Spin Caloritronics XI

May 23-27, 2022 | **Materials Research Laboratory**

University of Illinois at Urbana-Champaign

The Grainger College of Engineering

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

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Dear Colleagues and Friends,

After a two-year delay, we are finally looking forward to welcoming you to Urbana for a vibrant scientific exchange on the interplay between spins and heat. Spin Caloritronics XI is the 11th installment of the Spin Caloritronics workshops that began in Leiden, The Netherlands in 2009. Originally, these workshops focused on the direct coupling between charge, spin, and heat currents. The topics have evolved over the past decade to include a broad range of non-equilibrium phenomena that are important to spin transport and magnetization dynamics. While the initial focus was mainly on ferromagnetic materials, there are now related ideas being pursued especially for antiferromagnetic materials, but also for materials that are not magnetically ordered at all, such as paramagnets and ferroelectrics. In addition, the many different ways of transferring angular momentum between materials underlie a broad range of potential technological applications and provides a fertile area for scientific discovery.

We hope that you will find the program invigorating and that you will enjoy again an in-person meeting with your colleagues. We are looking forward to heated debates about the newest spin-phenomena.

Best regards,

David Cahill & Axel Hoffmann

 

SPIN CALORITRONICS XI SPONSORS:

ILLINOIS
Illinois Quantum Information Science & Technology Center
GRAINGER COLLEGE OF ENGINEERING

I-MRSEC

ILLINOIS
Materials Research Laboratory

ILLINOIS
Materials Science & Engineering
GRAINGER COLLEGE OF ENGINEERING

SPIN CALORITRONICS XI PARTNERS:

AJA International, Inc.

CRYOGENIC
CRYOGENIC LIMITED

IEEE MAGNETICS

OXFORD INSTRUMENTS

THINGS TO DO IN THE AREA

Elevate Trampoline Park - Elevate Trampoline Park is a 30000-square-foot indoor activity center in Champaign, offering everything from trampolines, parkour, foam pits and much more

Skateland - For over 40 years, Skateland has been entertaining families. They offer Laser Zone Laser Tag as an added attraction. The arcade will provide hours of entertainment where you will no doubt win lots of tickets to redeem at the Stuff Shop. After a hard day of fun and play, nothing satisfies like a cold drink and a slice of homemade pizza. Kids of all ages will love skating at Skateland.

Savoy 16 Movie Theater - IMAX, 3D, Reserved Seating, Advance Ticketing, Bargain Tuesdays & More.

Champaign-Urbana Adventures in Time & Space - YOU HAVE ONE HOUR TO SAVE THE WORLD! Located in downtown Urbana, Illinois, these escape rooms make for a great activity. Teams of 2-10 players have 60 minutes to find clues, complete puzzles, discover secret doors, and solve a greater mystery. Each of our adventures takes place in a different setting and time period. From dispelling evil spirits in a haunted cabin to foiling the plot of a tyrannical wizard, the scenarios are designed to make players feel like they are living out a movie!

University of Illinois Ice Arena - Located at 406 East Armory Avenue in Champaign, this campus facility caters to skaters of all ages and level of skill. It has open public skating available several times throughout the week, including lunchtime skates (perfect for days off school) and weekends.

The Pottery Place: Paint Your Own Pottery - The Pottery Place is open for customers! Whether you want to create your own gifts, are looking for a unique party idea, or just enjoy painting pottery, The Pottery Place is a relaxing, inspiring space to gather and create! Take and Make Kits are now available for at home painting!

Museums - There's a lot to learn and discover at our area museums and attractions. From interactive museums to supercomputers, we're filled with a lot of "fun facts" to take home and impress your family https://www.visitchampaigncounty.org/things-to-do/museums-and-technology

Urbana's Market at the Square - Join thousands of residents and visitors in Downtown Urbana every Saturday, 7 AM to noon, from May through October, to celebrate everything local! Since 1979, Urbana's Market at the Square has been a mainstay for Urbana and the surrounding area by connecting the community with local growers and artisans. Shop one of the best selections of made- and grown-in-Illinois products including: produce, meat, dairy, honey, local beer and wine, flowers, handmade art and crafts, and more. Saturday morning at Urbana's Market at the Square is one of our city's signature institutions! It's a great way to kick off your weekend.

Shopping at Marketplace Mall **& North Prospect** - Market Place Shopping Center is an enclosed shopping mall located in Champaign, Illinois, US. The mall's anchor stores are Dick's Sporting Goods, Field & Stream, JCPenney, Macy's, and Costco Wholesale. It is the second largest enclosed shopping mall in Central Illinois. North Prospect also hosts stores such as TJMaxx, HomeGoods, Hobby Lobby, and more!

University of Illinois Arboretum - The Arboretum's gardens, collections, and habitats are transforming 160 acres of the University's south campus in Urbana-Champaign into an exceptional "living laboratory" for students in plant sciences and fine and applied arts, as well as an oasis of natural beauty open to the public. The gardens are open dawn to dusk spring through fall. You are always welcome to walk through the gardens on your own. Traditional Japanese gardens surround Japan House. These gardens are very different than Western gardens, with a focus on the natural landscape, utilizing plants, rustic stone, and water. Instead of bright color and symmetry, these gardens focus on green foliage and natural shapes of plants. The design of the gardens creates an extraordinarily peaceful and tranquil environment.

Champaign County Forest Preserve - The CCFP operates seven forests covering almost 4,000 acres in Champaign County and serves a wide range of offerings from trails, to splash pads, to night sky viewings and much more.

Art Walk at Meadowbrook Park - We invite you to visit Meadowbrook Park, located at Windsor Road and Race Street in Urbana, Illinois. Meadowbrook Park’s 130 acres offer a myriad of recreational opportunities. Whether your interest is art, walking, cycling, natural areas, family fun, or simply enjoying the variety of gardens we have here, you won’t forget how much fun you had at Meadowbrook Park.

The Literary: **Books & Brunch & Coffee & Wine**- Downtown Champaign's book bar. Worth a stop for unique gifts, good drinks, and great books!

The Fire Doll Artisan Chandlery - features an exciting retail and studio experience for candle lovers! Come visit us during normal business hours to watch candles being made while perusing a wide variety of handmade artisan candles, wax melts, and more! You will also find a lovely selection of artisan candle accessories, bath & body products, stationery, and much much more... all from woman-owned businesses both local and around the globe. We also host a Candle Happy Hour thrice weekly on Wednesdays, Thursdays, and Fridays from 6:30pm - 8:00pm! Reservations are required.

Alto Vineyards**: Wine Tasting** - The second location of Alto Vineyards, one of the largest and most award-winning wineries in Illinois. Come in any time for $5.00 walk-in wine tastings and unique wine-related gifts. Taste a few wines and relax in beautiful country setting just outside of Champaign, IL.

Prairie Fruits Farm & Creamery**: Goat cheese tastings and visits with the goats** - While we welcome visitors, we are, first and foremost, a diverse working farm. During the height of our production and marketing season (March through December), we are busy making cheese, taking care of the goats, tending the orchard, selling cheese and fruits at farmers' markets and hosting farm dinners and other farm events. During our farm's open hours, visitors can walk around the farm, visit with the goats, pick fruits when in season, and see the cheese making process through our viewing window. Seasonally, the farm is open for self-guided farm visits and farm product purchasing.

Illinois Amish Country – plan for an afternoon. Arcola, Arthur, Sullivan and Tuscola invite you to travel back. Travel back to a simpler time, where craftsmen and artisans create beauty with their hands. Travel back for heirloom antiques and unique shops. Travel back for one-of-a-kind recreation and dining experiences that will appeal to your whole family.

SCHEDULE AT A GLANCE

<table>
<tr><th>TIME</th><th>SUNDAY</th><th>MONDAY</th><th>TUESDAY</th><th>WEDNESDAY</th><th>THURSDAY</th><th>FRIDAY</th></tr>
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<tr><td>8:15</td><td>Welcome</td><td>Registration</td><td>Registration</td><td>Registration</td><td>Registration</td></tr>
<tr><td>8:30</td><td rowspan="2">Session I</td><td rowspan="2">Session IV</td><td rowspan="2">Session VII</td><td rowspan="2">Session IX</td><td rowspan="2">Session XII</td></tr>
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<tr><td>10:00</td><td>Coffee Break</td><td>Coffee Break</td><td>Coffee Break</td><td>Coffee Break</td><td>Coffee Break</td></tr>
<tr><td>10:30</td><td rowspan="2">Session II</td><td rowspan="2">Session V</td><td rowspan="2">Session VIII</td><td rowspan="2">Session X</td><td>Session XIII</td></tr>
<tr><td>11:00</td><td>Closing Remarks</td></tr>
<tr><td>noon</td><td rowspan="3">Lunch</td><td rowspan="3">Lunch</td><td rowspan="4">Lunch</td><td rowspan="3">Lunch</td><td rowspan="13"></td></tr>
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<tr><td>16:00</td><td>Poster Session</td><td>Poster Session</td><td>Poster Session</td></tr>
<tr><td>17:00</td><td rowspan="3">Welcome Reception & Registration</td><td rowspan="2">Women’s Networking Social</td><td rowspan="5">LabEscape</td><td rowspan="5">LabEscape</td></tr>
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<tr><td>19:00</td><td rowspan="3"></td></tr>
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<tr><td>21:00</td><td></td></tr>
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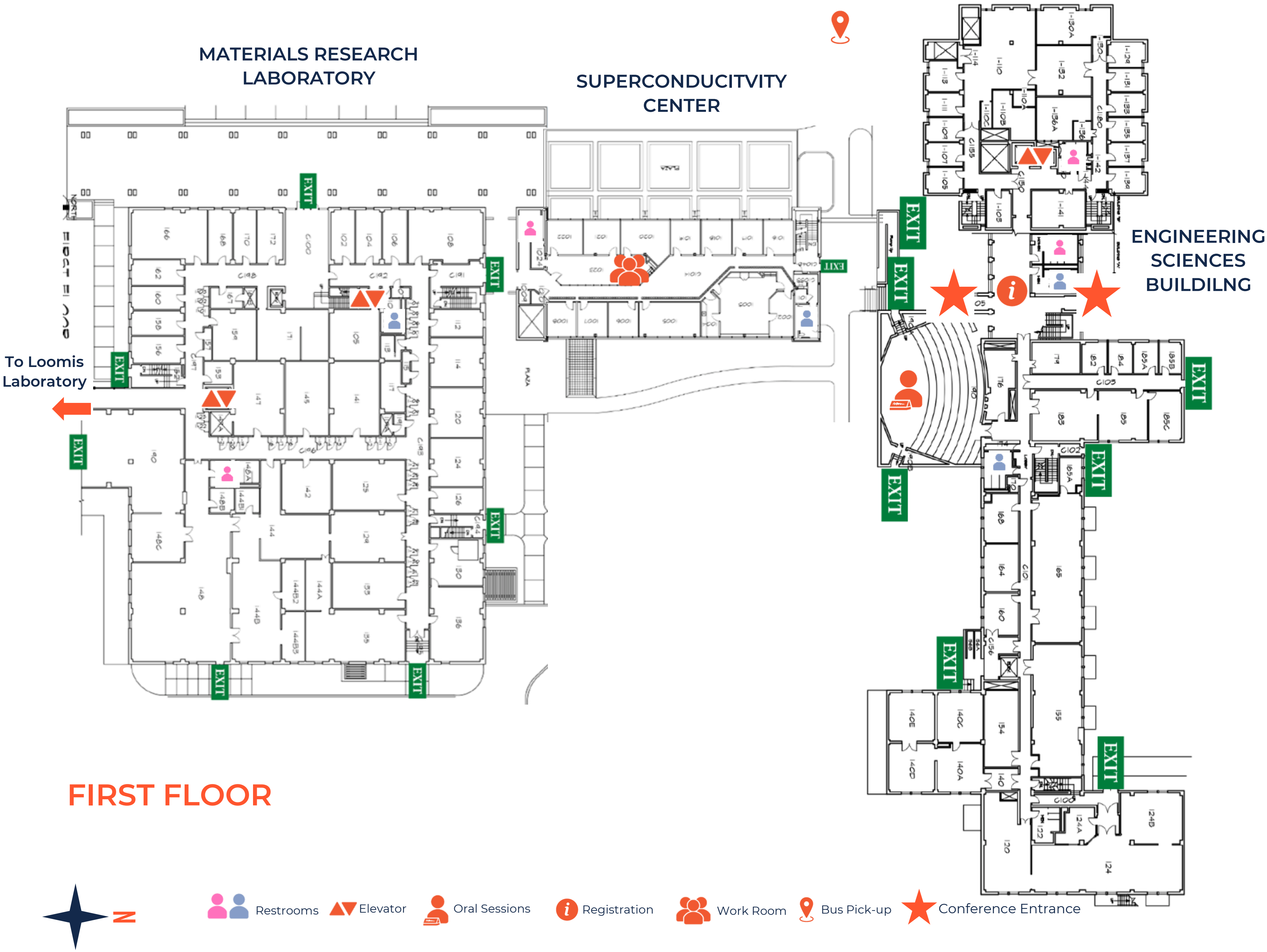
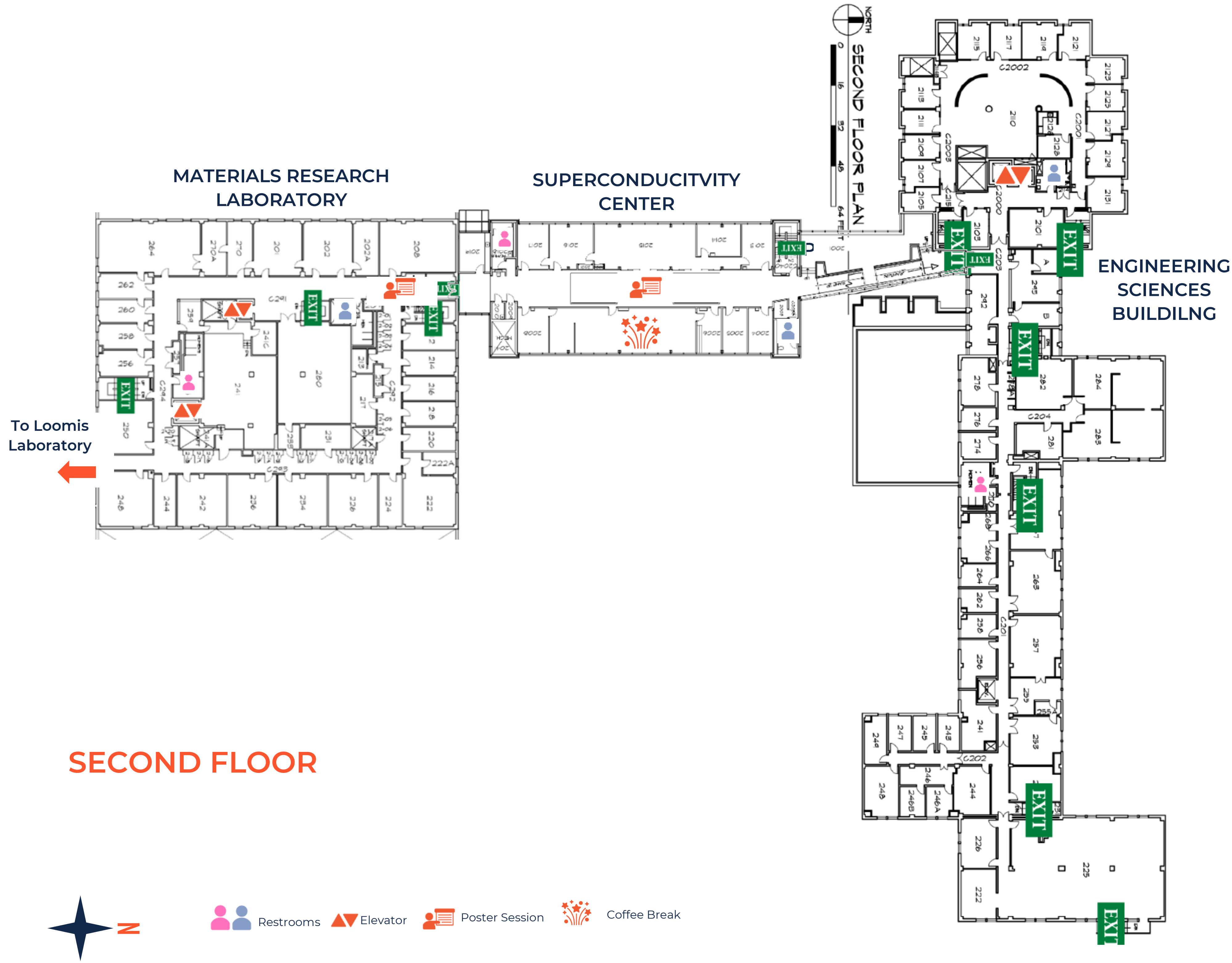

MATERIALS RESEARCH LABORATORY
SUPERCONDUCITVITY CENTER
ENGINEERING SCIENCES BUILDILNG
To Loomis Laboratory
FIRST FLOOR
EXIT
N
Restrooms
Elevator
Oral Sessions
Registration
Work Room
Bus Pick-up
Conference Entrance

SECOND FLOOR



CONFERENCE INFORMATION

Oral sessions:
190 Engineering Sciences Building
1101 W. Springfield Ave.
Urbana, IL 61801

Invited talks will span 25 minutes, with a 5-minute question and answer session to follow. Contributed talks will span 12 minutes, with a 3-minute question and answer session to follow. Keeping with the tradition of previous Spin Caloritronics meetings each oral presenter will chair the subsequent oral presentation.

