Spin Mechanics 4

February 20th – 25th, 2017

Fairmont Chateau Lake Louise

Alberta, Canada

Organizing Committee:

Prof. Mark Freeman, University of Alberta
Prof. Can-Ming Hu, University of Manitoba
Joseph Losby, University of Alberta
Vincent Sauer, University of Alberta
Mika Terada, IMR, Tohoku University

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Canada Research Chairs
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Canadä

The 39th Reimei Workshop of the
Advanced Science Research Center (ASRC),
JAEA , Japan

Dear Participants,

Welcome to Spin Mechanics 4! Following invigorating meetings in Japan and Germany, the University of Alberta and University of Manitoba are honoured to host SM 4 in Canada, nestled in the magnificent Rocky Mountains of Banff National Park. We are especially happy to welcome you here during our nation's 150th anniversary! This workshop brings together leading researchers working on all different perspectives of spin mechanics which we hope will stimulate further progress in the understanding and control of coupled spin-mechanical-optical-electronic systems.

The program for SM 4 will include 2 keynote addresses, 30 invited oral presentations and nearly 60 posters. In addition 3 tutorial talks will lay a foundation of knowledge for non experts, enabling cross pollination of ideas between the subfields of spin mechanics. There is also ample time set aside for discussion sessions in the inspiring setting of a natural UNESCO World Heritage Site.

We look forward to a week of inspiring scientific discussion and we wish you a rewarding and fruitful experience at SM 4.

On Behalf of the SM 4 Organizing Committee.

Prof. Mark Freeman

Prof. Can-Ming Hu

Conference Logistics

Venue

- All events are located in the Mt. Temple Wing.
- **The Registration desk** is in Mt. Temple Ballroom Foyer.
- **Oral presentations** will take place in the Mt. Temple Ballroom "A".
- **The Poster Session and Round Tables** will be held in Mt. Temple Ballroom "B".
- **Meals** will be held in the Lago Restaurant.

Fairmont Chateau Lake Louise
111 Lake Louise Dr, Lake Louise, AB T0L 1E0
http://www.fairmont.com/lake-louise/

Outdoor Activities:

Some Outdoor Activities at SM4 The rocky mountains boast a myriad of outdoor activities, including skating, snowshoeing and of course skiing. Equipment rentals are available in Chateau Mountain Sports located next to the front desk lobby. Some outdoor wear is also available, such as snow boots, ski jackets and pants. More information on the equipment available and prices is available at:

http://www.chateaumountainsports.com/rentalinformation/

Some options include:

- **Skating on Lake Louise**

Located right outside Chateau Lake Louise, skating on Lake Louise offers spectacular views of Victoria Glacier and the Rocky Mountains. Two hour and full day rentals are available ($13/$16) and hockey stick rentals are also an option (for use on an additional rink near Nordic shop).

- **Snowshoeing and Cross Country Skiing**

A variety of snowshoeing and cross country skiing trails are available starting just outside Chateau Lake Louise. More information can be found on the Parks Canada website:

goo.gl/0aq3F7

Two hour and full day rentals ($15/$20) are available for snowshoes with various rental lengths available for cross country skis.

- **Downhill Skiing/Snowboarding**

Lake Louise ski resort is a 15 minute drive from Chateau Lake Louise with half and full day ($81/$99) as well as multi-day lift tickets available. Ski rentals are available at Chateau Lake Louise or the ski resort and a complimentary shuttle is provided by Chateau Lake Louise. More information can be found at:

http://www.skilouise.com/

Transportation:

The Fairmont Chateau Lake Louise is easily reached by shuttle service (request pick up at Chateau Lake Louise)

http://www.brewster.ca/transportation/brewster-banff-airport-express/

or

rental car from Calgary International Airport http://www.yyc.com/.

Detailed information can be found on the Fairmont Chateau Lake Louise's website. The conference rate for self parking is $15 CAD/day. Please note that self-parking rate will appear as $30/day when you make your reservation, but the $15/day contracted rate will apply at the time of payment.

Shuttle

Calgary - Canmore - Banff - Lake Louise - Jasper

Depart Calgary Downtown	-	-	10:50	-	-	-	14:35	-	17:35	-
Depart Calgary Intl Airport	8:30	9:30	-	11:30	13:00	14:00	15:30	17:15	18:30	22:00
Depart Kananaskis Village	-	-	-	-	13:30	-	16:00	-	19:00	-
Depart Stoney Nakoda Resort	-	-	-	-	14:10	-	16:40	-	19:40	-
Depart Canmore	9:50	10:50	-	12:50	14:20	15:20	16:50	18:35	19:50	23:20
Arrive Banff	10:15	11:15	12:20	13:15	14:45	15:45	17:15	19:00	20:15	23:45
Depart Banff to Jasper				13:30						
Depart Banff to Sunshine Village				14:00	15:15	16:30	18:00	19:30	20:45	
Depart Banff to Lake Louise	11:00	12:00	13:00	14:00	15:15	-	17:45	19:30	20:45	
Arrive Sunshine Village				14:35	15:50	17:05	18:35	20:05	21:00	
Arrive Lake Louise	11:45	12:45	14:00	15:00	16:15	-	18:45	20:30	21:45	-
Arrive Jasper				17:30						

Jasper - Lake Louise - Banff - Canmore - Calgary

Depart Jasper to Banff				7:00					
Depart Lake Louise	6:15	-	8:15	10:15	-	12:15	14:00	15:30	17:15
Depart Sunshine Village		8:00	9:00	11:00		12:15	14:30		17:00
Arrive Banff	7:30	-	9:30	11:30	-	13:30	15:15	16:15	18:30
Depart Banff	8:00	9:00	10:00	12:00	13:00	14:00	15:45	17:15	19:30
Depart Canmore	8:25	9:25	10:25	12:25	13:25	14:25	16:10	17:40	19:55
Depart Kananaskis Village	8:00	-	-	12:00	-	-	-	-	-
Depart Stoney Nakoda Resort	8:35	-	-	12:35	-	-	-	-	-
Arrive Calgary Intl Airport	9:45	10:45	11:45	13:45	14:45	15:45	17:30	19:00	21:45
Arrive Calgary Downtown	10:15	-	-	14:15	-	16:15	18:00	-	21:00

Schedule

2017
Monday, Feb 20
Tuesday, Feb 21
Wednesday, Feb 22
Thursday, Feb 23
Friday, Feb 24
Saturday, Feb 25
6 AM
7 AM
8 AM
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10 AM
11 AM
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1 PM
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6 PM
7 PM
8 PM
9 PM
10 PM
11 PM
6:00 PM Dinner
7:30 PM Welcome Reception
6:30 AM Breakfast
8:00 AM Chudnovsky
9:06 AM Barclay
Break
10:12 AM Schliesser
10:48 AM Balestro
11:24 AM Maekawa
12:00 PM Lunch
1:00 PM Informal Discussions
5:30 PM Poster Session
7:15 PM Dinner
8:30 PM LIGO Detector
9:15 PM LIGO Experiment
10:00 PM LIGO Reception
6:30 AM Breakfast
8:00 AM Gönnenwein
9:06 AM Sinova
Break
10:12 AM Kläui
10:48 AM Kovalev
11:24 AM Silva
12:00 PM Lunch
1:00 PM Informal Discussions
5:30 PM Saitoh
6:06 PM Åkerman
6:42 PM Hammel
7:30 PM Dinner
6:30 AM Breakfast
8:00 AM Clerk
9:06 AM Flatté
Break
10:12 AM Bai
10:48 AM You
11:24 AM Tobar
12:00 PM Lunch
1:00 PM Informal Discussions
2:00 PM Chien
2:36 PM Buchanan
3:12 PM Jungwirth
3:48 PM Poster Session
4:54 PM Jayich
5:30 PM Davis
6:06 PM Sankey
8:00 PM Banquet
6:30 AM Breakfast
8:00 AM Roukes
9:06 AM Budakian
Break
10:12 AM Braakman
10:48 AM Hübl
11:24 AM Klein
12:00 PM Lunch
1:00 PM Informal Discussions
5:30 PM Lupton
6:06 PM Jander
6:42 PM Pigeau
7:30 PM Dinner
6:30 AM Breakfast
8:00 AM Tang
8:36 AM Serga
9:12 AM Blanter
Break
10:12 AM Nakamura
10:48 AM Bauer
Concluding Remarks
12:00 PM Lunch

Program

Monday (Feb 20, 2017)	
18:00-	*Dinner*
19:30-21:00	*Welcome reception*

Tuesday (Feb 21, 2017)	
6:30-7:50	*Breakfast*

Session I Spin mechanics, optomechanics, magnetic (7:50-12:00)

Chairperson: Mark Freeman

7:50-8:00	*Welcome and opening remarks*
8:00-9:06	*Keynote Address* **Spin-Rotation Coupling: One Hundred Years After Einstein de Haas and Barnett Experiments** Eugene M. Chudnovsky The City University of New York
9:06-9:42	*Invited talk* **Nanophotonic optomechanical devices: towards coupling photons, phonons and spins** Paul Barclay University of Calgary
9:42-10:12	*Nutrition Break*
10:12-10:48	*Invited talk* **Hybrid quantum systems with ultrahigh-Q nanomechanical resonators** Albert Schliesser Niels Bohr Institute
10:48-11:24	*Invited talk* **Quantum Einstein de Haas Effect Studied With Molecular Spintronic Devices** Franck Balestro Institute Néel, CNRS, Grenoble

11:24-12:00	*Invited talk* **Mechanical Effects on Spintronics** Sadamichi Maekawa Advanced Science Research Center, Japan Atomic Energy Agency
12:00-13:00	*Lunch*
13:00-17:30	*Informal discussions*
17:30-19:15	*Poster session*
19:15-20:30	*Dinner*
20:30-22:00	*Special LIGO session*
22:00-23:00	*LIGO reception – with LLWI*

Wednesday (Feb 22, 2017)

6:30-8:00	*Breakfast*

Session II Spin orbit coupling, DMI (8:00-12:00)

Chairperson: Zhu Diao

8:00-9:06	*Tutorial talk* **Spintronics** Sebastian T. B. Göennenwein Walther Meissner Institute, Bavarian Academy of Sciences
9:06-9:42	*Invited talk* **Topological antiferromagnetic Spin-orbitronics** Jairo Sinova Johannes Gutenberg University, Mainz
9:42-10:12	*Nutrition Break*

10:12-10:48	*Invited talk*	

10:12-10:48 *Invited talk*

Spin-orbit coupling in ferro- and antiferromagnets

Mathias Kläui
Johannes Gutenberg University, Mainz

10:48-11:24 *Invited talk*

Magnon-mediated Dzyaloshinskii-Moriya torques, heat pumping, and spin Nernst effect

Alexey Kovalev
University of Nebraska - Lincoln

11:24-12:00 *Invited talk*

Evidence for a common origin of spin-orbit torque and the Dzyaloshinskii-Moriya interaction at a Py/Pt interface

Thomas J. Silva
National Institute for Standards and Technology

12:00-13:00 Lunch

13:00-14:00 Informal discussions

Session III Spin mechanics, optomechanics, magnetic (17:50-19:18)

Chairperson: Joe Losby

17:30-18:06 *Invited talk*

Fluid and mechanical spintronics

Eiji Saitoh
Tohoku University

18:06-18:42 *Invited talk*

Long-range mutual synchronization of spin torque and spin Hall nano-oscillators

Johan Åkerman
University of Gothenburg

18:42-19:18 *Invited talk*

Spin transport by collective spin excitations

P. Chris Hammel
The Ohio State University

19:30-21:00 *Dinner*

Thursday (Feb 23, 2017)

6:30-8:00	*Breakfast*

Session IV Cavity mediated magnons (8:00-12:00)

Chairperson: John Q. Xiao

8:00-9:06	*Tutorial talk* **Quantum-limited and backaction evading measurements in optomechanics** Aashish Clerk McGill University
9:06-9:42	*Invited talk* **The quantum limit of interacting magnetic waves** Michael Flatté University of Iowa
9:42-10:12	*Nutrition Break*
10:12-10:48	*Invited talk* **Photon mediated non-local manipulation of spin current using microwave cavity** Lihui Bai University of Manitoba
10:48-11:24	*Invited talk* **Magnon Kerr effect in a cavity quantum electrodynamics system** Jian-Qiang You Beijing Computational Science Research Center
11:24-12:00	*Invited talk* **High-Q and Novel Cavity Structures for Photon-Spin Strong Coupling** Michael Tobar University of Western Australia
12:00-13:00	*Lunch*
13:00-14:00	*Informal discussions*

Session V Novel devices, switching (14:00-15:48)

Chairperson: Joseph Barker

14:00-14:36 *Invited talk*

Zero-field current switching of a single ferromagnetic layer

Chia-Ling Chien
Johns Hopkins University

14:36-15:12 *Invited talk*

Spin dynamics of a magnetic antivortex

Kristen Buchanan
Colorado State University

15:12-15:48 *Invited talk*

Electrical switching of an antiferromagnet

Tomas Jungwirth
Academy of Sciences of the Czech Republic & University of Nottingham

15:48-16:24 Poster session

Session VI Spin mechanics, optomechanics, magnetic (16:54-18:42)

Chairperson: Vincent Sauer

16:54-17:30 *Invited talk*

Mechanics and spins in diamond

Ania C. Bleszynski Jayich
University of California Santa Barbara

17:30-18:06 *Invited talk*

Cavity-Optomechanical Torque Sensors

John Davis
University of Alberta

18:06-18:42 *Invited talk*

"Trampoline" mechanical resonators for ultrasensitive force detection and optomechanics (plus some spin transfer)

Jack Sankey
McGill University

20:00-22:00 *Banquet*

Friday (Feb 24, 2017)

6:30-8:00	*Breakfast*

Session VII Spin mechanics, optomechanics, magnetic (8:00-12:00)

Chairperson: Wayne Hiebert

8:00-9:06	*Tutorial talk* **Perspectives on nano mechanics, past, present and future** Michael Roukes California Institute of Technology
9:06-9:42	*Invited talk* **Force-detected magnetic resonance imaging and spectroscopy using silicon nanowire mechanical resonators** Raffi Budakian University of Waterloo
9:42-10:12	*Nutrition Break*
10:12-10:48	*Invited talk* **Nanowire force microscopy and dynamic cantilever magnetometry** Floris Braakman University of Basel
10:48-11:24	*Invited talk* **Frequency tuning and coherent dynamics of nanostring resonators** Hans Huebl Walther Meissner Institute, Bavarian Academy of Sciences
11:24-12:00	*Invited talk* **Dynamical dipolar coupling in pairs of 25 nm thick YIG nano-disks** Olivier Klein SPINTEC, CEA-Grenoble
12:00-13:00	*Lunch*
13:00-14:00	*Informal discussions*

Session VIII Novel devices, switching (17:30-19:18)

Chairperson: Jacob Burgess

17:30-18:06	*Invited talk*
	Coherent spin physics in OLEDs
	John Lupton University of Regensburg
18:06-18:42	*Invited talk*
	Non-degenerate parametric pumping of spin waves by acoustic waves
	Albrecht Jander Oregon State University
18:42-19:18	*Invited talk*
	Hybrid quantum optomechanics
	Benjamin Pigeau Institute Néel, CNRS, Grenoble
19:30-21:00	*Dinner*

Saturday (Feb 25, 2017)

6:30-8:00	*Breakfast*

Session IX Cavity mediated magnons (8:00-12:00)

Chairperson: Can-Ming Hu

8:00-8:36	*Invited talk*
	Cavity Electrodynamics of Magnons
	Hong X. Tang Yale University
8:36-9:12	*Invited talk*
	Accumulation of hybrid magneto-elastic quasi-particles in a ferrimagnet
	Alexander Serga Technical University of Kaiserslautern

9:12-9:48	*Invited talk*
	Cavity Optomagnonics
	Yaroslav M. Blanter Kavli Institute of Nanoscience, Delft University of Technology
9:48-10:12	Nutrition Break
10:12-10.48	*Invited talk*
	Quantum magnonics in a ferromagnetic sphere
	Yasunobu Nakamura University of Tokyo
10:48-11:54	*Keynote Address*
	Spin Mechanics with YIG
	Gerrit E. W. Bauer Tohoku University
11:54-12:00	*Concluding Remarks*
12:00-13:00	*Lunch*
13:00-	*Departure*

Poster session

P01 Optomechanics with hybrid carbon nanotube resonators

Alexandros Tavernarakis, Adrian Bachtold, Alex Nowak, Alexandros Stavrinadis and Pierre Verlot

P02 Study of interactions between elastic, spin and electromagnetic waves in elastic continuum

Miro Belov and Mark Freeman

P03 Kittel-like spin dynamic investigations in a mono-crystalline YIG microdisk

Fatemeh Fani Sani, Joe E. Losby , Miro Belov, Doug Vick , and Mark R. Freeman

P04 Silicon nitride trampoline resonators for spin polarization via resonant spin-mechanics coupling

Ran Fischer, Cindy Regal, Gabriel Assumpcao, Nir Kampel,Robert Peterson, Thomas Knief and Yiheng Lin

P05 Nonreciprocal reconfigurable microwave optomechanical circuit

Alexey Feofanov, Nathan Bernier,Daniel Toth, Akshay Koottandavida, Andreas Nunnenkamp and Tobias Kippenberg

P06 A dissipative quantum reservoir for microwave light using a mechanical oscillator

Alexey Feofanov,Andreas Nunnenkamp, Daniel Toth, Nathan Bernier and Tobias Kippenberg

P07 Light scattering by magnons in whispering gallery mode cavities

Sanchar Sharma, Gerrit E. W. Bauer and Yaroslav M. Blanter

P08 Momentum as the Fundamental Basis of Quantum Superposition

Jonathan Sharp

P09 Cryogenic Optomechanical Torque Sensor

Bradley Hauer, Paul Kim, Callum Doolin, Fabien Souris and John Davis

P10 Coupled Spin-Light dynamics in Cavity Optomagnonics

Silvia Viola Kusminskiy, Florian Marquardt and Hong X. Tang

P11 Shape Memory Alloys in Hybrid Spintronic Devices

Andreas Becker and Andreas Hütten

Ka Shen, Benedetta Flebus, Gerrit E. W. Bauer and Rembert Duine

P22 Polarization-selective coupling between cavity microwave photon and magnon

Yongsheng Gui, Jinwei Rao, Bimu Yao, Sandeep Kaur, Yutong Zhao, Can-Ming Hu

P23 Spin dynamical phase and antiresonance in a strongly coupled magnon-photon system

Michael Harder, Paul Hyde, Lihui Bai, Christophe Match, and Can-Ming Hu

P24 Towards Quantum Magnonics

Richard Morris, Arjan van Loo, Alexy Karenowska and Sandoko Kosen

P25 Optomagnonics in Magnetic Solids

Tianyu Liu, Hong X. Tang, Michael Flatté and Xufeng Zhang

P26 Characterization of backward volume spin waves in microstructured waveguides for the mechanical detection of the magnon angular momentum

