SPIN CALORITRONICS IX
2018

JUNE 24–29
COLUMBUS
OHIO

Spin Caloritronics IX Conference

Thank you for joining us for the Spin Caloritronics IX Conference here at The Ohio State University in Columbus, Ohio. We hope that your stay with us is as enjoyable as it is informative.

This booklet contains information:

- About Columbus
- Activities to do in Columbus,
- Restaurants near campus,
- About the conference,
- Speaker abstracts, and
- Poster abstracts

For additional information or questions, please contact Renee (ripley.25@osu.edu), Rachel (page.257@osu.edu), or Alison (scott.1452@osu.edu).

Welcome!

Co-Organizers:
Joseph P. Heremans
P. Christopher Hammel

Sponsors:

This workshop is supported by the Center for Emergent Materials: an NSF MRSEC, Army Research Office, OSU College of Engineering, OSU Institute for Materials Research, OSU Office of Energy and Environment, and OSU Department of Mechanical and Aerospace Engineering

EXPERIENCE COLUMBUS:

There's an energy and excitement in Columbus that's going to hit you as soon as you arrive. Big things are happening here, and you're invited to join in. The city is booming, and not just in population. The Columbus Museum of Art added a spectacular new wing, and the Scioto Mile puts 33 acres of new riverfront parkland in the heart of downtown. The innovative food scene melds artisan food producers with imaginative chefs to create meals that are far greater than the sum of their parts. Nationally acclaimed distilleries work together with brewers, coffee roasters and high-end cocktail bars, black box stages, music halls and dive bars to deliver unforgettable nightlife. Neighborhoods on all sides of downtown are bursting with new places to eat and shop, and artists are shaping new areas of the city into dynamic spaces to explore. It's time to get to know the Columbus that grew up when you weren't looking.

From: www.experiencecolumbus.com

Entertainment
(Area code 614 for all phone numbers)

General Information

Experience Columbus………………………………………………………...221- 6623
http://www.experiencecolumbus.com

Attractions

South Campus Gateway (with a movie theater)
http://www.southcampusgateway.com

North Market………………………………………………………………….463 - 9664
www.northmarket.com

Columbus Zoo……………………………………………………………...645 - 3400
http://www.columbuszoo.org

German Village
www.germanvillage.com

The Short North
www.theshortnorth.org

The Arena District
www.arenadistrict.com

Performing Art/Theater

CAPA - Columbus Association for the Performing Arts……………………….469 - 0939
hwww.capa.com

BalletMet Columbus………………………………………………………….229 - 4860
http://www.balletmet.org

Columbus Symphony Orchestra……………………………………………...228 - 8600
www.columbussymphony.com

CATCO - Contemporary American Theater Company……………………....469 - 0939
www.catco.org

Funny Bone Comedy Club…………………………………………………….471 - 5653
http://www.columbusfunnybone.com/

Drake Performance and Event Center at Ohio State…………………………….292 - 2295
drake.osu.edu

Wexner Center for the Arts……………………………………………………….292 - 3535
www.wexarts.org

Museums

Columbus Metropolitan Library……………………………………………………645 - 2275
http://www.columbuslibrary.org

Columbus Museum of Art………………………………………………………….221 - 4848
www.columbusmuseum.org

COSI - Center of Science & Industry…………………………………………....228 - 2674
www.cosi.org

Live Music

LC Pavillion (Promowest)…………………………………………………….……..461 -5483
http://www.promowestlive.com/search?venue=7

Newport Hall………………………………………………………………………..294 - 1659
http://www.promowestlive.com/search?venue=3

Barrister Hall……………………………………………………………….....621 - 1213

Ticketmaster………………………………………………………………...431 - 3600
www.ticketmaster.com

COTA Accessible Activities

Columbus Zoo and Aquarium
Located in Powell just north of Columbus the Columbus Zoo has been named the number one zoo in the United States. Directed by Jack Hanna it is home to over 9,000 animals.
Tickets: $14.99 for Franklin County* resident
$19.99 for those Outside of Franklin County
*Zoo guests will be asked to provide a valid driver's license, state-issued ID or a current utility bill to receive Franklin County Pricing
**Check to see if other graduate students can buy tickets for you at the Union through the D-Tix program for $8
Group Tickets (15 or more): $14
Car Parking: $10.00
Bus Parking: Free

Zoombezi Bay
Water park adjacent to the Columbus Zoo includes 21+ lazy river, action river, wave pool, 17 slides & raft slides
Tickets: $29.99 (online)
Tickets include admission to the Columbus Zoo

Columbus Museum of Art
The art museum is located in downtown Columbus highlights include early Cubist paintings by Picasso, Cezanne, Monet and others.
Hours: 10 AM – 5:00 PM Tues, Wed, Fri, Sat, Sun
10 AM – 9:00 PM Thursday
Closed Monday
Tickets: Free Sunday
$8 for Students with ID

COMFEST
COMFEST, short for Community Festival, is a long time tradition in Columbus where people gather to listen to live music, buy food & drinks at
When: June 22-24
Where: Goodale Blvd and Park St (Short North)

WaterFire
An exciting art exhibit – bonfires are set up in the Scioto River and audience members enjoy art, music and activities
When: See website http://waterfire.org/
Gates open at 6:30, live music at 7:30, fires lit at 8:30, concludes at 10:30
Where: Genoa Park

COSI
The Center of Science and Industry is a science museum in downtown Columbus.
When: Mon-Sat 10AM-5PM & Sun Noon-6PM
Where: 333 W Broad St

Cost: $25

**Check to see if other graduate students can buy tickets for you at the Union through the D-Tix program for $8

Columbus Clippers

The Triple-A minor league affiliate of the Cleveland Indians play at Huntington Park in downtown Columbus

Schedule: http://www.milb.com/schedule/index.jsp?sid=t445

Tickets: ~$10 Reserved Seats

Columbus Crew

An American professional soccer club that competes in Major League Soccer.

Schedule: http://www.thecrew.com/schedule

Tickets: $15-55

Franklin Park Conservatory and Botanical Gardens

Butterfly garden, greenhouse & botanical gardens

Hours: 10 AM – PM Daily

10 AM – 8 PM Wednesday

Tickets: $12 Adults

$9 for Students with ID

Activities Requiring Transportation
Interested? Ask Michelle and she'll try to set something up!

Cedar Point

364-acre amusement park located on a Lake Erie peninsula in Sandusky, Ohio. Cedar Point has the second most roller coasters in the world (16) and the only amusement park in the world with four roller coasters taller than 200 feet. It is about a 2 and half hour drive from Columbus.

Tickets: Online Prices $44.99
Group Tickets (15 or more): $37
Bus Parking: $20/day
Car Parking: $15/car/day
Buy online at https://www.cedarpoint.com/tickets/
Location: (2.5 hour drive) 1 Cedar Point Dr, Sandusky, OH 44870
Hours: Usually opened 10 AM – 10 PM Sun, Mon, Tues, Wed, Thurs, Fri
10 AM – Midnight Saturdays
Check Hours at https://www.cedarpoint.com/hours-directions

Soak City

Water park adjacent to Cedar Point with 5 pools and 12 water slides including a wave pool, swim up bar, 2 lazy rivers, and a rafting slide.

Tickets: Online Price $32.99
Buy online at https://www.soakcitycp.com/tickets/
Hours: Usually opened 10 AM – 8 PM
Check Hours at https://www.soakcitycp.com/hours-directions

Trapper John's Canoe Livery

Canoe, kayak and tube rentals on Big Darby Creek about 20 minutes south west of campus

The Sampler: ~1-2 hours $15/person
The Upper Trip: ~2-4 hours $20/person
The Lower Trip: ~2-4 hours $20/person until 3 PM
The Full Day Trip: ~4-6 hours combines the upper and lower trip, offered before 11 AM, $25/person
Tube Rentals: $9/tube

Hocking Hills

A popular hiking and camping destination about an hour south of Columbus. Popular hiking sites include caves & waterfalls

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Campus Area Restaurants

5-10 Minute Walk from the Blackwell

Buffalo Wild Wings- 2151 N. High Street
Table Service, American

Cazuela's- 2247 N. High Street
Table Service, Mexican

Noodles & Co.- 2124 High Street
Counter Service, Multi

Panera Bread- 300 W. Lane Ave.
Counter Service, Multi

Tommy's- 174 W. Lane Ave.
Counter Service, Pizza

10-15 Minute Walk from the Blackwell

Buckeye Donuts- 1998 N. High Street
Counter Service, Multi

Dunkin' Donuts- 8235 N. High Street
Counter Service, American

McDonald's- 1972 N. High Street
Counter Service, American

Moe's Southwest Grill- 2040 N. High Street
Counter Service, Mexican

Moy's Chinese Restaurant- 1994 N. High Street
Table Service, Chinese

Panda Express- 2044 North High Street
Counter Service, Chinese

Wendy's- 2004 N. High Street
Counter Service, American

15-20 Minute Walk from the Blackwell

Apollos- 1758 N. High
Counter Service, Greek

Bibibop- 1717 N. High Street
Counter Service, Korean

Chipotle- 1726 N. High Street
Counter Service, Mexican

Mad Mex- 1542 N. High St
Table Service, Mexican

Raising Canes Chicken- 10 E. 11th Ave.
Counter Service, American

Starbucks- 1782 N. High Street
Counter Service, Multi

Trism- 1636 N. High Street
Counter Service, Multi

Short North Area Restaurants

Bakersfield- 733 N. High Street
Table Service, Mexican

Basi Italia- 811 Highland Street
Table Service, Italian

Basil- 1124 N. High St
Table Service, Thai

Brassica- 680 N. High Street
Counter Service, Mediterranean

Condado- 1227 N. High Street
Table Service, Mexican

Forno- 721 N. High Street
Table Service, American

Marcella's- 615 N. High Street
Table Service, Italian

Melt- 840 N. High Street
Table Service, American

Northstar Café- 951 N. High Street
Counter Service, Multi, Vegan

The Eagle- 790 N. High Street
Table Service, American

The Guild House- 624 N. High Street
Table Service, American

The Pearl- 641 N. High Street
Table Service, Multi

A complete list of Short North food offerings can be found at http://shortnorth.org/eat-drink/dinner/.

About Spin Caloritronics IX

1. **Summary:**

Spin caloritronics is the study of thermally driven spin fluxes. The community of scientists working on the topic meets annually in a series of Spin Caloritronics workshops. The 9th in the series will be organized at the Ohio State University campus June 25-29, 2018.

Spin caloritronics is a subset of the general study of spin and magnetization dynamics, covering time-dependent, spin-based phenomena and properties, such as spin transport, that are out of thermodynamic equilibrium. Spins can reside on localized electrons in magnetically ordered ferromagnets, ferrimagnets, and antiferromagnets (AFM) that can reside on itinerant electrons in magnetically ordered electrical conductors. In the latter, spin transport accompanies electrical charge transport. Spin residing on localized electrons also can transport magnetization and heat via magnons (spin-precession waves). Research over the last 10 years has emphasized coupled linear transport (Onsager relations) of spin, charge, and entropy by conduction electrons, and charge and entropy by magnons. Spin transport across interfaces between magnetic and non-magnetic materials is of particular interest as the interface breaks the symmetry of the lattice, giving rise to important new phenomena. Spin transfer occurs by a mechanisms called spin-transfer torque, based on the conservation of (spin) angular momentum. Spin transfer torque is the physical principle underlying spin-based memories (MRAM and STT-MRAM), which dominate the Random Access Memory (RAM) market today. Its fundamental study is of the utmost technological relevance for the electronics industry in general, and for the Army in particular.

