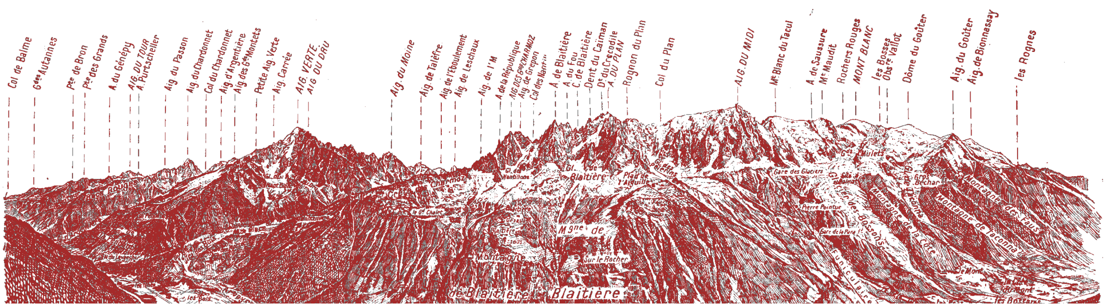
ÉCOLE DE
PHYSIQUE
DES HOUCHES

Spin Mechanics$^{(5)}$ and Nano-MRI$^{(6)}$

February 11$^{\mathrm{th}}$-16$^{\mathrm{th}}$, 2018



© Guide Vallot

Spin Mechanics[5] and Nano-MRI[6]

École de Physique des Houches, Chamonix, France

February 11$^{\text{th}}$-16$^{\text{th}}$, 2018

Organizing committee

- Olivier Arcizet,
  Institut Néel, CNRS / Université Grenoble-Alpes
  25 r des Martyrs, 38042 Grenoble, France.
- Olivier Klein,
  SPINTEC, CEA-Grenoble / Université Grenoble-Alpes / CNRS,
  17 r des Martyrs, 38054 Grenoble, France.
- Benjamin Pigeau,
  Institut Néel, CNRS / Université Grenoble-Alpes
  25 r des Martyrs, 38042 Grenoble, France.

Scientific committee

- Gerrit E.W. Bauer,
  Tohoku University, Japan.
  ✉: g.e.bauer@tudelft.nl
- Ania Bleszynski Jayich,
  University of Santa Barbara, United States .
  ✉: ania@physics.ucsb.edu
- Raffi Budakian,
  University of Waterloo, Canada.
  ✉: rbudakian@uwaterloo.ca
- Eugene Chudnovsky,
  New York, United States.
  ✉: eugene.chudnovsky@lehman.cuny.edu
- Thierry Debuischert,
  Thales TRT, France.
  ✉: thierry.debuisschert@thalesgroup.com
- Christian Degen,
  Technische Hochschule Zürich, Switzerland.
  ✉: degenc@ethz.ch
- Mark Freeman,
  University of Alberta, Canada.
  ✉: mark.freeman@ualberta.ca
- Sebastian Gönnenwein,
  Dresden University, Germany.
  ✉: sebastian.goennenwein@tu-dresden.de
- Chris Hammel,
  Ohio State University, United States.
  ✉: hammel@physics.osu.edu
- Vincent Jacques,
  Laboratoire Charles Coulomb, France.
  ✉: vincent.jacques@umontpellier.fr
- John Marohn,
  Cornell University, United States.
  ✉: john.marohn@cornell.edu
- Fabio Pistolesi,
  Laboratoire Ondes et Matière d'Aquitaine, France.
  ✉: fabio.pistolesi@u-bordeaux.fr
- Peter Rabl,
  Atominstitut TU Wien, Austria.
  ✉: peter.rabl@ati.ac.at
- Eiji Saitoh,
  Tohoku University, Japan.
  ✉: saitoheijig@gmail.com
- Philip Treutlein,
  University of Basel, Switzerland.
  ✉: philipp.treutlein@unibas.ch,
- Wolfgang Wernsdorfer,
  Karlsruhe University, Germany.
  ✉: wolfgang.wernsdorfer@kit.edu

Sponsors

Welcome Address

Welcome to the joint workshop Spin Mechanics and Nano-MRI, whose purpose is to bring together these two communities interested in the broader development of novel techniques to excite and detect spin dynamics at the nanoscale. Following invigorating meetings in USA, Switzerland, Japan, Germany, and Canada, the Université Grenoble-Alpes / CNRS / CEA-Grenoble are honoured to host this workshop in Chamonix, nestled in the magnificent settings of the Mont Blanc. We are especially happy to welcome you here at the École de Physique des Houches, which has the notoriety of inviting future Nobel prize winner! This workshop brings together leading researchers working on all different perspectives of spin mechanics and nano-MRI which we hope will stimulate further progress in the understanding and control of coupled spin-mechanical-optical-electronic systems. The program will include 42 invited oral presentations and 24 posters. In addition 4 tutorials 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 the french Alps. We look forward to a week of inspiring scientific discussion and we wish you a rewarding and fruitful experience.
On Behalf of the Organizing Committee.

Contents

About the school

Three types of events are hosted by the school:

The Summer School sessions

The summer school sessions are aimed primarily towards advanced students and young postdoctoral researchers, willing to deepen their knowledge or to start in a new field.

The sessions last from 4 to 5 weeks and the courses are long (up to 12 hours of lectures for a given subject). This allows a thorough pedagogical approach, up to the frontiers of modern research, and to cover all aspects of a given subject. This long duration also favors exchanges, discussions and working groups between participants.

The summer school programs are selected by the Board about two years in advance. If you have suggestions, or if you are interested in organizing a session, contact the Director of the School.

The Workshops

The rest of the year is dedicated to workshops, lasting one, two or sometimes three weeks, which bring together theoreticians and experimentalists. Participants exchange knowledge and are confronted by different view points that may lead to the definition of new research programmes. Meetings of the Center of Physics are usually organised in order to leave enough time for discussion in groups that meet in small, separate work rooms.

Any project of workshop at the Center must be first discussed with the Director of the School.

The Predoctoral School

The Predoctoral School brings together young beginners in scientific research.The aim of the Predoctoral School is to help them acquire a broader base in physics and place their thesis work in proper context. It can also prepare them for a richer scientific career by avoiding too much specialisation too early.

History

Les Houches School of Physics has been welcoming physicists from around the world since 1951. The School has seen the biggest names in modern physics training young researchers at the start of their careers, some of whom have since won Nobel prizes for physics. The school perpetuates a tradition of excellence, while continuing to adapt to the evolutions of science.

The origins of the school

Les Houches School of Physics was founded in 1951 by a young French physicist, Cécile DeWitt-Morette. She wanted to help to rebuild her country, which, like so many others in the wake of the war, was lagging seriously behind in the teaching and practice of modern physics.

The dynamic and visionary Cécile DeWitt-Morette succeeded in building a school, with the few resources available, to which leading world specialists would come to share their knowledge with groups of around thirty students from different countries (mostly France and other European countries, but not only). The setting is idyllic, lying above the Chamonix valley, in full view of the Mont-Blanc mountains. However, back then, living conditions were very rudimentary: the sessions lasted eight weeks (the two months of the university summer holidays), staying in mountain chalets will no facilities, a few kilometres from Les Houches village.

Immediate recognition

History relates that the first class, on quantic mechanics, was held in 1951 by Léon van Hove. The school quickly attracted interest from the biggest names in physics, including Enrico Fermi, Wolfgang Pauli, Murray Gell-Mann and John Bardeen, to name but a few. Cécile DeWitt-Morette also promoted unknown youngsters: in 1951, Walter Kohn (1998 Nobel prize for chemistry), aged 28, gave a class on solid state physics. Philippe Nozières was asked to organise a session on the N-body problem in 1958, when he was just 26 years old. The school's students have included Pierre-Gilles de Gennes, Georges Charpak, and Claude Cohen-Tannoudji, future winners of the Nobel prize for physics, and later on, mathematician Alain Connes (Fields medal 1982). All have had the opportunity to testify their immense gratitude to the school.

- Nobel prizes who came to les Houches:

P.W. Anderson, came to les Houches in 1967. Nobel prize in 1977.

J. Bardeen, came to les Houches in 1956. Nobel prizes in 1956 and 1972.

N. Bloembergen , came to les Houches in 1964. Nobel prize in 1981.

A. Bohr, came to les Houches in 1955. Nobel prize in 1975.

A. Chamberlain, came to les Houches in 1957. Nobel prize in 1959.

S. Chu, came to les Houches in 1999. Nobel prize in 1997.

C. Cohen-Tannoudji, came to les Houches in 1964. Nobel prize in 1997.

A. Connes, came to les Houches in 1970. Fields Medalist in 1982.

L.N. Cooper, came to les Houches. Nobel prize in 1972.

E.A. Cornell, came to les Houches in 1999. Nobel prize in 2001.

F. Englert, came to les Houches in 1979. Nobel prize in 2013.

E. Fermi, came to les Houches in 1954. Nobel prize in 1938.

R. Feynman, came to les Houches in 1976. Nobel prize in 1965.

R. Glauber, came to les Houches in 1954 and 1964. Nobel prize in 2005.

M. Gell-Mann, came to les Houches in 1952. Nobel prize in 1969.

P.G. de Gennes, came to les Houches in 1953 and 1967. Nobel prize in 1991.

D.J. Gross, came to les Houches in 1975. Nobel prize in 2004.

D.M. Haldane, came to les Houches in 2008. Nobel prize in 2016.

S. Haroche, came to les Houches in 1990. Nobel prize in 2012.

G. Hooft, came to les Houches in 1975. Nobel prize in 1999.

J.H. Jensen, came to les Houches in 1953. Nobel prize in 1963.

A. Kastler, came to les Houches in 1951. Nobel prize in 1966.

W. Ketterle, came to les Houches in 1999 and 2010. Nobel prize in 2001.

W. Kohn, came to les Houches in 1951 and 1967. Nobel prize in 2003.

W. Lamb, came to les Houches in 1964. Nobel prize in 1955.

T.D. Lee, came to les Houches in 1975. Nobel prize in 1957.

A. Leggett, came to les Houches in 1986. Nobel prize in 2003.

A.B. McDonald, came to les Houches in 1994. Nobel prize in 2015.

B. Mottelson, came to les Houches in 1958. Nobel prize in 1975.

L. Néel, came to les Houches in 1956 and 1961. Nobel prize in 1970.

W. Pauli, came to les Houches in 1951, 1952 and 1955. Nobel prize in 1945.

A. Penzias, came to les Houches in 1974. Nobel prize in 1978.

W.D. Phillips, came to les Houches in 1999 and 2010. Nobel prize in 1997.

N. Ramsey, came to les Houches in 1955. Nobel prize in 1989.

A. Salam, came to les Houches in 1957. Nobel prize in 1979.

E. Segré, came to les Houches in 1951. Nobel prize in 1959.

B. Schmidt, came to les Houches in 1990. Nobel prize in 2011.

J.R. Schrieffer, came to les Houches in 1958. Nobel prize in 1972.

J. Schwinger, came to les Houches in 1955. Nobel prize in 1965.

W. Shockley, came to les Houches in 1953. Nobel prize in 1956.

J. Steinberger, came to les Houches in 1960. Nobel prize in 1988.

R. Thom, came to les Houches. Fields Medalist in 1958.

K. S. Thorne, came to Les Houches in 1963, 1966, 1972, 1982. Nobel prize in 2017.

D.J. Thouless, came to les Houches in 1978. Nobel prize in 2016.

C. Townes, came to les Houches in 1955. Nobel prize in 1964.

JG Veltman, came to les Houches in 1976. Nobel prize in 1999.

EP Wigner, came to les Houches in 1955. Nobel prize in 1963.

KG Wilson, came to les Houches in 1975. Nobel prize in 1982.

E. Witten, came to les Houches. Fields Medalist in 1990.

C.N. Yang, came to les Houches in 1957. Nobel prize in 1958.

- Famous professors and students who came to les Houches

ALAIN CONNES,
Fields Medalist 1982

CLAUDE COHEN TANNOUDJI,
Nobel Prize 1997

ENRICO FERMI,
Nobel Prize 1938

JOHN BARDEEN,
Nobel Prize 1956 and 1972

LEON VAN HOVE,
CERN director 1976-1980

PIERRE GILLES DE GENNES,
Nobel prize 1991

RICHARD FEYNMAN,
Nobel Prize 1965

WOLFGANG PAULI,
Nobel Prize 1945

During the 1950s and 60s, Les Houches School of Physics had a considerable impact on the development of top level physics in France and beyond. Its operational concept has been copied throughout the world. NATO, through Norman Ramsey, very quickly offered its support to the school, and launched its Advanced Study Institutes in 1958, based on the model of Les Houches.

The school today

The school has changed over the years, although some of its traditions have been preserved and it continues to attract world leaders in the field. The main events of the year remain the two summer schools (in-depth, month-long courses in July and August on innovative themes). These form a kind of post-doctoral school, which has remained something of a trademark for Les Houches. Various courses and shorter, more specialised conferences are organised throughout the year in the "Physics Centre". Some are intended for all researchers (from beginners to experts) while others are primarily designed for post-graduate students (doctoral courses). Aside from the educational aspects, these meetings also enable the development of scientific collaborations. Effective professional and social networks are frequent by-products of Les Houches schools.

The school has kept up with the evolutions of science, opening up to peripheral fields, such as mathematics, earth sciences, chemistry and biology. The interactions between these disciplines are actually very often at the core of the issues investigated nowadays in Les Houches.

Major milestones

- 1977: creation of the "Physics Centre"

- More specialised, shorter conferences are now organised all year round, with the specific ambition of promoting more original themes, bringing together physicists from different cultures and scientists from different disciplines. 1988: creation of the "Pre-doctoral School"

  More general courses for young researchers working on their theses, or even before starting. Today, the term "doctoral course" is more commonly used.

Access

By plane

Geneva Airport is 1 hour drive from les Houches. Once you have landed, you can reach the school using a shuttle service, the regular bus service or by train.

Shuttle service

The simplest way is to use a shuttle service (approximately 40 euros up to the school, book at least three days in advance). If you already have your return date, we would recommend to book a return trip. > Consult the list of companies

Beware: we do not recommend the Alpybus company (they do not reach the school).

Price discounts are available with Mountain Drop-Offs. To find Mountain Drop-Offs' meeting point easily in the Geneva Airport please consult the video How to find Mountain Drop-Offs at Geneva Airport.

Regular bus service

There is also a regular bus service between Geneva and Les Houches (only once or twice a day). One should then take a taxi for the last 5 kms from the Les Houches village to the school (the total cost is similar to that of the limousine).

Train

One can also travel from Geneva to Les Houches by train (+ taxi from the train station to the School), but it is quite complicated (3 connections) and long (go through Annemasse on the French side or through Martigny on the Swiss side).

By train

Arrival at the Les Houches station, with one change at Saint-Gervais (from France), or at Martigny (from Switzerland). There are about 10 trains per day between St Gervais and Les Houches (schedules, 20mn trip). Then we strongly advise you to take a taxi to go up to the school (5km).

Taxi phone numbers :

- (+33/0)6-07-26-36-62,
- (+33/0)6.22.75.19.37,
- (+33/ 0)6.12.35.30.72.

By road

Les Houches are easily accessible from France (A41 highway), from Switzerland (Martigny and Col des Montets) and from Italy through the Mont Blanc Tunnel. From Geneva and Le Fayet

8km before Chamonix, 300 m after passing under the tunnel, bear right by the first road out for "Les Houches Bellevue". When arriving at the cable car station "Bellevue", turn right and continue upwards (roughly 2 km starting from the teleferic). 500m after the cable car station "Prarion", turn left and follow small arrows at crossroads. Continue up to the end of Route de la Côte des Chavants. Here you are!