Moritz Geilen, Burkard Hillebrands, Joe Losby, Mark Freeman, Philipp Pirro and Thomas Meyer

P27 Revealing of decaying spin waves as the main source of heating in spin transfer torque driven Heusler-Pt waveguides

Thomas Meyer, Alexander Serga, Burkard Hillebrands, Frank Heussner, Hiroshi Naganuma, Koki Mukaiyama, Mikihiko Oogane, Philipp Pirro, Thomas Brcher and Yasuo Ando

P28 Non-local magnetoresistance by magnon transport in the magnetic insulators yttrium iron garnet and gadolinium iron garnet

Nynke Vlietstra, Hans Huebl, Kathrin Ganzhorn, Rudolf Gross, Sebastian T. B. Göennenwein and Stephan Geprägs

P29 Voltage control of cavity magnon polariton

Bimu Yao, Sandeep Kaur, Yongsheng Gui, Jinwei Rao, Can-Ming Hu

P30 Sensitively imaging magnetization structure and dynamics using picosecond laser heating

Jason Bartell, Colin Jermain, Daniel Ralph, Fengyuan Yang, Gregory Fuchs, Jack Brangham, Jonathan Karsch and Sriharsha Aradhya

P31 Spin-Mechanical Inertia in Antiferromagnet

Ran Cheng, Xiaochuan Wu and Di Xiao

P32 Non-integral-spin magnons in untextured magnets

Invited Talks

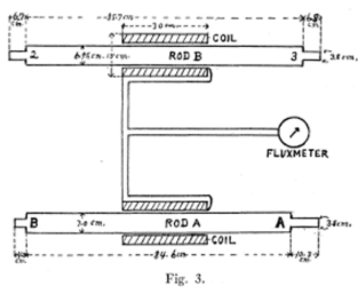
Spin-Rotation Coupling: One Hundred Years After Einstein de Haas and Barnett Experiments

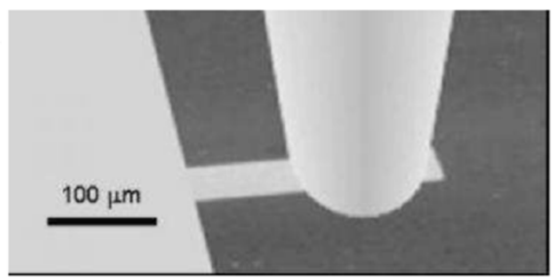
Tue
21 Feb
8:00-9:06

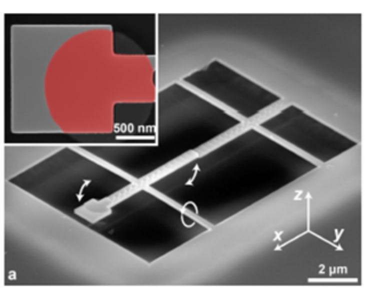
Eugene M. Chudnovsky

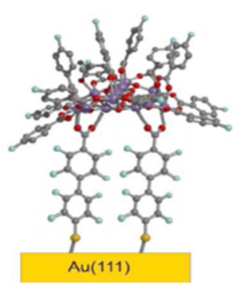
Department of Physics and Astronomy, Herbert H. Lehman College, The City University of New York, 250 Bedford Park Boulevard West, Bronx, New York 10468-1589, USA

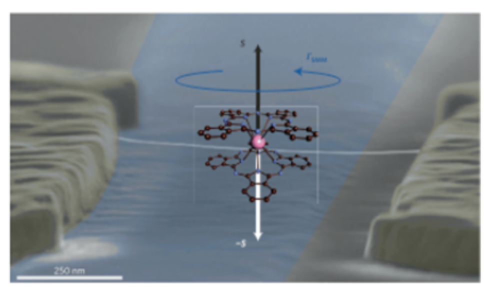
Century-long studies of spin-rotation coupling will be reviewed, starting with Einstein - de Haas and Barnett experiments, and ending with modern-time experiments on torsional nano-oscillators and quantum Einstein de Haas effect in magnetic molecules chemisorbed on surfaces and grafted on carbon nanotubes. Open questions related to microscopic mechanisms of the conservation of the total angular momentum in solids will be discussed.











Tue
21 Feb.
9:06-9:42

Nanophotonic optomechanical devices: towards coupling photons, phonons and spins

Paul Barclay

Department of Physics and Astronomy & Institute for Quantum Science and Technology, University of Calgary, Calgary, AB, T2N 1N4, Canada

Optomechanical devices enhance the optical radiation pressure induced interaction between light and mechanical resonators. This interaction can be harnessed to enable coherent conversion of light to mesoscopic phonons with frequencies ranging from kHz to GHz. Through control of these phonons, new approaches for manipulating and probing solid state spin systems are feasible.

In this talk I will present recent advances in creating such nanoscale "spin-optomechanical" devices. I will first present results demonstrating some of the first optomechanical devices fabricated from single crystal diamond [1, 2], which in addition to having remarkable mechanical properties (e.g. ultrahigh mechanical Q*f product), can be used for optomechanical control of single electron spins. I will then discuss silicon based nanophotonic devices that allow optomechanical probing of the magnetic properties of nanostructures, providing routine on-chip photonic readout of the nanomagnetic susceptibility of single magnetic defects [3]. Finally, I will comment on the prospect of cooling these devices into their quantum ground state, enabling studies coupling single phonons to electronic or magnetic spin systems.

References

[1] B. Khanaliloo, H. Jayakumar, A. C. Hryciw, D. Lake, H. Kaviani, P. E. Barclay, "Single crystal diamond nanobeam waveguide optomechanics," Physical Review X 5, 041051 (2015)
[2] M. Mitchell, B. Khanaliloo, D. Lake, P. E. Barclay, "Low-dissipation cavity optomechanics in single crystal diamond," Optica 3, 963 (2016)
[3] M. Wu, N. L.-Y. Wu, T. Firdous, F. F. Sani, J. E. Losby, M. R. Freeman, P. E. Barclay, "Nanocavity optomechanical torque magnetometry and RF susceptometry," Nature Nanotechnology (Advanced Online Publication, doi:10.1038/nnano.2016.226, 2016)

Hybrid quantum systems with ultrahigh-Q nanomechanical resonators

Tue
21 Feb
10:12-10:48

Albert Schliesser

Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, Denmark

We report a multimode optomechanical system with quantum cooperativity $C_q = 4g^2/\kappa\gamma >> 1$ already at moderate cryogenic temperature $T \sim 10$ K [1]. Here, $\gamma = k_B T/\hbar Q$ is the quantum decoherence rate of the mechanical system, and $Q \sim 10^7$ the mechanical quality factor. In this regime, the quantum backaction of the optical measurement dominates over the thermal Langevin noise. As a consequence, optical measurements create quantum correlations between the optical and mechanical degrees of freedom, which are measured as ponderomotive squeezing (-2.4 dB) of the light emerging from the cavity. In the multimode setting investigated here, we observe optically-induced hybridisation of mechanical modes, and the generation of squeezed light by hybrid modes [1].

Furthermore, we have implemented a hybrid system by combining this optomechanical system with a room-temperature atomic ensemble [2]. A light beam probes the spin state through Faraday interaction, and subsequently the motion of the nanomechanical membrane. We show that it is possible to cancel part of the measurements quantum backaction by appropriately tailoring the light-spin, and subsequent light-mechanical interaction.

Finally, we report on the development of a novel type of membrane and string resonators with dramatically reduced decoherence [3]. By patterning a phononic crystal directly into a stressed SiN membrane we realise a soft clamp for a localised defect mode. Its engineered mode shape exhibits reduced curvature and therefore dissipation, reaching room-temperature Qf-products in excess of 10^{14} Hz the highest reported to date as well as $Q \sim 10^9$ at $T \sim 4$ K. The corresponding room temperature coherence time approaches that of optically trapped dielectric particles, and for cryogenic operation becomes comparable ($\sim$1 ms) to that of trapped ions. Extensive characterisation through laser-based imaging of mode shapes [3] and stress distribution [4] confirms a model that quantitatively predicts the quality factors over a wide parameter range.

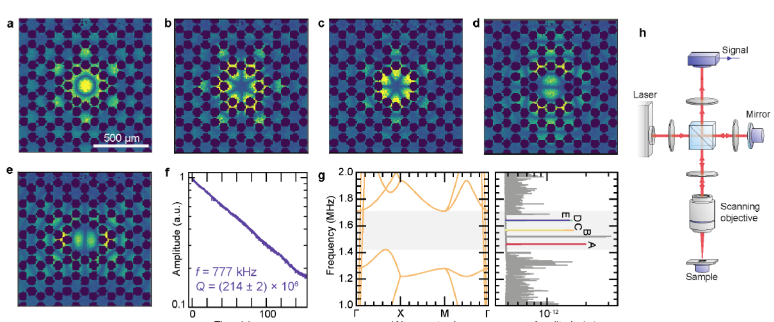


Fig. 1 a)-e) Displacement patterns of soft-clamped, ultra-coherent modes in a stressed SiN membrane with phononic patterning [3]. (f) Room-temperature ringdown of the 'E' mode, yielding Q = 214 · 10⁶ and Q f = 166 THz. (g) Left, simulated band diagram of the phononic pattern, with a quasi-bandgap in the MHz region. Right, Thermal displacement noise spectrum, which confirms the presence of the bandgap, as well as the five defect modes A-E (grey peak is for calibration). (h) Simplified schematic of the scanning-laser interferometry setup, with which the images and spectra were obtained [4]

References

[1] W. H. P. Nielsen, Y. Tsaturyan, C. B. Mller, E. S. Polzik, and A. Schliesser, PNAS 114, 62 (2017).
[2] C. B. Mller, R. A. Thomas, G. Vasilakis, E. Zeuthen, Y. Tsaturyan, K. Jensen, A. Schliesser, K. Hammerer and E. S. Polzik, arXiv:1608.03613
[3] Y. Tsaturyan, A. Barg, E. S. Polzik, and A. Schliesser, arXiv:1608.00937
[4] A. Barg, Y. Tsaturyan, E. Belhage, H. P. W. Nielsen, C. B. Mller, and A. Schliesser, Applied Physics B 123, 8 (2017).
[5] T. Capelle, Y. Tsaturyan, A. Barg, and A. Schliesser, in preparation.

Quantum Einstein de Haas Effect Studied With Molecular Spintronic Devices

Tue
21 Feb
10:48-11:24

Marc Ganzhorn[1], Svetlana Klyatskaya[2], Mario Ruben[2], F. Balestro[1] and Wolfgang Wernsdorfer[2]

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One hundred years ago it has been discovered that a change of magnetization in a macroscopic magnetic object results in a mechanical rotation of this magnet[1]. The effect, known as Einstein de Haas or Richardson effect, demonstrates that a spin angular momentum in the magnet compensates for the mechanical angular momentum associated with its rotation. The experiment is therefore a macroscopic manifestation of the conservation of total angular momentum and energy in eletronic spins. According to Noether's theorem, conservation of angular momentum follows from a system's rotational invariance and would be valid for the ensemble of spins in a macroscopic ferromagnet as well as for an individual spin. It has been recently proposed that single spin systems would therefore manifest an Einstein de Haas effect at the quantum level[1].

Here we propose the first experimental realization of a quantum Einstein-de Haas experiment and describe a macroscopic manifestation of the conservation of total angular momentum in individual spins, using a single molecule magnet coupled to a nanomechanical resonator. We demonstrate that the spin associated with the single molecule magnet is then subject to conservation of total angular momentum and energy which results in a total suppression of the molecules quantum tunneling of magnetization[3].

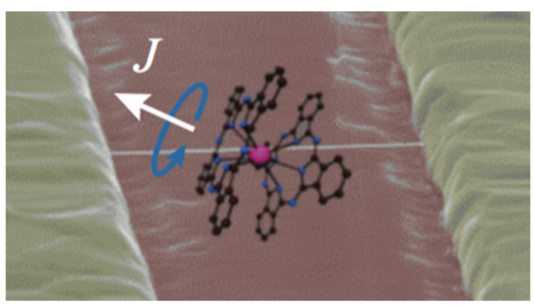

Figure: For the quantum Einstein-de Haas experiment, the false color scanning electron micrograph shows a suspended carbon nanotube with a local metallic backgate (red) functionalized with a $TbPc_2$ single molecule magnet. Due to conservation of the total angular momentum, the magnetization reversal of J = 6 (white arrow) in a magnetic field results in a rotation of the single molecule magnet (blue arrow), thus generating a quantized phonon mode in the carbon nanotube nanoelectromechanical resonator.

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Mechanical Effects on Spintronics

Tue
21 Feb
11:24-12:00

Sadamichi Maekawa

The Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan

We introduce mechanical effects on spintronics [1] and propose a variety of novel spintronics phenomena [2]. In particular, the coupling between nuclear spin and mechanical rotation is demonstrated [3]. Since the Bernett field is enhanced by three orders of magnitudes in nuclei more than electron spins, the nuclear-magnetic-resonance (NMR) with mechanical rotation introduces new applications. In addition to the Bernett effect, the mechanical rotation induces the spin-Berry phase which gives rise to additional resonance phenomena in NMR [4].

We observe the generation of spin current by the flow of liquid metals. Combining this effect with the inverse spin Hall effect, the spin-hydrodynamic generation of electricity is obtained [5].

The coupling between mechanical motion and a variety of spins may be identified as a quantum version of the Einstein-de Haas effect and Bernett effect discovered in 1915.

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Tue
21 Feb
19:30-21:00

LIGO Detector & Gravitational Waves at LIGO (experiment)

Szabolcs Marka & Imre Bartos
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The after dinner session on Tuesday will feature two talks from the LIGO collaboration. The session is joint with the Lake Louise Winter Institute, a particle physics meeting being held simultaneously at the Fairmont Chateau Lake Louise. The first speaker, Prof. Szabolcs Marka, will focus on the LIGO detector (20:30 - 21:15). The second talk, by Dr. Imre Bartos, will discuss the observations of gravitational waves (21:15 - 22:00).

Much early work in cavity optomechanics and quantum-limited sensing was inspired by the goal of a gravitational wave detector. The success of LIGO makes it a compelling point of contact between our two workshops. Both speakers in this special session hail from Columbia University.

Spintronics

Wed
22 Feb
8:00-9:06

Sebastian T. B. Göennenwein

Institut für Festkörperphysik, Technische Universität Dresden, D-01062 Dresden, Germany,
and
Center for Transport and Devices of Emergent Materials, Technische Universität Dresden, D-01062 Dresden

The performance of modern electronic devices hinges on the transport, storage, amplification and/or detection of electronic charge. In close analogy, one can also envisage transporting, storing, sensing or amplifying spin angular momentum, taking advantage of spin-polarized charge currents or even pure spin currents. In general terms, the field of spintronics addresses the physics and the properties of structures featuring spin-based functionality. The tutorial shall give an introduction to spintronics and spin transport from an experimentalists perspective. I will discuss basic concepts behind charge and spin current transport, and address the interconversion between charge and spin currents based on spin Hall physics. The main focus of the tutorial will then be on spintronic devices and spin current transport-related phenomena.

Wed
22 Feb
9:06-9:48

Topological Antiferromagnetic Spin-orbitronics

Jairo Sinova

Institut für Physik, Johannes Gutenberg Universität Mainz, 55128 Mainz, Germany

Antiferromagnetic spintronics considers the active manipulation of the antiferromagnetic order parameter in spin-based devices. An additional concept that has emerged is that antiferromagnets provide a unifying platform for realizing synergies among three prominent fields of contemporary condensed matter physics: Dirac quasiparticles and topological phases. Here spintronic devices made of antiferromagnets with their unique symmetries will allow us to control the emergence and to study the properties of Dirac/Weyl fermion topological phases that are otherwise principally immune against external stimuli. In return, the resulting topological magneto-transport phenomena open the prospect of new, highly efficient means for operating the antiferromagnetic memory-logic devices. We discuss how these topological phases emerge and how their robustness depend on the relative orientation of the Neel order parameter that can be manipulated by Neel spin-orbit torques. If time allows, we will further discuss the generation and excitation of skyrmionic textures in simple geometries.

Spin - orbit coupling in ferro- and antiferromagnets

Wed
22 Feb
10:12-10:48

Mathias Kläui

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The coupling of the mechanical lattice degree of freedom to the spin system by spin-orbit effects gives rise to a range of exciting mechanisms that can be key enablers for future low power GreenIT devices.

The three main challenges that need to be met concern the stability of spin structures, their efficient manipulation and finally the low loss transport of spin information [1].

So firstly to obtain ultimate stability, topological spin structures that emerge due to the Dzyaloshinskii-Moriya interaction (DMI) at structurally asymmetric interfaces, such as chiral domain walls and skyrmions with enhanced topological protection can be used [2-4]. We have investigated in detail their dynamics and find that it is governed by the topology of their spin structures [3]. By designing the materials, we can even obtain a skyrmion lattice phase as the ground state of the thin films [3].

Secondly, for ultimately efficient spin manipulation in ferromagnets and antiferromagnets, we use spin-orbit torques, that can transfer more than 1 per electron by transferring not only spin but also orbital angular momentum. We combine ultimately stable skyrmions with spin orbit torques into a skyrmion racetrack device [3], where the real time imaging of the trajectories allows us to quantify the novel skyrmion Hall effect [4].

Finally to obtain efficient spin transport, we study the coupling between phonons and magnons in ferro- and antiferromagnetic insulators that can be used as spin conduits for long distance spin transport [5]. We establish that both, bulk and interface effects play a key role and together govern the measured spin transport signals in ferro-, ferri- and antiferromagnetic compounds [5,6]

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Wed
22 Feb
10:48-11:24

Magnon-mediated Dzyaloshinskii-Moriya torques, heat pumping, and spin Nernst effect

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[2]Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA

We predict that a temperature gradient can induce a magnon-mediated spin Hall response in a collinear antiferromagnet with Dzyaloshinskii-Moriya interactions [1]. We have developed a linear response theory based on the Luttinger approach of the gravitational scalar potential which gives a general condition for a Hall current to be well defined, even when the thermal Hall response is forbidden by symmetry. We applied our theory to honeycomb lattice antiferromagnet and studied a role of magnon edge states in a finite geometry. As examples, we considered single and bi-layer honeycomb antiferromagnets where the nearest neighbor exchange interactions and the second nearest neighbor Dzyaloshinskii-Moriya interactions were present. From our analysis, we suggest to look for the magnon-mediated spin Nernst effect in insulating antiferromagnets that are invariant under (i) a global time reversal symmetry or under (ii) a combined operation of time reversal and inversion symmetries. In both cases, the thermal Hall effect is zero while the spin Nernst effect can be present. We have also considered transport of magnons and its relation to non-equilibrium magnon-mediated spin torques [2]. In particular, a temperature gradient can induce a magnon-mediated intrinsic torque in systems with broken inversion symmetry and spin-orbit interactions. With the help of a microscopic linear response theory of nonequilibrium magnon-mediated torques and spin currents we identify the interband and intraband components that manifest in ferromagnets with Dzyaloshinskii-Moriya interactions. To illustrate and assess the importance of such effects, we have applied the linear response theory to the magnon-mediated Nernst and torque responses in a kagome and honeycomb lattice ferromagnets. With the help of Onsager reciprocity principle we establish a connection to magnon-mediated contribution to Dzyaloshinskii-Moriya interactions. We suggest that magnons can lead to temperature dependence in Dzyaloshinskii-Moriya interactions. Finally, in a system with broken inversion symmetry and spin-orbit interactions we predict the magnon-mediated heat and spin pumping by magnetization precession.