Poster sessions:
2nd Floor Hallway
Superconductivity Center
100 S. Goodwin Ave.
Urbana, IL 61801

All posters should be displayed Monday through Thursday. **Monday, May 23**, presenters of **odd-numbered posters** should be present during the poster session, and **Tuesday, May 24**, presenters of **even-numbered posters** should be present during the poster session. On **Thursday, May 26**, we encourage **ALL** poster presenters to be present at their posters.

Coffee breaks:
2008 Superconductivity Center
100 S. Goodwin Ave.
Urbana, IL 61801

Workroom *(available Monday through Friday from 8:00 am - 5:00 pm)*
1023 Superconductivity Center
100 S. Goodwin Ave.
Urbana, IL 61801

Internet Connectivity:
1. While on campus, connect your device to the Wi-Fi network "IllinoisNet_Guest"
2. Open a browser window and navigate to illinois.edu.
3. Your browser should be redirected to our Wi-Fi Captive Portal page. If you don't see a captive portal page, close your browser app entirely and start from step 2 again. You can also try and go to https://go.illinois.edu/illinoisnet
4. As a guest or visitor, click the link at the bottom of the page and you can self-register an account. This account will be valid until 4am the next day, after which you will be prompted to create a new account.
5. After a brief moment the system should then inform you that you have been given Internet access. Visitors should choose Click Here for Wi-Fi Access. Keep in mind that any visitor accounts created in this way are only valid until 4am the following day, after which you will need to repeat this process.

CONFERENCE EVENTS

Welcome Reception

A welcome reception, sponsored by Oxford Instruments, will be held in conjunction with early registration at Pour Bros. Craft Taproom in Downtown Champaign on Sunday, May 22, 2022, from 5:00-8:00pm. Pour Bros. curates an ever-changing small-batch menu of craft beer, ciders, meads, and amazing handcrafted cocktails You will also be able to enjoy a selection of “Fresh & Authentic Mexican Food” catered by Maize Mexican Grill.

Women’s Networking Social

A women’s networking social, open to all, will take place in the first-floor atrium at the Holonyak Micro & Nanotechnology Laboratory on Monday, May 23, 2022, from 5:00-7:00pm. Sponsored by IEEE Magnetics Society Chicago Chapter, come and enjoy hors d'oeuvres and drinks while connecting with others in the Spin Caloritronics community.

LabEscape

World-renowned quantum physicist Professor Alberta Pauline Schrödenberg is quarantining and desperately needs your help — the fate and security of the entire world hang in the balance. You'll have to search her lab, solve mind-blowing puzzles to reveal clues, and hopefully find a way to complete your mission - saving us all! As featured in The New York Times, this APS- and NSF-funded outreach project is, we believe, the world’s first science-based 'escape-room', in which all the puzzles involve various physics phenomena. They’ve run nearly 9000 Agents through, including ~1000 scientists (at the annual AAPT meeting in DC, the APS meeting in Boston, and the DAMOP meeting in Milwaukee), and received nearly all 5-star ratings, with many participants saying LabEscape was the best escape room they’d ever done.

LabEscape will be available FREE for Spin Caloritronics XI attendees Tuesday and Thursday evenings (5:30pm, 6:50pm, 8:10pm, and 9:30pm slots), in 258 Loomis Laboratory. Create a team of 4-7 Agents (or join someone else’s) and sign up online: https://my.physics.illinois.edu/extranet/labescape/spin-cal-2022/

Allerton Park and Retreat Center Excursion and Conference Dinner

The conference dinner will take place at Allerton Park and Retreat Center in Monticello, IL on Wednesday, May 25, 2022. Depart on one of the early buses and enjoy a walk through sculpture gardens or one of the many hiking trails, or arrive on the later bus in time for a 5:00pm cocktail hour, sponsored by AJA International. The dinner, catered by Blue Dragonfly Catering will begin at 6:00pm and end by 9:00pm. Please see the Conference Schedule for bus departure times to and from the dinner.

About The Venue: *“Built as a private residence by artist and philanthropist Robert Allerton in 1900, Allerton Park and Retreat Center is a historical treasure that was donated to the University of Illinois in 1946. The property contains 1,500 acres of woodland and prairie areas, a mansion and reflecting pond, a 10-acre meadow, formal sculpture gardens, hiking trails, a café, and several lodging facilities”*

CONFERENCE SCHEDULE

SUNDAY, MAY 22, 2022

5:00 pm — Welcome Reception and Registration
Pour Bros. Craft Taproom
40 E. University Ave.
Champaign, IL 61820

8:00 pm — Reception Concludes

MONDAY, MAY 23, 2022

8:00 am — Registration
Lobby – Engineering Sciences Building

8:15 am — Welcome
190 Engineering Sciences Building

Session I - Antiferromagnets I
190 Engineering Sciences Building

8:30 am — Enrique del Barco, University of Central Florida
"Coherent Sub-Terahertz Spin Pumping from an Insulating Antiferromagnet"

9:00 am — Helena Reichlova, Technical University Dresden
"Anomalous Nernst effect in Antiferromagnetic Thin Films"

9:30 am — Timo Kuschel, Bielefeld University
"Thermally induced spin transport in NiO thin films"

10:00 am — Coffee Break
2008 Superconductivity Center

Session II -Antiferromagnets II (Cr_2O_3 and others)
190 Engineering Sciences Building

10:30 am — Anand Bhattacharya, Argonne National Laboratory
"Sensing and control of spin sublattices of Cr_2O_3 by electrical means"

11:00 am — Shaloo Rakheja, University of Illinois Urbana-Champaign
"Physics and modeling of antiferromagnetic memory and oscillator devices based on Cr_2O_3"

MONDAY, MAY 23, 2022

11:30 am — Robin Neumann, Martin Luther University Halle-Wittenberg
"Thermal Hall Effect of Magnons in Collinear Antiferromagnetic Insulators: Signatures of Magnetic and Topological Phase Transitions"

11:45 am — Azel Murzabekova, University of Illinois Urbana-Champaign
"THz-induced optical activity in the non-collinear metallic antiferromagnet $Fe_{1/3}NbS_2$"

Noon — Lunch Break

Session III - Antiferromagnets III (non-collinear systems)
190 Engineering Sciences Building

2:00 pm — Jinsong Xu, Johns Hopkins University
"Observation of Vector Spin Seebeck Effect in a Non-Collinear Antiferromagnet"

2:30 pm — Joseph Sklenar, Wayne State University
"Hybridizing Antiferromagnetic Magnons with Spin Pumping and Exchange Fields"

3:00 pm — Stuart Parkin, Max Plank Institute of Microstructure Physics
"Seeded Spin Orbit Torque manipulation of the magnetic structure of chiral kagome antiferromagnets"

3:30 pm — Coffee Break
2008 Superconductivity Center

4:00 pm — Poster Session (odd-numbered posters)

5:00 pm — Women's Networking Social
Holonyak Micro & Nanotechnology Lab
First Floor Atrium
208 N. Wright St.
Urbana, IL 61801

7:00 pm — Social Concludes

TUESDAY, MAY 24, 2022

8:15 am — Registration
Lobby – Engineering Sciences Building

Session IV - Spin Seebeck Effects
190 Engineering Sciences Building

8:30 am — Kyung-Jin Lee, Korea Advanced Institute of Science and Technology
"Enhanced Spin Seebeck Effect via Oxygen Manipulation"

9:00 am — Eiji Saitoh, University of Tokyo
"Coupling of electron and nuclear spins in spin caloritronics"

9:30 am — Douglas Natelson, Rice University
"Magnon Shot Noise in a Longitudinal Spin Seebeck Device"

10:00 am — Coffee Break
2008 Superconductivity Center

Session V - Magnetic Insulators
190 Engineering Sciences Building

10:30 am — Andrew Kent, New York University
"Spin-orbit torques in antiferromagnet insulator/heavy metal heterostructures"

11:00 am — Li Shi, University of Texas at Austin
"Frequency-dependent Spin Caloritronic Phenomena in a Metal-Magnetic Insulator Heterostructure"

11:30 am — Hyungyu Jin, Pohang University of Science and Technology
"Transverse thermoelectric energy conversion utilizing spin Seebeck and anomalous Nernst effects"

11:45 am — Alberto Anadón, Université de Lorraine
"Thermal spin current generation in multifunctional materials and interfaces"

Noon — Lunch Break

Session VI - Thermal Transport Effects
190 Engineering Sciences Building

2:00 pm — Claudia Felser, Max Planck Institute for Chemical Physics of Solids
"Nernst effect in Magnetic topological Materials"

TUESDAY, MAY 24, 2022

2:30 pm	Barry Zink, University of Denver “Field-dependent Nonelectronic Thermal Conductivity and Magnon Drag in a Metallic Ferromagnet with Low Gilbert Damping”
3:00 pm	Hyejin Jang, Seoul National University “Nonequilibrium Heat Transport Probed by Ultrafast Magnetic Thermometry”
3:30pm	Coffee Break ***2008 Superconductivity Center***
4:00 pm	Poster Session (even-numbered posters)
5:00 pm	Poster Session Concludes
5:30 pm	LabEscape *(registration required)* ***258 - Loomis Laboratory*** 1110 W Green St Urbana, IL
11:00 pm	LabEscape Concludes

WEDNESDAY, MAY 25, 2022

8:15 am	Registration ***Lobby – Engineering Sciences Building***

Session VII - Magnon Spin Transport
190 Engineering Sciences Building

8:30 am	Bart van Wees, University of Groningen (virtual) “Giant magnon spin conductivity approaching the two dimensional transport regime in ultrathin yttrium iron garnet films”
9:00 am	Matthias Althammer, Walther-Meißner-Institut “Observation of the magnon Hanle effect in antiferromagnetic insulators”
9:30 am	Hiroto Adachi, Okayama University “Spin transport using antiferromagnetic magnons and superconducting vortices”
10:00 am	Coffee Break ***2008 Superconductivity Center***

WEDNESDAY, MAY 25, 2022

Session VIII – Dynamics
190 Engineering Sciences Building

10:30 am — Valentina Bisogni, Brookhaven National Laboratory
"Resonant Inelastic X-ray Scattering to probe collective spin dynamics in magnonic materials"

11:00 am — Richard Wilson, University of California, Riverside
"Relationship between composition and heating induced energy and spin dynamics in magnetic materials"

11:30 am — Markus Münzenberg, University of Greifswald
"Ultrafast spintronics on attosecond time scales"

12:00 pm — Lunch Break

Allerton Park Retreat Excursion and Conference Dinner
Allerton Park & Retreat Center, 515 Old Timber Rd., Monticello, IL 61856

All buses will load at: *Materials Research Laboratory, 104 South Goodwin Ave., Urbana, IL 61801*

2:15 pm — Load bus #1 for Allerton Park Retreat Excursion and Conference Dinner
2:45 pm — Load bus #2 for Allerton Park Retreat Excursion and Conference Dinner
4:00 pm — Load bus #3 for Allerton Park Retreat Excursion and Conference Dinner

5:00 pm — Cocktail Hour Begins

6:00 pm — Conference Dinner Begins

7:45 pm — Load bus #1 to return to Materials Research Laboratory
8:15 pm — Load bus #2 to return to Materials Research Laboratory
8:45 pm — Load bus #3 to return to Materials Research Laboratory

9:00 pm — Conference Dinner Ends

THURSDAY, MAY 26, 2022

8:15 am Registration
Lobby – Engineering Sciences Building

Session IX – Microscopy
190 Engineering Sciences Building

8:30 am Greg Fuchs, Cornell University
"Magneto-thermal Microscopy and Single-spin Microscopy of Complex Magnetic Materials"

9:00 am Jörg Wunderlich, University of Regensburg
"Magneto-Seebeck microscopy of spin-orbit torque driven domain wall motion in a collinear antiferromagnet"

9:30 am Chunhui (Rita) Du, University of California-San Diego
"Harnessing Nitrogen Vacancy Centers in Diamond for Next-Generation Quantum Science and Technology"

10:00 am Coffee Break
2008 Superconductivity Center

Session X - Fundamental Properties
190 Engineering Sciences Building

10:30 am Felix Casanova, CIC nanoGUNE
"Interfacial exchange field in heavy metal/magnetic insulators"

11:00 am Joseph Barker, University of Leeds
"Temperature dependence of exchange stiffness"

11:30 am Rakshit Jain, Cornell University
"Origins of transverse voltages generated by thermal gradients and electric fields in ferrimagnetic-insulator/heavy-metal bilayers"

11:45 am Kayla Nguyen, University of Illinois Urbana-Champaign
"Angstrom-Scale Mapping of the Local Magnetic Moment in Metallic Antiferromagnet Fe_2As using 4D-STEM"

Noon Lunch Break

THURSDAY, MAY 26, 2022

Session XI - Spin Torques
190 Engineering Sciences Building

2:00 pm — Igor Barsukov, University of California, Riverside
"Interplay of spin-torque and nonlinearity: Disentangling and controlling magnon processes in nanomagnets"

2:30 pm — Jingsheng Chen, National University of Singapore
"Symmetry-dependent field-free switching of perpendicular magnetization"

3:00 pm — Vivek Amin, Indiana University-Purdue University Indianapolis
"Unconventional Spin-Orbit Torques in Ferromagnetic Trilayers"

3:30pm — Coffee Break
2008 Superconductivity Center

4:00 pm — Poster Session (all posters)

5:00 pm — Poster Session Concludes

5:30 pm — LabEscape *(registration required)*
258 - Loomis Laboratory
1110 W Green St
Urbana, IL

11:00 pm — LabEscape Concludes

FRIDAY, MAY 27, 2022

8:15 am — Registration
Lobby – Engineering Sciences Building

Session XII - Future of Spin Caloritronics and Ferroelectrics
190 Engineering Sciences Building

8:30 am — Ken-ichi Uchida, National Institute for Materials Science (virtual)
"Future directions in spin caloritronics"

9:00 am — Alexey Kovalev, University of Nebraska-Lincoln
"Superfluid Spin Transport"

FRIDAY, MAY 27, 2022

9:30 am Joseph Heremans, The Ohio State University
"Polarization caloritronics: electric field dependence of the thermal conductivity and diffusivity of lead zirconium titanate"

10:00 am Coffee Break
2008 Superconductivity Center

Session XIII - Novel Dynamic Concepts
190 Engineering Sciences Building

10:30 am Aleš Hrabec, ETH Zürich
"Computation with Magnetic Domain Walls and Oscillators"

11:00 am Benedetta Flebus, Boston College
"Unveiling new phenomena in dissipative magnetic systems"

11:30 am Closing Remarks

POSTER SESSION PROGRAM

2nd Floor Hallway
Superconductivity Center
100 S. Goodwin Ave.
Urbana, IL 61801

All posters are expected to be displayed from Monday (5/23) at 3:30 pm until Thursday (5/26) at 5:00 pm. The poster sessions will be Monday, Tuesday, and Thursday from 4:00–5:00 pm. Presenters of odd-numbered posters are expected to be present at their posters during the poster sessions on Monday (5/23) and Thursday (5/26), while presenters of even-numbered posters are expected to be present at their posters during the poster sessions Tuesday (5/24) and Thursday (5/26).

