in deformed crystals
	Coffee	
11:00~11:30	Back	Spin Hall Voltage from DC and AC spin currents
11:30~12:00	Klaui	Strain – induced domain wall manipulation
12:00~12:30	Hickey	Temperature Dependence of the Spin Hall Magnetoresistance in YIG/Pt Films
	Lunch	
14:30~15:00	Chantrell	Enhanced damping at ferromagnet – antiferromagnet interfaces
15:00~15:30	Kovalev	Skyrmionic spin Seebeck effect via dissipative thermomagnonic torques
15:30~16:00	Tserkovnyak	Theory of electromechanical coupling in dynamical graphene
	Coffee	
16:30~17:00	Nagaosa	Thermal motion of skyrmions
17:00~17:30	Tatara	Magnetization Textures in the Presence of Spin-Orbit Interaction
17:30~18:00	Murakami	Berry-curvature dynamics of magnon wavepackets
18:30		Bus departure from IMR
19:00~		Conference dinner

24^{th} (Tue)

09:00~09:30	Sinova	Spin-orbit torque in Ferromagnetic and Antiferromagnetic systems
09:30~10:00	Ieda	Renomalization of spin-rotation coupling and Barnett fields
10:00~10:30	Takahashi	Spin Hall magnetoresistance in a trilayer system with noncollinear magnetizations
	Coffee	
11:00~11:30	Stiles	Coupling between Magnetization and the Lattice
11:30~12:00	Xia	First principle study on the TST at MgO based tunnel junctions and spin wave excitation at Au-YIG interface
12:00~12:30	Wang	Entropy Force behind Thermal Gradient Driven Domain Wall Propagation
	Lunch	
14:00~14:30	Kohno	Anomalous Hall effect and persistent current induced by spin chirality in the diffusive regime
14:30~15:00	Adachi	Enhanced dc spin pumping into a fluctuating ferromagnet near Tc
15:00~15:30	Tretiakov	Spin Texture Dynamics in Ferromagnetic and Antiferromagnetic Structures
15:30~16:00	Uchida	Experimental progress on spin Seebeck effect

Oral Sessions

Thermal properties of magnons, and magnetic properties of phonons

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This lecture will focus on heat transport by phonons and magnons, and particularly on the effect of magnetic fields on these heat carriers. The spin Seebeck effect is currently understood to be due to thermally driven spin fluxes, arising either from magnon thermal conductivity or from phonon-magnon or phonon-electron drag. Recent experiments qualify the effects of both of these contributions.

Magnon heat flux is relatively easy to isolate experimentally in YIG at temperatures below 10 K. This systems serves as a didactic platform to illustrate the origin of heat-driven spin fluxes. Above 50 K, the magnon dispersion relations of YIG complicate the temperature dependence of the spin Seebeck effect, and necessitate the introduction of the concept of “sub-thermal magnons” pioneered by Ref [1].

Phonons, in turn, are not classically associated with magnetism. We report the experimental observation of a magnetic field dependence of the lattice thermal conductivity on InSb, a diamagnetic semiconductor in which heat is conducted almost exclusively by phonons. This effect is associated with a local diamagnetic moment that arises from the local movement of atoms during phonon propagation. These moments in turn arise from the local changes in the valence band due to the local distortion of the lattice. The diamagnetic moment is quite small (of order of $10^{-5}\mu_B H$), but, because it is localized around individual atoms, it results in sharp gradients in magnetization. This results in a force on the atoms that creates a measureable magnetic field dependence of the bond anharmonicity, at least in a solid where the anharmonicity itself is small. This phonon-induced diamagnetic moment is the analog of the phonon-mediated electrical polarization, which induces anharmonicities used in the design of thermoelectric materials, and is at the origin of the difference between the dielectric constants at low and at optical frequencies.

[1] Tikhonov & al., *Nature Commun.*, 4, 145 (2013);

Sat-02

Exploring the Quantum with Solid State Systems

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The combination of photon boxes (cavities) with superconducting, magnetic, semiconducting, mechanical, etc. nanosystems leads to the fascinating field of solid state circuit quantum electrodynamics (QED), allowing the study of a rich variety of interesting phenomena. Meanwhile, in solid state circuit-QED systems the strong and ultra-strong coupling regime, where the coupling rate between solid state quantum two-level systems (qubits) and the cavity reaches a considerable fraction of the cavity transition frequency, can be achieved. This allows for the study of novel physics beyond the seminal Jaynes-Cummings model. Moreover, the combination of solid state quantum systems based on of different quantum degrees of freedom allows one to exploit the optimum properties of the various subsystems in so-called hybrid quantum systems. Such systems are promising for quantum communication, computing and simulation. We discuss the foundations of solid state circuit QED and outline the present state of development for a few specific systems.

(i) Superconducting circuit QED systems made impressive progress over the last decade. They are rapidly growing in complexity and approaching applications. Their combination with solid state systems exploiting other quantum degrees of freedom (magnetic, mechanic, plasmonic, etc.) in complex hybrid systems is promising.

(ii) The combination of superconducting microwave cavities and mechanical nanosystems results in the field of circuit nano-electromechanics. Here, the parametric coupling of photonic and mechanical degrees of freedom gives rise to a host of electro-mechanical phenomena such as quantum-limited displacement measurements, sideband cooling or amplification of mechanical motion. Likewise, this interaction provides mechanically mediated functionality for the processing of electromagnetic signals. For example, using electromagnetically induced transparency (EMIT) and absorption (EMIA) all-electromagnetic field-controlled tunable slowing and advancing of microwave signals, with millisecond distortion-free delay and negligible losses, can be realized. The inclusion of magnetic nanosystems seems promising.

(iii) Superconducting-magnetic circuit QED systems can be realized by coupling non-interacting spin ensembles or strongly coupled spins in a ferromagnet (e.g. the ferrimagnetic insulator $Y_3Fe_5O_{12}$ (YIG)) to a superconducting CPW microwave resonator. Recently, the strong coupling regime between YIG and a microwave cavity has been reached, allowing for the coherent exchange of quantized excitations (magnons and photons) in such a hybrid quantum systems.

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Nonlinear phonon dynamics in electromechanical resonators

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Coupled mechanical resonators are expected to provide a novel stage for phonon to play their correlated and collective dynamics. We used GaAs/AlGaAs-based piezoelectric mechanical resonators [1,2] with the structurally coupled geometries to demonstrate their cooperative dynamics. For paired mechanical resonators, applying a pump signal at the frequency difference of two orthogonal modes allows their parametric coupling under the perfect electrical control. It makes the vibration energy to be transferred from one to the other [3], enabling the rapid oscillation control of high-Q mechanical resonator [4]. The propagation characteristics of mechanical vibration in one-dimensional array of membrane resonators are also studied. The periodic structure leads to the dispersion relation with an apparent phononic band gap [5,6]. The nonlinear interaction between the waveguide and an isolated resonator enabled the dynamic propagation control. The functions of electromechanical resonators are expected to be markedly improved and extended through the integration with electrically controlled mutual coupling.

[1] I. Mahboob and H. Yamaguchi, Nature Nanotechnol. 3, 275 (2008).
[2] I. Mahboob, K. Nishiguchi, H. Okamoto and H. Yamaguchi, Nature Phys. 8, 387 (2012).
[3] H. Okamoto, A. Gourgout, C.-Y. Chang, K. Onomitsu, I. Mahboob, E. Y. Chang, and H. Yamaguchi, Nature Phys. 9, 480 (2013).
[4] H. Yamaguchi, H. Okamoto, and I. Mahboob, Appl. Phys. Express 5, 014001 (2012).
[5] D. Hatanaka, I. Mahboob, K. Onomitsu, and H. Yamaguchi, Appl. Phys. Lett. 102, 213102 (2013).
[6] D. Hatanaka, I. Mahboob, K. Onomitsu and H. Yamaguchi, to be published in Nature Nanotechnol. (2014)..

Spin currents

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An elementary introduction to spin current science for beginners (not for specialists or professors), comprising a lecture and a study tour.

1. Spin and spin current
2. Methods for measuring spin currents
3. Methods for generating spin currents

Phonon Mediated Magnon Condensate

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It is known, that magnons, which form a Bose-Einstein condensate (BEC) at the bottom of the spectrum of a parametrically populated magnon gas, have minimal intrinsic damping, and thus possess the longest possible lifetime. Therefore, the magnon BEC might be considered as a promising data carrier candidate in modern magnonics. However, due to its zero group velocity the BEC cannot be directly applied to information processing and transfer. Spin-orbit coupling effects may modify the BEC state and allow for new functionalities. Here we report on a magnon-phonon condensate, which possesses an intrinsic non-zero group velocity. The BEC formation was studied in phase space by means of time- and wavevector-resolved Brillouin light scattering spectroscopy. The measurements were performed at room temperature in a tangentially magnetized single crystal yttrium-iron-garnet film. Two spectral points of magnon concentration are detected: the first one is associated with the classical magnon BEC at a global energy minimum of the magnon gas; the second one corresponds to the hybridization area of the backward volume magnetostatic wave and a transversal acoustic phonon branch. The hybridization leads to the appearance of mixed magnon-phonon states, which possess significant magnetic properties even below the energy minimum of the pure magnon spectrum. Consequently, they can effectively collect quasi-particles from the magnon gas. On the other hand, as pure elastic excitations are introduced in equations of motion in linear form, no further transition of the hybridised quasi-particles to phonon states with lower energies is possible. As a result, a virtual energy minimum originates below the bottom of the pure magnon spectrum. The existence of this minimum drastically modifies the dynamics of the magnon gas: the parametrically injected magnons can spontaneously condense at this spectral point and form there a magnon-phonon quasi-particle condensate flowing with a non-zero group velocity.

In the case of spatially uniform pumping this flow does not change the density of the condensate, as at each point the magnon efflux and influx compensate each other. However, at the edge of the pumping area, a pronounced asymmetry of the magnon density is observed. The explanation is straightforward: The magnon-phonon condensate, which moves to the probing point from the opposite side of the resonator, is significantly populated as it aggregates the thermalized gaseous magnons over the entire width of the pumping area. At the same time the intensity of the hybrid phase propagating to the probing point from the neighboring resonator's edge is negligibly small. Support by the DFG within the SFB/TRR 49 is acknowledged.

Nanomechanics with Spins

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Conservation of the total angular momentum, spin + angular momentum, leads to the coupling between mechanical rotation of a body and magnetic moments inside the body, which is known as Einstein – de Haas effect. We have studied mechanisms of that effect in application to a number of problems that involve quantum spins in nanoresonators and molecules. Our research on spin tunnelling in magnetic molecules that have full or partial mechanical freedom has been recently reviewed in Ref. [1]. Recent experiments of Wernsdorfer's group with a single magnetic molecule drafted onto a carbon nanotube prompted us to investigate coupled quantum dynamics of a spin and a mechanical resonator [2]. In a separate study we have shown that a solid containing two-state systems may exhibit forces of quantum origin and proposed an example of such a force in a crystal of magnetic molecules in the field gradient [3]. In application to nanocantilevers, universal mechanism of damping of the cantilever motion by paramagnetic spins has been suggested that expresses the damping rate in terms of the imaginary part of the magnetic susceptibility [4]. We have also studied the possibility of switching the magnetic moment in a nanoresonator by the combined effect of the spin-polarized current and a mechanical kick [5].

[1] E. M. Chudnovsky, *Spin Tunneling in Magnetic Molecules that Have Full or Partial Mechanical Freedom*, Chapter 3 in the book: Molecular Magnets, Physics and Applications, Springer 2014.

[2] M. F. O'Keeffe, E. M. Chudnovsky, and D. A. Garanin, Phys. Rev. B **87**, 174418 (2013).

[3] E. M. Chudnovsky, J. Tejada, and R. Zarzuela, Phys. Rev. B 88, 220409(R) (2013).

[4] E. M. Chudnovsky and D. A. Garanin, Cond-Mat, arXiv:1402.2326.

[5] L. Cai, R. Jaafar, and E. M. Chudnovsky, Cond-Mat, arXiv:1402.7100

Correlation effects in skew scattering

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I will discuss recent work on correlation effects on skew scattering, relevant to experiments on non-local inverse spin and spin Hall effects. The theory of skew scattering in metals can be traced back to the original calculations of Mott for spin-orbit scattering from a local atomic potential. In current devices the microscopic origin of impurity skew scattering for anomalous Hall and spin Hall effects is usually sought in terms of phase shift analysis. I will discuss recent cases where we have to go beyond a simple impurity picture to include correlation effects, either because scattering is from spins that are correlated from site to site [1] or because electronic phase shifts at a given site depend on many-body correlations for the local atomic orbitals and hybridizing states and can thus be influenced by changes in the electronic wavefunctions due to proximity to a surface, strength of local correlations [2,3].

This work is based on collaborations with Bo Gu, Sadamichi Maekawa, Michiyasu Mori and Xu Zhuo of the ASRC, JAEA.

[1] B. Gu, T. Ziman, S. Maekawa, Physical Review B 86, 241303(R) (2013)
[2] B. Gu, Z. Xu, M. Mori, T. Ziman, S. Maekawa, 'Sign and magnitude of spin Hall effect in CuBi alloys' *Submitted* (2014)
[3] Z. Xu, B. Gu, M. Mori, T. Ziman, S. Maekawa, 'Sign change of the spin Hall effect due to electron correlation in nonmagnetic CuIr alloys', *To be submitted* (2014).

Sun-04

Spin current generation in F/N heterostructures

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In ferromagnet/normal metal (F/N) heterostructures, pure spin currents arise when the magnetization in F is driven out of thermal equilibrium. This process is referred to as spin pumping [1] if the spin currents are driven by coherent, radio-frequency magnetization dynamics (i.e., by ferromagnetic resonance), while the spin currents arising from incoherent, thermal magnetization excitations are usually discussed in terms of the spin Seebeck effect (SSE) [2].
In the talk, I will first review our spin pumping experiments in metallic F/N heterostructures, in which the coherent magnetization dynamics are either driven conventionally, via an externally applied microwave magnetic field, or acoustically, via radio-frequency elastic strains.
The second part of the talk then will be devoted to recent spin Seebeck effect measurements in magnetic insulator/normal metal heterostructures. More specifically, we have investigated the spin Seebeck effect in $Gd_3Fe_5O_{12}$/Pt (GdIG/Pt) thin film hybrids as a function of temperature *T*, and observed two consecutive sign changes of the spin Seebeck voltage upon lowering *T* from room temperature to 20 K. The first SSE sign change occurs around the magnetic compensation temperature T_{comp} = 260 K of GdIG, as predicted by a recent theoretical model by Ohnuma *et al.* [3]. The second (unexpected) SSE sign change takes place in the vicinity of 70 K. We attribute the second SSE sign change to spin currents arising from the Gd magnetic sublattice, which become sizeable only at temperatures below the so-called Gd ordering temperature [4].

