Reimei / GP-Spin / ICC-IMR
International Workshop

TOHOKU
UNIVERSITY

New Excitations in Spintronics

10-14 January 2018

Institute for Materials Research, Tohoku University

Sendai, Japan

IMR Lecture Hall [ground floor, building 2]

Reimei / GP-Spin / ICC-IMR
International Workshop

New Excitations in Spintronics

Abstract Book

Acknowledgements

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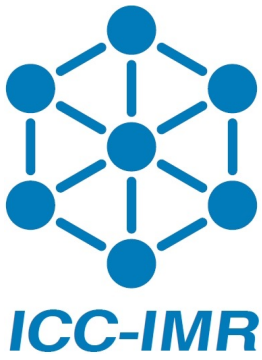

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Program

Day 1 (Wednesday, 10 January)

08:30~09:00 Registration

09:00~09:30 Opening Remarks
Sadamichi Maekawa (Japan Atomic Energy Agency)
Koki Takanashi (Tohoku University)

Wed-01 9:30~10:00
Burkard Hillebrands (TU Kaiserslautern)
"New ways to produce a magnonic macroscopic quantum state"

Wed-02 10:00~10:30
Takeshi Seki (Tohoku University)
"Observation of Anomalous Ettingshausen Effect in a Ferromagnetic FePt Thin Film"

Wed-03 10:30~11:00
Koji Usami (University of Tokyo)
"Cavity opto-magnonics with ferromagnetic spheres"

11:00~11:30 Coffee break

Wed-04 11:30~12:00
Bart van Wees (University of Groningen)
"Magnon spin transport in ferromagnetic insulators"

Wed-05 12:00~12:30
Wei Han (Peking University)
"Spin Dynamics in Topological Insulator and Superconducting Thin Films"

Wed-06 12:30~13:00
Toeno van der Sar (Delft University of Technology)
"Probing spin waves using single-spin magnetometry"

13:00~14:30 Lunch break (registration 13:00~14:00)

Wed-07 14:30~15:00
Katsushi Hashimoto (Tohoku University)
"Nuclear Resonance Spectroscopic Imaging of Hyperfine-Coupled Quantum Hall System"

Wed-08 15:00~15:30
Kazuhisa Kakurai (Neutron Science and Technology Center, CROSS)
"Neutron Scattering Investigations on Magnetic Structure and Excitation in Multiferroic Y-Type Hexaferrite $(Ba,Sr)_2Co_2Fe_{11}AlO_{22}$"

Wed-09 15:30~16:00
Yuki Shiomi (University of Tokyo)
"Thermal Generation of Spin Current in Zigzag-Chain Antiferromagnets"

16:00~16:30 Coffee break

Wed-10 16:30~17:00
Evgeny Y. Tsymbal (University of Nebraska-Lincoln)
"Reversible spin texture in ferroelectric oxides"

Wed-11 17:00~17:30
Ke Xia (Beijing Normal University)
"Synchronized spin-photon coupling"

Wed-12 17:30~18:00
Masafumi Shirai (Tohoku University)
"Enhancement of Voltage-Controlled Magnetic Anisotropy by Ir Insertion into Fe/MgO Interface"

Day 2 (Thursday, 11 January)

Thu-01 08:30~09:00
Hiromi Yuasa (Kyushu University)
"Inserted layer effect on Spin Mixing Conductance in Spin Seebeck Effect"

Thu-02 09:00~09:30
Hiroto Adachi (Okayama University)
"Theory of spin pumping into superconductors"

Thu-03 09:30~10:00
Rembert Duine (Utrecht University)
"Spin transport in topological magnon insulators"

Thu-04 10:00~10:30
Tomas Jungwirth (Academy of Sciences of the Czech Republic)
"THz electrical writing speed in an antiferromagnetic memory"

10:30~11:00 Coffee break

Thu-05 11:00~11:30
Mathias Kläui (JGU Mainz)
"Spin transport in insulator spintronics systems"

Thu-06 11:30~12:00
Michael Coey (Trinity College Dublin)
"Compensated Ferrimagnetic Half-Metals"

Thu-07 12:00~12:30
Shunsuke Fukami (Tohoku University)
"Spin-orbit torque switching in ferromagnetic heterostructures and its application"

Thu-08 12:30~13:00
Jiang Xiao (Fudan University)
"Non-von Neumann Spin Wave Computing"

13:00~14:30 Lunch break

Thu-09 14:30~15:00
Shigemi Mizukami (Tohoku University)
"Laser-induced spin dynamics and THz emission in metallic magnets"

Thu-10 15:00~15:30
Yaroslav Blanter (Delft University of Technology)
"Brillouin Scattering in Cavity Optomagnonics"

Thu-11 15:30~16:00
Olivier Klein (SPINTEC, Grenoble)
"Spin conductance in YIG driven from thermal to subthermal magnons regime"

16:00~16:30 Coffee break

Thu-12 16:30~17:00
Tobias Kampfrath (Freie Universität Berlin)
"The ultimate speed of the spin-dependent and spin Seebeck effect: insights and applications"

Thu-13 17:00~17:30
Yoshichika Otani (University of Tokyo)
"Acoustic Spin Pumping into Rashba Interface"

Thu-14 17:30~18:00
Masaki Mizuguchi (Tohoku University)
"Nernst Effect in Nanostructures"

19:00~ Conference dinner

Day 3 (Friday, 12 January)

Fri-01 09:00~09:30
Haiming Yu (Beihang University)
"Magnonic cavities in YIG-based ferromagnetic nanostructures"

Fri-02 09:30~10:00
Yasuhiro Niimi (Osaka University)
"Detection of spin dynamics with spin current"

Fri-03 10:00~10:30
Sven Rogge (UNSW)
"Engineered Hamiltonians for strongly correlated Fermions"

10:30~11:00 Coffee break

Fri-04 11:00~11:30
Takuya Satoh (Kyushu University)
"Optical Excitation of Magnons in Antiferromagnets"

Fri-05 11:30~12:00
Paul McClarty (Max Planck Institute for the Physics of Complex Systems)
"Topological Triplon Modes in a Shastry-Sutherland Magnet"

Fri-06 12:00~12:30
Sebastian T. B. Goennenwein (Technische Universität Dresden)
"Spin Hall Magnetoresistance in Ferrimagnets and Antiferromagnets"

Fri-07 12:30~13:00
Takashi Kikkawa (Tohoku University)
"Hybridized magnon-phonon excitation in spin Seebeck effect"

13:00~14:30 Lunch break

Fri-08 14:30~15:00
Igor Žutić (University at Buffalo)
"Novel Excitations with Magnetic Proximity Effects"

Fri-09 15:00~15:30
Hiroshi Kohno (Nagoya University)
"Microscopic Theory of Magnonic Torques Induced by Temperature Gradient"

Fri-10 15:30~16:00
Shuichi Murakami (Tokyo Institute of Technology)
"Edelstein effects in inversion asymmetric crystals"

16:00~16:30 Coffee break

Fri-11 16:30~17:00
Naoto Nagaosa (RIKEN)
"Theory of Skyrmion glass"

Fri-12 17:00~17:30
Yusuke Nambu (Tohoku University)
"Magnetic excitations in YIG: Neutron scattering study"

Fri-13 17:30~18:00
Gen Tatara (RIKEN)
"Effective gauge field theory of spin-charge conservation and electromagnetic cross correlation effects"

Poster Session (10-12 January)

P-01 **Takumi Funato** (Nagoya University)
"Generation of spin current from lattice distortion dynamics"

P-02 **Bo Gu** (Japan Atomic Energy Agency)
"Enhanced magneto-optical Kerr effect at Fe/insulator interfaces"

P-03 **Jun'ichi Ieda** (Japan Atomic Energy Agency)
"Magnetic anisotropy in the Rashba spin-orbit coupled antiferromagnets"

P-04 **Yusuke Imai** (Nagoya University)
"Cross-correlated electron-magnon transport on the surface of magnetic topological insulator"

P-05 **Martin Jourdan** (JGU Mainz)
"Writing and Reading antiferromagnetic Mn_2Au: Néel spin-orbit torques and large AMR"

P-06 **Yong-Chang Lau** (University of Tokyo)
"Spin Hall effect from hybridized 3d-4p orbitals"

P-07 **Alejandro O. Leon** (Tohoku University)
"Controlling the rare-earth spin with voltages"

P-08 **Jing Liu** (University of Groningen)
"Transport of thermal magnons under the influence of the microwave-excited GHz magnons"

P-09 **Yi Liu** (Beijing Normal University)
"Magnon-phonon relaxation in yttrium iron garnet from first principles"

P-10 **Jotaro Nakane** (Nagoya University)
"Dynamics of angular momenta in spin-phonon system"

P-11 **Kazuki Nakazawa** (Nagoya University)
"Topological Hall effect from strong to weak coupling"

P-12 **Koichi Oyanagi** (Tohoku University)
"Magnon-polaron transport in the nonlocal spin Seebeck effect"

P-13 **Henri Saarikoski** (RIKEN)
"Geometric Phase Switching in Mesoscopic Rings"

P-14 **Richard Schlitz** (Technische Universität Dresden)
"Spin Hall Magnetoresistance in antiferromagnet/Pt heterostructures"

P-15 **Sanchar Sharma** (Delft University of Technology)
"Light scattering by magnons in whispering gallery mode cavities"

P-16 **Takuya Taira** (Okayama University)
"Microscopic derivation of spin diffusion equation: A Green's function approach"

P-17 **Camilo Ulloa** (Utrecht University)
"Magnon spin-Hall magnetoresistance of a gapped quantum paramagnet"

P-18 **Terufumi Yamaguchi** (Nagoya University)
"Microscopic spin transport theory for coupled electron-magnon systems"

P-19 **Kei Yamamoto** (University of Alabama/JAEA)
"Transport properties of antiferromagnetic Dirac quasi-particles"

P-20 **Yutaka Yamamoto** (Okayama University)
"Spin Seebeck effect in simple ferromagnets near T_c: A Ginzburg-Landau approach"

P-21 **Weichao Yu** (Fudan University)
"Logic-in-Memory Approach toward Universal Magnonic Computation via Synthetic Antiferromagnets"

P-22 **Jakub Zázvorka** (JGU Mainz)
"Skyrmion diffusion in Ta-based material with perpendicular magnetic anisotropy"

Day 4 (Saturday, 13 January)

&

Day 5 (Sunday, 14 January)

Zao Satellite

Oral Sessions

New ways to produce a magnonic macroscopic quantum state

B. Hillebrands[a]

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Recently the formation of magnon Bose-Einstein condensates (BEC) in extended magnetic films attracted large attention [1, 2]. In previous studies, the conditions for the formation of the BEC were created by parametric pumping. Here, a fundamentally new approach is presented. Fast DC current pulses applied to yttrium-iron-garnet (YIG)/Pt microstructures result in a strong heating. Consequently, this leads to an increased number of magnons, distributed over the whole spectrum. Once the current is switched off the microsized system cools down rapidly. This results in a strong increase of the magnon density at the bottom of the spectrum, leading to the formation of a magnon BEC under suitable conditions. That we have observed using time-resolved Brillouin light scattering spectroscopy. Our experiment shows, that the BEC formation depends on the magnon temperature and the timescale of the cooling process.

Additionally, micromagnetic simulations performed in magnetic microstructures show the ability of Bose-Einstein condensation in a quantized magnon spectrum. By implementation of a local parametric pumping source, we observe a strong increase in population of the states at the bottom of the magnon spectrum. Nonlinear scattering processes of magnons in a microstructure play an important role in the formation of this macroscopic quantum state.

This research is supported by ERC Starting Grant 678309 MagnonCircuits, ERC Advanced Grant 694709 SuperMagnonics and DFG Grant DU 1427/2-1.

[1] S.O. Demokritov *et al*., *Nature* **443**, 430 (2006).
[2] A.A. Serga, *et al*., *Nat. Commun*. **5**, 3452 (2014).

Observation of Anomalous Ettingshausen Effect in a Ferromagnetic FePt Thin Film

T. Seki,[a,b,*] R. Iguchi,[c] K. Takanashi,[a,b] and K. Uchida[b,c,d]

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Anomalous Nernst effect (ANE) and anomalous Ettingshausen effect (AEE) are famous thermoelectric effects in ferromagnets that have been known for a long time [Ref. 1]. The coexistence of magnetization ($\boldsymbol{M}$) and temperature gradient ($\nabla \boldsymbol{T}$) produces anomalous Nernst voltage whereas charge current ($\boldsymbol{J}_c$) and $\boldsymbol{M}$ leads to $\nabla \boldsymbol{T}$ due to the AEE. The AEE in a ferromagnetic thin film has not been examined yet although the ANE has widely been studied for a variety of ferromagnetic materials. In other words, the temperature modulation induced by the AEE has not been understood for ferromagnetic thin films.

Also, one may be aware of the similarity of AEE and spin Peltier effect (SPE). SPE has recently been observed in a junction with a ferrimagnetic insulator yttrium iron garnet (YIG) and a paramagnetic metal Pt [Refs. 2,3]. In the case of SPE, the spin current ($\boldsymbol{J}_s$) converted from $\boldsymbol{J}_c$ produces heat current ($\boldsymbol{J}_q$) due to the transfer of spin angular momentum and energy, resulting in $\nabla \boldsymbol{T}$. For both ANE and SPE cases, $\boldsymbol{J}_c$ leads to $\nabla \boldsymbol{T}$ under $\boldsymbol{M}$. This means that it is crucial to clarify the contributions from AEE and SPE in the induced temperature modulation.

In this talk, we show the observation of AEE in a ferromagnetic FePt thin film [Ref. 4]. The active infrared emission microscopy called lock-in thermography (LIT) [Refs. 3,5-7] enables us to visualize the temperature modulation in the FePt thin film. The temperature profile induced by AEE is clearly changed by varying $\boldsymbol{M}$ from the in-plane direction to the out-of-plane direction. We give direct evidence of different symmetries for AEE and SPE from the different thermal images for AEE and SPE.