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Evidence for a common origin of spin-orbit torque and the Dzyaloshinskii-Moriya interaction at a Py/Pt interface

Wed
22 Feb
11:24-12:00

Thomas J. Silva[1], Alexy Karenowska[2], Andrew Berger[1], Eric Edwards[1], Hans Nembach[3], Justin Shaw[1], Mathias Weiler[4]

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Harnessing spin-charge conversion through current-driven spin torques and spin precession-driven charge currents is widely regarded as a key for the development of scalable and efficient spintronic devices. These conversion processes occur across ferromagnet/normal metal (FM/NM) interfaces where there is strong spin-orbit coupling (SOC) but where details of the underlying physics are still much debated. SOC also underlies the interfacial Dzyaloshinskii-Moriya interaction (DMI). While efficient spin-charge conversion and large DMI often coincide, a causal connection between these two phenomena has not yet been experimentally established. It was recently proposed that a Rashba Hamiltonian operative at a FM/NM interface gives rise to both spin-orbit torques (SOT) and DMI, such that the presence one effect implies the other [1]. Despite the complexity of interfacial spin interactions, this theory provides a simple, testable quantitative relation between the DMI and SOT. Here, we use a powerful new microwave spectroscopy method to detect inverse spin-charge conversion processes in FM/NM bilayers [2] and demonstrate that the magnitude of the SOT is in good agreement with the theoretically-predicted value based on the previously measured value of DMI in identical bilayers [3].

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Wed
22 Feb
17:30-18:06

Fluid and mechanical spintronics

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and Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan.

Spin current refers to a flow of electrons spin angular momentum in condensed matter, which is detectable by using the inverse spin Hall effect. Various phenomena induced by spin currents, such as spin-transfer torque and spin Seebeck effects have been discovered so far. Here I will give an introduction to phonon anomaly in spin Seebeck effects, spin current generated in a classical fluid, and spinon spin current generated in a quantum spin liquid state.

Long-range mutual synchronization of spin torque and spin Hall nano-oscillators

Wed
22 Feb
18:06-18:42

Johan Åkerman

NanOsc AB, SE-Kista 164 40, Sweden
Department of Materials and Nanophysics, School of Information and Communication Technology, KTH Royal Institute of Technology, Electrum 229, SE-16440 Kista, Sweden
Department of Physics, University of Gothenburg, SE-412 96, Gothenburg, Sweden

In this talk I will discuss our most recent advances in synchronizing both nano-contact spin torque oscillators (NC-STOs) and spin Hall nano-oscillators (SHNOs). The synchronization of NC-STOs [1-3] is mediated by propagating spin waves (SWs), which, under the influence of the local Oersted field, form SW beams. Not only have we recently demonstrated the robust synchronization between two oscillators separated by over 1 micron, but also the driven synchronization of up to five oscillators by purposefully taking advantage of such SW beams [1]. More recently, a new breed of nanoscale magnetic oscillator, which rely on the transverse spin currents generated by the spin Hall effect, have emerged. Our particular SHNO device geometry relies on a nano-constriction [2] to focus the spin currents and stabilize auto-oscillations. By carefully considering the importance of the applied field angle we have demonstrated the robust synchronization of up to nine serially connected SHNOs [3]. The mutual synchronization is observed both as a strong increase in the power and coherence of the electrically measured microwave signal. The mutual synchronization is also optically probed using scanning micro-focused Brillouin light scattering microscopy (μ-BLS), providing the first direct imaging of synchronized nano-magnetic oscillators. Through tailoring of the region connecting two SHNOs, we are able to extend the synchronization range to 4 m. Given the design flexibility of nano-constriction SHNOs, and the very long synchronization range, we argue that our results open up many research and application opportunities where coherent phase locking is believed to be advantageous, e.g. for energy efficient spin wave computing on the nanoscale.

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Wed
22 Feb
18:42-19:18

Spin Transport by Collective Spin Excitations

P. Chris Hammel

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We report studies of angular momentum transport and magnetic dynamics in diverse insulating materials. We have shown that spin transport is exponentially suppressed by insulating diamagnetic barriers, but we find that collective spin excitations in various materials can enable robust spin transport in insulators. We present studies that reveal efficient spin transport in Yttrium Iron Garnet (YIG) even in the presence of magnetic-field defined barriers that require inter-conversion between magnons of dissimilar energy. Optical detection of Ferromagnetic Resonance (FMR) in YIG by means of nitrogen-vacancy (NV) defect centers in diamond reveals the role of spin waves in this dipole-mediated spin transfer process and presents a powerful approach to broadband, spatially resolved FMR detection for these and related studies. We find that fluctuating antiferromagnetic (AF) spin correlations also enable efficient spin transport having decay lengths approaching 10 nm in insulating antiferromagnets. While the spin decay length increases with the strength of the AF correlations, AF magnon spin transport is robust against the absence of long-range order. This research performed in collaboration with F.Y. Yang, V.P. Bhallamudi, C.H. Du, R. Adur, H.L. Wang, C.S. Wolfe, A.J. Berger and S.A. Manuilov, and is supported by the U.S. DOE through Grant DE-FG02-03ER46054, by the NSF MRSEC program through Grant 1420451 and by the Army Research Office through Grant W911NF-16-1-0547.

Quantum-limited and backaction evading measurements in optomechanics

Thu
23 Feb
8:00-9:06

Aashish Clerk

Department of Physics, McGill University, Montreal QC, Canada

In this tutorial-style talk, I'll give an introduction to various aspects of how quantum mechanics constrains measurements in optomechanics. Among the topics I'll cover include the formal definition of the quantum limit on continuous position measurement, techniques for beating the "standard" quantum limit, and back-action evading measurement strategies. Time permitting, I will end by discussing our recent work on two-mode backaction evading measurements and connections to autonomous feedback protocols (i.e. "reservoir engineering") for stabilizing entangled mechanical (or magnonic) states.

Thu
23 Feb
9:06-9:42

The quantum limit of interacting magnetic waves

Michael Flatté

Optical Science and Technology Center and Department of Physics and Astronomy,
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The dynamic response of magnetic materials lacks time-reversal symmetry and can often be described through the propagation and evolution of waves of magnetic orientation, or spin waves. These spin waves, or magnons when quantized, can move without electric charge motion, yet spin-orbit interactions allow the spin waves to couple, sometimes very strongly, both to voltages and to illumination. I will describe progress over the last several years in calculating and understanding, in collaboration with experimentalists, the coupling of magnons to microwave[1,2] and optical photons[3] as well as the manipulation of spin-wave propagation with a voltage[4]. In analogy with optomechanics, two photons will interact, within a cavity containing a ferrite, with a magnon mode to coherently modify the spontaneous emission rate, to exhibit electromagnetically-induced transparency and even to reach the strongly-coupled quantum regime[3]. Patterned magnetic media can also amplify voltage-dependent effects to produce voltage-tunable oscillators or filters[5].

Recently we have predicted a new effect called nonlocal magnon drag, whereby a flow of magnons in one sheet will drag magnons in a neighboring, disconnected sheet[6]. The presence of the magnetization in the two sheets introduces a twist in the drag, producing a transverse spin current. As a final example, we predict that quantum-coherent spin centers can sense the magnetic susceptibility of nearby materials, distinct from the magnetization of the material itself, and so this provides a potential method of detecting superconductors or magnetic dead layers without applied magnetic fields[7].

Work supported in part by ONR, AFOSR, DARPA, and NSF.

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Photon mediated non-local manipulation of spin current using microwave cavity

Thu
23 Feb
10:12-10:48

Lihui Bai[1], Michael Harder[1], Paul Hyde[1], Zhaohui Zhang[1], Y. P. Chen[2], John Q. Xiao[2] and Can-Ming Hu[1]

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As a strongly coupled magnon-photon system, the cavity-magnon-polariton (CMP) offers many potential applications for information processing. Typically such information processing applications would require manipulation of the energy exchange between the magnon and photon subsystems which, in a CMP system, relies on the cooperativity and can therefore be easily controlled. However in order to measure the extent of such an exchange, the spin subsystem must be locally detected. This obstacle can be overcome through electrical detection techniques. In our work we have combined electrical detection via the spin pumping effect with microwave transmission measurements in order to locally detect both the individual photon and spin subsystems of the CMP in a system comprised of one microwave cavity mode and two magnetic samples. Through controlling the cooperativity of one magnetic sample, while locally detecting another, we demonstrate a non-local spin current manipulation mediated by the cavity mode. We have demonstrated such a non-local spin current manipulation over a spatial separation up to 38 mm (limited only by the cavity size), which is orders of magnitude longer than either the spin coherence or diffusion length in materials. Therefore our work demonstrates the capability of strong spin-photon coupling for long range spin current manipulation, which we expect to play an important role in the development of cavity spintronics.

Thu
23 Feb
10:48-11:24

Magnon Kerr effect in a cavity quantum electrodynamics system

Jian-Qiang You

Quantum Physics and Quantum Information Division, Beijing Computational Science Research Center, Beijing 100193, China

We report the experimental demonstration of the magnon Kerr effect in a cavity quantum electrodynamics system, where magnons in a small yttrium iron garnet (YIG) sphere are strongly but dispersively coupled to the microwave photons in a three-dimensional cavity. When considerable magnons are generated by pumping the YIG sphere, the Kerr effect gives rise to a shift of the cavity central frequency and yields more appreciable shifts of the magnon modes, including the Kittel mode (i.e., the ferromagnetic resonance mode), which holds homogeneous magnetization, and the magnetostatic (MS) modes, which have inhomogeneous magnetization. We derive an analytical relation between the magnon frequency shift and the pumping power for a uniformly magnetized YIG sphere and find that it agrees very well with the experimental results of the Kittel mode. In contrast, the experimental results of MS modes deviate from this relation owing to the spatial variations of the MS modes over the sample. To enhance the magnon Kerr effect, the pumping field is designed to directly drive the YIG sphere and its coupling to the magnons is strengthened using a loop antenna. Moreover, this field is tuned very off-resonance with the cavity mode to avoid producing any appreciable effects on the cavity. Our work is the first convincing study of a cavity QED system with magnon Kerr effect and paves the way to experimentally explore nonlinear effects in the cavity QED system with magnons.

High-Q and Novel Cavity Structures for Photon-Spin Strong Coupling

Thu
23 Feb
11:24-12:00

Michael Tobar

ARC Centre of Excellence for Engineered Quantum Systems, University of Western Australia, 35 Stirling Highway, Crawley, Western Australia, 6009, Australia

Strong coupling between microwave photons and spins at millikelvin temperatures is necessary to realise quantum information processing. We will present our most recent results in coupling strongly to a variety of cavity and spin systems. Novel cavity systems include whispering gallery modes, 3D lumped element meta-structures based on the reentrant cavity and dielectric TE modes. Spin systems include paramagnetic iron group and rare-earth impurities doped in low-loss crystalline materials (such as YSO, YAP and Silicon), P1 centers in diamond and magnons in ferrimagnetic YIG.

In particular we will focus on new cavities, which couple photons and magnons in YIG spheres in a super- and ultra-strong way at around 20 mK in temperature. Few/Single photon couplings (or normal mode splitting, 2g) of more than 7 GHz at microwave frequencies are obtained for a 15.5 GHz mode. Types of cavities include multiple post reentrant cavities, which co-couple photons at different frequencies with a coupling greater that the free spectral range, as well as spherical loaded dielectric cavity resonators. In such cavities we show that the bare dielectric properties can be obtained by polarizing all ferromagnetic effects and magnon spin wave modes to high energy using a 7 Tesla magnet. We also show that at zero-field, collective effects of the spins significantly perturb the photon modes. Other effects like time-reversal symmetry breaking are observed.

Thu
23 Feb
14:00-14:36

Zero-field current switching of a single ferromagnetic layer

Chia-Ling Chien

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Spin Hall effect (SHE) switching allows current switching of a single ferromagnetic (FM) layer in contact with a heavy metal (HM), where the pure spin current from the HM switches the adjacent FM layer via the spin orbit torque (SOT). However, this highly attractive scheme cannot occur unless a magnetic field is also applied along the current direction, or with some built-in asymmetry in the structure, thus greatly diminishing its utility. In this work, we describe the essential role of the magnetic field, which not only breaks geometrical symmetry and but also causes asymmetrical domain wall motion that accomplishes switching. More importantly, we demonstrate a new method of exploiting competing SOT by exploiting HMs with opposite spin Hall angles, different Dzyaloshinskii-Moriya interaction constants, and competing pure spin current. We describe the intricate physics that accomplishes current switching of a single ferromagnetic layer in zero magnetic field.

Spin dynamics of a magnetic antivortex

Thu
23 Feb
14:36-15:12

Kristen S. Buchanan
Department of Physics, Colorado State University, Fort Collins, CO, USA

Topological spin textures in patterned magnetic nanostructures including magnetic vortices and skyrmions are currently attracting a great deal of attention because they exhibit a variety of interesting properties, especially in the dynamic regime. The magnetic antivortex, the topological counterpart of a vortex that involves spins that sweep in from two opposite sides (e.g. the top and bottom) and out toward the other two (e.g., left and right), has received much less attention, in part because it is more difficult to stabilize. Here, we investigate the dynamic behavior of a magnetic antivortex stabilized at the intersection of orthogonal microstrips made of Permalloy using a combination of micro-focus Brillouin light scattering (micro-BLS) and micromagnetic simulations. The simulations show a rich dynamic response that includes analogs of the gyrotropic, azimuthal, and radial modes of a magnetic vortex. Additional complexities are, however, observed due to coupling between the antivortex excitations and propagating spin waves in the attached microstrips. We have detected several of these modes by micro-BLS [1]. A comparison of measurements made with an antivortex vs. a saturated spin configuration at the intersection shows that intersection spin state can be used to influence the mode structure in the microstrips, which suggests new possibilities for spin wave manipulation and generation.

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Thu
23 Feb
15:12-15:48

Electrical switching of an antiferromagnet

Tomas Jungwirth

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Louis Néel pointed out in his Nobel lecture that while abundant and interesting from theoretical viewpoint, antiferromagnets did not seem to have any applications. Indeed, the alternating directions of magnetic moments on individual atoms and the resulting zero net magnetization make antiferromagnets hard to control by tools common in ferromagnets. Strong coupling would be achieved if the externally generated field had a sign alternating on the scale of a lattice constant at which moments alternate in antiferromagnets. However, generating such a field has been regarded unfeasible, hindering the research and applications of these abundant magnetic materials. We will discuss a recent prediction that relativistic quantum mechanics may offer a staggered current induced field whose sign alternates within the magnetic unit cell. The staggered spin-orbit field can facilitate a reversible switching of an antiferromagnet with comparable efficiency to the switching of ferromagnets by conventional uniform magnetic fields. We will then discuss suitable antiferromagnetic materials and a demonstration of the complete writing/storage/readout functionality in PC compatible demonstrator device. The absence of dipolar fields in the zero net moment antiferromagnets allows for a multiple-stability of the memory states that are invisible to magnetic probes and robust against external magnetic field perturbations. Moreover, antiferromagnets have ultra-fast internal spin dynamics, opening the prospect of picosecond timescales for switching, both in the coherent single domain regime and by ultra-fast domain wall motion.

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Mechanics and spins in diamond

Thu
23 Feb
16:54-17:30

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Single crystal diamond mechanical resonators are a promising platform for hybrid quantum systems comprising spins and phonons. Diamond mechanical resonators exhibit exceptionally high quality factors and diamond plays host to a highly coherent atomic-scale spin system: the nitrogen vacancy (NV) center. Through its strain sensitivity, the NV can be coupled coherently to a mechanical degree of freedom. We have characterized the strain sensitivity of the NV centers ground state spin, as well as its optical transitions. Through strain coupling, we show that mechanical control of individual spins in diamond is possible. These results are encouraging for proposals to use such a spin-mechanical platform for spin-squeezing, phonon-mediated spin-spin interactions, and phonon cooling of macroscopic mechanical resonators. We discuss the necessary steps needed to reach these goals and current progress including improvements in diamond fabrication, NV formation, and readout techniques.

Thu
23 Feb
17:30-18:06

Cavity-Optomechanical Torque Sensors

John Davis
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Reducing the moment of inertia improves the sensitivity of a mechanically-based torque sensor, the parallel of reducing the mass of a force sensor, yet the correspondingly small displacements can be difficult to measure. To resolve this, we incorporate cavity optomechanics, which involves co-localizing an optical and mechanical resonance. With the resulting enhanced readout, cavity-optomechanical torque sensors are now limited only by thermal noise. Further progress requires thermalizing such sensors to low temperatures, where sensitivity limitations are instead imposed by quantum noise. By cooling a cavity-optomechanical torque sensor to 25 mK, we have demonstrated a torque sensitivity of 2.9 yNm $Hz^{-1/2}$. At just over a factor of ten above its quantum-limited sensitivity, such cryogenic optomechanical torque sensors will enable both static and dynamic measurements of integrated samples at the level of a few hundred spins.

"Trampoline" mechanical resonators for ultrasensitive force detection and optomechanics (plus some spin transfer)

Thu
23 Feb
18:06-18:42

Jack Sankey

Department of Physics, McGill University, Montral, Quebec, H3A 2T8 Canada

Mechanical systems are ubiquitous throughout society, from oscillators in timekeeping devices to accelerometers and electronic filters in automobiles and cell phones. They also comprise an indispensable set of tools for fundamental and applied science: using tiny mechanical elements, for example, it is possible to "feel around" surfaces at the atomic scale, and using human-scale masses, LIGO currently "listens" to gravitational waves emitted by violent events across the universe. In the field of optomechanics, we have exploited the forces exerted by radiation to gain a new level of control over these systems at all size scales.

In this talk I will discuss our recent efforts to create pristine mechanical sensors and manipulate/enhance them with laser light. We have fabricated nanogram-scale "trampolines" having extremely low damping parameters (ringing for six minutes when struck) and record low force sensitivities (below 20 attonewtons at room temperature). These trampolines also have excellent optical properties and are well-suited for optomechanical applications. Of note, the combined mechanical and optical parameters will provide access to a regime in which an extraordinarily small amount of light – at the level of a single photon – exerts a profound influence over the trampoline's trajectory. I will discuss progress toward optically levitating these (and related) devices to further improve their performance, discuss progress toward realizing a new and weird type of optomechanical interaction wherein light strongly influences the geometry and mass of a mechanical mode.