From Chamonix

Bear right for "Les Houches-Chef-Lieu", turn right in Les Houches, go ahead at the cable car station "Bellevue". Then proceed as above.

Cars may be rented from Geneva and from Chamonix, it is useful to make a reservation. What to do in Les Houches and in the valley?

See for example: `http://www.leshouches.com` and `http://www.chamonix.com`

ADDRESS OF THE SCHOOL:

Les Houches School of Physics
140 Chemin de la Côte
F-74310 Les Houches

Open street maps

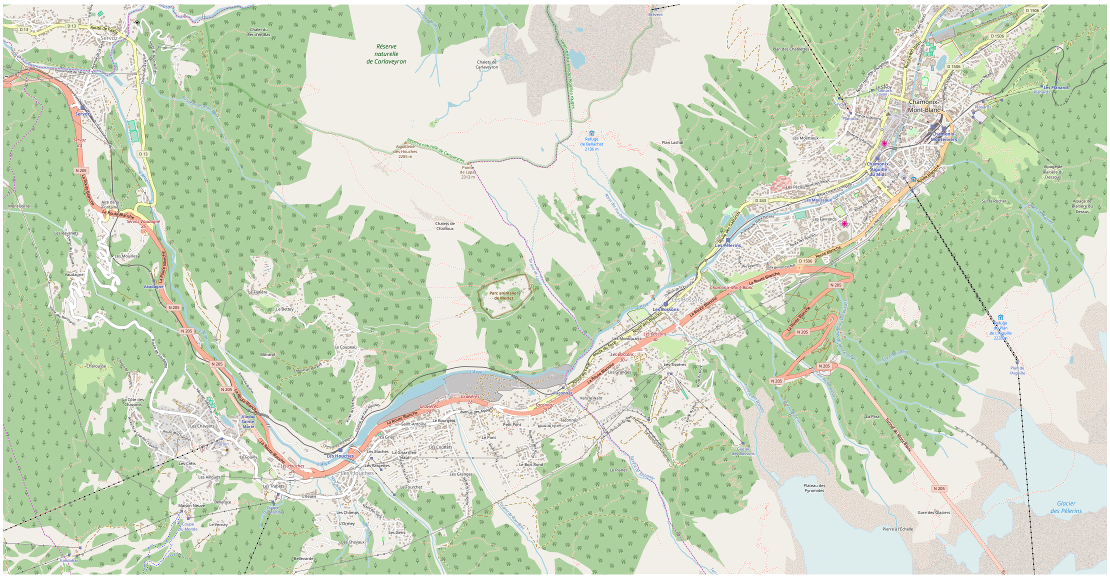


Figure 1: Village de Chamonix

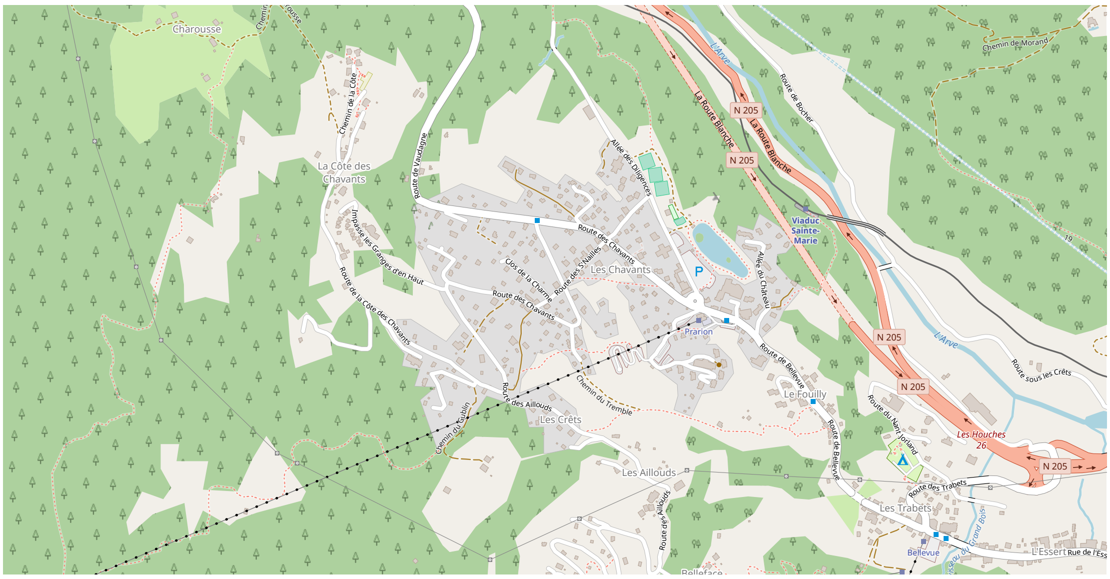
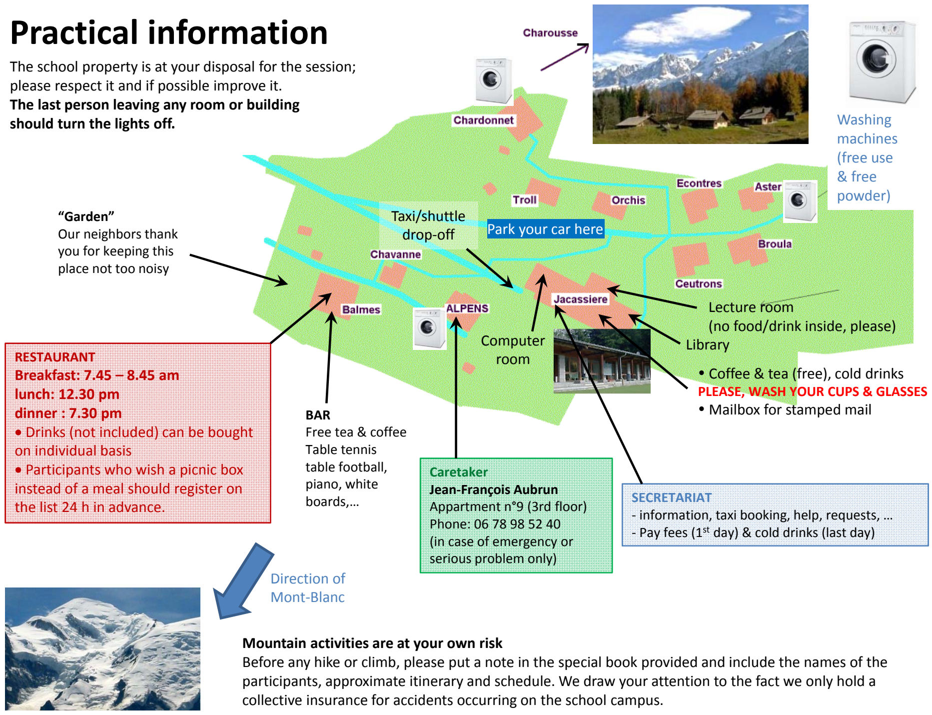
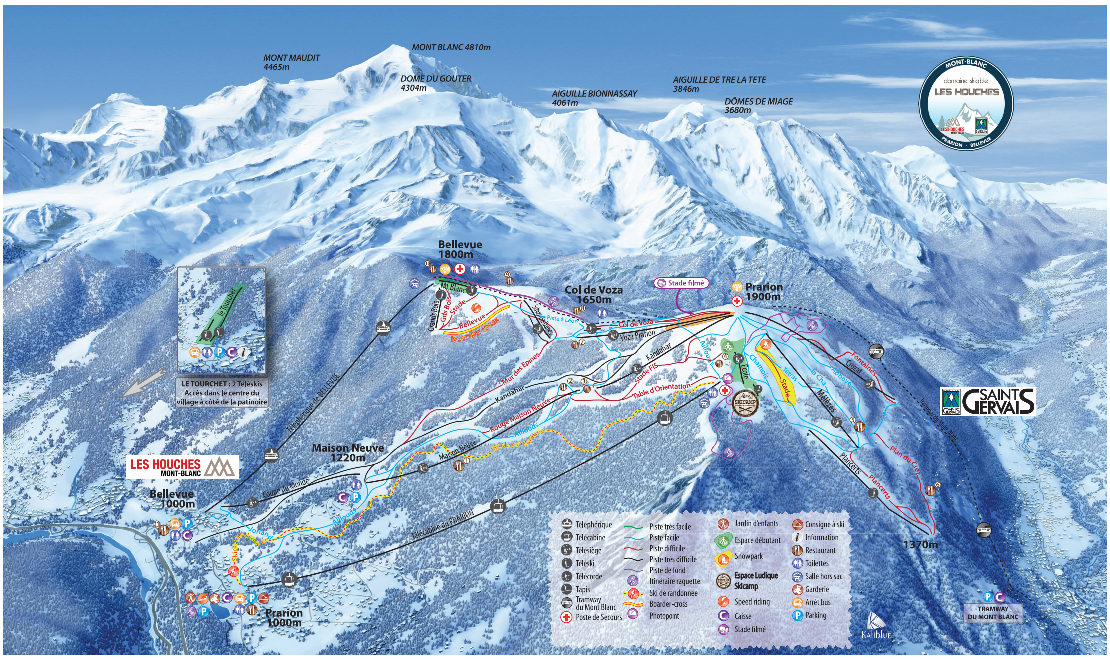


Figure 2: Hameaux des Houches

Map of the École de Physique



Ski slopes: Prarion – Saint-Gervais



Timetable of spin mechanics and nano-MRI workshop

	Sunday, Feb 11	Monday, Feb 12	Tuesday, Feb 13	Wednesday, Feb 14	Thursday, Feb 15	Friday, Feb 16
07:00 - 08:00		07:30 Breakfeast	07:30 Breakfeast	07:30 Breakfeast	07:30 Breakfeast	07:30 Breakfeast
08:00 - 09:00		08:15 Welcome Address 08:30 P. Rabl T01	08:30 V. Jacques T02	08:30 M. Freeman T03	08:30 C. Fermon T04	08:30 A. Slavin I33
09:00 - 10:00		09:40 W. Wernsdorfer I01	09:40 A. Bleszynski Jayich I08	09:40 M. Poggio I15	09:40 S. Probst I25	09:05 J. Barker I34 09:40 S. Goennenwein
10:00 - 11:00		10:15 Coffee break 10:45 G. Fuchs I02	10:15 Coffee break 10:45 P.C. Hammel I09	10:15 Coffee break 10:45 G. de Loubens I16	10:15 Coffee break 10:45 J.P. Tetienne I26	10:15 Coffee break 10:45 G. Schmidt I36
11:00 - 12:00		11:20 A. Bachtold I03 11:55 F. Pistolesi I04	11:20 P. Maletinsky I10 11:55 T. van der Sar I11	11:20 V. Sauer I17 11:55 Y. Band I18	11:20 M. Nesladek I27 11:55 A. Retzker I28	11:20 Y. Tao I37 11:55 H. Schultheiss I38
12:00 - 13:00		12:30 Lunch	12:30 Lunch	12:30 Lunch	12:30 Lunch	12:30 Lunch
13:00 - 14:00		13:30 Informal discussions P01	13:30 Informal discussions P02	13:30 Informal discussions P01	13:30 Informal discussions P01	
14:00 - 15:00						
15:00 - 16:00						
16:00 - 17:00	16:00 Registration					
17:00 - 18:00		17:15 G. Bauer I05 17:50 Y. Nozaki I06	17:15 D. Mason I12 17:50 T. Oosterkamp I13	17:15 R. Budakian I19 17:50 C. Degen I20	17:15 F. Balestro I29 17:55 C.M. Hu I30	
18:00 - 19:00		18:25 E. Saitoh I07	18:25 H. Huebl I14	18:25 J. Marohn I21	18:25 A. Finkler I31	
19:00 - 20:00	19:30 Dinner	19:00 Dinner	19:00 Dinner	19:00 Dinner	19:00 E. Chudnovsky I32 19:35 Banquet	
20:00 - 21:00	20:30 Welcome cocktail	20:00 Poster 1 P01	20:00 Poster 2 P02	20:00 Y. Tserkovnyak I22 20:35 R. Duine I23		
21:00 - 22:00				21:10 M. Sato I24		

Program

Monday, Feb 12th

07:30 - 08:15 *Breakfeast*

08:15 - 08:30 *Welcome Address*

Session 1: Hybrid systems

08:30 - 09:40 *T01 : Tutorial*

Hybrid Spin Mechanical Systems

Peter Rabl
Atominstitut, TU Wien, Wiedner Hauptstrasse 8-10, 1040 Wien, Austria

09:40 - 10:15 *I01 : Invited Talk*

Quantum Einstein de Haas Effect studied with molecular spintronic devices

Wolfgang Wernsdorfer
PHI-INT, KIT, 76131 Karlsruhe, Germany

10:15 - 10:45 *Nutrition Break*

10:45 - 11:20 *I02 : Invited Talk*

Quantum Control Over Diamond Nitrogen-Vacancy Centers Using a Mechanical Resonator

Gregory Fuchs
Cornell University, 228 Clark Hall, Cornell University, Ithaca, NY 14853, United States

11:20 - 11:55 *I03 : Invited Talk*

Towards spin detection with a nanotube resonator

Adrian Bachtold
ICFO, Barcelona, Spain

11:55 - 12:30 *I04 : Invited Talk*

Tunable spin-polaron state in a singly clamped semiconducting carbon nanotube

Fabio Pistolesi
Université de Bordeaux and CNRS, LOMA, Cours de la liberation, Talence, France

12:30 - 13:30 *Lunch*

13:30 - 17:15 *Informal discussions*

Session 2: Hybrid systems

17:15 - 17:50 *I05 : Invited Talk*

Spin mechanics with magnetic insulators

Gerrit Bauer
Institute for Materials Research, Tohoku University, Aoba-ku, Katahira 2-1-1 Sendai 980-8577, Japan

17:50 - 18:25 *I06 : Invited Talk*

Alternating spin current generation in Cu thin film by injecting surface acoustic waves

Yukio Nozaki
Keio University, Yokohama 223-8522, Japan

18:25 - 19:00 *I07 : Invited Talk*

Spinon and Phonon in Spintronics

Eiji Saitoh
WPI-Advanced Institute for Materials Research, Tohoku University, 2-1-1 Katahira Aoba-ku, Sendai, 980-8577, Japan

19:00 - 20:00	*Dinner*
20:00 - 21:45	*Poster 1*

Tuesday, Feb 13th

07:30 - 08:30 *Breakfeast*

Session 1: NV magnetometry

08:30 - 09:40 *T02 : Tutorial*

Imaging magnetic field at the nanoscale with a single spin microscope

Vincent Jacques
Laboratoire Charles Coulomb, Université de Montpellier and CNRS, UMR 5221, Laboratoire Charles Coulomb, Université de Montpellier, Bat. 21 CC074, 1 place Eugène Bataillon, 34095 Montpellier cedex, France

09:40 - 10:15 *I08 : Invited Talk*

Quantum sensing and imaging with diamond spins

Ania Bleszynski Jayich
University of California Santa Barbara, UCSB Physics Dept, United States

10:15 - 10:45 *Nutrition Break*

10:45 - 11:20 *I09 : Invited Talk*

Broadband Paramagnetic Resonance Spectroscopy Through Non-resonant Coupling to NV Centers in Diamond