[1] S. R. Boona, R. C. Myers, and J. P. Heremans, *Energy Environ. Sci.* **7**, 885 (2014).
[2] J. Flipse, F. K. Dejene, D. Wagenaar, G. E. W. Bauer, J. B. Youssef, and B. J. van Wees, *Phys. Rev. Lett.* **113**, 027601 (2014).
[3] S. Daimon, R. Iguchi, T. Hioki, E. Saitoh, and K. Uchida, *Nat. Commun.* **7**, 13754 (2016).
[4] T. Seki, R. Iguchi, K. Takanashi, and K. Uchida, *arXiv*:1709.05449.
[5] S. Daimon, K. Uchida, R. Iguchi, T. Hioki, and E. Saitoh, *Phys. Rev. B* **96**, 024424 (2017).
[6] K. Uchida, R. Iguchi, S. Daimon, R. Ramos, A. Anadon, I. Lucas, P. A. Algarabel, L. Morellon, M. H. Aguirre, M. R. Ibarra, and E. Saitoh, *Phys. Rev. B* **95**, 184437 (2017).
[7] Y. Hirayama, R. Iguchi, X.-F. Miao, K. Hono, and K. Uchida, *Appl. Phys. Lett.* **111**, 163901 (2017).

Caivty opto-magnonics with ferromagnetic spheres

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Quantum magnonics [1] links the well-developed quantum coherent control to the blooming field of magnonics. The unique properties of a long-lived magnons in ferromagnetic spheres made of yttrium iron garnet (YIG) offer new possibilities in the field of quantum electronics, too. Here, we report our activities on opto-magnonics with ferromagnetic spheres. In particular, we present the experiment in which the coherent and bidirectional conversions between microwave and optical photons via ferromagnetic magnons is realized [2]. We also discuss the result in the field of ``cavity opto-magnonics", where magnons in a spherical YIG crystal interact with photons in a whispering gallery mode supported by the same crystal [3].

[1] Y. Tabuchi, *et. al.,* C. R. Physique **17**, 729 (2016).
[2] R. Hisatomi, *et. al.,* Phys. Rev. B **93**, 174427 (2016).
[3] A. Osada, *et. al.,* Phys. Rev. Lett. **116**, 223601 (2016).

Magnon spin transport in ferrimagnetic insulators

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I will present an update of our recent research of magnon spin injection, transport and detection in YIG based ferrimagnetic insulator devices. First I will discuss how non-local spin Seebeck measurements indicate the importance of the magnon chemical potential for a complete description of the (magnon) spin Seebeck effect. I will show that care has to be taken for the extraction of the correct magnon spin relxation length [1].
Second I will demonstrate the operation of a magnon spin based field effect transistor, where the magnon spin conductance between source and drain electrodes is modulated by changing the magnon density in the YIG channel. This is done by injecting/extracting magnons using the spin Hall effect in a Pt modulator gate electrode [2].
Finally, I will discuss our recent discovery that permalloy (Py) electrodes are a very efficient injectors/detectors of magnon spins in YIG, having efficiencies comparable to Pt. We have also found that in addition to the conventional (magnetization direction independent) spin Hall/inverse spin Hall effect based mechanism for injection detection of magnons spins, an additional (even stronger) magnetization direction dependent effect is observed, which we associate with the anomalous spin Hall effect, the generation of spin current perpendicular to the current and magnetization directions [3].

[1] J. Shan et al., Phys. Rev. B **96**, 184427 (2017)
[2] L.C. Cornelissen et al., arXiv: , submitted to Phys. Rev. Lett.
[3] K. Das et al., arXiv:1708.01752, submitted to Phys. Rev. Lett.

Spin Dynamics in Topological Insulator and Superconducting Thin Films

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Spin pumping refers to the angular momentum transfer between a ferromagnet and an adjacent material under the magnetization resoance condition via the *s-d* exchange interaction at the interface. It is a powerful tool to probe the dynamic spin susceptibilty of the adjacent materials.

In this talk, I will present our experimental studies of the spin dynamics in two extoic materials: topological insulators and a s-wave superconducting film. I will first discuss the spin pumping into topological insulators, including SmB_6 bulk, and BiSbTe thin films. The spin to charge conversion in SmB_6 is consistent with the spin-momentum locked properties of the toplogical surface states [1]. The spin pumping efficiencey from Py to SmB_6 is hard to estimate due to the complexity of the Gilbert damping of Py [2]. Hence, the ferrimagnetic insulator $Y_3Fe_5O_{12}$ (YIG)-topological insulator (BiSbTe) heterostructures are investigated and the spin pumping efficency is enhanced at the Dirac point of BiSbTe due to the spin momentum locking properties and resoant magnon absoption [3]. The last part of my talk will discuss the spin dynamics in NbN thin films, probed by spin pumping from a ferromagnetic insulator [4].

References:

[1] Song, et al, Nature Communications, **7**, 13485, (2016).
[2] Zhao, et al, Scientific Reports, **6**, 22890, (2016).
[3] Tang, et al, submitted (2017).
[4] Yao, et al, submitted (2017).

Probing spin waves using single-spin magnetometry

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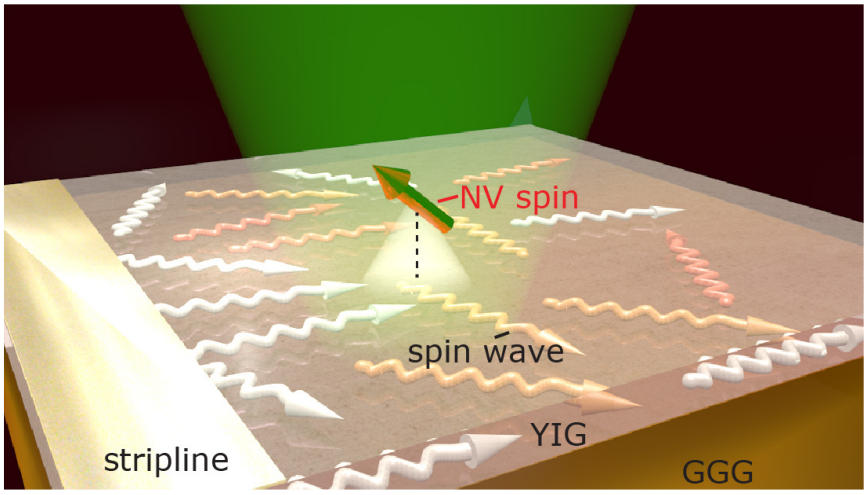
Spin waves are the elementary spin excitations of magnetic materials. They provide fundamental insight into magnetic order and may play a key role in future information processing. Spin waves can be probed via the magnetic fields they generate, but this requires a technique with high sensitivity and nanometer sensor-sample distances. I will present the use of the excellent magnetic-field sensitivity of nitrogen-vacancy sensor spins in diamond to explore spin-wave physics in ferromagnets. I will describe the nanoscale characterization of spin-wave resonances, thermally excited spin waves, and spin-wave chemical potentials [1,2]. These techniques open up exciting possibilities for imaging and control of spin transport in mesoscopic spin systems.



A single NV spin is an atomic-sized magnetic-field sensor that can locally detect and image the magnetic fields generated by spin waves

[1] T. van der Sar*, F. Casola*, et al., Nanometre-scale probing of spin waves using single electron spins. *Nat. Commun.* **6**, 7886 (2015).

[2] C. Du*, T. van der Sar*, T. Zhou*, et al., Control and local measurement of the spin chemical potential in a magnetic insulator. *Science* **357**, 196 (2017).

Nuclear Resonance Spectroscopic Imaging of Hyperfine-Coupled Quantum Hall System

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Nuclear resonance (NR) spectroscopy is one of the powerful tools to probe both electron and nuclear spin polarization in conduction electron systems. Some macroscopic aspects of various quantum Hall (QH) spin systems have been studied by, e.g., resistively-detected or optical Knight-shift measurements, implying an essential role of local variation of spin polarization.

To directly access the local spin characteristics, we performed NR spectroscopic mapping via the scanning-probe NR technique [1]. The scanning metallic tip was used to apply an RF electric field to nuclear spins in a 20-nm-wide GaAs quantum well located 165 nm below the surface. The electric field at a NR frequency couples with the quadrupolar nuclear spins such as ^{75}As nuclear spins with total spin $I = 3/2$. The resulting local NR was, in turn, resistively detected by measuring the longitudinal voltage at constant source-drain current I_{sd}. All measurements were conducted with pumping dynamic nuclear polarization (DNP) in the nonequilibrium $\nu = 1$ QH breakdown regime [2] at a sample temperature below 300 mK at magnetic fields of 7-8 T.

Using the recorded spectroscopic data, we constructed NR-intensity and Knight-sift images, which, respectively, revealed the spatial distribution of the DNP and electron spin polarization. We found that distribution of the DNP strongly changed with slightly increasing ν from 1. Furthermore, we found significant reduction of the electron spin polarization along the sample, demonstrating electron heating along the direction of the electron drift in QH breakdown. These results highlight the ability of our technique to reveal the microscopic aspects of electron/nuclear spin polarization.

[1] K. Hashimoto, et al., *AIP Advances* **6**, 075024 (2016).

[2] M. Kawamura, et al., *Appl. Phys. Lett.* **90**, 022102 (2007).

Neutron Scattering Investigations on Magnetic Structure and Excitation in Multiferroic Y-Type Hexaferrite $(Ba,Sr)_2Co_2Fe_{11}AlO_{22}$

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The discovery of magnetoelectric (ME) effects caused by a cycloidal spin order has initiated an intense research on new class of ME materials [1]. Among them one interesting class of materials is the hexaferrites such as Y-type ($A_2Me_2Fe_{12}O_{22}$: *Me*=transition metal) , M-type ($AFe_{12}O_{19}$: *A*=Pb, Ca, Sr, Ba, etc.), where types of elementary blocks and their stacking order are different [2]. These materials are being extensively investigated because they exhibit spin-driven ferroelectricity associated with non-collinear magnetic structures in relatively low magnetic field and high temperature region [3,4]. The Y-type hexaferrite $(Ba,Sr)_2Co_2Fe_{11}AlO_{22}$ (BSCoFAO) was recently reported to exhibit spin-driven ferroelectricity and electric-field induced magnetization switching at room temperature [5].

In this presentation we report on the neutron diffraction and inelastic scattering experiments to investigate the magnetic ordering and magnetic excitation in the room temperature multiferroic Y-type hexaferrite material BSCoFAO [6].

[1] T. Kimura, T. Goto, H. Shintani, K. Ishizaka, T. Arima, Y. Tokura, *Nature* ***426***, 55 (2003).
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[6] T. Nakajima, Y. Tokunaga, M. Matsuda, S. Dissanayake, J. Fernandez-Baca, K. Kakurai, Y. Taguchi, Y. Tokura, and T. Arima, *Phys. Rev. B* ***94,*** 195154 (2016).

Thermal Generation of Spin Current in Zigzag-Chain Antiferromagnets

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In this presentation, we report thermal generation effects of spin currents in two antiferromagnetic materials with zigzag spin-chain structures: $MnPS_3$ [1] and α-$Cu_2V_2O_7$ [2].

For a layered antiferromagnetic insulator $MnPS_3$ in contact with two Pt strips, we observed signature of a magnon Nernst effect, an antiferromagnetic analogue of the magnon Hall effect in ferromagnetic insulators [1]. Thermoelectric voltage measured in the Pt strips grown on the $MnPS_3$ single crystals was found to exhibit nonmonotonic temperature dependence at low temperatures, which is unlikely to be explained by electronic origins in Pt but can be ascribed to the inverse spin Hall voltage induced by the magnon Nernst effect.

For α-$Cu_2V_2O_7$/Pt bilayers, we performed the measurement of the longitudinal spin Seebeck effect [2]. The antiferromagnetic spin Seebeck effect was clearly observed and its temperature and magnetic-field dependences were analysed by a magnon spin current theory. The numerical calculation of spin Seebeck voltages using magnetic parameters of α-$Cu_2V_2O_7$ determined by previous neutron scattering studies reveals that the antiferromagnetic spin Seebeck effect for α-$Cu_2V_2O_7$/Pt is consistent with the reported magnon dispersions.

This work was done in collaboration with R. Takashima, D. Okuyama, G. Gitgeatpong, P. Piyawongwatthana, K. Matan, T. J. Sato, and E. Saitoh.

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Reversible spin texture in ferroelectric oxides

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Spin-orbit coupling is known to be responsible for non-trivial spin configurations and a number of emergent physical phenomena. Ferroelectric materials are especially interesting in this regard due to their non-centrosymmetric atomic structure and reversible spontaneous polarization, which allows for a non-volatile electrical control of the spin degrees of freedom. Here, we explore two classes of ferroelectric oxide materials, which belong to non-symmorphic space-group symmetry.

First, we consider a technologically relevant oxide material, HfO_2, exhibiting robust ferroelectricity in a non-centrosymmetric orthorhombic phase. Using density-functional theory (DFT) calculations, we investigate the spin-dependent electronic structure of the ferroelectric HfO_2 and show the appearance of chiral spin textures driven by spin-orbit coupling [1]. Based on an appropriate model, we find that the Rashba-type spin texture dominates around the valence band maximum, while the Dresselhaus-type spin texture prevails around the conduction band minimum. The latter is characterized by a very large Dresselhaus constant, which allows using this material as a tunnel barrier to produce tunnelling anomalous and spin Hall effects that are reversible by ferroelectric polarization.

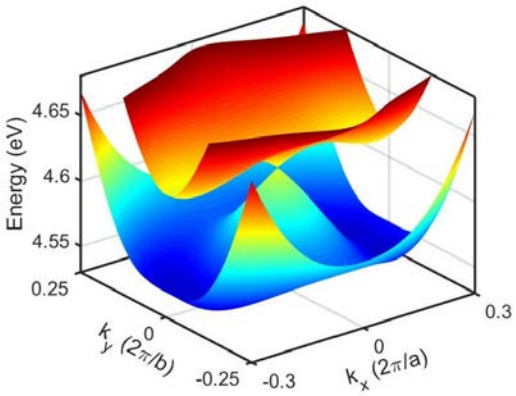

Fig. 1. 3D Dirac point near the conduction band minimum of ferroelectric HfO_2.

Another example involves a class of materials capable to maintain a persistent spin texture, i.e. uniform spin configuration over a large part of the Brillouin zone. This property has been predicted to support an extraordinarily long spin lifetime of carriers promising for spintronics applications. Here we demonstrate that the persistent spin texture can be enforced by the non-symmorphic space-group symmetry of the crystal. Along certain high symmetry lines in the Brillouin zone, the spin-orbit splitting combined with the lattice degrees of freedom imposes a constraint on the effective Hamiltonian, which only retains terms with the spin-orbit field independent of the momentum orientation, thus maintaining the persistent spin texture. We illustrate this behaviour using DFT calculations for bulk perovskite $BiInO_3$, a wide band gap semiconductor, which reveals the persistent spin texture at the conduction band minimum. Our results broaden the range of materials, which may be employed in spintronics.