Antiferromagnets

1. Yinchuan Lu, University of Illinois Urbana-Champaign
   "Temperature dependent spin-current generation in FeRh films as measured with THz emission spectroscopy"
2. Mebatsion Gebre, University of Illinois Urbana-Champaign
   "Bulk Single Crystal Growth and Transport Properties of Metallic Antiferromagnet, Mn_2Au"
3. Junehu Park, University of Illinois Urbana-Champaign
   "Strain Effect on Magnetocrystalline Anisotropy of Metallic Antiferromagnets from First-Principles"
4. Soho Shim, University of Illinois Urbana-Champaign
   "Unidirectional magnetoresistance in antiferromagnet/heavy-metal bilayers"
5. Myoung-Woo Yoo, University of Illinois Urbana-Champaign
   "Magnetic Octupole Dynamics in Non-collinear Antiferromagnets"

Magnon Spin Transport

6. Obed Alves Santos, University of Groningen
   "Counter-intuitive giant spin magnon conductivity in ultrathin YIG films"
7. Xochitl Aguilar-Pujol, CIC nanoGUNE
   "Detection of Magnon Currents in EuS"
8. Wenqin He, Chinese Academy of Sciences
   "Magnon Junction Effect in $Y_3Fe_5O_{12}$/CoO/$Y_3Fe_5O_{12}$ Insulating Heterostructures"
9. Zheng Ren Yan, Chinese Academy of Sciences
   "Magnon Blocking Effect in an Magnon Junction“
10. Michael Vogel, University of Kassel
    "Driving a magnetic texture by magnon currents"

Heat Transport

11. Nicolas Marchal, Université Catholique de Louvain
 "Magnetically Activated Flexible Thermoelectric Switches based on Interconnected Nanowire Networks"
12. Brandi Wooten, The Ohio State University
 "Thermal Conductivity Study of Piezoelectric PZT Stack"
13. Joonsang Kang, The Ohio State University
 "Thermal chiral anomaly in Weyl semimetal BiSb alloy"

Seebeck and Nernst Effects

14. Sang Jun Park, Pohang University of Science and Technology
 "Designing efficient spin thermoelectric devices via engineering magnon-phonon thermal coupling"
15. Hyun Yu, Pohang University of Science and Technology
 "Anomalous Nernst effect in the compensated ferrimagnets, Fe-Ln alloys (Ln = Gd, Tb, Dy, Ho, and Er)"
16. Min Y. Kim, Pohang University of Science and Technology
 "The Effect of Spin-orbital Entropy on Anomalous Nernst Effect"

Spin Torques and Magnetotransport

17. Shuchen Li, University of Illinois Urbana-Champaign
 "Spin-orbit Torques in Magnetron-Sputtered $MoTe_2$"
18. Claudio Gonzalez-Fuentes, Universidad Tecnica Federico Santa Maria
 "Magneto-optical detection of spin-orbit torque vector with first order Kerr effects"
19. Sara Catalano, CIC nanoGUNE
 "Spin Hall magnetoresistance effect from a disordered interface"

Microscopy and Optical Effects

20. Kisung Kang, University of Illinois Urbana-Champaign
 "Temperature-dependent optical and magneto-optical spectra of ferromagnetic BCC Fe: First-principles study"
21. Cody Friesen, University of Hamburg
 "Scanning tunneling microscopy platform for low-temperature, vector magnetic field spin-caloritronic studies"
22. Robert Puttock, National Physical Laboratory
 "Local Thermoelectric Response from a Single Néel Domain Wall"

Dynamics

23. Dingbin Huang, University of Minnesota
 "Magnetization Dynamics of Spintronic Materials Enabled by Ultrafast Optical Metrology"
24. Dreycen Foiles, University of Illinois Urbana-Champaign
 "Deformation Induced Skyrmion Rotation and Orbital Motion"

SPEAKER ABSTRACTS

In order of appearance in program

Coherent Sub-Terahertz Spin Pumping from an Insulating Antiferromagnet

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Emerging phenomena, such as the spin-Hall effect (SHE), spin pumping, and spin-transfer torque (STT), allow for interconversion between charge and spin currents and the generation of magnetization dynamics that could potentially lead to faster, denser, and more energy efficient, non-volatile memory and logic devices. Present STT-based devices rely on ferromagnetic (FM) materials as their active constituents. However, the flexibility offered by the intrinsic net magnetization and anisotropy for detecting and manipulating the magnetic state of ferromagnets also translates into limitations in terms of density (neighboring elements can couple through stray fields), speed (frequencies are limited to the GHz range), and frequency tunability (external magnetic fields needed). A new direction in the field of spintronics is to employ antiferromagnetic (AF) materials. In contrast to ferromagnets, where magnetic anisotropy dominates spin dynamics, in antiferromagnets spin dynamics are governed by the interatomic exchange interaction energies, which are orders of magnitude larger than the magnetic anisotropy energy, leading to the potential for ultrafast information processing and communication in the THz frequency range, with broadband frequency tunability without the need of external magnetic fields.

I will present the first evidence of sub-terahertz coherent spin pumping at the interface of a uniaxial insulating antiferromagnet MnF_2 and platinum thin films, measured by the ISHE voltage signal arising from spin-charge conversion in the platinum layer. The ISHE signal depends on the chirality of the dynamical modes of the antiferromagnet, which is selectively excited and modulated by the handedness of the circularly polarized sub-THz irradiation (see figure). Contrary to the case of ferromagnets, antiferromagnetic spin pumping exhibits a sign dependence on the chirality of dynamical modes, allowing for the unambiguous distinction between coherent spin pumping and the thermally-driven, chirality-independent spin Seebeck effect. Our results open the door to the controlled generation of coherent pure spin currents with antiferromagnets at unprecedented high frequencies.

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Anomalous Nernst effect in Antiferromagnetic Thin Films

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The anomalous Nernst effect (ANE) refers to the voltage generated perpendicular both to an applied thermal gradient and magnetic field in a material with long range magnetic order. It was long time believed to be present only in ferromagnets and of negligible magnitude. Following the recent development of the Berry phase concept, additional intrinsic contributions to the ANE were identified. Large ANE coefficients were experimentally confirmed in ferromagnets with complex topology of their band structure, both in bulk and thin film form [1,2]. Furthermore ANE, similar to the anomalous Hall effect (AHE), was shown to be present in materials with vanishing magnetization. Several examples of the ANE in non-collinear antiferromagnets will be discussed in this talk [3.4].

Very recently also the collinear antiferromagnets were shown to exhibit AHE [5.6] arising from their spin and crystal symmetry. In these particular materials ANE can be equally present and first experimental indication of the ANE in a collinear antiferromagnet will be presented [7]. In the last part of the talk an overview of the ANE coefficients in antiferromagnetic films will be given and possible pathways to increase the ANE are discussed.

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Thermally induced spin transport in NiO thin films

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Antiferromagnetic thin films, e.g. NiO, have shown to efficiently transmit spin currents that are induced by spin pumping [1,2], spin Seebeck effect [3-5] and in nonlocal magnon spin transport experiments [6]. In some of these studies, the spin transport through about 1nm NiO is more efficient than passing the spins across the interface without any NiO [1,3,5]. The spin diffusion length in NiO can be determined by the exponential decay of the spin transport with increasing NiO thickness. Here, spin pumping experiments yield 9-11nm spin diffusion length in NiO [1], while thermally induced spin currents provide a smaller spin diffusion length of 2.5-4nm in NiO [3,4]. In these studies, the role of NiO as an active component inducing additional spin current has not been discussed, so far.

In our contribution, we will present local and nonlocal thermally induced spin transport through NiO thin films grown on the ferrimagnets (FMs) $Y_3Fe_5O_{12}$ and Fe_3O_4. We will discuss the role of NiO as an efficient spin current conductor if thin enough, but also as an active spin current generator. The latter can be detected if other spin current contributions are suppressed.

In order to quantitatively compare the spin transport efficiencies between the different FM spin current generators, we normalize our local spin Seebeck voltages to the experimentally determined heat flux that vertically passes the sample stacks [7]. For both FMs, we observe a maximum in the spin transport efficiency for about 1nm of NiO in accordance to earlier reports [1,3,5].

The spin diffusion length in our NiO deposited on Fe_3O_4 can be determined to about 3nm and is larger than the value for our NiO placed on $Y_3Fe_5O_{12}$. For both sample types and thicker NiO layers, the NiO thickness dependence deviates from the exponential decay and flattens [8]. This behaviour hints to a contribution of thermally induced spin currents in NiO itself. These become dominant over the spin currents generated in the FM for larger NiO thicknesses since the FM-induced spin currents are already blocked. Our results support the claim that NiO is not only a passive layer in this kind of stacks but actively contributes. We will discuss the preconditions for NiO to contribute in this way with respect to the recently observed uncompensated magnetic depth profile of NiO thin films investigated by x-ray resonant magnetic reflectivity [9].

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Sensing and control of spin sublattices of Cr_2O_3 by electrical means

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A central goal of antiferromagnetic spintronics is to sense and control the magnetic state of an antiferromagnet. While the magnetic state of a metallic antiferromagnet (AF) may be read out using magnetoresistance measurements, this is not an option for insulating AF materials. The spin Seebeck effect (SSE), where thermal gradients are used to drive magnon spin currents, has proven to be an effective probe[1] of AF order. Substantial spin currents have been measured using the SSE in AF insulators Cr_2O_3[2] and MnF_2[3], and this has been used to probe their spin-flop transitions. In this talk I will present our results on sputtered Pt/Cr_2O_3 (0001)/Pt heterostructures. In these devices, the spin currents generated by thermal gradients are detected using the inverse spin Hall effect (ISHE) in epitaxial thin films of Pt, grown both as an underlayer beneath and as an overlayer on top of the Cr_2O_3 film. Cr_2O_3 is unique in that the spins on the top and bottom surfaces of (0001) oriented films are uncompensated, and belong to separate magnetic sublattices, even in the presence of surface roughness. Using the ISHE in both top and bottom Pt layers[4], we find that the SSE is strongly sensitive to the respective sublattice magnetization. As a result, we are able to track the exact orientation of both sublattices upon application of a magnetic field, including during spin-flop processes. Furthermore, Cr_2O_3 is a classic linear magnetoelectric, where an electric field applied in the [0001] direction can be used to tune the net magnetization[5]. In this context, I will discuss how the application of electric fields in the Pt/Cr_2O_3/Pt heterostructures can be used to tune magnon spin currents, generated using thermal gradients[5].

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Physics and modeling of antiferromagnetic memory and oscillator devices based on Cr_2O_3

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Chromium oxide (Cr_2O_3) is a unique AFM material as it displays the linear magnetoelectric effect, which establishes a direct way to control its domain state via the application of voltage [1]. When electric and magnetic fields are simultaneously applied on Cr_2O_3, the resulting magnetoelectric pressure lifts the degeneracy of 180-degree AFM orders and the domain state is subject to reversal. The magnetoelectric switching is expected to be more energy efficient compared to spin torque assisted switching of the order parameter in metallic AFMs [2].

In this abstract, we will present the physics and analytic models of electric field induced switching of the Néel vector in Cr_2O_3. The impact of boron (B) doping to elevate the Néel temperature, while also making B:Cr_2O_3 a multi-functional AFM that can be switched in the absence of magnetic fields will be discussed. The Néel order in Cr_2O_3 can also be excited via torques induced by non-equilibrium spin polarization generated from electric currents. In this case, the order parameter undergoes steady-state precession, which can reciprocally pump spins to act as a tunable terahertz nano-oscillator.

We analyze the switching mechanism in Cr_2O_3 in terms of coherent (fast) and distributed (slow) modes, each of which has a unique energy barrier [3]. Our theory predicts that switching proceeds through slower modes, on a timescale of 100s of nanoseconds, at moderate electric fields, which has also been confirmed experimentally [4]. Our models reveal that the magnetoelectric switching in Cr_2O_3 could take place at sub-pJ energy levels. However, ultrafast switching requires stronger electric fields and improved dielectric strength of the material, which could be partly addressed via boron doping. In addition, boron doping helps elevate the Néel temperature of Cr_2O_3 to above 400 K, approximately 100 K higher than the Néel temperature of the undoped sample. Recent experimental work has shown that in boron-doped Cr_2O_3, the domain switching is controlled by electric field alone without the influence of magnetic field [5]. Measurements show that there is an induced polarization which couples to the AFM order indirectly via strain. Depending on the direction of electric field, the strain can be made compressive or tensile, allowing the domain to switch between in-plane and perpendicular orientations. We estimate a speed of 100 ps for 90-degree planar relaxation of the Néel order.

In addition to domain switching via voltages in Cr_2O_3, injection of spin torque exerts torque on alternating spin moments, which can excite the steady state precessions of the Néel order at terahertz frequencies. We determine the bistability between equilibrium and periodic solutions and find algebraic expressions for the angular velocity and fundamental frequency of precession: this is useful for device design and benchmarking computation models. We have also extended our computational framework to analyze the Néel order dynamics in noncollinear coplanar AFMs: Mn_3Ir and Mn_3Sn [2].

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Thermal Hall Effect of Magnons in Collinear Antiferromagnetic Insulators: Signatures of Magnetic and Topological Phase Transitions

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The thermal Hall effect, i.e., transverse heat transport induced by a longitudinal temperature gradient and topology are closely intertwined since both effects are related to the Berry curvature, which is similar to a magnetic field in reciprocal space. In insulators, heat transport is caused partially by magnons, the bosonic quasiparticles of spin waves. The possibility of topological magnon bands and nontrivial edge states was predicted by several theoretical studies, but the experimental detection is notoriously difficult. Quantized transport, what is a clear signature of topological electrons, does not exist for bosons due to their lack of the Pauli exclusion principle.

In this talk, the thermal Hall conductivity of magnons in a collinear antiferromagnet is discussed as an indicator for magnetic and topological phase transitions. A magnetic field drives the system from its antiferromagnetic phase via a spin-flop phase to the field-polarized phase. In addition to these magnetic phase transition, topological phase transitions occur in the spin-flop phase. Signatures in the heat transport admit tracing these phase transitions, which cause signal changes of several orders of magnitude. The variation of temperature provides a tool to discern experimentally the two types of phase transitions. We suggest the van der Waals magnet $MnPS_3$ as a platform, for which we make numerical predictions.

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THz-induced optical activity in the non-collinear metallic antiferromagnet $Fe_{1/3}NbS_2$**

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The intercalated transition metal dichalcogenide $Fe_{1/3}NbS_2$ has received considerable attention due to its suitability for antiferromagnetic (AFM) spintronic devices. Recently, it has been demonstrated that the AFM order in $Fe_{1/3}NbS_2$ can be switched by applying DC pulses with current densities orders of magnitude lower than in other antiferromagnetic materials. In this work, we use ultrafast THz-pump, near-infrared-probe spectroscopy to observe a transient change in the Kerr ellipticity in response to a strong THz pump pulse. We find that this change is peaked at the Nèel temperature (50K) and persists at even higher temperatures. We will discuss possible reasons for this behavior in terms of competing magnetic phases present in $Fe_{1/3}NbS_2$ and critical dynamics near the phase transition. Our results highlight the possibility of manipulating AFM ordering in metals at THz timescales.

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Observation of Vector Spin Seebeck Effect in a Non-Collinear Antiferromagnet

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Spintronic phenomena to date have been established in ferromagnets (FMs) with collinear moments (e.g., Fe, Co, $Y_3Fe_5O_{12}$), where all the moments can be aligned to give a large magnetization (***M***). In such collinear FMs, spin injection via spin Seebeck effect (SSE) is always along the out-of-plane direction (longitudinal SSE), but not in the in-plane direction (transverse SSE).

In non-collinear antiferromagnets (AFs), there are magnetic moments in directions other than that along the net magnetization ***M***, allowing general pure spin current phenomena to be established. In this work, we report the observation of vector SSE in non-collinear AF $LuFeO_3$, where temperature gradients along both out-of-plane and in-plane direction can inject pure spin current and generate a voltage in the heavy metal via the inverse spin Hall effect (Fig. 1). We show that the thermovoltages are due to the magnetization from the canted moments in $LuFeO_3$. One can exploit vector SSE as a vector magnetometer for detecting very small magnetization in non-collinear AF insulators. To establish vector SSE in $LuFeO_3$, we have ruled out the possibility of magnon Hall effect (MHE) in $LuFeO_3$. These novel results expand the realm of spintronics and enable new device architectures for AF spintronics and reveal general pure spin current phenomena beyond those in collinear magnets.

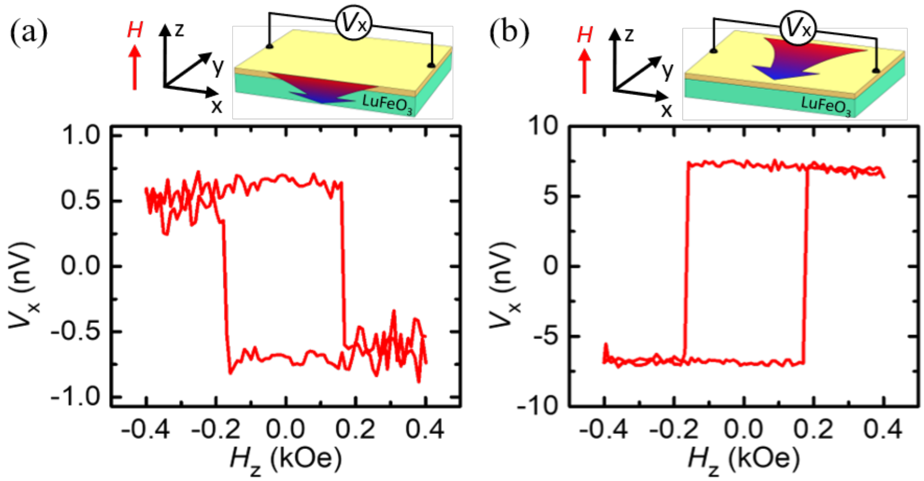

Fig. 1. (a) Longitudinal SSE under out-of-plane $\nabla_z T$, and (b) transverse SSE under in-plane $\nabla_y T$ in $LuFeO_3$/W.