I will finish by briefly discussing an unrelated project to couple spin-transfer-controlled nanoscale magnetic circuits to atom-like defects in single-crystal diamond.

Fri
24 Feb
8:00-9:06

Perspectives on nano mechanics, past, present and future

Michael Roukes
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USA

Force-detected magnetic resonance imaging and spectroscopy using silicon nanowire mechanical resonators

Fri
24 Feb
9:06-9:42

Raffi Budakian

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Magnetic resonance imaging (MRI) has had a profound impact on biology and medicine. Key to its success has been the unique ability to combine imaging with nuclear magnetic resonance spectroscopy, a capability that has led to a host of powerful modalities for imaging spins. Although it remains a significant challenge, there is considerable interest to extend these powerful spectroscopic and imaging capabilities to the nanometer scale. In this talk, I will discuss a new platform for force-detected magnetic resonance detection that allows us to bring many aspects of NMR spectroscopy to the nanometer scale. In particular, I will focus on the development of optimal control theory (OCT) pulses that incorporate average Hamiltonian theory and realize high fidelity unitary operations. I will present recent results demonstrating the use of OCT-based line narrowing pulse sequences that suppress the dipolar evolution and increase the spin coherence time of proton spins in polystyrene at 4 K by a factor of 500, from 11 s to 6 ms. This advance has allowed us to image proton spins in one dimension with 2-nm spatial resolution. More generally, through the use of OCT pulses, we now have the ability to perform high-resolution NMR spectroscopy on nanometer scale nuclear spin ensembles.

Fri
24 Feb.
10:12-10:48

Nanowire Force Microscopy and Dynamic Cantilever Magnetometry

Floris Braakman[1], Andrea Mehlin[1], Anna Fontcuberta i Morral[2], Arne Buchter[1], Boris Groß[1], Daniel Rüffer[2], Davide Cadeddu[1], Denis Vasyukov[1], Dennis Weber[1], Dirk Grundler[2], Dong Liang[1], Fei Xue[1], Gözde Tütüncüoglu[2], Martino Poggio[1], Matthew Stolt[3], MingLiang Tian[4], Nicola Rossi[1], and Song Jin[3]

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We describe the use of grown nanowires (NWs) as scanning directional force sensors. By virtue of slight asymmetries in geometry, a NW's flexural modes are split into doublets which oscillate along two orthogonal axes. By monitoring the frequency shift and direction of oscillation of both modes as we scan the NW above a surface, we construct a map of all in-plane tip-sample force derivatives. This capability, combined with the exquisite force sensitivity of NW sensors, allows for a type of atomic force microscopy especially suited to measuring the size and direction of weak tip-sample forces [1]. Due to their geometry, NWs are well-suited as scanning probes, when arranged in the pendulum geometry, i.e. with their long axis perpendicular to the sample surface. They can be grown in a variety of sizes and from different materials, allowing access to a wide range of mechanical frequencies and spring constants. Furthermore, NWs can be grown as heterostructures, making it possible to incorporate elements such as quantum dots. We present measurements of the vectorial electrostatic field of a sample with multi-edged gate electrodes and distinguish two different types of tip-sample forces. These results demonstrate the potential of NWs as highly tunable mechanical resonators that can be used as functional elements in a new type of scanning force microscopy.

The detection of magnetic moments of individual nanoscale particles presents an additional experimental challenge. Here, we present measurements of nanometer-scale magnets based on sensitive mechanical detection of magnetic torque: dynamic cantilever magnetometry (DCM) [2]. With the use of ultrasensitive cantilevers, DCM allows us to collect information on the saturation magnetization, anisotropy, switching behavior, and magnetic phases. We discuss DCM measurements of the magnetic skyrmion phase in MnSi nanowires [3] and in $GaVa_4S_8$, which supports a Néel-type skyrmion phase. We also show results from experiments on ferromagnetic nanotubes [2, 3], interesting because of their potential flux-closure ground state at low applied magnetic fields. Using this technique, we were able to detect the entrance of vortices at the NT ends, nucleating the magnetization reversal. These features correspond well with micromagnetic simulations of the NT reversal process, showing that our samples can be described as idealized ferromagnetic NTs.

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Fri
24 Feb
10:48-11:24

Frequency tuning and coherent dynamics of nanostring resonators

Hans Hübl

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Individual micro- and nanomechanical elements are extensively studied due to their importance in force and mass sensing applications, while resonator networks are key for the investigation of coupling physics and synchronization effects.

In my talk I will discuss both cases: (i) utilizing the nanostring for sensing the magnetoelastic coupling constant of a magnetic thin and (ii) frequency control of a nanostring resonator network.

Sensing requires that the mechanical properties of the vibrational element are altered by an external stimulus and thus become encoded in its resonance frequency and damping rate. In other words the property of interest has to couple to the mechanical degree of freedom. Here, the magnetostriction present in the in thin magnetic film modifies the total stress in the bilayer nanostring based on the magnetic film and a silicon nitride layer and hereby changes the resonance frequency of its fundamental vibrational mode. This allows for a quantitative determination of the magnetostriction constant of the magnetic material. I will discuss the measurement techniques as well as the sensitivity of the sensing platform.

Nanomechanical resonator networks are ideal candidates for the investigation of strong coupling physics, synchronization, non-linear dynamics. Furthermore, they are discussed for all-mechanical information processing and quantum storage platforms. All of these applications, however, require the possibility to tune the relevant mode frequencies independently and to operate the resonators in the strong coupling regime. I will discuss how the fundamental mode frequencies of both nanostrings can be tuned independently using a strong drive tone resonant with one of the higher harmonic modes. This tuning concept relies on an effective increase of the pre-stress in a highly excited nanobeam, known as geometric nonlinearity. With the two nanobeams tuned in resonance, we observe coherent excitation exchange between the fundamental modes of the two nanostrings corresponding to Rabi oscillations of a quantum two-level systems. In addition, experimental investigation of classical Landau-Zener dynamics demonstrates that this coupling and tuning concept paves the way for a selective phonon transfer between two spatially separated mechanical resonators.

Dynamical dipolar coupling in pairs of 25 nm thick YIG nano-disks

Fri
24 Feb
11:24-12:00

Olivier Klein[1], G. de Loubens[2], N. Beaulieu[2,3], Y. Li[2], V. V. Naletov[1,4], L. Vila[1], J. Ben Youssef[3]

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In the past years, ultra-thin films of Yttrium Iron garnet ($Y_3Fe_5O_{12}$, YIG) have become highly desirable in the context of magnonics [1] and its coupling to spintronics [2]. Due to its record low damping ($\alpha = 3\times10^{-5}$ in bulk), YIG is the magnetic material of choice to propagate and manipulate spin-waves. Having YIG films with thickness down to a few tens of nanometers is important to enhance interfacial effects with an adjacent metallic layer, e.g. to reach sizable spin-orbit torques at a YIG—Pt interface [3]. It is also required to pattern those films by standard nanofabrication techniques, e.g. to engineer the spin-wave spectrum of individual nanostructures [4]. Nanometer thick epitaxial YIG films with excellent dynamical quality (α down to 2×10^{-4}) have recently been grown by pulsed laser deposition [5]. Liquid phase epitaxy (LPE), the reference method to grow micrometer thick films with bulk-like dynamical properties, has long be thought to be inappropriate for thinner films, despite some encouraging results obtained on 200 nm thick films [6]. In this study, we will show that LPE can actually be used to grow YIG films with thickness from 17 nm to 200 nm and with damping parameters ranging from less than 4×10^{-4} down to 7×10^{-5} (extracted from broadband FMR between 1 GHz and 20 GHz). In order to characterize the dynamical dipolar interaction between YIG nanostructures, we have patterned from a 25 nm film pairs of YIG nano-disks with variable diameters and edge-to-edge separation. We use a magnetic resonance force microscope (MRFM) and take advantage of the stray field gradient produced by the magnetic tip to continuously tune and detune the resonance frequencies of adjacent nanodisks [7]. The magneto-dipolar interaction is revealed by the frequency anti-crossing and by the variation of the resonant peaks amplitude, as shown in Figure 1. In a pair of touching nano-disks with diameter of 470 nm, the strength of the dynamical dipolar coupling is $\Omega/\gamma = 20$ Oe, more than five times the resonance linewidth. This is a promising result to achieve control of the spin-wave dispersion in magnonic crystals based on YIG nanostructures.

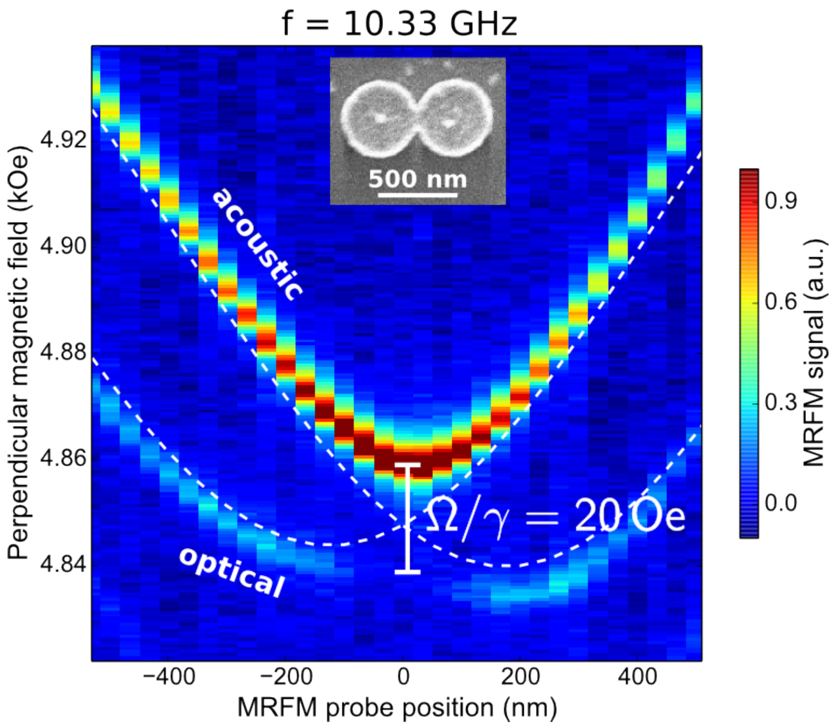

Figure 1: (color online) Density plot of the spin-wave spectra measured as a function of the MRFM probe position above a pair of touching YIG nano-disks (SEM image in inset). The excitation frequency is fixed to 10.33 GHz. The acoustic and optical modes of the system are excited by the uniform microwave field at large and low field, respectively. The dashed lines show the expected behavior in the absence of magneto-dipolar coupling. The anti-crossing and the variation in amplitude of both eigen-modes (extinction of the optical mode and strong enhancement of the acoustic mode) are the experimental signatures of the dynamical dipolar coupling, whose strength is given by the splitting between the modes.

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Coherent spin physics in OLEDs

Fri
24 Feb
17:30-18:06

John Lupton

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The ability of some animals to navigate using Earths magnetic field is truly perplexing. How can tiny fields of one Gauss induce physiologically relevant reactions when Zeeman shifts are over a million times smaller than kT? The secret appears to lie in field-induced modifications to the effect of hyperfine interactions which become relevant because of the exceptionally long spin coherence times of radical pairs. OLEDs provide an unrivaled proving ground to explore the interplay between spin coherence, spin correlations and external fields through spin-dependent transport and luminescence.

Spin-lattice relaxation in OLEDs is virtually independent of temperature and very slow. Spin dephasing over microseconds can be quantified by pulsed magnetic resonance using conventional echo schemes. Slow spin dephasing enables the direct observation of spin-Rabi flopping of both electron and hole species, which, under suitable resonance conditions, couple with each other to give spin beating. Such signals are, in principle, sensitive down to the single carrier within the OLED, since the measurement reports on spin permutation symmetry rather than on thermal spin polarization. As the sole parameter determining the resonance condition is the g-factor, compact OLED-based low-frequency resonance circuits can be designed to serve as versatile magnetometers. With novel dual singlet-triplet emitters, singlet-triplet oscillations in the radical-pair can now also be probed directly by a color change in emission.

Recent highlights in exploiting coherent singlet-triplet oscillations in OLEDs include the demonstration of direct control of the hyperfine interaction by room-temperature NMR, quantification of the zero-field splitting of intermolecular carrier-pair species, and the direct manifestation of the elusive ac-Zeeman and spin-Dicke effects.

Fri
24 Feb
18:06-18:42

Non-degenerate Parametric Pumping of Spin Waves by Acoustic Waves

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We demonstrate the parametric pumping of spin waves by longitudinal acoustic waves in YIG. Backward volume magnetostatic spin waves in the frequency range of 1.2 GHz - 1.3 GHz travelling in a YIG film have been amplified using an acoustic wave resonator driven at frequencies near twice the spin wave frequency. The existence of a distinct pump threshold that increases quadratically with frequency offset and the observation of a counter-propagating idler wave provide convincing evidence of the nonlinear parametric pumping process.

Parametric pumping involves the nonlinear interaction between three waves, the signal spin wave at frequency f_s, the idler spin wave at frequency f_i, and the pump at frequency f_p. Energy conservation dictates that the three frequencies satisfy the relation $f_p=f_s+f_i$.

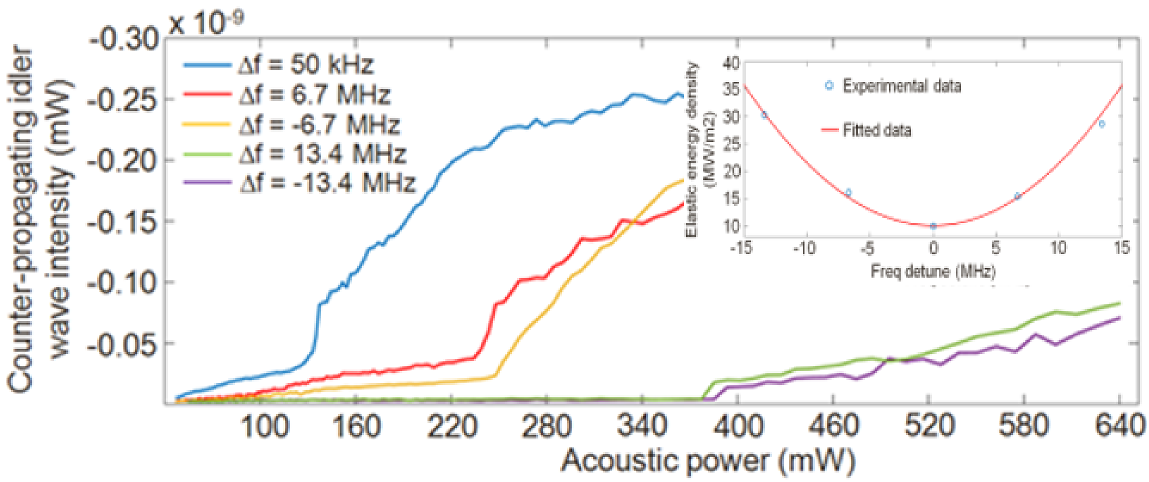

Fig. 1 Parametrically generated idler wave intensity as a function of acoustic pump power for several different pump frequencies. The inset shows the threshold acoustic intensity versus frequency offset.

In the present experiments, the pump is a standing acoustic wave which couples to the spin waves via magnetoelastic coupling in the YIG. To conserve momentum, the idler wave propagates counter to the signal wave.

In previous work [1] we studied only the degenerate case, $f_p=2f_s$. Under this condition the signal and idler waves occur at the same frequency, making it difficult to distinguish the idler wave from the inevitable electromagnetic feedthrough of the signal wave excitation. In the present experiments, we extend the work to the non-degenerate case, where the counter-propagating idler as well as a distinct threshold for its appearance are clearly observed. The experimentally determined threshold for pumping, at an acoustic amplitude of 40 pm, is similar in magnitude to the threshold predicted by a recent theoretical treatment by Keshtgar et al. [2]. The quadratic increase in threshold with frequency offset from the degenerate case indicates a spin wave damping linewidth of δ H=1 Oe, which is typical for the films used.

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Fri
24 Feb
18:42-19:18

Hybrid quantum optomechanics

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A hybrid system consisting in a mechanical oscillator coupled to a purely quantum object is a powerful tool to study the quantum to macroscopic world interface. This is a unique route toward the creation of counter intuitive non classical states of motion. The emblematic signatures of quantum electrodynamics, such as Rabi oscillations of the quantum system population and Mollow triplet physics, are expected to arise from the hybrid coupling [2].

Here we investigate the dynamics of a SiC nanowire coupled to a nano-diamond hosting a single Nitrogen Vacancy defect. The SiC wire have intrinsically large oscillation amplitudes at high frequency and exhibit two orthogonal nearly degenerated polarisations. Regarding their ultra low masses they are very accurate vectorial force sensor, exhibiting room temperature sensitivities in the attoNewton range [1]. The NV centre contains a single electronic (S=1) spin that can be manipulated and readout using laser light. Similarly to a Stern-Gerlach experiment, the Zeeman energy of the spin is coupled to the oscillator position using a strong magnetic field gradient. The spin energy is therefore parametrically modulated at the mechanical frequency. It will be evidenced that this system has the potential to enter the strong coupling regime [1]. Moreover the parametric interaction can be turned resonant using a microwave dressing of the NV spin. In the dressed basis, the Rabi frequency of the spin population can be tuned to the mechanical frequency. As a result of this QED like interaction a phonon-dressed Mollow triplet is observed in the Rabi frequency of the spin [3]. These results pave the way to the observation quantum forces, namely the single spin back-action onto the mechanical oscillator.

The outstanding sensitivity of SiC nanowires is also harnessed to probe other types of forces. In particular the vectorial nature of these force fields can be mapped with great accuracy. We have demonstrated the principle of such capability by mapping the electrostatic field created by a sharp metallic tip [4]. This experiment will lead to the measurement of fundamental vacuum fluctuation forces (or Casimir forces) in novel and unexplored geometries.

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Cavity Electrodynamics of Magnons

Sat
25 Feb
8:00-8:36

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Hybrid magnonic systems have emerged recently as an important approach for coherent information processing. The great tunability and long lifetime make magnon an ideal information carriers. We demonstrate, that particularly in magnetic insulator yttrium iron garnet (YIG), the coupling between magnon and microwave photons can reach the strong and even ultrastrong coupling regime thanks to the large spin density in YIG. Moreover, since YIG possesses excellent mechanical and optical properties, we show that by leveraging strongly coupled cavity magnonics system, coherent coupling between magnon and phonon, between magnon and optical photons can be all realized. Our work firmly establishes the great potential of magnons as an information transducer that can support coherent information inter-conversion of information carrier among different physics domains.