P. Chris Hammel
Ohio State University, Department of Physics, 191 W. Woodruff Ave, Columbus, OH, USA

11:20 - 11:55 *I10 : Invited Talk*

Quantum sensing with single spins in diamond nanostructures

Patrick Maletinsky
Basel University, Klingelbergstrasse 82, 4056 Basel, Switzerland

11:55 - 12:30 *I11 : Invited Talk*

Probing correlated-spin dynamics using single-spin magnetometry

Toeno van der Sar

Delft University of Technology, Lorentzweg 1, 2628CJ, Delft, Netherlands

12:30 - 13:30 *Lunch*

13:30 - 17:15 *Informal discussions*

Session 1: Ultra-sensitive mechanical sensors

17:15 - 17:50 *I12 : Invited Talk*

Ultracoherent Mechanical Oscillators for Quantum Optomechanics and Hybrid Systems

David Mason

Niels Bohr Institute, Blegdamsvej 17, 2100 København Ø, Denmark

17:50 - 18:25 *I13 : Invited Talk*

Magnetic resonance force microscopy at temperatures well below 100 mK

Tjerk Oosterkamp

Kamerlingh Onnes laboratory, Leiden University, Niels Bohrweg 2, 2333CA LEIDEN, Netherlands

18:25 - 19:00 *I14 : Invited Talk*

Stressing Spins and Tuning Strings

Hans Huebl

Walther-Meissner-Institut, Walther-Meissner-Str. 8, 85748 Garching, Germany

19:00 - 20:00 *Dinner*

20:00 - 21:45 *Poster 2*

07:30 - 08:30 *Breakfeast*

Session 2: Ultra-sensitive mechanical sensors

08:30 - 09:40 *T03 : Tutorial*

Nano- and Optomechanics-enabled Magnetometries

Mark R. Freeman
University of Alberta, 3-195 CCIS University of Alberta, Edmonton AB T6G 2E1, Canada

09:40 - 10:15 *I15 : Invited Talk*

Nanomechanics and Nanomagnetism

Martino Poggio
Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland

10:15 - 10:45 *Nutrition Break*

10:45 - 11:20 *I16 : Invited Talk*

Deeply nonlinear ferromagnetic resonance in a YIG nano-disk: MRFM spectroscopy of spin-wave instabilities

Grégoire de Loubens
Service de Physique de l'Etat Condensé, CEA, CNRS, Université Paris-Saclay, Orme des Mersisiers, CEA Saclay, 91191 Gif-sur-Yvette, France

11:20 - 11:55 *I17 : Invited Talk*

Nanomechanical torque magnetometry on bilayer Co/CoO$_x$ micro-disks

Vincent T. K. Sauer
Department of Physics, University of Alberta and Nanotechnology Research Centre, National Research Council 4-181 CCIS, University of Alberta, Edmonton, AB T6G 2E1, and , 11421 Saskatchewan Dr NW, Edmonton, AB T6G 2M9, 4-181 CCIS, University of Alberta, Edmonton, AB T6G 2E1, Canada

11:55 - 12:30 *I18 : Invited Talk*

Dynamics of a Magnetic Needle in a Magnetic field: Magnetometer Sensitivity to Landau–Lifshitz–Gilbert Damping

Yehuda Band

Ben-Gurion University, P.O.B. 653 Beer-Sheva 8410501, Israel, Israel

12:30 - 13:30 *Lunch*

13:30 - 17:15 *Informal discussions*

Session 1: nano - Magnetic Resonance Imaging

17:15 - 17:50 *I19 : Invited Talk*

High-resolution nanoscale nuclear magnetic resonance imaging and spectroscopy

Raffi Budakian

University of Waterloo, Department of Physics and Institute for Quantum Computing, 200 University Ave. W, Waterloo, ON N2L3G1, Canada

17:50 - 18:25 *I20 : Invited Talk*

Advances in Magnetic Resonance Force Microscopy

Christian Degen

ETH Zurich, Department of Physics, Otto Stern Weg 1, 8093 Zurich, Switzerland

18:25 - 19:00 *I21 : Invited Talk*

Harnessing electron-spin labels and dynamic nuclear polarization in scanned-probe nanoscale magnetic resonance imaging experiments

John Marohn

Department of Chemistry and Chemical Biology, Cornell University Ithaca, New York 14853-1301, USA

Session 1: Spintronics

20:00 - 20:35 *I22 : Invited Talk*

Spin hydrodynamics in insulators

Yaroslav Tserkovnyak
UCLA, Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095, United States

20:35 - 21:10 *I23 : Invited Talk*

Spin-rotation coupling in viscous electron fluids

Rembert Duine
Institute for Theoretical Physics, Utrecht University, Institute for Theoretical Physics, Utrecht University, Leuvenlaan 4, 3584 CE Utrecht, The Netherlands, Netherlands

21:10 - 21:45 *I24 : Invited Talk*

Ultrafast Spintronics with Topological Lasers

Masahiro Sato
Ibaraki University, 2-1-1 Bunkyo, Mito, Ibaraki 310-8512, Japan, Japan

Thursday, Feb 15th

07:30 - 08:30 *Breakfeast*

Session 2: nano - Magnetic Resonance Imaging

08:30 - 09:40 *T04 : Tutorial*

Magnetic Resonance Spectroscopy

Claude Fermon

SPEC, CEA-Saclay, 91191 Gif-Sur-Yvette, France

09:40 - 10:15 *I25 : Invited Talk*

High sensitivity quantum limited electron-spin resonance spectroscopy

Sebastian Probst

CEA Saclay, Quantronics Group, SPEC / CEA Saclay, 91191 Gif-sur-Yvette CEDEX, France

10:15 - 10:45 *Nutrition Break*

10:45 - 11:20 *I26 : Invited Talk*

Nanoscale detection and hyperpolarisation of nuclear spins using cross-relaxation in diamond

Jean-Philippe Tetienne

University of Melbourne, School of Physics, Parkville, VIC 3010, Australia

11:20 - 11:55 *I27 : Invited Talk*

Electrically Detected Magnetic Resonance of NV Spin States in Diamond: Towards Coherent Driving and readout of Single Spin Qubits

Milos Nesladek

University Hasselt and IMEC, Milos Nesladek (invited), Belgium

11:55 - 12:30 *I28 : Invited Talk*

Limits on spectral resolution measurements by quantum probes for nano NMR

Alex Retzker

The Hebrew University, Racah Institute of Physics, Edmond J. Safra campus. Danciger B Building, room 203, Hebrew University of Jerusalem, Israel 91904, Israel

12:30 - 13:30 *Lunch*

13:30 - 17:15 *Informal discussions*

Session 1: Quantum Information

17:15 - 17:55 *I29 : Invited Talk*

Operating Quantum States in Single Magnetic Molecules: Implementation of Quantum Gates and Algorithm

Franck Balestro
UGA-CNRS-Institut Néel, 25 rue des martyrs, 38042 Grenoble cedex 9, France

17:55 - 18:25 *I30 : Invited Talk*

Cavity Spintronics

Can-Ming Hu
University of Manitoba, University of Manitoba, Winnipeg, R3T 2N2, Canada

18:25 - 19:00 *I31 : Invited Talk*

Magnetic Resonance of Correlated Spins using a Single Spin Sensor

Amit Finkler
Weizmann Institute of Science, 234 Herzl St., Rehovot 7610001, Israel

19:00 - 19:35 *I32 : Invited Talk*

Skyrmions in 2D Spin Systems with Disorder

Eugene Chudnovsky
CUNY Lehman College and Graduate School, Bronx, NY 10468-1589, U.S.A.

19:35 - 21:45 *Banquet*

07:30 - 08:30 *Breakfeast*

Session 2: Spintronics

08:30 - 09:05 *I33 : Invited Talk*

Current-induced dynamics in antiferromagnets: generation of THz-frequency signals

Andrei N. Slavin
Oakland University, 146 Library Drive, Rochester, MI 48309-4479, United States

09:05 - 09:40 *I34 : Invited Talk*

Atomistic spin dynamics of magnetic insulators

Joseph Barker
Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan

09:40 - 10:45 *I35 : Invited Talk*

Pure spin currents in magnetic insulator/metal hybrid structures

Sebastian T. B. Goennenwein
Institut für Festkörper- und Materialphysik (IFMP), Technische Universität Dresden, 01062 Dresden, Germany

10:15 - 10:45 *Nutrition Break*

10:45 - 11:20 *I36 : Invited Talk*

Making high quality freestanding magnon nanoresonators

Georg Schmidt
Institut für Physik, Universität Halle, Von-Danckelmann-Platz 3, 06120 Halle, Germany

11:20 - 11:55 *I37 : Invited Talk*

Single-crystalline FeCo nanowires as ultra-high magnetic gradient sources

Ye Tao
Rowland Institute at Harvard, 100 Edwin H Land Blvd, Cambridge, MA 02142, United States

11:55 - 12:30 *I38 : Invited Talk*

Magnon transport by spin textures

Helmut Schultheiss

Helmholtz-Center Dresden-Rossendorf, Bautzner Landstraße 400, 01328 Dresden, Germany

12:30 - 13:30 *Lunch*

Abstracts

Hybrid Spin Mechanical Systems

Peter Rabl†

Atominstitut, TU Wien, Wiedner Hauptstrasse 8-10, 1040 Wien, Austria

† Email: peter.rabl@ati.ac.at

The coherent integration of individual quantum systems into larger networks is one of the main challenges for the realization of quantum technologies. The rapid progress in the fabrication and control of micro- and nanomechanical systems opens many new possibilities to achieve this goal by using functionalized micro- and nanomechanical resonators for the conversion and transduction of quantum signals between different spin-, charge-, or optical qubit systems. In this tutorial I will review some of the basic schemes for coupling mechanical resonators to other microscopic quantum systems with the main focus being placed on spin qubits associated with defect centers in diamond. In the second part of the tutorial I will then discuss how such hybrid spin-mechanics systems can potentially be used for quantum information processing applications.

Inv. I01
Monday
09:40

Quantum Einstein de Haas Effect studied with molecular spintronic devices

Wolfgang Wernsdorfer†

PHI-INT, KIT, 76131 Karlsruhe, Germany

† Email: wolfgang.wernsdorfer@kit.edu

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. 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.[1–3] 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 molecule's quantum tunneling of magnetization.[4]

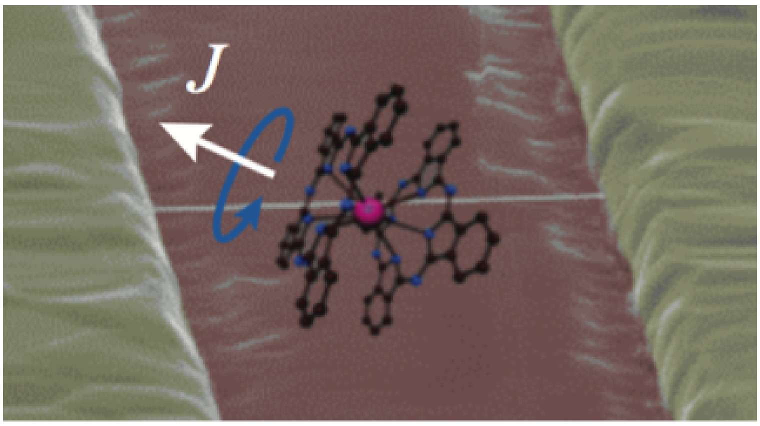


Figure 1: (Color online) The false color scanning electron micrograph shows a suspended carbon nanotube with a local metallic backgate (red) functionalized with a TbPc2 single molecule magnet. Due to conservation of the total angular momentum, the magnetization reversal of J = 6 (white arrow) in a magnetic field results in a rotation of the single molecule magnet (blue arrow).

1. Chudnovsky, E. M. Conservation of angular momentum in the problem of tunneling of the magnetic moment. *Physical Review Letters* **72,** 3433–3436 (May 1994).

2. Chudnovsky, E. M., Garanin, D. A. & Schilling, R. Universal mechanism of spin relaxation in solids. *Physical Review B* **72.** doi:10.1103/physrevb.72.094426 (Sept. 2005).

3. Garanin, D. A. & Chudnovsky, E. M. Quantum Entanglement of a Tunneling Spin with Mechanical Modes of a Torsional Resonator. *Physical Review X* **1.** doi:10.1103/physrevx.1.011005 (Aug. 2011).

4. Ganzhorn, M., Klyatskaya, S., Ruben, M. & Wernsdorfer, W. Quantum Einstein-de Haas effect. *Nature Communications* **7,** 11443 (Apr. 2016).

Inv. I02
Monday
10:45

Quantum Control Over Diamond Nitrogen-Vacancy Centers Using a Mechanical Resonator

Gregory Fuchs†

Cornell University, 228 Clark Hall, Cornell University, Ithaca, NY 14853, United States

E. R. MacQuarrie, H. Chen, M. Otten and T. Gosavi

Cornell University, Ithaca, NY 14853, United States

S. Bhave

Purdue University, West Laffayette, IN 47907, United States

† Email: gdf9@cornell.edu

Creating and studying coherent interactions between solid-state qubits and mechanical resonators is a challenge at the intersection of atomic physics, condensed matter physics, and engineering. Furthermore, there is growing consensus that mechanical motion is a "plastic" degree of freedom for solid-state qubits, with the potential to form a interface between spins, photons and phonons. This has motivated intense research into the coherent interactions between mechanical resonators and qubits formed from photons, trapped atoms, superconducting circuits, quantum dots, and nitrogen-vacancy (NV) centers in diamond, to name a few. I will describe our experiments to coherently control NV center spins through their coupling to the dynamic crystal lattice strain of a gigahertz-frequency mechanical resonator. In high-quality diamond mechanical resonators, we demonstrate coherent Rabi oscillations of NV center spins driven by mechanical motion instead of an oscillating magnetic field [1, 2]. Furthermore, we show that a mechanical resonator is a resource to prolog the NV center's spin coherence [2]. Finally, we examine how resonator strain can couple to NV centers through their excited-state, using either spin-strain coupling at room temperature [3] or orbital-strain coupling low temperature.

1. MacQuarrie, E. R., Gosavi, T. A., Jungwirth, N. R., Bhave, S. A. & Fuchs, G. D. Mechanical Spin Control of Nitrogen-Vacancy Centers in Diamond. *Physical Review Letters* **111.** doi:10.1103/physrevlett.111.227602 (Nov. 2013).

2. MacQuarrie, E. R. *et al.* Coherent control of a nitrogen-vacancy center spin ensemble with a diamond mechanical resonator. *Optica* **2,** 233 (Mar. 2015).

3. MacQuarrie, E. R., Otten, M., Gray, S. K. & Fuchs, G. D. Cooling a mechanical resonator with nitrogen-vacancy centres using a room temperature excited state spin–strain interaction. *Nature Communications* **8,** 14358 (Feb. 2017).

Towards spin detection with a nanotube resonator

Inv. I03
Monday
11:20

Adrian Bachtold†

ICFO, Barcelona, Spain

† Email: adrian.bachtold@icfo.eu

Mechanical resonators based on carbon nanotubes feature a series of truly exceptional properties. Carbon nanotubes are so small that they make the lightest resonators fabricated thus far. In addition, the quality factor Q becomes extremely large at cryogenic temperature, up to 5 million [1]. Because of this combination of low mass and high quality factor, the motion is enormously sensitive to the environment. The most notable consequence is that nanotube resonators are exceptional sensors of force [1]. The thermal force noise can reach the level of $\sim 1\ \mathrm{zN}/\sqrt{\mathrm{Hz}}$. In this talk, I will present our efforts to detect the nuclear spins of the ^{13}C atoms naturally present in the carbon nanotube.