[1] Y. Tserkovnyak *et al.*, Phys. Rev. Lett. **88**, 117601 (2002).
[2] K. Uchida *et al.*, Nature Mater. **9**, 894 (2010).
[3] Y. Ohnuma *et al.*, Phys. Rev. B **87**, 014423 (2013).
[4] S. Geprägs *et al.*, arXiv 1405.4971 (2014)

Sun-05

Strain Mediated Nanoscale Multiferroics – Analysis and Experiments

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Present day electromagnetic devices (e.g. memory, and antennas rely on a discovery made by Oersted 200 years ago where a current passing through a wire generates a magnetic field. While extremely useful this approach has significant limitations in the nanoscale. Recent discoveries suggest that a ferromagnetic material's intrinsic magnetization can be manipulated with an electric field (i.e. multiferroic) and thereby overcome the deficiencies associated with Oersted's discovery. This multiferroic approach to electrically control magnetism is enhanced by using physical phenomenon present in nanoscale magnetic elements such as the elimination of domain walls or near transitions such as superparamagnetic behavior [1].

This presentation provides experimental/analytical data on nanoscale multiferroic elements. Analysis consists of micromagnetic simulations (Landau-Lifshitz-Gilbert LLG) coupled with elastodynamics using the electrostatic approximation producing seven fully coupled partial differential equations. Qualitative and quantitative verification of the model (see Figure 1) is achieved with comparison to experimental data (as well as other modelling approaches) on single magnetic domain magnetostrictive elements. The modelling effort guides fabrication and testing of a variety of structures including nanoscale rings, oval shapes, and superparamagnetic elements. Experimental data obtained from Photoemission Electron Microscopy PEEM [2], Magnetic Force Microscopy MFM [3], Lorentz Transmission Electron Microscopy TEM and SQUID [1] demonstrates electrical control of multi-domain, single domain and superparamagnetic phenomenon. These results strongly support the hypothesis that the nanoscale multiferroic approach is a replacement for Oersted's current through the wire in the nanoscale.

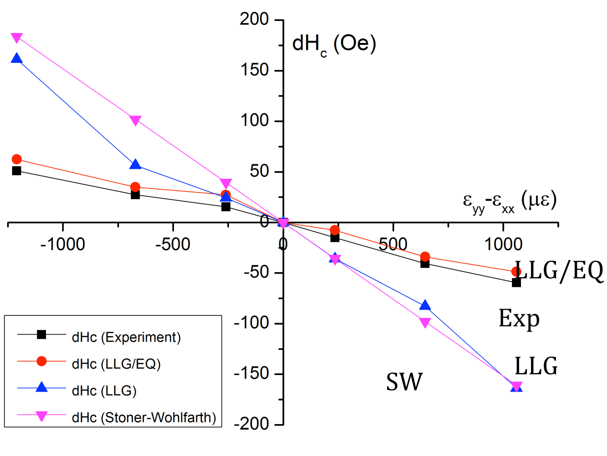

Figure 1 Comparison of Experiments to models.

[1] Kim, H.K.D. et al. , *Nano Letters*, 13(3):884 - 888 (March 2013)

[2] Buzzi, M., et al., *Physical Review Letters*, 111(2):027204 - 027208 (2013)

[3] Hockel, J.L. et al. , *Applied Physics Letters*, 100(2):022401 - 022403 (2012)

[4] Hockel et al. *Applied Physics Letters*, 102(24):242901 - 242905 (2013)

Coupling magnetism and mechanics on a molecular level

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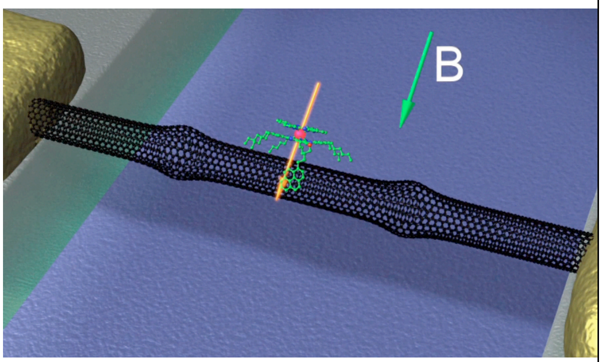
The magnetism of a nanoscale object, like single molecule magnets or atoms, is typically governed by the laws of quantum mechanics. Various quantum effects ranging from tunneling processes to coherent phenomena have for instance been observed in single molecule magnets. Probing the quantum nature of such molecular magnets however remains a challenging task and requires the use of an appropriate magnetometer, preferably one with molecular dimensions itself. Following the trend of carbon nanotube based magnetometers, we developed a magnetometer design based on a carbon nanotube nano-electromechanical system (NEMS). In order to achieve a molecular sensitivity, the carbon nanotube NEMS should exhibit large quality factors and allow a strong coupling to a molecular magnet. Indeed, we have demonstrated a strong coupling of a carbon nanotube's quantized mechanical motion to the magnetization of a terbium double decker single molecule magnet. As a consequence of the strong spin-phonon coupling, we can observe the nuclear spin states of the terbium ion in the molecule in magnetization reversal measurements at cryogenic temperatures[1]. Those results were confirmed by using a different type of detector, that allowed the observation of the coherent manipulation of a single nuclear spin[2,3].

[1] M. Ganzhorn, S. Klyatskaya, M. Ruben, W. Wernsdorfer. *Nature Nanotechnology* **8**, 165 (2013)
[2] R. Vincent, S. Klyatskaya, M. Ruben, W. Wernsdorfer, F. Balestro. *Nature* **488**, 357 (2012).
[3] S. Thiele, F. Balestro, R. Ballou, S. Klyatskaya, M. Ruben, W. Wernsdorfer. *Science* **to appear**, (2014)



Toward quantum magnonics: hybridizing magnon mode in ferromagnet with superconducting qubit

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Concepts and technologies of quantum coherent control were initially developed in microscopic systems such as atoms, nuclear and electron spins. However, triggered by the emergence of quantum information science, they have recently been extended toward more macroscopic degrees of freedom such as collective excitations in solid. The most pronounced example is electromagnetic excitations in superconducting circuits, in which superconducting qubits have been realized by exploiting the nonlinearity provided by Josephson junctions [1]. The artificial two-level systems, or 'atoms', coupled with superconducting resonators and other quantum systems have been enjoying rich physics and applications of circuit quantum electrodynamics (circuit QED) and hybrid quantum systems.

Spin-wave excitations (magnons) in magnetic materials are another well-known collective excitation which is commonly studied in magnetism and spintronics. Sometimes they have a long lifetime, for example, in the typical ferromagnetic insulator, yttrium iron garnet (YIG). While the magnon physics both in the exchange- and dipolar-interaction dominated regimes have been studied for many decades, experiments aiming at the single-magnon limit have been elusive until recently [2].

We have investigated ferromagnetic resonance of a mm-scale YIG sphere at low temperature (~10 mK) and low power (~ −140 dBm). The sphere is placed in a microwave cavity resonator made of oxygen-free copper and biased with a static field of about 0.3 T. We demonstrate coherent coupling between the magnon mode (the Kittel mode) with the microwave cavity mode (~10 GHz), even in the quantum limit where both the average magnon and photon numbers are less than one. The coupling strength amounts to more than 100 MHz, much larger than the few-MHz linewidths of the magnon and the cavity modes [3].

We also discuss how to couple the magnon mode with a superconducting qubit via a resonator. Coherent coupling with a qubit enables quantum control and measurement of the magnon excitations and thus opens a field of quantum magnonics.

This work was done in collaboration with Y. Tabuchi, S. Ishino, T. Ishikawa, R. Yamazaki, and K. Usami.

[1] Y. Nakamura, Yu. A. Pashkin, and J. S. Tsai, Nature **398**, 786 (1999).
[2] H. Huebl *et al.*, Phys. Rev. Lett. **111**, 127003 (2013).
[3] Y. Tabuchi *et al.*, in preparation.

Sun-08

Mechanical systems as transducers

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Mechanical resonators can be easily coupled to external degrees of freedom such as spin, charge, photons, or superconducting phase. In particular, this coupling becomes extremely important in view of recent observations of quantized mechanical motion, which makes mechanical systems attractive for the usage as quantum state transducers. In the first part of the talk, I will discuss quantum state transduction and, in particular, how two mechanical resonators coupled to one microwave resonator and two spins can facilitate entanglement generation between the spins.[1] In the second part, I will discuss the effects of non-linearity and use the example of the dc SQUID coupled to a mechanical resonator. If the resonator is driven, and the driving frequency is comparable to the plasma frequency of the SQUID, the system acts as a Josephson parametric amplifier, known to be bistable. I demonstrate that the interaction between SQUID and mechanical resonator may lead to multistability of the amplifier thus radically cnaging its behavior.[2]

[1] N. Didier, S. Pugnetti, Ya. M. Blanter, and R. Fazio, Solid State Communications Special issue, in press (http://dx.doi.org/10.1016/j.ssc.2014.02.029), 2014.

[2] O. Shevchuk, R. Fazio, and Ya. M. Blanter, in preparation

Mechanical-FMR spectroscopy of YIG|Pt nanodisks

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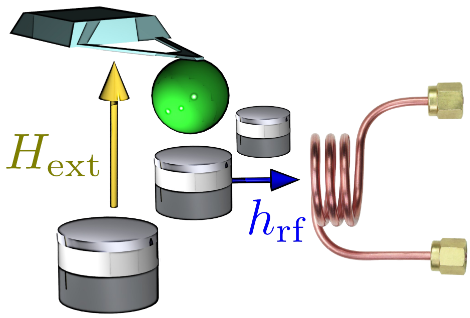

***FIG.1:** Schematic of the mechanical-FMR setup.*

Using the ability of magnetic resonance force microscopy to study the ferromagnetic resonance linewidth of a buried nanostructure, we report on an experimental study of the damping in individual nanodisks of YIG or YIG|Pt. The layer composition consists of 20 nm thick yttrium iron garnet (YIG) grown by pulsed laser deposition either bare or covered by 13 nm of Pt. We find that the linewidth in the nanostructure is sensibly smaller than the one measured in the extended film. Analysis of the frequency dependence of the spectral linewidth indicates that the improvement is principally due to the suppression of the inhomogeneous part of the broadening due to geometrical confinement, suggesting that only the homogeneous broadening contributes to the linewidth of the nanostructure. For the bare YIG nano-disks, the broadening is associated to a damping constant $\alpha = 4\cdot10^{-4}$. A threefold increase of the linewidth is observed for the series with Pt cap layer, attributed to the spin pumping effect (spin mixing conductance $G_{\uparrow\downarrow} = 1.55\cdot10^{14}\ \Omega^{-1}m^{-2}$) through the interface. Connecting these YIG|Pt nano-disks to external contact electrodes allows us to study the change of linewidth produced when a charge current flows in the Pt and a pure spin current is injected in the YIG by the direct spin Hall effect.

[1] C. Hahn *et al.* Appl. Phys. Lett. (2014)
[2] O. d'Allivy Kelly, *et al.* Appl. Phys. Lett. 103, 082408 (2013)

Mechanical Rotations of Chiral Molecular Dimers Induced by Scanning Tunneling Microscope

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The study on molecular motors is a new interdisciplinary field of research where chemistry, physics, biology, and nanotechnology are involved and intimately related with each other. One of its goal is to achieve spin-driven mechanical rotation based on the principle of the Einstein de Haas effect [1]. In this talk, we report dynamic behaviors of asymmetric Pt-porphyrin derivative molecules (with three tert-butylphenyl groups and one methoxycarbonylphenyl group) on a Au(111) surface induced by a low-temperature scanning tunneling microscope (STM).

The molecules are found to be trapped on atomic-scale impurities bound at the elbows of Au(111) herringbone reconstruction. These molecules exhibit thermally-activated rotation at 80 K if the impurity location coincides with the geometrical center of the molecule, indicating that the impurity site works as a rotation axis for the molecules [2]. Lowering the surface temperature down to 5 K stops these rotations. At this temperature, a stepwise rotation of the molecules can be induced by applying voltage pulses at the center of the molecule. The threshold voltage for inducing rotation corresponds well with the molecular resonances in the dI/dV spectra on the molecule. This suggests that the rotation is triggered by electron injection into a molecular resonance state and the following inelastic electron energy transfer to the vibrational mode [3].

Furthermore, these molecules form supramolecular dimers on Au(111). They are trapped at the impurity sites and can be rotated by electron injection as well. The rotational direction is determined by the chirality of the dimer and can be inversed by manipulation using the STM tip. This opens up the possibility of assembling complex molecular motors piece-by-piece and of tuning their functions *in situ*.

This study was performed by collaboration with P. Mishra, T. Nakayama, T. Ono, J. Hill, W. V. Rossom, K. Ariga, and C. Joachim.

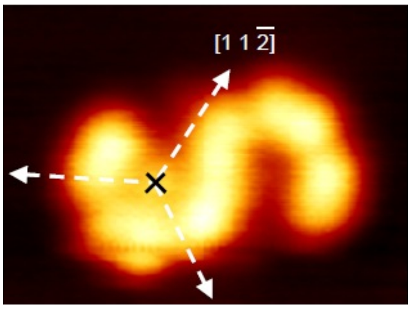

Fig.1 STM image of Pt-porphyrin derivative supramolecular dimer. The cross indicates the position of the pinning center on the surface.

[1] T. Ono, and H. Kohno, J. Magn. Soc. Jpn. **31**, 305 (2007).

[2] C. Manzano *et al.*, Nature Mater. **8**, 576 (2009).

[3] U. G. E. Perera *et al.*, Nature Nanotech. **8**, 46 (2013).

Non-local Spin Injection into a Superconducting Niobium with Strong SO interaction

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We demonstrate spin injection into superconducting Nb by employing a spin absorption technique in lateral spin valve structures. Our device typically consists of two ferromagnetic Permalloy (Py: $Ni_{81}Fe_{19}$) wires and a Nb wire in between bridged by a nonmagnetic Cu wire as in Fig. 1. This device enables us to determine τ_{sf} of superconducting Nb free from the superfluous effects such as the magnetic proximity effect on a superconductor [1] or the charging effect in a small tunnel junction [2]. Compared with previous studies, Nb is employed as a superconductor because it is more intriguing in that it can bring about novel phenomena like the spin Hall effect due to its strong spin-orbit (SO) interaction, and it has even higher superconducting critical temperature T_C than Al. We used the spin absorption technique, which is efficient for injecting a pure spin current into materials with strong SO interaction [3,4]. Below T_C, the amount of the absorbed spin current anomalously depends on the spin injection current. Calculations based on the Usadel equation can well reproduce the experimental results and show that the spin current is absorbed into superconducting Nb considering the superconducting gap of Nb with the proximity effect and the strong SO interaction. Our calculations can directly estimate τ_{sf} in the superconducting state and demonstrate that it becomes more than 4 times longer than that in the normal state, consistent with the theoretical prediction [5].