Spin caloritronics is distinguished by the fact that thermal excitation gives the most intense spin fluxes achievable [Weiler et al., *Phys. Rev. Lett.* **111**, 176601 (2013)] by any means. It provides a spin flux roughly two orders of magnitude more intense than spin pumping using ferromagnetic resonance, and three orders of magnitude more than electrically pumped fluxes (Spin-Hall magnetoresistance). The field started with the discovery of the spin-Seebeck effect (SSE) in 2008, which was the first new thermomagnetic effect discovered in a century.

At the conference, we expect to see new discoveries from around the world in the following fields, and to discuss future research prospects for the coming decade. Under strong enough driving forces, transport can depart from linearity and new collective spin modes may develop, some of them labeled “Bose-Einstein condensates;” the quest for their observation continues to spur experimental and theoretical activity. Topological effects are not confined to the electron system, but also expected in magnon dispersions. Several new results explore in detail the magnon-phonon interaction, a necessary step to transfer entropy from the phonon system to the magnon system. New results are also expected to be presented on spin transport in antiferromagnets and in chiral structures like skyrmions. AFMs offer new prospects because their spin dynamics are much faster than those in ferromagnets (resonance frequencies are 1 to 2 orders of magnitude higher) and also because the choice of AFM insulating materials is much broader than that of insulating ferromagnets. SSE effects through AFMs have been reported by several groups. Skyrmions are the smallest possible domain-reversal structure, enabling the exploration of the smallest possible magnetic device size. The Dzyaloshinskii-Moriya interaction (DMI) that arises from broken inversion symmetry and spin–orbit coupling, and stabilizes chiral spin structures gives rise to a thermal magnon-Hall effect, which is possibly the only transport property sensitive to it.

2. Topics to be Covered

The conference focuses on thermal spin transport, but includes new results in the fields of spin transport and spin dynamics in general.

- Thermal spin transport
  - Spin-Seebeck effect
  - Magnon-drag
  - Magnon-phonon interactions
- Collective spin modes, macroscopic effects
  - Thermally-driven macroscopic dynamics
  - Other macroscopic dynamics
  - Condensation
  - Magnon Bose-Einstein Condensation
- Topological effects, Weyl points
  - Magnons
  - Electrons
- Spin currents through antiferromagnets
- Chiral structures
  - Dzyaloshinskii-Moriya interaction
  - Skyrmions, heat-induced skyrmion dynamics
  - Thermal Hall effects
- Magnetization dynamics
  - Insulators
  - Metals

Speaker Abstracts

Adachi
Barsukov
Cahill
Cheng
Du
Duine
Flatté
Fuchs
Goennenwein
Heremans
Hillebrands
Hoffmann
Hou
Jin
Johnston-Halperin
Kläui
Kovalev
Myers
Nowak
Ohnuma
Reiss
Schmidt
Li Shi
Tserkovnyak
Uchida
Vashaee
Vasyuchka
Wang
Xiao
Yang
Zhang

Spin Seebeck/Pumping Effect near a Phase Transition Point

Hiroto Adachi, Yutaka Yamamoto, Takuya Taira, Masanori Ichioka

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Tsushima-naka 3-1-1, Okayama 700-8530, Japan

Abstract: The spin Seebeck effect and spin pumping are now established as versatile means for spin current generation [1]. Both methods essentially rely on the existence of out-of-equilibrium magnons, where the former uses thermal bias to excite nonequilibrium magnons whereas the latter utilizes microwave. We ask how these phenomena are affected by a phase transition. Here we consider the following two examples:

1) Spin-Seebeck effect near the magnetic transition
2) Spin pumping near the superconducting transition

In the first part, we discuss the spin Seebeck effect in the vicinity of the Curie temperature TCurie [2,3,4]. Using the time-dependent Ginzburg-Landau model under thermal agitation, we show that when the magnet is a simple ferromagnet composed of a single sublattice, temperature dependence of the spin Seebeck effect is proportional to that of the magnetization near TCurie, i.e., ~(TCurie - T)1/2.

In the second part, we consider the spin pumping into superconductors near the superconducting transition temperature Tsc [5]. Starting from weak-coupling BCS Hamiltonian we show that, when the superconducting gap is not completely suppressed at the ferromagnet/superconductor interface (which seems to be the case if a magnetic insulator is used), a pronounced coherence peak appears in the signal immediately below Tsc [6,7].

Finally, if time allows, we present recent result on the spin diffusion equation in superconductors just below Tsc [8]. We believe this has relevance to the quite recent experiment reported in [9].

References:

[1] S. Maekawa et al., J. Phys. Soc. Jpn. 82, 102002 (2013).
[2] H. Adachi, Y. Yamamoto, M. Ichioka, J. Phys. D: Appl. Phys. 51, 144001 (2018).
[3] K. Uchida et al., Phys. Rev. X 4, 041023 (2014).
[4] J. Barker and G. E. W. Bauer, Phys. Rev. Lett. 117, 217201 (2016).
[5] M. Inoue, M. Ichioka, H. Adachi, Phys. Rev. B 96, 024414 (2017).
[6] Y. Yao et al., arXiv:1710.10833 (2017).
[7] M. Umeda et al., arXiv:1801.07943 (2018).
[8] T. Taira et al., in preparation.
[9] K.-R. Jeon et al., Nature Mater. (2018), doi:10.1038/s41563-018-0058-9.

Condensation of Magnons in Coupled Spin Systems

Igor Barsukov

Physics and Astronomy, University of California Riverside, Riverside, California USA

Abstract: Magnon condensates driven by thermal spin current have been recently realized [1] in nanowires based on bilayers of ferrimagnetic insulator Yttrium Iron Garnet (YIG) and Platinum. Via ohmic heating of the Pt layer, a temperature gradient is established across the YIG/Pt interface. The thermal spin current compensates the damping of YIG and creates a magnonic condensate that manifests through auto-oscillations of the lowest spin-wave mode of the nanowire. The auto-oscillations generate a microwave signal by means of magnetoresistive effects in Pt, resulting in a low-power emission from the device. Recently, magnetic systems consisting of two ferromagnets have attracted much attention due to tunable spin-orbit torques [2] in metallic ferromagnets. Here, nanodevices consisting of YIG/Permalloy (Py) bilayers are presented. Interfacial spin coupling is discussed, that leads to an increased susceptibility of Py spin system to the YIG magnetization and allows for measuring the spin-wave spectrum of the nanowire. Using micromagnetic simulations, the spin-wave modes are shown to be localized in the individual layers in the low-frequency regime and to hybridize in the high-frequency regime. The thermal spin-torques and spin-orbit torques are evaluated by angular dependent microwave spectroscopy and by controlling thermal spin currents via nanodevice design. In devices with large thermal spin current contribution, angular momentum is transferred to the YIG system through injection of incoherent thermal magnons from the Py spin system, leading to condensation of the low-energy YIG-like mode. The auto-oscillatory dynamics results in a strong microwave emission from the device owing to the large magnetoresistance of Py. Energy loss due to ohmic heating is the major bottleneck for the performance of nanoelectronics devices. Thermally generated spin currents can be employed to harvest the waste heat and to operate spintronic devices, such as tunable microwave oscillators and spin wave emitters.

This work was supported by Spins and Heat in Nanoscale Electronic Systems (SHINES), an Energy Frontier Research Center funded by the US Department of Energy.

References:

[1] C. Safranski et al., *Nat. Commun.* 8, 117 (2017).
[2] T. Taniguchi et al., *Phys. Rev. Appl.* 3, 044001 (2015).

Ultrafast Thermometry using Linear and Quadratic Magneto-Optic Kerr Effects in Metallic Ferromagnetic and Antiferromagnetic Materials

David G. Cahill, Hyejin Jang, Kexin Yang

Department of Materials Science and Engineering and Materials Research Laboratory, University of Illinois, Urbana, IL USA

Abstract: Time-resolved measurements of the magneto-optic Kerr effect (TR-MOKE) are commonly used to study how the magnetization dynamics of ferromagnetic materials respond to fast temperature excursions and heat currents. Here, we flip the situation around and describe how TR-MOKE provides an ultrafast thermometer for studies of the physics of heat conduction. TR-MOKE—i.e., measurements of transient changes in the *polarization* of a reflected probe beam—has some unique advantages over the more conventional time-domain thermoreflectance (TDTR) approach that is based on measurements of the transient changes in the *intensity* of a reflected probe beam. For example, the signal in a TR-MOKE measurement is localized to the magnetic layer while the signal from a TDTR measurement is dependent on entire temperature field that interacts with the probe beam. Thus, TR-MOKE can accurately report the temperature of semi-transparent magnetic layers or magnetic layers that are buried within a complex multilayer structures. We have previously used TR-MOKE to measure the in-plane thermal conductivity of MoS_2, the thermal conductance of Pt/a-SiO_2 interfaces, and the grain-to-matrix thermal transport in HAMR media. We are currently using TR-MOKE to test the validity of the three-temperature model of heat transport in Pt/Co/Pt trilayers, and the thermal conductance of MgO and $MgAl_2O_4$ tunnel barriers. Recently, we have extended the TR-MOKE approach to make use of the transient changes in optical constants that are proportional to the quadratic terms in the magnetization, TR-QMOKE. TR-QMOKE provides an experimentally convenient probe of the magnetic temperature of ferromagnetic layers with in-plane magnetization and can also be applied to metallic antiferromagnetic materials. In our initial studies of the metallic antiferromagnet Fe_2As, we observe, as expected, that the amplitude of the TR-QMOKE signal has a temperature dependence comparable to the temperature dependence of the magnetic heat capacity.

Magnon-Mediated Interlayer Coupling and Spin-Transfer Torques

Ran Cheng

Department of Physics, Carnegie Mellon University, Pittsburgh, Pennsylvania USA
Department of Electrical and Computer Engineering, University of California Riverside, Riverside, California USA

Abstract: Magnons are the quanta of spin-wave excitations that can transport information over long distances without incurring Joule heating. They are promising alternatives to electrons in building low-dissipation devices. However, to fully function as electrons, magnons should bear an intrinsic degree of freedom similar to the electron spin. In an antiferromagnet with uniaxial anisotropy, symmetry guarantees the coexistence of both spin-up and spin-down magnons, forming a unique degree of freedom capable of encoding information. Guided by the resemblance between antiferromagnetic magnons and electrons with spin being an active variable, we propose a magnonic analogue of spin-valve composed of insulating ferromagnet/antiferromagnet/ferromagnet trilayer. We find that magnons inside the antiferromagnetic spacer can mediate an effective exchange coupling between the two ferromagnets, which exhibits a qualitatively different behavior compared to the well-known RKKY interaction. Furthermore, a temperature gradient can deliver spin angular momenta from one ferromagnet to the other in the form of magnonic spin-transfer torque, which can be utilized to realize thermal switching.

Control and Local Measurement of the Spin Chemical Potential in a Magnetic Insulator

Chunhui Du

Harvard University, Cambridge, Massachusetts USA

Abstract: In recent decades, a large scientific effort has focused on harnessing spin transport for providing insights into novel materials and low-dissipation information processing. We introduce single spin magnetometry based on nitrogen-vacancy (NV) centers in diamond as a new and generic platform to locally probe spin chemical potentials which essentially determine the flow of spin currents. We use this platform to investigate magnons in a magnetic insulator yttrium iron garnet (YIG) on a 100 nanometer length scale. We demonstrate that the local magnon chemical potential can be systematically controlled through both ferromagnetic resonance and electrical spin excitation, which agrees well with the theoretical analysis of the underlying multi-magnon processes. Our results open up new possibilities for nanoscale imaging and manipulation of spin-related phenomena in condensed-matter systems.