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Hybridizing Antiferromagnetic Magnons with Spin Pumping and Exchange Fields

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The richness in both the dispersion and energy of antiferromagnetic magnons has spurred the magnetism community to consider antiferromagnets for future spintronic/magnonic applications. However, the excitation and control of antiferromagnetic magnons remains challenging, especially when compared to ferromagnetic counterparts. A middle ground is found with synthetic antiferromagnet metamaterials, where acoustic and optical magnons exist at GHz frequencies. In these materials so far, the magnon energy spectrum has been *tuned* by hybridizing optical and acoustic magnons using symmetry breaking external fields or dipolar interactions [1,2]. Here, we theoretically predict [3] and experimentally demonstrate the existence of two new magnon-magnon interactions that occur when magnons are localized on the surface and interior magnetic layers of an antiferromagnet. We show that field-like torques, generated by interlayer exchange fields, selectively hybridize acoustic-acoustic or optical-optical magnon pairs. Uniquely, acoustic-optical interactions are generated by interlayer spin pumping, which exerts antidamping torques on magnetic layers at the expense of their neighbors. Surprisingly, this viscous damping of magnetization dynamics leads to *viscous coupling* of magnons. We compare the coherent and incoherent thermal magnon spectra to learn that magnon coherence is essential for the viscous coupling of magnons to occur. Our work significantly expands ways of engineering magnon-magnon interactions within antiferromagnets and quantum hybrid magnonic materials.

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Seeded Spin Orbit Torque manipulation of the magnetic structure of chiral kagome antiferromagnets

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The current induced spin-transfer and spin-orbit torque (SOT) switching of ferromagnets has had huge impact in spintronics, both fundamental and technological. For practical technological applications, the magnitude of the switching currents must be minimized to allow for minimum sized write transistors. Thus, of great interest are magnetic layers with reduced magnetization such as ferrimagnetic Heusler compounds[1] or antiferromagnetic compounds. In the latter category there has been great interest recently in non-colinear antiferromagnets which have unique properties such as an anomalous Hall effect, even though the magnetization is zero or nearly zero[2]. The manipulation of the magnetic state of such antiferromagnets by spin torques is highly interesting. Here we discuss the manipulation of the magnetic state of the chiral kagome antiferrromagnet, Mn_3Sn, using SOT[3].

SOT switching to date has involved spin currents that are generated in heavy metal layers via the spin Hall effect, and that are allowed to diffuse into proximal ferromagnetic or ferrimagnetic layers and, thereby, transfer spin angular momentum to these layers so providing torques to manipulate their magnetization. Short spin-diffusion lengths limit the thickness of such switchable magnetic layers, and, thereby, limits the thermal stability of switchable magnetic nano-elements for spintronic memory applications. Here we report a novel Seeded Spin-Orbit Torque (SSOT) by which current can set the magnetic states of even thick layers (~100 nm) of the chiral kagome antiferromagnet Mn_3Sn. The mechanism involves setting the orientation of the antiferromagnetic domains in a thin region at the interface of the Mn_3Sn layer with spin currents generated in an adjacent heavy metal layer via the spin Hall effect. At the same time the Mn_3Sn layer is heated above its magnetic ordering temperature via the current passed through the heavy metal/ Mn_3Sn bilayer that is used to generate the spin current. This interface region seeds the resulting spin texture of the entire Mn_3Sn layer as it cools down when the current is switched off. Thus, this SSOT mechanism overcomes the thickness limitation of conventional spin-orbit torques. We explore the dependence of the SSOT switching on temperature, magnetic field and the length and rise and fall times of the switching current pulses. We demonstrate, for example, the key role played by the fall time of the current pulse which, if too short does not provide the needed interface layer SOT. We also demonstrate that short, nanosecond long pulses can manipulate the magnetic state of Mn3Sn layers. SSOT switching in Mn_3Sn can be extended beyond chiral antiferromagnets to diverse magnetic systems and provides a path towards the development of highly efficient, high speed and thermally stable spintronic devices.

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Enhanced Spin Seebeck Effect via Oxygen Manipulation

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Spin Seebeck effect (SSE) refers to the generation of an electric voltage transverse to a temperature gradient via a magnon current. SSE offers efficient thermoelectric devices because the transverse geometry of SSE greatly simplifies the device structure and enables to utilize waste heat from a large-area source. However, SSE suffers from a low thermoelectric conversion efficiency that must be improved for widespread application. We show that SSE signal substantially enhances by oxidizing a ferromagnet in normal metal/ferromagnet/oxide structures [1]. In W/CoFeB/AlOx structures, voltage-induced interfacial oxidation of CoFeB enhances SSE signal by an order of magnitude. Our theory suggests that this enhancement results from an increased magnon density in the oxidized region with reduced exchange interaction, which in turn increases a gradient of magnon chemical potential and associated magnon current. This work has been done in collaboration with Byong-Guk Park's group at KAIST.

If time is allowed, we also discuss interesting features of compensated ferrimagnets [2], including magnon-photon coupling [3] and magnon-magnon entanglement [4].

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Coupling of electron and nuclear spins in spin caloritronics

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Nuclear spins in magnets carry angular momentum when they are hybridized with electron spin excitation. In this talk, spectroscopic study on such hybridized nuclear-spin excitation and spin-caloritronic effects based on such hybridization, nuclear spin Seebeck effects, will be discussed [1,2].

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Magnon Shot Noise in a Longitudinal Spin Seebeck Device

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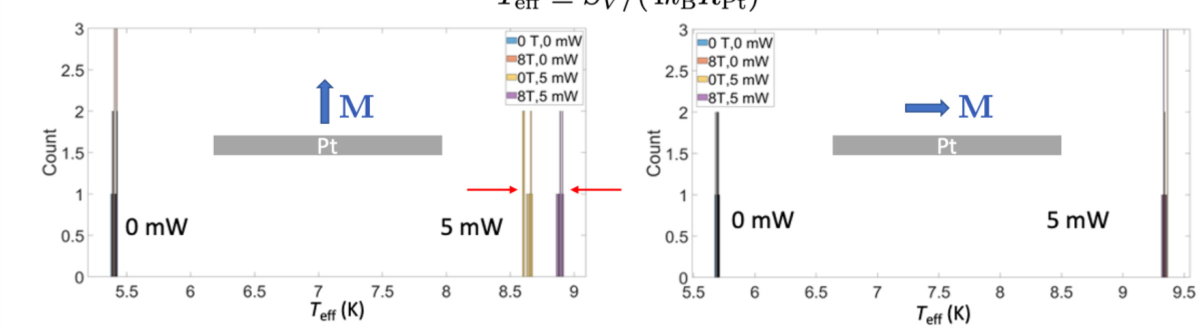
Electronic shot noise results from the arrival of discrete charge carriers and encodes information about their charge magnitude and statistics. In a driven angular momentum current carried by discrete magnons each transporting angular momentum $\hbar$, analogous spin shot noise is similarly expected. Several different theoretical predictions exist for this type of noise, but to date there are no experimental reports of its detection. In devices based on yttrium iron garnet (YIG) films on gadolinium gallium garnet (GGG) substrates, we use a temperature gradient to drive a magnon current via the spin Seebeck effect (SSE), which is detected via the inverse spin Hall effect (ISHE) in a Pt wire. The SSE signal at low temperatures clearly includes a contribution at high fields from the paramagnetic response of the GGG, showing that in this case the dominant SSE signal results from the temperature gradient across the GGG/YIG heterostructure, rather than the YIG/Pt interface. At the lowest temperatures examined (5 K), we find a contribution to the spin Seebeck voltage noise that is present when the magnetization is oriented transverse to the Pt ISH detector but absent when the magnetization is parallel to the Pt wire, as would be expected for spin shot noise. At higher temperatures (30 K), the variance in the noise is larger and no difference in noise with field orientation is discernable. We compare the magnitude of this noise to theoretical expectations for spin shot noise and find that the detected response is about 0.1% of the simplest assumption that the spin shot noise should be $2\hbar$ × the spin current. The detected response is also about 4% of an estimate from a model devised for a version of the SSE case. We discuss possible reasons for this discrepancy. Spin shot noise has the potential to reveal statistics and correlations in systems where angular momentum is carried by more exotic emergent excitations.

$$T_{\rm eff} \equiv S_V/(4k_{\rm B}R_{\rm Pt})$$



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Spin-orbit torques in antiferromagnet insulator/heavy metal heterostructures

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The effect of spin currents on the magnetic order of insulating antiferromagnets (AFMs) is of fundamental interest and can enable new applications. In this talk I will highlight our experimental studies of the effect of current pulses and spin-orbit torques on AFM order. We conducted two types of experiments: (1) Direct x-ray imaging of electrical switching of antiferromagnetic Néel order [1] and (2) Harmonic Hall effect measurements that make it possible to determine the form and magnitudes of the spin-torques that act on the Néel vector [2]. In both cases we have studied c-axis oriented α-Fe_2O_3 films, a predominantly easy-plane AFM, with an interface to Pt, where the Pt was patterned into the shape of a Hall cross. X-ray photoelectron emission microscopy shows that current pulses lead to reversible and repeatable switching with the current direction determining the final state. However, current pulses also produce irreversible changes in domain structure, in and even outside the current path, showing the thermal effects are important to the switching. We then used harmonic Hall signals to determine the amplitudes of field-like and damping-like spin orbit torques. Out-of-plane field scans were shown to be essential to determining the damping-like component of the torques. In contrast to ferromagnetic/heavy metal heterostructures, our results demonstrate that the field-like torques are significantly larger than the damping-like torques, which we correlate with the presence of a large imaginary component of the α-Fe_2O_3/Pt interface spin-mixing conductance. Our experiments highlight some of the significant differences between current-induced torques and switching of ferromagnetic and antiferromagnets.

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Frequency-dependent Spin Caloritronic Phenomena in a Metal-Magnetic Insulator Heterostructure

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Heavy metal (HM)/magnet bilayers host many magnetoresistance (MR) and spin caloritronic (SC) phenomena that have been observed in past electrical measurements of samples with different layer thickness and magnetic field directions. Here we report transport measurements that employ a high-frequency electrical current in a platinum (Pt) film on a ferrimagnetic yttrium iron garnet (YIG) layer to reduce the thermal penetration depth to the scales of fundamental magnon transport lengths. The observed frequency dependence of the longitudinal and transverse electrical signals at first and second harmonic frequencies are analyzed with a model that accounts for both interface and bulk spin Seebeck effects. The measurements and analysis show that the spin Peltier effect and electron-phonon scattering result in a much larger measured unidirectional MR of the Pt/YIG heterostructure than existing theories that neglect the interplay between MR and SC effects. In comparison, the anomalous Ettingshausen effect associated with proximity-induced ferromagnetism in the metal film cannot yield the observed frequency dependence. In conjunction with lock-in Brillouin light scattering measurements of the spin injection across the Pt/YIG interface, the frequency-dependent measurements provide insight into the elusive magnon transport properties.

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Transverse thermoelectric energy conversion utilizing spin Seebeck and anomalous Nernst effects

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A concept of transverse thermoelectric energy conversion has recently been emerging as an alternative to overcome the limitations of the conventional longitudinal counterpart.[1] In a transverse thermoelectric device, a charge current is generated in the direction perpendicular to the applied temperature gradient, which allows that the device performance scales with extrinsic dimensions. Transverse devices do not require the use of separate n and p-type materials, since the plane in which the output voltage arises is always isothermal. Thus, transverse thermoelectric devices can have significantly less complex structure and manufacturing than those of longitudinal devices. Among various spin calotritronic effects, the spin-Seebeck effect (SSE) and anomalous Nernst effect (ANE) have drawn particular interest due to their potential as a suitable transverse thermoelectric conversion mechanism. In the SSE, a temperature gradient on a spin-polarized material creates a spin current that is driven into an adjacent material (Pt). There, the injected spin current is converted into a transverse electric field by the inverse spin-Hall effect via spin-orbit interactions. On the other hand, the ANE utilizes various skew scattering mechanisms of spin polarized electrons, which lead to a transverse electric field perpendicular to both of the applied temperature gradient and magnetization directions. For those two effects to be successfully implemented in real applications, many material- and devie-level challenges need to be addressed. In this talk, our recent research efforts to develop highly-efficient SSE and ANE devices are introduced.

Acknowledgements

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Thermal spin current generation in multifunctional materials and interfaces

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The seach for ferromagnetic insulating materials with multifunctional properties is currently a highly sought after objective in spintronics. In current spintronics, functional devices are typically made of a bilayer composed of a material with large spin-orbit coupling (NM) and a ferromagnet (FM). These type of devices allow functionalities like the manipulation of the FM magnetization by the spin Hall effect (SHE)[1] in the NM or energy harvesting by means of its inverse counterpart the inverse spin Hall effect.[2] Insulating ferrimagnets are preferred for this purpose to pave the way towards low dissipation spintronics devices.[3] Additional functionalities like the possibility of the electric field control of the magnetic properties of such systems could be given to these heterostructures through the introduction of multifunctional ferromagnets opening the possibility of having more efficient and versatile devices.[4]

We have studied the thermo-spin current generation in bilayers composed of Pt and the multifunctional magnetoelectric $Ga_{0.6}Fe_{1.4}O_3$ (GFO).[5] We compare the performance of this new system with the widely used yttrium iron garnet obtaining a similar value of the spin Seebeck effect,[6] likewise to what was observed previously in spin Hall magnetoresistance.[7] In addition, by fabrication of thermo-spin devices with controlled dimensions we are able to accurately quantify the relevant parameters of the thermal effects.

In order to obtain more efficient devices based on thermo-spin phenomena, the role of interfaces and 2D materials can also be relevant. Here, we also explore the effect of a graphene monolayer between a Co and a NM layers and its interfacial spin transport properties by means of thermo-spin measurements. We show that a gr monolayer retains the spin current injected into the HM from the bottom Co layer. This has been observed by detecting a net reduction in the sum of the spin Seebeck and interfacial contributions due to the presence of gr and independent from the spin Hall angle sign of the HM used.[8]

These results pave the way for the use of the magnetoelectric multiferroic GFO with a view to control the spin current production of NM/FM heterostructures by an electric field and the use of graphene interfaces for tuning the spin conversion.

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Nernst effect in Magnetic topological Materials

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Topology, a mathematical concept, recently became a hot and truly transdisciplinary topic in condensed matter physics, solid state chemistry and materials science. All 200 000 inorganic materials were recently classified into trivial and topological materials, such as topological insulators, Dirac, Weyl and nodal-line semimetals, and topological metals [1]. More than 25% of all materials host topological bands around the Fermi energy. Beyond the single particle picture, we have identified first antiferromagnetic topological materials [2]. Experimentally, we have realized ferromagnetic materials, examples are Co_2MnGa and $Co_3Sn_2S_2$. Surprisingly all crossings in the band structure of ferromagnets are Weyl nodes or nodal lines [3]. Mn_3Sn and $YbMnBi_2$ are examples of non collinear antiferromagnetic Weyl semimetals. All these materials show giant values for the anomalous Hall and Nernst effect [4]. Our goal is to identify new quantum-materials for highly efficient spintronics, quantum computing and energy conversion.