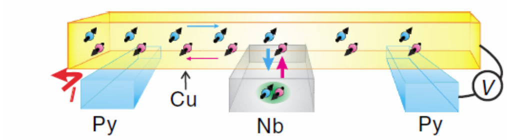

Fig. 1 Schematic illustration of a typical device structure.

[1] Y.-S. Shin, H.-J. Lee, and H.-W. Lee, *Phys. Rev. B* **71**, 144513 (2005).
[2] C. D. Chen,W. Kuo, D. S. Chung, J. H. Shyu, and C. S.Wu, *Phys. Rev. Lett.*, **88**, 047004 (2002).
[3] Y. Niimi, Y. Kawanishi, D. H.Wei, C. Deranlot, H. X. Yang, M. Chshiev, T. Valet, A. Fert, and Y. Otani, *Phys. Rev. Lett.*, **109**, 156602 (2012).
[4] M. Morota, Y. Niimi, K. Ohnishi, D. H. Wei, T. Tanaka, H. Kontani, T. Kimura, and Y. Otani, *Phys. Rev. B*, **83**, 174405 (2011).
[5] T. Yamashita, S. Takahashi, H. Imamura, and S. Maekawa, *Phys. Rev. B*, **65**, 172509 (2002).

Sun-12

Anomalous Nernst effects in ferromagnetic metallic thin films and their thermoelectric application

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The discovery of spin Seebeck effect has explosively expanded spin caloritronics [1]. On the other hand, the anomalous Nernst effect (ANE) is a phenomenon where an electric field is induced along the vector product direction of temperature gradient and magnetization. Although ANE has been well known since a long time ago, the systematic investigation including material dependence has not been made and the mechanism has neither fully elucidated. In this study, we have directly measured ANE in epitaxial $L1_0$-ordered FePt thin films with perpendicular magnetization, and succeeded in estimating the effect quantitatively for nano-scaled devices (Fig. 1)[2]. Not only ANE but anomalous Hall effects of ferromagnetic alloy films with several magnetic anisotropy energies (K_u) were also measured systematically, and investigated the relation between the two effects.

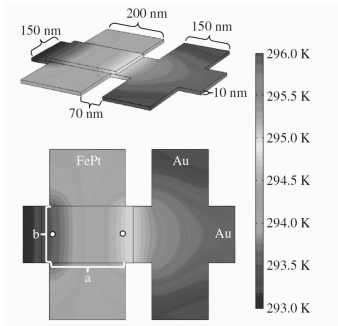

Fig. 1 A plan view of simulated temperature distribution.

We also proposed a new-type of thermopile consisting of two ferromagnetic materials with ANE of opposite signs[3]. The combination of perpendicularly magnetized FePt and MnGa wires enhanced the ANE voltage effectively. The thermopower of the present ANE device is one or two orders of magnitude lower than that of Seebeck modules using general thermoelectric materials. However, we have a chance of finding new magnetic materials or new stacked or embedded magnetic nanostructures that result in much higher ANE voltage values and realization of ANE-based thermoelectric applications.

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[1] K. Uchida *et al.*, *Nature*, **455**, 778 (2008).
[2] M. Mizuguchi *et al.*, *Appl. Phys. Exp.*, **5**, 093002 (2012).
[3] Y. Sakuraba, M. Mizuguchi *et al.*, *Appl. Phys. Exp.*, **6**, 033003 (2013).

Nanomechanical AC Susceptometry and Spectroscopy of Individual Mesoscopic Magnets

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A novel method for simultaneous detection of both DC and time-dependent magnetic signatures in individual mesoscopic structures has emerged from early studies in spin mechanics. Multifrequency nanomechanical detection of AC susceptibility and its harmonics highlights reversible nonlinearities in the magnetization response of a single yttrium iron garnet (YIG) element, separating them from hysteretic jumps in the DC magnetization [1].

Scaling the approach to higher excitation frequencies, we report preliminary results from simultaneous observations of magnetic hysteresis curves and magnetic resonances for a thin Permalloy disk. These measurements represent the beginnings of a "lab-on-a-chip" platform for the characterization of mesoscopic magnets.

[1] J.E. Losby, et al., *Solid State Commun* (2014), http://dx/doi.org/10.1016/j.ssc.2013.08.006

Interactions of Spin Waves and Acoustic Waves in Yttrium Iron Garnet Films

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Acoustic waves and spin waves interact in magnetostrictive materials via magnetoelastic coupling: through the Villari effect, the temporally and spatially varying strain in the acoustic waves produces a corresponding variation in the local anisotropy of the magnetostrictive material. We report a series of experiments that demonstrate specific acoustic/spin wave interactions in yttrium iron garnet (YIG) thin films.

In the first experiment, the *wavelengths* of the spin waves and acoustic waves, both propagating in a YIG film, are matched. The spatially periodic modulation of the YIG anisotropy by the acoustic wave presents a Bragg grating to the spin waves, which are partially reflected. Since the Bragg grating moves with the velocity of the acoustic waves (which is about 1/10 of the spin wave velocity) the reflected spin waves experience a Doppler shift (Fig. 1). Remarkably, for backward volume spin waves, this Doppler shift is seen to be the reverse of the normal due to the negative spin wave dispersion [1].

In the second experiment, we demonstrate the parametric amplification of spin waves by acoustic waves in YIG. In this experiment, the *frequencies* of the spin and acoustic waves are matched such that the acoustic wave is at twice the frequency of the spin wave. Under these conditions, the time-periodic modulation of the effective anisotropy field results in parametric pumping of the spin wave. The experimental results, shown in Fig. 2, demonstrate an amplification of the spin waves in the presence of acoustic waves as well as a clear threshold for this non-linear interaction.

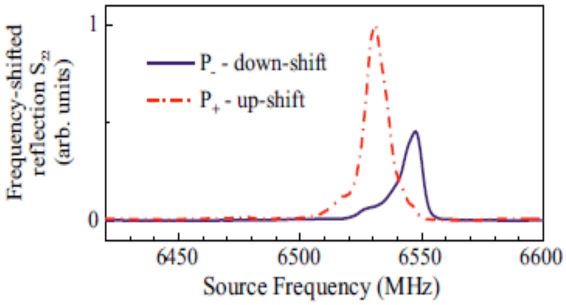

Fig. 1. Reverse Doppler shift seen in spin waves reflecting from the moving Bragg grating created by an acoustic wave.

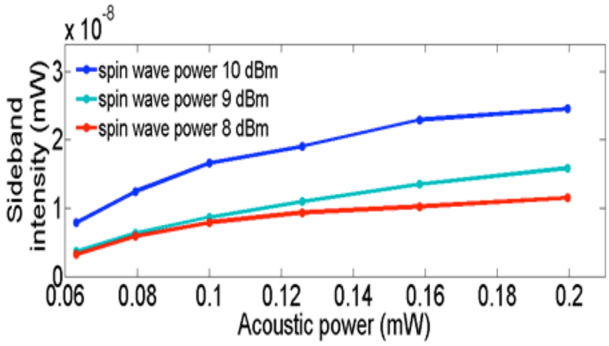

Fig. 2. Spin wave modulation (sideband intensity) caused by an acoustic wave, versus acoustic power for various spin wave amplitudes.

[1] A. Chumak, et al., *Phys. Rev. B*, **81**,140404 (2010).

Spin transport in deformed crystals

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A key concept in the recent progress in spintronics is "spin current", i.e. the flow of electron spin. Since the spin current is a nonconserved quantity, the utilization of spin current is much more challenging than that of charge current. Rapid progress in nanotechnology in the last decade, however, has allowed us to generate and manipulate spin currents by using magnetization dynamics and spin-orbit interaction [1]. In recent years, much attention has been paid to alternative ways of generating spin currents: spin-current generation by mechanical motion [2].

When a condensed matter rotates, a gauge field due to mechanical rotation emerges. Classically, the gauge field due to rotation couples to electron mass and that yields the Colioris effect. According to the quantum theory in an accelerating frame, the emergent field couples to electron spin. The coupling between spin and the gauge field originates from an intrinsic nature of spinor in curved spacetime [3].

In the presence of the surface acoustic wave (SAW), the elastically driven rotational motion induces a gauge field, which is responsible for spin current generation [4]. We solve the spin diffusion equation augmented by the field and show that the larger spin current can be obtained in a material with relatively weak spin-orbit coupling such as Al and Cu.

We also discuss spin transport in a crystal with ripples and dislocations. We show that electron spin couples to gauge fields induced by ripples and dislocations using low energy approximation of the generally covariant Dirac equation.

We thank N. Yokoi and E. Saitoh for valuable discussions and collaboration.

[1] S. Maekawa, S. Valenzuela, E. Saitoh, and T. Kimura, ed., *Spin current* (Oxford University Press, Oxford, 2012).

[2] M. Matsuo, J. Ieda, E. Saitoh, and M. Maekawa, *Phys. Rev. Lett.* **106**, 076601 (2011).

[3] D. Brill and J. Wheeler, *Rev. Mod. Phys.* **29**, 465 (1957).

[4] M. Matsuo, J. Ieda, K. Harii, E. Saitoh and M. Maekawa, *Phys. Rev. B* **87**, 180402(R) (2013); J. Ieda, M. Matsuo, and M. Maekawa, *Solid State Communications, in press*.

Spin Hall voltages from DC and AC spin currents

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The recent discovery of the spin pumping effect and the spin Hall effect has stimulated the research on metallic magnetic nanostructures. Here a comprehensive study of the spin Hall effect in metallic multilayers will be presented.

We study the direct as well as the inverse spin Hall effect [1-4]. In the case of the inverse spin Hall effect pure spin currents are injected by spin pumping from the ferromagnet into the normal metal [1]. The injected spin current has a large ac component transverse to the static magnetization direction and a very small dc component parallel to the magnetization direction. The inverse SHE converts this spin current into charge current. The corresponding inverse SHE voltages induced by spin pumping at ferromagnetic resonance (FMR) are measured in permalloy/platinum and permalloy/gold multilayers in various excitation geometries and as a function of frequency in order to separate the contributions of anisotropic magneto-resistance and spin Hall effect. The obtained spin Hall voltage is also studied as a function of temperature and the results are compared to theoretical models. In addition we demonstrate experimental evidence for the ac component of inverse SHE voltages generated by spin pumping [5,6]. We will also briefly discuss the case of Tantalum/Permalloy.

In a second set of experiments using identical samples we study the direct spin Hall effect. Here a dc current is applied to a ferromagnet/normal metal layer stack and the spin Hall effect causes the injection of a spin current into the normal metal layer [2,3]. This spin current is absorbed in the ferromagnet and causes a spin transfer torque. Using time and spatially resolved Kerr microscopy we measure the transferred spin momentum and compute the spin Hall angle.

[1] E. Saitoh et al., Appl. Phys. Lett. **88**, 182509 (2006).
[2] K. Ando et al., Phys. Rev. Lett. **101**, 036601, (2008).
[3] V. E. Demidov, et al., Phys. Rev. Lett. **107**, 107204 (2011).
[4] O. Mosendz, et. al Phys. Rev. Lett. **104**, 046601 (2010).
[5] D. Wei et al., arXiv:1307.2961.
[6] C. Hahn et al., Phys. Rev. Lett. **111**, 217204 (2013).

Strain – induced domain wall manipulation

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The interplay between mechanical degrees of freedom and the spin degree of freedom leads to a number of exciting possibilities. On the one hand, ultra-fast magnetization dynamics relies on the phonon channel for angular momentum dissipation. In particular using short laser pulses have been shown to generate demagnetization effects that can only be explained if significant angular momentum is transferred to the lattice and recently ultra-fast diffusive spin currents generated by fs laser pulses have shown to manipulate the magnetization on a fs timescale [1].

On the other hand, mechanical changes can also influence the spin degree of freedom due to spin – orbit coupling. This is exploited in (artificial-)multiferroics, where one uses electric fields to vary the lattice and via magnetoelectric coupling thus the magnetic properties. The appeal of this approach is the possibility to manipulate magnetization with very low power, as electric fields without continuous electric currents suffice to change the magnetization.

We have exploited different systems, where the interplay between mechanical and spin degrees of freedom is studied to understand the underlying physical phenomena.

The first system is a magnetic layer (Ni, Fe_3O_4) on top of a piezoelectric crystal (PMN-PT). The application of an electric field across the PMN-PT substrate generates a uniaxial in-plane stress that strains the magnetic layer on top as well. The uniaxial stress then generates a uniaxial magnetocrystalline anisotropy in the magnetic material due to magnetoelastic coupling. Using this method we reversible displace domain walls in nanostructures including non-volatile switching paving a way for low power devices [2]. By comparing the spin structure changes induced by the strain with micromagnetic simulations we quantify the induced anisotropy showing that the strain is efficiently completely transferred to the magnetic layer [3].

In multiferroic heterostructures further direct coupling mechanisms by charge doping and exchange coupling are possible. We show that in BFO-LSMO multilayers we can strongly modify the magnetic properties of the LSMO by the BFO [4].

Finally strain can also be induced in strongly correlated oxides that exhibit phase transitions. An example is VO_2 that exhibits a structural phase transition between a monoclinic and a rutile phase with temperature. Ni grown on top shows thus a phase-transition induced anisotropy [5] that allows us to tailor the magnetic properties on a fast timescale.

[1] B. Pfau et al., Nature Comm. **3**, 1100 (2012).
[2] S. Finizio et al., SPIN **3**, 1340008 (2013). Appl. Phys. Lett. **100**, 022401 (2012)
[3] S. Finizio et al., Phys. Rev. Appl. **1**, 021001 (2014).
[4] S. Finizio et al., (in press 2014)
[5] J. de la Venta et al., Appl. Phys. Lett. **102**, 122404 (2013).