Sat
25 Feb
8:36-9:12

Accumulation of hybrid magneto-elastic quasi-particles in a ferrimagnet

Alexander Serga

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It is known that an ensemble of magnons, quanta of a spin wave, can be prepared as a Bose gas of weakly interacting quasi-particles with conservation of the particle number. The external pumping of magnons into the system causes an increase in the chemical potential of a thermalized magnon gas. When it becomes equal to the minimal magnon energy a magnon Bose-Einstein condensate (BEC) may form at this spectral point. However, magnon-phonon scattering processes can significantly modify this scenario. Our observations of the magnon BEC in a single-crystal film of yttrium iron garnet ($Y_3Fe_5O_{12}$) by means of wavevector-resolved Brillouin Light Scattering (BLS) spectroscopy resulted in the discovery of a novel condensation phenomenon mediated by magneto-elastic interaction: A spontaneous accumulation of hybrid magneto-elastic bosonic quasi-particles at the intersection of the lowest spin-wave mode and a transversal acoustic wave.

This accumulation is the result of a bottleneck in the downward spectral flow of the pumped magnons. The accumulation occurs in a spectral point whose position is determined by the passage from the magnon to the phonon branch and, thus, depends on the strength of the magneto-elastic interaction. As opposed to the classical magnon BEC, the accumulated magneto-elastic bosons have significantly non-zero group velocity (about 200 m/s in our experiment) and, thus, possess strong radiation losses. As a result, the density of these particles depends on their travel path through the thermalized cloud of the pumped magnons and consequently on the width of the pumping area.

The developed theoretical model describes the experimentally observed peak of hybrid magneto-elastic quasi-particles. Moreover, it proves the saturation effect in accumulation of quasi-particles: An increase in the pumping power leads to the increase of the magnon BEC population and a following reduction of the bottleneck effect.

The work is supported by the Deutsche Forschungsgemeinschaft within the SFB/TR 49 Condensed Matter Systems with Variable Many-Body Interactions, by EU-FET (Grant In-Spin 612759), and by the Graduate School Material Sciences in Mainz (MAINZ) through DFG funding of the Excellence Initiative (GSC-266).

Cavity Optomagnonics

Yaroslav M. Blanter
Kavli Institute of Nanoscience, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands

Sat
25 Feb
9:12-9:48

Recently, seminal experiments of the Nakamura group demonstrated the coherent coupling of the elementary excitation of a ferromagnet (YIG sphere) with a superconducting qubit via cavity microwave photons. Other groups performed similar experiments with optical cavities, setting up the field of cavity optomagnonics, with the main focus on quantum coherence in ferromagnets. We will give a short overview of the field and then turn to the specific problem of photon-magnon interaction. In particular, we will demonstrate how magnons influence transmission through the optical cavity, show that there is a strong asymmetry between Stokes and anti-Stokes peaks for reflected light, and discuss how light can selectively create magnons.

Sat
25 Feb
10:12-10:48

Quantum magnonics in a ferromagnetic sphere

Yasunobu Nakamura
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Center for Emergent Matter Science (CEMS), RIKEN, Wako, Saitama 351-0198, Japan

A 1-mm ϕ sphere of yttrium iron garnet, a well-known ferro(ferri)magnetic insulator, contains $\sim 10^{19}$ net electron spins aligned in one direction. The spins, rigidly ordered by the exchange interaction and also interacting via the dipole forces, support collective excitations in the magnetostatic modes [1]. We control the quantum state of one of such modes coherently at the single magnon level by using a superconducting qubit. The qubit and the Kittel mode, the magnetostatic mode with spatially uniform spin precessions in the sphere, are strongly coupled via a microwave cavity mode, which results in the magnon-induced vacuum Rabi splitting of the qubit as well as Rabi oscillations between the qubit and the single-magnon excitation at resonance [2]. When the qubit and the Kittle mode are detuned, the dispersive interaction allows us to determine the magnon number distributions through the qubit spectroscopy [3]. These experiments demonstrate the potential of magnons as a quantum information carrier in the microwave domain. Coherent interaction of magnons with infrared light is also investigated [4,5].

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Spin Mechanics with YIG

Sat
25 Feb
10:48-11:54

Gerrit E. W. Bauer

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WPI Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan

One of the subfields of spin mechanics addresses the interaction between spin and lattice waves. Magnetic insulators such as yttrium iron garnet (YIG) are very suitable materials to investigate the magnon-phonon coupling because of the combination of a high Curie temperature and a high quality of the magnetization and lattice dynamics. Incoherent magnon-phonon scattering is important to understand spin transport in magnetic insulators that are actuated electrically and thermally by heavy metal contacts, in local or non-local configurations. The coherent magnon-phonon interaction gives rise to hybrid states or magnon-polarons . These have been identified in spatiotemporally resolved Kerr rotation experiments that observe the magnetization waves generated by focussed fs optical excitation. The strong coupling of magnons and phonons to coherent magnon-polarons also gives rise to transport anomalies that are detected as sharp peaks or dips in the spin Seebeck effect as a function of applied magnetic field.

This talk will review the progress in understanding magnon-phonon interactions in YIG with emphasis on the theoretical issues.

Poster Presentations

Optomechanics with hybrid carbon nanotube resonators

Tue
21 Feb
17:30-

P01

Alexandros Tavernarakis[1], Adrian Bachtold[1], Alex Nowak[1], Alexandros Stavrinadis[1] and Pierre Verlot[2]

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The field of optomechanics has achieved impressive progress in the last 10 years while very recently it stepped into the quantum regime [1,2]. Such remarkable advance relied on the technological revolution in the fabrication of nano-optomechanical systems. In this work we used a hybrid, carbon nanotube-based optomechanical system to push nano-optomechanics to even lower scales. Indeed, carbon nanotubes have recently been shown to be the most sensitive nanomechanical transducers. Their extremely low mass make them an exceptionally good sensor allowing the detection of forces at the 10 zN level and single-proton resolution mass spectroscopy [3,4]. However, these performances remain confined to cryogenic temperatures, where their exquisite nanomechanical properties are typically 4 to 5 orders of magnitude better than in ambient conditions. Here, we present our first experimental results towards the exploration of nano-optomechanical detection in the limit of a weak optical coupling at room temperature. The detection of nanometer-scale object using optical means represents an experimental challenge because the overlap with the laser beam is limited by the diffraction limit. We approached the problem of the very low photon scattering rate by attaching an efficient optical scatterer at the tip of singly clamped carbon nanotube resonators using a Scanning Electron Microscope (SEM) equipped with a gas injection system. Our experimental setup is based a non-invasive, ultra-sensitive nano-optomechanical detection method: a laser beam is tightly focused onto the the hybrid nano-structure and the scattered photons are measured with an avalanche photodiode. In this work we demonstrate high signal-to-noise motion readout even at very low optical power. We provide a full mechanical characterization and calibration of the resonator while light-induced dynamical back-action effects are measured. We record force sensitivity, breaking the attonewton limit for the first time at room temperature while we show that optomechanical effects at this scale enable to further enhance the force sensitivity below the thermal limit. This work paves the way towards macroscopic quantum tests and quantum sensing applications at room temperature.

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Study of interactions between elastic, spin and electromagnetic waves in elastic continuum

Tue
21 Feb
17:30-

P02

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The latest development of micro-, nano-, photonic- electromechanical devices calls for fast numerical simulations of coupled elastic and electromagnetic systems. We study interaction of elastic waves propagating through a ferromagnetic medium in the presence of electromagnetic radiation [1-3].

The coupling of elastic deformations in the presence of magnetic fields leads to the problem of conservation of angular momentum and spin in the mechanical systems containing permanent magnetic moments. Our approach is based on finite deformations of elastic continuum while the particle (of a numerical grid) of a solid body has additional micro-rotational degrees of freedom in addition to regular deformation, shear and rigid rotation [5-6]. The balance equations for the linear and angular momenta are augmented by Maxwell equations [4], energy/entropy transport equations, in addition to conservation laws for mass and charge.

Einstein de Haas and/or Barnett effects point at the coupling between spin and lattice continuum through spin-orbital interactions and are excellent candidates for numerical experiment to test validity of the proposed coupled systems of equations. We hope to demonstrate the physics of coupling of magnetization dynamics and elastic vibrations in numerical models which are implemented either in Comsol Multiphysics or in a scheme based on finite differences in time domain (FDTD) run on graphical parallel units (GPU and CUDA) [7].

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P03

Kittel-like spin dynamic investigations in a mono-crystalline YIG microdisk

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Owing to the weak dependence of Kittel mode on ferromagnetic film geometry, it can be used as a touchstone for determining films fundamental properties [1]. For a magnetic structure like a disk, there is a rich spin resonance spectrum. The confined modes can exhibit the non-monotonic evolution of frequency with field familiar from Kittel modes [2]. We use torque-mixing magnetic resonance spectroscopy (TMRS) [3], with the high sensitivity and broadband capability to observe spin resonances in a single 3D yttrium iron garnet (YIG) microdisk.

Focused ion beam has been used for milling an individual disk out of a mono-crystalline YIG film. However, the disruption by Ga+ ions reduces the magnetic properties of YIG crystal near the surface and creates a magnetically-dead shell encapsulating the magnetic core of the resultant structure. The effective g-factor of the specimen is obtained directly from the slope of Kittel-like modes, while comparison of the measured spectrum with micromagnetic simulation offers additional insight on the shape of the magnetic core resulting from the milling process.

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Silicon nitride trampoline resonators for spin polarization via resonant spin-mechanics coupling

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P04

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Stoichiometric silicon nitride (Si_3N_4) films are a unique material in the field of nanomechanics due to their high internal stress that enables high mechanical quality factors along with high resonance frequencies. Moreover, the low optical absorption of Si3N4 films allow these resonators to be incorporated in a high finesse optical cavity displaying optomechanical phenomena, such as ground-state cooling, precision force and displacement sensing, and microwave-optical transducers.

Here we propose a scheme to resonantly couple Si_3N_4 film resonators with 1 - 10 MHz resonant frequency to either nuclear or electronic spins. The resonators are placed inside a high finesse cavity, which allows efficient damping of the mechanical resonator to its grounds-state, while reducing its displacement noise. A resonant coupling between an optically cooled mechanical resonator to spins enables polarization of the latter species. The spin-mechanics resonant coupling opens new paths for detection of nanoscale magnetic resonance force microscopy using normal mode splitting or selective mode detection.

To boost spin-mechanics coupling, we fabricate low-mass $\sim$MHz frequency Si_3N_4 trampoline resonators, which recently displayed extremely high quality factors. These resonators have an increased zero-point motion by an order of magnitude compared to bare membranes with same edge length. Employing ring-down measurements, these resonators display quality factors of 10^7 at room temperature, and $3x10^7$ at 4 K.

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P05

Nonreciprocal reconfigurable microwave optomechanical circuit

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Devices that achieve nonreciprocal microwave transmission are ubiquitous in radar and radio-frequency communication systems, and commonly rely on magnetically biased ferrite materials. Such devices are also indispensable in the readout chains of superconducting quantum circuits as they protect sensitive quantum systems from the noise emitted by readout electronics. Since ferrite-based nonreciprocal devices are bulky, lossy, and require large magnetic fields, there has been significant interest in magnetic-field-free on-chip alternatives, such as those recently implemented using Josephson junctions. Here we realize reconfigurable nonreciprocal transmission between two microwave modes using purely optomechanical interactions in a superconducting electromechanical circuit. The scheme relies on purposely breaking the symmetry between two mechanically-mediated dissipative coupling pathways. This enables reconfigurable nonreciprocal isolation on-chip without any external magnetic field, rendering it fully compatible with superconducting quantum circuits. All-optomechanically-mediated nonreciprocity demonstrated here can be extended to implement other types of devices such as directional amplifiers and circulators, and it forms the basis towards realizing topological states of light and sound.

A dissipative quantum reservoir for microwave light using a mechanical oscillator

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P06

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Isolation of a system from its environment is often desirable, from precision measurements to control of individual quantum systems; however, dissipation can also be a useful resource. Remarkably, engineered dissipation enables the preparation of quantum states of atoms, ions or superconducting qubits as well as their stabilization. This is achieved by a suitably engineered coupling to a dissipative cold reservoir formed by electromagnetic modes. Similarly, in the field of cavity electro- and optomechanics, the control over mechanical oscillators utilizes the inherently cold, dissipative nature of the electromagnetic degree of freedom. Breaking from this paradigm, recent theoretical work has considered the opposite regime in which the dissipation of the mechanical oscillator dominates and provides a cold, dissipative reservoir to an electromagnetic mode. Here we realize this reversed dissipation regime in a microwave cavity optomechanical system and realize a quasi-instantaneous, cold reservoir for microwave light. Coupling to this reservoir enables to manipulate the susceptibility of the microwave cavity, corresponding to dynamical backaction control of the microwave field. Additionally, we observe the onset of parametric instability, i.e. the stimulated emission of microwaves (masing). Equally important, the reservoir can function as a useful quantum resource. We evidence this by employing the engineered cold reservoir to implement a large gain (above 40 dB) phase preserving microwave amplifier that operates 0.87 quanta above the limit of added noise imposed by quantum mechanics. Such a dissipative cold reservoir forms the basis of microwave entanglement schemes, the study of dissipative quantum phase transitions, amplifiers with unlimited gain-bandwidth product and non-reciprocal devices, thereby extending the available toolbox of quantum-limited microwave manipulation techniques.

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P07

Light scattering by magnons in whispering gallery mode cavities

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Photons incident on a magnet can be inelastically scattered, such that the scattered photons carry useful information about magnons. The scattering can be boosted by using the magnet itself as an optical cavity. Here, we study inelastic scattering of photons by a spherical magnet where the latter acts as an optical whispering gallery mode cavity. We find two regimes based on the angular momentum of the magnon involved. For low angular momentum magnons, we find a pronounced asymmetry in the Stokes and anti-Stokes scattering probability attributed to an effective polarization dependent birefringence. Our results in this regime are consistent with the recent experiments. For high angular momentum magnons, we find that only one of the Stokes or anti-Stokes peaks exist depending on the direction of the magnetization. We also show that, in this regime, this system can be used for experimentally determining the dependence of magnons frequency on its angular momentum, tantamount to magnon spectroscopy by light scattering.

Momentum as the Fundamental Basis of Quantum Superposition

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P08

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A new variant of quantum mechanics which may lead to novel experimental tests in nanomechanical systems will be described. Although the postulates of quantum mechanics do not specify any fundamental (or preferred) basis for superposition, based on compelling arguments exploiting spacetime symmetry (Sharp, 2016), we propose that the fundamental basis for superposition is momentum. In summary, the new spacetime model leading to this conclusion is as follows. By focusing on the direct experience of relativistic observers, a new spacetime ontology, consisting of many coexisting 3+1D spaces, is proposed. Each space is akin to an inertial reference frame (pairs being related by the Lorentz boost), but is real and containing unique content. We will equate coexistence with superposition. Two key facts are that firstly, no violations of Lorentz invariance are introduced, and secondly, that the spacetime is inherently non-local due to the existence of multiple spaces, rendering this a uniquely quantum-friendly relativistic spacetime. This many-spaces spacetime contains 4D Minkowski spacetime as a classical limiting case.

An active coupling between spaces with a form determined by adherence to two relativistic observational conditions is proposed. This is a necessary step to allow dynamic behavior. These observational conditions are the simultaneous measurement of length and the colocal measurement of duration, and follow from the space-time symmetry of the Lorentz boost (Sharp, 2016). By endowing the spaces with complex content (roughly matter), the coupling between spaces is found to give rise to non-local complex wave equations. By postulating that this purely relativistic wave phenomenon is in fact quantum wave mechanics, we find that Plancks constant plays an essential spacetime role, specifically the inter-space coupling is proportional to 1/h. One might say that the many spaces are held together by a quantum glue. Coexistence of spaces is then equated with quantum superposition, and quantum behavior emerges directly from the spacetime structure.

Since spaces are related pairwise by a relative velocity, superposition of spaces corresponds to superposition of momentum. This spacetime argument therefore solidly puts momentum as the fundamental basis of superposition. This is a departure from the consensus understanding of quantum mechanics, however is in accord with Feynman's comment that the base states of the world for an electron are momentum and spin (including spin as a species of momentum).

The purpose of presenting this new theory at an experimental workshop is to explore the capabilities of the nanomechanical regime to test experimental predictions of this non-standard version of quantum mechanics. Several areas are potentially touched upon, including the types of superposition that can exist, and the conditions under which reduction of the quantum state occurs. A key message is that the physical behavior (i.e. unitary evolution vs. collapse vs. classical) in any particular experimental setting is determined by the status of the momentum superposition, and only indirectly by other parameters such as physical dimension, mass or particle number.

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Cryogenic Optomechanical Torque Sensor

Tue
21 Feb
17:30-

P09

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A significant direction in nanoscale spin sensing is the mechanical detection of torques associated with static and dynamic magnetism. To this end, mechanical torque sensors have been steadily improved by reducing their moment-of-inertia, and therefore spin limit-of-detection. Yet along with smaller moment of inertias, comes difficulty in the detection of mechanical motion. Over the past decade remarkable advances have been made in detection of ultra-small mechanical displacements using the technique of cavity optomechanics, to the point where thermal noise is exclusively the limiting factor in cavity optomechanical torque sensors. To combat thermal noise, we have built a cryogenic optomechanical detection system, and have recently demonstrated thermalization of torsional resonators down to 25 mK. At this temperature we find a torque sensitivity of 2.9 yNm/Hz$^{1/2}$, just eleven times above the standard quantum limit for this device. Furthermore, we have nanofabricated these torsional resonators to include both mesoscopic superconducting samples, and nanomagnetic samples. We will present our progress in measurements of these spin mechanical devices.

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P10

Coupled Spin-Light dynamics in Cavity Optomagnonics

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Experiments during the past two years have shown strong resonant photon-magnon coupling in microwave cavities, while coupling in the optical regime was demonstrated very recently for the first time. Unlike with microwaves, the coupling in optical cavities is parametric, akin to optomechanical systems. This line of research promises to evolve into a new field of optomagnonics, aimed at the coherent manipulation of elementary magnetic excitations by optical means. In this work we derive the microscopic optomagnonic Hamiltonian. In the linear regime the system reduces to the well-known optomechanical case, with remarkably large coupling. Going beyond that, we study the optically induced nonlinear classical dynamics of a macrospin. In the fast cavity regime we obtain an effective equation of motion for the spin and show that the light field induces a dissipative term reminiscent of Gilbert damping. The induced dissipation coefficient however can change sign on the Bloch sphere, giving rise to self-sustained oscillations. When the full dynamics of the system is considered, the system can enter a chaotic regime by successive period doubling of the oscillations.

Shape Memory Alloys in Hybrid Spintronic Devices

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P11

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Ferromagnetic shape memory alloys (FSMAs) gained a lot of attention due to their large magnetoelastic coupling, which can achieve field induced strains in Ni-Mn-based Heusler alloys in the order of 10.