1. Güttinger, J. *et al.* Energy-dependent path of dissipation in nanomechanical resonators. *Nature Nanotechnology* **12,** 631–636 (May 2017).

Inv. I04
Monday
11:55

Tunable spin-polaron state in a singly clamped semiconducting carbon nanotube

Fabio Pistolesi[†]

Université de Bordeaux and CNRS, LOMA, Cours de la liberation, Talence, France

R. Shekhter

Department of Physics, University of Gothenburg, SE-412 96 Goteborg, Sweden

[†] Email: fabio.pistolesi@u-bordeaux.fr

In this talk we consider a semiconducting carbon nanotube (CNT) lying on a ferromagnetic insulating substrate with one end passing the substrate and suspended over a metallic gate. We assume that the polarized substrate induces an exchange interaction acting as a local magnetic field for the electrons in the nonsuspended CNT side. We show that one can generate electrostatically a tunable spin-polarized polaronic state localized at the bending end of the CNT. We argue that at low temperatures manipulation and detection of the localized quantum spin state are possible (see also [1]).

1. Pistolesi, F. & Shekhter, R. Tunable spin-polaron state in a singly clamped semiconducting carbon nanotube. *Physical Review B* **92.** doi:10.1103/physrevb.92.035423 (July 2015).

Spin mechanics with magnetic insulators

Inv. I05
Monday
17:15

Gerrit Bauer†

Institute for Materials Research, Tohoku University, Aoba-ku, Katahira 2-1-1 Sendai 980-8577, Japan

† Email: g.e.w.bauer@imr.tohoku.ac.jp

The coupling between spin and mechanical degrees of freedom in condensed matter manifests itself in different equilibrium and non-equilibrium situations. Magnetic insulators such as yttrium iron garnet with high magnetic and mechanical quality are very suited to study such spin mechanical effects. In the past wo years we addressed their effects on the FMR or isolated nanoparticles [1] and optical properties [2, 3] and spin Seebeck effect of thin films [4–7]. In this talk I will review these topics and present new results with focus on the theoretical description.

1. Keshtgar, H., Streib, S., Kamra, A., Blanter, Y. M. & Bauer, G. E. W. Magnetomechanical coupling and ferromagnetic resonance in magnetic nanoparticles. *Physical Review B* **95.** doi:10.1103/physrevb.95.134447 (Apr. 2017).
2. Shen, K. & Bauer, G. E. Laser-Induced Spatiotemporal Dynamics of Magnetic Films. *Physical Review Letters* **115.** doi:10.1103/physrevlett.115.197201 (Nov. 2015).
3. Hashimoto, Y. *et al.* All-optical observation and reconstruction of spin wave dispersion. *Nature Communications* **8,** 15859 (June 2017).
4. Kikkawa, T. *et al.* Magnon Polarons in the Spin Seebeck Effect. *Physical Review Letters* **117.** doi:10.1103/physrevlett.117.207203 (Nov. 2016).
5. Flebus, B. *et al.* Magnon-polaron transport in magnetic insulators. *Physical Review B* **95.** doi:10.1103/physrevb.95.144420 (Apr. 2017).
6. Cornelissen, L. J. *et al.* Nonlocal magnon-polaron transport in yttrium iron garnet. *Physical Review B* **96.** doi:10.1103/physrevb.96.104441 (Sept. 2017).
7. Cornelissen, L. J., Peters, K. J. H., Bauer, G. E. W., Duine, R. A. & van Wees, B. J. Magnon spin transport driven by the magnon chemical potential in a magnetic insulator. *Physical Review B* **94.** doi:10.1103/physrevb.94.014412 (July 2016).

Alternating spin current generation in Cu thin film by injecting surface acoustic waves

Inv. I06
Monday
17:50

Yukio Nozaki†

Keio University, Yokohama 223-8522, Japan

D. Kobayashi and T. Yoshikawa

Keio University, Yokohama 223-8522, Japan

S. Maekawa

Japan Atomic Energy Agency, Tokai 319-1195, Japan

M. Matsuo, R. Iguchi and E. Saitoh

Tohoku University, Sendai 980-8577, Japan

† Email: `nozaki@phys.keio.ac.jp`

Spin angular momentum which is one of the degrees of freedom in electron can be mutually converted with a macroscopic rotation according to the conservation low of angular momentum. The conversion from the spin angular momentum to the macroscopic rotation was experimentally demonstrated in ferromagnetic bodies by Einstein and De Haas while Barnett succeeded its inverse conversion. Very recently, from the analytical solution of the Dirac equation with a general covariance, Matsuo et al. theoretically predicted that the same kind of mutual conversion can be realized for free electrons in non-magnetic metals with a weak spin orbital coupling [1]. We demonstrated a conversion of alternating spin current (SC) from a macroscopic rotation generated by surface acoustic wave (SAW) which propagates in a NiFe / Cu bilayer deposited on a $LiNbO_3$ substrate [2] Ȧn FMR excited in the NiFe layer was successfully observed when the fundamental frequency of SAW matched with the FMR frequency. The strength of FMR excitation was strongly suppressed when the Cu layer was removed from the bilayer or an insulating SiO_2 layer was inserted in the interface of the bilayer. This is the clear evidence that the alternating SC generated in Cu layer via spin-rotation coupling (SRC) plays an important role for the FMR excitation. The angular dependence of the strength of FMR excitation quantitatively supports the successful generation of alternating SC using SAW via SRC. Our experimental result will open the way to generate an alternating SC in variety of SAW devices without using ferromagnets and/or nonmagnetic materials with large spin-orbital coupling.

1. Matsuo, M., Ieda, J., Harii, K., Saitoh, E. & Maekawa, S. Mechanical generation of spin current by spin-rotation coupling. *Physical Review B* **87.** doi:`10.1103/physrevb.87.180402` (May 2013).
2. Kobayashi, D. *et al.* Spin Current Generation Using a Surface Acoustic Wave Generated via Spin-Rotation Coupling. *Physical Review Letters* **119.** doi:`10.1103/physrevlett.119.077202` (Aug. 2017).

Spinon and Phonon in Spintronics

Inv. I07
Monday
18:25

Eiji Saitoh†

WPI-Advanced Institute for Materials Research, Tohoku University, 2-1-1 Katahira Aoba-ku, Sendai, 980-8577, Japan

† Email: eizi@imr.tohoku.ac.jp

Generation and utilization of a flow of spin angular momentum of electrons in condensed matter, called spin current, are the key challenge of today's nano-scale magnetism and spintronics. The discovery of the inverse spin Hall effect (ISHE) [1], the conversion of spin current into electric voltage via spin-orbit interaction, has allowed researchers to detect and utilize spin current directly, and, since then, many spin-current driven effects have been discovered by exploiting the ISHE. In my talk, I will give an introduction to the following topics:

1. Spin-Liquid spin current carried by spinons [2],
2. Phonon anomaly in spin Seebeck effects [3], and
3. Spin current coupled with mechanical motion [4],

to discuss the general mechanism of spin-current interaction.

1. Saitoh, E., Ueda, M., Miyajima, H. & Tatara, G. Conversion of spin current into charge current at room temperature: Inverse spin-Hall effect. *Applied Physics Letters* **88,** 182509 (May 2006).
2. Hirobe, D. *et al.* One-dimensional spinon spin currents. *Nature Physics* **13,** 30–34 (Sept. 2016).
3. Kikkawa, T. *et al.* Magnon Polarons in the Spin Seebeck Effect. *Physical Review Letters* **117.** doi:10.1103/physrevlett.117.207203 (Nov. 2016).
4. Takahashi, R. *et al.* Spin hydrodynamic generation. *Nature Physics* **12,** 52–56 (Nov. 2015).

Imaging magnetic field at the nanoscale with a single spin microscope

Vincent Jacques[†]

Laboratoire Charles Coulomb, Université de Montpellier and CNRS, UMR 5221, Laboratoire Charles Coulomb, Université de Montpellier, Bat. 21 CC074, 1 place Eugène Bataillon, 34095 Montpellier cedex, France

[†] Email: vincent.jacques@umontpellier.fr

In the past years, it was realized that the experimental methods allowing for the detection of single spins in the solid-state, which were initially developed for quantum information science, open new avenues for high sensitivity magnetometry at the nanoscale. In that spirit, it was proposed to use the electronic spin of a single nitrogen-vacancy (NV) defect in diamond as an atomic-sized magnetic field sensor. This approach promises significant advances in magnetic imaging since it provides non-invasive, quantitative and vectorial magnetic field measurements, with an unprecedented combination of spatial resolution and magnetic sensitivity under ambient conditions.

In this talk, I will illustrate how scanning-NV magnetometry can be used as a powerful tool for exploring condensed-matter physics, focusing on chiral spin textures in ultrathin magnetic materials.

Quantum sensing and imaging with diamond spins

Inv. I08
Tuesday
09:40

Ania Bleszynski Jayich†

University of California Santa Barbara, UCSB Physics Dept, United States

A. Jenkins, S. Baumann, D. Bluvstein, A. Ariyaratne and S. Meynell

Physics Department, University of California Santa Barbara, Santa Barbara, CA USA

† Email: ania@physics.ucsb.edu

The nitrogen vacancy (NV) center in diamond is an atomic-scale defect in diamond that is highly sensitive to a wide variety of fields: magnetic, electric, thermal, and strain. Here I discuss an NV-based imaging platform (Fig. 1) where we have incorporated an NV center into a scanning probe microscope and used it to image vortices in superconductors and skyrmions, nanoscale topological spin textures, in thin film magnetic multilayers. I also discuss recent experiments that utlize the NV center's sensitivity to fluctuating magnetic fields to image the conductivity of a proximal sample with nanoscale spatial resolution. A grand challenge to improving the spatial resolution and magnetic sensitivity of the NV is mitigating surface-induced quantum decoherence, which I will discuss in the second part of this talk. Decoherence at interfaces is a universal problem that affects many quantum technologies, but the microscopic origins are as yet unclear. With its sensitivity to electric and magnetic fields over a wide range of frequencies, we have used the NV center as a noise spectrometer to spectroscopically probe sources of surface-related decoherence, differentiating between electric and magnetic origins. These studies guide the ongoing development of quantum control and diamond surface preparation techniques, pushing towards the ultimate goal of NV-based single nuclear spin imaging.

Broadband Paramagnetic Resonance Spectroscopy Through Non-resonant Coupling to NV Centers in Diamond

Tuesday
10:45

P. Chris Hammel†
Ohio State University, Department of Physics, 191 W. Woodruff Ave, Columbus, OH, USA
C. M. Purser, V. P. Bhallamudi, C. S. Wolfe, H. Yusuf, B. A. McCullian and C. Jayaprakash
Department of Physics, Ohio State University, Columbus, OH, 43210 USA
M. Flatté
Department of Physics and Astronomy, 203 Van Allen Hall, Iowa City, Iowa 52242-1479, USA

† Email: `hammel@physics.osu.edu`

We and others [1–3] have recently reported optical detection of magnetic resonance that avoids the need for resonant overlap of the target and nitrogen-vacancy (NV) sensor spins by exploiting target-spin induced NV spin relaxation. The relaxation is due to fluctuating magnetic fields which, in the case of ferromagnets (FM), result from the decay of the coherently driven mode into spinwaves. This provides a sensitive approach to measuring damping at the nanoscale. Here we report NV-based MR spectroscopy of paramagnetic spins by a related mechanism. As in the case of FMR detection, this is a broadband detection mode that is sensitive to excitation of spin dynamics at frequencies separate from the NV resonance conditions. Here we describe spectroscopic measurements of P1 center spins in diamond, which reveal their expected anisotropic hyperfine structure and g-factor. The technique can be extended to spins outside diamond, and should provide a versatile and sensitive technique for MR spectroscopy at the micro- to nanoscale. This research is supported by the Army Research Office through Grant W911NF-16-1-0547, by the NSF MRSEC program through Grant DMR-1420451 and by the U.S. DOE through Grant DE-FG02-03ER46054.

1. Wolfe, C. S. *et al.* Off-resonant manipulation of spins in diamond via precessing magnetization of a proximal ferromagnet. *Physical Review B* **89.** doi:`10.1103/physrevb.89.180406` (May 2014).
2. Van der Sar, T., Casola, F., Walsworth, R. & Yacoby, A. Nanometre-scale probing of spin waves using single-electron spins. *Nature Communications* **6,** 7886 (Aug. 2015).
3. Du, C. *et al.* Control and local measurement of the spin chemical potential in a magnetic insulator. *Science* **357,** 195–198 (July 2017).

Quantum sensing with single spins in diamond nanostructures

Inv. I10
Tuesday
11:20

Patrick Maletinsky†

Basel University, Klingelbergstrasse 82, 4056 Basel, Switzerland

† Email: patrick.maletinsky@unibas.ch

Electronic spins yield excellent quantum sensors, offering quantitative, nanoscale sensing and imaging [1] down to the level of single spins [2]. Over the last years, the Basel Quantum Sensing Group has developed all-diamond scanning probes [3, 4], which offer robust, highly-sensitive platforms to employ Nitrogen-Vacancy (NV) centre spins for such single-spin quantum sensing, with a key scientific focus on condensed matter physics applications. I will describe our recent advances in applying this novel and unique quantum-sensing technology to study nano-magnetism at room temperature as well as mesoscopic systems in cryogenic environments down to the millikelvin range. Specifically, I will discuss the impact of NV magnetometry on the emerging field of antiferromagnetic spintronics [5], where our quantum sensors can address thin-film antiferromagnets with unprecedented performance to reveal nanoscale domains [6] and non-trivial spin-textures [7]. In addition, I will present our recent advances in cryogenic NV magnetometry, including high-precision imaging of individual vortices in thin film superconductors [8], current-imaging in mesoscopic conductors and preliminary data from our recently completed millikelvin NV magnetometer. The performance and robustness of our nanoscale quantum sensing technology recently also led to the creation of ”Qnami”, the world’s first company to commercialise nanoscale quantum sensing solutions. The scientific achievements of NV magnetometry demonstrated here and in several groups worldwide, now together with the commercial availability of user-friendly solutions for nanoscale quantum sensing, establish this technique as a powerful tool for magnetic sensing and imaging on the nanoscale – a tool that we hope to see spreading into ever more laboratories in the coming years.

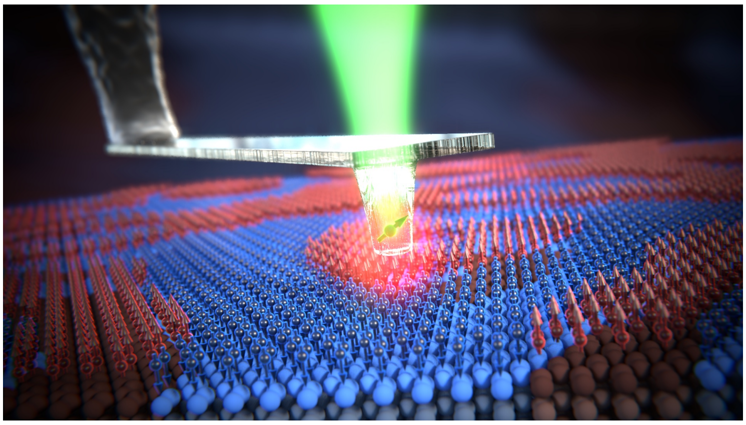


Figure 1: (Color online) Artists rendering of the all-diamond scanning probe tips used in this work for nanoscale quantum sensing with single spins.