Temperature Dependence of the Spin Hall Magnetoresistance in YIG/Pt Films

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We report on the temperature dependence of the recently discovered Spin Hall magnetoresistance in a Yttrium Iron Garnet (YIG) / Platinum (Pt) thin film. The YIG/Pt layers are an ideal choice as the combination of an insulating magnetic material and the high spin orbit interaction in Pt gives a relatively large magnetoresistance and no electrical conduction occurs in the YIG. The temperature dependence of the magnetoresistance was measured between 1.4 K and 280 K from which the temperature dependence of the spin diffusion length in Pt has been extracted. We found that the best agreement between our data and the recently published[1] theory of the spin Hall magnetoresistance is given by an assumed Elliot-Yafet mechanism of spin relaxation with temperature independent spin Hall angle and spin mixing conductance.

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[1] Y.-T. Chen, S. Takahashi, H. Nakayama, M. Althammer, S. T. B. Goennenwein, E. Saitoh, and G. E. W. Bauer, Phys. Rev. B **87**, 144411 (Apr 2013).

Enhanced damping at ferromagnet -antiferromagnet interfaces

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It has been found that there is an enhancement of the Gilbert damping in the ferromagnetic (FM) layer of FM/AFM coupled devices [1]. This is surprising due to the large difference in the frequency of the uniform modes between FM and AF materials. The precise mechanism for the enhancement of the damping is not known. We show that the increase in damping in the FM layer is due to the excitation of a local mode within the AF to which it is coupled. This acts as an energy sink to which the FM can dissipate energy. We identify the material parameters which determine the strength of the additional damping. Our approach is twofold. First we present a study of a simple FM/AF bilayer based on an analytic description, where the AF is described in an atomistic sense. This allows energy to propagate through the AF from the interface. Such a description allows us to go beyond a simple coherent spin model and to study the effects of non collinearity within the AF layer. Secondly we present a numerical simulation using an atomistic model with the damping determined by direct simulation of an FMR experiment. The two approaches are in excellent qualitative agreement and give damping enhancement comparable to experimental values. We find that a local mode in the AF is excited from a coupled FM film, which effectively damps energy transferred from the FM. This damping is relatively large for moderate and high interface coupling strengths. We also find blocking of the excitation by exchange frustration arising from rough interfaces. This is intriguing and gives insight into how interface roughness affects the FM/AFM pinning field. Our results suggest that the disorder at the interface reduces the area of the AF which couples effectively with the FM.

[1] Smith, N., Carey, M. & Childress, J. Phys. Rev. B 81, 184431 (2010)

Mon-08

Skyrmionic spin Seebeck effect via dissipative thermomagnonic torques

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Sizable coupling of spin to thermal flows leads to yet another knob by which we can control magnetization and magnetic textures such as domain walls as confirmed in recent experiments [1]. We derive thermomagnonic torque and its β-type dissipative correction from the stochastic Landau-Lifshitz-Gilbert equation. The β-type dissipative correction describes viscous coupling between magnetic dynamics and magnonic current and it stems from spin mistracking of the magnetic order parameter. We show that thermomagnonic torque is important for describing temperature gradient induced motion of skyrmions in helical magnets while dissipative correction plays an essential role in generating transverse Magnus force. The sign of the Magnus force is indicative of two regimes (i) $\alpha<\beta$ and (ii) $\alpha>\beta$ where according to our calculations the stochastic LLG equation results in the regime (i), here α is the Gilbert damping. We propose to detect such skyrmionic motion by employing the transverse spin Seebeck effect geometry (see Fig. 1). Our theory provides the minimalistic phenomenological description while further studies could incorporate magnon-magnon, magnon-phonon and magnon scattering on impurities by constructing a microscopic kinetic theory.

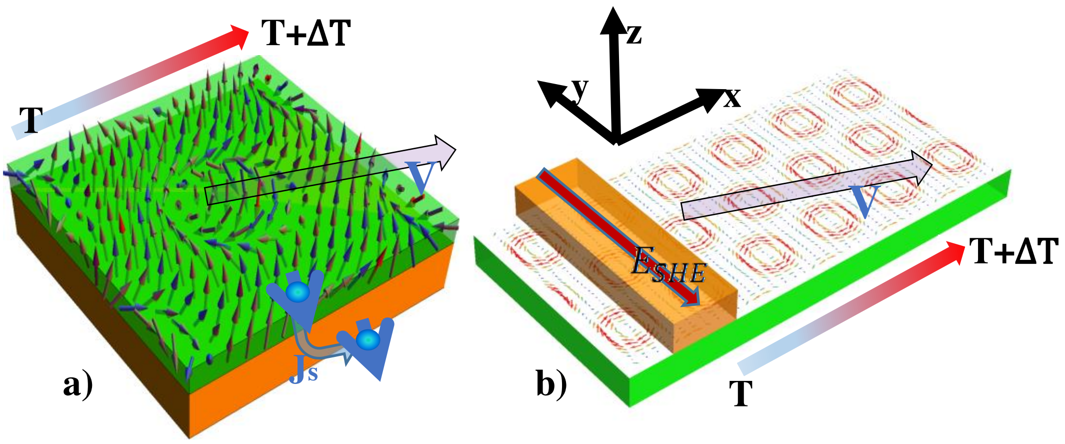

Fig 1, a) The magnon current induced by temperature gradient exerts spin torque on magnetization which leads to skyrmion motion in the direction of the hot region with an additional Hall-like side motion. An additional non-magnetic layer, such as Pt, can be used in order to detect the spin pumping resulting from skyrmionic motion, i.e. via the inverse spin Hall effect. b) Spin Seebeck effect geometry can be used for detection of the Hall-like motion of skyrmions. Due to mostly out-of-plane magnetization configuration the ordinary spin Seebeck effect should be suppressed.

[1] W. Jiang, P. Upadhyaya, Y. Fan et al., Phys. Rev. Lett. 110, 177202 (2013)

Theory of electromechanical coupling in dynamical graphene

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We study the coupling between elastic membrane distortions and Dirac electrons in a dynamical sheet of graphene. This coupling can be understood in terms of an effective gauge field acting on electrons, which has two contributions: (quasi)static and purely dynamic, of the Berry-phase origin, both in general engendering fictitious electric and magnetic fields. The static gauge potential (along with the electromagnetic field that it parametrizes) is known to be of opposite sign at the K and K′ valleys, while we find the same dynamic gauge potential at the two valleys, similarly to the true electromagnetic field. The mechanical fluctuations can thus mediate an indirect coupling between charge and valley degrees of freedom.

Thermal motion of skyrmions

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A swirling spin texture in magnets, skyrmion, is an emergent particle with topological stability. It has been recently discovered in several chiral magnets with DM spin-orbit interaction, and now regarded as a promising candidate for the future electronics. Its dynamics is governed by the spin Berry phase and is distinct from that of the usual Newtonian particle. In this talk, I will discuss the time-dependent dynamics of the skyrmions with the random stochastic torque representing the thermal agitation. First we discuss the Browning motion to derive the mass and dissipation of the skyrmion. Next, the scattering process between the magnons and a skyrmion is analysed, and lastly we discuss the Ratchet motion of skymion micro crystal studied both experimentally and theoretically. Collaborators of these works are J. Iwasaki, W. Koshibae, Aron Beekman, M. Mostovoy, J.D. Zang, M. Mochizuki, J. H. Park, J. H. Han, C. Schuette, A. Rosch, X. Z. Yu, Y. Matsui, Y. Onose, N. Kanazawa, T. Ideue, Y. Shiomi, Y. Taguchi, and Y. Tokura.

References

[1] N. Nagaosa and Y. Tokura, Nature Nanotechnology 8, 899 (2013).

Emergent Spin Electromagnetism Induced by Magnetization Textures in the Presence of Spin-orbit Interaction

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Magnetic textures in metallic systems induces emergent electromagnetic fields which couples to electrons' spin [1]. These fields have been experimentally observed by use of the anomalous Hall effect and motion of domain wall and vortices [2] and magnetic skyrmion lattice [3].

The spin electromagnetic fields in the presence of spin-orbit interaction has been explored recently [4-8]. It turned out that Rashba interaction introduces a novel spin gauge field resulting in Rashba-induced spin Berry's phase, but the structure of the Maxwell's equation is unchanged [7]. When spin relaxation is present, the emergent fields satisfy the Maxwell's equation but with an emergent monopole term [4]. The newly found monopole is expected to play crucial roles in converting a spin signal into electric one, i.e., in the integration of spintronics into conventional electronics. The case of (Ga,Mn)As is also mentioned.

[1] Volovik, J. Phys. C, 20, L83 (1987).
[2] Yang et al., Phys. Rev. Lett. 102, 067201 (2009).
[3] Schulz et al., Nat Phys, 8, 301 (2012).
[4] Takeuchi et al., J. Phys. Soc. Jap., 81, 033705; J. Korean Phys. Soc. 61, 1331 (2012).
[5] Kim, Moon, Lee, and Lee, Phys. Rev. Lett. 108, 217202 (2012).
[6] Tatara, Nakabayashi, and Lee, Phys. Rev. B 87, 054403 (2013).
[7] Nakabayashi, Tatara, New J. Phys. 16, 015016 (2014).
[8] Tatara, Nakabayashi, Journal of Applied Physics, 115 , 172609 (2014).

Berry-curvature dynamics of magnon wavepackets

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Magnons in ferromagnets form band structure and therefore we can associate the wavefunctions with Berry curvature in momentum space. The Berry curvature of magnons causes various physical phenomena such as thermal Hall effect [1,2]. In the presentation, we describe the magnetostatic waves (magnons) in terms of the bosonic Bogoliubov-de Gennes Hamiltonian [3] and calculate how the magnon thermal Hall conductivity behaves as a function of magnetic field and temperature. In particular, when the temperature is higher than the temperature scale for external magnetic field, the magnon thermal Hall conductivity becomes independent of temperature. We also present how this Berry curvature affects the dynamics of the magnon wavepacket within semiclassical theory. At the edge of a magnet it gives rise to the Goos-Hänchen shift, known in optics (Fig.1). We also discuss possible measurement of this shift in a magnet with a step, used for the observation of the Snell's law for spin waves in Ref.[4].

[1] R. Matsumoto, S. Murakami, Phys. Rev. Lett. **106**, 197202 (2011).
[2] R. Matsumoto, S. Murakami, Phys. Rev. B **84**, 184406 (2011).
[3] R. Matsumoto, R. Shindou and S. Murakami, Phys. Rev. B **89**, 054420 (2014).
[4] K. Tanabe, R. Matsumoto, J. Ohe, S. Murakami, T. Moriyama, D. Chiba, K. Kobayashi, and T. Ono, Appl. Phys. Express **7**, 053001 (2014)

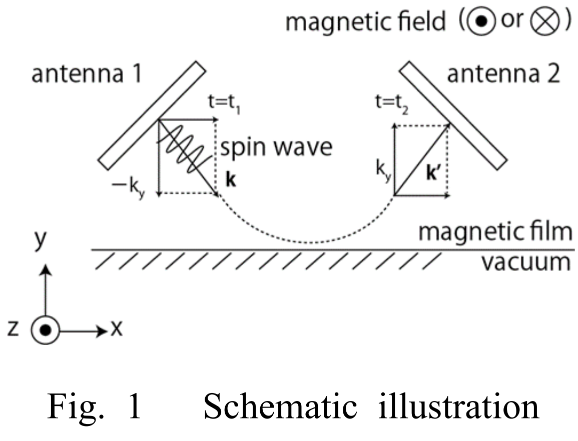

Fig. 1 Schematic illustration of Goos-Hänchen shift of magnons at the edge.

Spin-orbit torque in Ferromagnetic and Antiferromagnetic systems

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Abstract: As current-driven torques are becoming more relevant in future MRAM technologies, in-plane current magnetization dynamics driven by the so called Rashba spin-orbit torques or through a combination of spin-Hall effect and spin-transfer torque has become more and more important. Understanding these torques is paramount to maximize their use. In recent experiments we have shown that in addition to the intrinsic SHE and STT effect there exists an intrinsic spin-orbit torque originating from the Berry phase of the spin-orbit coupled Bloch electrons analogous to the intrinsic spin Hall effect. This type of torques can be observed through SO-FMR driven experiments. We show this new type of toques in theory and experiments in GaMnAs and show that it can be of similar strength to the strong field-like torque. In addition, we extend these physics to a new type of order-parameter manipulation by currents by examining the combined effect of spin-orbit coupling and anti-ferromagnetic order. We show that in broken inversion symmetry anti-ferromagnets a current will induced a non-equilibrium Néel-order field that will act directly on the Néel order parameter, hence making the direct manipulation of anti-ferromagnets without auxiliary exchange biased coupling to other ferromagnets a new and exciting possibility.

References

[1] H. Kurebayashi, Jairo Sinova, D. Fang, A. C. Irvine, J. Wunderlich, V. Novak, R. P. Campion, B. L. Gallagher, E. K. Vehstedt, L. P. Zarbo, K. Vyborny, A. J. Ferguson, T. Jungwirth, “Observation of a Berry phase anti-damping spin-orbit torque”, submitted to Nature Nanotechnology (2013); arXiv:1306.1893 (2013)

Renormalization of spin-rotation coupling and Barnett fields

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There are two physical mechanisms that combine magnetism and mechanical rotation. One is the Einstein de Haas (EdH) effect, the other the Barnett effect. The former refers to a phenomenon that, when a material body is magnetized by applying a magnetic field, it starts rotating as a consequence of angular-momentum conservation of the magnetization and the body. The EdH effect has been shown to be promising in application to nanomechanics and spintronics. The reciprocal of the EdH effect, the Barnett effect, posits that an electrically neutral body is magnetized when it is rotated, implying an emergent magnetic field, i.e., the Barnett field. Both the effects essentially originate from the spin-rotation coupling.

We show the enhancement of the spin-rotation coupling due to the interband mixing [1]. The Bloch wave functions in the presence of mechanical rotation are constructed with the generalized crystal momentum that includes a gauge potential originating from the rotation. Using the Kane model, the renormalized spin-rotation coupling is explicitly derived. As a result of the renormalization, the Barnett field, the mechanical torque on an electron spin, and the spin current generation due to elastic deformation [2] will be strongly enhanced.

We also discuss recent experimental results on observation of the Barnett field in solids by nuclear magnetic resonance [3] and its implication in future spin mechanics applications.

We thank H. Chudo, M. Ono, K. Harii, R. Haruki, S. Okayasu, H. Yasuoka, and E. Saitoh for valuable discussions and collaboration.

[1] M. Matsuo, J. Ieda and M. Maekawa, *Phys. Rev. B* **87**, 115301 (2013).

[2] M. Matsuo, J. Ieda, K. Harii, E. Saitoh and M. Maekawa, *Phys. Rev. B* **87**, 180402(R) (2013).