Our goal is to investigate the phase transformation by using the tunnel magnetoresistance effect (TMR), since it was demonstrated with an AFM-cantilever that the TMR is sensitive to mechanical strains [5]. Thus in our work FSMAs are utilized either as ferromagnetic electrodes ($Ni_{50-x}Co_xMn_{30}Al_{20}$/MgO/ $Co_{40}Fe_{40}B_{20}$) or as an underlying layer beneath the magnetic tunnel junction ($Ni_{50-x}Co_xMn_{30}Al_{20}$/ $Co_{40}Fe_{40}B_{20}$/MgO/ $Co_{40}Fe_{40}B_{20}$).

The off-stoichiometric $N_{50-x}Co_xMn_{30}Al_{20}$ thin films are grown by sputter deposition and patterned by e-beam lithography. X-ray diffraction measurements indicate a B2 crystal structure. An untypical change in the TMR amplitude is observed in tunnel junctions on top of the Heusler alloy upon heating the sample. We suggest that this phenomenon arises from the induced strain of the reverse martensitic transformation. Furthermore the FSMA will act as a ferromagnetic electrode if the magnetic properties are enhanced by substituting Ni with Co atoms. At x=10 a TMR of about 2.5% at room temperature and 6% at 10 K is measured in $Ni_{50-x}Co_xMn_{30}Al_{20}$ /MgO/$Co_{40}Fe_{40}B_{20}$ tunnel junctions while no TMR is found over the measured temperature range in samples with x=4.

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P12

Dependence of longitudinal spin Seebeck effect and anomalous Nernst effect on band gap properties for $Pt/NiFe_2O_{4-x}$ bilayers

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In the emerging fields of spintronics and spin caloritronics recently discovered phenomena such as the spin Hall effect and the spin Seebeck effect enable the generation, manipulation and detection of spin polarized currents in ferro(i)magnetic insulators (FMIs). Pt has been employed quite often for generating and detecting a pure spin current, if adjacent to a magnetic insulator, although the question of magnetic proximity effects (MPE) has to be taken into account. Due to its close vicinity to the Stoner criterion Pt could be spin polarized at the interface, when adjacent to the FMI. Consequently, additional parasitic effects such as the anomalous Nernst effect (ANE) [1] can be induced preventing the right appraisal of the measured longitudinal spin Seebeck effect (LSSE) voltage. In this project, we implemented x-ray resonant magnetic reflectivity [2] to investigate possible magnetic proximity effects in Pt on sputter-deposited $Pt/NiFe_2O_4$, $Pt/NiFe_2O_{4-x}$, as well as on $Pt/Ni_{33}Fe_{67}$ samples [3-4]. We exhibit no magnetic response down to a limit of 0.04 μ_B per spin polarized Pt atom for the $Pt/NiFe_2O_4$ bilayer and 0.1 μ_B for the $Pt/NiFe_2O_{4-x}$ bilayers. For the all-metallic $Pt/Ni_{33}Fe_{67}$ bilayer we extract a maximum magnetic moment of 0.48 μ_B. Additionally, we investigate the transport phenomena [5] by separating the ANE contribution, intrinsic and proximity-induced, from the LSSE voltage while measuring in in-plane and out-of-plane magnetized configurations in the presence of different temperature gradient directions [6]. For this purpose, samples with and without Pt on top were prepared simultaneously. We find well pronounced proximity-induced ANE for the $Pt/Ni_{33}Fe_{67}$ bilayer, whereas for the $Pt/NiFe_2O_{4-x}$ bilayers the absence of any proximity-induced ANE contribution to the LSSE voltage confirms the non-existence of MPE in Pt. In parallel, we introduce the heat flux calculation instead of the temperature gradient determination since, thus, we can eliminate the systematic errors due to the thermal surface resistances allowing the reproducibility of our results and the comparability between different samples and setups [7]. Finally, we probe the dependence of the aforementioned effects on the electrical conductivity and on the band gap energy of the samples. We observe a distinct increase of the SSE while the bandgap energy increases and the conductivity decreases, whereas the ANE shows the opposite behaviour.

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P13

Imaging vortex magnetization configurations in ferromagnetic nanotubes by XMCD-PEEM

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The study of magnetic nanostructures is motivated by their potential as elements in dense magnetic memories [1] or as probes in high-resolution imaging applications [2]. Ferromagnetic nanotubes (NTs) are a particularly promising morphology, given their lack of a magnetic core. At equilibrium, this hollow geometry can stabilize vortex-like flux-closure configurations. Core-free NTs are predicted to support stable low-field configurations including the mixed state consisting of an axial central domain with vortex-like caps of circumferential magnetization, as well as a global vortex state, in which all magnetization points circumferentially around the tube axis. The stability of either the mixed or vortex configuration at zero-field has been predicted to depend on the aspect ratio of the tubular structures [3].

We perform x-ray magnetic circular dichroism photoemission electron microscopy (XMCD-PEEM) experiments at the Swiss Light Source, Paul Scherrer Institute [4] to image the remnant magnetic configurations of CoFeB and Permalloy NTs with different aspect ratios at room temperature.

Our study reveals that for long NTs the magnetic configuration is a mixed state, while short enough NTs can occupy a stable global vortex state in remanence. The aspect ratio plays a crucial role in stabilizing the global vortex state, as predicted by analytical theory [3]. We also carry out detailed micro-magnetic simulations of our magnetic nanostructures, which show a close correspondence to our measurements and shed light on the mechanisms stabilizing the observed configurations. Our XMCD-PEEM measurements reveal important insights into formation and nature of stable magnetic configurations in magnetic nanostructures. Furthermore, they demonstrate the promise of using geometry - not only material to program the equilibrium magnetic configuration of ferromagnetic NTs.

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P14

Skyrmion motion induced by plane stress waves

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Magnetic skyrmions have attracted much attention recently because of their potential applications in spintronic memory devices, such as racetrack memories. Low threshold currents and ability to change their shapes to move around pinning centers make skyrmions an attractive alternative to domain walls for storing information.

Skyrmions are typically driven by currents and magnetic fields. Here, we propose an alternative method of driving skyrmions using plane stress waves (Rayleigh waves) in a chiral ferromagnetic nanotrack. We find that the effective force due to surface acoustic waves couples both to the helicity and the topological charge of the skyrmion. This coupling can be used to probe the helicity of the skyrmion as well as the nature of the Dzyaloshinskii-Moriya interaction [1]. This is particularly important when a ferromagnet lacks both surface- and bulk-inversion symmetry.

One way to generate plane stress waves is using a pair of interdigital transducers (IDTs) placed along edges of a nanowire. As the nanowire is subject to half-open space boundary conditions, the skyrmion is driven by normal stress in this setup. We find that skyrmions get pinned at the antinodes of the stress wave, much similar to domain walls, which enables skyrmion motion by detuned IDTs [2,3].

Alternatively, we consider a nanotrack sandwiched between a piezoelectric layer and a substrate, with electrical contacts placed on top, which results in shear stress in addition to normal stress in nanotrack. For a domain wall, the presence of the shear forces do not make any qualitative difference [2], however, we find that for skyrmions this is not the case, and in the presence of both normal and shear components, the skyrmions can be driven by a standing stress wave.

We find micromagnetic simulations to be in good agreement with the equations of motion derived for the soft-modes, which include the emergent skyrmion mass term [4].

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Modification of phonon processes in nano-structured impurity doped host materials

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P15

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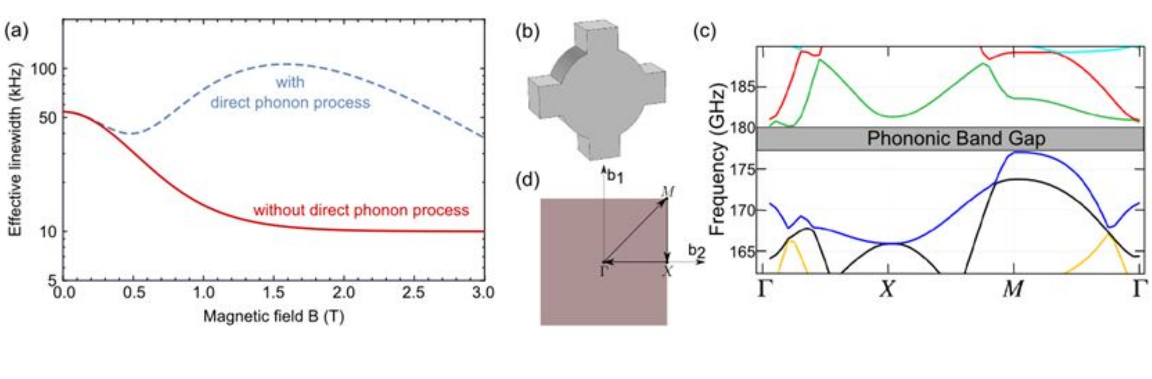
Nano-structuring impurity-doped host materials affects the phonon density of states and thereby modifies the spin dynamics induced by interaction with phonons. We propose the use of nanostructured materials in the form of powders or phononic bandgap crystals to enable or improve persistent spectral hole-burning and coherence for inhomogeneously broadened absorption lines in rare-earth-ion-doped crystals as well as silicon vacancy centers in diamond. This is crucial for applications such as optical quantum memories and on chip quantum information processing.

First, as an example, we discuss how phonon engineering can enable spectral hole-burning and reduce homogeneous linewidths in erbium-doped materials operating in the convenient telecommunication band, and present simulations for density of states of nano-sized powders and phononic crystals for the case of Y_2SiO_5, a widely-used material in current quantum memory research. In the figure below, the effect of phonon restriction on the homogeneous linewidth (a) together with the geometry of the phononic crystal (b) and its bandstructure (c) are shown for a typical, erbium doped material. Panel (d) of the Figure shows the points of the reciprocal lattice of the phononic crystal traversed in the band structure.

Second, we will report on experimental investigation towards the realization of impurity-doped nanocrystals with good spectroscopic properties. We found that crystal properties such as nuclear spin lifetime are strongly affected by mechanical treatment, and spectral hole-burning can serve as a sensitive method to characterize the quality of REI doped powders. Furthermore, results suggesting that atomic dynamics are indeed modified in such nanocrystals are presented.

Finally, we will also present initial results of our investigations towards silicon vacancy centers embedded in nano sized structures. The nanostructured environment is expected to strongly improve the silicon vacancy centers spin coherence time and in return allow the use of such centers for quantum information processing applications.



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Controlling Nitrogen-Vacancy Center Spins with a Mechanical Resonator

Evan MacQuarrie and Gregory Fuchs

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The spin state of the nitrogen-vacancy (NV) center in diamond offers a promising platform for the development of quantum technologies and investigations into spin dynamics at the nanoscale. With lengthy coherence times even at room temperature ($T_2 \sim \mu$s, $T_2^* \sim$ms), NV centers present one path towards quantum information in the solid state and enable precision metrology with atomic scale spatial resolution. The NV center spin state can be coherently manipulated with resonant magnetic fields, electric fields, or, at cryogenic temperatures, optical fields. Here, we demonstrate direct mechanical control of an NV center spin by coherently driving magnetically-forbidden spin transitions with the resonant lattice strain generated by a bulk-mode mechanical resonator [1,2]. We then employ this mechanical driving to perform continuous dynamical decoupling and extend the inhomogeneous dephasing time of a single NV center spin [3]. Finally, we experimentally demonstrate that a spin-strain coupling exists within the NV center room temperature excited state. After measuring this interaction to be 13.5±0.5 times stronger than the ground state spin-strain coupling, we propose and theoretically analyze a dissipative protocol that uses this newly discovered coupling to cool a mechanical resonator. We determine that, for a dense NV center ensemble, the proposed protocol can cool a mechanical mode to a fraction of its thermal phonon population from room temperature [4]. The methods of mechanical spin control developed here unlock a new degree of freedom within the NV center Hamiltonian that may enable new sensing modes and could provide a route to diamond-mechanical resonator hybrid quantum systems.

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Magnetic properties of Fe_4 molecules compressed in the junction of a scanning tunneling microscope

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Single molecule magnets (SMMs) offer a method of creating tailored magnetic clusters with a wide range of properties. This presents enticing possibilities in spintronics applications. However many promising SMMs are large and fragile. This constitutes a challenge in creating SMM based spintronic devices, as well as hindering scanning probe surfaces studies exploring how molecules would behave in device-like environments. Robust molecules, such as the Fe_4 molecule [1], therefore offer particularly important opportunities to make practical progress in SMM based spintronics.

Here we present low temperature scanning tunneling microscopy (STM) measurements where individual Fe_4 single molecule magnets are probed spectroscopically. Magnetic excitations at meV energies can be detected. Variations in excitation energies, due to environmental and configuration changes on the surface are resolvable. Strong tip interactions create a challenging experimental scenario and necessitate the use of a correlation between excitation energy and general topography to identify intact molecules. These intact molecules exhibit significantly boosted intramolecular exchange when compared to bulk molecular crystals. *Ab initio* calculations show that the boost can be explained by a minimal compression of the magnetic molecular core, likely induced by the STM tip [2]. This experiment emphasizes the possibility of tuning magnetic properties in spintronic devices by mechanical interactions as well as demonstrating that Fe_4 remains suitable for spintronic applications when incorporated into prototype device.

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Probing the Nuclear Spin-Lattice Relaxation Time at the Nanoscale

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Nuclear spin-lattice relaxation times are measured on copper using magnetic resonance force microscopy performed at temperatures down to 42 mK. The low temperature is verified by comparison with the Korringa relation. Measuring spin-lattice relaxation times locally at very low temperatures opens up the possibility to measure the magnetic properties of inhomogeneous electron systems realized in oxide interfaces, topological insulators and other strongly correlated electron systems such as high-Tc superconductors. [1]

Furthermore, we present an innovative method for MRFM with ultra-low dissipation, by using the higher modes of the mechanical detector as radio frequency (rf) source. This method allows MRFM on samples without the need to be close to an rf source. Furthermore, since rf sources require currents that give dissipation, our method enables nuclear magnetic resonance experiments at ultra-low temperatures. Removing the need for an on-chip rf source is an important step towards a MRFM which can be widely used in condensed matter physics. [2]

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Direct imaging of a vortex state in short CoFeB nanotubes by scanning SQUID

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Ferromagnetic nanotubes (FNTs) are attracting attention as potential elements in continuosly minituarizing magnetic memory. As the physical size of a unit of information reaches nanoscale, mutual interactions between the units become increasingly important. Nanotubes, presenting topologically non-trivial surfaces, support stable flux-closure magnetization configurations which produce minimal stray fields, thus reducing collective interactions of their assemblies to minimun. These configurations have also been shown to favor fast and reproducible reversal processes.

Unitl recently, studies of single FNTs were challenging, due to their extremely non-planar topography, small sizes, and consequently small magnetic signals. Although cantilever magnetometry [1] and magnetotransport measurements [2] have significantly advanced the experimental determination of the magnetic configuration of FNTs, magnetic imaging of FNTs has remained an unresolved challenge.

In this work we report direct magnetic imaging of single CoFeB nanotubes of various lengths using a scanning SQUID-on-tip sensor [3]. The combined sensitivity, spatial resolution, and large range of operational magnetic fields of the nanoSQUID allow us to image the magnetic configuration of the FNTs at various points it their magnetic hysteresis loop. We find evidence for a stable global vortex state near zero applied field and show that its existence depends on the length and the geometrical perfection of the tubes.

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Proximity-induced supercondcutivity and quantum interference in topological crystalline insulator SnTe devices

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Topological states of matter host a variety of new physics that is promising for future technology. Among these phenomena, the emergence of metallic symmetry-protected topological surface states (TSS) are of major interest [1,2]. Due to their helical spin nature, the coupling of topological matter to a nearby superconductor is forsaken to host unconventional proximity-induced supercondcutivity [2,3], as well as zero-energy Andreev excitations - so-called Majorana bound states (MBS) [3]. Here, we report on topological crystalline insulator (TCI) SnTe - a prime representative of the TCI class [4] - thin films. The appearance of weak-antilocalization (WAL) effects in low temperature transport measurements verify the presence of topological surface channels and attest their protection [5,6]. Further, we demonstrate the fabrication of superconducting Quantum interference devices (SQUIDs) of SnTe/Nb hybrid structures. Our findings show strong proximity-induced supercondcutivity in the surface of SnTe. The presence of MBS at the interface between superconductor/topological material is predicted to enter with a shift in periodicity from 2π to 4π in DC SQUID Experiments [7]. The analysis of the SQUID Response on external magnetic fields suggest the absence of 4π oscillation periodics, but show additional features expected for surface state carried supercurrents, such as unconventional Fraunhofer-shapes [8,9]. Our data Supports the view of SnTe as a promising material platform to investigate topological superconductivity, strong spin-orbit interaction and Majorana physics.

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Magnon-polaron transport in magnetic insulators

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We investigate the effects of magnetoelastic coupling on the transport properties of magnetic insulators. The coupling between elastic and magnetic excitations gives rise to magnon-polaron modes. We develop a Boltzmann transport theory for magnon-polarons and we derive expressions for the magnon-polaron spin and heat transport coefficients, and spin diffusion length. Our results shows that the experimentally observed anomalous features in the field and temperature dependence of the spin Seebeck effect can be explained by magnon-polaron formation. Furthermore, the comparison between theory and experimental data provides unique information about the relative magnetic and acoustic quality of the sample. We predict similar features in the magnon spin and heat conductivity and magnon injection measurements.

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Polarization-selective coupling between cavity microwave photon and magnon

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When an electromagnetic wave propagates in a magnetic material, its magnetic fields can drive the magnetization precession. The mutual coupling between the macroscopic electrodynamics and magnetization dynamics results in a hybrid electromagnetic mode of the media, i.e., magnon polariton. In light of this principle, a cavity magnon polariton (CMP) has been recently studied in a coupled magnon-cavity photon system, in which a low damping bulk ferromagnetic insulator is set either on-top of a 2D planar cavity or inside a high quality 3D microwave cavity. In this work, we discuss the design and implementation for a novel CMP, where the polarization of microwave in the microstrip resonator can be easily tuned from elliptical polarization, to linear polarization, and to circular polarization. This on-chip device enables the investigation of polarization-selective rules of the CMP. To explain the experimental observation, we provide a concise classical model, which accurately highlights the key physics of phase correlation between the polarized microwave photon and magnetization dynamics. This general CMP model may open up new avenues for materials characterization and microwave applications.