Manipulating Magnons with Spin Currents

Rembert Duine

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Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

Abstract: In this talk I will discuss how the interaction between electronic spin current and magnetic order gives rise to new possibilities for magnon manipulation. Examples to be discussed are magnon spin currents in non-local set-ups consisting of metals and magnetic insulators, and magnonic event horizons that are implemented using bulk spin transfer torques in metallic ferromagnets.

Nonlocal Drag of Magnons in a Ferromagnetic Bilayer

Michael Flatté

Department of Physics and Astronomy, University of Iowa
Department of Electrical and Computer Engineering, University of Iowa

Abstract: The flow of thermal magnons in a magnetic material is often thought to have little interaction with the surroundings, and to move with little dissipation or drag. Exceptionally long diffusion lengths and relaxation times appear to occur, especially for thermal magnons in yttrium iron garnet (YIG). It is difficult to disentangle the role of different scattering mechanisms in such measurements, since they all occur at once. In analogy to the observation of Coulomb drag in bilayer 2DEGs, in which the contribution of the Coulomb interaction to the electric resistivity is studied by measuring the interlayer resistivity, we present a theoretical study of the drag effect of magnons in a ferromagnetic bilayer structure to focus on the contribution of the dipolar interactions to the magnon current resistivity and the magnon thermal resistivity[1]. We show that a magnon current running in one layer can induce a temperature gradient and/or a chemical potential gradient in the other layer, depending on the boundary conditions. The drag effect is largest when the magnon current propagates parallel to the magnetization, however for oblique magnon currents there is also a transverse current of magnons. We examine the effect for practical parameters, and find that the predicted induced temperature gradient is readily observable.

References:
[1] T. Liu and M. E. Flatté, *PRL* 116, 237202 (2016).

Time-Resolved Magneto-Thermal Microscopy: High-Resolution Dynamic Imaging of Magnetic Materials using Picosecond Heat Pulses

Greg Fuchs

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Abstract: Research into magnetic devices – emerging memory, logic, and oscillator technologies – is enabled by magnetic imaging techniques that possess simultaneous picosecond temporal resolution and 10 – 100 nm spatial resolution. Conventionally, this combination is available only at facility-based research centers using e.g., pulsed x-ray dichroism techniques. In addition, many of the most exciting magnetic material systems, including ultrathin ferromagnetic or antiferromagnetic insulators buried beneath heavy metals are difficult to image with any method. To address these challenges in an accessible way, we have developed a table-top spatiotemporal magnetic microscope based on picosecond heat pulses that takes advantage of magneto-thermal interactions including the anomalous Nernst effect [1] and the longitudinal spin Seebeck effect [2]. Using focused light as a picosecond heating source, we first demonstrate that these imaging modalities have time resolution on the order of 10 ps and sensitivities to magnetization angle of 0.1-0.3 $/\sqrt{Hz}$ for ferromagnetic metals and insulators. In combination with phase-sensitive microwave current imaging, phase-sensitive ferromagnetic resonance imaging [3] enables direct imaging of the gigahertz-frequency magnetic driving torque vector, which is valuable for understanding spin-orbit interactions [4]. We also demonstrate magneto-thermal imaging of antiferromagnetic order in FeRh and NiO, offering a simple and accessible method to study spin-orbit torque switching of antiferromagnetic materials. Finally, I will describe how time-resolved magnetic imaging can be extended to greatly exceed the optical diffraction limit, both theoretically [5] and experimentally. We demonstrate scanning a sharp gold tip illuminated by picosecond laser pulses as the basis of a nanoscale spatiotemporal magnetic microscope.

References:

[1] J. M. Bartell, D. H. Ngai, Z. Leng, and G. D. Fuchs, *Nat. Commun.* 6, 8460 (2015).
[2] J. M. Bartell, C. L. Jermain, S. V. Aradhya, J. T. Brangham, F. Yang, D. C. Ralph, and G. D. Fuchs, *Phys. Rev. Appl.* 7, 044004 (2017).
[3] F. Guo, J. M. Bartell, D. H. Ngai, and G. D. Fuchs, *Phys. Rev. Appl.* 4, 044004 (2015).
[4] F. Guo, J. M. Bartell, and G. D. Fuchs, *Phys. Rev. B* 93, 144415 (2016).
[5] J. C. Karsch, J. M. Bartell, and G. D. Fuchs, *APL Photonics* 2, 086103 (2017).

Observation of the Spin Nernst Effect in Platinum

Sebastian T. B. Goennenwein

Institut für Festkörper- und Materialphysik, Technische Universität Dresden, Dresden

Abstract: Thermoelectric effects – arising from the interplay between thermal and charge transport phenomena – have been studied extensively and are considered well established. However, upon taking into account the spin degree of freedom, qualitatively new phenomena arise. A prototype example for these so-called magneto-thermoelectric or spin-caloritronic effects is the spin-Seebeck effect, in which a thermal gradient drives a pure spin current.

In contrast to their thermoelectric counterparts, not all spin-caloritronic effects predicted from theory have yet been observed in experiment. One of these 'missing' phenomena is the spin-Nernst effect, in which a thermal gradient gives rise to a transverse pure spin current. We have recently observed the spin-Nernst effect in yttrium iron garnet/platinum (YIG/Pt) thin film bilayers [1]. Upon applying a thermal gradient within the YIG/Pt bilayer plane, a pure spin current flows in the direction orthogonal to the thermal drive. We detect this spin current as a thermopower voltage, generated via magnetization-orientation dependent spin transfer into the adjacent YIG layer. Our data shows that the spin Nernst and the spin Hall effect in Pt have different signs, but comparable magnitude, in agreement with first-principles calculations.

References:

[1] S. Meyer *et al.*, *Nature Materials* 16, 977 (2017).

Spin-enhanced thermopower and Nernst effects in metals and semiconductors.

Yuanhua Zheng[1], Bin He[1], Michael Adams[1], Sarah J. Watzman[1], Koen Vandaele[1], Benedetta Flebus[2], Wolfgang Windl[1], Rembert Duine[3], Yaroslav Tserkovnyak[2,] D. Vashaee[4] and Joseph P. Heremans[1]

[1] The Ohio State University
[2] University of California Los Angeles
[3] University of Utrecht, the Netherlands
[4] North Carolina State Univeristy

Abstract: Magnon-drag, a phenomenon closely related to the spin-Seebeck effect, enhances the thermopower of metals by an order of magnitude. This phenomenon is particularly pronounced in metals, in which the classical electronic thermopower is limited by the Mott relation, which dictates that the thermopower must decrease inversely with the charge carrier concentration. In contrast, magnons, being bosons, have a "magnonic thermopower" that is the specific heat per particle [1] and does not decrease with concentration. The effect was demonstrated to dominate the thermopower of Fe, Co and Ni; these results will be extended here to new alloys in the Fe-Co system specifically designed to maximize the effect. New data on the Nernst thermopower of ferromagnetic MnBi suggest a magnon contribution to the anomalous Nernst effect in that material, in a geometry that close to that of the spin-Seebeck one, suggesting the presence of a self-spin-Seebeck effect in that material.

Going beyond magnon-drag, thermopower enhancements persist in disordered spin systems, such as in MnTe in the paramagnetic regime, as is reported elsewhere [2] is this conference. We report new data in Cr-Mn alloys that suggest a similar origin.

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Bose-Einstein Condensation of Magnons by Instant Cooling

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Abstract: A room-temperature magnon Bose-Einstein condensate (BEC) observed in magnetic insulators (single-crystal films of yttrium iron garnet, YIG) [1,2] has a large potential in high-speed and low-power information processing and data transfer. Recently, we have succeeded to create magnon supercurrents by introducing a spatial phase gradient into a BEC wave function [3]. The discovery of the room-temperature magnon supercurrent transport opens door to studies of magnonic macroscopic quantum transport phenomena as a novel approach in the field of information processing.

At the same time, the miniaturization of supercurrent-based magnonic devices constitutes an extraordinary challenge for their future applications. Conventionally, the conditions for the formation of the BEC are created in macroscopic YIG samples by powerful microwave parametric pumping injecting a large number of magnons. Here, a fundamentally new approach is presented. Fast DC-current pulses applied to YIG/Pt microstructures result in a strong heating. Consequently, this leads to an increased number of magnons, distributed over the whole magnon spectrum. Once the current is switched off the system cools down rapidly. This results in a strong increase of the magnon density at the bottom of the spectrum during the cooling of the magnetic structure, leading to the formation of magnon BEC. We have observed this phenomenon by time-resolved Brillouin light scattering spectroscopy. Our experiment shows, that the BEC formation depends on the magnon temperature and the timescale of the cooling process.

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Spin-to-Charge Current Conversion from Interfacial Rashba Spin-Orbit Coupling

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Abstract: It has long been known that interfacial symmetry breaking can give rise to so-called Rashba spin-orbit coupling. Using spin pumping for injecting spin currents we have investigated the spin-to-charge current conversion in Ag, Cu, and Au layers combined with Bi and Sb, and we observed the largest effects for Ag/Bi and Ag/Sb [1]. Focusing on Ag/Bi we showed that the reversed effect of charge-to-spin current conversion is sufficiently strong for driving the magnetization of an adjacent ferromagnet into resonance [2]. The dependence on the Ag layer thickness demonstrates indeed the interfacial nature of the effect. Furthermore, we explored whether the interfacial spin-to-charge current conversion also is effective at ultrafast time-scale. Using femtosecond optical pumping, we can generate ultra-fast spin-currents in CoFeB, and detect THz radiation pulses that originate from the spin-to-charge current conversion due to the Rashba-Edelstein effect at the interface of an adjacent Ag/Bi bilayer [3]. Interestingly, we see additionally a smaller orthogonal THz electric field generated that depends on the circular polarization of the incoming optical pump pulse.

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Néel Vector Orientation Control of Spin Current in Antiferromagnetic Insulator

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Abstract: Effective spin current manipulation is the key process to realize the spin-based transistor, and unfortunately proved to be quite challenging in the electron-based spin channels in which the propagation of spin current relies on the isotropic electron diffusion. Recent works show that spin can transmit through antiferromagnetic insulators [1,2] in which itinerant electrons cannot pass, indicating alternative methods for spin manipulation. In this talk, the speaker will introduce their recent progress in the effective manipulation of spin current in antiferromagnetic insulators with methods different from those in conductive materials. The spin current switching by the control of the Néel vector orientation will be introduced, with the presentation of a novel effect: spin colossal magnetoresistance[3-6]. These findings pave the road towards antiferromagnetic-insulator-based spin transistor and memory.

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Improving Efficiency of Spin-Based Thermoelectric Devices

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Abstract: Since the discovery of the spin-Seebeck effect (SSE) in 2008, a considerable amount of work has been done to unravel fundamental aspects of SSE as well as to observe SSE in different material systems. Relatively less attention has been paid to engineering aspects of spin-Seebeck devices where the energy conversion efficiency, indicated by the figure-of-merit (zT_{SSE}), matters much. Here we attempt to improve zT_{SSE} of spin-Seebeck devices utilizing an approach widely used in thermoelectrics research: separating different energy carriers through length-selective scattering. In a ferrite system, we find the length scale of magnons that contribute to the SSE is shorter than that in yttrium iron garnet (YIG). This enables us to design a composite device wherein phonons are selectively scattered without degrading spin-Seebeck signals, leading to an inproved zT_{SSE}. We present the fabrication method of such a device as well as experimental results.
If time allows, we will also present our recent work on magnon-electron drag in a bulk superparamagnet on a preliminary level.