[3] H. Chudo, M. Ono, K. Harii, M. Matsuo, J. Ieda, R. Haruki, S. Okayasu, S. Maekawa, H. Yasuoka, and E. Saitoh, *submitted.*

Spin Hall magnetoresistance in a trilayer system with noncollinear magnetizations

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Spin Hall magnetoresistance in a trilayer system which consists of a normal metal in a spacer layer and ferromagnetic insulators such as yttrium iron garnet (YIG) in the outer layers is theoretically studied. The spin Hall magnetoresistance (SMR) is the resistance change induced by the simultaneous action of the spin Hall effect and the inverse spin Hall effect in the normal-metal layer with spin-orbit interaction such as platinum (Pt) [1-3], which will be sensitive to the magnetic configuration of magnetizations in the two ferromagnetic layers. In this presentation, we consider in a noncollinear (scissor-type) magnetic configuration, which is realized in anti-ferromagnetically coupled magnetizations in a magnetic field, and investigate how the spin Hall magnetoresistance depends on the relative angle of the scissor magnetizations. It is shown that the spin Hall magnetoresistance in the scissor magnetizations exhibits a strong angular dependence for a small relative angle region, when the thickness of the normal-metal layer is smaller than the spin diffusion length. The magnetization dynamics is also discussed [4].

[1] H. Nakayama, M. Althammer, *et al*., *Phys. Rev. Lett.* **110**, 206601 (2013).

[2] Y.-T. Chen *et al*., *Phys. Rev. B* **87**, 144411 (2013).

[3] T. Chiba *et al*., *Appl. Phys. Lett.* **102**, 192412 (2013); arXiv:1404.2360 (2014).

[4] S. Takahashi, *Appl. Phys. Lett.* **104**, 052407 (2014).

Coupling between Magnetization and the Lattice

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Conservation of angular momentum is a useful rule for understanding current-induced magnetization dynamics. Early in the development of the field it was particularly useful because only two reservoirs of angular momentum were considered, the magnetization and the spin accumulation of the conduction electrons. A change in one implied a change in the other. In fact, this was only true on the short time scale in which the magnetization was considered essentially stationary. On the time scale of the magnetization dynamics, magnetic damping would transfer angular momentum from the magnetization to the lattice. In addition, when considering the transport over the whole device, spin-flip scattering would couple angular momentum between spin accumulation and the lattice. In fact, when considering the whole circuit, in which the current entering and existing the device is unpolarised, the net transfer of angular momentum was between the magnetization and the lattice.

Recently, interest has focused on systems with strong spin-orbit coupling, in which the coupling between several reservoirs of angular momentum need to be considered [1]. In this case, it is useful to explicitly consider four reservoirs of angular momentum, the magnetization, the lattice, the conduction electron spin accumulation, and the conduction electron orbital angular momentum. The simultaneous transfer between these reservoirs leads to surprising effects like persistent spin transfer torques, in which there is a continual transfer of angular momentum from the lattice to the orbital angular momentum to the conduction electron and finally to the magnetization. In this case, the net spin transfer torque does not decrease with distance.

Even more recently, strong spin transfer torques have been observed in bilayers of ferromagnets and non-magnetic with strong spin-orbit coupling [2]. While it is clear that spin-orbit coupling plays a crucial in these systems. It is still not clear where the important coupling is and what the details of the angular momentum transfer are.

[1] P. M. Haney and M. D. Stiles, *Physical Review Letters* **105**, 126602 (2010).
[2] P. M. Haney, H.-W. Lee, K.-J. Lee, A. Manchon, and M. D. Stiles, *Physical Review B* **87**, 174411 (2013); K. J. Lee, H. W. Lee, A. Manchon, P. M. Haney, and M. D. Stiles, *Physical Review B* **88**, 214417 (2013).

First principle study on the TST at MgO based tunnel junctions and spin wave excitation at Au-YIG interface

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In this talk, we will report calculations of the thermal spin transfer torque (TST) in CoFe|MgO|CoFe and Fe|MgO|Fe|MgO|Fe tunnel junctions based on realistic electronic structures. We show that the TST in a CoFe|MgO|CoFe junction with sharp CoFe|MgO interfaces and ultrathin MgO barriers amounts to 10^{-9} J/m2/K at room temperature, which is much smaller than previously found for Fe|MgO|Fe junction with same barrier thickness. However, interfacial oxygen vacancies (OVs) can enhance the TST in CoFe|MgO|CoFe junctions again. We also compute angular dependent TST that provide more information to compare with experiments. We find the quantum well states in the double -barrier tunnel junctions can greatly enchance the TST.

Based on the frist principle calculated electronic structure of YIG, we extract the parameters of the Heisenberg model for YIG. We will also discuss the study on the spin wave exciation of YIG with the spin injction at Au-YIG interface.

Entropy Force behind Thermal Gradient Driven Domain Wall Propagation

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There is no doubt that a thermal gradient can be used to manipulate spins in a magnetic texture like skyrmions and domain walls (DWs). There are many channels that a thermal gradient can interact with spins. For example, a thermal gradient can affect spins through the thermoelectric effects by which spin polarized electric current is generated in a ferromagnetic metal. In turn, the thermally generated electric current can interact with magnetic texture via spin-transfer torque (STT). A thermal gradient can also generate magnons or spin waves that interact with magnetic textures. This effect should be important in a ferromagnetic insulator. Spin waves (or magnons) interact with magnetic domain walls (DWs) in a complicated way that a DW can propagate either along or against magnon flow, similar to its electron counterpart. Probably differ from its electron counterpart, it will be very difficult to understand why a DW can move along the magnon flow if the angular momentum transfer is the only mechanism behind the magnon driven DW motion. Thus, there must be other interaction between spin waves and magnetic textures. In terms of thermal gradient driven DW propagation along a nanowire, a DW always propagates to the hot region of a magnetic insulator wire. We theoretically illustrate why it is surely so by showing that DW entropy is always larger than that of a domain as long as material parameters do not depend on spin textures. Equivalently, the DW free energy is smaller than that of a domain. The larger DW entropy is related to the enhancement of magnon density of states at low energy originated from the phase shift of a spin wave passing through a DW as well as localized spin waves in a DW structure. The theory explains well why the free energy of a wire is linearly decrease with the temperature when the DW moves to the hot region. The result explains also why the magnetic domain widths decrease with the temperature.

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Tue-07

Anomalous Hall effect and persistent current induced by spin chirality in the diffusive regime

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We revisit the subject of anomalous Hall effect and persistent current due to spin chirality, a noncoplanar spin configuration, in the weak exchange coupling regime [1,2], and consider vertex corrections due to normal impurities that determine the transport. This amounts to considering the diffusive nature of electron motion, as well as spin conservation at the scattering from normal impurities, and changes the characteristic length scale from the electron mean free path to the spin diffusion length. The pre-existing circular persistent current, responsible for the anomalous Hall response, is identified by calculating the typical magnitude of the equilibrium current. Some mechanical aspects will also be addressed.

[1] G. Tatara and H. Kawamura, J. Phys. Soc. Jpn. 71, 011007 (2002).
[2] G. Tatara and H. Kohno, Phys. Rev. B67, 113316 (2003).
[3] K. Nakazawa and H. Kohno, submitted to J. Phys. Soc. Jpn.

Tue-08

Enhanced dc spin pumping into a fluctuating ferromagnet near Tc

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There has been a growing demand for an efficient method of generating a spin current because it is a key quantity in driving the functionality of spintronic devices. An emerging technique called "spin pumping" [1], i.e., a spin injection from a precessing ferromagnet into an adjacent spin sink, is now established as a versatile method for the spin current generation. The spin pumping has an advantage that it is not accompanied by any charge transfer across the spin injector/spin sink interface [2] and thus free from the impedance mismatch problem which often hinders a spin injection into semiconductors.

In this talk, we theoretically discuss the possibility of acheving a gigantic enhancement of the spin pumping [3]. We show that, when an itinerant ferromagnet near its Curie temperature Tc is used as the spin sink, the resultant spin pumping is largely increased owing to the fluctuation enhancement of the spin conductance across the precessing ferromagnet/spin sink interface. As an example, the enhanced spin pumping into nickel palladium alloy (Tc~20K) from yttrium iron garnet is analyzed by means of a self-consistent renormalization scheme, and it is predicted that the enhancement can be as large as tenfold.

[1] Y. Tserkovnyak et al., *Phys. Rev. Lett.*, **88**, 117601 (2002).
[2] K. Ando et al., *Nature Mater.* **10**, 655 (2011).
[3] Y. Ohnuma et al., arXiv: 1404.0768.

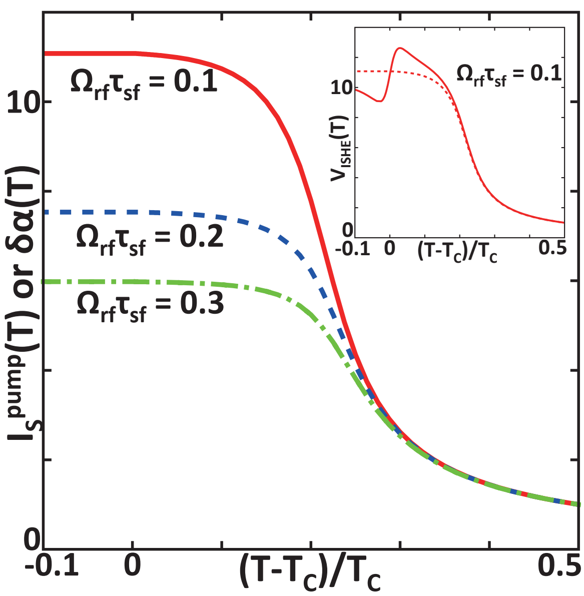

Fig. 1 Pumped spin current I_s^{pump} or additional Gilbert damping $\delta\alpha$, calculated for a NiPd/YIG bilayer as a function of reduced temperature. Inset: Temperature dependence of the inverse spin Hall voltage used to detect the enhanced spin pumping electrically.

Spin Texture Dynamics in Ferromagnetic and Antiferromagnetic Structures

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Ferromagnetic (FM) and antiferromagnetic (AFM) structures can be employed to manipulate and store information by means of topological spin textures, such as skyrmions, vortices, or domain walls (DWs). We study field and current driven spin-texture dynamics in thin FM and AFM nanostructures. We derive effective equations of motion describing the dynamics of spin-texture soft modes associated with topological defects. Because these spin textures are topological objects, the equations are rather universal and depend only on a few parameters. This method also allows to include in FMs such effects as Dzyaloshinskii-Moriya (DM) interaction in spin spiral structures [1] and translational non-invariance of non-uniform nanowires [2]. In AFMs, the dynamics is more complex because of the coupling between the staggered field and magnetization. Nevertheless, using collective coordinate approach we are able to describe the AFM spin-texture dynamics and show that it is equivalent to the motion of a massive particle subjected to friction and external forces [3]. Furthermore, it will be argued that the combined effects of space curvature and spin-orbit induced DM interaction can lead to even more exciting possibilities for DW propagation. Collaborators of this research are Ar. Abanov, A. Brataas, A. Goussev, Y. Liu, A. Qaiumzadeh, J. Robbins, V. Slastikov, and E. G. Tveten.

[1] O. A. Tretiakov and Ar. Abanov, *Phys. Rev. Lett.*, **105**, 157201 (2010).

[2] O. A. Tretiakov, Y. Liu, and Ar. Abanov, *Phys. Rev. Lett.*, **108**, 247201 (2012).

[3] E. G. Tveten, A. Qaiumzadeh, O. A. Tretiakov, and A. Brataas, *Phys. Rev. Lett.*, **110**, 127208 (2013).

Experimental progress on spin Seebeck effect

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The spin Seebeck effect (SSE) refers to the generation of a spin voltage as a result of a temperature gradient in magnetic materials [1-3]. Here, a spin voltage is a potential for electron spins to drive a nonequilibrium spin current; when a conductor is attached to a ferromagnet with a finite spin voltage, it induces a spin injection into the conductor. The SSE is of crucial importance in spintronics and spin caloritronics, since it enables simple and versatile generation of a spin current from heat.

In this talk, we report recent experimental progress on the SSE. Especially, we will focus on the following two topics:

(1) Longitudinal SSE suppressed by frozen magnetization dynamics in YIG [4] ,
(2) Quantitative temperature dependence of the longitudinal SSE in high temperature region [5].

These results provide a crucial piece of information for understanding the physics of the SSE.

We thank E. Saitoh, S. Maekawa, G. E. W. Bauer, H. Adachi, T. Kikkawa, and S. Daimon for their support and valuable discussions.

[1] K. Uchida, S. Takahashi, K. Harii, J. Ieda, W. Koshibae, K. Ando, S. Maekawa, and E. Saitoh, *Nature*, 455, 778 (2008).
[2] K. Uchida *et al.*, *Nature Mater.*, 9, 894 (2010).
[3] K. Uchida, H. Adachi, T. Ota, H. Nakayama, S. Maekawa, and E. Saitoh, *Appl. Phys. Lett.*, 97, 172505 (2010).
[4] T. Kikkawa *et al.* (to be submitted).
[5] K. Uchida *et al.* (to be submitted).

Poster Sessions

Orientation Dependent Spin Mixing Conductance of the Au|$CoFe_2O_4$ interface

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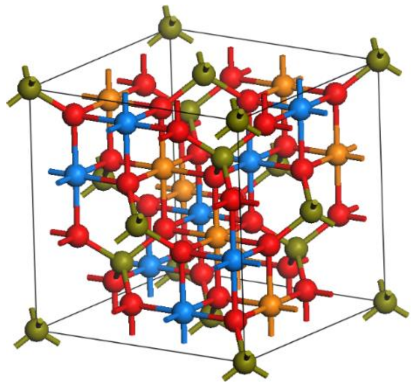

Recently, Isasa [1] reported a strong dependence of the spin mixing conductance of the magnetic insulator $CoFe_2O_4$ (the figure on the right) with Pt contacts on crystal orientation. Here we report spin mixing conductances of $CoFe_2O_4$|Au interfaces calculated with the LDA/GGA+C [2-5] method that depend on both crystal orientation and termination of the ferromagnet. For the fcc(111) orientation, the spin mixing conductances can differ by more than a factor of 10 between Fe_1Co and O-terminations.

A model analysis shows that the spin mixing conductance depends linearly on the interfacial magnetic moment density. While we confirm that large anisotropies exist, a detailed agreement is not observed and requires more investigations.