Spin dynamical phase and antiresonance in a strongly coupled magnon-photon system

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Strong light-matter interactions in condensed matter systems are a rich source of physics, underlying such important concepts as the polariton, while holding the key to new technological development, such as quantum information processing and coherent spintronic manipulations. In this direction much work has recently been devoted to the strong magnon-photon interactions between low loss magnetic materials and high quality microwave cavities/resonators, motivated by the potential for large coherent coupling in magnetically ordered systems. However in order to exploit the coherent nature of these polaritons in future applications a better understanding of the phase properties, and phase characterization techniques are needed. Motivated by the known role of the relative phase in the line shape signatures of spintronic systems, in this work we have performed a systematic study of the microwave transmission line shape in a cavity-magnon-polariton system. At fixed fields we observe the expected Lorentz line shape of transmission measurements, however at fixed frequencies we observe an asymmetric line shape which can be tuned by the microwave frequency. These features are well described by a dynamic phase correlation model accounting for the boundary conditions of Maxwells equations within the Landau-Lifshitz-Gilbert description of magnetization dynamics. This model also predicts an antiresonance, i.e. the suppression of the microwave transmission, indicating a relative phase change between the magnon response and the driving microwave field. We experimentally observe this antiresonance feature and demonstrate that such behaviour can be used to interpret the phase evolution of the coupled magnon-microwave system. Thus our work provides a standard procedure for the line shape and phase analysis of the cavity-magnon-polariton, while also enabling the phase characterization of the individual magnon/microwave subsystems.

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Towards Quantum Magnonics

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Recent developments in the field of magnonics and magnon spintronics have opened up new opportunities for investigations at the quantum level. Using measurement techniques and structures common in contemporary quantum measurement, we lay the groundwork for experiments accessing the new physics and technological opportunities presented by hybrid quantum magnonic systems.

Optomagnonics in Magnetic Solids

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Coherent conversion of photons to magnons, and back, provides a natural mechanism for rapid control of interactions between stationary spins with long coherence times and high-speed photons. Despite the large frequency difference between optical photons and magnons, coherent conversion can be achieved through a three-particle interaction between one magnon and two photons whose frequency difference is resonant with the magnon frequency, as in optomechanics with two photons and a phonon. The large spin density of a transparent ferromagnetic insulator (such as the ferrite yttrium iron garnet) in an optical cavity provides an intrinsic photon-magnon coupling strength that we calculate to exceed reported optomechanical couplings. A large cavity photon number and properly selected cavity detuning produce a predicted effective coupling strength sufficient for observing electromagnetically induced transparency and the Purcell effect, and even to reach the ultra-strong coupling regime.

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Characterization of backward volume spin waves in microstructured waveguides for the mechanical detection of the magnon angular momentum

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In metallic ferromagnets the magnon-phonon-scattering and the magnon-electron-scattering mechanisms are the most important damping mechanisms. In these processes energy, linear and angular momentum of the magnon is finally transferred to the phononic system.

This work aims for the investigation of the angular momentum transfer of decaying propagating spin waves. This transfer of angular momentum results in a rotational torque acting on the magnetic layer, which can be observed by a rotational motion if the waveguide is fabricated on top of a released mechanical resonator. The latest progress in torque detection using bridge resonators and optical fibers provides the required sensitivity to measure changes in the magnetisation of microscopic elements, like the ferromagnetic resonance [1] or switching of magnetic vortices [2]. However, the experimental proof of the angular momentum transfer from decaying spin waves to the phononic system is still missing.

One of the challenges for these investigations is that the excitation of the spin waves has to take place outside of the resonator. To align the angular momentum of the spin waves with the torsional mode of the bridge resonator, the spin waves have to propagate in the backward volume geometry. Compared to the Damon-Eshbach geometry the backward volume geometry has a significantly lower group velocity and is more difficult to excite using conventional stripline antennas.

In this contribution we present the characterization of backward volume spin waves in microstructured waveguides. The waveguides are produced from Permalloy with a thickness of 100 nm capped with 7 nm Aluminium and are between 1.3 m and 4 m wide. The spin waves were generated by a coplanar wave guide to select the spin-wave wavevector with the highest group velocity. The exponential amplitude decay lengths of the spin waves were obtained via Brillioin light scattering microscopy. In the experiment, decay lengths up to 4.1 m have been measured, which is sufficient to propagate from the antenna onto the resonator. Thus, these results pave the way for future direct measurements of the angular momentum transfer of propagating spin waves to the phononic system.

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Revealing of decaying spin waves as the main source of heating in spin-transfer torque driven Heusler-Pt waveguides

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Recently, the field of magnon spintronics experienced a lot of interest and developed towards applications. However, the limitation of any application using magnons as information carrier is the lifetime and the propagation length of the spin waves. These properties are mainly determined by the Gilbert damping parameter [1]. This lead to the development of new low-damping materials such as the Cobalt-based Heusler compounds [2]. Another way to manipulate the effective damping of spin waves is the spin-transfer torque effect (STT) [3]. Especially in combination with the spin-Hall effect (SHE) [4] to generate pure spin currents in a normal metal, this effect allows for a manipulation of the effective magnon damping in any magnonic devices.

In this contribution, we employ the SHE and STT effect to manipulate the effective spin-wave damping in a Pt-covered microstructured spin-wave waveguide made from the low damping Heusler compound $Co_2Mn_{0.6}Fe_{0.4}Si$. By applying DC current pulses to the CMFS/Pt waveguide and performing time-resolved Brillouin light scattering microscopy measurements, this allows for the investigation of the temporal evolution of the transitional spin-wave dynamics. The presented results reveal that the waveguide is strongly heated by decaying spin waves. In general, magnon-phonon scattering is one of the main relaxation mechanisms for spin waves. Thus, the energy is transferred from the magnonic system to the phononic system, resulting in an increased temperature. In contrast, the measurements show that Joule heating only plays a minor role and can be neglected.

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Non-local magnetoresistance by magnon transport in the magnetic insulators yttrium iron garnet and gadolinium iron garnet

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In recent years, the ferrimagnetic insulating material yttrium iron garnet (YIG) has been intensively studied, mostly in combination with an adjacent few-nm-thick platinum (Pt) layer. Besides the local generation and detection of pure spin currents in such a bilayer system, it was for the first time shown in 2015 that it is also possible to generate non-local signals by transporting pure spin currents through the electrical insulating YIG layer by diffusion of incoherent magnons (spin waves) [1,2]. Two different techniques can be applied for the generation of these non-equilibrium magnons. One is electrical injection using the charge to spin conversion in the Pt-injector strip, by the spin Hall effect. The second mechanism is the thermal excitation of magnons by Joule-heating in the Pt-injector strip, giving rise to the spin-Seebeck effect (SSE). By studying the non-local signals as a function of injector-detector distance, temperature, and magnetic field orientation, different length scales involved in the magnon diffusion process can be investigated [1-4].

Currently, most experiments are focussed on the non-local injection and detection of magnon transport in YIG. However, by replacing YIG with the magnetic insulating material gadolinium iron garnet (GdIG) we are able to probe the influence of a non-trivial magnetic order on the non-local transport of magnon modes and are even able to tune its magnetic properties with temperature. In particular, GdIG allows to investigate the impact of modes with different chiralities on the non-local magnetoresistance, as well as of spin canting effects, where the magnetic sublattices are no longer aligned (anti)parallel [5,6]. As for the local SSE measurements in GdIG [6], we investigate the influence of the different magnetic sublattices in magnon-mediated as well as SSE non-local transport experiments.

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Voltage control of cavity magnon polariton

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Coupling between photon and magnon dynamics is a field of long standing interest. Very recently, interest in the physics of magnon-photon coupling has grown rapidly due to the development of microwave cavity and spintronic techniques. Experimental progress has shown that the strong coupling between magnon and photon can be easily achieved by inserting a low damping magnetic material into a high-quality microwave cavity, which generates cavity magnon polariton (CMP). Furthermore, it has been demonstrated that magnon-photon coupling is a promising approach to develop long-lifetime, multimode quantum memories, and quantum transducers that have the ability to link various quantum systems. In order to further use the controlled photon-magnon coupling for advanced spintronic applications like the planar CMOS platform, in this work we present a method to use voltage to control the cavity photon-magnon coupling in a 2D planar cavity. By appropriately tuning the voltage and the magnetic bias, resonant frequency, quality factor of cavity is tuned, the generated CMP is observed with the controllable rabi-oscillation frequency. Furthermore, due to the high tunability of coupling system, CMP can be controlled in different coupling regime (from electromagnetically induced transparency to strong coupling). This electrical control of cavity magnon polariton may open up avenues for designing advanced on-chip microwave devices that utilize light-matter interaction.

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Sensitively imaging magnetization structure and dynamics using picosecond laser heating

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I will present time-resolved longitudinal spin Seebeck effect (TRLSSE) measurements of magnetization structure and dynamics in yttrium iron garnet (YIG)/Pt bilayers and progress toward using thermal gradients for sub-100 nm magnetic microscopy. YIG, and other insulating ferromagnetic materials, has proven useful for the study of spin transfer torque and magnetothermal effects due to material characteristics such as low Gilbert damping and magnon-phonon coupling. Moreover, in bilayers consisting YIG and a heavy, non-magnetic metal (such as Pt) the spin Hall effect can be used to convert between spin and charge current. This enables electrical control and readout of the ferromagnetic insulator. In bilayers made with thin (20 nm) YIG films however, it is challenging to measure local, time-varying magnetization because the magneto-optical signals are small. As a complementary approach, we show that the magneto-thermal measurements can be used for sensitive, stroboscopic microscopy of YIG magnetization. In this approach, local picosecond laser heating creates a short lived spin current via the longitudinal spin Seebeck effect. The spin current is then transduced into a charge current via the inverse spin Hall effect, providing a measurement of the local magnetic moment. We demonstrate the effectiveness of TRLSSE microscopy for submicron imaging of YIG magnetization structure and dynamics with sub-100 ps temporal resolution and sensitivity to magnetic orientation of 0.3 deg/Hz.

The spatial resolution of magneto-thermal based techniques such as TRLSSE and time-resolved anomalous Nernst effect (TRANE) microscopies, is set by the size of the heat source. Since thermal gradients are not subject to the optical diffraction limit, these thermal gradient based techniques offer the potential for high resolution microscopy by using near field techniques. I will present our most recent work advancing thermal gradient based microscopy towards sub-100 nm resolution using plasmonic enhancement from a scanning tip.

Spin-Mechanical Inertia in Antiferromagnet

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Coupling between magnetic and mechanical motions causes numerous striking phenomena in nanomagnets, where the conservation of angular momentum serves as a guiding principle. In an antiferromagnet with vanishing magnetization, however, the order parameter carriers no angular momentum, suggesting that new fundamental rules are required to understand spin-mechanical effects. We demonstrate that the antiferromagnetic ordering modifies the tensor of inertia of a rigid body. When the magnetic anisotropy is strong, the effect amounts to the adiabatic following of the antiparallel spins with the crystal rotation, which exhibits temperature dependence due to thermal excitations. Such spin-mechanical inertia produces measurable results in nanomagnets.

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Non-integral-spin magnons in untextured magnets

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Interactions are responsible for intriguing physics, e.g. emergence of exotic ground states and excitations, in a wide range of systems. Here we theoretically demonstrate that dipole-dipole interactions lead to bosonic eigen excitations with spin ranging from zero to above $\hbar$ in magnets with uniformly magnetized ground states. These exotic excitations can be interpreted as quantum coherent conglomerates of magnons, the eigen-excitations when the dipolar interactions are disregarded. We further find that the eigenmodes in an easy-axis antiferromagnet are spin-zero quasiparticles instead of the widely believed spin $\pm\hbar$ magnons. The latter re-emerge when the symmetry is broken by a sufficiently large applied magnetic field. The spin greater than $\hbar$ is accompanied by vacuum fluctuations and raises the question of the relation to elementary arguments regarding angular momentum conservation in spin-mechanical coupling.

Ground-state cooling a mechanical oscillator by spin-dependent transport and Andreev reflection

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We study the ground-state cooling of a mechanical oscillator coupled to the charge or the spin of a quantum dot inserted between spin-polarized or a normal metal and a superconducting contact. Such a system can be realized e.g. by a suspended carbon nanotube quantum dot with a suitable coupling between a vibrational mode and the charge or spin. We show that ground-state cooling of the mechanical oscillator can be achieved for many of the oscillator's modes simultaneously as well as selectively for single modes. We discuss different modes of operation which also include single mode cooling by resonance, which is tunable by a magnetic field. We finally discuss how the oscillators state can be detected in the current-voltage characteristic.

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Dynamic Cantilever Magnetometry On Individual Magnetic Nanoparticles

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Mechanical oscillators such as Si cantilevers can serve as sensitive transducers for information on the magnetic configuration of nanoscale particles, which are attached to the tip of one of these cantilever. In an externally applied magnetic field, the magnetic particle will exert a torque on the cantilever. This results in a shift of the resonance frequency of the cantilever, thereby being the quantity providing information on the magnetic particle. This technique is known as dynamic cantilever magnetometry, allowing to investigate quantities such as saturation magnetization, anisotropy or more general magnetic behavior such as switching or magnetic phases.

With this technique we have studied e.g. the magnetic skyrmion phase in $GaVa_4S_8$ and MnSi nanowires, where in the latter effects of reduced dimensionality could be shown [2]. Another example is the investigation of ferromagnetic nanotubes [1, 2], interesting because of their potential flux-closure ground state at low applied magnetic fields. In this contribution we will present our most recent results.

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Spin-mediated dissipation and frequency shifts of resonators

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Many disciplines in physics try to understand the interaction of their well behaving resonator with the environment: for example because they want to circumvent this interaction or they want to probe the environment. However, what if the environment is affected by the currents in the electromagnetic resonator or by the movement of the mechanical resonator and vice versa?

Here we present the missing calculation that explains the physics that is needed in the quantitative modelling of spins or two level fluctuations in the environment of quantum computing devices, detectors for astronomy, magnetic resonance force microscopy, nano-MRI, and hybrid quantum devices: the anomalous temperature dependence of the dissipation factor and resonance frequency of resonators due to the interaction with the environment that can be modeled as an ensemble of spins.

We calculate the change of the properties of a resonator, when coupled to a semi-classical spin by means of the magnetic field. Starting with the Lagrangian of the complete system, we provide an analytical expression for the linear response function for the motion of the resonator, thereby considering the influence of the resonator on the spin (or two level system) and vice versa. This analysis shows that the resonance frequency and effective dissipation factor can change significantly due to the relaxation times of the spin. We first derive this for a system consisting of a spin and mechanical resonator and thereafter apply the same calculations to an electromagnetic resonator. Moreover, the applicability of the method is generalized to a resonator coupled to two-level systems and more, providing a key to understand some of the problems of two-level systems in quantum devices.

We also have measured the dissipation and frequency shift of a magnetically coupled cantilever in the vicinity of a silicon chip, down to 25 mK. The dissipation and frequency shift originates from the interaction with the unpaired electrons, associated with the dangling bonds in the native oxide layer of the silicon, which form a two-dimensional system of electron spins. We approach the sample with a 3.43 m-diameter magnetic particle attached to an ultrasoft cantilever and measure the frequency shift and quality factor as a function of temperature and the distance. Using the theoretical analysis from above, we are able to fit the data and extract the relaxation time $T_1 = 0.39 \pm 0.08$ ms and spin density $\sigma = 0.14 \pm 0.01$ spins per nm^2. Our analysis shows that at temperatures 500 mK magnetic dissipation is an important source of noncontact friction.

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Quantitative separation of the anisotropic magnetothermopower and planar Nernst effect by the rotation of an in-plane thermal gradient

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A thermal gradient as the driving force for spin currents plays a key role in spin caloritronics. In this field the spin Seebeck effect (SSE) is of major interest and was investigated in terms of in-plane thermal gradients inducing perpendicular spin currents (transverse SSE) and out-of-plane thermal gradients generating parallel spin currents (longitudinal SSE). Up to now all spincaloric experiments employ a spatially fixed thermal gradient. Thus anisotropic measurements with respect to well defined crystallographic directions were not possible. We introduce a new experimental setup that allows not only the in-plane rotation of the external magnetic field, but also the rotation of an in-plane thermal gradient controlled by optical temperature detection. The rotation of the temperature gradient induces a phase shift of the dependence of the voltage signal on the external field. This shift allows to unambiguously determine the Seebeck voltage and its dependence on the angle between magnetization and temperature gradient (anisotropic magnetothermopower, AMTP), and the planar Nernst effect in one experiment. In addition, our results fit remarkably well with theoretical simulations. The observed negative AMTP in Py clearly reveals that the magneto-Seebeck effect perpendicular to the magnetization is larger than the parallel magnetothermal transport. The ability of a reliable rotation of thermal gradients with respect to crystal structures opens a new door for thermomagnetic and spin caloritronic measurements. Future experiments on this base will address anisotropic spin Seebeck and spin Nernst effect measurements depending on the crystal structure orientation.

Magnetomechanical coupling and ferromagnetic resonance in magnetic nanoparticles

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We address the theory of the coupled lattice and magnetization dynamics of freely suspended single-domain nanoparticles. Magnetic anisotropy generates low-frequency satellite peaks in the microwave absorption spectrum and a blueshift of the ferromagnetic resonance (FMR) frequency. The low-frequency resonances are very sharp with maxima exceeding that of the FMR, because their magnetic and mechanical precessions are locked, thereby suppressing Gilbert damping. Magnetic nanoparticles can operate as nearly ideal motors that convert electromagnetic into mechanical energy. The Barnett/Einstein-de Haas effect is significant even in the absence of a net rotation.

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Atomistic spin dynamics with a semi-quantum thermostat

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Atomistic spin dynamics is a formalism based on the Heisenberg model and Landau-Lifshitz-Gilbert equation. Thermal effects are included using Langevin dynamics - stochastic perturbing fields. The formalism is often used to study the thermodynamics of specific materials or non-linear and non-equilibrium effects in spin dynamics in general. However the use of classical approximations in the formalism, especially with respect to the thermal noise, has been questioned by some.

We investigate performing atomistic spin dynamics using a semi-quantum thermostat where instead of white noise, the quantum fluctuation dissipation theorem is obeyed. This provides Planck statistics in an otherwise classical formalism. We find that this corrects many issues with the atomistic formalism as the UV region of spin waves is correctly cutoff, avoiding the ultraviolet catastrophe. Interestingly and in contrast to conventional classical spin dynamics, the length of the magnetic moment now plays a similar role to the length of the spin in quantum formalisms, despite the lack of spin quantisation.

One of the most important aspects is that the low temperature properties of magnetic materials can now be calculated with quantitative accuracy, where previously only the high temperature results could be described well. We demonstrate this for the important material yttrium iron garnet (YIG) by calculating the specific heat capacity. We find excellent agreement with the measurements of Boona and Heremans [1] at low temperature (below 10K) where they were able to freeze the magnons. At higher temperatures (above 30K) we demonstrate that YIG can no longer be approximated by a quadratic spin Hamiltonian, although this is often used in theory work.

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Magnetic hyperthermia in the Neel and Brownian rotation framework

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Cancer is one of the most severe and widespread health problems faced by todays medicine. The existing techniques (such as surgery, chemotherapy and radiotherapy) have low survival rate and strong side effects. Magnetic hyperthermia is an emerging cancer therapy which can be applied on its own or in an adjuvant setting with chemotherapy or radiotherapy. It consists of inserting biocompatible magnetic nanoparticles (MNPs) inside the tumorous cell. Then by applying an oscillating magnetic field, the particles will generate heat. The tumour cells are more sensitive to temperature increase than the healthy ones. If the heat is controlled such that the temperature increase is maintained between 43-47 Celsius, then only the tumour tissue is destroyed, leading to a non-invasive treatment method. Despite all the advantages, magnetic hyperthermia still needs substantial research in order to understand the mechanism involved.