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High-Q Spin Wave Excitations in the Organic-Based Ferrimagnet Vanadium Tetracyanoethylene

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Abstract: The study of coherent magnonic interactions relies implicitly on the ability to excite and exploit long-lived spin wave excitations in a magnetic material. That requirement has led to the nearly universal reliance on yittrium iron garnet (YIG), which for half a century has reigned as the unchallenged leader in high-Q, low loss magnetic resonance, and more recently in studies of spin-thermal effects, despite extensive efforts to identify alternative materials. Surprisingly, the organic-based ferrimagnet vanadium tetracyanoethylene ($V[TCNE]_2$) has emerged recently as a compelling alternative to YIG. In contrast to other organic-based materials, $V[TCNE]_2$ exhibits a Curie temperature of over 600 K with robust room temperature hysteresis with sharp switching to full saturation. Further, since $V[TCNE]_2$ is grown via chemical vapor deposition (CVD) at 50 °C, it can be conformally deposited as a thin film on a wide variety of substrates. Our recent work has exploited this potential to construct a microwave waveguide in which $V[TCNE]_2$ is deposited as a bridge across two coplanar waveguides, exhibiting standing wave spin-wave resonances with Q of over 3,200 at X-band (9.86 GHz) and under ambient conditions. This Q rivals the very best thin-film YIG devices, which must be grown epitaxially on GGG substrates at temperatures over 800 °C. Work in preparation shows that this Q can be enhanced further by moving to the thick-film geometry, which is well known to reduce surface scattering, yielding Qs over 8,000. When added to the ease of patterning and integration afforded by the low temperature CVD deposition process, these results clearly demonstrate the potential for $V[TCNE]_2$ to play a major role in the development of long-lived coherent spin wave excitations in quantum magnonic devices. Further, while spin-thermal physics in this system is still largely unexplored, we note that the low electrical conductivity and lack of structural order suggest a larger role for magnetothermal effects than is found in more traditional inorganic materials.

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Long Distance Spin Transport in Magnetic Insulators

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Abstract: Current devices made of *ferromagnetic* materials with charge-based spin currents used in spintronic devices have a number of drawbacks due to their *parasitic magnetic stray fields*, their large magnetic damping and ohmic losses, and, due to their intrinsically low characteristic frequencies that respectively limit their density integration, their power consumption and operation speed. The two key challenges are thus to design devices that remove stray fields and charge transport. Theoretically, it was predicted that pure spin current could be generated, transported, and employed in antiferromagnetic insulators to enable such new devices [1-3]. However experimentally, only a few systems have been investigated, most relying on coupled ferromagnet (FM)/antiferromagnet (AFM) layers [4-7]. A key limiting factor for the transport of a spin-current in insulating antiferromagnets has been the reported spin-diffusion length of only a few nanometers.[5-8]

We have recently studied spin transport across ferromagnetic and antiferromagnetic insulators in a magnon spin-valved device.[9] Here, combining two ferromagnets, decoupled by an CoO antiferromagnetic spacer, we measure a different spin transport signal of > 100%, depending on whether the ferromagnetic layers are aligned parallel or anti-parallel, which is reminiscent of the behaviour of a charge-based spin valve.[9]

Using single-crystal Fe_2O_3, we probe spin transport in insulating antiferromagnets over long distances. We first probe the direction of the Néel order parameter by spin-Hall magnetoresistance [10] to identify the antiferromagnetic spin configuration. We then use appropriately engineered non-local geometries to study high frequency magnon propagation in an antiferromagnetic insulator: our devices consist of platinum (Pt) strips, deposited on different 3d insulating antiferromagnetic compounds along easy or hard axes. When we apply a current in a platinum strip, we inject magnons by both thermal effect (second harmonic signal) and by spin-Hall effect (first harmonic signal), and detect their propagation in a second platinum strip by inverse spin-Hall effect. Based on the geometry of our system, we unambiguously distinguish long-distance transport based on equilibrium (Bose-Einstein condensate) or nonequilibrium magnons. The underlying physical mechanisms in our experiments allow us to observe the persistence of the two signals for distances of tens of micrometers, i.e more than two orders of magnitude larger than previous reports in antiferromagnetic thin films.[11] Those results demonstrate the possibility of propagating long distance magnons in antiferromagnetic insulators, opening the way to spin-electronics devices with antiferromagnets.[11]

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From Skyrmions to Antiskyrmions: Nucleation, Control, and Stability.

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Abstract: A stable skyrmion representing the smallest realizable magnetic texture could be an ideal element for ultra-dense magnetic memories. Magnetic antiskyrmions are analogs of skyrmions with opposite topological charge and same polarity [1]. Just like skyrmions, antiskyrmions can be stabilized by the Dzyaloshinskii-Moriya interactions (DMI) as has been demonstrated in a recent experiment [2]. Even though there are many similarities between skyrmions and antiskyrmions the main difference is that antiskyrmions are anisotropic and require systems with lower symmetry [3]. Here, we discuss nucleation, control, and stability of isolated antiskyrmion in magnetic thin films. To properly describe the system, we employ the new boundary conditions [4] and study boundary magnetization tilting in ferromagnets with lower symmetry DMI. Our results indicate that antiskyrmions can be efficiently nucleated at edges. We also present our results on the antiskyrmion dynamics in a nanotrack.

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Enhanced Spin Caloritronics in Lattice-Matched $NiFe_2O_4$ Thin Films

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Abstract: The magnon spin transport characteristics and spin caloritronic properties of the ferrimagnetic insulator yttrium iron garnet (YIG) are astonishing. That is why this material has become one of the standard materials for spin Seebeck effect (SSE) investigations and non-local magnon spin transport experiments. Other insulating materials such as the spinel ferrite NiFe2O4 (NFO) can also be used for local [1-4] and nonlocal SSE [5] investigations and has some advantages over YIG, e.g. the possibility to tune the conductivity from insulating to conducting via oxygen reduction [6,7]. However, the magnetic properties (e.g. Gilbert damping) of NFO grown on standard substrates such as MgO or MgAl2O4 (MAO) are much worse than for YIG mainly due to antiphase boundaries induced by the bad lattice mismatch with MAO of 3.2%. Surprisingly, the use of spinel gallate substrates (MgGa2O4 or CoGa2O4) results in lattice-matched growth of NFO (0.8% or 0.2%, respectively) with vanishing antiphase boundaries and thus reduced Gilbert damping and sharp magnetic switching [8].
In my talk, I will present the spin caloritronic properties of this lattice-matched NFO prepared by pulsed laser deposited. We observe an increase in the local SSE voltage compared to NFO grown on MAO [9]. In the nonlocal transport experiments, enhanced signals are observed for both electrically and thermally (non-local SSE) excited magnons [10]. However, the magnon relaxation length of NFO on the different substrates is found to be between 2.5µm and 3.1µm at room temperature independent from the lattice matching. Moreover, at both room and low temperatures, we observe magnon-polaron signatures in the nonlocal SSE signals [10] as have recently been detected for YIG as well [11]. Our results demonstrate the excellent spin caloritronic and magnon spin transport quality of NFO thin films grown on lattice-matched substrates that are comparable with those of YIG.

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Microwave Magnons and the Intrinsic Spin Seebeck Effect in Yttrium Iron Garnet

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Abstract: When a heat pulse is delivered to yttrium iron garnet (YIG), spin currents are generated over vastly different time scales. Within the first nanosecond, the temperature difference between hot electrons in platinum and cold magnons in YIG, generate an interfacial spin current into platinum. However, in bulk YIG there is an additional spin current generated by the intrinsic spin-Seebeck effect, which evolves on longer timescales. As heat flows into YIG, this bulk spin current diffuses into the platinum layer. Time-domain spin-Seebeck data are collected as a function of temperature to investigate the relative contribution of the interfacial and bulk spin currents in the total spin-Seebeck signal in bulk YIG. A digitally modulated laser diode provides the heating pulse and a high bandwidth oscilloscope is used to capture the spin-Seebeck waveform from nano- to milliseconds. The time-dependent spin-Seebeck data are well fit to a model using the coupled spin/heat transport equations from which we determine the thermally excited magnon lifetime as well as the magnitude of the bulk and interface driven spin currents. The bulk spin current dominates the magnitude and temperature dependence of the spin-Seebeck effect, peaking near 80K, while the interfacial component has a comparatively weak variation with temperature. Very surprisingly, the thermal magnon lifetime lies in the few micro-second range over all temperatures. These lifetimes correlate with those of microwave driven magnetic resonance modes in YIG, suggesting that microwave magnons are strong contributors to the spin-Seebeck signal in bulk YIG.

Comparing Spin Dynamics in Ferro- and Antiferromagnets

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Abstract: Antiferromagnetic materials are in the focus of current research in magnetism because of their potential for applications in spintronics. Possible advantages of spintronic devices based on antiferromagnetic materials include their lack of stray fields, the low susceptibility to external fields, and the rich choice of new materials, including a variety of antiferromagnetic insulators.

This talk focuses on a comparison between spin dynamics in ferromagnets and antiferromagnets, respectively, based on spin model simulations within the framework of the stochastic Landau-Lifshitz equation. For the domain wall motion, we find a much larger domain wall mobility in antiferromagnets as compared to ferromagnets. We present a new concept for a magnonic spin valve based on a trilayer of ferromagnetic and antiferromagnetic materials and we investigate the superparamagnetic limit of antiferromagnetic nanoparticles, focusing on a comparison to the known properties of ferromagnetic nanoparticles.

Theory of Spin Current Noise

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Abstract: The fluctuation of electric current in electronic devices provides various information on electronic transport [1]. For example, the effective temperature of electrons is obtained from the noise in the thermal equilibrium state (Onsager relation), and the effective charge reflecting the quantum many-body effect of the carriers of the current is obtained from the noise under the high bias voltage (shot noise).

Similarly, it has been proposed theoretically that the fluctuation of spin current in spintronic devices tells us information on spin transport in the squeezed state of magnons [2] and one-dimensional quantum spin chains [3]. In this talk, we show that valuable information about spin pumping [4] and the spin-Seebeck effect [5] may be obtained by detecting the spin current noise at the interface of a bilayer of a paramagnetic metal (PM) and a ferromagnetic insulator (FI).

Starting with a PM-FI interface model with both spin-conserving and non-spin-conserving processes, we have calculated the spin current and spin current noise generated at the interface using the nonequilibrium Green's functional method. In the spin shot noise region, we show that the spin-current noise gives rise to the effective spin carried by a magnon modified by the non-spin-conserving process at the interface [6,7].

In the thermal equilibrium noise region, we derive that the effective temperature of the PM-FI system or the interfacial conductance of the spin current is obtained from the Onsager's relation between the thermal spin current noise and the spin current [7]. We suggest that the influence of heat generation in the spin pumping, i.e., the spin Seebeck effect, may be separated by measurement of spin current noise [6.7].

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Magnon-Mediated Interlayer Coupling and Spin-Transfer Torques

Seebeck-, Tunneling Magneto-Seebeck Effect and Thermal Stability in Magnetic Tunnel Junctions

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Abstract: For the Seebeck voltage in magnetic tunnel junctions (MTJs) and the related tunneling magneto-Seebeck effect (TMS), only few materials have been studied so far with Seebeck voltages of only some microvolt, and moderate TMS ratio.

Here, we demonstrate that highly asymmetric band structures of half-metallic Heusler compounds are good prerequisites for enhancing spin-dependent thermoelectric effects. This becomes evident when considering the asymmetry of the spin-split density of electronic states around the Fermi level that determines the spin-dependent thermoelectric transport in magnetic tunnel junctions. We identify Co_2FeAl and Co_2FeSi Heusler compounds as good candidate materials due to their energy gaps in the minority density of states, and demonstrate devices with substantially larger Seebeck voltages and tunnel magneto-Seebeck effect ratios than the commonly used Co-Fe-B-based junctions.