	001			111		
Terminations	Fe	Fe_1O	CoO	Fe	Fe_1Co	O
$G_{\uparrow\downarrow}$	2.8239	1.2768	3.2647	1.1483	9.0078	0.6308
Exp[1]	6.5~15			0.14~0.36		
MMD	10.50	21.51	15.64	12.12	30.48	<0.1
MMD2	15.642	<0.1	10.495	<0.1	<0.1	<0.1

Table 1. Spin mixing conductances of $CoFe_2O_4$ |Au for different crystal faces as well as the magnetic moment density (MMD) corresponding to each termination. MMD2 is the magnetic moment density of the first two monolayers (including empty spheres) nearest to the termination (≤ 1.4Å). The spin mixing conductances are in units of $10^{14}\Omega^{-1}\cdot \mathrm{m}^{-2}$ and magnetic moment densities in $\mu_B \cdot \mathrm{nm}^{-2}$.

[1] M. Isasa, A. Bedoya-Pinto, F. Golmar, L. E. Hueso, J. Fontcuberta, and F. Casanova, arXiv: 1307.1267 (2013).
[2] W. Ching, Z.-q. Gu, and Y.-N. Xu, Journal of Applied Physics 89, 6883 (2001).
[3] A. Rogalev, J. Goulon, *et al*., J. Magn. Magn. Mater. 321, 3945 (2009).
[4] V. Fiorentini and A. Baldereschi, Phys. Rev. B 51, 17196 (1995).
[5] X. Jia, K. Liu, K. Xia, and G. E. Bauer, EPL 96, 17005 (2011).

Actuation, propagation, and detection of transverse magnetoelastic waves in ferromagnets

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Motivated by recent experiments [1,2] we study propagation of transverse acoustic waves through a ferromagnetic medium with special attention to the boundary conditions at the interface with an ultrasonic actuator. In analogy to charge and spin transport in conductors, we formulate the energy transport through the system as a scattering problem. We find that the magneto-elastic coupling leads to a non-vanishing magnetic (elastic) energy accompanying the acoustic (spin) waves with a resonantly enhanced effect around the anti-crossing in the dispersion relations.

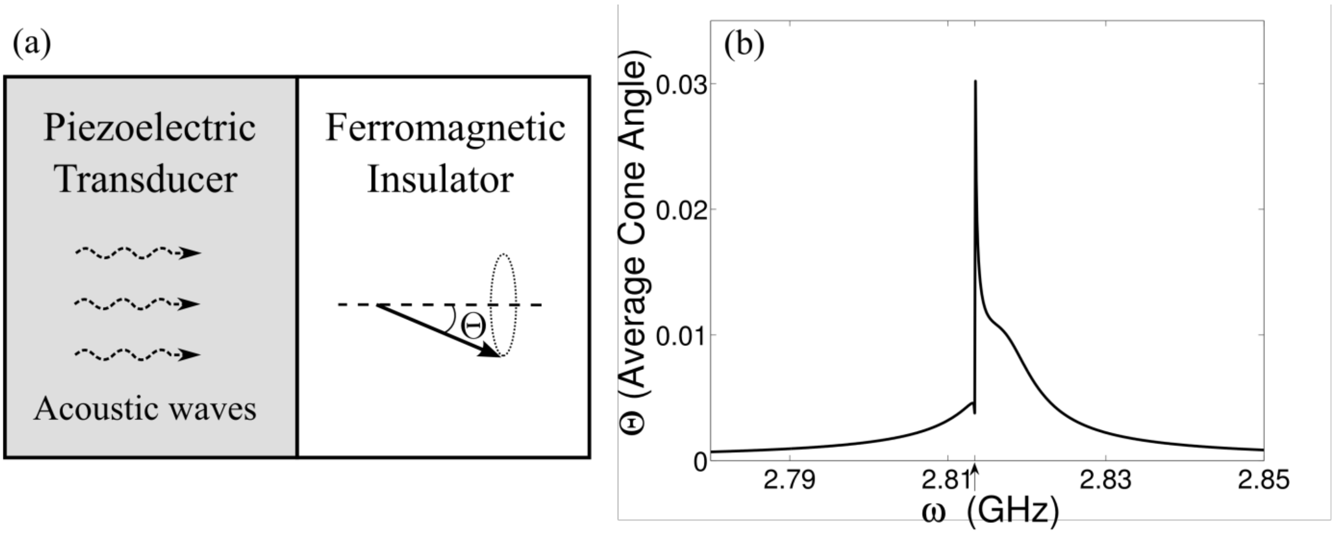

Fig. 1 (a) Schematic of setup. Transverse acoustic waves injected into a ferromagnetic insulator excite magnetization dynamics by means of the magneto-elastic coupling. (b) Average cone angle (of the magnetization precession) for incident acoustic energy flux density of $1W/m^2$ vs. frequency of acoustic waves. The arrow on the x axis indicates the ferromagnetic resonance frequency.

[1] M. Weiler et al., Phys. Rev. Lett. **108**, 176601 (2012).
[2] K. Uchida et al., Nat. Mater. **10**, 737 (2011).
[3] A. Kamra and G. E. W. Bauer, arXiv:1306.6268v2, Sol. Stat. Comm. SI: Spin Mechanics (2013).

Spin currents induced by thermal phonons

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Pure spin currents, i.e. the flow of angular momentum without an associated net charge current, allow for the excitation and detection of magnetization dynamics. Until 2008, the spin currents in question were generated by the so-called *spin pumping* process [1], in which the collective magnetization precession mode (magnon) of a ferromagnet is excited via microwave radiation and subsequently relaxes by emitting a pure spin current into an adjacent normal (not magnetically ordered) metal. With the discovery of the *spin Seebeck effect* [2,3], in which a ferromagnet/normal metal stack is exposed to a thermal gradient, spin current generation from a much broader spectrum of magnons became possible, i.e. by exploiting the coupling between the magnetic modes and the broad thermal phonon spectrum.
Here we summarize key results of our ongoing experimental and theoretical studies on the spin Seebeck effect, including 3D finite elements simulations accounting for the individual, coupled temperature profiles of phonons, electrons and magnons [4], transient spin Seebeck measurements with (thermal) excitation frequencies of up to 50 MHz [5], and a simplified spin Seebeck measurement scheme removing the need for additional heaters [6]. Additionally we show recent spin Seebeck measurements on compensated ferrimagnets in which the spin current qualitatively changes as a function of temperature.

[1] Y. Tserkovnyak, A. Brataas, and G. E. W. Bauer, *Phys. Rev. B* **66**, 224403 (2002).
[2] K. Uchida, S. Takahashi, K. Harii, J. Ieda, W. Koshibae, K. Ando, S. Maekawa, E. Saitoh, *Nature* **455**, 778 (2008).
[3] K. Uchida, H. Adachi, T. Ota, H. Nakayama, S. Maekawa, and E. Saitoh, *Appl. Phys. Lett.* **97**, 172505 (2010).
[4] M. Schreier, A. Kamra, M. Weiler, J. Xiao, G. E. W. Bauer, R. Gross, and S. T. B. Goennenwein, *Phys. Rev. B* **88**, 094410 (2013).
[5] N. Roschewsky, M. Schreier, A. Kamra, F. Schade, K. Ganzhorn, S. Meyer, H. Huebl, S. Geprägs, R. Gross, S. T. B. Goennenwein, arXiv:1309.3986
[6] M. Schreier, N. Roschewsky, E. Dobler, S. Meyer, H. Huebl, R. Gross, and S. T. B. Goennenwein, *Appl. Phys. Lett.* **103**, 242404 (2013).

Control of parametric amplification via spin-transfer torque of a pure spin current in Heusler/Pt bilayers

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We present the control of the effective spin-wave damping by the spin-transfer torque exerted by a pure spin current injected into Heusler compound microstructures [1]. Here, the pure spin current is generated by a DC current in a Pt layer on top of the magnetic layer via the spin-Hall effect [2]. This pure spin current can act on the magnetization in the magnetic layer and decrease or even compensate the Gilbert damping via the spin-transfer torque [3].

The damping is a very crucial parameter for any magnetization dynamics and the possibility to control this parameter, i.e. to further reduce the damping, gives access to novel nonlinear phenomena [4]. Especially, the cobalt-based Heusler compounds used in this work provide an already very low Gilbert damping [5]. Thus, the threshold for all spin-torque driven phenomena is comparably low and only small current densities in the Pt layer are needed.

The presented results were obtained using Brillouin light scattering microscopy [6]. Brillouin light scattering is the inelastic scattering of photons on magnons, the quanta of spin waves. By investigating the frequency and the intensity of the inelastically scattered light, the frequency and the intensity of the spin waves can be obtained.

The results show a strong influence of the pure spin current on the effective damping in the magnetic layer. They show the feasibility of using a DC current in a Pt layer to control the effective damping in an adjacent Heusler layer. Thus, this is very interesting for possible applications using spin waves or for the investigation of nonlinear effects especially in Heusler compounds.

The presented results were obtained in the framework of the Japanese-German Research Unit "Advanced spintronic materials and transport phenomena (ASPIMATT)", funded by JST and DFG.

[1] V. E. Demidov, et al., Nature materials 11, 1028 (2012).
[2] J. E. Hirsch, PRL 83, 1834 (1999).
[3] J.C. Slonczewski, JMMM 159, 261 (1999).
[4] T. Sebastian, et al., PRL 110, 067201 (2013).
[5] T. Sebastian, et al., APL 103, 112402 (2012).
[6] V. E. Demidov, et al., APL 85, 2866 (2004).

Spin Seebeck and other thermoelectric effects in $Ga_{1-x}Mn_xAs$ thin films

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If a magnetic semiconductor film is exposed to a temperature gradient and external magnetic field, it may show a number of thermoelectric effects like anomalous Nernst effect (ANE) or anisotropic magneto-thermopower, also known as planar Nernst effect (PNE). If Pt stripes are deposited on the surface of the film, the spin Seebeck effect (SSE) may appear [1,2]. Experimentally it is a challenging task to separate the different effects thus possibly proving the existence of the novel Spin Seebeck effect. If the temperature gradient is replaced with a charge current, the planar Hall effect (PHE) can furthermore be observed. The measurement of the PHE provides the opportunity to extract the orientation of the easy axes of magnetization.

In this work we perform a comprehensive investigation of thermoelectric (with temperature gradient) and galvanomagnetic (with charge current) effects in magnetic GaAs/GaMnAs/Pt and GaAs/GaMnAs systems.

We observed Planar Nernst Effect as contribution to the transverse voltages measured in sample subjected to an in-plane temperature gradient The measurement of the ANE provided us the opportunity to estimate the ANE coefficient of the material and showed the importance of the out-of-plane temperature gradient for TTSE experiments By PHE measurement we determined the orientation of the easy axis and reconstructed the processes of the switching of the magnetization between the easy axis. The obtained results are in agreement with [3,4] Magneto optical Kerr microscopy visually confirmed the results of PHE investigations

[1] C.M. Jaworski et al., Nat. Mater. 9, 898 (2010);
[2] K. Uchida *et al*., Nature **455**, 778 (2008);
[2] D. Y. Shin, S. J. Chung, Sanghoon Lee, X. Liu and J. K. Furdyna, Phys. Rev. B. 76, 035327 (2007);
[3] U. Welp, V. K. Vlasko-Vlasov, X. Liu, J. K. Furdyna, and T. Wojtowicz, Phys. Rev. Lett. 90, 167206 (2003).

Temporal evolution of the longitudinal spin Seebeck effect

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The spin Seebeck effect (SSE) is one of the most fascinating phenomena in the contemporary era of spin-caloritronics [1, 2]. Currently, this phenomenon has attracted much attention due to its potential applications [3]. Although there have been numerous experimental and theoretical studies, the underlying physics of this effect is yet not well understood. To shed light on the controversial physics, we developed an entirely new experimental approach where we studied the temporal evolution of the SSE in YIG|Pt bilayer structures in the longitudinal configuration.

In the longitudinal SSE, a thermal gradient is created perpendicular to the film plane, and the spin current generated by thermal excitations of magnetization (thermal magnons) is measured along the thermal gradient. The generated spin current is measured as an electric signal in the adjacent nonmagnetic metal (Pt) by means of the inverse spin Hall effect. In our experimental setup, the vertical thermal gradient in the YIG film was created using long laser pulses in order to carry out time-resolved measurements of the longitudinal SSE.

Our findings reveal the longitudinal SSE is a submicrosecond fast phenomenon governed by the thermal-magnons diffusion in thermal gradient in the magnetic material. A comparison of experimental results with the thermal-driven magnon diffusion model demonstrates that the temporal behavior of the longitudinal spin Seebeck effect depends on the time evolution of the temperature gradient in the vicinity of the YIG|Pt interface. An effective thermal-magnon diffusion length of 500 nm is estimated for the YIG|Pt bilayer system.

Financial supports by the Deutsche Forschungsgemeinschaft (SE 1771/4-1) within Priority Program 1538 “Spin Caloric Transport” is gratefully acknowledged.

[1] G.E.W. Bauer et al., *Nature Mater.* **11**, 391 (2012).
[2] K. Uchida et al., *Nature* **455**, 778 (2008).
[3] A. Kirihara et al., *Nature Mater.* **11**, 686 (2012).

Barnett levels in the rotating free electron gas

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The Barnett effect, i.e. the reorientation of the electron spin by mechanical rotation, was discovered at the dawn of quantum mechanics and provided first evidence for an anomalous g-factor of the electron [1,2]. Superseded by electron spin resonance to measure g-factors, gyromagnetic methods have been largely forgotten in the last decades. However, in recent years, the miniaturization of electric circuits and mechanical systems revived some interest (see e,g, [3]).

The Barnett effect can be understood in terms of classical mechanics: A gyroscopic wheel aligns its angular momentum with the axis of an impressed rotation in order to minimize energy. Modeling a magnetic moment as a gyroscopic wheel, one finds that rotation is equivalent to a "Barnett" gauge field in the rotating frame, $\vec{B}_g = -\vec{\omega}/\gamma$, where $\vec{\omega}$ denotes the rotation axis and $\gamma = g|e|/2m$. Direct observation of the Barnett field through nuclear magnetic resonance measurement has recently been reported [4].

We demonstrate that this Barnett gauge field not only acts on the electron spin but on the orbital motion characteristically different from a conventional magnetic field (and also of neutral particles). We illustrate this by comparing the "Barnett" level spectra of the rotating two-dimensional electron gas with that of the Landau levels in external magnetic fields. The rotation-induced magnetization of spin-less electrons leads to a purely paramagnetic response.

[1] S. J. Barnett, Phys. Rev. **6**, 239 (1915).
[2] S. J. Barnett, Rev. Mod. Phys **7**, 129 (1935).
[3] S. Bretzel et al., Appl. Phys. Lett. **95**, 122504 (2009).
[4] H. Chudo *et al.* (unpublished); K. Harii *et al*. (unpublished).