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Synchronized spin-photon coupling

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We study spin-photon coupling in cavity in the presence of relative phase shift between magnetic and electric components of the microwave. We show that the anticrossing gap can be manipulated by varying the relative phase. Increasing the phase difference leads to narrowing the anticrossing gap of hybridized modes and eventually to phase locked coupling at the value of relative phase close to π. The FMR and cavity modes become phase locked and oscillate at almost the same frequency near the resonance frequency. Characteristic linewidth drop and transmission amplitude enhancement are demonstrated. The phase resolved spin-photon coupling can be used both for phase imaging and controlling coupling parameters

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Enhancement of Voltage-Controlled Magnetic Anisotropy by Ir Insertion into Fe/MgO Interface

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Voltage-controlled magnetic anisotropy (VCMA) is promising technique for reducing energy consumption of magnetization switching in magnetic tunnel junctions (MTJ). The magnetization switching by voltage pulse was demonstrated on Fe/MgO/FeCo and CoFeB/MgO/CoFeB MTJ, however, the typical VCMA coefficients reported so far are 30-40 fJ/Vm. In this work, we theoretically investigated the VCMA of TM/Fe and MgO/TM/Fe thin films, where TM denotes 5*d* transition-metal monolayer, by means of first-principles density-functional calculation.

First, we evaluated the VCMA of TM/Fe and found that the VCMA exceeds 100 fJ/Vm for the Ta/Fe, W/Fe, Os/Fe, and Ir/Fe films. In particular, the Ir/Fe film has the largest value, 263 fJ/Vm, which is about 8 times larger than that for the Fe film, and possesses huge perpendicular magnetic anisotropy energy (MAE) greater than 10 mJ/m^2. Analyzing the MAE and VCMA in the Ir/Fe film by the second-order perturbation theory in terms of spin-orbit coupling [1], we found that the MAE and VCMA are predominantly originated from the Ir layer. The spin-flip term between occupied majority-spin and unoccupied minority-spin states plays a crucial role in the MAE of the Ir layer. On the other hand, both the spin-conservation term between occupied and unoccupied majority-spin sates and the spin-flip term between occupied minority- and unoccupied majority-spin states contribute to the VCMA.

Next, we evaluated the MAE and VCMA of MgO/TM/Fe films and obtained an in-plane MAE (-15 mJ/m^2) and a huge VCMA (-298 fJ/Vm) for the MgO/Ir/Fe film. Note that the VCMA of the MgO/Ir/Fe film has opposite sign to that of the Ir/Fe film. This peculiar results are originated from the hybridization between Ir 5d($3z^2$-r^2) and O 2p(z) orbitals at the Ir/MgO interface. The hybridization causes the shift of Ir 5d($3z^2$-r^2) states to higher energy side and as a result the Ir 5d($3z^2$-r^2) states in the majority-spin bands are located near the Fermi level, leading to in-plane contribution to MAE and the sign change in VCMA. In conclusion, the enhancement of VCMA can be expected by the Ir insertion into Fe/MgO interface due to strong spin-orbit coupling of Ir atom as well as the hybridization effect of Ir 5d orbitals.

This work was accomplished in collaboration with M. Tsujikawa and was funded by ImPACT Program of Council for Science, Technology and Innovation, Cabinet Office, Government of Japan.

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Inserted layer effect on Spin Mixing Conductance in Spin Seebeck Effect

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In order to enhance the spin Seebeck voltage for a practical use, it is important to control the spin Hall angle and the spin mixing conductance independently. However, they have been estimated concurrently and it is difficult to discuss them separately. In this report, we studied the spin Seebeck voltage by inserting the very thin layer into the interface of YIG and nonmagnetic metal, so as to distingish the contribution from the interface and the bulk. The base samples are YIG/Pt and YIG/$Ta_{50}W_{50}$ where Pt has been used as a standard nonmagnetic layer frequently and $Ta_{50}W_{50}$ has the higher spin Hall angle than Pt and even W. The materials of inserted layers are Ru and Mn. The purpose of Ru insertion is the oxygen diffusion barrier becase the $Ta_{50}W_{50}$ is especially easy to be oxidized [2], and that of Mn insertion is the magnon scattering enhancement [3] because the Mn magnetic momets alignment is not simple. Since the thickness of inserted layer was 0.5 nm, we can roughly neglect the spin Hall angle contribution from the inserted layers to the voltage. Figure 1 shows the magnitude of the spin Seebeck coefficients |S|. First, Ru insertion improved |S| in the system YIG/$Ta_{50}W_{50}$ as expected. Also, we obtined the Ru insertion effect in YIG/Pt sytstem although Pt is hard to be oxidized. Is means that the interface of YIG/Ru has not only oxygen diffusion barrier effect but the intrinsically high spin mixing conductance compare to YIG/Pt. Next, Mn insertion increased |S| in the both systems of YIG/Pt and YIG/$Ta_{50}W_{50}$. Since Mn is easier to be oxidized than Pt, it is considered that the magnon scattering ehnaced |S|. In conclusion, thin layer insertion is a good approach to control the the spin Hall angle in the bulk and spin mixing conductance at the interface separetely, which is important to improve the spin Seebeck voltage.

This work was supported by PRESTO-JST (JPMJPR15R8), and Tateisi Science and Technology Foundation.

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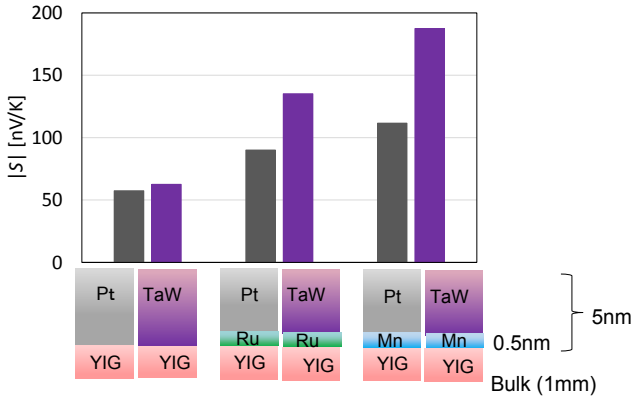

Fig. 1 Magnitude of spin Seebeck coefficient.

Theory of spin pumping into superconductors

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It is an interesting problem to think about the dynamical aspect of the interplay of spin and superconductivity, since the binding energy of a spin-frozen singlet Cooper pair is as low as a few Kelvin such that its property is highly susceptible to magnetic perturbations. Here, we consider spin pumping into an s-wave superconductor (Fig. 1), i.e., microwave-driven spin current injection from a ferromagnet into the adjacent target material (the superconductor, in the present case) [1].

Our idea largely relies on the notion that spin pumping is intimately related to the dynamical spin susceptibility of target materials [2]. Evaluating the susceptibility by fully taking account of impurity spin-orbit scattering that is indispensable to describe diffusive spin transport with finite spin diffusion length, we calculate temperature dependence of the spin pumping signal [3]. We then found that, when the superconducting gap is not completely suppressed at the ferromagnet/superconductor interface (which is expected to be the case if a magnetic insulator is used), a pronounced coherence peak appears in the signal immediately below the superconducting transition temperature Tc (see Fig. 2).

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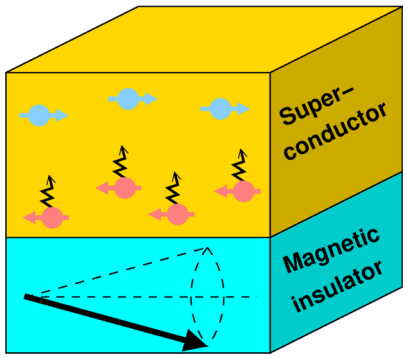

Fig. 1: Schematic view of the system considered here.

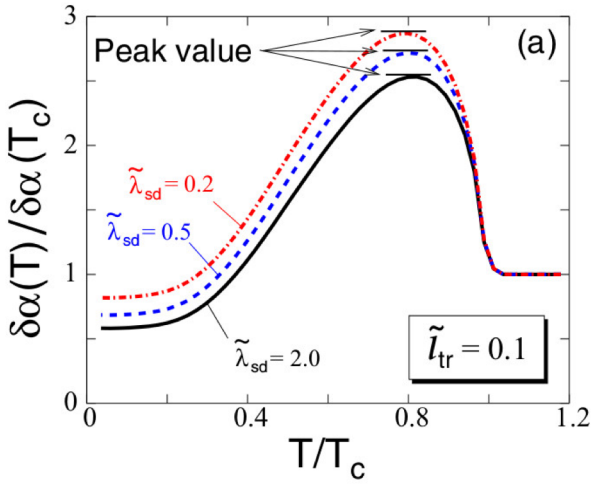

Fig. 2: Temperature dependence of the spin pumping signal [3]. Here, $\tilde{\lambda} = \lambda/\xi_{BCS}$ and $\tilde{l}_{tr} = l_{tr}/\xi_{BCS}$ are spin diffusion length and mean free path normalized by ξ_{BCS} (~200nm for Nb).

Spin transport in topological magnon insulators

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We investigate the spin transport properties of a topological magnon insulator, a magnetic insulator characterized by topologically nontrivial bulk magnon bands and protected magnon edge modes located in the bulk band gaps. Employing the Landau-Lifshitz-Gilbert phenomenology, we calculate the spin current driven through a normal metal|topological magnon insulator|normal metal heterostructure by a spin accumulation imbalance between the metals, with and without random lattice defects. We show that bulk and edge transport are characterized by different length scales. In clean systems, Gilbert damping affects the edge current more strongly than the bulk current. In contrast, in dirty samples, topologically protected edge magnons dominate long-range spin transport.

THz electrical writing speed in an antiferromagnetic memory

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The interest in antiferromagnetic spintronics was prompted by the recent theoretical prediction and experimental discovery of the electrical switching in antiferromagnets by a staggered spin-orbit torque field at ambient conditions. This was followed by upscaling of the writing speed to the GHz range, and by demonstrating a fabrication compatibility with III-V semiconductors or Si, and a device compatibility with common microelectronic circuitry. These initial experiments verified several unique features of antiferromagnetic bit cells, including their magnetic field hardness, absence of fringing stray fields, and neuron-like multi-level memory-logic functionality. In this talk we will show theoretically and experimentally that in antiferromagnetic memory devices, the speed of reversible electrical writing can be scaled up to THz. The energy required for writing with the THz speed is comparable to that of the GHz speed. In addition, throughout the entire studied range from Hz to THz, only one current-induced spin-orbit torque mechanism is responsible for the switching. Our work shows that antiferromagnets can exceed by orders of magnitude the highest electrical writing speeds achieved in the state-of-the-art ferromagnetic memories, opening the prospect of memory technology development reaching the elusive THz band.

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Spin transport in insulator spintronics systems

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Spin transport in ferroic magnetic insulator systems has recently attracted significant interest due to low damping of magnonic spin currents in insulators and efficient transport in ferro-, ferri- and antiferromagnetic compounds. We have studied the spin transport in ferro(i)magnetic insulators [1-3] and found that the detected spin current signals depend both on the bulk properties of the insulator [1,2] but also on the detector material and in particular the interface properties [3]. While spin transport in single insulating magnetic layers is thus attractive for applications, controlled manipulation of the magnonic spin current is necessary. For charge-based spintronic devices, the spin valve effect that leads to a different spin current transmission of two magnetic layers is well established [4], for magnonic spin currents in insulating magnets, the analog has been missing so far. We report on spin pumping [5] measurements in a magnonic spin valve device made of collinear magnetic yttrium iron garnet (YIG)/CoO/Co multilayers. By means of microwaves and external magnetic fields YIG is brought into ferromagnetic resonance, resulting in a pure spin current propagating through the sample stack including the antiferromagnet and finally being detected in the Co layer via the inverse spin Hall effect. For parallel and antiparallel alignment of the YIG and Co layers, we observe a very different amplitude of the detected magnonic spin current signal with a spin valve effect amplitude of 120%. In addition to the spin pumping signal peak, a second peak is observed at ferromagnetic resonance that depends on the Co orientation, which is ascribed to an anomalous Hall effect induced spin rectification in the Co layer [5]. Finally we explore spin transport in pure antiferromagnetic insulator systems [6]. We find a detectable spin Hall magnetoresistance above the spin flop transition field in 3d metal oxides with collinear spin structure [7]. Furthermore we explore these systems for superfluid spin transport including coherence effects are recently suggested [6,7].

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Compensated Ferrimagnetic Half-Metals

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Compensated half-metallic ferrimagnets (CFHMs) are magnets with a spin gap, and an electron occupancy and temperature that ensures compensation of two inequivalent antiparallel chemical sublattices. Unlike an antiferromagnet, the two sublattices are unrelated by a simple translation & time reversal symmetry operation, and the conduction electrons belong predominantly to only one of the two sublattices. Ferrimagnetic and antiferromagnetic resonance modes lie in the high GHz/low THz range. The materials therefore combine the best features of a highly spin-polarized metallic ferromagnet with the best features of an antiferromagnet. They also present a unique opportunity to study quasi-antiferromagnetic (zero-moment) domains and domain walls with standard magneto-optical imaging techniques, because they exhibit a strong Kerr signal that arises from one of the two magnetic sublattices. This is demonstrated by direct domain imaging and the variation of MOKE, AHE and TMR as a function of composition or temperature through the compensation point. The materials offer an unusual degree of tunability the of magnetic excitations in device-quality spintronic thin films.

The prototypical compensated half-metallic ferrimagnet is Mn_2Ru_xGa (MRG), which we have investigated in detail since we discovered it in 2013. The coercivity diverges at compensation in films that are tetragonally deformed under biaxial substrate strain, which means that a single layer can potentially replace a synthetic antiferromagnetic stack with exchange bias. Sub-terahertz modes are detected optically. Recently we have found that a single film shows evidence of spin-orbit torque in the 2ω response in transverse resistivity, and may potentially be switched by an in-plabe current.

Applications of MRG, and potential extensions of this materials class will be discussed.