For the CoFeB based MTJs with ultrathin electrodes and perpendicular magnetic anisotropy, we show that they can be tailored to obtain a controlled crossover from ferromagnetic to superparamagnetic behavior. In the latter state, temperature and electric field can be used to realize a real random number generator driven only by thermal energy.

Freestanding YIG magnon nanoresonators with very low damping

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Abstract: 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 12@8 GHz. Further investigation was done using scanning time resolved magnetooptical 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 $\alpha = 2\text{x}10^{-4}$ with a linewidth of 1.5 Oe at 8 GHz. The modes observed can be nicely reproduced in 3D micromagnetic simulations.

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Detection of Spin-Peltier Magnetoresistance and Spin-Hall Injection of Large Magnon Populations

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Abstract: Analogous to the corresponding properties of charge carriers in semiconductor devices, the density, energy, and spin diffusion length of magnons in a magnetic insulator (MI) are fundamental quantities for emerging spintronic devices. Here, we introduce lock-in Brillouin light scattering and magnetoresistance measurements as sensitive probes of these properties of magnons, injected from a normal metal, platinum, into a prototypical MI, yttrium iron garnet. By detecting an elusive spin-Peltier magnetoresistance and showing its dominance over proximity-induced magnetism in platinum, the measurements and analysis find that the spin Hall effect can inject nonequilibrium magnons with an appreciable energy flux and a population as high as the typical charge carrier density in doped semiconductors. The ability to disentangle and quantify magnon-injection mechanisms can enable future-generation MI-based spintronics.

Hydrodynamics and Topological Spin Currents in Amorphous Magnets

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Abstract: Coherent spin transport mediated by topologically stable textures, offers promising perspectives for the design of energetically efficient devices for applications in spintronics. However, in contrast to spinor condensates and He-3, collective spin transport in solid state is limited by parasitic anisotropies rooted in relativistic interactions and spatial inhomogeneities. Here, we propose that structural disorder in amorphous materials can average out the effect of these undesired couplings. To illustrate this, we construct a hydrodynamic description of spin dynamics in insulating amorphous magnets, where the currents are defined in terms of coherent rotations of a non-collinear texture. Our theory includes dissipation and nonequilibrium torques at the interface with metallic reservoirs. This framework allows us to determine different regimes of coherent dynamics and their salient features in nonlocal magneto-transport measurements.

Observation of Anisotropic Magneto-Peltier Effect

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Abstract: The Peltier effect converts a charge current into a heat current in a conductor and its performance is described by the Peltier coefficient. To exploit the Peltier effect for thermoelectric cooling/heating, junctions of two conductors with different Peltier coefficients have been believed to be indispensable so far. Here we upset this conventional wisdom by demonstrating Peltier cooling/heating in a single material without junctions. This is realized by an anisotropic magneto-Peltier effect (AMPE), a phenomenon that the Peltier coefficient depends on the angle between the directions of a charge current and magnetization in a ferromagnet [1]. By using active thermography techniques [2-5], we successfully observed the temperature change induced by the AMPE in a plain Ni slab, and found that its thermoelectric properties can be redesigned simply by changing the current and magnetization configurations. Our experimental results demonstrate the suitability of Ni for the AMPE and the importance of spin-orbit interaction in its mechanism. The AMPE observed here fills in the missing piece of thermoelectric phenomena in ferromagnetic materials and opens up new ways of thermal management technologies for electronic and spintronic devices.

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Understanding the Spin Entropy and Drag Effects in Thermoelectric Properties of Antiferromagnetic Semiconductor Manganese Telluride

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Abstract: While the progress in traditional thermoelectric materials research based on the engineering of the charge carriers and phonons characteristics is reaching a plateau, adding spin and spin wave to the picture offers new degrees of freedom for developing new materials with unprecedented thermoelectric properties. The effect of spin on thermoelectric properties is a non-trivial topic with many aspects. In particular, spin entropy in hopping systems, dilute Kondo systems due to the resonant interaction of the magnetic impurities with free electrons, and magnon electron drag in magnetically ordered systems have all resulted in enhancement of the thermopower. Another significant effect, although not yet theoretically confirmed, is the paramagnon drag. Paramagnon drag has been experimentally observed in many paramagnetic spin fluctuation systems such as $(Sc,Lu,Y)Co_2$ [1] or UAl_2 [2] near their spin fluctuation temperatures. MnTe, a semiconducting A-type antiferromagnet, shows a robust magnon-electron drag near and below the Neel temperature. Interestingly, as we will show, this rather large enhancement of the thermopower did not diminish above the Neel temperature (~305K) and remained consistently high up to ~1000 K (our highest measurement temperature). We will discuss several possible explanations of the observed large thermopower above the ordering temperature. Although spin entropy, magnon drag, and paramagnon drag have already shown zT enhancement in several materials, this is the first time that such effects lead to zT>1. A better understanding of the thermopower in the paramagnetic phase of MnTe can guide the development of higher performance thermoelectric materials which are not limited to the trade-off between the electrical conductivity and the thermopower.

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Spin Seebeck Effect and Ballistic Transport of Quasi-Acoustic Magnons in Room-Temperature Yttrium Iron Garnet Films

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Abstract: We studied the transient behavior of the spin current generated by the longitudinal spin Seebeck effect (LSSE) in a set of platinum-coated yttrium iron garnet (YIG) films of different thicknesses [1]. The LSSE was induced by means of pulsed microwave heating of the Pt layer and the spin currents were measured electrically using the inverse spin Hall effect in the same layer. We demonstrate that the time evolution of the LSSE is determined by the evolution of the thermal gradient triggering the flux of thermal magnons in the vicinity of the YIG/Pt interface. These magnons move ballistically within the YIG film with a constant group velocity, while their number decays exponentially within an effective propagation length. The ballistic flight of the magnons with energies above 20 K is a result of their almost linear dispersion law, similar to that of acoustic phonons. By fitting the time-dependent LSSE signal for different film thicknesses varying by almost three orders of magnitude, we found that the effective propagation length is practically independent of the YIG film thickness. We consider this fact as strong support of a ballistic transport scenario—the ballistic propagation of quasiacoustic magnons in room temperature YIG.

Financial support by Deutsche Forschungsgemeinschaft (DFG) within Priority Program 1538 'Spin Caloric Transport' and DFG project INST 248/178-1 are gratefully acknowledged.

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Investigations of Spin Precession in Perpendicular Magnetic Materials Enabled by Time-Resolved Magneto-Optical *Kerr* Effect

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Abstract: Time-Resolved Magneto-Optical *Kerr* Effect (TR-MOKE) is an all-optical method based on the ultrafast pump-probe technique that can be used to study the magnetization dynamics of materials, in addition to thermal and mechanical characterization. With optical excitation and the capability of reaching large magnetic fields, TR-MOKE can probe spin precession at high resonance frequencies (up to a few hundreds of GHz), beyond those achievable by conventional Ferromagnetic Resonance (FMR) methods. In this talk, we demonstrate the use of TR-MOKE to study the spin precession of two model material systems with large perpendicular magnetic anisotropy (PMA). The first model system is a series of tungsten (W)-seeded CoFeB thin films, capable of sustaining good PMA after post-annealing at temperatures of up to 400 °C. We measure the Gilbert damping (α) of W-seeded CoFeB films, and attribute the dependence of α on the annealing temperature to two competing effects: the enhanced crystallization of CoFeB and the dead-layer growth occurring at the CoFeB interfaces. The second model system of interest is composed of perpendicular ferromagnetic $[Co/Pd]_n$ multilayers with varying anisotropy. We use ultrafast-laser heating to launch acoustic strain waves and capture their coupling with the spin precession in these $[Co/Pd]_n$ multilayers. Understandings on such a strain-spin coupling may shed light on manipulating the precession and switching the magnetization in magnetoacoustic devices.

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Magnetic Texture Based Magnonics

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Abstract: As a collective quasiparticle excitation of the magnetic order, spin waves can propagate in both conducting and insulating materials with little dissipation. Magnetic material with non-trivial magnetic texture provides a unified information memory and processing platform [1,2].

We demonstrate that, in the presence of Dzyaloshinskii-Moriya interaction, an antiferromagnetic domain wall acts as a spin-wave polarizer or a spin-wave retarder [3]. Based on the same principle, the spin wave driven domain wall motion in antiferromagnet also strongly depends on the linear polarization of the injected spin waves [4].

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Dynamic Spin Transport in Antiferromagnetic Insulators: Angular Dependent Spin Pumping in $Y_3Fe_5O_{12}$/NiO/Pt Trilayers

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Abstract: In recent years, pure spin transport driven by ferromagnetic resonance (FMR) spin pumping or a thermal gradient has attracted intense interest and become one of the most active frontiers in condensed matter and materials physics. Extensive research efforts have demonstrated pure spin currents in a broad range of materials, which enrich our understanding of dynamically-driven spin transport and open new paradigms for energy-efficient, spin-based technologies. Antiferromagnetic (AF) insulators possess various desired attributes, such as low loss and high speed up to THz frequencies, for future spintronic applications.

To probe the dynamic spin transport phenomena and the underlying mechanisms in AF insulators, we use high-quality $Y_3Fe_5O_{12}$ (YIG) epitaxial thin films excited by FMR as a source to inject spins into AF insulator NiO layers and detect the transmitted spin current using inverse spin Hall effect (ISHE) signals in YIG/NiO/Pt trilayers [1, 2]. We observed robust spin currents from YIG to Pt across AF insulators, which initially enhances the ISHE signals and can transmit spin currents up to 100 nm thickness, demonstrating highly efficient spin transport through an AF insulator carried by magnetic excitations. Recently, we studied the angular dependence of spin pumping in a series of YIG/NiO/Pt trilayers as the orientation of the applied magnetic field is rotated out of plane. Typically, a cosinoidal angular dependence is expected for spin pumping signals. However, we detected clear deviation from a cosinoidal behavior in the angular dependence. This phenomenon is the result of a combination of the magnon scattering at the interfaces, exchange interaction, magnetic anisotropy in the AF layer, and adiabatic transport of AF spin flux. A theoretical understanding of the experimental results is currently underway.

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Spin Orbit Torque Oscillators by Dipole Field-Localized Spin Wave Modes

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Abstract: Auto-oscillation of a ferromagnet due to spin-orbit torques in response to a dc current is of wide interest as a flexible mechanism for generating controllable high frequency magnetic dynamics. We use localized spin wave modes [1] that are confined by strongly inhomogeneous dipole magnetic field of a nearby micromagnet to manipulate their response to spin-orbit generated spin currents. This provides variable spatial confinement and systematic tuning of magnon spectrum, which offers a new approach to study the impact of multi-mode interactions [2] on auto-oscillations by continuously tuning the spectral separations of dipole field-localized modes. Here we demonstrate electrical spin-torque ferromagnetic resonance and auto-oscillations of well-resolved dipole field-localized modes in a Py/Pt strip. Localized modes can be anti-damped efficiently [3], and driven into narrow-line width, large-amplitude auto-oscillations, persisting up to room temperature. This new approach has demonstrated auto-oscillation with a line width of 5 MHz at 80 K which increases to 20 MHz at room temperature. A linear temperature dependence of line width for the first localized mode indicates that its line width is dominantly limited by thermal fluctuations. We report characteristic behaviors, and discuss the role of reduced scattering channels.