Theory of spin Hall magnetoresistance for alternating currents

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The magnetic insulator yttrium iron garnet (YIG) has attracted much attention as a new spintronic material for magnetic information technology because of its very low magnetization damping and the demonstration that spin waves can be excited electrically by the spin transfer torque [1]. However, the current-induced spin wave excitation is a strongly non-linear process and the critical threshold currents found by the experiment in ref. 1 have not yet been explained.

Here we suggest and model a simpler method to get to grips with the important current-magnetization interaction in the YIG|Pt system without a problematic threshold, *viz*. by employing the recently discovered spin Hall magnetoresistance (SMR) [2] to detect current-induced spin torque ferromagnetic resonance (ST-FMR) [3] in the system sketched in Fig. 1. We study alternating current-induced magnetization dynamics of a magnetic insulator such as YIG through the spin transfer effect by Pt contacts [4]. Calculating the magnetization dynamics by the Landau-Lifshitz-Gilbert equation with a current-induced oscillating spin transfer torque, we find that a DC voltage is generated in Pt as an SMR-induced rectification effect. The DC voltage generation as a function of frequency can be easily measured and directly proves the current-induced magnetization dynamics.

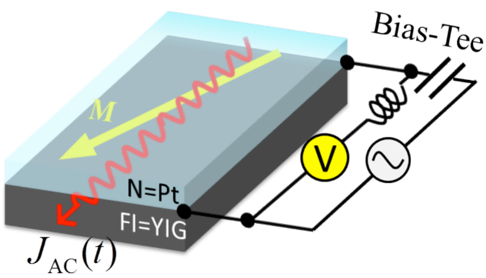

Fig.1: Schematic of the Pt|YIG device to detect the ST-FMR spectrum.

[1] Y. Kajiwara *et al.*, Nature **464**, 262 (2010).
[2] H. Nakayama *et al.*, *Phys. Rev. Lett.,* **110**, 206601 (2013).
[3] L. Liu *et al.*, *Phys. Rev. Lett.,* **106**, 036601 (2011).
[4] T. Chiba *et al.*, arXiv:1404.2360 (2014).

Superfluid Spin Transport in Magnetic Insulators

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Theoretical proposals for realizing and detecting spin supercurrent in various magnetic insulators are reported [1,2]. Superfluid spin transport is achieved by inserting a magnet between two metallic reservoirs and establishing a spin accumulation in one reservoir such that a spin bias is applied across the magnet. We first consider temperatures well below the magnetic ordering temperature where spin transport is mainly mediated by the condensate. There, Landau-Lifshitz and magneto-circuit theories are used to directly relate spin supercurrent in different parts of the heterostructure to the spin-mixing conductances characterizing the magnet-metal interfaces and the bulk magnetic damping parameters, quantities all obtainable from experiments. Thermal corrections to spin transport are also discussed. We show how spin superfluidity can be detected in a magnetically-mediated nonlocal conductance experiment.

References:
[1] So Takei and Yaroslav Tserkovnyak, arXiv:1311.0288 (2013).
[2] So Takei, Bertrand I. Halperin, Amir Yacoby, and Yaroslav Tserkovnyak, arXiv:1404.3987 (2014).

Current-induced magnetization dynamics in two magnetic insulators separated by a normal metal

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In this work, we study the magnetization dynamics of two thin-film ferromagnetic insulators (FIs) separated by a normal metal (N) in the macrospin model. A current through N induces a spin Hall current flowing in the perpendicular direction that can actuate the magnetization via the spin-transfer torque. In the absence of spin-Hall induced torques, spin pumping couples the two layers, resulting in an in-phase and an out-of-phase mode [1]. We derive expressions for the effective current-controlled Gilbert damping and the critical currents for the onset of magnetization dynamics including the effects of spin pumping. The current-induced torques generates a mode-dependent amplitude asymmetry between the two FIs. One can also imagine superlattices consisting of metals and magnetic insulators. These superlattices allow for spin waves propagating in the out-of-plane direction. We briefly discuss the current-induced magnetization dynamics in these systems.

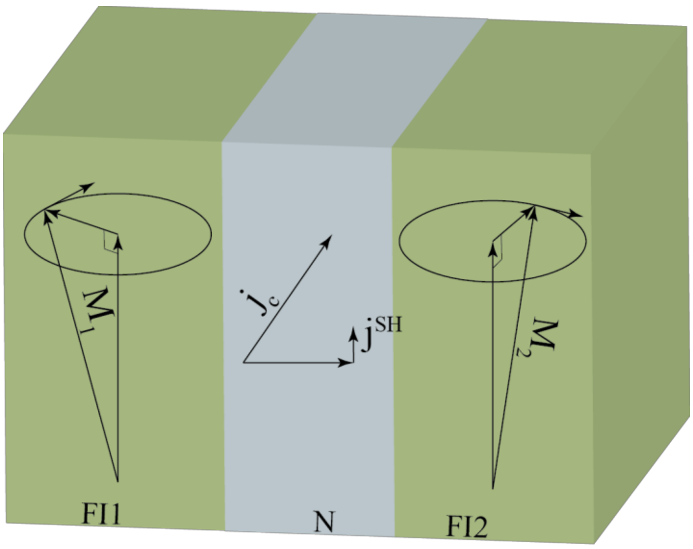

Figure 1: Illustration of the FI|N|FI system. A spin Hall current leads to additional magnetic torques on the two FIs.

[1] B. Heinrich, Y. Tserkovnyak, G. Woltersdorf, A. Brataas, R. Urban and G. E. W. Bauer, Phys. Rev. Lett. **90**, 187601 (2003)

Spin Seebeck Power Conversion

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The ever increasing waste of energy in the form of heat dissipated into the environment is an important part of the global energy crisis. In principle, this heat can, even at moderate temperature, be harvested by thermoelectric devices based on the Seebeck effect. The efficiency of a thermoelectric generator based on the conventional Seebeck effect can be represented by the dimensionless figure of merit ZT that includes the materials' properties.

Recently, it was discovered that a temperature gradient in a ferromagnetic insulators creates a spin current in an adjacent non-magnetic metal [1]. The spin-orbit interaction in this non-magnetic metal transforms the spin current into a transverse charge current by the inverse spin Hall effect (ISHE). The combination of thermal spin injection by the collective excitations of the magnetic order parameter and the ISHE is now referred to as spin Seebeck effect (SSE). The SSE is attractive for large area thermoelectric power generation [2]. However, since the physical mechanism of the SSE is different from the conventional one, the conventional definition of ZT fails.

We model thermoelectric power conversion based on the SSE and find that ZT is proportional to the product of resistivity times spin-flip length of the metal, which offers a convenient way to improve efficiency. However, a quadratic dependence on the spin Hall angle strongly suppresses the efficiency for most materials. We therefore propose an alternative method to generate energy from thermally generated spin currents by using a spin valve rather than the ISHE [3], which will be shown to perform better in micro and nanostructures.

[1] K. Uchida, et al, *Nature Mater.* **9**, 894 (2010).
[2] A. Kirihara, et al, *Nature Mater.* **11**, 686 (2012).
[3] A.B. Cahaya, et. al., *Appl. Phys. Lett.* 104, 042402 (2014)

Magnetostriction in Nanomechanical Beams

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Nanomechanical sensors have demonstrated excellent force sensitivity [1], allowing for the detection of individual spins on surfaces [2]. Here, we apply this sensor concept for the investigation of the effect of magnetostriction on the mechanical properties of a nanostring. To this end we use optical interferometry to experimentally investigate a 25 µm long and 300 nm wide highly stressed silicon nitride beam covered by a 10 nm thin film of cobalt. We study the eigenfrequency of this nanostring at room temperature as function of both, the direction and the magnitude of the magnetic field. For magnetic fields applied parallel to the film plane and perpendicular to the beam, we find a decrease in the resonance frequency by 7.6 kHz compared to fields applied along the beam direction. We explain this 10^{-3} change in the resonance frequency quantitatively by taking into account the effect of the magnetization orientation dependent magnetostriction. This opens the path for further magneto-mechanical experiments in nanostructures

[1] J. Moser et al., Nature Nanotechnology **8**, 493 (2013)

[2] D. Rugar et al., Nature **430**, 329 (2004)

Interaction of heat currents and spin currents by variational principles

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The study of spin-based electronics is a topical and challenging subject in solid-state physics which includes the manipulation of spin degrees of freedom. Bearing high potential for future technology and applications it is desirable to find proper means for the creation and control of spin currents. Applying temperature gradients to magnetic samples is a state-of-the-art method to generate magnetisation dynamics. Since the discovery of the Spin-Seebeck effect [1] in 2008 a new subfield of magnetism called spin-caloritronics has developed which focuses on the interaction of spins with heat currents [2].

The usual setup utilises uniform temperature gradients which means that the gradient of the scalar temperature field is a constant. From this the question arises what will be the effect of nonuniform temperature gradients characterized by a spatial varying gradient of the temperature distribution instead of uniform ones?

Here we present initial studies referring to that topic [3]. Based on a Lagrangian approach the energy excitations in ferromagnets are investigated in case the temperature gradient is coupled to the local magnetization. Proposing the action functional for the magnetothermal coupled system the relevant equations of motion are derived. As classical heat transport and magnetization dynamics occur on well separated time scales only the coupling between the spatially varying part of the temperature field and the magnetization is relevant. The magnetothermal coupling with a definite sign breaks the time inversion symmetry and leads to damped spin waves. Applying the model to nanowires it is demonstrated that the energy spectrum is significantly affected by the boundary conditions as well as the initial temperature distribution. The magnetothermal coupling is several orders of magnitude stronger for open wires compared to isolated ones.

[1] K. Uchida, S. Takahashi, K. Harii, J. Ieda, W. Koshibae, K. Ando, S. Maekawa and E. Saitoh, *Nature*, **455**, 778 (2008).

[2] G.E.W. Bauer, E. Saitoh and B.J. van Wees, *Nat. Mater.*, **11**, 391 (2012).

[3] T. Bose and S. Trimper, *Phys. Lett. A*, **376**, 3386 (2012).

Thermal magnon activiation and detection in a Pt|YIG bilayer system

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$Y_2Fe_5O_{12}$ or yttrium iron garnet (YIG) is a ferrimagnetic insulator that attracts a lot of attention from the spintronics community due to its low magnetic damping. This makes YIG an interesting material to study the transport of spin waves (magnons). In a Pt|YIG bilayer film, magnons in the YIG can be excited by means of the spin Hall effect (SHE) and spin-transfer torque. These non-equilibrium magnons can be detected using a second Pt strip (see figure 1.), where they are converted into a voltage through spin pumping and the inverse spin Hall effect (ISHE). Recent reports indicate a strong magnon-phonon interaction in YIG, resulting in a thermal relaxation length λ_{m-ph} on the order of nanometers [1,2]. We aim to measure this relaxation length using a device geometry as shown in figure 1. Varying the distance x between the Pt spin current injector and detector and measuring the ISHE signal V in the detector should allow us to extract the magnon relaxation length via $V(x) \sim e^{-x/\lambda_{m-ph}}$.

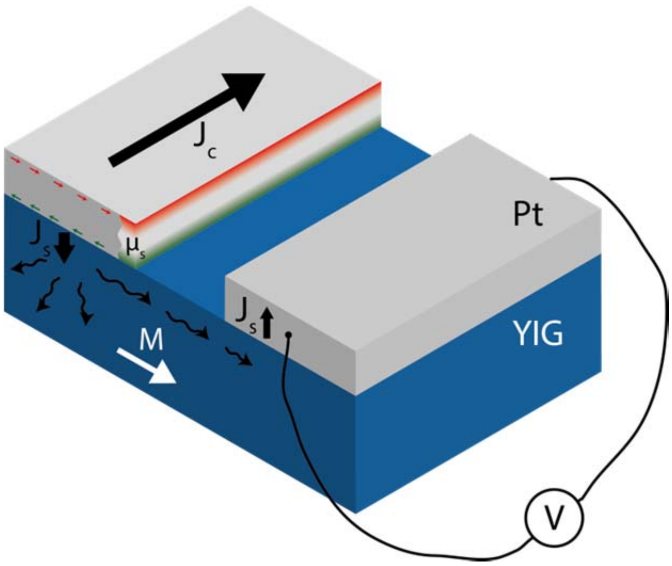

Figure 1. Schematic overview of the device. A spin accumulation μ_s is created in the left Pt strip by the spin Hall effect. μ_s injects a spin current J_s in the YIG due to spin transfer torque. The spin current diffuses to the right Pt detector where it generates an ISHE voltage V via spin pumping.

[1] J.Flipse, F.K. Dejene, D. Wagenaar, G.E.W. Bauer, J. Ben Youssef, B.J. van Wees, arXiv:1311.4772 (2013)
[2] Schreier, M., Kamra, A., Weiler, M., Xiao, J., Bauer, G.E.W., Gross, R., & Goennenwein, S.T.B., *Physical Review B*, 88(9), 094410 (2013).

Renormalization group study of thermal transport in the disordered Fermi liquid: An example for the use of Luttinger¹s gravitational potentials

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We present a detailed study of thermal transport in the disordered Fermi liquid with short range interactions. To the end we merge Luttinger's idea of using gravitational potentials for the analysis of thermal phenomena with the renormalization group approach in the Keldysh technique. The gravitational potentials are introduced as auxiliary sources that couple to the heat density in the action. These sources are a convenient means for generating expressions for the heat density and the heat density-heat density correlation function from the partition function. We analyze both the static and dynamical parts of the heat density-heat density correlation function. In particular, we check that the renormalization group flow of the diffusion coefficient, the frequency constant and the interaction constants as well as of the gravitational potentials is consistent with the phenomenological form of the correlation function, reflecting its relation to the specific heat and the constraints imposed by energy conservation. The main result of our analysis is that the Wiedemann-Franz law holds in the presence of disorder despite the quantum corrections to electric and thermal conductivities that arise at low temperatures.

Higher order exchange interactions leading to metamagnetism in FeRh

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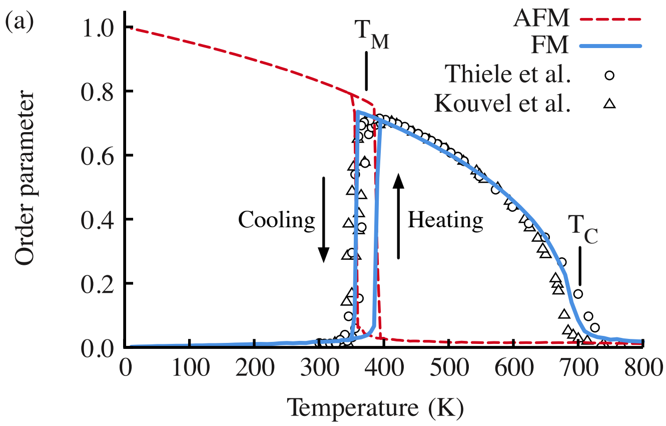

Fig 1. A comparison of the AFM and FM order in our model with experimental measurements of the FM magnetization.