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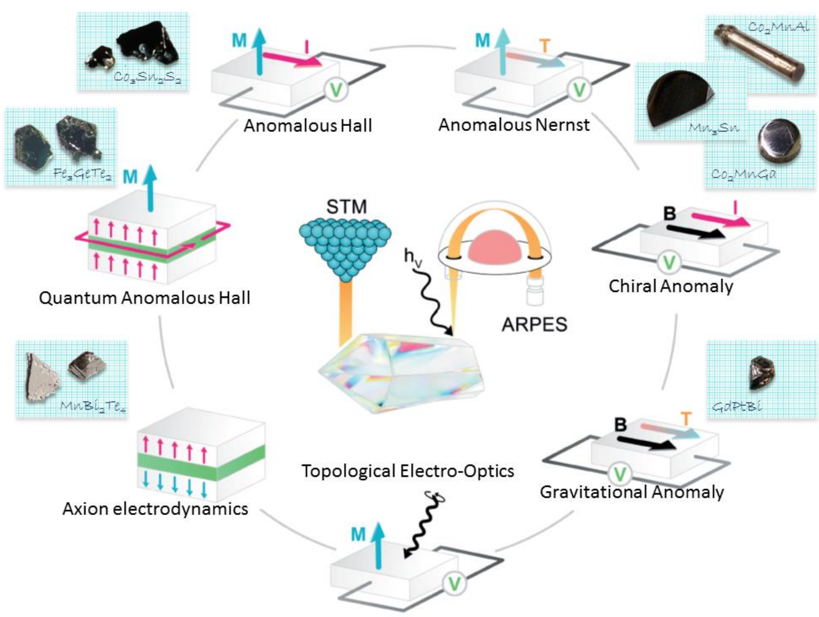

Field-dependent Nonelectronic Thermal Conductivity and Magnon Drag in a Metallic Ferromagnet with Low Gilbert Damping

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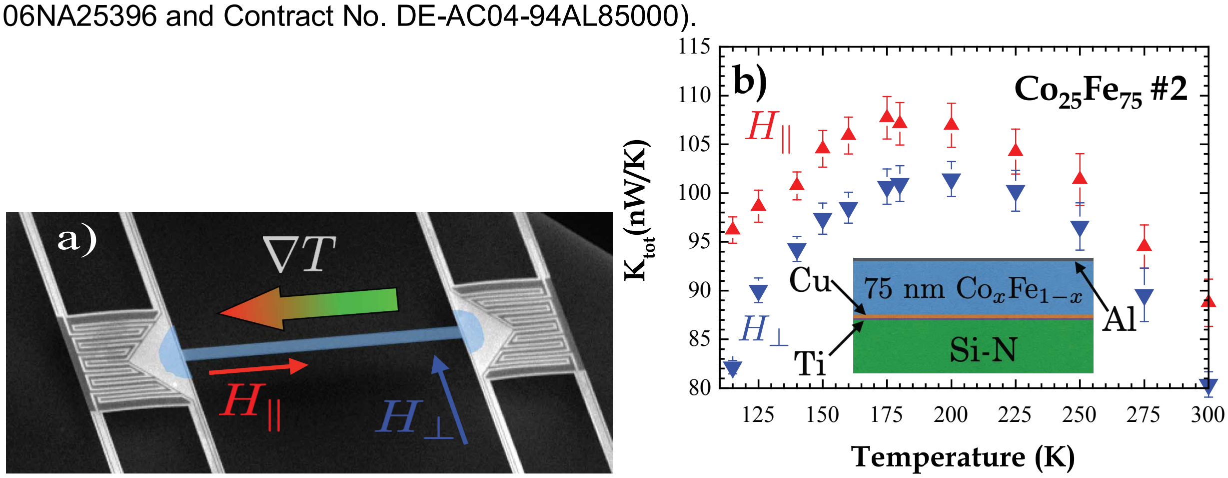
Heat conduction in metals is typically dominated by electron transport since electrons carry both charge and heat. In magnetic metals magnons, or spin waves, excitations of the magnetic order can be used to transport information. Heat conduction via magnons has been previously shown mostly for insulating magnets with low Gilbert damping and resulting long spin-wave lifetimes where conduction electrons cannot contribute. Here we show that thin films of properly optimized metallic ferromagnetic (FM) alloys show significant nonelectronic contributions to heat conduction, which furthermore depend on the direction of an applied magnetic field. These measurements are enabled by micromachined thermal isolation platforms (see panel a below) optimized for thermal conductivity measurements of thin-film systems. We furthermore show field-dependence of the thermopower, evidencing an unusual form of magnon drag in the same material, the cobalt-iron alloy with 25% Co. This composition has been shown to have exceptionally low damping for a metallic FM. The thermal conductivity of a 75-nm-thick film of the 25% Co alloy changes by more than 20% at some temperatures (panel b), while a reference sample with 50% cobalt that has much higher damping shows no field-direction dependence. Our measurements indicate that applied magnetic fields alter the magnon lifetimes in these films and that these magnons contribute to thermal conductivity in this metallic magnetic alloy with low Gilbert damping. If time allows, I will also discuss recent work demonstrating evaporated Cr films for spin-charge conversion.[3] We gratefully acknowledge support from the NSF (DMR-1709646, DMR-2004646). And use of fabrication facilities at the Center for Integrated Nanotechnologies, a DOE Office of Science User Facility (Contract No. 319 DE-AC52-06NA25396 and Contract No. DE-AC04-94AL85000).



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Nonequilibrium Heat Transport Probed by Ultrafast Magnetic Thermometry

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The interaction between electrons and phonons is responsible for a variety of physical properties of solids, such as electrical conductivity, superconductivity, polaron conduction, and piezoelectricity. In particular, in metals, electrons and phonons exchange energy at picosecond timescales when they are not in thermal equilibrium. This energy transfer serves as an important driver for the ultrafast switching of magnetic memory. However, the experimental investigation of nonequilibrium dynamics in materials remains challenging and limits our fundamental understanding and applications for fast and energy-efficient devices. In this work, we demonstrate that a magnetic thermometer, which is a sub-nm-thick Co layer, can effectively examine the nonequilibrium heat transport as well as local-equilibrium heat transport in adjacent layers. The magnetization of Co informs the magnon temperature specific to the position of the ultrathin Co layer, and can be conveniently detected via the magneto-optic Kerr effect. Using this thermometry, we investigate the nonequilibrium dynamics in transition metals, Pt or Ru, by using Co embedded in thicker Pt or Ru layers.[1] In addition, we were able to determine the effective thermal conductance of the 2-nm-thick oxide tunnel barrier, MgO or $MgAl_2O_4$, in magnetic tunnel junctions.[2] The accurate value of the thermal conductance of the oxide barrier is important for quantitative evaluation of the tunnel magneto-Seebeck effect. Finally, we discuss the limitations and on-going work of ultrafast thermometry by taking the all-optical switching of ferromagnets[3] as an example.

For this work, I acknowledge my colleagues in Prof. David Cahill's group at UIUC and Prof. Jeffrey Bokor's group at UC Berkeley, USA.

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Giant magnon spin conductivity approaching the two dimensional transport regime in ultrathin yttrium iron garnet films

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Conductivities are key material parameters that govern various types of transport (electronic charge, spin, heat etc.) driven by thermodynamic forces. Magnons, the elementary excitations of the magnetic order, flow under the gradient of a magnon chemical potential[1,2] in proportion to a magnon (spin) conductivity σ_m. The magnetic insulator yttrium iron garnet (YIG) is the material of choice for efficient magnon spin transport. In this talk I discuss the observation of an unexpected giant σ_m in record-thin YIG films with thicknesses down to 3.7 nm when the number of occupied two-dimensional (2D) subbands (corresponding to discrete transverse magnon modes) is reduced from a large number to a few, which corresponds to a transition from 3D to (approaching) 2D magnon transport[3]. We extract a 2D spin conductivity (~ 1 S) at room temperature, only comparable to the (electronic) spin conductivity of the high-mobility two-dimensional electron gas in GaAs quantum wells at millikelvin temperatures. I will discuss the relevant theoretical developments[4] , and conclude with a future outlook including the potential that such high magnon spin conductivities may offer unique opportunities to develop low-dissipation magnon-based spintronic devices.

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Observation of the magnon Hanle effect in antiferromagnetic insulators

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The spin-1/2 of an electron makes it an archetypal two-level system and inspires the description of other two-level systems using an analogous pseudospin. The quantized spin excitations of an ordered antiferromagnet represent pairs of spin-up and -down magnons and thus can be characterized by a magnonic pseudospin. The similarity between electronic spin and magnonic pseudospin has triggered the prediction of exciting phenomena like emergent spin-orbit coupling and topological states in antiferromagnetic magnonics. In the last years, first experimental observations of the associated dynamics of antiferromagnetic pseudospin have been reported [1,2,3]. Based on these findings, we will expand the concept of magnon pseudospin and the description of magnon pseudospin dynamics [4,5] and discuss the influence of dimensionality on the magnon Hanle effect. Additionally, we show our recent experiments demonstrating control of magnon spin transport and pseudospin dynamics in thin films with varying thickness of the antiferromagnetic insulator hematite (α-Fe_2O_3) utilizing two Pt strips for all-electrical magnon injection and detection [3] . We observe an oscillation in polarity of the magnon spin signal at the detector as a function of the applied magnetic field, which we quantitatively explain in terms of diffusive magnon transport. In particular, we observe a coherent precession of the magnon pseudospin caused by the easy-plane anisotropy and the Dzyaloshinskii-Moriya interaction. Moreover, we find peculiar changes in the magnon spin signal for thicker hematite layers indicating contributions from low energy magnons with finite spin. Our results are paramount in unnlocking the high potential of antiferromagnetic magnonics towards the realization of electronics-inspired phenomena.

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Spin transport using antiferromagnetic magnons and superconducting vortices

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Both collinear antiferromagnets and spin-singlet superconductors do not possess spontaneous magnetization under zero magnetic field. Nevertheless, they exhibit intriguing spin transport characteristics of their own [1,2]. In this talk, we discuss the following two topics:

(i) Antiferromagnetic spin Seebeck effect (AF SSE) across the spin-flop transition [3]
(ii) Vortex spin Hall effect [4]

The first topic is motivated by a recent experiment reporting the sign change of the AF SSE across the spin-flop transition in Cr_2O_3 [1]. Because such a sign change was NOT observed previously either in Cr_2O_3 [5] or MnF_2 [6], clarification of whether or not the sign change is a generic property of a simple uniaxial antiferromagnet is an important issue. We investigate the AF SSE in a numerical simulation based on the time-dependent Ginzburg-Landau equation. We find that a special interfacial exchange coupling between the Neel vector of AF insulator and itinerant spin density of heavy metal, having the same symmetry as the exchange coupling used to describe the exchange bias effect, is the key parameter for the sign change [3].

The second topic is motivated by a SSE experiment using YIG/NbN [2]. There, a pronounced peak in the SSE signal was observed at the superconducting transition of NbN, and the result was interpreted in terms of the coherence peak effect predicted for the spin pumping into superconductors [7]. However, the interpretation in terms of the coherence peak effect was subsequently questioned [8] since the coherence peak effect emerges only from an extremely low energy magnons (<< superconducting gap), whereas the SSE involves magnons with energies comparable to *Tc* (~ superconducting gap). We show that the experimental result can be explained by the scenario of the vortex spin Hall effect, a novel spin Hall effect driven by the motion of superconducting vortices [4].

This work was supported by JSPS KAKENHI Grant No. 19K05253, and by the Asahi Glass Foundation.

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Resonant Inelastic X-ray Scattering to probe collective spin dynamics in magnonic materials

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The past years have witnessed an increasing interest in the field of quantum materials (QM), not only thanks to their fascinating behaviour as a macroscopic manifestation of quantum mechanics, but also for the opportunities that these materials offer in terms of 'emergence' of functional properties, making QMs appealing for the next types of electronics.

Among them, magnonics - dealing with transport phenomena conveyed by magnons and other collective spin excitations - is particularly relevant when low-power and energy-efficient applications are concerned.

In this talk, I will focus on a novel approach to investigate magnonic materials and devices using soft Resonant Inelastic X-ray Scattering (RIXS). I will present recent results achieved on i) ferromagnetic thin films of Fe metal, addressing the evolution of the spin dynamics as a function of thickness [1]; ii) Yttrium Iron Garnet under Spin Seebeck effect, visualizing the magnon modes contributing to the magnon current with energy- and momentum-resolution [2].

This work was supported by the U.S. Department of Energy (DOE), Office of Science, Basic Energy Sciences, Early Career Award Program.

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Relationship between composition and heating induced energy and spin dynamics in magnetic materials

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Spin caloritronic phenomena describe how energy gradients leads to spin-currents. These phenomena result from flows of energy between different thermal excitations that can store heat, e.g. electrons, magnons, and phonons. In this talk, I describe how energy transfer coefficients between electrons, phonons, and magnons depend on material composition. We characterize the ultrafast energy and magnetization dynamics of ferromagnetic metals and rare-earth iron garnets. We use a combination of wavelength dependent time-resolved magneto optic Kerr effect, and time-domain thermoreflectance experiments to characterize the rate of energy and spin-transfer between electrons, magnons, and phonons in these material systems. We find energy and spin transfer rates vary by a factor of 4 depending on material composition. Our investigation sheds light on how elemental composition and quasi-particle scattering rates govern energy and spin dynamics on femtosecond (ultrafast dynamics), nanosecond (magnetic precession and damping), and steady-state time-scales (thermal transport of energy).

Ultrafast spintronics on attosecond time scales

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Magnetization manipulation is an indispensable tool for both basic and applied research. I will discuss an actual overview on ultrafast magnetism and THz spintronics [1].

The dynamics of the spin response depends on the energy transfer from the laser excited electrons to the spins within the first femtoseconds [1]. Due to the non-equilibrium electron distribution in layered nanoscale spintronic devices, ultrafast spin currents are generated and contribute to the laser driven spin dynamics. Ultrafast laser-driven spin currents can be converted via the spin-Hall effect into a charge current burst [2] that can even compete with state-of-art THz emitters [3]. They allow to map topological spin structures, and their THz dynamics, with potentially with sub micron resolution as we recently demonstrated [4]. We have also recently shown that attosecond lasers are breaking new frontiers and records towards the observation of coherent spin processes on ever shorter time scales, reaching Petaherz light frequency spintronics. Using light wave coherent charge transfer, driven by a few cycle laser pulse, I will report the first coherent attosecond magnetism in layered spintronic devices [5]. These experiments, the fastest spin-dynamics observed experimentally, fit perfectly to the time scales for time resolved DFT, from theoretical sides revealing a coherent electron transfer at interfaces *in operado*. This opens up applications of coherent spin current processes. We acknowledge funding by PetaSpin, Horizon 2020 FET Open and META-ZIK Plasmark-T, BMBF Unternehmen Region.

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Magneto-thermal Microscopy and Single-spin Microscopy of Complex Magnetic Materials

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A key challenge for understanding the advanced functionality of magnetic materials with complex spin order is to establish lab-accessible probes that couple to magnetic degrees of freedom on the appropriate spatial and temporal scales. Magneto-thermal interactions are ubiquitous in materials and heterostructures with spin-orbit coupling or Berry curvature, which enables the application of magneto-thermal interactions as a probe to study a broad group of materials that can be difficult to study with other table-top techniques. This presentation will focus on time-resolved magneto-thermal microscopy, which we have applied to spatiotemporal imaging of spin order in a wide range of materials including ferromagnetic metals,[1] ferromagnetic insulators,[2] antiferromagnetic metals[3,4] and antiferromagnetic insulators.[5] The principle of operation relies on the coupling between spin, charge, and heat, such as through the anomalous Nernst effect or the spin Seebeck effect. Because temperature gradients that are tightly confined in both space and time using micro-focused laser pulses, these effects form the natural basis for a microscopy. We have recently established a scanning near-field magneto-thermal microscope that achieves 100-nm-scale spatial resolution while retaining the ~10 ps temporal resolution,[6] making this microscope an interesting table-top alternative to facility-based X-ray microscopy. Finally, I will mention a complimentary effort in which we scan the quantum spin of a single diamond nitrogen-vacancy center to probe complex materials to understand the interplay of charge, heat, and spin in an antiferromagnetic material.

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Magneto-Seebeck microscopy of spin-orbit torque driven domain wall motion in a collinear antiferromagnet

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We introduce a novel microscopy for antiferromagnetic nanostructures based on the local generation and detection of photo-currents. We apply this method to the collinear and fully compensated antiferromagnet CuMnAs where the photocurrents result from the local variation of the magneto-Seebeck effect (MSE). Using a scattering near-field microscope, we display narrow 180-degree domain walls (DWs) and provide experimental evidence for reversible spin-orbit torque-driven domain wall motion of 180-degree domain walls. MSE-based microscopy can be applied in principle to the large class of conductive antiferromagnets. Unlike the established X-ray linear dichroism microscopy based on large-area synchrotrons, photocurrent-based microscopy can be easily performed with ordinary laboratory equipment.

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Harnessing Nitrogen Vacancy Centers in Diamond for Next-Generation Quantum Science and Technology

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Advanced quantum systems are integral to scientific research and modern technology enabling a wide range of emerging applications. Nitrogen vacancy (NV) centers, optically active atomic defects in diamond, are naturally relevant in this context due to their unprecedented spatial and field sensitivity, single-spin addressability, and remarkable functionality over a broad temperature range. Many of these advantages derive from the quantum-mechanical nature of NV centers that are endowed by excellent quantum coherence, controllable entanglement, and high fidelity of operations. In this talk, I will present our recent work on developing state-of-the-art NV-based quantum sensing and imaging techniques and demonstrate their direct applications to address the current challenges in both condensed matter physics and quantum sciences and technologies. Specifically, we have utilized NV centers to probe the exotic charge and spin properties of emergent quantum materials including topological superconductors [1], magnetic topological materials [2], and antiferromagnetic insulators [3]. We also integrate NV centers with functional magnetic devices to develop hybrid quantum systems [4], promoting the role of NV center at the forefront of quantum technologies. Lastly, I will briefly discuss our ongoing efforts to explore quantum sensing using emergent color centers in two-dimensional materials beyond NVs [5], which is promising to realize atomic-scale detection sensitivity.