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Poster Abstracts

Adams
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Application for Magnon Drag in Metal Thermoelectrics

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Abstract: The magnon drag contribution to thermopower in ferromagnetic metals can be up to ten times larger than diffusion thermopower, making thermoelectric metals viable for power generation. [1] Metal construction eliminates the design constraints of semiconductor modules, such as the need for cube-shaped legs, elemental purity, solder, or additional heat exchangers. Metals can withstand much higher temperatures than semiconductors, allowing a larger Carnot efficiency. In these designs, the hot side of the generator is fueled by combustion and the cold side is maintained by fuel/air cooling with the metal walls forming a counterflow heat exchanger. Unlike in thermoelectric modules, heat conduction within the metal is useful for preheating the reactants. Due to the large temperature gradient in this generator, we quantify the performance by efficiency rather than *ZT*. From measured exhaust temperature and voltage, the calculated efficiency reaches up to 10%.

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Magnetic Dynamic Properties of Ultra-low Damping Epitaxial $Co_{25}Fe_{75}$ Thin Films

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Abstract: Materials with low magnetic damping draw attention in spintronics due to their low-loss magnetic dynamics and ability to efficiently generate spin currents through ferromagnetic resonance (FMR). Insulating ferromagnets (FM), such as $Y_3Fe_5O_{12}$, have proven advantageous in many spin pumping and spin caloritronics applications. However, a metallic FM with comparable magnetic damping was only recently discovered since metallic FMs have relatively large damping due to conduction electron scattering. Metallic FMs with low magnetic damping allow for devices to be created that take advantage of the spin degree of freedom in charge currents. Recent work by Schoen *et al*. has shown $Co_{25}Fe_{75}$ to be an ideal candidate for these devices with ultra-low magnetic damping. We have deposited epitaxial $Co_{25}Fe_{75}$ films on MgO and $MgAl_2O_4$ (MAO) substrates by off-axis sputtering and measured Gilbert damping less than 10^{-3}. In addition, we measured the in-plane angular dependence of the FMR linewidth and resonance field as it allows us to extract the in-plane magnetic anisotropy. Deconvolution of the FMR linewidth into the Gilbert damping, inhomogeneous broadening, and two-magnon scattering components gives further insight into the nature of the damping within these films. We find that there is a thickness dependence of effective magnetization, anisotropy fields, and two magnon scattering for $Co_{25}Fe_{75}$ films between 3 and 32 nm thicknesses deposited on MgO and MAO. Fitting the angular dependence of the linewidth allows us to extract the perpendicular uniaxial anisotropy, in-plane magnetocrystalline anisotropy, and two-magnon scattering contributions. From these thickness dependencies and the trend of the inhomogeneity of the local crystallographic axes, we can conclude that the smaller lattice mismatch of $Co_{25}Fe_{75}$ and MAO gives better crystal quality and a faster crystal relaxation of $Co_{25}Fe_{75}$.

Spin Seebeck Effect in $Y_3Fe_5O_{12}$/NiO/Pt Thin Film Heterostructures

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Abstract: Spin currents play an essential role in transferring angular momentum across layers in thin film heterostructures. The spin Seebeck effect (SSE), where a thermal gradient across a ferromagnet generates spin current, has been in the focus of spintronics studies since it is one of the most efficient ways to generate spin currents. Additionally, antiferromagnets are gaining attention recently due to their advantageous properties like zero net magnetization, low magnetic susceptibility and very fast spin dynamics. They are also capable of generating most of the spin-orbit and magneto-transport effects seen in ferromagnets.

In this work, we report spin Seebeck effect measured in Ferromagnet (FM)/Antiferromagnet (AFM)/Heavy Metal (HM) layers with very thin AFM layers by studying $Y_3Fe_5O_{12}$ (20 nm)/NiO(2 nm)/Pt (5 nm) structures. The SSE is measured with the $Y_3Fe_5O_{12}$ magnetized in-plane (relative the current direction), using a lock-in technique that probes the response at 2ω. By varying the current amplitude, magnetic field direction and temperature we characterize the amplitude of SSE in a comparative study between $Y_3Fe_5O_{12}$ (20 nm)/NiO(2 nm)/Pt (5 nm) and $Y_3Fe_5O_{12}$ (20 nm)/Pt (5 nm). Our results show that not only spin transport is possible through thin NiO layers but there is also an increase in the spin-Seebeck effect magnitude. We correlate this increase in the spin-Seebeck effect magnitude with an increase in the magnetic susceptibility of NiO. Our results suggest that the spin Seebeck effect can be used to characterize the response of thin antiferromagnetic materials and optimize their spin-transport characteristics.

Magnon Spin Valve Effect in An Insulator-Spintronics Multilayer System

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Abstract: The discovery of the giant magnetoresistance (GMR) [1, 2] marked a key step towards the research field of spintronics [3]. In charge-based spintronic devices, the spin valve effect that leads to a different spin current transmission between two ferromagnets as a function of their relative alignment is well established [1,2]. For magnonic spin currents in insulating magnets, the analog was missing so far.

We report on ferromagnetic resonance spin pumping [4] measurements in a spin valve-like devices made of collinear magnetic yttrium iron garnet (YIG)/CoO/Co multilayers. By means of ferromagnetic resonance, the YIG layer emits a pure spin current that propagates through the sample stack and finally is detected in the Co layer via the inverse spin Hall effect [5]. Additional to the transfer of the magnonic spin currents and de-coupling of the two ferromagnets, the antiferromagnetic CoO layer increases the Co coercive field via exchange bias. This allows one to switch between a parallel or antiparallel alignment of the YIG and Co magnetization at the YIG resonance field. For the distinct alignment states, we observe a very different amplitude of the detected magnonic spin current voltage. This *magnon spin valve effect* exhibits an amplitude of 120% [6]. In addition to the spin pumping signal peak, a second peak is observed at ferromagnetic resonance that depends on the Co orientation, which is ascribed to an anomalous Hall effect induced spin rectification in the Co layer [6].

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The Effect of Spin Entropy on the Interaction of the Electromagnetic Wave with Materials

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Abstract: In recent years, remarkable activity has been reported on the effects of the electromagnetic wave on chemical reactions and materials processing. Reactions which usually take hours or even days to complete have been shown to be completed in significantly shorter time by using the microwave. There has been much debate on whether these effects have purely thermal origins resulted from dielectric absorption of the electromagnetic field, or there exist non-thermal effects that would directly or indirectly alter the chemical reactions. Considering that the microwave photons have energies orders of magnitude smaller than the chemical bonds, microwave excitations seem cannot dissociate the bonds, and can only increase the temperature of the material by exciting the rotation and/or torsion of the dipoles. However, as we will discuss, this is not the whole story. Molecules with multiple spin entropy configurations have shown significantly higher absorption of the electromagnetic field, which can not be explained by dielectric absorption. In this regard, studying the dissociation of a molecule based on the internal energy can help us better understand the effect of the electromagnetic field on chemical reactions and reaction rates.

We modeled the master equation including the effects of the electromagnetic field. The master equation describes the time evolution of a system. Gillespie's exact stochastic method was used to model the chemical reactions occurring within the system. From statistical mechanics density of states was calculated to model as the input to the system. We extracted parameters such as temperature changes, number of reactions taking place, and the internal energy of the system. The vibrational and rotational states were evaluated while counting the densities of states. Based on the Jahn-teller spin crossover, a split in the energy levels leading to a change in the density of states was modeled. The results showed a significant increase in the number of trajectories undergoing dissociation compared to the system without the microwave. It was shown that the amplified dissociation rate was due to the resonance absorption and emission of the microwave photons inducing a transition between states of different spin configurations. These results may at least partly explain some of the extraordinary effects of the electromagnetic interactions with materials.

Spin Seebeck Imaging of Spin-Torque Switching in Antiferromagnetic Pt/Nio Heterostructures

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Abstract: We study the spin Seebeck microscope as a powerful and sensitive method for imaging antiferromagnetic order. Recently, anti-damping spin-orbit torques have been used to reorient Néel order in antiferromagnetic devices. While readout of the Néel orientation via spin Hall magnetoresistance (SMR) enables all-electrical manipulation and detection, understanding the microscopic details of the switching mechanism has been hindered due to a lack of lab-accessible methods to image the Néel order. Using spin Seebeck microscopy, we study spin-orbit torque switching in Pt/NiO(111)/Pt and Pt/NiO (111) devices. We resolve antiferromagnetic S-domains within crystalline T-domains. In addition we find a linear correlation between the spin-torque-induced changes in the SMR and the integrated spin Seebeck signal, confirming that we image antiferromagnetic order. These measurements reveal antiferromagnetic domain wall motion and domain flopping, providing new understanding of antiferromagnetic switching using spin-orbit torques.

Spin Contributions to Thermal and Electronic Transport in Manganese Selenide Alloys

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Abstract: MnSe is a semiconductor with a direct bandgap of 2.3 eV, native p-type conductivity, and is also a Type I antiferromagnet with a Neel temperature (T_N) of 180 K. It has a rock-salt crystal structure, and is fully soluble with MnTe (T_N=308 K), which has a NiAs (hexagonal) crystal structure. Near the Neel temperature, these materials exhibit a significant increase in Seebeck coefficient due to a strong magnon electron drag effect. We synthesized and characterized the electrical and thermal transport properties of p-type MnSe and $MnSe_{0.5}Te_{0.5}$ alloys. It was shown that it is possible to tune the temperature range for optimum thermoelectric performance by changing the alloy composition. By defect engineering with intentional impurities and nano-structuring, the other vital thermoelectric parameters (σ, κ) can be engineered to produce significant increases in efficiency in a targeted temperature range.

Giant Anomalous Nernst Effect Observed in Single Crystal MnBi

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Abstract: MnBi is a high temperature ferromagnet (T_c=630 K) and crystalizes in the HCP structure. Its thermal transport properties have remained uninvestigated. The anisotropic transport properties (including resistivity, thermal conductivity, thermopower and Nernst effect) of two MnBi single crystals are measured and presented here separately from 80 K to 420 K in magnetic field up to 1.4 T along different crystallographic axis. We observed a giant anomalous Nernst effect in both α_{xyz} and α_{zyx} configurations (the first index indicates the direction of the flux, the second of the measured field, the third of the applied magnetic field, z=hexagonal axis). The anomalous Nernst thermopower in α_{zyx} configuration decays with temperature while in the α_{xyz} configuration the anomalous Nernst effect strengthens. Anomalous Hall effect is also observed. We suspect the presence of a strong magnon contribution to the anomalous Nernst effect. This can be understood as a self-Spin Seebeck effect, whereby a thermally driven magnon flux in the sample generates a spin polarization of the conduction electrons through magnon-electron scattering. This in turn gives rise to an inverse spin-Hall effects via spin-orbit coupling in the materials itself.

Thermoelectric Microscopy of Magnetic Skyrmions

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Abstract: The magnetic skyrmion is a nanoscale topological element in magnetic materials with broken inversion symmetry, which is characterized by winding of the spin configuration [1-2]. Because of its topological distinct configuration and its low current threshold for blowing, the skyrmions have been intensely studied by using electron-beam, X-ray, and magneto-optical microscopies [1-3]. In this presentation, we show that the skyrmions can be imaged via thermoelectric voltages and it has advantageous sensitivity to reveal chirality of Néel skyrmions in metallic multilayers.

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Dominance of the Magnon Chemical Potential in the Temperature Dependence of the Longitudinal Spin Seebeck Effect in Pt/YIG

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Abstract: Recent experimental and theoretical works describe the production of spin currents within ferromagnetic insulators (FMI), typically yttrium iron garnet (YIG), in terms of local temperature and spin chemical potential gradients, the former being known as the bulk spin Seebeck effect (SSE). Similarly, spins are driven across normal metal / ferromagnet interfaces by the finite magnon-electron temperature difference (ΔT_{me}) and the finite difference in the spin chemical potential ($\Delta\mu$). Previous work in the time domain has demonstrated the importance of bulk magnon transport for SSE in platinum-YIG structures as well as demonstrating that ΔT_{me} evolves on picosecond time scales. However, the relative contribution of the mechanisms to the total magnitude of SSE in Pt/YIG is still unknown. Here, we present pulsed laser measurements of time resolved SSE in Pt/YIG from 20-300 K using a high bandwidth setup. The high bandwidth enables us to experimentally separate the SSE signals which evolve on during the laser rise time. Utilizing a one temperature model we solve the time domain spin and heat transport equations for our sample geometry and demonstrate that $\Delta\mu$ at the interface dominates both the temperature dependence and magnitude of SSE in the Pt/YIG system.