The metamagnetic transformation of FeRh from antiferromagnetic (AFM) to ferromagnetic (FM) ordering has been studied for more than 70 years. The potential for technological applications is high, because the transition temperature is T_M = 350K and this can also be tuned through changes in composition, strain, doping and magnetic fields. However, it is still debated whether the phase transition is a thermodynamic magnetic phenomenon or caused by the lattice expansion which is observed. We investigate the possibility of a magnetic phase transition caused by higher order effective four spin interactions which occur between the Fe moments due to a non-linear behavior of the Rh moment [1]. We implement a statistical thermodynamic model using the techniques of atomistic spin dynamics. In a Hamiltonian of bilinear and four spin terms we demonstrate that a first order AFM-FM metamagnetic phase transition exists and agreement is found for the transition temperature (TM) and Curie temperature (TC) – reproducing experimental magnetization curves. The greater thermal dependence of four spin energy compared to the competing bilinear term is the cause of the phase transition. We also consider the timescale on which the phase transition can occur. This is important in light of sub-picosecond laser heating experiments, which show the FM order to be produced before the lattice expansion, on a picosecond timescale [2]. We find that a moderately large Gilbert damping parameter (α = 0.1) is needed to agree with these experiments.

[1] O.N. Mryasov, *Phase Transitions* **78**, 197 (2005)
[2] G. Ju et al., *Phys. Rev. Lett.* **93**, 197403 (2004)

Spin Seebeck effect in antiferromagnets and compensated ferrimagnets

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The spin Seebeck effect (SSE) is the mechanism of the generation of spin voltage by temperature gradient in a ferromagnet. The SSE is now established as a universal aspect of ferromagnets since it is obtained in a variety of ferromagnets. Since its discovery in 2008 [1], this phenomenon has attracted much attention as a simple way of generating spin currents that are needed for the future spin-based technology.

Here we consider a possibility of observing the SSE in a ferrimagnet with vanishing magnetization caused by the compensation effect [2]. The Heisenberg Hamiltonian with two sublattices is solved by the Holstein-Primakoff transformation. The model has two magnon branches in general. To consider the SSE signal in the ferrimagnet, we used the model that a paramagnetic metal combined with the ferrimagnet.

In this presentation we show that when the size of spins on the two sublattices are unequal and the two magnons have different stiffnesses, the condition for magnetization compensation is different from the condition for thermal-spin-injection compensation. This means that the SSE is obtained at the magnetization compensation point even in the absence of global magnetization, as shown in Fig.1 [3].

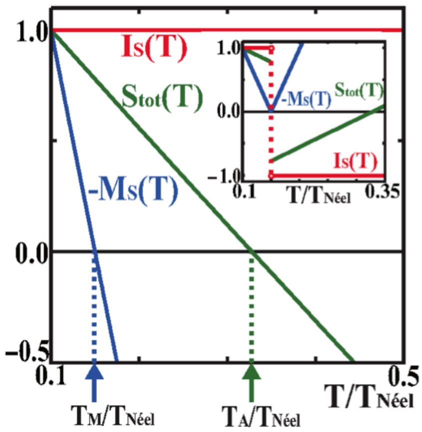

Fig.1 Temperature dependence of the SSE signal, saturation magnetization, and total angular at the compensation point. The data is normalized by its value at $T/T_{Néel} = 0.1$ [3].

[1] K. Uchida, S. Takahashi, K. Harii, J. Ieda, W. Koshibae, K. Ando, S. Maekawa and E. Saitoh, *Nature (London)* **455**, 778 (2008).
[2] R. C. LeCraw, J. P. Remeika and H. Matthews, *J. Appl. Phys.* **36**, 901 (1965).
[3] Y. Ohnuma, H. Adachi, E. Saitoh, and S. Maekawa, *Phys. Rev. B* **87**, 014423 (2013).

Nanomechanics of a semiconducting beam coupled to ferromagnetic electrodes

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Semiconducting nanowire electromechanics offers opportunity for studying thermal transport [1] and coherent manipulation [2]. Our nanoelectromechanical devices are fabricated using semiconducting InAs nanowires with ferromagnetic permalloy electrodes. The electrodes serve as clamping points as well as electrical contacts to InAs nanowires. The resonant frequency of our devices is ~ 50 MHz primarily determined by the diameter of ~ 100 nm and the suspension length of ~ 3 μm. The Q of our devices at 5 K is ~ 10000; this allows us to measure small frequency shifts accurately. We measure the resonant frequency using heterodyne mixing.

Motivation for such a device structure is to couple the magnetization of electrodes to mechanics of the nanowire through a static, or dynamic change in the magnetization. Preliminary experiments show that as we sweep the magnetic field through 0 T the resonant frequency of the device increases symmetrically around zero magnetic field. This response of frequency shift near 0 T is not seen in devices with non-magnetic electrodes. Several possible mechanisms including magnetostriction and dynamical micromagnetic response are being explored.

[1]Abhilash, T. S. et al. Nano Lett. 12, 6432–6435 (2012).

[2]Faust, T., Rieger, J., Seitner, M. J., Kotthaus, J. P. & Weig, E. M. , Nat Phys 9, 485–488 (2013).

Nanomechanical Transduction of Broadband Magnetization Processes in a Mesoscopic, Single-crystal Yttrium Iron Garnet disk

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For quantitative understanding and control magnetization dynamics in magnetic nanostructures it is necessary, in general, to have concurrent knowledge of their quasi-static magnetic landscape and corresponding dynamical responses. These landscapes can be defined by spatial inhomogeneities (disorder) and anisotropy (shape, magnetocrystalline), which can significantly affect their magnetization processes and AC response. A substantial contributor to magnetic disorder on the nanoscale are grain boundaries, which are intrinsic to most lithographically patterned magnetic nanostructures. Monocrystalline materials form a model class of micromagnetic systems which are desirable for minimizing the grain boundary dominated disorder background, but their fabrication is generally not amenable to traditional lithography methods.

Here, a micromagnetic disk was milled from a monocrystalline yttrium iron garnet (YIG) bulk film using a focused ion beam. Afterwards, the disk was nanomanipulated onto a torsional resonator for nanomechanical torque magnetometry measurements, which has emerged to become a powerful tool for gaining quantitative insight into quasi-static magnetization processes. Using a recently developed nanomechanical "lab-on-a-chip" detection scheme for capturing DC magnetization and AC susceptibility, simultaneously [1], we find the YIG disk's magnetization response is essentially Barkhausen-free while accompanied by a rich resonance profile.

REFERENCE

[1] J.E. Losby et al. Solid State Comm. (2014) (In press, special issue on Spin Mechanics) http://dx.doi.org/10.1016/j.ssc.2013.08.006 .

Direct observation of Barnett field by spinning nuclear magnetic resonance

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Angular momentum conversion between spins and mechanical rotation is a promising candidate of a mechanism for micro driving devices. Fundamental phenomena of the angular momentum conversion are the Einstein-de Haas effect (body rotation due to its magnetizing) [1], and the Barnett effect (magnetizing by body rotation) [2]. The Barnett effect implies that an effective magnetic field, called Barnett field, arises in a rotating body.

To measure the Barnett field by nuclear magnetic resonance (NMR) method, the detection has to be done on the rotating frame same as the body. The reason for this is that, if there are relative velocity between the signal detector and the body (signal emitter), an extrinsic NMR frequency shift arises from the relative velocity. To overcome the difficulty, we developed a new detection method in NMR, and directly measured the Barnett field [3]. The detection on the rotating frame was realized by the newly developed tuning circuit that consists of a sample and detection coil both installed in the same rotor.

The NMR resonance frequency, which is proportional to the magnetic field acting on nuclei, is shifted under rotation and the frequency shift is proportional to the angular velocity of sample rotation. The result means that the nuclei feel additional magnetic field to the external field. It is a direct evidence for the existence of Barnett field.

[1] A. Einstein and W. J. de Haas, Verh. Dtsch. Phys. Ges., **17**, 152 (1915).
[2] S. J. Barnett, Phys. Rev., **6**, 239 (1915).
[3] H. Chudo *et al*., accepted by APEX.

Quantum-State Control of a Ferromagnetic Magnon Mode Coupled to a Superconducting Qubit

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Recently, transducing a quantum state between a superconducting qubit and an optical mode has been intensively studied to realize long-distance quantum communication. As a candidate for such transducing media, we focus on ensemble of electron spins in ferromagnetic materials. In the long wavelength limit, magnon modes, consisting of ferromagnetic electron-spin ensemble, become macroscopic modes. In particular, the spatially uniform mode with a huge dipole moment is called Kittel mode. This mode has advantages of strong coupling and easy mode-matching with an external electromagnetic field.

Yttrium iron garnet (YIG) is a representative ferrimagnetic insulator, known for its narrow ferromagnetic resonance (FMR) linewidth. We couple microwave photons in TE_{101} mode of the rectangular copper cavity to Kittel mode magnons in a single-crystal YIG sphere mounted in the cavity at 10 mK, and obtain the coupling strength of 47 MHz between the cavity and the magnon mode for a sample with a diameter of 0.5 mm, for example. The coupling strength is much stronger than the cavity linewidth of 2.7 MHz and the magnon mode linewidth of 1.1 MHz [1]. On the other hand, the magnon linewidth shows peculiar temperature dependence below 1 K. We discuss correspondence between such behavior and the theory of the relaxation due to a bath of two level systems [2].

It is possible to couple coherently Kittel mode and a superconducting qubit via a cavity mode. We couple a single-crystal YIG sphere and a transmon-type superconducting qubit, both mounted in the rectangular copper cavity, via virtual microwave photons in TE_{102} mode. By sweeping the magnon frequency, we observe an anticrossing suggesting strong coupling. We also observe a parametric coupling, where two photons are involved. Such a process allows one to switch on and off the coupling between a magnon mode and a superconducting qubit. We believe that such a coupling also permits quantum-state control of the magnon mode in time domain. We are preparing for experiments to generate non-classical states of the magnon mode, such as Fock states and squeezed states.

[1] Y. Tabuchi *et al.*, arXiv:1405.1913 (2014).
[2] J. H. Van Vleck, J. Appl. Phys. 35, 882 (1964).

Dynamic manipulation of propagating phonons in a phonon waveguide

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Recently, phonons have been recognized as an important tool to manipulate spin degree of freedom via spin-phonon interactions, enabling the generation of pure spin currents [1] and the implementation of spin qubits [2]. An understanding of the means to control phonons is essential for the development of phonon-based spin devices for which a key ingredient is the active control of phonons. To that end, we have developed a membrane-based phonon waveguide (WG) in which the phonon propagation can be dynamically controlled at room temperature [3].

Figure 1 shows an SEM image of the phonon WG and the measurement setup. The phonon WG consists of a one-dimensional array of GaAs-based membrane resonators using conventional micromachining processes. In the center of the WG, a cavity membrane is created by increasing the separation to the adjacent membranes. Applying an alternating voltage at 5.745 MHz to the electrode on the right edge membrane can piezoelectrically excite phonons, i.e. mechanical vibrations, that travel through the cavity and are measured on the left edge membrane (blue line in Fig. 2). Simultaneously, localized phonons at 1.860 MHz are excited from the cavity which induces a frequency blue-shift in the WG mode. Therefore, the WG mode at 5.745 MHz is no longer available (red line in Fig. 2). This dynamic phonon WG architecture provides a promising platform to manipulate spins with mobile mechanical vibrations.

[1] K. Uchida et al., *Nature Mater*. 10, 737 (2011). [2] E. R. MacQuarrie et al., *Phys. Rev. Lett*. 111, 227602 (2013). [3] D. Hatanaka et al., arXiv:1401.5573.

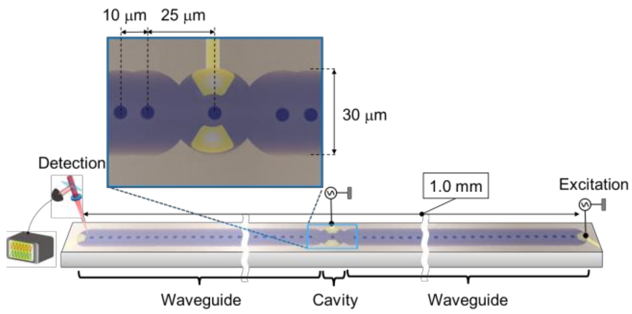

Fig. 1 The cavity-embedded phonon WG and its measurement set-up.

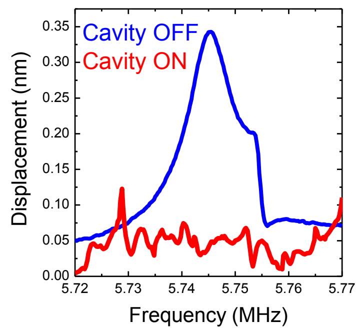

Fig. 2 The response of the WG mode with/without the cavity excitation.

Spin Mechanics 2 program

start	21st June (Sat)	22nd June (Sun)	23rd June (Mon)	24th June (Tue)	25th June (Wed)
8:30	Registration 1	*Posters up all time*			
9:00	Opening (Takanashi)	Hillebrands	Freeman	Sinova	
9:30	Tutorial 1 (Heremans)	Chudnovsky	Jander	Ieda	
10:00		Ziman	Matsuo	Takahashi	
10:30		Coffee break			
11:00	Coffee break	Gönnenwein	Back	Stiles	
11:30	Tutorial 2 (Gross)	Carman	Kläui	Xia	
12:00		Balestro	Hickey	Wang	*Hot Spring arr. at IMR*
12:30		Lunch break			
13:00	Registration 2 Lunch break				IMR to RIEC
13:30					RIEC Workshop
14:00				Kohno	
14:30	Tutorial 3 (Yamaguchi)	Nakamura	Chantrell	Adachi	
15:00		Blanter	Kovalev	Tretiakov	
15:30		Klein	Tserkovnyak	Uchida	
16:00	Coffee break				
16:30	Tutorial 4 (Saitoh)	Uchihashi	Nagaosa		
17:00		Otani	Tatara	*Hot Spring dep.*	
17:30		Mizuguchi	Murakami		
18:00	*Posters up all time*				
18:30			*Dinner dep.*		
19:00			*Conference Dinner*		

Lunch MAP