Spin-orbit torque switching in ferromagnetic heterostructures and its application

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Spin-orbit torque induced magnetization switching in ferromagnetic heterostructures offers various opportunities in conventional integrated circuits and artificial intelligence [1]. Heterostructures with antiferromagnets have been a focus of particular interest not only from fundamental but also from application points of view. We have shown a field-free switching in a heterostructure with an antiferromagnetic PtMn and a ferromagnetic Co/Ni multilayer with a perpendicular easy axis [2], and a proof-of-concept demonstration of an artificial neural network based neuromorphic computing, where the prototype device array showing analog-like switching is utilized as artificial synapses [3]. In this presentation, we will review the field-free switching of the PtMn/[Co/Ni] system and neuromorphic computing demonstration, and discuss some physics and material science behind the operation. Magnetization reversal mode [4], direction and magnitude of the spin-orbit torque and Dzyaloshinskii-Moriya interaction [5], and stack structure dependence of the magnetic and curren-induced switching properties [6] will be elaborated.

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Non-von Neumann Spin Wave Computing

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As a collective quasiparticle excitation of the magnetic order in magnetic materials, spin wave, or magnon when quantized, can propagate in both conducting and insulating materials with little dissipation. Magnetic material with non-trivia magnetic texture provides a unified information memory and processing platform.

Here we study the behaviors of the spin waves in ferromagnetic and antiferromagnetic domain walls. [1, 2] Specifically, we investigate the role of the polarization degree of freedom of spin waves in the antiferromagnet. We found that the domain wall can be used for complex spin wave manipulations, including conducting, reflecting, refracting, and polarizing spin waves. Therefore, simple textures like domain wall can be used to construct various spin wave devices. [3] Inversely, we study the back reaction of spin waves on the domain wall, and show that domain wall can be effectively moved by controlling the linear polarization direction of spin waves. [4] Utilizing the polarized spin waves to control the domain walls in antiferromagnetic wires, we propose a theoretical scheme to realize non-von Neumann spin wave computing with processing-in-memory architecture. [5]

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Laser-induced spin dynamics and THz emission in metallic magnets

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Pulse-laser induced dynamical phenomena in magnetic metals have attracted much attention. Among many interesting topics, we have studied on THz magnetization precession dynamics and low Gilbert damping in Mn-based ordered alloys with huge perpendicular magnetic anisotropy [1-3].

Recently we also developed the space-time-resolved pump-probe magneto-optical Kerr microscope for investigation of laser-induced spin dynamics in micron-sized area. Then, we succeeded to observe the focused laser-induced propagating spin-wave in metallic NiFe films, by which one can obtain the information of spin-wave dispersion relation and reciprocity for metallic films in micron-scale [4,5].

Pulse-laser induced THz emission in metals is also a hot topic in this research area [6]. We recently found that laser-induced THz emission intensity for Ta/CoFeB/MgO structure was largely enhanced by the sample annealing, which may relate to the enhancement of spin polarization due to the crystallization of CoFeB [7].

In this presentation, we will discuss the above-mentioned two recent topics. These works were partially supported by KAKENHI Nano-spin conversion science (26103004) and KAKENHI (16H03846).

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Brillouin Scattering in Cavity Optomagnonics

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Brillouin light scattering is an established technique to study magnons, the elementary excitations of a magnet. Its efficiency can be enhanced by cavities that concentrate the light intensity. Here, we theoretically study inelastic scattering of photons by a magnetic sphere that supports optical whispering gallery modes in a plane normal to the magnetization. Magnons with low angular momenta scatter the light in the forward direction with a pronounced asymmetry in the Stokes and the anti-Stokes scattering strength, consistent with earlier studies. Magnons with large angular momenta constitute Damon Eschbach modes are shown to inelastically reflect light. The reflection spectrum contains either a Stokes or anti-Stokes peak, depending on the direction of the magnetization, a selection rule that can be explained by the chirality of the Damon Eshbach magnons. The controllable energy transfer can be used to manage the thermodynamics of the magnet by light. We will also discuss recent developments in magnon manipulation.

Spin conductance in YIG driven from thermal to subthermal magnons regime

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We report a study on spin conductance through ultra-thin extended films of epitaxial Yttrium Iron Garnet (YIG), where spin transport is provided by propagating spin waves, that are generated and detected by direct and inverse spin Hall effects [1] in two Pt wires deposited on top [2-4] (cf. FIG1). While at low current the spin conductance is dominated by transport of exchange magnons, at high current, the spin conductance is dominated by magnetostatic magnons [4], which are low-damping non-equilibrium magnons thermalized near the spectral bottom by magnon-magnon interaction, with consequent a sensitivity to the applied magnetic field (cf. FIG2). This picture is supported by microfocus Brillouin Light. We believe that our current findings are not only important from the from the funda-mental point of view, but might be also useful for future applications. While transport of thermal magnons are difficult to control [5] due to their relatively high energies, the subthermal magnons could be efficiently controlled by variation of relatively weak magnetic fields.

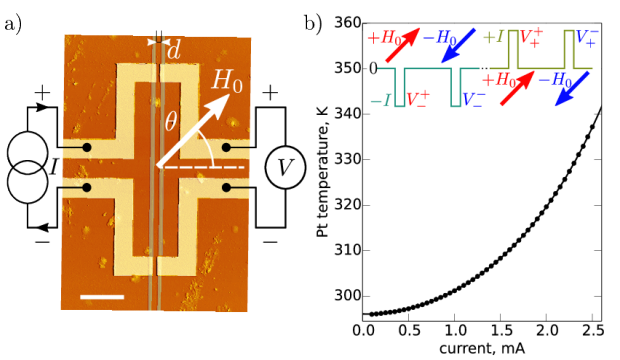

FIG 1: a) Top view of the lateral device. Two vertical Pt wires (grey) are placed at a distance d = 1.2 µm apart on top of a 18 nm thick YIG film (scale bar is 5 µm). The non-local conductance I-V (injector-detector) is measured using negative and positive current pulses while rotating the magnetic field H_0 in-plane by an angle θ. Panel b)shows the temperature elevation produced in the Pt injector by Joule heating while increasing the pulse amplitude I.

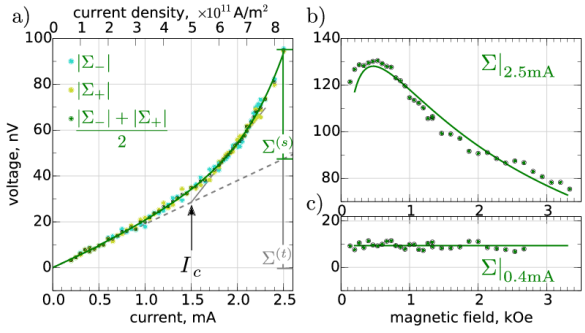

FIG 2: Current dependence of the sum signal $\Sigma_{\mp}=(V_{\mp}^{+}+V_{\mp}^{-})/2$ averaged over the two current polarities. The dashed line is a linear fit of the low current regime and the arrow marks the onset at which the spin transport deviates from linear behavior. Spin transport excited by SOT can be separated in two independent channels: a linear contribution $\Sigma^{(t)}$ taken on by magnons transporting thermal heat and $\Sigma^{(s)}$, an additional magnons' conduction channel that emer-ges above I_c. Variation of Σ as a function of magnetic field for two different current intensities b) above and c) bellow I_c.

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The ultimate speed of the spin-dependent and spin Seebeck effect: insights and applications

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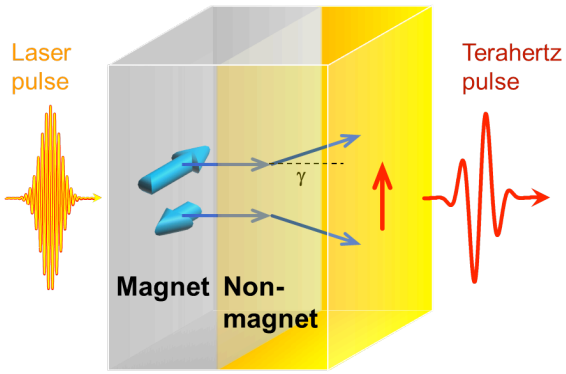

The spin-dependent and spin Seebeck effects are powerful phenomena to launch spin currents from, respectively, insulating and conducting thin films into an adjacent metal by simply inducing an out-of-plane temperature gradient. To reveal the initial elementary steps leading to the formation of the Seebeck spin current, we probe its ultimate speed with 10 fs time resolution in prototypical magnetic (F)|heavy metal (N) bilayers. Following excitation of the metal layers with an ultrashort laser pulse, the spin current injected into the N layer is converted into an in-plane charge current by the inverse spins Hall effect. The charge flow acts as a source of a terahertz (THz) electromagnetic pulse that is detected all-optically by electrooptic sampling [1].

For yttrium iron garnet (YIG)|Pt bilayers, we find the spin Seebeck current rises within ~200 fs, a hallmark of the photoexcited electrons in the metal approaching a Fermi-Dirac distribution. Model-supported analysis shows the spin-current amplitude follows the dynamics of the electrons in the metal film (N) quasi-instantaneously because they impinge on the interface with a correlation time of only ~4 fs and deflect the spins of the magnetic layer (F) without inertia [2]. For all-metallic Fe|Pt bilayers, the spin-dependent Seebeck current exhibits a three orders of magnitude larger amplitude and even faster bipolar dynamics than in YIG|Pt.

Promising applications for contact-free interface probing, spin-noise detection, terahertz spin pumping [2], high-throughput material characterization and efficient generation of broadband THz pulses [3] emerge.

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Acoustic Spin Pumping into Rashba Interface

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Spin-rotation coupling and magneto-elastic effect [1-3] have recently been suggested applicable to the spin current generation.

The spin-rotation coupling was demonstrated as Barnett effect and Einstein-de Hass effect and later has been measured in magnetic micro-cantilever and analysed by the domain wall motion [4]. Here we show the surface acoustic wave, passing through ferromagnetic materials, generates the time variable effective field through spin-lattice coupling. It excites ferromagnetic resonance, pumping spin current into an adjacent nonmagnetic layer. Then, either inverse spin Hall effect or inverse Rashba Edelstein effect in the system, converts spin current into charge current, generating voltage signal. In the present work, we used Rayleigh-type surface acoustic waves in GHz regime to induce coherent elastic motion, thereby spin currents were resonantly generated at room temperature. The results indicate that the surface acoustic wave becomes an efficient tool to generate spin currents for spintronic devices.

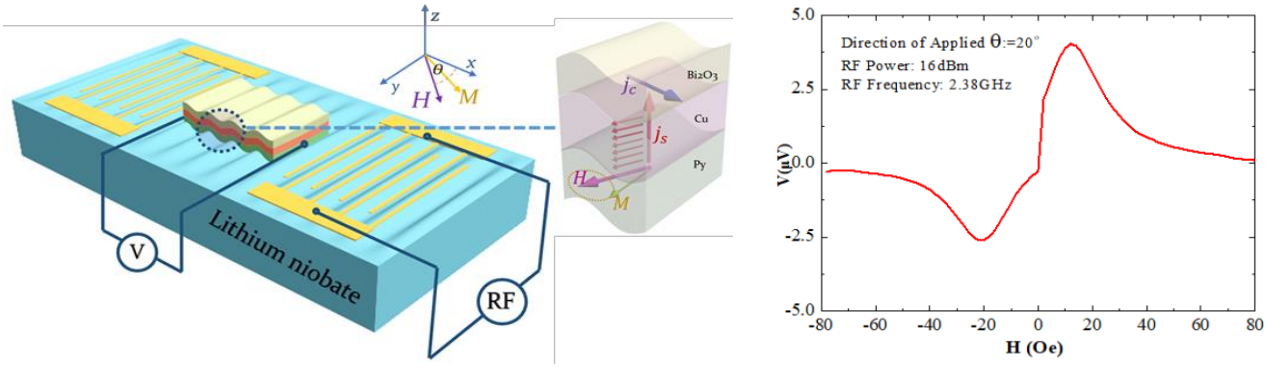

Figure: (left) Illustration of experiment setup. The surface acoustic waves generated by applying RF voltage on interdigital transducers and the longitudinal voltage has been measured by nano-voltmeter while applying a external magnetic field *H*. (right) Rectified voltage induced by acoustic spin pumping with Rashba interface is plotted as a function of external bias magnetic field.

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Nernst Effect in Nanostructures

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The correlation between spin and charge in electronic transports has been energetically studied in a scheme of spintronics research. Recently, the coupling between heat current, spin current and charge current is also attracting much attention, and this newly established filed is called “spin caloritronics”. The recent discovery of the spin Seebeck effect has explosively expanded this field, and a number of thermomagnetic effects related to spin current have been investigated. On the other hand, the Nernst effect is a common thermomagnetic effect, which has been known for a long time. When a temperature gradient is applied on a material with spontaneous magnetization, an electric field is induced in the perpendicular direction to both the temperature gradient and the magnetization, which is called the anomalous Nernst effect (ANE). We have reported ANE measurements of $L1_0$-ordered epitaxial FePt thin films for studying thermomagnetic effects in ordered alloys[1,2], and we also investigated the material dependence of ANE in several perpendicularly magnetized ordered-alloy thin films[3]. Obtaining materials with a large ANE is indispensable to realize a practical application of ANE-based energy conversion. From this point of view, this paper describes our study on the correlation between magnetic anisotropy and the ANE in various materials. The enhancement effect of ANE with spin-wave spin currents in nanostructures is discussed with theoretical viewpoints. Moreover, a novel material with the strong anisotropy in ANE[4] and spin caloritronic devices with nanostructures for ANE-based energy conversion application will be shown.

This research was partly supported by JST-CREST and a Grant-in-Aid for Scientific Research (S) (25220910) from Japan Society for the Promotion of Science.

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Magnonic cavities in YIG-based ferromagnetic nanostructures

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The strong couplings between a cavity photon and spin wave excitations (magnons) have been recently investigated [1-4], known as cavity photon-magnon polaritons. We studied experimentally strong couplings between in-plane standing spin waves in 20 nm-thick YIG film and ferromagnetic resonance (FMR) of metallic nanowires [4]. Such observations are considered as magnonic cavities in view of its analog to the cavity photon-magnon polaritons. Large anticrossing gaps up to 1.58 GHz are observed experimentally (Fig. 1). Control experiments and simulations reveal that the interface exchange coupling is the dominating mechanism. The coupling strength is tunable over a large interval by switching between different magnetic states. The coherent control of spin waves by surface induced strong coupling is of interest for magnonic devices.