Assessing a Three-Temperature Model for Laser-Induced Thermal Transport in Pt/Co/Pt Trilayers

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Abstract: Ultrafast demagnetization of metallic ferromagnets has been described by a phenomenological three-temperature model (3TM). However, the assumption of internal thermal equilibrium of each heat reservoir makes the model inadequate to capture initial dynamics when the carriers are driven out of equilibrium. In this work, we design a tri-layer structure, Pt/Co/Pt to examine the validity of the 3TM and its relevant material parameters. In our samples, a sub-nm-thick Co layer is placed under an optically thick (40 nm) or thin (2 nm) Pt layer. We use two thermometers, i.e., time-domain thermoreflectance and time-resolved magneto-optic Kerr effect to monitor temperature evolution of electrons, phonons, and magnons, when Co is either indirectly or directly heated by a laser pulse. The non-thermal character of electrons is incorporated as a longer absorption depth but does not show significant delay in heating of thermal electrons. The temperature evolution of the three carriers in all measurement geometries can be adequately described by a 3TM with consistent material parameters and the extended absorption depth of 16 nm. The electron-phonon coupling of Pt is determined as 6×10^{17} W m^{-3} K^{-1} for the room-temperature estimate of the electronic heat capacity coefficient of Pt, i.e., 400 J m^{-3} K^{-2}.

Efficiency enhancement of spin based thermoelectric devices via separation of phonon and magnon currents

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Abstract: Significant progress in fundamental understanding of the spin Seebeck effect (SSE) has been made using yttrium iron garnet (YIG)/Pt bilayer structure as a standard system. From engineering point of view, the thermoelectric efficiency of the YIG/Pt system is still far lower than that of charge based thermoelectric devices [1]. Thus, the need for developing a highly efficient spin Seebeck device is increasing for the sake of its practical applications. Here, we report the enhancement of thermoelectric efficiency in Ni-ferrite/Pt bilayer structure via effective separation of phonon and magnon currents. Different weight percentages of Al_2O_3 nano-inclusions (< 40nm) were introduced into polycrystalline Ni-ferrite slabs and the temperature dependence of the longitudinal spin Seebeck signal in Ni-ferrite/Pt was measured. We observe the spin Seebeck coefficient remains nearly constant (~ 100 nV/K) over the measured samples, while the thermal conductivity decreases with the amount of Al_2O_3. Through high magnetic field measurements, we find that in Ni-ferrites, the length scale of magnons relevant to SSE is relatively short compared to those in YIG [2]. This allows selective scattering of phonons while not affecting SSE by introducing scattering centers with an appropriate length scale, which in turn can lead to an improvement of the thermoelectric efficiency.

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Vectorial Observation of the Spin Seebeck Effect in $NiFe_2O_4$ Thin Films on Differently Oriented Latticematched Substrates

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Abstract: The longitudinal spin Seebeck effect (LSSE) refers to the generation of a spin current by and parallel to a temperature gradient [1] or a heat flux [2]. The spin current is converted into a charge current via the inverse spin Hall effect (ISHE) in Pt, which can be detected in two orthogonal in-plane film dimensions. The ISHE voltages depend on the orientation of the spin polarization vector, which is affected by the magnetization direction determined by the magnetic anisotropy and magnetic domain states of the spin-current-generating material. Here, we report on two orthogonal in-plane LSSE measurements carried out simultaneously for Pt on $NiFe_2O_4$ (NFO), a robust spin-Seebeck material [3-5], to show how magnetization reversal processes can be understood by analyzing these LSSE voltages. This new method presents a spin caloric alternative to vectorial magnetometry using, e.g., the magnetooptic Kerr effect [6,7], and goes beyond the vectorial interpretations in LSSE measurements done so far [8].

Vectorial LSSE measurements were performed on 450 nm thick NFO films grown on $MgGa_2O_4$ (MGO) and $CoGa_2O_4$ (CGO) substrates9 that are lattice-matched to NFO and either (001)- or (110)-oriented examining the magnetic in-plane anisotropy. Additional magnetic characterization of the samples has been realized by measuring magnetization curves via vibrating sample magnetometry and performing in-plane ferromagnetic resonance measurements of the angular dependence of the resonant field. The results demonstrate that we can use this technique to analyze the lattice mismatch between film and substrate leading to a strain anisotropy in the NFO thin film, which is higher for the MGO substrate compared to the CGO substrate. Moreover, the combined LSSE voltage measurements can be utilized to reveal the complete magnetization reversal process establishing a new alternative vectorial magnetometry technique based on spin caloric effects.

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Polarization-Selective Spin Wave Driven Domain Wall Motion in Antiferromagnet

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Abstract: The control of magnetic domain walls is essential for the magnetic-based memory and logic applications. As an elementary excitation of magnetic order, spin wave is capable of moving magnetic domain walls just as the conducting electric current. Ferromagnetic spin waves can only be right-circularly polarized. In contrast, antiferromagnetic spin waves have full polarization degree of freedom, including both left- and right-circular polarizations, as well as all possible linear or elliptical ones. Here we demonstrate that, due to the Dzyaloshinskii-Moriya interaction, the spin wave driven domain wall motion in antiferromagnets strongly depends on the linear polarization direction of the injected spin waves. Steering domain wall motion by simply tuning the polarization of spin waves offers new designing principles for domain-wall based information processing devices.

Magnetization Precession in W/CoFeB/MgO Films Enabled by TR-MOKE Measurements

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Abstract: To advance the field of spintronics, it is imperative to study the material properties of magnetic thin films, such as the Gilbert damping parameter (α) to improve performance. For technologies such as magnetoresistive random access memory (MRAM), the recent focus has been on materials with perpendicular magnetic anisotropy (PMA) due to their reduced critical switching current and higher memory density. In this work, we utilize the time-resolved magneto-optical Kerr effect (TR-MOKE) technique to study the magnetization dynamics within PMA materials. TR-MOKE has several advantages over the traditional ferromagnetic resonance (FMR) technique, such as the ability to measure higher frequencies (up to a few hundred GHz) of films with large PMA that are otherwise undetectable with conventional FMR. One of the most widely used PMA thin-film stacks is Ta/CoFeB/MgO; however, post-annealing at temperatures exceeding 350 °C leads to the failure of the CoFeB thin film to keep the PMA property. We replace the Ta seed layer with W, and discovered that this stack of W/CoFeB/MgO that can sustain annealing temperatures up to 400 °C while still maintaining superb PMA properties and a relatively low Gilbert damping of ~0.02.

Probing Short-Range Magnetic Order in a Geometrically Frustrated Magnet by Spin Seebeck Effect

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Abstract: Competing magnetic interactions in geometrically frustrated magnets give rise to new forms of correlated matter, such as spin liquids and spin ices. Characterizing the magnetic structure of these states has been difficult due to the absence of long-range order. Here, we demonstrate that the spin Seebeck effect (SSE) is a sensitive probe of magnetic short-range order (SRO) in geometrically frustrated magnets. In low temperature (2-5 K) SSE measurements on a model frustrated magnet $Gd_3Ga_5O_{12}$, we observe modulations in the spin current on top of a smooth background. By comparing to existing neutron diffraction data, we find that these modulations arise from field-induced magnetic ordering that is short-range in nature. The observed SRO is anisotropic with the direction of applied field, which is verified by theoretical calculation.

Readout of Magnetic Resonance from Organic Ferrimagnet VTCNE using NV Centers in Diamond

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Abstract: Magnetic systems present a promising avenue for robust and room-temperature signal processing, transmission, and storage at the nanoscale. Low damping magnetic thin films will play a key role in realizing spin based computational elements. Organic-based magnetic systems have shown high-quality resonance properties across a wide range of substrates which can be an issue for magnetic oxide based devices. A local probe of magnetic resonance is desirable for nanoscale characterization since inductive based techniques typically require large samples and are spatially insensitive. Recently our group demonstrated that the Nitrogen-Vacancy (NV) defect centers in diamond can serve as a platform for local, broadband, optical readout of magnetic resonance from a proximal magnetic film. Here we report broadband optically detected ferromagnetic resonance (ODFMR) from a micron-thick layer of the high quality organic-based ferrimagnet vanadium tetracyanoethylene ($V(TCNE)_x$ ($x \approx 2$)) grown on a single crystal diamond substrate which is host to an ensemble of NV centers. This work demonstrates the utility of the NV center as a local readout element for organic-based magnetic systems.

Dzyaloshinskii-Moriya Interaction at $SrRuO_3$-$SrIrO_3$ Bilayer

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Abstract: Dzyaloshinskii-Moriya interaction (DMI) in magnetic material cants magnetic moments, enables magnetic phases such as chiral structure and magnetic skyrmion and is of potential for the next-generation magnetic memory and logic devices. Unlike traditional B20 materials, which DMI depends on bulk crystal non-certrosymmetric structure, thin film heterostructure gives more flexibility in engineering DMI through symmetry breaking at interfaces. This work will explore the possibility of DMI tuning at transition-metal perovskite $SrIrO_3$/$SrRuO_3$ bilayer interface. We report the synthesis of this epitaxial bilayer structure using magnetron sputtering and film quality characterized by X-ray diffraction and scan transmission electron microscopy. In addition, Hall effect measurement was conducted to test for DMI related transport properties.

Spin Hydrodynamics in Amorphous Magnets

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Abstract: Coherent spin transport in solid state is limited by parasitic anisotropies that may arise either intrinsically or due to fabrication processes. For this reason, we propose amorphous magnets as platforms for spin superfluidity, provided that the structural disorder in these materials can average out the effect of undesired couplings. We establish nonlinear equations describing the hydrodynamics of spin in insulating amorphous magnets, where the currents are defined in terms of coherent rotations of a noncollinear texture [1]. Our theory includes dissipation and nonequilibrium torques at the interface with metallic reservoirs [2]. This framework allows us to determine different regimes of coherent dynamics and their salient features in nonlocal magneto-transport measurements. Our work paves the way for future studies on macroscopic spin dynamics in materials with frustrated interactions.

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Gate-tuned Longitudinal Spin Seebeck Effect in Topological Insulators

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Abstract: The recent study of the topological spin Seebeck effect (SSE) in magnetic insulator (MI)/topological insulator (TI) heterostructures [1] has raised an interesting question about the effect of the Fermi level position in the band of the topological surface states of the TI and the tuning of the Fermi level without resorting to doping the TI with different amount of impurities. In this work, in order to perform the Fermi level tuning in both top and bottom surfaces of the TI, we fabricate longitudinal SSE devices on STO substrates with a 100 nm HfO_2 high-k dielectric top layer. In this structure, the STO substrate acts as a high-k dielectric for bottom gating, while the heater atop HfO_2 also serves as a top gate. The MI/TI heterostructure samples consist of a 30 nm YIG grown by pulsed laser deposition and a 5 quintuple layer thick $(Bi_{1-x}Sb_x)_2Te_3$ (x = 0.2, 0.30) TI thin film grown by molecular beam epitaxy. As both top and bottom gate voltages are swept, the resistance of the TI sample shows expected changes as the Fermi level position is continuously varied. However, as the heater is turned on to measure the SSE response V_{SSE} while the gate voltages are simultaneously swept, we find that the V_{SSE}/R ratio shows a decreasing trend as the system approaches the Dirac point. More experiments on TI samples with Fermi level closer to the Dirac point will be performed to corroborate these results.