1. Rondin, L. *et al.* Magnetometry with nitrogen-vacancy defects in diamond. *Reports on Progress in Physics* **77,** 056503 (May 2014).

2. Grinolds, M. S. *et al.* Nanoscale magnetic imaging of a single electron spin under ambient conditions. *Nature Physics* **9,** 215–219 (Feb. 2013).
3. Appel, P. *et al.* Fabrication of all diamond scanning probes for nanoscale magnetometry. *Review of Scientific Instruments* **87,** 063703 (June 2016).
4. Maletinsky, P. *et al.* A robust scanning diamond sensor for nanoscale imaging with single nitrogen-vacancy centres. *Nature Nanotechnology* **7,** 320–324 (Apr. 2012).
5. Jungwirth, T., Marti, X., Wadley, P. & Wunderlich, J. Antiferromagnetic spintronics. *Nature Nanotechnology* **11,** 231–241 (Mar. 2016).
6. Kosub, T. *et al.* Purely antiferromagnetic magnetoelectric random access memory. *Nature Communications* **8,** 13985 (Jan. 2017).
7. Gross, I. *et al.* Real-space imaging of non-collinear antiferromagnetic order with a single-spin magnetometer. *Nature* **549,** 252–256 (Sept. 2017).
8. Thiel, L. *et al.* Quantitative nanoscale vortex imaging using a cryogenic quantum magnetometer. *Nature Nanotechnology* **11,** 677–681 (May 2016).

Probing correlated-spin dynamics using single-spin magnetometry

Toeno van der Sar[†]

Delft University of Technology, Lorentzweg 1, 2628CJ, Delft, Netherlands

[†] Email: t.vandersar@tudelft.nl

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

Ultracoherent Mechanical Oscillators for Quantum Optomechanics and Hybrid Systems

Inv. I12
Tuesday
17:15

David Mason†
Niels Bohr Institute, Blegdamsvej 17, 2100 København Ø, Denmark
M. Rossi, J. Chen, Y. Seis, S. Saarinen, Y. Tsaturyan and A. Schliesser
Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, Denmark

† Email: drmason@nbi.ku.dk

Modern optomechanics has been enabled by the availability of high quality mechanical resonators. Here, we present ongoing work with recently-pioneered [1] 'ultracoherent' membranes, which exploit phononic engineering and soft-clamping techniques to achieve unprecedented mechanical coherence. With Q-factors of 10^8 at room temperature and nearly 10^9 at T$\sim$10K, these devices enable novel experiments in various regimes.

First, by moderate cryogenic cooling, we can readily achieve quantum cooperativities $C_Q = 4g^2/\kappa\gamma \gg 1$, enabling quantum protocols with a mechanical system whose thermal decoherence rate (γ) approaches that of trapped ions ($\sim$1 ms). This should allow, for instance, stroboscopic QND localization of a single mechanical mode, or using a novel multimode device, two-mode mechanical squeezing and entanglement. Remarkably, these membranes can even achieve $C_Q > 1$ without cryogenic cooling, and by integration with low-noise fiber mirrors, achieve a macroscopic room-temperature system capable of quantum behavior.

We also exploit the high Q of these resonators to advance the capabilities of various hybrid systems. These include electro-optomechanical systems[2] as well as systems in which the membrane motion couples to the collective spin of a room-temperature atomic ensemble[3]. Finally, our soft-clamping techniques can also be exploited to advance force sensing applications. Towards this end, we have developed low-mass soft-clamped resonators, which seek to advance scanning force microscopy (in particular, MRFM) by moving beyond the usual tip-as-sensor paradigm, and exploiting our ultracoherent mechanical devices.

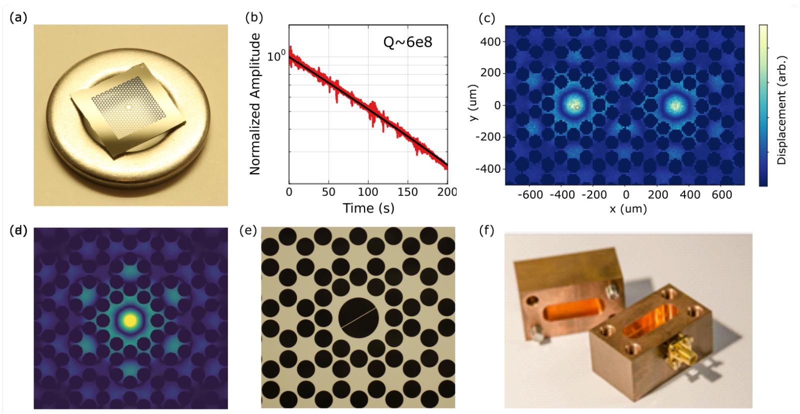


Figure 1: (Color online) Figure 1 (a) Ultracoherent membrane. (b) Mechanical ringdown at T=4K. (c) Displacement pattern of two-mode device. (d) Displacement pattern of soft-clamped membrane. (e) Nanomechanical ribbon for force sensing. (f) 3D Electromechanical cavity

1. Tsaturyan, Y., Barg, A., Polzik, E. S. & Schliesser, A. Ultracoherent nanomechanical resonators via soft clamping and dissipation dilution. *Nature Nanotechnology* **12,** 776–783 (June 2017).

2. Bagci, T. *et al.* Optical detection of radio waves through a nanomechanical transducer. *Nature* **507,** 81–85 (Mar. 2014).
3. Møller, C. B. *et al.* Quantum back-action-evading measurement of motion in a negative mass reference frame. *Nature* **547,** 191–195 (July 2017).

Magnetic resonance force microscopy at temperatures well below 100 mK

Tjerk Oosterkamp†

Kamerlingh Onnes laboratory, Leiden University, Niels Bohrweg 2, 2333CA LEIDEN, Netherlands

M. de Wit, G. Welker and J. Wagenaar

Kamerlingh Onnes laboratory, Leiden University, Niels Bohrweg 2, 2333CA LEIDEN, Netherlands

† Email: oosterkamp@physics.leidenuniv.nl

We investigate whether Magnetic resonance force microscopy (MRFM) is capable of maintaining its extremely high sensitivities and three-dimensional imaging with nanometer resolution when lowering its operation temperature by one or even two orders of magnitude compared to current work at temperatures between 0.5K and 4.2K. We present how we have successfully reduced cantilever heating during the read-out, by switching from laser interferometry to SQUID read-out and address its advantages and disadvantages. Additionally, we present our results so far, in generating the necessary B1 fields by sending a current through a superconducting microwire rather than a copper microwire. So far we have measured the nuclear spin-lattice relaxation times on copper at temperatures down to 42 mK, verified by the Korringa relation [1] with an interaction volume of $(30\text{nm})^3$. Despite the reduction in operation temperature and a record force sensitivity of less than 0.5 $\text{aN}/\sqrt{\text{Hz}}$ we find that this force sensitivity is severely reduced when approaching a surface. It turns out that cold electron spins on a surface lead to a large cantilever dissipation. We have conducted a detailed study of the dissipation and frequency shifts of a cantilever interacting with all surrounding spins, allowing us to experimentally determine the density and relaxation time of dangling bonds on a SiO2 surface [2] and understanding some of the problems involving two level systems. Finally, we have developed an innovative method for using the higher modes of the mechanical detector as radio-frequency (rf) source, removing the need for an on-chip rf source [3].

1. Wagenaar, J. *et al.* Probing the Nuclear Spin-Lattice Relaxation Time at the Nanoscale. *Physical Review Applied* **6.** doi:10.1103/physrevapplied.6.014007 (July 2016).
2. De Voogd, J. M., Wagenaar, J. J. T. & Oosterkamp, T. H. Dissipation and resonance frequency shift of a resonator magnetically coupled to a semiclassical spin. *Scientific Reports* **7,** 42239 (Feb. 2017).
3. Wagenaar, J. *et al.* Mechanical Generation of Radio-Frequency Fields in Nuclear-Magnetic-Resonance Force Microscopy. *Physical Review Applied* **7.** doi:10.1103/physrevapplied.7.024019 (Feb. 2017).

Stressing Spins and Tuning Strings

Inv. I14
Tuesday
18:25

Hans Huebl†

Walther-Meissner-Institut, Walther-Meissner-Str. 8, 85748 Garching, Germany

† Email: huebl@wmi.badw.de

Spinmechanics discusses in the most general sense how spin or magnetization properties couple to lattice degrees of freedom. In my presentation, I will give an overview over various manifestiations of spinmechanical effects. In particular, I will discuss (i) the sensing of magnetoelasticity via the mechanical properties of nano-mechanical string resonators, enabling direct access to nanoscale magnetic objects, (ii) the mechanical sensing of spin accumulation in metals, and (iii) the electroelastic control of of the spin-properties in paramagnetic ensambles.

Tut. T03
Wednesday
08:30

Nano- and Optomechanics-enabled Magnetometries

Mark R. Freeman†
University of Alberta, 3-195 CCIS University of Alberta, Edmonton AB T6G 2E1, Canada
J.E. Losby and V.T.K. Sauer
University of Alberta, Edmonton, AB, Canada T6G 2E1

† Email: mark.freeman@ualberta.ca

The storied role of mechanical measurements in the elucidation of physical phenomena continues unabated. We review recent progress in instrumentation for mechanical detection of magnetic torques, along with current and potential applications. Nanofabrication has led to a good variety of well-coupled magnetic/mechanical structures, and a roster of powerful techniques for observing nanomechanical responses to magnetic torque.

Following a broader overview[1–4], we will survey advances driven by progress in optomechanics for torque sensing. High-finesse optical cavities for readout of mechanical motion have been harnessed for sensitive magnetometries and susceptometries[5, 6]. The parameter space for further improvement continues to expand, for example through the introduction of optical traps for nanotorsional applications, torsional metamaterials, and magnetic feedback cooling of torque sensors[7–9].

1. Moreland, J. Micromechanical instruments for ferromagnetic measurements. *Journal of Physics D: Applied Physics* **36,** R39–R12 (Feb. 2003).
2. Lipfert, J., van Oene, M. M., Lee, M., Pedaci, F. & Dekker, N. H. Torque Spectroscopy for the Study of Rotary Motion in Biological Systems. *Chemical Reviews* **115,** 1449–1474 (Dec. 2014).
3. Forstner, S. *et al.* Ultrasensitive Optomechanical Magnetometry. *Advanced Materials* **26,** 6348–6353 (June 2014).
4. Zhang, W. *et al.* Giant facet-dependent spin-orbit torque and spin Hall conductivity in the triangular antiferromagnet IrMn3. *Science Advances* **2,** e1600759–e1600759 (Sept. 2016).
5. Kim, P. H. *et al.* Nanoscale torsional optomechanics. *Applied Physics Letters* **102,** 053102 (Feb. 2013).
6. Wu, M. *et al.* Dissipative and Dispersive Optomechanics in a Nanocavity Torque Sensor. *Physical Review X* **4.** doi:10.1103/physrevx.4.021052 (June 2014).
7. Hoang, T. M. *et al.* Torsional Optomechanics of a Levitated Nonspherical Nanoparticle. *Physical Review Letters* **117.** doi:10.1103/physrevlett.117.123604 (Sept. 2016).
8. Frenzel, T., Kadic, M. & Wegener, M. Three-dimensional mechanical metamaterials with a twist. *Science* **358,** 1072–1074 (Nov. 2017).
9. Kim, P. H. *et al.* Magnetic actuation and feedback cooling of a cavity optomechanical torque sensor. *Nature Communications* **8.** doi:10.1038/s41467-017-01380-z (Nov. 2017).

Nanomechanics and Nanomagnetism

Martino Poggio†

Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland

N. Rossi, A. Mehlin, B. Gross, F. Braakman, L. Ceccarelli, D. Vasyukov, M. Wyss and D. Cadeddu

Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland

† Email: `martino.poggio@unibas.ch`

I will discuss recent experiments in our group aimed at determining the magnetization configuration and reversal processes in nanometer-scale magnets. First, I will discuss sensitive measurements of torque magnetometry and how they can be used to observe magnetization reversal and magnetic phase transitions in individual nanomagnets. I will then discuss the advantages of scaling down mechanical torque transducers from conventional 'top-down' cantilever sensors to state-of-the-art 'bottom-up' structures. In particular, I will show torque magnetometry experiments using nanowire (NW) structures. Finally, I will introduce our scanning probe experiments aimed at imaging magnetism on the nanometer-scale. In this context, I will discuss experiments using a scanning nanometer-scale superconducting quantum interference device (SQUID) to map the stray magnetic field produced by individual nanomagnets.

Inv. I16
Wednesday
10:45

Deeply nonlinear ferromagnetic resonance in a YIG nano-disk: MRFM spectroscopy of spin-wave instabilities

Grégoire de Loubens†

Service de Physique de l'Etat Condensé, CEA, CNRS, Université Paris-Saclay, Orme des Mersisiers, CEA Saclay, 91191 Gif-sur-Yvette, France

Y. Li, V. Naletov

SPEC, CEA, CNRS, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

O. Klein

SPINTEC, CEA, CNRS and Université Grenoble Alpes, 38054 Grenoble, France

P. Bortolotti, V. Cros, A. Anane

Unité Mixte de Physique CNRS, Thales, Univ. Paris-Sud, Université Paris-Saclay, 91767 Palaiseau, France

† Email: gregoire.deloubens@cea.fr

Magnetization dynamics is strongly nonlinear, yielding a series of interesting phenomena. It is well known that in ferromagnetic resonance of extended films, spin-wave (SW) instabilities quickly develop as the excitation power is increased [1], preventing to achieve large angle of uniform precession. The situation is quite different in nanostructures, where SW modes are highly quantized due to the geometric confinement, and expected to influence less the magnetization dynamics in the nonlinear regime. In this work, we probe the magnetization dynamics of an ultra-low damping YIG nano-disk [2] using magnetic resonance force microscopy (MRFM). Ultra-large amplitude precession with complete suppression of the longitudinal component is achieved by pumping the sample with a uniform microwave field. Strikingly, we measure that the foldover shift is not constantly growing as the power is increased, but instead presents plateaus, pointing towards nonlinear energy dissipation to quantized SW modes, which is confirmed by micromagnetic simulations. In addition, by applying a second microwave field we are able to excite the SW resonances in the large-amplitude precession state. The lowest energy mode corresponds to the uniform nutation of the magnetization about its stable precession trajectory, whose frequency was shown to have a similar form as the Rabi formula, generalized to take into account nonlinearities [3]. Micromagnetic simulations show that higher order modes are nutation modes with spatial gradients, i.e., SW nutation modes.

1. Suhl, H. The theory of ferromagnetic resonance at high signal powers. *Journal of Physics and Chemistry of Solids* **1,** 209–227 (Jan. 1957).
2. Hahn, C. *et al.* Measurement of the intrinsic damping constant in individual nanodisks of Y3Fe5O12 and Y3Fe5O12|Pt. *Applied Physics Letters* **104,** 152410 (Apr. 2014).
3. Bertotti, G., Mayergoyz, I. D. & Serpico, C. Spin-Wave Instabilities in Large-Scale Nonlinear Magnetization Dynamics. *Physical Review Letters* **87.** doi:10.1103/physrevlett.87.217203 (Nov. 2001).