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Interfacial exchange field in heavy metal/magnetic insulators

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Spin-dependent scattering transport at heavy metal (HM)/magnetic insulator (MI) interfaces can be described in terms of three parameters: the so-called spin-sink conductance G_s and the real and imaginary part of the spin-mixing conductance, $G_{\uparrow\downarrow} = G_r + iG_i$ [1,2]. Each parameter is relevant for different spin-dependent phenomena. For instance, G_s originates from spin-flip processes and therefore is the leading parameter in electrical and thermal excitation of magnons [3], whereas G_r represents a spin-transfer torque to the magnetization and plays a fundamental role in spin-pumping experiments [4]. On the other hand, G_i quantifies the interfacial exchange field, which induces a field-like torque in the conduction electrons of the HM. The quantification of G_i is important for example in spin-splitting field experiments in superconductivity [5]. These conductances are broadly studied in ferrimagnetic insulators, where usually the contribution of G_r is much larger than that of G_i [6], leading to only few reports on the exchange field at HM/MI interfaces [7, 8].

In this talk, I will show the three spin conductance terms obtained by spin Hall magnetoresistance (SMR) in two new systems: a paramagnetic insulator (PMI) such as $Gd_3Ga_5O_{12}$ (GGG) [9] and a ferromagnetic insulator (FMI) such as EuS [10]. By SMR measurements as a function of magnetic field in the case of the PMI and as a function of temperature in the case of the FMI, and taking advantage of the newly developed microscopic theory for SMR [2], we can extract relevant microscopic parameters. One prominent example is the exchange interaction between the 1*s* electrons in Pt and the 4*f* electrons of Gd in the GGG (J_{sf} ~ –2 meV) or Eu in EuS (J_{sf} ~ –3.5 meV), indicating the *s−f* exchange coupling is antiferromagnetic and of the same order in both systems. Our results demonstrate that, in HM/PMI interfaces at large magnetic field, the field-like torque contribution (G_i) is as important as the spin-transfer torque contribution (G_r) [9]. Furthermore, for the HM/FMI case, we demonstrate for the first time experimentally a G_i which is larger than G_r [10]. Unlike in ferrimagnets, where the local magnetic moments at the interfaces are partially compensated, all local moments contribute equally to the interfacial exchange field in these two studied examples, giving rise to such a large G_i.

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Temperature dependence of exchange stiffness

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Macroscopic properties such as magnetic anisotropy (K) and exchange stiffness (A) are temperature dependent due to thermal spin fluctuations. Understanding and calculating their temperature dependence is important to create realistic micromagnetic models, to interpret experiments and to make theoretical predictions. For example, it has recently become important to quantify the strength of the Dzyaloshinskii–Moriya interaction interaction in thin films and the most straight forward methods for doing this rely on knowing A(T) and K(T) [1]. The temperature dependence of exchange stiffness has been previously calculated giving power laws of $A(T)/A(0) = m^{1.8}$ [2]. However, this does not appear compatible with the fundamental spin wave theory which predicts that *spin wave* stiffness in a ferromagnet scales as $T^{5/2}$ [3] with no general power law in *m*.

Using our recently developed quantum thermostat for spin dynamics we can now make quantitative calculations [4] and recover the agreement with the $T^{5/2}$ result from spin wave theory. However, the link between *spin wave* stiffness and the *exchange* stiffness at finite temperatures appears to also be confused in the literature, with two different, incompatible expressions. We have clarified the situation and found that the change in stiffness of the thermal spin waves must be augmented with the change in energy cost for putting twists into the magnetization (e.g. domain walls, skyrmions) at finite temperatures to fully describe the temperature dependence of exchange stiffness. We prove the correctness of this by calculating the temperature dependence of a Bloch domain wall and show that it follows our calculated scaling functions. We find the exchange stiffness to have a considerably lower temperature dependence than previous calculations suggest.

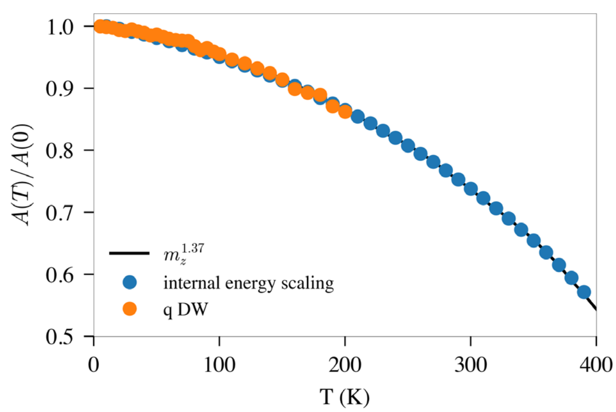

Figure 1: Temperature dependence of exchange stiffness inferred from the temperature dependence of the Bloch domain wall width (orange) compared to calculations based on the internal energy (blue).

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Origins of transverse voltages generated by thermal gradients and electric fields in ferrimagnetic-insulator/heavy-metal bilayers

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We compare thermal-gradient-driven transverse voltages in ferrimagnetic-insulator/heavy-metal bilayers ($Tm_3Fe_5O_{12}$/W and $Tm_3Fe_5O_{12}$/Pt) to corresponding electrically driven transverse resistances at and above room temperature. We find for $Tm_3Fe_5O_{12}$/W that the thermal and electrical effects can be explained by a common spin-current detection mechanism, the physics underlying spin Hall magnetoresistance (SMR). However, for $Tm_3Fe_5O_{12}$/Pt the ratio of the electrically driven transverse voltages (planar Hall signal/anomalous Hall signal) is much larger than the ratio of corresponding thermal-gradient signals, a result which is very different from expectations for an SMR-based mechanism alone. We ascribe this difference to a proximity-induced magnetic layer at the $Tm_3Fe_5O_{12}$/Pt interface.

The paper related to this work can be found in Ref 1.

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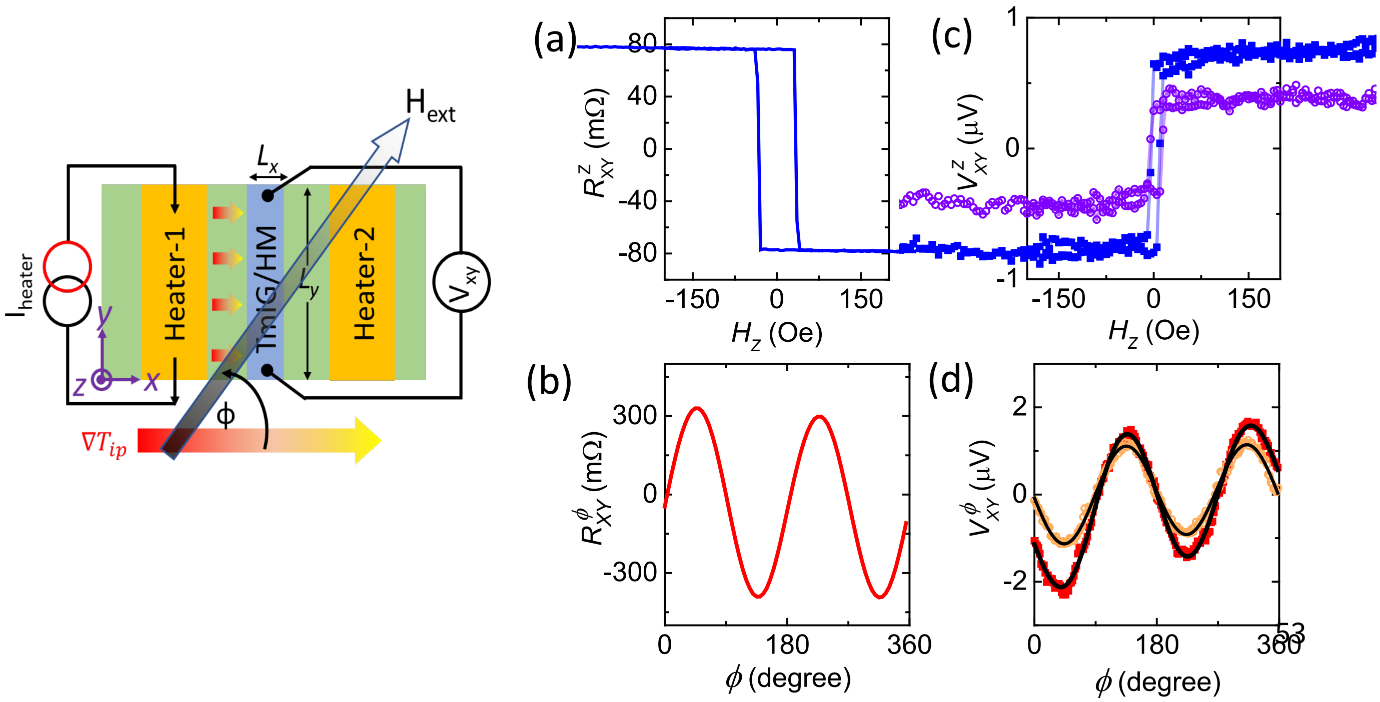
Figure 1: (Left) Schematic of the experimental setup for measurement of transverse voltages generated by a ∇T. (Right) Results for TmIG/W. Hall resistance of TmIG/W for (a) out-of-plane magnetic-field sweep and (b) in-plane field rotation for a field magnitude of 2.7 kOe. Thermally induced transverse voltages, (c) V^z_{xy} and (d) V^ϕ_{xy}, for a heater power of 630 mW and for two different heater spacings, d = 15µm (closed squares) and 50 µm (open circles).



Angstrom-Scale Mapping of the Local Magnetic Moment in Metallic Antiferromagnet Fe_2As using 4D-STEM

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Antiferromagnets are a promising platform for high density spintronic devices. Because of this, the ability to probe and visualize magnetism at atomic length scales is extremely important in the investigation of antiferromagnets. However, antiferromagnets have been a difficult class of materials to study because their magnetic moments align antiparallel, leading to a net-zero magnetization. In our work, we apply 4-dimensional scanning transmission electron microscopy (4D-STEM) with a fast, high dynamic range pixelated detector to investigate the magnetic structure of Fe_2As, a metallic antiferromagnet [1]. Using a combination of quantum mechanical electron scattering simulations [2] and experimental data, we show how the weak scattering signals from magnetism can be isolated in convergent beam electron diffraction patterns. We apply our findings to measure the direction and magnitude of the local magnetization and obtain up to 6 Å resolution in Fe_2As. Our results indicate new applications for 4D-STEM to study the magnetic structure of antiferromagnets.

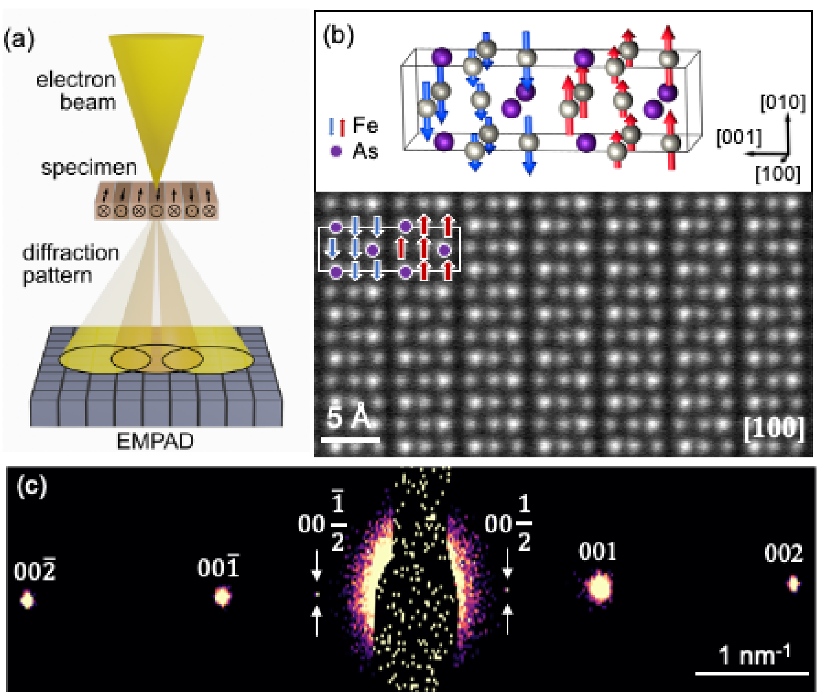

Fig 1. Experimental Set-up for Imaging Antiferromagnets: (a) 4D-STEM schematic showing diffraction from an antiferromagnet with an Angstrom size probe. (b) Atomic resolution ADF-STEM, red and blue arrows indicate the spins associated with their respective Fe atoms, the magnetization is divided into three-atom blocks. (c) TEM diffraction pattern where the signature from antiferromagnetic blocks are observed at the [0 0 1/2]. (d) Line profile of (c) to show the relative intensity of each peak.

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Interplay of spin-torque and nonlinearity:
Disentangling and controlling magnon processes in nanomagnets

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Nanoscale magnets are the building blocks of various spintronics technologies. However, many aspects of spin dynamics in the nanoscale geometrical confinement have remained elusive. For instance, untangling damping contributions and engineering spin-torque response in nanomagnets is often a challenging task.

Using magnetic tunnel junctions as a sample platform, we investigate the discrete magnon spectrum of individual zero-dimensional magnets and identify the inherent inter-magnon processes. While manipulation of magnetization by spin-torque is a key functionality of today's spintronics, we find that resonant magnon processes redefine and invert a nanomagnets response to spin-torque [1]. We discuss the mechanisms of this counter-intuitive interplay of nonlinearity and spin-torque, which has far-reaching implications for the performance of magnetic memory and oscillators.

Controlling magnon processes and thus forging the nonlinearity of a nanomagnet would add decisive functionality to existing and emerging technologies, in particular to magnetic neuromorphic systems where tunability of the nonlinear response is instrumental. We develop an approach for engineering magnon interaction by means of symmetry-breaking fields with nanoscale nonuniformity [2]. In a proof-of-concept, we employ a nanoscale synthetic antiferromagnet as a switchable source of such fields and achieve tunability of magnon coupling by at least one order of magnitude. The results open up avenues for controlling magnon processes by external stimuli at nanoscale and show prospects for spin-torque applications and quantum information technologies.

This work was supported by the National Science Foundation through Grant No. ECCS-1810541.

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Symmetry-dependent field-free switching of perpendicular magnetization

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Modern magnetic-memory technology requires all-electric control of perpendicular magnetization with low energy consumption. While spin-orbit torque (SOT) in heavy metal/ferromagnet (HM/FM) heterostructures holds promise for applications in magnetic random access memory, till today, it is limited to the in-plane direction. Such in-plane torque can switch perpendicular magnetization only deterministically with the help of additional symmetry breaking, e.g., through the application of an external magnetic field, an interlayer coupling or an asymmetric design. Instead, an out-of-plane spin-orbit torque could directly switch perpendicular magnetization. In current presentation, we report that we observe an out-of-plane spin-orbit torque in an HM/FM bilayer of $L1_1$-ordered CuPt/CoPt and demonstrate field-free switching of the perpendicular magnetization of the CoPt layer.[1] The low symmetry point group (3m1) at the CuPt/CoPt interface gives rise to this spin torque, herein after referred as 3m torque, which strongly depends on the relative orientation of current flow and crystal symmetry. We observe a 3-fold angular dependence in both the field-free switching and the current-induced out-of-plane effective field. Because of the intrinsic nature of the 3m torque, the field-free switching in CuPt/CoPt shows good endurance in cycling experiments. Experiments with the wide variety of SOT bilayers with low-symmetry point groups at the interface may uncover further unconventional spin-torques in future.

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Unconventional Spin-Orbit Torques in Ferromagnetic Trilayers

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We demonstrate using ab-initio and semiclassical transport calculations that unconventional spin-orbit torques arise through bulk and interfacial mechanisms in ferromagnetic trilayers. The unconventional nature of these spin-orbit torques derives both from novel spin current generation in single ferromagnetic layers and nonlocal interactions between the ferromagnetic layers. Finally, we discuss the thermal analogue of these unconventional spin-orbit torques driven by temperature gradients in ferromagnetic trilayers.

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Future directions in spin caloritronics

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In spin caloritronics, novel phenomena, principles, and functionalities based on the interplay between spin, charge, and heat currents have been discovered and investigated. This field is still in development, and there are remaining challenges with regard to fundamental physics and materials science. In this talk, we discuss the prospect of spin caloritronics based on recent research activities.