This work was supported as part of SHINES, an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Basic Energy Sciences under Award SC0012670.

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Spin Effects on Thermoelectric Properties of MnTe

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Abstract: Antiferromagnetic semiconductors (AFS) show a good prospect for thermoelectric application due to the benevolent spin effects such as spin entropy and magnon-electron drag. Both spin entropy and magnon-electron drag can contribute to enhancing the thermopower, which can consequently result in higher power factor and thermoelectric figure-of-merit. In this research, we have studied the thermoelectric properties of MnTe as one of the promising AFS material systems. α-MnTe, most common stable phase with NiAs hexagonal lattice at room-temperature, shows both spin entropy and magnon-electron drag phenomena due to the Mn^{2+} partially filled 3d orbitals as well as magnon quasi-particles below the Neel temperature (T_N ≈ 305 K). We synthesized and characterized bulk polycrystalline MnTe samples with different types of dopants including Li, Cr, Mg and Li/Cr co-doping. Electrical conductivity, thermopower, and thermal conductivity were measured for these samples to understand the contributions of spin entropy and magnon electron drag in the presence of different dopants. Quite different properties were observed depending on the nature of the dopant. With Li doping, MnTe showed good improvement in both electrical conductivity and thermopower. These samples showed both spin entropy and magnon-electron drag contributions in the thermopower. Cr, Mg and Li-Cr doped MnTe samples showed large thermopower, however, with small electrical conductivity. It was found that the large thermopower of these samples was due to electronic contribution with no or little contribution from the spin entropy or the magnon-electron drag probably due to an induced paramagnetic phase. In this poster, we will present and discuss the existing data. Further understanding of the transport properties of these materials deserves complementary experiments and theoretical studies.

Spinwave Sensing and Magnetic Resonance Spectroscopy using Nitrogen-Vacancy (NV) Centers in Diamond

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Abstract: Modern technological challenges include developing smaller, faster, more energy efficient sensors and information devices. As traditional electronics has approached the fundamental limits of what can be achieved using the charge degree of freedom, researchers have begun exploring spin-based platforms for future applications. While ferromagnetic excitations may themselves be used to store and transmit information (i.e., magnonics). Spinwaves have also drawn attention for their influence on spin diffusion in proximate spin channels. Here, we leverage the high sensitivity of nitrogen-vacancy (NV) centers in diamond to detect the fluctuating magnetic fields from spinwaves resonant with NV transitions. We systematically investigate NV-spin relaxation by spinwaves in which: 1) the NV-FM separation is controlled by a wedge-shaped spacer; 2) the applied magnetic field alters the wavevectors of spinwaves that are resonant with the NV spins; and 3) a microwave drive field enhances the populations of spinwaves scattered from coherently driven ferromagnetic resonance modes. We are thus able to probe both thermally excited spinwaves as well as scattering processes in poorly understood high-drive, low-field regimes. The atomic-size of the NV center suggests that the spatial resolution of these techniques may extend to the nanoscale pertinent to miniaturizing device elements.

Engineering Dzyaloshinskii-Moriya Interaction for Skyrmion-Antiskyrmion Pair Creation

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Abstract: We study various scenarios how both skyrmion and antiskyrmion can be retained in the process of skyrmion-antiskyrmion pair creation, thereby exploring the possibility to utilize both skyrmions and antiskyrmions for magnetic memory applications. In particular, the skyrmion-antiskyrmion pair can be created due to instabilities at interfaces with properly engineered Dzyaloshinskii-Moriya interactions. We study boundary conditions dictating the magnetization pro_le in the vicinity of an interface and demonstrate by diagonalizing the Bogoliubov-de-Gennes Hamiltonian the existence of an interface-driven instability leading to creation of skyrmion-antiskyrmion pair. We use micromagnetics simulations to confirm our analytical results.

Observation of LSSE in $NiFe_2O_4$/Pt Thin Films Grown on Lattice-Matched Substrates

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Abstract: Energy conversion from heat to electric energy via spin phenomena is the heart of spin caloritronics, the active and emerging area of research that combines thermoelectrics and spintronics. Recent works on the interaction between electron spin and heat flow have paved new directions in that field. One such example is the spin Seebeck effect, which involves the generation of a spin current by the application of a temperature gradient across a magnetic material, such as the spinel ferrite $NiFe_2O_4$ (NFO) [1-3]. However, thin films of spinel ferrites suffer from several structural and magnetic drawbacks that limit their efficient spin conversion. We show that by using substrates having a similar crystal structure and low lattice mismatch with NFO_4, one can overcome such limitations and demonstrate a spin injection from ferrimagnetic NFO thin films into a platinum layer. Furthermore, scanning transmission electron microscopy studies of the films reveal the absence of antiphase boundaries in the NFO films grown on $CoGa_2O_4$ and $MgGa_2O_4$ substrates. In contrast, anti-phase boundaries are present in the films deposited on the substrate with the largest lattice mismatch, namely $MgAl_2O_4$. We observe the longitudinal spin voltage signal (V_{LSSE}) significantly affected by the choice of the substrates which impose different strain (from 0.2 to 3.2%) on the thin film. It manifests in the reduction of anti-phase boundaries for lattice matched substrates, which seems to improve the V_{LSSE} signal.

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Bulk and Edge Spin Transport in Topological Magnon Insulators

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Abstract: We investigate the spin transport properties of a topological magnon insulator, a magnetic insulator characterized by topologically nontrivial bulk magnon bands and protected magnon edge modes located in the bulk band gaps. Employing the Landau-Lifshitz-Gilbert phenomenology, we calculate the spin current driven through a normal metal | topological magnon insulator | normal metal heterostructure by a spin accumulation imbalance between the metals, with and without random lattice defects. We show that bulk and edge transport are characterized by different length scales. This results in a characteristic system size where the magnon transport crosses over from being bulk-dominated for small systems to edge-dominated for larger systems. These findings are generic and relevant for topological transport in systems of non-conserved bosons.

Anistropic g-Factors of BiSb Semimetals

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Abstract: Bismuth and bismuth-based materials with small band gaps and large spin- orbit couplings exhibit novel physical phenomena such as giant spin Hall conductivities and three-dimensional topological insulator phases. Furthermore, a recent discovery of the Weyl semimetal phase with the chiral anomaly in the Bi and Sb alloys demonstrates the rich physics of these materials. In this work, we calculate another spin-orbit interaction related term, the g-factor in the BiSb alloys. Early studies of the g-tensor with a two band kp approach are valid only for electrons, and a more recent multi-band kp model is valid for electrons and holes. Here we present a full Brillouin zone calculation of the g-factor using a 16 band tight-binding Hamiltonian and report large, anisotropic g-factors in the BiSb alloys.

Superparamagnetic Limit of Antiferromagnetic Nanoparticles

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Abstract: Antiferromagnets are promising candidates as materials for future spintronic devices. Their advantages over ferromagnets include the lack of stray fields, the low susceptibility to external fields, the rich choice of new materials and faster spin dynamics [1,2]. However, the potential of spintronic devices is tied to the ability to scale down the magnetic structures to the nanometer regime. As for ferromagnets, the stability of antiferromagnetic nanostructures will be limited by thermal excitations – the superparamagetic limit [3,4]. We investigate the superparamagnetic limit of antiferromagnetic nanoparticles theoretically in the framework of atomistic spin dynamics, focusing on a comparison to the known properties of ferromagnetic particles. We find a drastically reduced stability because of the exchange enhancement of the attempt frequencies and the effective damping during the antiferromagnetic switching process.

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Nernst Thermopower in Bi-MnBi Composites

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Abstract: Magnetic materials in which thermal transport involves the generation of spin fluxes provide new opportunities to improve the thermal-to-electric energy conversion efficiency over that of conventional, electron-based thermoelectrics. In bulk ferromagnetic (FM) metals such as Co, Fe, and Ni, magnon dynamics in the material result in a magnonic contribution to total thermopower, as shown by Watzman et al. [1] In thin-film structures composed of a normal metal (NM) film, such as Pt, deposited on an electrically insulating FM, such as yttrium iron garnet (YIG), a thermally driven spin flux injected from the FM into the NM layer gives rise to inverse spin-Hall voltage in the NM layer. [2] This voltage is perpendicular to the temperature gradient and the applied magnetic field. [2] Although these thin-film structures are not suitable for power generation applications, it was shown by Boona et al. [3] that it is possible to obtain a contribution from the spin-Seebeck effect (SSE) to the Nernst thermopower in bulk nanocomposite structures composed of a NM (Pt) with strong spin-orbit interactions and a FM (Ni). In this work, Bi, which has a large spin-Hall angle and Nernst effect, will be used as a NM and MnBi as the FM. Bulk composites composed of Bi and MnBi needles will be studied specifically in a Nernst geometry to determine the SSE contribution to Nernst thermopower.

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Thermomagnetic Transport in Field-induced Weyl Semimetals.

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Abstract: $Bi_{1-x}Sb_x$ alloys with varying Sb concentration have bands that at x≈5 have a Dirac dispersion with the Dirac point at the L-point of the Brillouin zone. In strong magnetic fields, this Dirac point is theoretically expected to split into two field-induced Weyl points. This poster will present a theoretical concept of novel thermomagnetic transport in Weyl semimetals, the formation of field-induced Weyl points in $Bi_{1-x}Sb_x$ alloys and experimental magneto thermal conductivity of $Bi_{1-x}Sb_x$ alloys. Interestingly, a strong positive magneto thermal conductivity is observed at the composition and field where the Weyl points are expected to appear.

Efficiency Bounds on Thermoelectric Transport in Magnetic Fields: The Role of Inelastic Processes

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Abstract: It has been argued that breaking time-reversal symmetry can enhance thermoelectric efficiency. Benenti et al. recently claimed [1] that in this case one can achieve the Carnot efficiency with a finite power, which appears to contradict the second law of thermodynamics. This idea has attracted much interest recently; see refs. [2, 3] for example.

In order to investigate this claim and to seek high efficiency, we consider a mesoscopic thermoelectric device made of an Aharonov-Bohm ring threaded by a magnetic flux, incorporating electron-phonon scattering [4]. The model has a quantum dot and three reservoirs: two electronic reservoirs and a bosonic one. Electrons are inelastically scattered by bosons at the quantum dot. This three-terminal model can be reduced to an effective two-terminal one, that complies with the requirements of Benenti et al.

With this model, we find the following two results [5]: First, we find that, contrary to Benenti's claim [1], such a device cannot reach the Carnot efficiency under a magnetic field because of the non-negativity condition on the entropy production of the original model with three reservoirs. Second, we find that breaking time-reversal symmetry and including the electron-phonon interaction can enhance the thermoelectric efficiency significantly beyond the one without the interaction.

Since our work does not include spin degrees of freedom, we would like to discuss how to extend our work including spins.

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Magnon Drag and Spin Entropy Contribution to Thermopower of Li-Doped MnTe

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Abstract: In antiferromagnetic semiconductor MnTe, magnons enhance thermopower by an advective transport process called magnon drag effect below the Néel temperature of 307 K. This magnetic contribution, however, seems to extend above the Néel temperature. Spin entropy is ascribed to be the source of the enhancement. Here we present the specific heat, thermopower, Hall measurement of Li-doped MnTe. By separating the magnon contribution to the specific heat and calculating the carrier concentration, the magnon drag thermopower we calculate from the hydrodynamic model [1] agrees with the experiment. At the paramagnetic regime, a quantitative explanation is given based on the spin entropy theory [2].

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