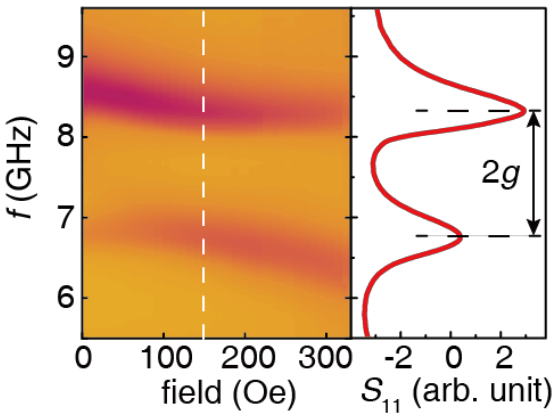

Fig. 1 Anticrossings between the YIG in-plane standing spin wave mode and the Co nanowire FMR mode at anitiparallel state of Co/YIG hybrid structures.

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Detection of spin dynamics with spin current

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Spin current, flow of spin angular momentum, is one of the most fundamental and essential physical quantities in the field of spintronics. Thus, its efficient generation, detection and manipulation have been intensively investigated so far. The spin Hall effect (SHE) and its inverse (ISHE) are well-known methods to generate and detect the spin current. It is widely accepted that the SHE and ISHE occur in nonmagnetic materials with strong spin-orbit interaction [1]. Recently, it has turned out that these effects can also take place even in magnetic materials such as ferromagnets (FM) [2] and antiferromagnets (AFM) [3]. Especially, in a weak ferromagnetic metal, spin fluctuations near the Curie temperature have been detected with the ISHE in a very sensitive manner [4]. The result indicates that spin dynamics in materials with complex spin structures could be detected by the spin current.

For this purpose, we have chosen spin glass. Spin glass is a typical magnetic frustrated system where the FM and AFM orderings compete each other. This competition results in a cusp in magnetization M vs temperature T for zero filed cooling at the spin glass temperature T_g where the magnetic moments are randomly frozen. However, there are few reports on spin transport in such spin glass systems.

In this work, we have studied the SHE in CuMnBi ternary alloys using the spin absorption method [5]. CuMn is a typical spin glass metal but does not show the SHE. On the other hand, CuBi shows a very large SHE [6]. We found that the SHE in CuMnBi starts to decrease far above T_g and becomes almost zero well below T_g. We propose an explanation in terms of a simple model considering the relative dynamics between the localized moment and the conduction electron spin (see Fig. 1).

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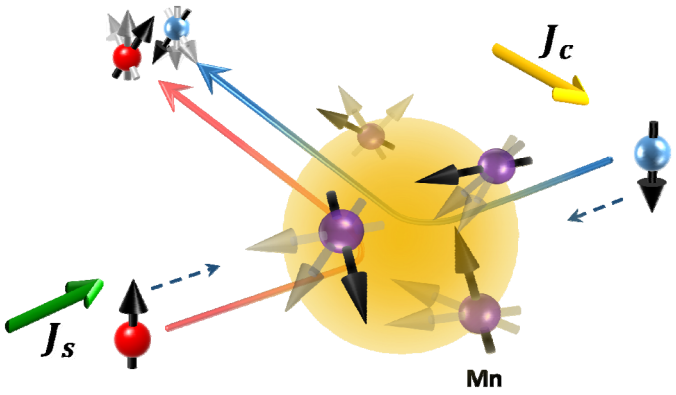

Fig. 1: Schematic of detection of spin fluctuations in spin glass via spin current.

Engineered Hamiltonians for strongly correlated Fermions

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Atomic-scale engineering reached the level of control where single-atom devices can be reproducibly fabricated with high yield. This talk focuses on the progress of single dopant atom placement in the context of engineered quantum matter. Silicon offers a particularly interesting platform for single dopants because when isotopically purified it acts as a "semiconductor vacuum" for spins. This leads to extraordinary coherence that is used to realise donor atom based qubits. Spatially resolved tunneling experiments reveal the spectrum and quantum state image of single atoms and tunnel coupled arrangements of atoms. These measurements grant access to the wavefunction of donors in the silicon lattice that makes it possible to pinpoint the dopants to their exact position in the lattice that is essential in the evaluation of engineered quantum matter. A first step towards engineered Hamiltonians for Fermionic systems in the form of atomic chains was taken where interacting dopants were employed to simulate a two-site Hubbard Hamiltonian at low effective temperatures with single-site resolution. Quasi-particle tunneling maps of spin-resolved states with atomic resolution reveal interference processes from which the entanglement entropy and Hubbard interactions are quantified. The aim of this work is to build a two-dimensional array of up to 30 spins in the solid state to implement complex highly correlated systems.

Optical Excitation of Magnons in Antiferromagnets

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All-optical magnetization switching has been studied extensively in recent years. A typical form of non-thermal magnetization control is the inverse Faraday effect (IFE). It involves rotation of the linear polarization of a probe pulse induced by a circularly polarized pump pulse in a transparent medium. Spin precession is also triggered with a linearly polarized pump pulse, in particular, a pulse polarized in a direction non-parallel to the crystal axes. This phenomenon is called the inverse Cotton-Mouton effect (ICME).

Antiferromagnets are promising materials with magnon frequencies extending into the terahertz range. Here we report all-optical excitation of magnons in antiferromagnetic NiO [1,2] and CoO [3] with quenched and unquenched orbital momenta, respectively. In CoO, magnon modes are coupled oscillations of spin and orbital momenta with comparable amplitudes. We demonstrate excitations of magnon modes by directly coupling light with electronic orbital angular momentum, providing possibilities to develop magneto-optical devices operating at several terahertz with high output-to-input ratio. In $YMnO_3$, its three magnetic oscillation eigenmodes are selectively excited by the three polarization eigenstates of the light via the inverse magneto-optical effects. The magnetic oscillation state is then transferred back into the polarization state of an optical probe pulse, thus completing an arbitrary optomagnonic write-read cycle [4].

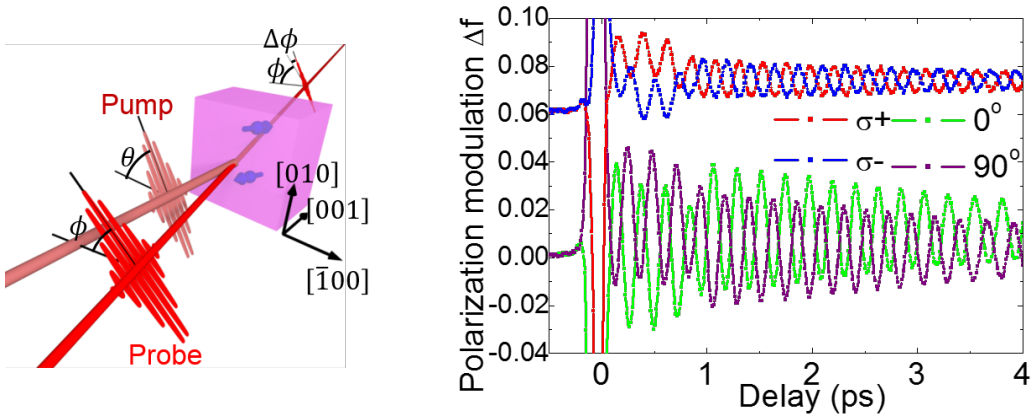

Figure Time-resolved pump-probe measurement in antiferromagnetic CoO (left). Excitation of magnetic oscillations with large amplitude (right) [3].

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Topological Triplon Modes in a Shastry-Sutherland Magnet

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The twin discoveries of the quantum Hall effect, in the 1980's, and of topoogical band insulators, in the 2000's, were landmarks in physics that enriched our view of the electronic properties of solids. In a nutshell, these discoveries have taught us that quantum mechanical wavefunctions in crystalline solids may carry nontrivial topological invariants which have ramifications for the observable physics. One of the side effects of the recent topological insulator revolution has been that such physics is much more widespread than was appreciated ten years ago. For example, while topological insulators were originally studied in the context of electron wavefunctions, recent work has led to proposals of topological insulators in bosonic systems: in photonic crystals, in the vibrational modes of crystals, and in the excitations of ordered magnets. Using inelastic neutron scattering along with theoretical calculations we demonstrate that, in a weak magnetic field, the dimerized quantum magnet $SrCu_2(BO_3)_2$ is a bosonic topological insulator with nonzero Chern number in the triplon bands and topologically protected chiral edge excitations.

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Spin Hall Magnetoresistance in Ferrimagnets and Antiferromagnets

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The spin Hall magnetoresistance (SMR) effect is governed by the transfer of spin angular momentum across the interface between a magnetic insulator and a thin metallic film. In the last few years, the SMR response of ferrimagnetic insulators with both collinear as well as non-collinear magnetic structure has been extensively investigated. The insights obtained from these efforts now pave the way for studying the magneto-transport response of antiferromagnetic insulator/metal heterostructures.

In the talk, I will briefly review the SMR response characteristic of collinear and non-collinear ferrimagnetic phases, and then discuss our recent magneto-transport experiments in antiferromagnetic insulator/Platinum heterostructures. In particular, I will address the evolution of the magneto-resistance across the Neel temperature of the antiferromagnet, and critically compare our experimental data with model calculations.

Hybridized magnon-phonon excitation in spin Seebeck effect

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The spin Seebeck effect (SSE) [1] refers to the generation of a spin current in magnetic materials by a temperature gradient. In the SSE, a thermally generated magnon spin current in a magnet is converted into a conduction-electron spin current in a metal attached to the magnet via the interfacial spin-exchange interaction. The spin current is detected as an electric voltage via the inverse spin Hall effect in the metal. Recent studies revealed that the SSE provides a sensitive probe for magnon dynamics in magnetic materials [2].

In this talk, we report sharp features in the SSE induced by hybridized magnon-phonon excitation (or magnon polarons [3-5]) at the band (anti-)crossings between the magnon and phonon dispersion curves in $Y_3Fe_5O_{12}$ (YIG). We observe anomalous saw-tooth structures in the magnetic field dependence of the SSE through a high-resolution field scan. The SSE anomalies appear when the magnon and phonon dispersion curves touch, which maximizes the magnon-polaron phase space. The experimental results are well reproduced by a Boltzmann equation including the magnetoelastic coupling. The sharp structures of the SSE can thereby be attributed to the spin current carried by magnon polarons exhibiting a longer propagation length than pure magnons. During the talk, we will also present the effect of Bi substitution to YIG on the magnon-polaron features in the SSE.

The work was done in collaboration with K. Oyanagi, T. Hioki, Y. Hashimoto, R. Ramos, Z. Qiu, M. Ishida, K. Uchida, E. Saitoh, G. E. W. Bauer, K. Shen, B. Flebus, R. A. Duine, L. J. Cornelissen, T. Kuschel, and B. J. van Wees.

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Novel Excitations with Magnetic Proximity Effects

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Proximity effects can transform a given material through its adjacent regions to become superconducting, magnetic, or topologically nontrivial, enabling unexplored device opportunities. In bulk materials, the sample size often dwarfs the characteristic lengths of proximity effects allowing their neglect. However, in 2D materials such as graphene, transition-metal dichalcogenides (TMDs) and 2D electron gas (2DEG), the situation is drastically different, even short-range magnetic proximity effects exceed their thickness and strongly modify spin transport and optical properties. In TMDs, where robust excitons, bound electron-hole pairs (binding energy > 100 meV), dominate their optical response, magnetic proximity effects cannot be described by the widely used single-particle description, but instead could convert between optically inactive and active excitons by rotating the magnetization in the substrate [1]. Magnetic and superconducting proximity effects could enable elusive Majorana bounds states (MBS) for a fault-tolerant quantum computing. Unlike Fermions or Bosons, exchanging (braiding) MBS yields a non-commutative phase, a sign of non-Abelian statistics and non-local degrees of freedom protected from local perturbations. Such MBS could be manipulated and braided in proximity-induced superconductivity in a 2DEG with tunable magnetic textures from the fringing fields of magnetic tunnel junctions [1,3].

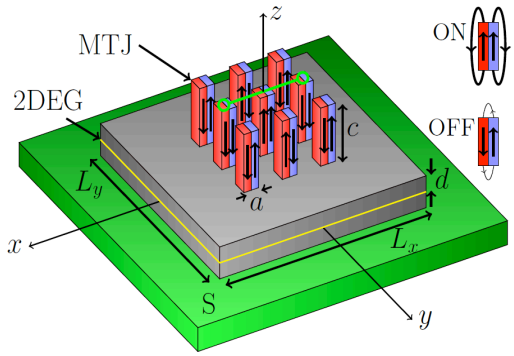

Fig. 1 2DEG is grown on the surface of a superconductor (S). A tunable magnetic texture from the fringing fields of MTJs modifies the proximity-induced superconductivity in a 2DEG to create and manipulate Majorana bound states (green circles) [2].

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Microscopic Theory of Magnonic Torques Induced by Temperature Gradient

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Driving a magnetic texture using unconventional means is one of the important subjects in spintronics. After extensive studies on the electrical driving, there has recently been a growing interest in thermal driving, especially of insulating magnets. The motions of domain walls and skyrmions induced by temperature gradients were demonstrated in experiments and by simulations, and several driving mechanisms have been proposed such as entropic force and torques due to spin waves (magnonic torques) including reflection force

We study thermally induced spin torques due to spin waves, or magnons, in a ferromagnet [1-3] based on the Luttinger's linear response theory for the treatment of temperature gradient [4]. The model we consider is "microscopic" in that it includes, in addition to localized spins responsible for the magnetization, a "reservoir" that introduces Gilbert damping into the spin system. Taking conduction electrons as the reservoir, which couple to the spins via the s–d exchange interaction, we calculate the magnonic spin-transfer torque and its dissipative correction (β term). Compared to the existing result $\beta = d\alpha/2$ from the exchange-stiffness (or gradient) torque, where α is the Gilbert damping and d is the spatial dimensionality, we found an additional contribution $\Delta\beta = \alpha/2$ from the s–d torque, resulting in $\beta = (d + 1)\alpha/2$ in total.

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Edelstein effects in inversion asymmetric crystals

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In the Edelstein effect, a current in the crystal induces a spin polarization. It occurs in crystals without inversion symmetry, as studied in Rashba systems and in the surface of topological insulators. The spin polarization vanishes in equilibrium, but in the presence of the current, the off-equilibrium electron distribution leads to nonzero spin polarization, due to the spin-split band structure.