Fundamental physics viewpoint: The expansion of the physics of spin caloritronics to nonlinear regime and to other fields/materials is important. Although conventional spin caloritronics focuses on linear-response transport phenomena, investigations on nonlinear spin caloritronics have been recently initiated [1,2]. As the first step in nonlinear spin caloritronics, the direct observation of the magneto-Thomson effect was reported [1], where a strong magnetic field dependence of the Thomson coefficient appeared in a BiSb alloy. In the nonlinear regime, several spin-caloritronic phenomena, such as electron-driven spin-dependent Thomson and magnon-driven spin Thomson effects, still remain to be observed. Exploring these phenomena will further invigorate the fundamental studies on spin caloritronics. Moreover, one of the new research directions is polarization caloritronics using ferroelectrics [3,4]; Tang and Bauer et al. theoretically predicted unconventional thermoelectric effects based on the dielectric polarization transport. The experimental verification of such phenomena requires the interdisciplinary fusion of spin caloritronics, ferroelectrics, and nanoscale science.

Materials science viewpoint: To realize the application of spin caloritronics, it is essential to develop materials with high spin–charge–heat interconversion properties. The recent fusion of spin caloritronics and topological materials science is a part of this effort. In addition to monolithic materials, hybrid or composite materials can be used to enhance the thermo-spin and magneto-thermoelectric conversion performances. For example, the hybrid thermoelectric generation based on the spin Seebeck and anomalous Nernst effects is enabled in ferromagnetic metal/ ferrimagnetic insulator junction systems and ferromagnetic/nonmagnetic bulk nanocomposites. Recently, Zhou et al. proposed and demonstrated giant transverse thermoelectric generation appearing in thermoelectric semiconductor/magnetic metal hybrid materials [5]. As this effect originates from the artificial hybridization of the Seebeck effect in the thermoelectric semiconductor and anomalous Hall effect in the magnetic metal, it is called the Seebeck-driven transverse thermoelectric generation. These experiments confirmed the usefulness of hybrid or composite materials, which may be a breakthrough approach for the next-generation spin caloritronics.

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Superfluid Spin Transistor

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An ability to control spin currents is important for probing many spin related phenomena in the field of spintronics and for designing logic and memory devices with low dissipation. Spin-orbit torque is an important example in which spin current flows across magnetic interface and helps to control magnetization dynamics. In this talk I will discuss the spin superfluid transport associated with collective modes in magnetic insulators. We observe that in two dimensional systems at finite temperatures spin superfluidity is affected by the presence of topological defects. We further propose to use the Hall response of topological defects, such as merons and antimerons, to spin currents in 2D magnetic insulator with in-plane anisotropy for identification of the Berezinskii-Kosterlitz-Thouless (BKT) transition in a transistor-like geometry. Our numerical results relying on a combination of Monte Carlo and spin dynamics simulations show transition from spin superfluidity to conventional spin transport, accompanied by the universal jump of the spin stiffness and exponential growth of the transverse vorticity current. We propose a superfluid spin transistor in which the spin and vorticity currents are modulated by tuning the in-plane magnet across BKT transition, e.g., by changing the exchange interaction, magnetic anisotropy, or temperature [1-2].

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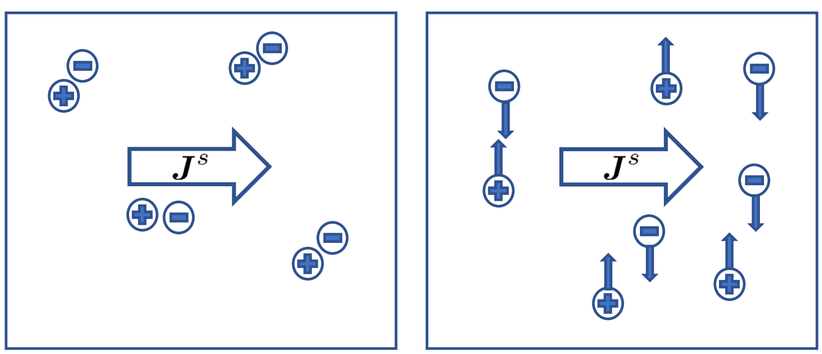

$T < T_{BKT}$ $T > T_{BKT}$

Polarization caloritronics: electric field dependence of the thermal conductivity and diffusivity of lead zirconium titanate

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Ferromagnetism and ferroelectricity, the spontaneous ordering of magnetic moments and of electric dipoles in solids, share many similar characteristics. In contrast, while the nature of the thermal fluctuations of the magnetic moments (i.e. magnons) in ferromagnets is well studied, those of the electric dipoles in ferroelectrics is not often discussed. A recent theoretical paper[1] poses that the ferroelectric magnon-equivalent, labeled ferrons, can transport a polarization flux j_P like magnons transport a magnetization flux j_M. The ferron can be seen as a subset of phonons that involve the motion of the atoms that carry the Born effective charge responsible for the polarization of the ferroelectric. In a real solid, this involves not only the optical phonons, but also the acoustic ones that carry most of the heat. Conversely, therefore, the heat flux transported j_Q must be a function of the applied electric field E. Here, the thermal conductivity $\kappa(E,T)$ of bulk ferroelectric lead zirconium titanate (PZT) is reported as a function of E and temperature T (see figure). We also report the diffusivity $D(E,T)$, which, to the first order, is a measure of the product of the phonon velocity and mean free path, as well as polarization measurements and lock-in thermoreflectance (LIT) results. A generalized polarization caloritronics theory will be presented that explains the sensitivity $d\kappa(E,T)/dE$ and $dD(E,T)/dE$ quite well. In essence, the applied electric field stiffens the acoustic phonon modes, decreasing the density of states and density of phonons at a given temperature.

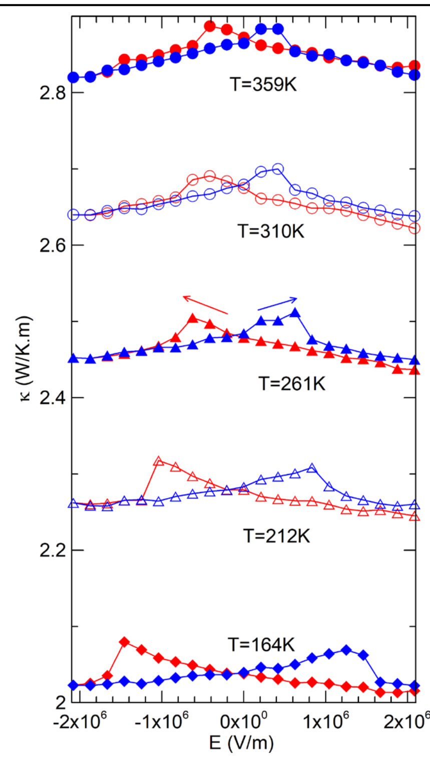

Figure. Thermal conductivity of a PZT stack as a function of applied electric field E for different temperatures. The arrows indicate the direction the electric field was swept in. The curves follow the polarization curves of the material.

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Computation with Magnetic Domain Walls and Oscillators

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In order to go beyond the traditional CMOS logic technology, novel spin-based logic architectures are being developed to provide nonvolatile data retention, near-zero leakage, and scalability. Architectures based on magnetic domain walls take the advantage of the fast motion, high density, non-volatility and flexible design of domain walls to process and store information in three dimensions. Here we demonstrate a method for performing all-electric logic operations and their cascading using domain wall racetracks [1].

Our concept is based on the recently developed chiral coupling mechanism between adjacent magnets where the magnetic anisotropy competes with the interfacial Dzyaloshinskii–Moriya interaction (DMI) in Pt/Co/AlOx trilayers [2-5]. When a narrow in-plane (IP) magnetized region is incorporated into an out-of-plane (OOP) magnetized track, it couples to its surrounding, leading to the antiferromagnetic alignment of the OOP magnetization on the left and right of the IP region. The chiral OOP-IP-OOP structure then serves as a domain wall inverter, the essential building block for all implementations of Boolean logic. Based on this principle, we realized reconfigurable NAND and NOR logic gates, making our concept for current-driven DW logic functionally complete. We also cascaded several NAND gates to build XOR and full adder gates, demonstrating electrical control of magnetic data and device interconnection in logic circuits. The functionality of logic circuits can be also expanded by the realization of a domain wall diode based on a geometrically tailored inverter [6].

We also broadened the application of chiral coupling towards dynamic computation [7]. By introducing inhomogeneous anisotropy in our system, spintronic oscillators with a chiral polar vortex ground state can be established. We investigated the mutual synchronization of such oscillators and demonstrated their potential for neuromorphic computing.

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Unveiling new phenomena in dissipative magnetic systems

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While magnetic systems have been extensively studied both from a fundamental physics perspective and as building blocks for a variety of applications, their topological properties, however, remain relatively unexplored due to their inherently dissipative nature.
I will start this talk by discussing how the recent introduction of non-Hermitian topological classifications has opened up opportunities for engineering topological phases in magnetic systems, and I will present our first proposal of a non-Hermitian topological magnonic system, i.e., a realization of a SSH non-Hermitian model via a one-dimensional spin-torque oscillator array [1,2].
Further, I will show how magnetic exceptional points can unveil large-amplitude auto-oscillatory regimes in nano-oscillators [3]. Finally, I will discuss the conditions under which magnetic insulating systems can host one of the most striking non-Hermitian phenomena with no Hermitian counterpart, i.e., the skin effect, which underlies the breakdown of the bulk-edge correspondence [4].
This work was partially supported by the National Science Foundation under Grant No. NSF DMR-2144086.

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POSTER ABSTRACTS

In numerical order

Temperature dependent spin-current generation in FeRh films as measured with THz emission spectroscopy

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THz emission from heterostructures of ferromagnetic (FM) and noble metal (NM) layers is attributed to spin-charge current conversion at the FM/NM interface, yet similar effects in bare magnetic thin films are not fully understood. Here we perform THz emission spectroscopy on thin films of FeRh, which is well known to undergo an antiferromagnetic to ferromagnetic phase transition around room temperature. The emitted THz field is observed to have a strong temperature dependence and a power-law dependence on the incident pump pulse fluence. Combined with the knowledge of the spin Hall angle, we extract a temperature dependent spin current across the metamagnetic transition.

*This work is supported by the Illinois Materials Research Science and Engineering Centers (MRSEC) award number DMR-1720633 and through the Illinois Materials Research Lab (MRL) facilities. Film growth is supported DOE, Office of Science, Materials Science and Engineering Division.

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Bulk Single Crystal Growth and Transport Properties of Metallic Antiferromagnet, Mn_2Au

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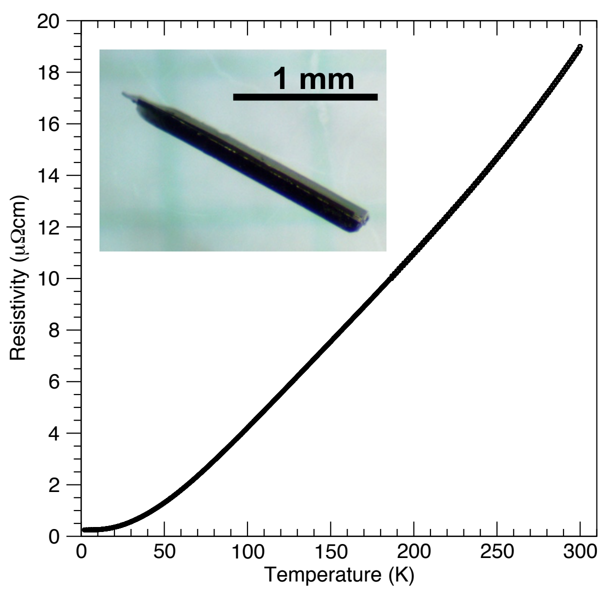
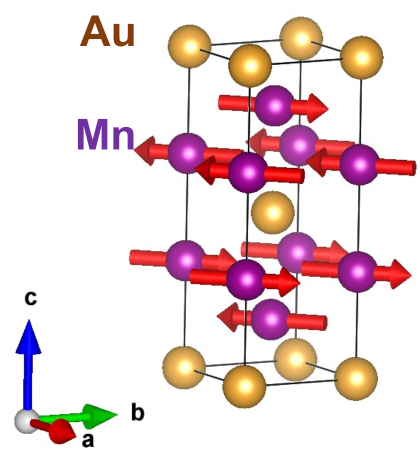
Mn_2Au is a metallic collinear antiferromagnet with a high projected Néel temperature of >1300 K [1]. Spin-orbit coupling induced anisotropy makes Mn_2Au promising for high temperature spintronics applications. While several thin-film studies demonstrate this, a bulk single crystal of this material, which would allow strain-free directional probe of transport and magnetic properties, has never been grown [2], [3]. The challenge in growing bulk single crystals arises from the decomposition of Mn_2Au into Mn and MnAu at 953 K, rather than melting congruently. In this work, we were able to grow up to 0.2 x 0.2 x 1.5 mm^3 bulk single crystals of Mn_2Au in bismuth flux. Powder XRD along with SEM-EDS is used to show that pure Mn_2Au can be isolated from flux. Our resistivity measurements confirm the metallic nature of Mn_2Au with a room temperature resistivity of ~ 20 μΩcm and a large residual resistivity ratio of ~74. Laue diffraction and electron backscatter diffraction are used to assess crystal orientation for upcoming studies of in-plane anisotropy and torque magnetometry.





This work was carried out in the Materials Research Laboratory Central Facilities, University of Illinois. This work was undertaken as part of the Illinois Materials Research Science and Engineering Center, supported by the National Science Foundation MRSEC program under NSF award number DMR-1720633.

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Strain Effect on Magnetocrystalline Anisotropy of Metallic Antiferromagnets from First-Principles

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There has been emerging interest in metallic antiferromagnets since the potential for electrical switching was shown, notable examples coming from CuMnAs and Mn_2Au [1,2]. Studying magnetocrystalline anisotropy is essential to understand spin dynamics and strain can be utilized to modify the anisotropy energy. In this study, we used first-principles density functional theory to compute the strain dependence of magnetocrystalline anisotropy for Fe_2As and Mn_2As, which have similar magnetic structure as CuMnAs. By testing the anisotropy with rotating spin directions out-of-plane and in-plane with respect to the easy plane, we show up to two orders of magnitude larger anisotropy in out-of-plane than in-plane.

We then applied uni-axial strain on Fe_2As and bi-axial strain on Mn_2As to simulate directional strain in thin films. From this we show a tendency to increase anisotropy under compression for Fe_2As and tension for Mn_2As. 30% reduction in out-of-plane magnetocrystalline anisotropy was resulted by 3.6% strained Mn_2As and 2% strained Fe_2As. In-plane magnetocrystalline anisotropy of Fe_2As with 2% uni-axial strain became 1000 times larger compared to the unstrained case, followed by distortion of tetragonal unit cell into orthorhombic. This study has shown change in anisotropy with strain and further investigation with larger range of strain would map the correlation between strain and energy to decide amount of strain that can optimize magnetocrystalline anisotropy for switching performances in the studied materials.

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Unidirectional magnetoresistance in antiferromagnet/heavy-metal bilayers

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The interplay between electronic transport and the antiferromagnetic order has attracted a surge of interest and recent studies have shown that a moderate change in the spin orientation of a collinear antiferromagnet may have a significant effect on the electronic band structure and subsequently manifest itself in transport properties [1]. Among numerous electrical probes to read out such magnetic order, unidirectional magnetoresistance (UMR), where the resistance changes under the reversal of the current direction, can provide rich insights into the transport properties of spin-orbit coupled systems. However, UMR has never been observed in antiferromagnets before, given the absence of intrinsic spin-dependent scattering. Here, we report that a sizable UMR can emerge in an antiferromagnetic system, specifically in a collinear-antiferromagnet/heavy-metal bilayer. The observed UMR evolves nonlinearly with increasing magnetic field, persists to large values at high magnetic field and, most notably, exhibits a sign change at a critical field, which is in stark contrast with the UMRs observed in ferromagnetic and non-magnetic systems [2-3]. We show that Rashba spin-orbit coupling alone cannot explain the sizable UMR in the antiferromagnetic bilayer and that field-induced spin canting plays a crucial role in enhancing the UMR. Our results can motivate the growing fields of non-centrosymmetric and topological systems, and suggest a route to the development of tunable antiferromagnet-based spintronics devices.

This research was primarily supported by the NSF through the University of Illinois at Urbana-Champaign Materials Research Science and Engineering Center DMR-1720633 and was carried out in part in the Materials Research Laboratory Central Research Facilities, University of Illinois. Thin-film growth at Argonne National Laboratory was supported by the U.S. Department of Energy, Office of Science, Materials Science and Engineering Division.