Nanomechanical torque magnetometry on bilayer Co/CoO$_x$ micro-disks

Vincent T. K. Sauer[†]

Department of Physics, University of Alberta and Nanotechnology Research Centre, National Research Council 4-181 CCIS, University of Alberta, Edmonton, AB T6G 2E1, and , 11421 Saskatchewan Dr NW, Edmonton, AB T6G 2M9, 4-181 CCIS, University of Alberta, Edmonton, AB T6G 2E1, Canada

J. E. Losby and M. R. Freeman

Department of Physics, University of Alberta, 4-181 CCIS, University of Alberta, Edmonton, AB, Canada T6G 2E1, and Nanotechnology Research Centre, National Research Council, 11421 Saskatchewan Dr NW, Edmonton, AB, Canada T6G 2M9

E. Luber

Department of Chemistry, University of Alberta, 11227 Saskatchewan Drive, University of Alberta, Edmonton, AB, Canada T6G 2G2, and Nanotechnology Research Centre, National Research Council, 11421 Saskatchewan Dr NW, Edmonton, AB, Canada T6G 2M9

M. Belov

Nanotechnology Research Centre, National Research Council, 11421 Saskatchewan Dr NW, Edmonton, AB, Canada T6G 2M9

[†] Email: `vsauer@ualberta.ca`

Nanomechanical torque magnetometry is performed on bilayer Co/CoO$_x$ micro-disk systems using silicon-on-insulator torsion paddle resonators. The bilayer consists of a base layer of 20 nm of sputtered Co followed by 10 nm of reactively sputtered CoO$_x$. The CoO$_x$ is deposited onto the Co without breaking vacuum. Disks of 1 and 1.5 μ m diameter are deposited on symmetrical, doubly-clamped, single paddle, torsion resonators with fundamental frequencies near 10 MHz. The effects of geometric confinement on antiferromagnetic systems are investigated through magnetization vs. field measurements taken on the disks at 300 K, 280 K, 50 K, and 30 K. This corresponds to temperatures above and below the Néel temperature of CoO (291 K) and Co_3O_4 (40 K). These measurements are taken with the sample cooled at both high and low fields, and the results are compared to measurements taken on the deposited continuous film.

Dynamics of a Magnetic Needle in a Magnetic field: Magnetometer Sensitivity to Landau–Lifshitz–Gilbert Damping

Inv 118
Wednesday
11:55

Yehuda Band†
Ben-Gurion University, P.O.B. 653 Beer-Sheva 8410501, Israel, Israel
Y. Avishai
P.O.B. 653 Beer-Sheva 8410501, Israel
A. Shnirman
Institut fur Theorie der Kondensierten Materie, Karlsruhe Institute of Technology, D-76128 Karlsruhe, Germany

† Email: `band@bgu.ac.il`

Recently, it was predicted that the sensitivity of a precessing magnetic needle magnetometer can surpass that of present state-of-the-art magnetometers by several orders of magnitude [1]. In order to model the dynamics of a single-domain magnetic needle in a magnetic field, the dissipation of spin components not along the axis of easiest magnetization must be taken into account [2]. Where there is dissipation, fluctuations are also present [3]. Fluctuations are a source of uncertainty that can affect the accuracy of the magnetometer. We calculate the dynamics of a magnetic needle in the presence of an external magnetic field and determine the uncertainty of a magnetic needle magnetometer due to the fluctuations that give rise to Gilbert damping [2], i.e., interactions with internal degrees of freedom such as lattice vibrations, spin waves, and thermal electric currents. We solve the Heisenberg equations of motion for the spin, $\hat{\mathbf{S}}$, the unit vector in the direction of the axis of easiest magnetization, $\hat{\mathbf{n}}$, and the total angular momentum, $\hat{\mathbf{J}}$, in mean-field approximation [4] by taking quantum expectation values of the equations, and noting that for large spin and orbital angular momentum, the standard deviation is small compared to the quantum average. When fluctuations are included, numerical solution of the stochastic equations is difficult when the anisotropy coefficient is large. Therefore we develop a perturbative solution around the adiabatic solution. Analysis of the uncertainty in such magnetic field measurements in the limit of small and large magnetic fields will be presented.

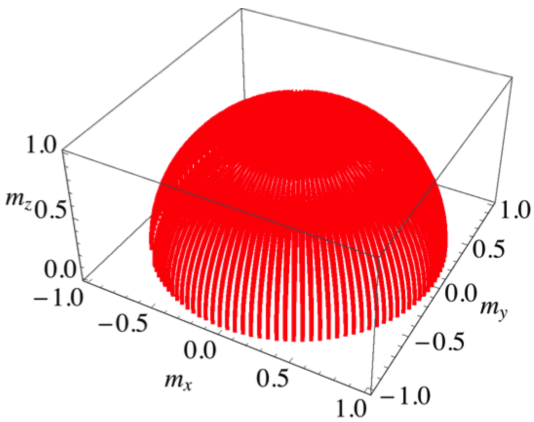


Figure 1: (Color online) Parametric plot of the needle spin unit vector $\mathbf{m}(t)$ [which is almost numerically equal to the needle axis vector $\mathbf{n}(t)$] for the high-field case.

1. Kimball, D. F. J., Sushkov, A. O. & Budker, D. Precessing Ferromagnetic Needle Magnetometer. *Physical Review Letters* **116.** doi:10.1103/physrevlett.116.190801 (May 2016).
2. Gilbert, T. Classics in Magnetics A Phenomenological Theory of Damping in Ferromagnetic Materials. *IEEE Transactions on Magnetics* **40,** 3443–3449 (Nov. 2004).
3. Callen, H. B. & Welton, T. A. Irreversibility and Generalized Noise. *Physical Review* **83,** 34–40 (July 1951).
4. Band, Y. B. & Ben-Shimol, Y. Molecules with an induced dipole moment in a stochastic electric field. *Physical Review E* **88.** doi:10.1103/physreve.88.042149 (Oct. 2013).

Inv. I19
Wednesday
17:15

High-resolution nanoscale nuclear magnetic resonance imaging and spectroscopy

Raffi Budakian†

University of Waterloo, Department of Physics and Institute for Quantum Computing, 200 University Ave. W, Waterloo, ON N2L3G1, Canada

William Rose, Holger Haas, and David Cory

200 University Ave. W, Waterloo ON, N2L3G1

† Email: rbudakian@uwaterloo.ca

I will present a new method for high-resolution nanoscale magnetic resonance imaging that combines the high spin sensitivity of nanowire-based force detection with the high spectral resolution of NMR spectroscopy. I will discuss the development of NMR pulses designed using optimal control theory (OCT) that enable high fidelity unitary operations to be implemented on nanoscale nuclear spin ensembles. One important capability in the realization high fidelity spin control is the ability to control the average spin Hamiltonians during the unitary evolution. Using OCT pulses that incorporate average Hamiltonian theory, we demonstrate a factor of 500 reduction of the proton spin resonance linewidth in a (50 nm)^3 volume of polystyrene, and image proton spins in one dimension with a spatial resolution below 2 nm [1]. I will discuss the application of these ideas to harness a broad range of high-resolution NMR techniques in the nano-MRI setting.

1. Rose, W. *et al.* High-Resolution Nanoscale Solid-State Nuclear Magnetic Resonance Spectroscopy. arXiv: 1707.01062v1 [cond-mat.mes-hall] (July 2017).

Advances in Magnetic Resonance Force Microscopy

Christian Degen†

ETH Zurich, Department of Physics, Otto Stern Weg 1, 8093 Zurich, Switzerland

A. Eichler

ETH Zurich, Department of Physics, Otto Stern Weg 1, 8093 Zurich, Switzerland

† Email: degenc@ethz.ch

Nanoscale magnetic resonance imaging (NanoMRI) is a challenging endeavor with important potential applications in nanomedicine, chemistry and solid state physics. One of the most advanced technologies in the field is magnetic resonance force microscopy (MRFM), which combines force-detected scanning microscopy and spin control through nuclear magnetic resonance. Progress in this field must often be earned through paradigm-shifting new technologies. In this talk, we will present a number of such innovations at various stages of implementation, ranging from the use of commercial hard drive heads as field sources, to novel mechanical sensor geometries, to surprising sensing methods using parametric resonators.

Harnessing electron-spin labels and dynamic nuclear polarization in scanned-probe nanoscale magnetic resonance imaging experiments

John Marohn[†]

Department of Chemistry and Chemical Biology, Cornell University Ithaca, New York 14853-1301, USA

Corinne E. Isaac, Hoang L. Nguyen, Michael C. Boucher, Hanyu Sun, Pamela T. Nasr and Elizabeth A. Curley

Department of Chemistry and Chemical Biology, Cornell University Ithaca, New York 14853-1301 USA

[†] Email: `john.marohn@cornell.edu`

I will describe my team's progress exploiting magnet-tipped attonewton-sensitivity cantilevers [1, 2] to image biological assemblies and as-fabricated devices. We have integrated magnet-tipped cantilevers into a scanned-probe microscope having three-dimensional coarse and fine positioning, operating at 4.2 kelvin, and having a 0 to 9 tesla magnetic field. We have carried out magnetic resonance experiments on a 200 nm thick film of polystyrene doped with a nitroxide free radical. This sample was spun-cast onto a coplanar waveguide (10 micrometer centerline, operating from dc to 40 Ghz). We could significantly reduce surface-related cantilever frequency noise by coating the sample with a 10 nm metal layer and applying a voltage to the cantilever. To align the cantilever with the coplanar waveguide's centerline we employ "edge-finder" cantilever frequency shifts fortuitously present when a voltage bias is applied to the waveguide's centerline [3]. We used force-gradient detection (e.g., frequency shifts) to sensitively detect Curie-law proton magnetization at 6 T, electron-spin resonance at 0.6 T, and hyperpolarized proton magnetization created by cross-effect dynamic nuclear polarization (DNP) at 0.6 T [4, 5]. To assess the potential improvements in MRFM imaging obtainable with DNP, we have developed a theory of the signal-to-noise ratio covering MRFM experiments detecting magnetization fluctuations (having a random sign) and Curie-law and hyperpolarized magnetization (with a well-defined sign). We have developed rapid Bayesian protocols for reconstructing proton-density images of isolated proteins from force-fluctuation maps and for determining the location of individual electron spins from frequency-shift maps [6].

1. Longenecker, J. G., Moore, E. W. & Marohn, J. A. Rapid serial prototyping of magnet-tipped attonewton-sensitivity cantilevers by focused ion beam manipulation. *Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena* **29,** 032001 (May 2011).
2. Longenecker, J. G. *et al.* High-Gradient Nanomagnets on Cantilevers for Sensitive Detection of Nuclear Magnetic Resonance. *ACS Nano* **6,** 9637–9645 (Oct. 2012).
3. Isaac, C. E., Curley, E. A., Nasr, P. T., Nguyen, H. L. & Marohn, J. A. Cryogenic positioning and alignment with micrometer precision. arXiv: `1710.01442v1 [cond-mat.mes-hall]` (Oct. 2017).
4. Issac, C. E. *et al.* Dynamic nuclear polarization in a magnetic resonance force microscope experiment. *Physical Chemistry Chemical Physics* **18,** 8806–8819 (2016).
5. Isaac, C. E. *et al.* Correction: Dynamic nuclear polarization in a magnetic resonance force microscope experiment. *Physical Chemistry Chemical Physics* **19,** 16282–16282 (2017).
6. Moore, E. W. *et al.* Scanned-probe detection of electron spin resonance from a nitroxide spin probe. *Proceedings of the National Academy of Sciences* **106,** 22251–22256 (Dec. 2009).

Spin hydrodynamics in insulators

Inv. I22
Wednesday
20:00

Yaroslav Tserkovnyak†

UCLA, Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095, United States

† Email: yaroslav@physics.ucla.edu

I will review recent progress in understanding novel transport phenomena in magnetic insulators. Central to this will be conservation laws that are rooted in topological invariance of certain types of magnetic field configurations. The continuity relations associated with such dynamic spin textures can mimic superfluid phenomena, even at high temperatures. Key examples will include easy-plane magnetic films, materials that harbor skyrmionic textures, and, surprisingly, disordered glassy spin systems. Recently developed magnetoelectric and thermoelectric techniques (e.g., based on spin Hall and spin Seebeck effects) are now allowing us to systematically access this physics in a range of materials, both old and new.

Inv. I23
Wednesday
20:35

Spin-rotation coupling in viscous electron fluids

Rembert Duine†

Institute for Theoretical Physics, Utrecht University, Institute for Theoretical Physics, Utrecht University, Leuvenlaan 4, 3584 CE Utrecht, The Netherlands, Netherlands

R.J. Doornenbal

Institute for Theoretical Physics, Utrecht University

Marco Polini

Istituto Italiano di Tecnologia, Graphene Labs, Genova

† Email: R.A.Duine@uu.nl

We consider spin-rotation coupling — the generation of spin polarization by vorticity — in viscous two-dimensional electron systems with spin-orbit coupling. We derive the hydrodynamic equations for spin and momentum densities in which their mutual coupling is determined by the rotational viscosity. We compute the rotational viscosity microscopically in the limits of weak and strong spin-orbit coupling. Estimates, based on recent experimental results, show that the spin-orbit coupling is strong enough for the spin-rotation coupling to be observed. On the one hand, this coupling provides a way to image viscous electron flows by imaging spin densities. On the other hand, we show that the spin polarizations generated by spin-rotation coupling in the hydrodynamic regime can, in principle, be much larger than the spin polarization generated, e.g. by the spin Hall effect, in the diffusive regime.

Ultrafast Spintronics with Topological Lasers

Masahiro Sato†
Ibaraki University, 2-1-1 Bunkyo, Mito, Ibaraki 310-8512, Japan, Japan
H. Fujita
Institute for Solid State Physics, University of Tokyo, Kashiwa 277-8581, Japan

† Email: masahiro.sato.phys@vc.ibaraki.ac.jp

Optical vortex (or vortex beam) is the singular laser beam carrying an intrinsic orbital angular momentum, [1] and has been actively studied especially as a new tool to control various kinds of matter. Due to the presence of the angular momentum, the vortex beam has a characteristic spatial distribution of electromagnetic fields. Making use of the spatial features, we theoretically propose new ways of generating/controlling magnetic nanostructures such as skyrmions and skyrmioniums [2] in magnets with vortex beams. We concentrate on two set ups: Applications of high- (ultraviolet, visible) and low-frequency (Tera Hz: THz) vortex beams to magnets. In the case of the high-frequency beam, its oscillation is too faster for typical spin dynamics and the spins cannot be directly coupled to the oscillating fields, while spins can feel heating driven by the beam. Based on Landau-Lifshitz-Gilbert (LLG) equation with the beam-driven heating, we show that vortex beams in ultraviolet or visible range can generate multiple ring-shape magnetic defects such as skyrmionium in chiral magnets. [3] On the other hand, when we apply THz vortex beams to magnets, the direct coupling between the spins and the electromagnetic fields becomes relevant and richer spin dynamics occur. We show from the LLG simulation that the magnetic resonance driven by THz vortex beam in usual ferromagnets leads to a nanostructure with a finite spin scalar chirality, [4] and it indicates the possibility of vortex-beam driven Hall effect in metallic magnets. We also show that THz vortex beam can simultaneously generate multiple skyrmions in chiral ferromagnets, depending on the value of the angular momentum, [4] if the beams are sufficiently focusing beyond its diffraction limit with near-field techniques. In the talk, I would like to carefully report the essential aspects of our proposal.