We propose an analogous effect for orbital angular momentum [1,2]. For example, in crystal with helical structure such as tellurium (Te) (Fig. 1(a)) [3], we propose that a current along the helical axis induces an orbital magnetization [1,2]. This is analogous to solenoids in classical electrodynamics. Within this analogy to solenoids, we quantify this effect by introducing a dimensionless parameter ξ (Fig. 1(c)), which represents a number of turns in the unit cell when regarded as a classical solenoid. We show that ξ is largely enhanced when the system is in the Weyl semimetal phase (Fig. 1(b)) [1,2]. Here the Weyl semimetal phase [4] is allowed by broken inversion symmetry, and it is shown that Te becomes a Weyl semimetal at higher pressure [3,5].

Moreover, we propose a similar effect appears for phonons. In crystals, each phonon eigenmode has angular momentum due to rotational motions of the nuclei (Fig. 1(d)), but their sum is zero in equilibrium. Meanwhile a heat current in the Te crystal induces a nonzero total angular momentum [6]. We evaluate this effect for GaN and Te by ab initio calculation, and propose experiments to measure this effect by various spin conversion phenomena.

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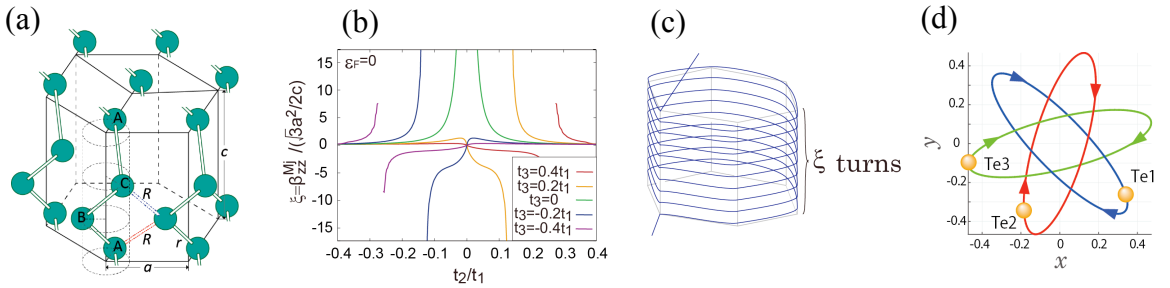

Fig.1: (a) Lattice structure of Te. (a) Dimensionless parameter ξ in the orbital Edelstein effect. (c) Physical interpretation of ξ. (d) Trajectories of Te atoms for some phonon mode.

Theory of skyrmion glass

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Skyrmions and skyrmion crystal (SkX) discovered in chiral magnets show novel physical properties originating from their nontrivial topology such as the stability against the annihilation and the motion driven by the ultralow current density, which can be advantageous for the applications such as magnetic memories. Especially, the chiral dynamics is a key to avoid the impurity potential and enhances its mobility. However, the collective pinning of SkX occurs by the disorder, which is crucial for its low energy properties. Here, we study theoretically the low energy dynamics of SkX in the presence of disorder effects in terms of replica field theory, and reveal nonreciprocal collective modes and their electromagnetic responses along the direction of external magnetic field, enhanced relaxation rate of mu-SR and NMR, and reduced pinning frequency compared with the helical state. Also we analyze the nonreciprocal voltage generation associated with the current driven motion of skyrmion strings. These results provide a firm basis to explore the glassy state of SkX.

Magnetic excitations in YIG: Neutron scattering study

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The spin Seebeck effect (SSE) [1] attracts much attention due to possible application to thermal spin generators for driving spintronics devices. The SSE is observed through the generation of spin current in ferromagnets and ferrimagnets under a temperature gradient. Driving spin currents thermally could lead to the manufacturing of a compact magnetic source without using electric current or magnetic field.

In magnetic insulators, the spin current is carried by spin-waves (magnons), and the SSE is governed by the spin dynamics rather than the simple static magnetism [2]. $Y_3Fe_5O_{12}$ (YIG) is a well-known ferrimagnet and frequently employ for the SSE, and has gradually attracted revisiting interest in neutron research [3] after almost 40 years [4]. Neutrons give us information on magnetism at the microscopic scale, which can help to address the mechanism of the macroscopic SSE based on quantitative analysis.

We thus performed inelastic neutron scattering investigations using a chopper spectrometer HYSPEC at Oak Ridge. Both magnetic and structural excitations in different Brillouin zones are clearly observed, and the temperature dependence of the gapped magnon mode compares nicely with the theoretical calculation [5]. Using finer energy resolution in a triple-axis spectrometer SIKA at ANSTO, we fully determined the energy dispersion at lower energy regime, which is not elucidated in [4]. In this talk, we show our recent neutron scattering results as well as magnon lifetime study if time allows. Quantitative estiamtion of magnon lifetime and conditions for an enhancement of the SSE signal would be essential to gain better spintronics materials.

This research prohect was conducted through a collaboration with Y. Okino, M. Fujita, K. Kakurai, T. Kikkawa, E. Saitoh, S. Shamoto, J. Barker, G. E. W. Bauer, M. Mori, and S. Maekawa.

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Effective gauge field theory of spin-charge conversion and electromagnetic cross correlation effects

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Spin current generation and spin-charge conversion phenomena due to spin-orbit inter- action are described in terms of spin gauge field arising from localized spin (magnetization) structures [1, 2]. Electromagnetic cross correlation effects and anomalous optical properties are discussed based on effective Lagrangian for conventional elect

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Poster Sessions

Generation of spin current from lattice distortion dynamics

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Generation of spin current from a mechanical motion of materials is one of the intriguing topics in spintronics. Recently, generation of spin current from the vorticity of liquid metal flow has been demonstrated experimentally [1]. It was also discussed theoretically that an a.c. spin current is induced by lattice distortion (acoustic phonon) [2]. Theoretical basis of these effects has been provided by the "spin-vorticity coupling" or the effective magnetic field that exists in the rotating (non-inertial) frame locally fixed on the material [3, 4]. It is, however, desirable to look at such effects from a different point of view.

We study theoretically the generation of spin current from lattice distortion dynamics combined with the effects of spin-orbit coupling (SOI). We consider nearly free electrons in a solid subjected to normal as well as spin-orbit impurities. The effects of lattice distortion are treated by a local transformation on the electrons. We calculate spin accumulation and spin current in response to the displacement field using linear response theory. In this presentation, we show the results obtained at the first order of SOI. In the calculation, we assume a small but general wave vector and frequency for the displacement field, and take into account the ladder type vertex corrections due to the impurity scattering. The obtained results will be discussed in comparison with those based on spin-vorticity coupling.

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Enhanced magneto-optical Kerr effect at Fe/insulator interfaces

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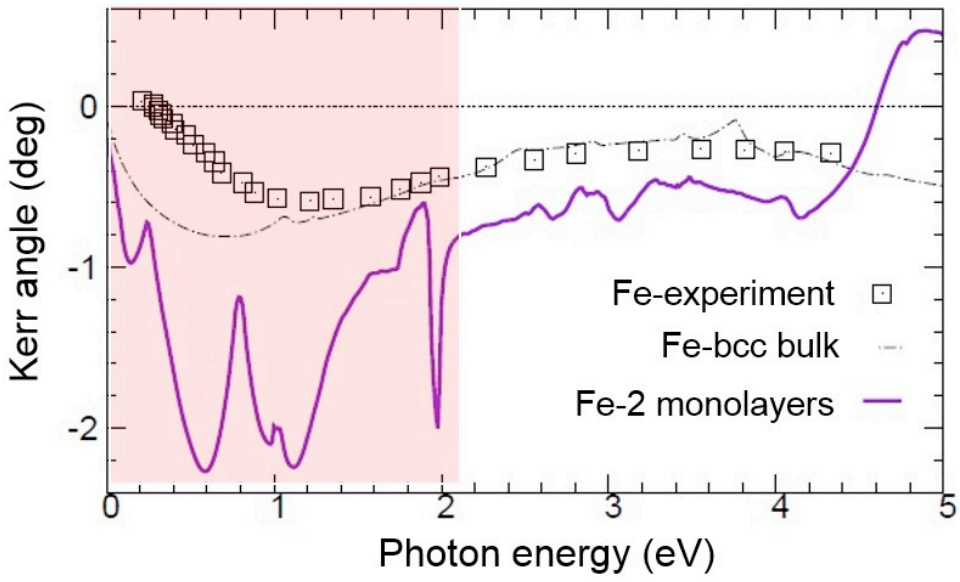
Magneto-optical Kerr effect (MOKE) is the phenomenon in which the light reflected from a magnetized material has a rotated plane of polarization. The MOKE originates from spin-orbit coupling in materials and has been extensively studied. Recently, the effect has played a significant role in the rapidly developing field of spintronics, such as the spin Hall effect, skyrmion Hall effect, and spin-orbit torques in magnetic bi-layers. For applications to magneto-optical devices, a large MOKE is required. By density functional theory calculations, we have found an enhanced MOKE in Fe/insulator interfaces. Our study indicates that interfacial Fe atoms in the Fe films have a low-dimensional nature, which causes the following two effects: (i) The diagonal component σ_{xx} of the optical conductivity decreases dramatically because the hopping integral for electrons between Fe atoms is suppressed by the low dimensionality. (ii) The off-diagonal component σ_{xy} of the optical conductivity does not change at low photon energies, but it is enhanced at photon energies around 2 eV, where we obtain enhanced orbital magnetic moments and spin-orbit correlations for the interfacial Fe atoms. A large Kerr angle develops in proportion to the ratio σ_{xy}/σ_{xx}. Our findings indicate an efficient way to enhance the effect of spin-orbit coupling at metal/insulator interfaces without using heavy elements.



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Magnetic anisotropy in the Rashba spin-orbit coupled antiferromagnets

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Magnetic anisotropy of an antiferromagnet (AFM) with the inversion symmetry breaking (ISB) is investigated. We focus on the effect of Rashba spin-orbit (RSO) interaction on the magnetic anisotropy energy (MAE). The RSO coupling that appears in a system with the ISB plays a leading role in spintronics. For a RSO coupled ferromagnet (FM), we have derived the MAE [1], in which the onset of the MAE is explained by the energy gain from the enhanced exchange splitting due to the RSO interaction. An important observation is that the induced MAE is quadratic in the RSO coupling constant, this allowing the electrical-field control of the MAE.

In contrast, for the RSO coupled AFMs, we show that the sign the MAE strongly depends on the type of the RSO coupling. In order to illustrate the effect of the RSO interaction on the MAE in AFMs, we study two representative lattice models: two-sublattice ordered AFM with the global ISB or the local ISB as schematically shown in Fig.1. The former is a model for the structural ISB at a surface or an interface [2] while the latter is a model for the noncentrosymmetric AFM like CuMnAs with the sublattice-dependent RSO coupling [3].

The global ISB model results in an easy-plane magnetic anisotropy for the small RSO coupling whereas, for a local ISB model, a perpendicular magnetic anisotropy (PMA) arises independent of the strength of the RSO coupling. Both results contrast with the FM case in which the condition for the PMA depends on the band structure and dimensionality. These MAE contributions have a key role in determining the direction of the Neel order parameter in AFM nanostructures and reflect the possibility of electrical-field control of the Neel vector.

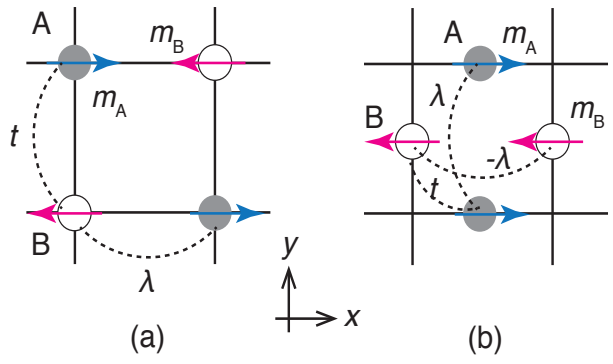

Fig. 1: The conduction electrons hop with t on the sublattice moments $\mathbf{m}_{A/B}$ where they interact via the exchange and the RSO interactions. (a) The global RSO model. (b) The sublattice-dependent RSO model.

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Cross-correlated electron-magnon transport on the surface of magnetic topological insulator

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Spin waves, or magnons, have attracted considerable attention recently because they can propagate in insulators without dissipation due to Joule heating [1]. On the other hand, when conduction electrons exist as well, various phenomena originating from the interplay of magnons and electrons are expected, such as exchange of spin currents between magnons and conduction electrons [2].

Recently, systems in which two dimensional Dirac electrons and ferromagnetism coexist were realized on the surface of magnetic topological insulators (MTI) by doping magnetic impurities in topological insulators [3,4]. On the surface of MTI, interesting phenomena caused by the coupling between the magnetization and Dirac electrons with spin-momentum locking have been studied experimentally and theoretically, such as quantized anomalous Hall effect [5] and unidirectional magnetoresistance [6].

In this work, we study the cross-correlated transport phenomena in a coupled electron-magnon system on the surface of MTI. In particular, we focus on the electron-drag magnon thermal Hall effect, in which a thermal Hall current of magnons is induced by the anomalous Hall effect of electrons. We have identified two possible mechanisms; one is the direct drag process, and the other is via the Dzyaloshinskii-Moriya interaction induced by Dirac electrons. We examine these two processes in detail including, e.g., the dependence on the magnetization direction.

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Writing and Reading antiferromagnetic Mn_2Au: Néel spin-orbit torques and large AMR.

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Using antiferromagnets as active elements in spintronics requires the ability to manipulate and read-out the Néel vector orientation. Here we demonstrate for Mn_2Au, a good conductor with a high ordering temperature suitable for applications, reproducible switching using current pulse generated bulk spin-orbit torques and read-out by magnetoresistance measurements. Reversible and consistent changes of the longitudinal resistance and planar Hall voltage of star-patterned epitaxial $Mn_2Au(001)$ thin films were generated by pulse current densities of $\cong 10^7$ A/cm^2. Consistent measurements of the AMR and PHE showed pulse current direction dependent reversible changes, providing direct evidence for Néel vector switching. Easy read-out of the switching is provided by a large amplitude of the AMR of more than 6%, which is more than an order of magnitude higher than previously observed for other antiferromagnetic systems and one of the highest AMR amplitudes found for metallic magnetic thin films. We can reproduce the magnitude of the effect theoretically by including realistic disorder and, in particular, find the same dependence of the amplitude on the crystallographic directions in the experiment as in the calculation.