The previous studies are constrained by one or more elements: 1) intrinsic properties and their distribution (particle size, anisotropy value, easy axis orientation), 2) extrinsic properties (AC magnetic field amplitude, AC field frequency), 3) the role of dipole interactions, 4) heat transfer from particle to the tumour, 5) mechanical rotation of the particles, 6) the viscosity of the fluid containing the nanoparticles and 7) the aggregation of the nanoparticles when placed inside the tumour. There are also two main mechanism of heating: magnetic rotation of the spin (Neel relaxation) and Brownian rotation of the particle. From the physics point of view, key steps are : 1) to develop realistic models of the heating process occurring when the particles are embedded within the viscous cellular environment and, 2) to have controlled experimental techniques to measure the particle properties and the heating output.

We investigate the two mechanism going from the single particle in a a fixed matrix to small agglomerates of particle embedded in flexible matrix. This allows to study the two mechanism (Neel and Brownian) first individually and finally combined together, which is the more realistic scenario in vivo application. For Neel relaxation we show that the magnetic behaviour can be categorized in 3 regions in terms of the applied field: a) low field region where the linear response theory approximation, developed in previous studies, can be used, b) the large field region where full hysteresis models are applicable and c) an intermediate region where the transition between the two behaviour occurs and the conventional approaches no longer apply.

The next step consists of investigating the mechanical torque response of the particles in the soft, viscous environment. This allow to study the role of Brownian rotation, which shows that for lower frequency limit the Brownian mechanism has a significant contribution.

Finally we present a model that allow the study of both mechanism simultaneously. The magnetic moment will rotate in a magnetic field coupled with the rotation of the particle itself in the fluid, leading to a rotation of the anisotropy easy axis. This model allows all the previous mentions constrains to be investigated.

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Magneto-Seebeck Tunneling Across a Vacuum Barrier

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The tunneling Seebeck effect has been intensively studied both for its impressive potential applications in e.g. waste heat recycling in electronics, and for the insights it can provide into fundamental solid state phenomena [1]. Recently, investigation of Seebeck tunneling in planar magnetic tunneling junctions (MTJs) has entrenched this phenomenon in the rapidly developing field of spin caloritronics [2,3]. These works have relied on tunneling barriers composed of insulators, e.g. MgO, to separate the planar magnetic leads. However the resulting data are necessarily averaged over extended surfaces and the methods used to grow and to study these structures face challenges in the small nanometer scale. Additionally the non-ideal tunneling barrier can complicate the interpretation of the tunneling process.

In this poster we will present measurements of Seebeck and magneto-Seebeck tunneling across a vacuum barrier obtained using spin-polarized scanning tunneling microscopy (SP-STM) [4]. Tunneling thermovoltage has been previously studied in the context of STM, both theoretically and experimentally [5,6]. To date however, these studies have lacked spin-contrast and the explored junction temperature range was limited. Thus we have performed scanning thermovoltage measurements between a spin-polarized bulk Cr tip and atomic layers of Fe on a W(110) substrate in UHV conditions (< 1E-10 mbar), at a junction temperature of T = 50 K. A 15 mW fiber-coupled diode laser was used to heat only the STM tip, creating the requisite temperature differential across the junction. The resultant tip temperature change can be estimated using a linear thermal expansion model, as well as predictions from the tunneling model presented in [6], which is also used to interpret the results.

These measurements can be performed with atomic resolution, and with previously unobtainable dynamic control over the tunneling junction parameters. With this approach the contribution of different surface materials and configurations to magneto-Seebeck tunneling can be probed and compared, thus enabling and accelerating the search for higher performing MTJs and further insight into their workings.

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Co-sputtered PtMnSb thin films and Pt/PtMnSb bilayers for spin-orbit torque investigations

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Spin-orbit torques (SOTs) in heavy metal/magnetic metal bilayers can be utilized to electrically manipulate and switch the magnetization in the magnetic layer.[1,2] Materials with non-centrosymmetric spin configurations can even be electrically controlled by an intrinsic SOT without any additional heavy metal layer. This has recently been demonstrated in the field of antiferromagnetic spintronics[3] for the room-temperature antiferromagnet CuMnAs.[4] Furthermore, an intrinsic SOT has been found in the room-temperature ferromagnet half-Heusler compound NiMnSb.[5] In this work, we prepare and investigate thin films of PtMnSb, which belongs to the same Heusler class of materials.[6,7] Using symmetry arguments regarding the crystal structure in connection with in principle analogies, which can be found in related microscopic calculations,[5] we expect a large intrinsic SOT. This analysis of the room-temperature ferromagnet PtMnSb is laying the groundwork for further investigation of the different spin-orbit torque contributions.[8]

We have fabricated PtMnSb thin films and additional PtMnSb/Pt bilayers on MgO(001) substrates with different film thickness by dc magnetron co-sputtering at high temperatures in an ultra-high vacuum chamber. The film properties were investigated by various techniques with a focus on their structure, stoichiometry, texture and surface topography. The bilayers show layer-by-layer growth in which Pt grows crystalline on the half-Heusler class material without significant interdiffusion. Detailed x-ray technique analysis in combination with high resolution transmission electron microscopy has been performed to identify the film growth and quality.

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Temperature dependence of the spin Hall angle and switching current in the nc-W(O)/CoFeB/MgO system with perpendicular magnetic anisotropy

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We investigated the temperature dependence of the switching current for a perpendicularly magnetized CoFeB film deposited on a nanocrystalline tungsten film with large oxygen content: nc-W(O). The effective spin Hall angle of about 0.22 is independent of temperature, whereas the switching current increases strongly at low temperature. The increase indicates that the current induced switching itself is thermally activated, in agreement with a recent theoretical prediction. The dependence of the switching current on the in-plane assist field suggests the presence of an interfacial Dzyaloshinskii-Moriya interaction with D$\simeq$0.23 mJ/m^2, intermediate between the Pt/CoFe and Ta/CoFe systems. We show that the nc-W(O) is insensitive to annealing, which makes this system a good choice for the integration into magnetic memory or logic devices that require a high-temperature annealing process during fabrication.

Tunneling magnetoresistance on perpendicular CoFeB-based junctions with perpendicular exchange bias

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Recently, magnetic tunnel junctions with perpendicular magnetized electrodes (pMTJs) combining perpendicular exchange bias (PEB) films have attracted considerable scientific interest. Their noteworthy properties of high thermal stability and low critical current for spin-transfer-torque induced magnetization switching or precession with perpendicular magnetic anisotropy (PMA), render them as promising candidates for high-density magnetoresistance random access memories and nanoscale oscillators [1]. In this project, we fabricated functionable pMTJs with PEB by taking into account three necessary primary requirements. Firstly, in the pinned part of the junction we obtain relatively large PEB fields [2] along with low coercive fields, in order to prevent the simultaneous switching of both electrodes. Secondly, the stacks for the switchable and pinned electrode are chosen to show high PMA in order to achieve the relative orientation of the electrodes to be parallel (low resistance) or antiparallel (high resistance) in the perpendicular direction of the field. Thirdly, the bottom part of the junction is preferred for the development of the pinned instead of the switchable part, for the reason that MnIr acts as an additional seed layer promoting the (111) texture and therefore providing higher PMA to the film [3]. The previous mentioned criteria are satisfied by the stacks: Ta/Pd/IrMn/CoFe/Ta/Co-Fe-B/MgO/Co-Fe-B/A/Pd where A=Hf, Ta displaying PEB fields of 500 Oe along with high PMA. From the magnetic loops is observed the noticeably higher PMA at zero field for the Hf capped CoFeB/MgO compared to the Ta capped CoFeB/MgO stack. Sequentially, we examine the magneto-transport properties of the stacks. The major TMR loops acquired at room temperature, present a value of tunnel magnetoresistance in Hf and Ta capped films equal to 50% and 40%, respectively. Hf in comparison with Ta is predicted to be a greater Boron absorbing material resulting in the enhancement of PMA and TMR [4-5]. Furthermore, the TMR measurements at several temperatures for both samples reveal a significantly enhanced TMR reaching 105% at 10K for the sample with Hf as a capping layer. For both samples is extracted the expected temperature/bias dependence of TMR which is consistent with the model of magnon assisted tunneling [6].

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Conservation of energy and linear momentum in DMI systems

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The antisymmetric form of the exchange interaction, the Dzyaloshinskii-Moriya interaction (DMI), arises in magnetic systems that lack inversion symmetry and have strong spin-orbit coupling. The magnetic ground state is modified by the DMI stabilizing chiral textures such as skyrmions and Neel type domain walls. The fluctuations around these stable configurations, the spin waves, are also modified by the DMI where a non-reciprocal dispersion relation is the signature of the interaction. Both, the textures and the spin waves under the influence of the DMI, are proven to be important for new spintronic and magnonic devices. In order to achieve more efficient devices, the transport of energy; linear, and angular momenta need to be fully understood.

In this work, we construct the energy-momentum tensor of the system using Noether's theorem and discuss the effects of the DMI. Invariance of the action under time and space translations result in the conservation of energy and linear momentum, respectively. The conserved physical quantities are described mathematically by continuity equations that relate the density of the physical quantity and the flux of it through the boundaries.

For the energy, after separating the slow (structure) and fast (spin waves) variables, the continuity equation resembles the electromagnetic case stated by the Poynting theorem. The rate of energy transfer in space equals the rate of work done on the spin current, plus the energy flux. We find that both the energy flux and the rate of work done on the spin current depend on the DMI. In the case where there is no dissipation, we find a linear relation between the center of mass velocity and the DMI strength. Recently, this linear relation has been found using micromagnetic simulations. This phenomenon leads to focusing and caustics useful for microwave devices and magnon-based computation.

For the linear momentum, the continuity equation results in the equation of motion for the magnetization structure. While Thiele's equation describes the motion of magnetic vortices, for skyrmions it is necessary to consider their mass to accurately describe their motion. In our formalism, the mass arises naturally as a deformation of the structure due to thermal fluctuations. In figure 1, we show the motion of a skyrmion at different temperatures. As the mass depends on the thermal fluctuations the equation of motion is modified. Our result provides a means to measuring the skyrmion mass as a function of temperature.

Minimal model of the spin-transfer torque and spin pumping caused by spin Hall effect

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In the normal metal/ferromagnetic insulator bilayer (such as Pt/YIG) and the normal metal/ferromagnetic metal bilayer (such as Pt/Co) where spin injection and ejection are achieved by the spin Hall effect in the normal metal, we propose a minimal model based on quantum tunneling of spins to explain the spin-transfer torque and spin pumping caused by the spin Hall effect[1]. The ratio of their dampinglike to fieldlike component depends on the tunneling wave function that is strongly influenced by generic material properties such as interface s-d coupling, insulating gap, and layer thickness. Moreover, quantum tunneling enables spin transfer even if the normal metal and the ferromagnet are not in direct contact but separated by a thin oxide layer or vacuum, as recently demonstrated in the Pt/oxide/YIG trilayer, which realizes the spintronic analog of field electron emission[2]. Novel quantum effects, such as the quantum interference in metallic heterostructures, are predicted to significantly influence the spin dynamics in these systems.

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All electro-mechanical detection of ferromagnetic resonance via the Wiedemann Effect

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The Wiedemann effect (WE) is mechanical twisting phenomena of axially magnetized wire with the Oersted field created by electrical current flow [1]. Here, we present additional functionality of WE enables mechanical detection of ferromagnetic resonance (FMR). Our system is constructed with suspended Py(NiFe)/Pt bilayer structure; in which magnetization precession in the Py layer is induced by applied rf-Oersted field and by spin Hall current on the Pt layer [2], and electrostatic force is applied to drive the mechanical resonator. Internal coupling between the mechanical torsion induced by the magnetization change and longitudinal strain arising from WE facilitates detecting FMR by the resonance frequency shift of the mechanical flexural mode, which can be explained by field dependent magnetoelastic properties based on magnetic anisotropy. The piezoresistive motional signal responding of the mechanical vibration enables detection of mechanical resonance in all electo-mechanical manner at room temperature [3]. The mechanically detected FMR is consistent with FMR measured by spin-torque FMR measurement technique [2] which is well followed by the Kittel's formula. Further, spin-transfer torque contribution to the mechanical reaction is discussed with our numerical expectation. This demonstrate that our scheme guarantees the scalability to downscale for low power driving of FMR and is suitable applying nano-scale spintronics architecture for realization of integrating circuit.

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Dual Control of Giant Field-like Spin Torque in Spin Filter Tunnel Junction

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Recent discoveries in the ferromagnet/insulator/ferromagnet (FM/I/FM) magnetic tunnel junctions (MTJs) have demonstrated that the relative orientation of the two FM electrodes can be either altered by an external magnetic field, i.e. the tunneling magnetoresistance (TMR) effect, or controlled by a spin-polarized current, i.e. the current-induced magnetization reversal via the spin transfer torque (STT) effect. The spin-transfer, $T_{\parallel}$, and field-like, $T_{\perp}$, components of the STT originate from different components of the spin current accumulated at the FM/I interface and can be expressed in terms of the interplay of spin current densities and of the non-equilibrium interlayer exchange couplings [1], respectively, solely in collinear configurations.

The insulator in conventional FM/I/FM MTJs plays only a passive role in the spin-polarized transport. The evolution beyond passive components has broadened the quest for multifunctional spintronic devices consisting of spin-filter (SF) barriers [2], which exploits the separation of the barrier heights of the two spin channels that can be in turn tuned via an external magnetic field.

In this study [3], the tight binding calculations and the non-equilibrium Green's function formalism is employed to study the effect of the SF-barrier magnetization on the bias behavior of both components of STT in noncollinear FM/I/SF/I/FM junctions. We predict a giant $T_{\perp}$ in contrast to conventional FM/I/FM junctions, which has linear bias dependence, is independent of the SF thickness, and has sign reversal via magnetic field switching. Our results suggest that the novel dual manipulation of $T_{\perp}$ either by a magnetic field or bias can be employed for reading or writing processes, respectively, in the next-generation field-like-spin-torque MRAM (FLST-MRAMs). Finally, our newly derived general expressions of noncollinear $T_{\parallel}$ and $T_{\perp}$ allows the efficient calculation of the STT from collinear ab initio electronic structure calculations [4,5]. (Contract No. NSC 102-2112-M-008-004-MY3)

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Tunnel magneto-Seebeck effect in MgAlO and MgO based magnetic tunnel junctions

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In recent years, the application of a temperature gradient to a magnetic tunnel junction (MTJ) attracted a lot of attention within the field of spin caloritronics. Here, the tunnel magneto-Seebeck (TMS) effect was predicted [1] and measured with two different techniques [2,3]. This effect describes the change of the Seebeck coefficient of an MTJ depending on the relative magnetization alignment of the two ferromagnetic electrodes, i.e., different voltages are measured in the antiparallel and parallel state if a temperature gradient is applied to the MTJ. Later on, the experimentally more challenging tunnel magneto-Peltier effect, which is the reciprocal effect of the TMS effect, was observed as well [4].

Subsequent studies focused on the improvement of effect sizes, film quality and the elimination of spurious signals. In particular, a giant TMS ratio of -3000% was found when applying an additional bias voltage across the MTJ [5], a significant improvement of the TMS ratio was obtained with the usage of half metallic ferromagnetic Heusler electrodes such as CoFeAl or CoFeSi [6] and parasitic effects originating from semiconducting substrates were clarified [7].

In our study, we focus on MTJs with MgAlO (MAO) barrier, since MAO is predicted to enable coherent tunneling [8] and, at the same time, exhibit an advantageous lattice mismatch (approx. 1%) with standard ferromagnetic electrodes such as Fe/CoFe/CoFeB when compared to MgO (approx. 5%) [9]. We are able to show that the symmetric contributions of the VI curves of our MAO based MTJs are explainable by the asymmetric properties of the barrier itself and, thus, are not able to unambiguously identify any contribution of an intrinsic TMS [10], as proposed by Zhang, Teixeria *et al.* [11,12].

Additionally, we prepared MTJs with MAO as well as MgO barriers with thicknesses ranging from 1 to 3nm to study the barrier thickness dependence of the TMS effect and to compare with theoretical predictions [13]. In case of MAO, we find a distinct maximum of the TMS effect at a nominal barrier thickness of 2.6nm, almost doubling the effect ratio measured at standard barrier thicknesses of 1.8nm to 2.0nm.

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Stern-Gerlach Dynamics

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The Stern-Gerlach effect displays the existence of spin, introduces entanglement between spin and space, and exemplifies measurement. As such it has become conceptually and pedagogically central to our understanding of quantum mechanics. How exactly the mechanics of spin enters in Stern-Gerlach is a complex process with a long story. In this contribution I review quantum mechanical methods to analyze the spin currents that enter Stern-Gerlach dynamics and contrast them to the omnipresent semi-classical treatment of the Stern-Gerlach effect.

Temperature Dependence Study of Spin Orbit Torque in Cu-Au Alloy

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Using an optimized fabrication, we have obtained a high quality $Cu_{40}Au_{60}$ /$Ni_{80}Fe_{20}$/Ti layered structures. We have studied the transport over a wide temperature ranging from 20 K to 300 K. To evaluate the size of spin orbit torques, we examine the harmonic Hall voltage measurement in this in-plane magnetized system. We find a striking difference in the temperature dependence of the two components: the damping-like term increases whereas field-like term decreases with an increasing temperature. We found a larger SOT in the thicker NM layer samples for both damping-like torque and field-like torque, which satisfied the diffusive SHE model and the spin Hall angle is significant larger in the alloy compared to the pure gold or copper. Linear scaling relation between spin Hall angle and resistivity suggests skew scattering mechanism as the main contributor of spin orbit torque.

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Antiferromagnetic Domain Wall as Spin Wave Polarizer and Retarder

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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 without Joule heating. Like the manipulation of its optical counterpart, the ability to manipulate spin wave polar- ization is not only important but also fundamental for magnonics, an emerging field in information processing that uses the low-dissipation spin wave as the information carrier. Due to the broken time reversal symmetry, ferromagnets can only accommodate the right-handed circularly polarized spin wave modes, which leaves no freedom for polarization manipulation. In contrast, antiferromagnets, with time reversal symmetry restored, have both left and right circular polarizations, as well as all linear and elliptical polarizations. Here we demonstrate theoretically and confirm by micromagnetic simulations that, in the presence of Dzyaloshinskii-Moriya interaction (DMI), an antiferromagnetic domain wall acts naturally as a spin wave polarizer or a spin wave retarder (waveplate). Our findings provide extremely simple yet flexible routes toward magnonic information processing by harnessing the polarization degree of freedom of spin wave.

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