1. Allen, L., Beijersbergen, M. W., Spreeuw, R. J. C. & Woerdman, J. P. Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes. *Physical Review A* **45,** 8185–8189 (June 1992).
2. Fert, A., Cros, V. & Sampaio, J. Skyrmions on the track. *Nature Nanotechnology* **8,** 152–156 (Mar. 2013).
3. Fujita, H. & Sato, M. Ultrafast generation of skyrmionic defects with vortex beams: Printing laser profiles on magnets. *Physical Review B* **95.** doi:10.1103/physrevb.95.054421 (Feb. 2017).
4. Fujita, H. & Sato, M. Encoding orbital angular momentum of light in magnets. *Physical Review B* **96.** doi:10.1103/physrevb.96.060407 (Aug. 2017).

Tut. T04
Thursday
08:30

Magnetic Resonance Spectroscopy

Claude Fermon†

SPEC, CEA-Saclay, 91191 Gif-Sur-Yvette, France

† Email: claude.fermon@cea.fr

(To be announced)

High sensitivity quantum limited electron-spin resonance spectroscopy

Inv. I25
Thursday
09:40

Sebastian Probst†

CEA Saclay, Quantronics Group, SPEC / CEA Saclay, 91191 Gif-sur-Yvette CEDEX, France

† Email: sebastian.probst@cea.fr

Electron spin resonance (ESR) spectroscopy is widely employed for the detection and characterization of paramagnetic species and their magnetic and chemical environment. In a classical ESR spectrometer, the spins precess in an external magnetic field and emit small microwave signals into a cavity, which are amplified and measured. In this work [1], we make use of the toolbox of circuit quantum electrodynamics to boost the sensitivity of such a spectrometer by many orders of magnitude to the level of 65 spins/$\sqrt{\mathrm{Hz}}$ with a signal-to-noise ratio of 1. This is achieved by using a low impedance, high quality factor superconducting micro-resonator in conjunction with a Josephson parametric amplifier operated below 20 mk [2]. The energy relaxation time T_1 of the spins (Bi donors in ^{28}Si) is limited by the Purcell effect to 20 ms allowing fast repetitive measurements while the coherence time T_2 is approximately 1.7 ms. The necessarily narrow bandwidth of our resonator distorts the shape of our short drive pulses and in order to control the spin ensemble more accurately, we employ shaped compensation pulses canceling the filtering effect of the cavity. Then, we perform electron spin echo envelope modulation (ESEEM) experiments at low magnetic fields allowing us to detect weakly coupled ^{29}Si nuclear spin impurities in our ^{28}Si sample. The sub pico-liter detection volume of our spectrometer makes it an interesting tool for investigating paramagnetic surfaces and, in particular, recently discovered 2D materials.

1. Probst, S. *et al.* Inductive-detection electron-spin resonance spectroscopy with 65 spins/ Hz sensitivity. *Applied Physics Letters* **111,** 202604 (Nov. 2017).
2. Bienfait, A. *et al.* Reaching the quantum limit of sensitivity in electron spin resonance. *Nature Nanotechnology* **11,** 253–257 (Dec. 2015).

Nanoscale detection and hyperpolarisation of nuclear spins using cross-relaxation in diamond

Inv. I26
Thursday
10:45

Jean-Philippe Tetienne†

University of Melbourne, School of Physics, Parkville, VIC 3010, Australia

† Email: jtetienne@unimelb.edu.au

The nitrogen-vacancy (NV) centre in diamond is a leading system for the detection and spectroscopy of spins in nanoscale samples. Most sensing schemes rely on driving of the NV spins with pulsed radiofrequency fields to engineer the NV Hamiltonian and make it sensitive to the target spins. In this talk, I will present an alternative approach to sensing that utilises cross-relaxation between the target spins and the probe NV spin, enabling all-optical spectroscopy of nearby electronic and nuclear spins [1–3]. I will then show how cross-relaxation can be used to transfer polarisation to the sample, with an efficiency enhanced by up to an order of magnitude over the established Hartmann-Hahn method, leading to the first observation of hyperpolarisation of external spins using a single NV probe [4]. These results suggest that cross-relaxation could be a useful for nanoscale magnetic resonance imaging.

1. Hall, L. T. *et al.* Detection of nanoscale electron spin resonance spectra demonstrated using nitrogen-vacancy centre probes in diamond. *Nature Communications* **7,** 10211 (Jan. 2016).

2. Wood, J. D. A. *et al.* Wide-band nanoscale magnetic resonance spectroscopy using quantum relaxation of a single spin in diamond. *Physical Review B* **94.** doi:10.1103/physrevb.94.155402 (Oct. 2016).

3. Wood, J. D. A. *et al.* Microwave-free nuclear magnetic resonance at molecular scales. *Nature Communications* **8,** 15950 (July 2017).

4. Broadway, D. A. *et al.* Quantum probe hyperpolarisation of molecular nuclear spins. arXiv: 1708.05906v2 [quant-ph] (Aug. 2017).

Electrically Detected Magnetic Resonance of NV Spin States in Diamond: Towards Coherent Driving and readout of Single Spin Qubits

Inv. I27
Thursday
11:20

Milos Nesladek†

University Hasselt and IMEC, Milos Nesladek (invited), Belgium

† Email: milos.nesladek@uhasselt.be

Scalable principles for quantum state readout are one of open questions in quantum technology. Building on the recent results of photoelectric detection of magnetic resonances (PDMR) [1, 2] we discuss the prospect of PDMR technique for solid-state qubit devices in diamond. One of the key PDMR advantages over the optical detected magnetic resonance (ODMR) technique are the high detection rates $\sim 5 \times 10^9$ sec^{-1}, exceeding orders of magnitude ODMR. Consequently, the novel detection technique might lead to the single shot readout of the NV centres quantum state and provide fast data acquisition at room temperature. To achieve this goal we discuss the photoelectric gain, used to obtain high detection rates on small NV spin qubit ensembles. The photophysics of the transitions on NV centre is reviewed and several scenarios for obtaining highest single/noise ratio are presented. We demonstrate pulsed PDMR measurements, compatible with coherent manipulation of the spin states realized on quantum chips. Finally we realize a single NV qubits read electrically. We discuss another defects such as NiV as a potential candidate for electrically read spin qubits in diamond.

1. Bourgeois, E. *et al.* Photoelectric detection of electron spin resonance of nitrogen-vacancy centres in diamond. *Nature Communications* **6,** 8577 (Oct. 2015).
2. Gulka, M. *et al.* Pulsed Photoelectric Coherent Manipulation and Detection of N-V Center Spins in Diamond. *Physical Review Applied* **7.** doi:10.1103/physrevapplied.7.044032 (Apr. 2017).

Inv. I28
Thursday
11:55

Limits on spectral resolution measurements by quantum probes for nano NMR

Alex Retzker†

The Hebrew University, Racah Institute of Physics, Edmond J. Safra campus. Danciger B Building, room 203, Hebrew University of Jerusalem, Israel 91904, Israel

Amit Rotem, Tuvia Gefen and Alex Retzker

The Hebrew University, Racah Institute of Physics Edmond J. Safra campus, Israel

Simon Schmitt and Liam McGuiness and Fedor Jelezko

2Institute for Quantum Optics, Ulm University, Albert-Einstein-Allee 11, Ulm 89081, Germany

† Email: `retzker@phys.huji.ac.il`

The limits of frequency resolution in nano NMR experiments have been discussed extensively in recent years. It is believed that there is a crucial difference between the ability to resolve a few frequencies and the precision of estimating a single one. Whereas the efficiency of single frequency estimation gradually increases with the square root of the number of measurements, the ability to resolve two frequencies is limited by the specific time scale of the probe and cannot be compensated for by extra measurements. In this talk I will show that the relationship between these quantities is more subtle and both are only limited by the Cramer-Rao bound of a single frequency estimation. The talk is based on [1, 2].

1. Schmitt, S. *et al.* Submillihertz magnetic spectroscopy performed with a nanoscale quantum sensor. *Science* **356,** 832–837 (May 2017).
2. Rotem, A. *et al.* Limits on spectral resolution measurements by quantum probes. arXiv: `1707.01902v1 [quant-ph]` (July 2017).

Operating Quantum States in Single Magnetic Molecules: Implementation of Quantum Gates and Algorithm

Inv. I29
Thursday
17:15

Franck Balestro†

UGA-CNRS-Institut Néel, 25 rue des martyrs, 38042 Grenoble cedex 9, France

C. Godfrin, R. Ballou, E. Bonet and S. Klyatskaya,

Institut Néel, CNRS, Grenoble Alpes University, BP 166, 38042 Grenoble, France

M. Ruben and W. Wernsdorfer

Institut of Nanotechnology (INT), Karlsruhe Institute of Technology (KIT), 76344 Eggenstein-Leopoldshafen, Germany

† Email: `franck.balestro@neel.cnrs.fr`

The application of quantum physics to the information theory turns out to be full of promises. The first step is to realize the basic block that encodes the quantum information, the qubit. Among all existing qubits, spin based devices are very attractive since they reveal electrical read-out and coherent manipulation. Beyond this, the more isolated a system is, the longer its quantum behavior remains, making of the nuclear spin a serious candidate for exhibiting long coherence time and consequently high numbers of quantum operation. In this context I worked on a molecular magnet spin transistor. This setup enabled us to read-out electrically both the electronic and the nuclear spin states and to coherently manipulate the nuclear spin of the Terbium ion [1, 2]. I will present the study of the dynamic of a single 3/2 nuclear spin under the influence of a microwave pulse. After the energies difference measurement between these states I will show the coherent manipulation of the three nuclear spin transitions up to 10MHz using only a microwave electric field with coherence time higher than 1ms. More than demonstrating the qubit dynamic, these measures demonstrate that a nuclear spin embedded in a molecular magnet transistor is a four quantum states system that can be fully controlled. Theoretical proposal demonstrated that quantum information processing could be implemented using a 3/2 spin such as quantum gates [3] and algorithm [4]. I will present the implementation of the Grover algorithm [5] to then show the implementation of the iSWAP gate and the measurement of its phase.

1. Thiele, S. *et al.* Electrically driven nuclear spin resonance in single-molecule magnets. *Science* **344,** 1135–1138 (June 2014).
2. Godfrin, C. *et al.* Electrical Read-Out of a Single Spin Using an Exchange-Coupled Quantum Dot. *ACS Nano* **11,** 3984–3989 (Apr. 2017).
3. Kiktenko, E. O., Fedorov, A. K., Man'ko, O. V. & Man'ko, V. I. Multilevel superconducting circuits as two-qubit systems: Operations, state preparation, and entropic inequalities. *Physical Review A* **91.** doi:`10.1103/physreva.91.042312` (Apr. 2015).
4. Leuenberger, M. N., Loss, D., Poggio, M. & Awschalom, D. D. Quantum Information Processing with Large Nuclear Spins in GaAs Semiconductors. *Physical Review Letters* **89.** doi:`10.1103/physrevlett.89.207601` (Oct. 2002).
5. Godfrin, C. *et al.* Operating Quantum States in Single Magnetic Molecules: Implementation of Grover's Quantum Algorithm. *Physical Review Letters* **119.** doi:`10.1103/physrevlett.119.187702` (Nov. 2017).

Cavity Spintronics

Can-Ming Hu[†]

University of Manitoba, University of Manitoba, Winnipeg, R3T 2N2, Canada

[†] Email: `hu@physics.umanitoba.ca`

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

In this new community, most groups utilize the hybrid and nonlocal nature of CMP to develop cavity-mediated coupling techniques for both spintronic and quantum applications. This stream of research, including our recent demonstration of cavity-mediated distant control of spin current [1], root on single-particle physics of CMP. In this talk, we will present a distinct feedback-coupled cavity technique, which we develop to study the cooperative dynamics of trillions of CMP. Utilizing such coherent dynamics of CMP ensembles, we demonstrate the control of magnon-photon Rabi frequency by changing the photon Fock state occupation, and we discover the evolution of CMP to cavity magnon triplet and cavity magnon quintuplet [Nature Comm. (2017), to be published]. Our results may open up new avenues for exploiting the light-matter interactions.

1. Bai, L. *et al.* Cavity Mediated Manipulation of Distant Spin Currents Using a Cavity-Magnon-Polariton. *Physical Review Letters* **118.** doi:`10.1103/physrevlett.118.217201` (May 2017).

Magnetic Resonance of Correlated Spins using a Single Spin Sensor

Amit Finkler†

Weizmann Institute of Science, 234 Herzl St., Rehovot 7610001, Israel

L. Schlipf, D. Dasari, B. Kern, K. Xu, M. Ternes and K. Kern

Max Planck Institute for Solid State Physics, Heisenbergstr. 1, 70569 Stuttgart, Germany

T. Oeckinghaus, A. Zappe, J. Wrachtrup

3. Physikalisches Institut, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

Mzkhailo Azarkh and Malte Drescher

University of Konstanz, Universitätsstr. 10, 78457 Konstanz, Germany

† Email: amit.finkler@weizmann.ac.il

With recent reports on the sensing of electron spins and nuclear spins from single proteins using the nitrogen-vacancy center in diamond, we attempt to constrain the number of participating spins. This is achieved by using doubly spin-labeled amino acids. Both room temperature and low temperature measurements are presented. We also show how one can gauge the dipolar couplng between a pair of spin labels in the limit of a very small (< 4) amount of molecules [1]. This is an almost mandatory requirement for sensing spins in more complex (and of interest for active research) molecules. Finally, we stress the importance of quantum-assisted methods in reducing the effective measurement time, which is critical for imaging purposes [2].

1. Schlipf, L. *et al.* A molecular quantum spin network controlled by a single qubit. *Science Advances* **3,** e1701116 (Aug. 2017).
2. Häberle, T. *et al.* Nuclear quantum-assisted magnetometer. *Review of Scientific Instruments* **88,** 013702 (Jan. 2017).

Inv. 132
Thursday
19:00

Skyrmions in 2D Spin Systems with Disorder

Eugene Chudnovsky†
CUNY Lehman College and Graduate School, Bronx, NY 10468-1589, U.S.A.
D. A. Garanin
CUNY Lehman College and Graduate School, Bronx, NY 10468-1589, U.S.A.
X. X. Zhang
King Abdullah University of Science and Technology, Thuwal 23995-6900, Saudi Arabia

† Email: eugene.chudnovsky@lehman.cuny.edu

Presence of topological defects in spin systems with quenched randomness has a profound effect on the long-range behavior [1, 2]. Application of a weak magnetic field to a 2D film with random local anisotropy results in a skyrmion glass, FIG.1. Quenched randomness stabilizes skyrmions that would otherwise collapse due the violation of the scale invariance by the atomic lattice [3]. Good understanding of the properties of the skyrmion glass, such as field dependence of the concentration of skyrmions, their average size and stability, has been achieved via scaling arguments and confirmed by large-scale numerical studies of spin lattices [4]. When quenched disorder is weak, evolution of labyrinth domains into compact topological structures on application of the magnetic field is governed by random configuration of Bloch lines inside domain walls [5]. Depending on the combination of Bloch lines, the magnetic domains evolve into individual skyrmions, biskyrmions, or more complex topological objects. While the geometry of such objects is sensitive to the parameters, their topological charge is uniquely determined by the topological charge of Bloch lines inside the magnetic domain from which the object emerges.