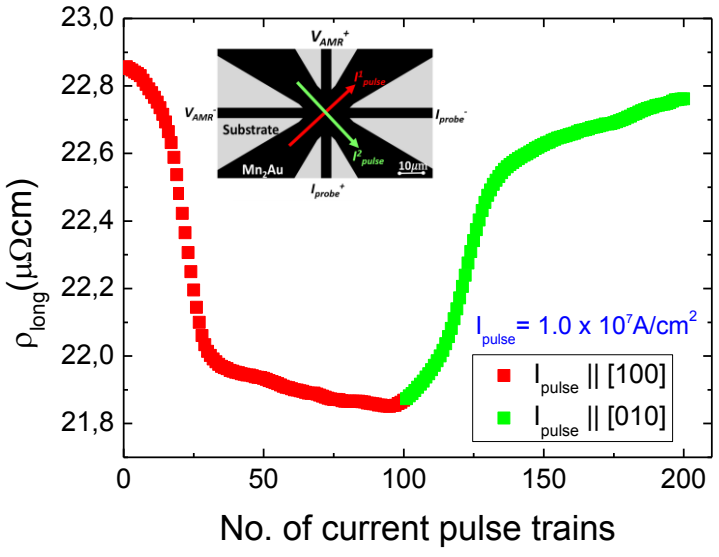

Fig.: Longitudinal resistivity vs. number of applied pulse trains. The inset shows the sample layout.

Spin Hall effect from hybridized 3d-4p orbitals

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We show that a paramagnetic B2 CoGa compound possesses large enough spin Hall angle to allow robust current-induced spin-orbit torques switching of perpendicularly-magnetized ferrimagnetic MnGa films in CoGa/MnGa/Oxide heterostructures[1]. The spin Hall efficiency estimated via spin Hall magnetoresistance and harmonic Hall measurements is +0.05±0.01, which is surprisingly large for a system that does not contain any heavy metal element. First-principles calculations corroborate our experimental observations and suggest that the hybridized Co 3d – Ga 4p orbitals is responsible for the intrinsic spin Hall effect. Our results suggest that efficient spin current generation can be realized in intermetallic by alloying a transition metal with a *p*-orbital element and by Fermi level tuning.

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Controlling the rare-earth spin with voltages

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The *voltage control of magnetism* has attracted much attention because it can save power to operate magnetic random access memories [1]. In magnetic multilayers, both voltage-induced ferromagnetic resonance [2,3] and magnetic switching [4,5] have been realized by the electric field dependence of the magnetic anisotropy [6]. However, a stronger spin-charge coupling would be highly desirable for practical applications of voltage-controlled devices. Here we demonstrate that this can be achieved by employing the strong spin-orbit interaction of the 4f subshell in rare earth atoms and the large electric field gradients at *insulator*|*metal* interfaces.

We study rare-earth magnetic moments with partially filled 4f-shells that are characterized by large spin-orbit interactions (SOI), which lock the 4f charge and spin densities. Space and time-varying voltages couple to the charge quadrupole of the ionic charge distribution, and via the SOI move the magnetic moment much more efficiently than for 3d transition metal ions. A possible device is made of rare earth-doped or substituted yttrium iron garnet with metal contacts, and it could be used for magnetization reversal and ferromagnetic resonance, among others.

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Transport of thermal magnons under the influence of the microwave-excited GHz magnons

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We investigate the transport of THz incoherent magnons under the influence of the GHz microwave field, which can excite GHz coherent magnons. Using the lateral non-local Pt|YIG|Pt structure (see Fig.1) [1], we electrically and thermally inject, and electrically detect thermal magnons with the presence of a certain radio-frequency magnetic field (h_{rf}). A static magnetic field (H_{ex}) is also applied to align the magnetization of 100- and 200-nm-thick YIG (M). When the ferromagnetic resonance (FMR) condition is reached ($H_{ex} = H_{FMR}$), we observe that non-local signals related to the THz magnons are modulated in both electrically and thermally injection cases with a magnitude of ~10% (Fig.2). A theory of local thermomagnonic torques [2] has been proposed to describe the interplay between the THz incoherent thermal magnons and GHz coherent magnons. Recently, by using diamond NV-center based magnetometry [3], the local thermomagnonic torques can be determined and the magnon chemical potential can be tuned by driving the system into FMR. Here, we want to study how the transport of the thermal magnons are influenced by this change of the magnon chemical potential induced by FMR [4]. One of the promising application of this study is to make a THz-magnon "transistor" with a GHz-magnon "gate".

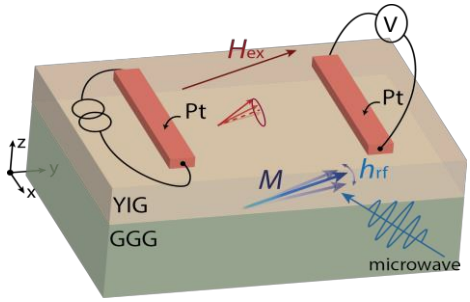

Fig.1 Illustration of the setup

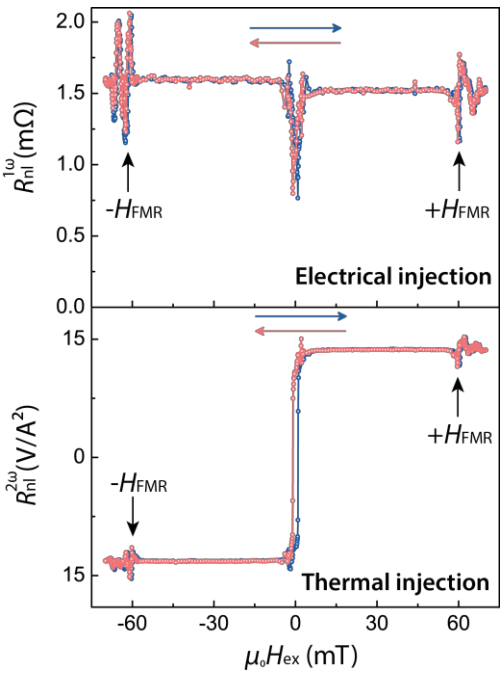

Fig.2 Non-local signals as a function of H_{ex}

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Magnon-phonon relaxation in yttrium iron garnet from first principles

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We combine the theoretical method of calculating spin wave excitation with the finite-temperature modeling of lattice vibration and calculate the magnon-phonon relaxation time in the technologically important material Yttrium iron garnet (YIG) from first principles. The finite lifetime of magnon excitation is found to arise from the fluctuation of the exchange interaction of magnetic atoms in YIG. At room temperature, the magnon spectra have significant broadening that is used to extract the magnon-phonon relaxation time quantitatively. The latter is a phenomenological parameter of great importance in YIG-based spintronics research. We find that the magnon-phonon relaxation time for the optical magnon is a constant while that for the acoustic magnon is proportional to $1/k^2$ in the long-wavelength regime.

Dynamics of angular momenta in spin-phonon system

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Interconversion, or transfer, of angular momentum among various degrees of freedom is a central paradigm in spintronics. Among others, the conversion of electron spin angular momentum into a mechanical one is of fundamental interest. Recently, through the consideration of the phonon Hall effect, the concept of phonon spin was introduced in Ref. [1], where it was pointed out that the phonon spin can have a non-negligible contribution in the Einstein-de Haas effect. A possible application of phonon spin was proposed in Ref. [2], where it was pointed out that phonon spin can actuate domain-wall motion.

Microscopic process of the angular momentum transfer between a single paramagnetic spin and the elastic lattice is an old problem, known as the paramagnetic spin-lattice relaxation. This subject received a renewed interest recently from the viewpoint of angular momentum transfer. Garanin and Chudnovsky investigated the relaxation of a localized spin via phonons, and found that the phonon spin plays a central role [3].

In this work, we show that phonons can carry orbital angular momentum; this led us to re-investigate the model in Ref. [3], where we found that the phonon orbital angular momentum is as essential as the phonon spin angular momentum in the relaxation process of the localized spin. The discrepancy of the results between Ref. [3] and ours is due to the difference in the expression of the orbital part of the angular momentum. We will be discussing the differences in the two orbital angular momenta in detail.

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Topological Hall effect from strong to weak coupling

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Electrons coupled to a noncoplanar spin texture exhibit a Hall effect [1], called topological Hall effect (THE) [2]. THE has been recognized as a phenomenon due to Berry phase in the strong coupling regime, but it was known to exist also in the weak coupling regime as shown by perturbation theory [3]. So far, however, the THE has been studied for the strong- and weak-coupling regimes separately

We have calculated topological Hall conductivity for a wide range of coupling, from strong to weak coupling, in each region indicated in the Figure. We focus on the so-called diffusive regime in which the wavelength of magnetic texture (q^{-1}) is longer than the electron mean free path ℓ. We present a unified treatment in terms of spin gauge field [4] by considering not only the adiabatic (Berry phase) component of the gauge field but also the nonadiabatic component.

While only the adiabatic contribution is important in the strong-coupling regime (region 0), it is completely cancelled by a part of the nonadiabatic contribution in the weak-coupling regime (region 1, 1', 2, 2'), where the THE is governed by the rest of the nonadiabatic terms.

We found a new weak-coupling region (region 1) that cannot be accessed by a simple perturbation theory, where the Hall conductivity is proportional to M, with $2M$ being the exchange splitting. Also, the effective magnetic field in region 2 is determined by the nonlocal spin chirality that consists of mutually distant spins due to the effect of electron diffusion. This is in contrast to the strong coupling case, where the effective field is determined by the local magnetic structure.

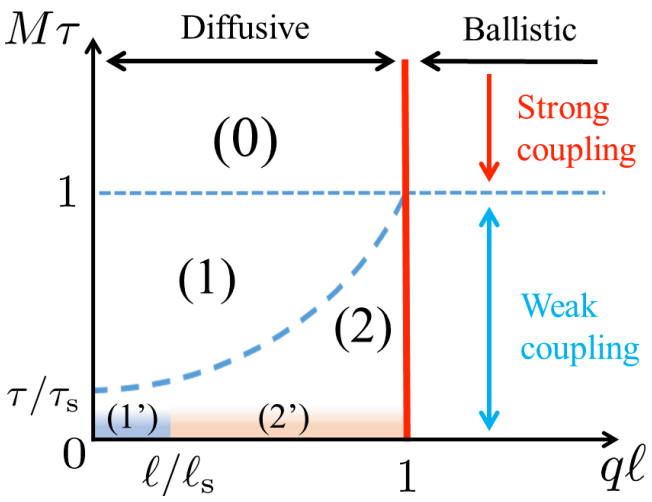

Figure: Characteristic regions in the diffusive regime in the $M\tau$-$q\ell$ plane. Regions 1' and 2' arise in the strong spin-relaxation regime.

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Magnon-polaron transport in the nonlocal spin Seebeck effect

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Nonlocal experiments are established methods to clarify transport properties of spin currents in metallic systems. Recently, a nonlocal experiment for detecting thermally generated magnonic spin current was reported in a magnetic insulator [1], which is called the nonlocal spin Seebeck effect (nlSSE) in analogy to the spin Seebeck effect (SSE). Generation of spin current is affected by phonons due to the magneto-elastic coupling in a magnetic insulator [2]. However, the effect of phonon on spin current transport is yet to be elucidated. In this study, we measured the nlSSE as a function of the magnetic field H, temperature T, and the sample dimensions and clarified the role of phonons in the spin current transport.

The sample comprises of two separate Pt strips patterned on a magnetic insulator yttrium iron garnet ($Y_3Fe_5O_{12}$: YIG) substrate. Two Pt strips operate as a spin current injector and detector. When the current is applied to the injector, the Joule heat excites magnons in the YIG by the SSE. The excited magnons propagate in the YIG and generate a voltage across the detector by the inverse spin Hall effect.

We measured V_{nlSSE} across the detector. V_{nlSSE} reverses its sign with the H direction, consistent with the expected symmetry of the nlSSE. At $\mu_0 H$ = 2.5 T, a clear dip-like structure appears in the H dependence of V_{nlSSE}, which is caused by the mixed magnon-phonon modes known as magnon-polarons. We explain the sharp structures in the nlSSE by the magnon chemical potential model including the effect of magnon-polaron formations in a material with high acoustic quality [3].

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Geometric Phase Switching in Mesoscopic Rings

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The geometric (Berry) phase acquired by an electron in a cyclic evolution depends strongly on the topology of the driving fields. An oscillating field in the adiabatic limit does not result in a Berry phase in contrast to a rotating field that gives a Berry phase of $\boldsymbol{\pi}$. Therefore a huge change in the geometric phase can be achieved with a relatively small change in the driving field via topological switching. This idea of a Berry phase switch was recently demonstrated in graphene resonators [1].

We consider here theoretically topological geometric phase switching in quasi-two-dimensional mesoscopic ring systems where the geometric phase is of *nonadiabatic* (Aharonov-Anandan) type of geometric phase. The ring system is either circular or polygonal (Fig. 1a). The driving field results from interplay between Bychov-Rashba and Dresselhaus [001] spin-orbit (SO) and in-plane magnetic fields. A prominent feature in resistance emerging in such a complex effective field is anisotropic resistance with respect to in-plane field direction.

We find that the topological transition of the effective geometric phase [2] is imprinted both in the resistance as well as in anisotropy oscillations (Fig. 1b). In circular rings the characteristic jumps in the anisotropy pattern emerge at low Dresselhaus fields (Fig. 1c). In calculations we use 1D models and 2D transport simulations using the Kwant code.

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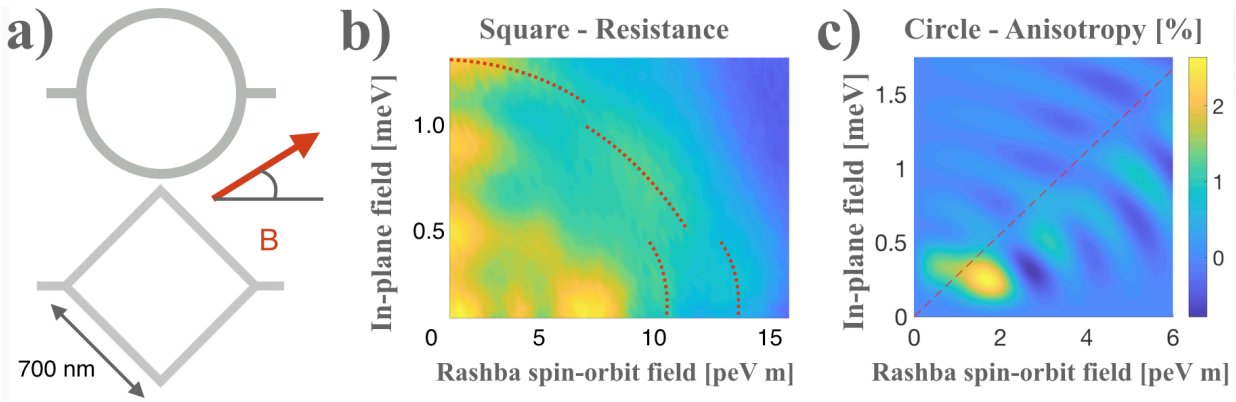

Fig. 1. Circular and square quantum rings (a). The geometric phase switching manifests as jumps in the interference pattern of resistance (b) and anisotropy (c).

Spin Hall Magnetoresistance in antiferromagnet/Pt heterostructures

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We investigate the impact of the anisotropy and the domain pattern on the spin Hall magnetoresistance in antiferromagnet/Pt bilayers. Our results suggest that experiments close to the Neel temperature of the antiferromagnetic layer allow to study the individual phases of the antiferromagnet already with comparably small magnetic fields due to the thermally activated exchange.

By rotating the magnetic field in three mutually orthogonal rotation planes, we establish the fingerprint of the spin Hall magnetoresistance also in antiferromagnet/Pt heterostructures, giving further insights into the impact of the anisotropy and the domain pattern. We furthermore highlight the limitations of the monodomainization model put forward recently in conjunction with measurements on NiO/Pt heterostructures [1,2] and discuss an alternative approach to explain the negative SMR signature.

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Light scattering by magnons in whispering gallery mode cavities

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Brillouin light scattering (BLS) spectroscopy is an established tool to study the elementary excitations (or quasiparticles) of a solid state system. It involves Stokes and anti-Stokes scattering of light, which is due to creation or destruction of quasiparticles respectively. In materials which interact strongly with light, this can also be a source of manipulating the quasiparticles. Such a manipulation can be enhanced by confining light in a cavity to increase the interaction time. Coupling of an optical cavity to quantas of sound waves, called phonons, is very well studied in the framework of cavity optomechanics. In contrast, coupling of light in cavities to magnons, which are elementary excitations of a magnetic structure, is an emerging field dubbed as cavity optomagnonics, with the first experiments done just a few years ago [1-3]. Its importance stems from several useful properties of magnons in magnetic insulators, for example Yttrium Iron Garnet (YIG), such as low damping, GHz frequencies and strong coupling to other systems with microwaves, electrons and phonons. A remarkable aspect of BLS via magnons is a pronounced and controllable asymmetry between the Stokes and anti-Stokes scattering. For a strong enough optomagnonic interaction, this gives an experimental knob to control the number of magnons. We theoretically study an example of a YIG sphere acting as a whispering gallery mode (WGM) cavity, a system which is being actively studied in experiments now. We discuss how to quantify and calculate the optomagnonic coupling in this case, investigating the physical mechanism behind the experimentally discovered huge asymmetry in Stokes and anti-Stokes scattering [4].

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Microscopic derivation of spin diffusion equation: A Green's function approach

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It has been widely accepted that the spin diffusion equation successfully describes the spin transport phenomena in a number of materials. So far, it has been derived from a phenomenological Bloch equation with diffusion [1], a simple kinetic equation with detailed balance [2,3], and a Boltzmann equation [4]. Nevertheless, in view of extending its derivation into a more complicated situation involving many-body effects, it is of great importance to derive it on the basis of many-body theoretical method.

Here, we present how to derive the spin diffusion equation by means of Green's function technique. Using the general relation [5] between the response function (spin susceptibility in the present case) and the relaxation function (Green's function for the spin diffusion equation in the present case), we derive the spin diffusion equation microscopically. Our formalism can naturally be applied to a situation that inevitably involves many-body effects.

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Magnon spin-Hall magnetoresistance of a gapped quantum paramagnet

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Motivated by recent experimental work[1] we consider spin transport between a normal metal and a gapped quantum paramagnet. We model the latter as the magnonic Mott-insulating phase[2] of an easy-plane ferromagnetic insulator. We evaluate the spin current mediated by the interface exchange coupling between the ferromagnet and the adjacent normal metal (see Fig. 1). For the strongly interacting magnons that we consider, this spin current gives rise to a spin-Hall magnetoresistance that strongly depends on the magnitude of the magnetic field, rather than its direction. This work may motivate electrical detection of the phases of quantum magnets and the incorporation of such materials into spintronic devices.

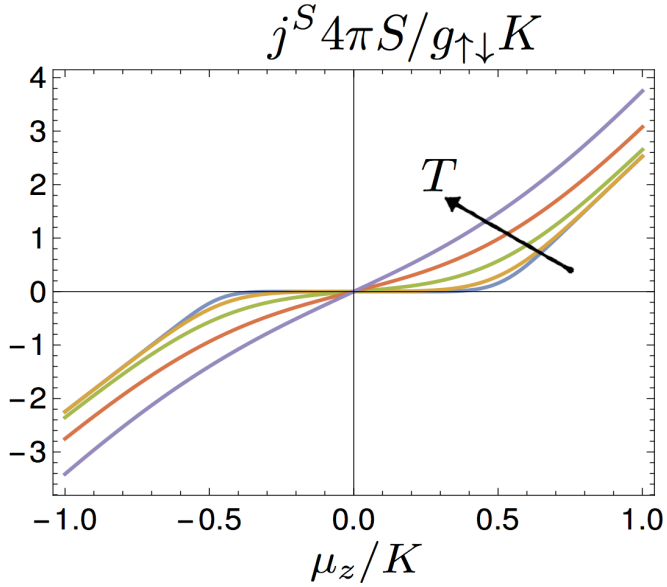

Fig. 1. Interface spin current as a function of spin accumulation for different values of the temperature. The temperatures go from kBT /K = 0.005 (blue) to kBT/K=2 (purple), where K is the anisotropy of the system.

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Microscopic spin transport theory for coupled electron-magnon systems

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In spintronics, mutual conversion between electric and spin currents is of central interest for the application of spin current. This process enables us to detect the spin current as an electrical signal, as well as to transmit information without electric current. Magnons are a good candidate whose spin current can be utilized in the future technological applications [1]. Therefore, it is important to study the interplay of conduction electrons and magnons from the viewpoint of spin transport.

There have been some experiments and theories on the interplay between conduction electrons and magnons. Experimentally, magnon-drag thermoelectric effects were observed in Fe [2], NiCu [3] and NiFe [4]. Theoretically, these effects have been studied phenomenologically [5,6] and microscopically [7]. On the other hand, in the microscopic study of magnonic spin torque under the influence of conduction electrons, the effects of vertex corrections are known to play important roles [8]. However, such delicate effects have not been considered so far for transport phenomena.

We study spin transport phenomena in a coupled electron-magnon system based on a microscopic model. We calculate magnonic, electric and heat currents by considering vertex corrections. For the treatment of a temperature gradient, we use Luttinger's method introducing gravitational potential [9]. Comparison with the phenomenological analysis is also made.

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Transport properties of antiferromagnetic Dirac quasi-particles

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We study the influence of changes in band structure topology on transport properties in antiferromagnetic Dirac nodal-line semimetals. In certain PT symmetric antiferromagnetic materials, such as CuMnAs, protected anti-crossings occur when the Neel vector is oriented along a crystallographic high-symmetry axis [1]. By an explicit computation for a model tight-binding Hamiltonian, we demonstrate that the metal-insulator phase transition mediated by the rotation of Neel vector manifests itself in a strong orientation dependence of charge and spin conductivity. Both crystalline and non-crystalline components of the anisotropies become enhanced due to the interplay between the s-d exchange and a strong spin-orbit interaction. This represents an extreme example of spin transport control via spin-orbit interactions.

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Spin Seebeck effect in simple ferromagnets near T_c: A Ginzburg-Landau approach

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A new spin injection phenomenon termed spin Seebeck effect has been attracting considerable attention as a versatile method for spin current generation simply by means of temperature bias [1]. So far, it has been understood that thermally-excited magnons play a central role in this phenomenon [2]. This viewpoint is now being challenged by a new experimental finding that studied the spin Seebeck effect in yttrium iron garnet near its transition temperature T_c [3]. In Ref. [3], it was reported that the spin Seebeck signal shows a power low behavior [signal $\sim (T_c - T)^3$] near T_c, whereas the subsequent numerical simulation concluded that a different behavior [signal $\sim (T_c - T)^{1/2}$] is expected if we rely on a simple magnon picture [4].

In this work we present the result of a simple Ginzburg-Landau approach to this problem. We found that, for a simple ferromagnet with only one sublattice, the same result as concluded in Ref. [4], i.e., signal $\sim (T_c - T)^{1/2}$, is derived. This result suggests that it is important to consider the ferrimagnetic nature of yttrium iron garnet in order to account for the experiment [3].

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Logic-in-Memory Approach toward Universal Magnonic Computation via Synthetic Antiferromagnets

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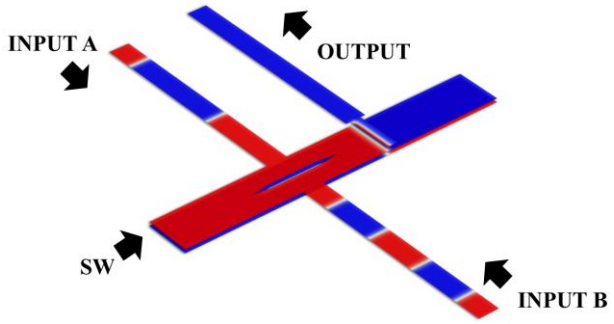
Spin waves (SW), or magnons are promising candidate as information carrier. The binary information is usually encoded into the amplitude, phase or frequency of spin waves. However, the polarization degree of freedom of spin waves can be harnessed in antiferromagnets (or synthetic antiferromagnets). The polarization of spin waves can be fully manipulated by antiferromagnetic domain walls (DW) as spin-wave polarizer and retarder. Furthermore, the antiferromagnetic domain wall motion depends on the polarization of injecting spin waves. In this work, we propose a logic-in-memory architecture by combining the spin-wave polarizer/retarder and the domain wall racetrack memory. Assisted by the polarized SWs, the DW racetrack memory can perform universal computation and store the information at the same time. The logic-in-memory device is in non-Von-Neumann structure with low dissipation (without CMOS), high speed (~GHz) and strong extendibility.



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Skyrmion diffusion in Ta-based material with perpendicular magnetic anisotropy.

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Magnetic skyrmions are topologically protected spin-structures emerging in materials with a broken inversion symmetry. They have been found bulk materials, as well in thin film multilayer systems of different compositions, where they are stabilized by the Dzyaloshinskii-Moryia interaction [1]. Skyrmion dynamics at room temperature has been frequently studied lately, as the possible applications of skyrmions include novel devices like the racetrack memory and the use in neural networks [2]. Recent findings show the dependence of skyrmion velocity on the driving current density in a thin nanowire as well as the occurrence of the skyrmion Hall effect [3], [4]. Also, the generation of larger skyrmion bubbles, to be able to observe by conventional MOKE microscopy, has been recently shown [5], [6]. However, the used material stacks need a rather significant external field for skyrmion nucleation and the goal, to get stable skyrmions at zero field, is yet to be achieved. In this contribution, we have studied a Ta-based material similar to the stack investigated by Yu et al. [7], engineered to exhibit perpendicular magnetic anisotropy (PMA) at room temperature. Worm domains and skyrmions are formed depending on the stack composition and the external magnetic field, with a very low coercive field of about 0.5 mT. Similar to the findings of Jiang et al. [5], we observe the generation of skyrmions with an out-of-plane field, where the skyrmions are moving with an external bias pulse applied, concluding to be N=1 skyrmion. The skyrmions move in the direction of the current pulses uniformly without any skyrmion Hall angle observed. With in-plane field sweeping, a skyrmion lattice is formed, where with electric pulsing skyrmion bubbles expand or contract, which is predicted for N=0 skyrmions. This means that there might be a transition between the two topological states in this material. The focus of this contribution is however the observation of skyrmion movement even without the application of external electric pulses. After nucleation, skyrmions exhibit diffusive dynamics to a diffusive behavior. The reason of these motions are thermal excitations, as there is a strong dependence of the skyrmion velocities on temperature visible. We tracked the trajectories of skyrmions and investigated the dependence of their mean-square-displacement (MSD). In conclusion, the skyrmions exhibit a very linear dependence of MSD over time and can be considered as rigid particles with diffusive behavior. The dependence of their diffusion parameter on their size and temperature was further investigated.

[1] R. Tomasello *et al.*, *Sci. Rep.* **4**, p. 6784 (2014).
[2] A. Fert, V. Cros, and J. Sampaio, Nat. Nanotechnol. **8**, pp. 152–156 (2013).
[3] S. Woo et al., Nat. Commun. **8**, p. 15573 (2017).
[4] K. Litzius et al., Nat. Phys. **13**, p. 170–175 (2017).
[5] W. Jiang et al., Science **349**, pp. 283–286 (2015).
[6] G. Chen, A. Mascaraque, A. T. N'Diaye, and A. K. Schmid, Appl. Phys. Lett. **106**, p. 242404 (2015).
[7] G. Yu et al., Nano Lett. **16**, pp. 1981–1988 (2016).

New Excitations in Spintronics Workshop Time Table

start	January 10 (Wed)	January 11 (Thu)	January 12 (Fri)	January 13 (Sat)	January 14 (Sun)
8:30	Registration	Yuasa		Zao Satellite	
9:00	Opening (Maekawa & Takanashi)	Adachi	Yu		
9:30	Hillebrands	Duine	Niimi		
10:00	Seki	Jungwirth	Rogge		
10:30	Usami	Coffee break			
11:00	Coffee break	Kläui	Satoh		
11:30	van Wees	Coey	McClarty		
12:00	Han	Fukami	Goennenwein		
12:30	van der Sar	Xiao	Kikkawa		
13:00	Registration	Lunch break			
13:30					
14:00					
14:30	Hashimoto	Mizukami	Žutić		
15:00	Kakurai	Blanter	Kohno		
15:30	Shiomi	Klein	Murakami		
16:00	Coffee break				
16:30	Tsymbal	Kampfrath	Nagaosa		
17:00	Xia	Otani	Nambu		
17:30	Shirai	Mizuguchi	Tatara		
18:00					
18:30					
19:00		Conference dinner			
Posters up all time					