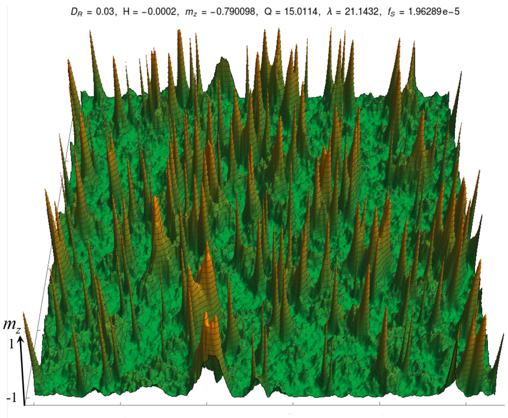


Figure 1: (Color online) Skyrmion glass in a disordered film

1. Proctor, T. C., Garanin, D. A. & Chudnovsky, E. M. Random Fields, Topology, and the Imry-Ma Argument. *Physical Review Letters* **112.** doi:10.1103/physrevlett.112.097201 (Mar. 2014).
2. Proctor, T. C. & Chudnovsky, E. M. Effect of a dilute random field on a continuous-symmetry order parameter. *Physical Review B* **91.** doi:10.1103/physrevb.91.140201 (Apr. 2015).
3. Cai, L., Chudnovsky, E. M. & Garanin, D. A. Collapse of skyrmions in two-dimensional ferromagnets and antiferromagnets. *Physical Review B* **86.** doi:10.1103/physrevb.86.024429 (July 2012).

4. Chudnovsky, E. M. & Garanin, D. A. Skyrmion Glass in a Disordered Magnetic Film. arXiv: 1710.10608v1 [cond-mat.mes-hall] (Oct. 2017).
5. Garanin, D. A. & Chudnovsky, E. M. Skyrmion Clusters From Bloch Lines in Ferromagnetic Films. arXiv: 1706.02994v1 [cond-mat.other] (June 2017).

Current-induced dynamics in antiferromagnets: generation of THz-frequency signals

Andrei N. Slavin†
Oakland University, 146 Library Drive, Rochester, MI 48309-4479, United States
O. Sulymenko
Taras Shevchenko National University of Kyiv, Kyiv 01601, Ukraine

† Email: slavin@oakland.edu

We propose a generator of THz-frequency signals based on a layered structure consisting of a current-driven platinum (Pt) layer and a layer of an antiferromagnet (AFM) with easy-plane anisotropy where the magnetization vectors of the AFM sublattices are canted inside the easy plane due to the Dzyaloshinskii-Moriya interaction (DMI) [1]. The DC electric current flowing in the Pt layer creates, due to the spin-Hall effect, a perpendicular spin current which, being injected into the AFM layer, tilts the DMI-canted AFM sublattices out of the easy plane, thus exposing them to the action of a strong internal exchange magnetic field of the AFM. The sublattice magnetizations along with the small net magnetization vector of a canted AFM start to rotate about the hard anisotropy axis of the AFM with the THz frequency proportional to the injected spin current and a square root of the AFM exchange field. The rotation of the small net magnetization results in the THz -frequency dipolar radiation that can be directly received by an adjacent (e.g. dielectric) resonator. We demonstrate theoretically that the generated frequencies in the range f =0.05- 2.0 THz are possible at the experimentally reachable magnitudes of the driving current density, and evaluate the power of the signal radiated into different types of resonators, showing that this power increases with the increase of the generation frequency f.

1. Sulymenko, O. R. *et al.* THz-Frequency Spin-Hall Auto-Oscillator Based on a Canted Antiferromagnet. arXiv: 1707.07491v1 [physics.app-ph] (July 2017).

Atomistic spin dynamics of magnetic insulators

Inv. I34
Friday
09:05

Joseph Barker†

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

G.E.W. Bauer

Institute for Materials Research, Tohoku University, Sendai 980-0011

S. Maehrlein and T. Kampfrath

Fritz Haber Institute of the Max Planck Society, Faradayweg 4-6, 14195 Berlin, Germany

† Email: joseph.barker@imr.tohoku.ac.jp

Atomistic spin dynamics is a classical formalism in which dynamics and thermodynamics of magnetic materials can be calculated. We focus our studies on magnetic insulators such as yttrium iron garnet (YIG) which is ubiquitous in the insulator spintronics, magnonics and spin mechanics communities. We have extended the classical spin dynamics formalism into the 'semi-classical' limit such that the magnons obey quantum statistics whilst the spins remain classical objects. This leads to a vast improvement in the quantitative calculation of material properties such as the magnon heat capacity. We will show recent progress in the calculation of magnon transport properties. We also present experimental evidence and a simple model for a spin-phonon interaction in the THz regime where the phonon excitation dynamically modifies the super exchange coupling leading to a transfer of spin angular moment between the two sublattices [1]. This causes the sublattice magnetization to decrease but maintains the total magnetization through angular momentum conservation.

1. Maehrlein, S. *et al.* Revealing spin-phonon interaction in ferrimagnetic insulators by ultrafast lattice excitation. arXiv: 1710.02700v1 [cond-mat.mtrl-sci] (Oct. 2017).

Pure spin currents in magnetic insulator/metal hybrid structures

Inv 25
Friday
09:40

Sebastian T. B. Goennenwein†

Institut für Festkörper- und Materialphysik (IFMP), Technische Universität Dresden, 01062 Dresden, Germany

† Email: `sebastian.goennenwein@tu-dresden.de`

Pure spin currents – i. e., directed flows of spin angular momentum – are a fascinating manifestation of spin physics in the solid state. Pure spin currents can propagate not only in metals and semiconductors, but also in magnetically ordered insulators. This makes a whole new set of materials and material combinations interesting for spin transport experiments and spin-electronic devices. A prototypical example for this development is the spin Hall magnetoresistance (SMR) effect, which arises in magnetic insulator/normal metal hybrid structures owing to the flow of spin angular momentum across the magnet/metal interface. In the last few years, the SMR response of ferrimagnetic insulators with both collinear as well as non-collinear magnetic structure has been extensively investigated. In addition, SMR-like experiments in non-local geometry in magnetic insulator/normal metal nanostructures enable the electrical quantification of the magnon diffusion length. The insights obtained from these experiments pave the way for studying pure spin current transport also in antiferromagnets. In the talk, I will briefly review the SMR response characteristic of collinear and non-collinear ferrimagnetic phases, and then discuss our recent magneto-transport experiments in antiferromagnetic insulator/Platinum heterostructures. In particular, I will critically compare our experimental data with model calculations, and address the evolution of the magneto-resistance across the Neel temperature of the antiferromagnet.

Making high quality freestanding magnon nanoresonators

Georg Schmidt[†]
Institut für Physik, Universität Halle, Von-Danckelmann-Platz 3, 06120 Halle, Germany
Frank Heyroth
Interdisziplinäres Zentrum für Materialwissenschaften, Universität Halle, Heinrich-Damerow Str. 4, 06120 Halle, Germany
Christoph Hauser, Philip Trempler, Rouven Dreyer, Georg Woltersdorf
Institut für Physik, Universität Halle, Von-Danckelmann-Platz 3, 06120 Halle, Germany

[†] Email: georg.schmidt@physik.uni-halle.de

Nano electromechanical systems have seen huge progress over the last decades. Recently coupling of mechanical to electromagnetic modes has gained importance because of possible use in so called transmons and their application for quantum computing [1],[2] . Yttrium Iron Garnet would be extremely interesting as a nanoresonator material because it combines long lifetimes as well for spin waves (magnons) as for mechanical waves (phonons) and a coupling mechanism for both (magnetoelastic coupling or magnetostriction). Coupling of magnons to phonons in YIG spheres of diameters of a few hundred micron has already been demonstrated[3] but making true 3D YIG nanoresonators would open up a new field of applications for nanooscillators. However, up to now no method was available to shape three dimensional nanostructures from monocrystalline YIG. We have developed a process to build monocrystalline freestanding 3D YIG nanoresonators. The structures can be designed as suspended bridges, cantilevers but also as more complex structures like for example suspended rings or disks. The structures were investigated using transmission electron microscopy indicating high crystalline quality. In ferromagnetic resonance different modes can be observed. The linewidth for an ensemble of 8000 bridges was as small as 7 Oe@6.5 GHz. Further investigation was done using time and spatially resolved Kerr microscopy. Here we see various standing spin waves including Damon Eshbach Modes and Backward Volume Modes. Based on these measurements also the damping for a single resonator could be determined to $\alpha < 4 \times 10^{-4}$. The modes observed can be nicely reproduced in 3D micromagnetic simulations.

1. O'Connell, A. D. *et al.* Quantum ground state and single-phonon control of a mechanical resonator. *Nature* **464,** 697–703 (Mar. 2010).
2. Chu, Y. *et al.* Quantum acoustics with superconducting qubits. *Science* **358,** 199–202 (Sept. 2017).
3. Zhang, W. *et al.* Giant facet-dependent spin-orbit torque and spin Hall conductivity in the triangular antiferromagnet IrMn3. *Science Advances* **2,** e1600759–e1600759 (Sept. 2016).

Single-crystalline FeCo nanowires as ultra-high magnetic gradient sources

Ye Tao[†]

Rowland Institute at Harvard, 100 Edwin H Land Blvd, Cambridge, MA 02142, United States

Christian L. Degen

Department of Physics, ETH Zurich, Otto Stern Weg 1, 8093 Zurich, Switzerland.

[†] Email: tao@rowland.harvard.edu

Magnetic nanostructures have played a central role in the development of magnetic resonance force microscopy (MRFM) [1–3] and force-based detection of magnetic moments [4]. Access to highly magnetic tips with precise, nanometer-resolution controls of tip geometry and material composition would further advance the technique by enabling closer approach of the gradient source to the sample [5, 6].

One approach to controllable tip geometries is the bottom-up growth of single-crystalline magnetic nanowires [7]. However, the production of nanowire materials, uniformly oriented along any arbitrarily chosen crystal orientation, is an important, yet unsolved, problem in material science [8]. A practical need for MRFM has thus led us to devise a generalizable solution to this material science problem, using FeCo as the demonstration material system.

We found a solution is based on the technique of glancing angle deposition [9] combined with a rapid switching of the deposition direction between crystal symmetry positions. We showcase the power and simplicity of the process in one-step fabrications of $< 100 >$, $< 110 >$, $< 111 >$, $< 210 >$, $< 310 >$, $< 320 >$ and $< 321 >$-oriented nanowires, three-dimensional nanowire spirals, core-shell heterostructures and axial hybrids. The resulting nanowires are single-crystals, have high saturation magnetization of 2.0(2) Tesla, and passivated by a surface oxide below 3 nm in thickness after one year of storage in air. Our results provide a new capability for tailoring the shape and properties of nanowires, should be generalizable to any material that can be grown as a single-crystal biaxial film, and has already offered a new route towards next-generation tip-on-cantilever MRFM sensors.

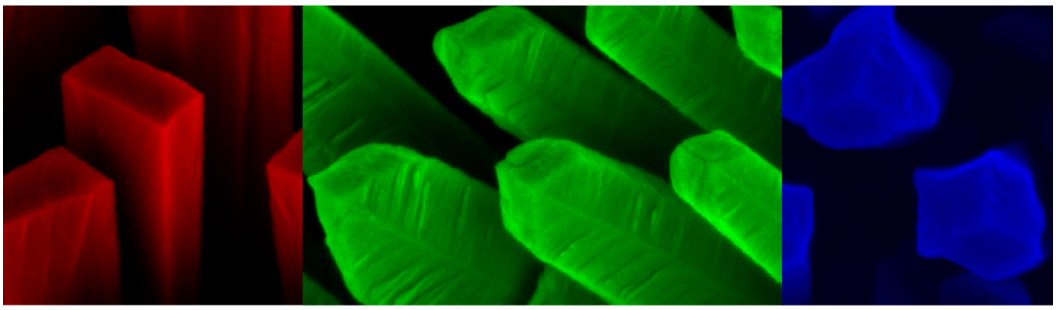


Figure 1: (Color online) Iron-cobalt single-crystal nanowires in different crystal orientations

1. Mamin, H. J., Poggio, M., Degen, C. L. & Rugar, D. Nuclear magnetic resonance imaging with 90-nm resolution. *Nature Nanotechnology* **2,** 301–306 (Apr. 2007).

2. Poggio, M., Degen, C. L., Rettner, C. T., Mamin, H. J. & Rugar, D. Nuclear magnetic resonance force microscopy with a microwire rf source. *Applied Physics Letters* **90,** 263111 (June 2007).

3. Nichol, J. M., Hemesath, E. R., Lauhon, L. J. & Budakian, R. Nanomechanical detection of nuclear magnetic resonance using a silicon nanowire oscillator. *Physical Review B* **85.** doi:10.1103/physrevb.85.054414 (Feb. 2012).

4. Tao, Y., Eichler, A., Holzherr, T. & Degen, C. L. Ultrasensitive mechanical detection of magnetic moment using a commercial disk drive write head. *Nature Communications* **7,** 12714 (Sept. 2016).

5. Kuehn, S., Loring, R. F. & Marohn, J. A. Dielectric Fluctuations and the Origins of Noncontact Friction. *Physical Review Letters* **96.** doi:10.1103/physrevlett.96.156103 (Apr. 2006).

6. Overweg, H. C. *et al.* Probing the magnetic moment of FePt micromagnets prepared by focused ion beam milling. *Applied Physics Letters* **107,** 072402 (Aug. 2015).

7. Chan, K. T. *et al.* Oriented Growth of Single-Crystal Ni Nanowires onto Amorphous SiO2. *Nano Letters* **10,** 5070–5075 (Dec. 2010).

8. Dasgupta, N. P. *et al.* 25th Anniversary Article: Semiconductor Nanowires - Synthesis, Characterization, and Applications. *Advanced Materials* **26,** 2137–2184 (Mar. 2014).

9. Hawkeye, M. M. & Brett, M. J. Glancing angle deposition: Fabrication, properties, and applications of micro- and nanostructured thin films. *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films* **25,** 1317 (2007).

Magnon transport by spin textures

Ix-I38
Friday
11:55

Helmut Schultheiss†

Helmholtz-Center Dresden-Rossendorf, Bautzner Landstraße 400, 01328 Dresden, Germany

† Email: `h.schultheiss@hzdr.de`

One of the grand challenges in quantum and condensed matter physics is to harness the spin of electrons for information technologies. While spintronics, based on charge transport by spin polarized electrons, made its leap in data storage by providing extremely sensitive detectors in magnetic hard-drives, it turned out to be challenging to transport spin information without great losses. With magnonics a visionary concept inspired researchers worldwide: Utilize magnons - the collective excitation quanta of the spin system in magnetically ordered materials - as carriers for spin information.

While macroscopic prototypes of magnonic logic gates already have been demonstrated, the full potential of magnonics lies in the combination of magnons with nano-sized spin textures. Both magnons and spin textures share a common ground set by the interplay of dipolar, spin-orbit and exchange energies rendering them perfect interaction partners. Magnons are fast, sensitive to the spins' directions and easily driven far from equilibrium. Spin textures are robust, non-volatile and still reprogrammable on ultrashort timescales.

In this presentation I will discuss magnon propagation in spin textures and how these magnons can be locally excited in spin textures by pure spin currents [1, 2].

1. Wagner, K. *et al.* Magnetic domain walls as reconfigurable spin-wave nanochannels. *Nature Nanotechnology* **11,** 432–436 (Feb. 2016).
2. Vogt, K. *et al.* Realization of a spin-wave multiplexer. *Nature Communications* **5.** doi:`10.1038/ncomms4727` (Apr. 2014).

Posters

Author Index