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Magnetic Octupole Dynamics in Non-collinear Antiferromagnets

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Antiferromagnets (AFs) are promising candidates for next-generation spintronic devices, because of distinct benefits, such as fast magnetization dynamics and reduced crosstalk from magnetostatic interactions [1]. Towards this end, non-collinear AFs are particularly interesting for AF spintronics [2], since they exhibit a large anomalous Hall effect and magneto-optical Kerr effect which can be used for detecting the magnetic order [3]. Furthermore, the magnetic order can be modulated electrically by spin-orbit torques [4]. However, the detailed magnetization dynamics in the non-collinear AFs have not been satisfactorily explored. Here, we theoretically investigate spin dynamics in the non-collinear AFs, Mn_3Sn, with a focus on the dynamics of the cluster magnetic octupoles. We prepare a minimal atomistic-spin model on a two-dimensional kagome lattice [5]. From the model, we numerically calculate the oscillation and switching dynamics among degenerate stable configurations based on the Landau-Lifshitz Gilbert equation [6]. From the result, we find that the dynamics of the octupoles could be different from the magnetic dipole dynamics in ferromagnetic systems, because conventional precession vanishes during the octupole dynamics. This work provides a perspective for further investigations with respect to non-collinear AF spintronics.

This work is supported by the NSF through the Illinois MRSEC (DMR-1720633).

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Couter-intuitive giant spin magnon conductivity in ultrathin YIG films

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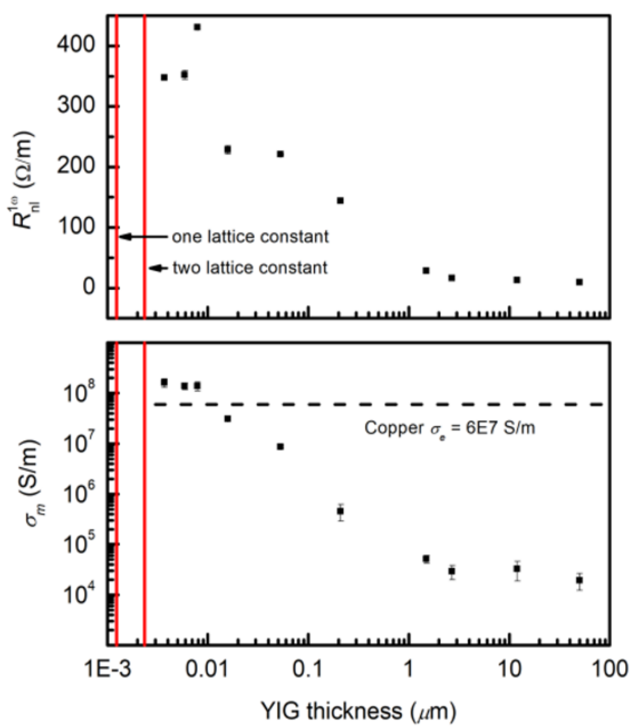
In the last couple of years, studies on magnonics based on nonlocal geometry have become the center of interest, opening new possibilities to investigate magnon transport in a wide range of materials while making magnonic-based devices more attractive to actual electronics. One example is the hybrid magnon transistor, where a middle modulator strip of Py is placed between the injector and detector Pt strips.[1] In the late experiment was possible to control the magnon conductivity on the YIG channel by means of the spin Hall effect, anomalous spin Hall effect, and the magnetic gating effect. Although many experiments on this subject have already been made, there is no report of a systematic investigation on the YIG thickness dependence of the magnon conductivity. Here we report a giant magnon conductivity in ultrathin Yttrium Iron Garnet.[2] Counter-intuitively we observe the enhancement of about four orders of magnitude of the magnon conductivity for YIG film thinner than 10 nm compared to the bulk value. Finite-element modeling of the diffusive magnon transport confirms this conclusion. This enhancement is a consequence of the dimensionality behavior of the magnons subbands below the thermal energy (kT).



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Detection of Magnon Currents in EuS

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Magnons, the quanta of spin wave excitations in magnetic systems, allow for the transport of spin angular momentum through magnetic compounds, including insulators. The ability to control the injection, propagation, and detection of such magnon spin currents represents an asset for the progress of spintronics. So far, magnon transport have been studied mainly through $Y_3Fe_5O_{12}$ (YIG) and a few other ferri- and antiferromagnetic insulators [1], while there exist many materials in which their behaviour is little-known. Here, we study for the first time the generation of thermal magnon currents in 15-nm-thick films of the ferromagnetic insulator europium sulfide (EuS), which exhibits a Curie temperature T_c = 19 K in thin films [2]. We perform non-local (NL) transport measurements using Pt electrodes, with different separation distances d, as magnon injectors and detectors. We study the NL voltage, generated at the detector due to the inverse spin Hall effect (ISHE), depending on the in-plane angle between the sample magnetization and the polarization direction of the spins induced by ISHE in the Pt, for the temperature range 2 K < T < 30 K. The second harmonic component of the NL voltage indicates that thermal magnon currents generated in the injector flow to the detector for distances ranging from d = 0.8 μm up to d = 2 μm and for temperatures T < 20 K. By analyzing the length dependence of the second harmonic signal we evaluate the magnon propagation length in the EuS films, which we find to be relatively short, as compared to the YIG case. We discuss our results considering the Gilbert damping and the Curie temperature of the EuS films.

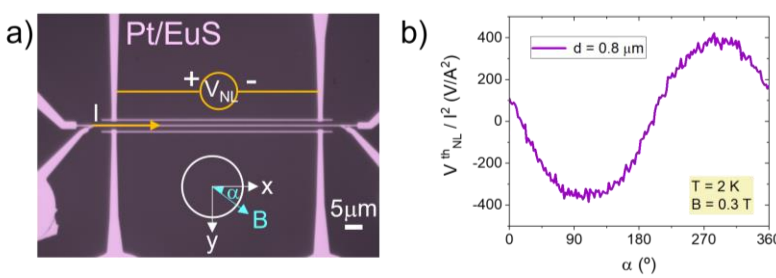

Figure 1. a) Microscope image of a non-local device used in this work (d = 1.25 mm, d = 1.5 mm). b) Representative angular-dependent non-local signal detected for thermally excited magnons.

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Magnon Junction Effect in $Y_3Fe_5O_{12}$/CoO/$Y_3Fe_5O_{12}$ Insulating Heterostructures

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Magnonics as an emerging frontier of spintronics aims using magnons to deliver information free from electron scattering and as-induced Joule heating. In general, magnon currents can be excited both thermally and electrically in magnetic insulators, by applying a current in an adjacent heavy-metal layer. Here, we report another kind of magnon junctions (MJs) composed by $Y_3Fe_5O_{12}$/CoO/$Y_3Fe_5O_{12}$ heterostructures in which $Y_3Fe_5O_{12}$ and CoO are respectively ferrimagnetic and antiferromagnetic insulators. A temperature gradient can drive a high (low) magnon current via spin Seebeck effect when the $Y_3Fe_5O_{12}$ layers in an MJ are configurated at the parallel (antiparallel) state, showing a spin valve-like behavior. Electrically injected magnon current could also be controlled by the MJs, contributing to a magnon-mediated nonlocal spin-Hall magnetoresistance (SMR). Furthermore, compared with its NiO counterpart, both magnon junction and magnon-mediate SMR effects can be clearly observed at room temperature for the CoO-based magnon junctions which can possibly be applied as a building block for room-temperature magnon-based memory or logic devices.

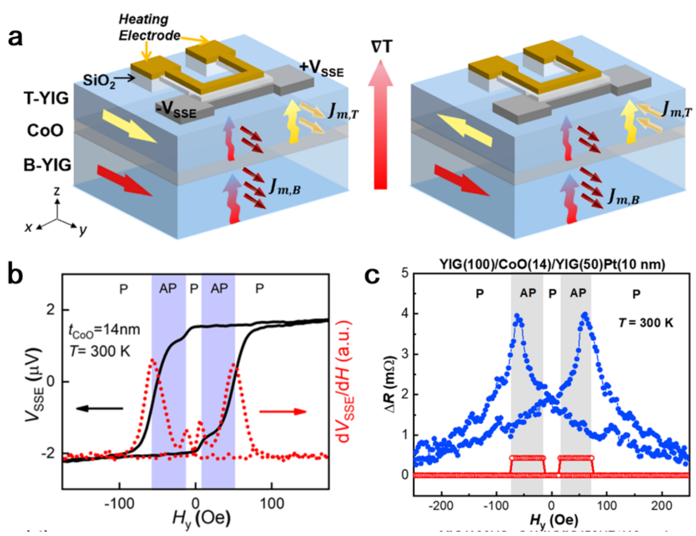

Figure **a**, Schematics of the magnon junction effect and its measurement steup for MJs where a temperature gradient is applied to excite a magnon current by the spin Seebeck effect. **b**, Field dependence of V_{SSE} for the MJ with t=14 nm (black line) and field dependence of dV_{SSE}/dH (red line) at 300 K.**c**, Electrically injected magnon current could also be controlled by the MJs, contributing to a magnon-mediated nonlocal spin-Hall magnetoresistance (SMR).

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Acknowledgments

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Magnon Blocking Effect in an Magnon Junction

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We study magnon transmission in the sandwich structure of ferromagnetic insulators (FMIs), antifer□romagnetic insulators (AFMI), and ferromagnetic insulators (FMI) by atomistic spin-model simulations. Magnon junction effects (MJEs), which have been reported in magnon junction (MJ) experiments[1], can be reproduced in this work, demonstrating the importance of spin-dependent magnon blocking effects (MBEs) in a MJ structure[2]. Moreover, AFMI spacers with various structures are investigated. We show that the MJE is sensitive to the characteristics of the AFMI spacer such as orientation of Néel vector, types of AFMI spin configuration, and intrinsic exchange interaction. It is found that these phenomena are rooted in the magnon selection rules between two FMIs of different magnonic polarization. Based on the mechanism studied above, we further propose an in-plane MJE and give a feasible experimental predic□tion using nonlocal magnon-mediated current-drag measurement. Our work provides insight into magnon transmission in MJ and serves as a promising tool for future magnon circuits.

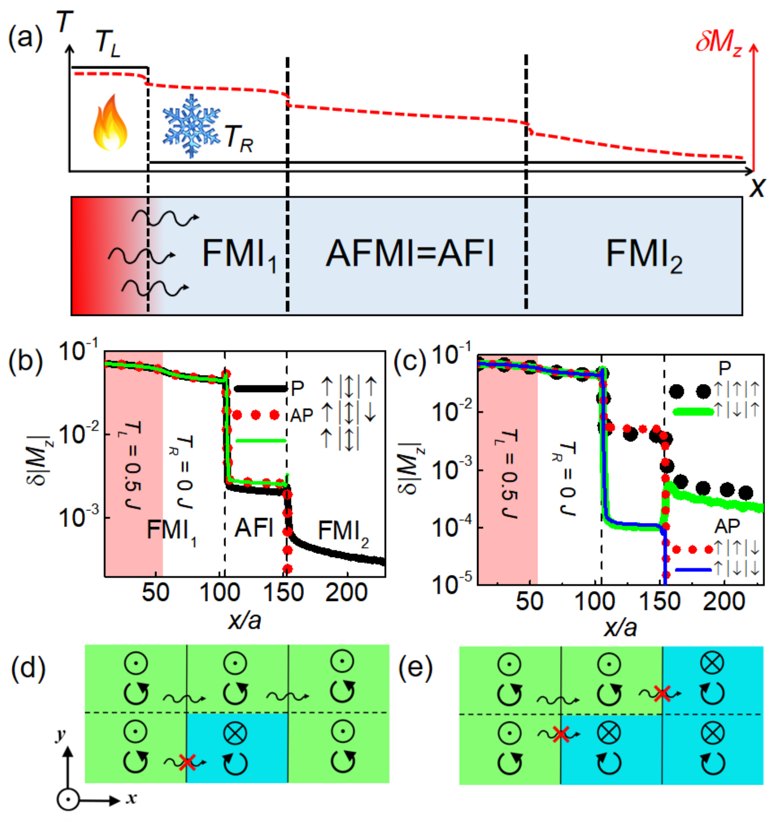

Figure **a**, Schematics of the magnon junction effect and and space dependence of magnon potential. **b**, Magnon potential as a function of layer (x) of P and AP state and FMI1-AFMI systemJ. **c,** Separated channel dependent from (b): ↑|↑|↑, ↑|↓|↑,↑|↑|↓, and ↑|↓|↓. **d** and **e** Schematics of spin-dependent magnon blocking of P and AP state, respectively

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Driving a magnetic texture by magnon currents

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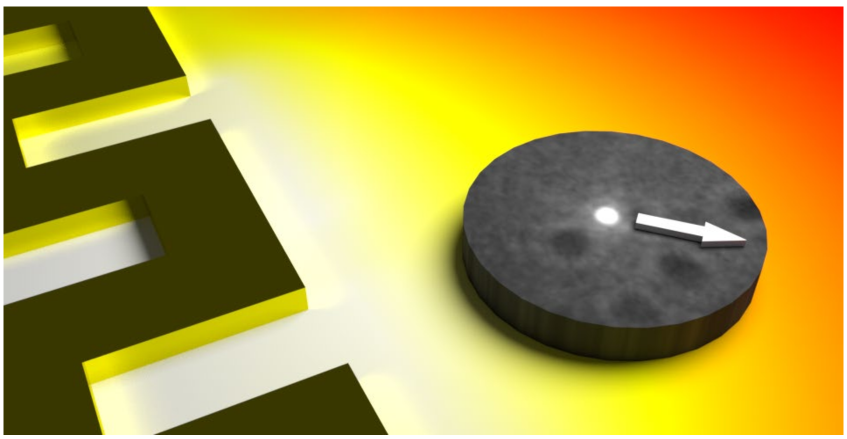

Fig. 1: A magnetic vortex core inside a Py disk is placed in a large temperature gradient created by a meander-type heater. Large deflections of the vortex core are observed depending on the temperature gradient and the polarity of the vortex core.

Thermally-induced spin dynamics in solids have sparked broad interest in both fundamental physics and spintronic applications [1,2]. As theoretically proposed, thermally excited magnons created by temperature gradients can be used to manipulate spin textures such as topological magnetic solitons [3,4]. However, in practice, the effectiveness of such thermomagnonic torques has remained a problem. Using high-resolution Lorentz Transmission Electron Microscopy, the dynamics of magnetic vortex cores in thin ferromagnetic platelets controlled by thermomagnonic torques are explored here. Large deflections of the magnetic vortex core transverse to the direction of the temperature gradient are observed. The magnitude of the contribution of the associated torques is determined using a generalized Thiele equation model. Our findings pave the path for thermomagnonic currents to manipulate magnetic domains on the nanoscale and shed light on the relationship between temperature and spin.

The authors gratefully acknowledge financial support from the DFG within SpinCaT (SPP 1538) and the BMBF.

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Magnetically Activated Flexible Thermoelectric Switches based on Interconnected Nanowire Networks

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Template-assisted electrodeposition of interconnected nanowire networks revealed to be a promising technique to develop flexible macroscopic spin caloritronic devices [1-4]. The 3D nanowire networks are fabricated by direct electrodeposition in track-etched polymer templates with crossed nano-channels. This technique allows the fabrication of crossed nanowires consisting of both homogeneous ferromagnetic metals and multilayer stack with successive layers of ferromagnetic and non-magnetic metals, with controlled morphology and material composition. The interconnected multilayer nanowire networks exhibit large magnetoresistance and magneto-thermoelectric effects [1-3], easily characterized thanks to the current-perpendicular-to-plane configuration in such structure. The giant magneto-thermoelectric effects in multilayer structures result from the very contrasting spin-dependent Seebeck coefficients that have been experimentally extracted for several ferromagnetic metals and alloys [1-3]. In the present work, thermocouples formed from two dissimilar arrays of interconnected magnetic nanowires are used to realize flexible thermoelectric switches providing optimal magnetic-field-induced control of the sign and magnitude of the thermopower. The two legs, one formed by homogeneous nanowires and the other by multilayer nanowires, are connected electrically in series and thermally in parallel (Figure 1 left). The magnetic sensitivity of this design is dominated by the multilayer leg, leading to large control of the thermoelectric output voltage. By fine-tuning their respective compositions, an ideal on/off ratio in the switching of the thermoelectric output voltage (from 0 to few tens of μV) can be achieved in the presence of a magnetic field (Figure 1 right). This work paves the way to the development of thermally activated sensors and logic devices, exploiting the residual thermal energy of hot surfaces with complex geometry. Our lightweight devices withstand repeated mechanical stress, have low toxicity, can be easily shaped without dimensional limitations. On this basis, the present work also contributes to the emergence of flexible thermoelectric materials and devices to address the rapid development of miniature, lightweight, and functional portable electronic devices [5].

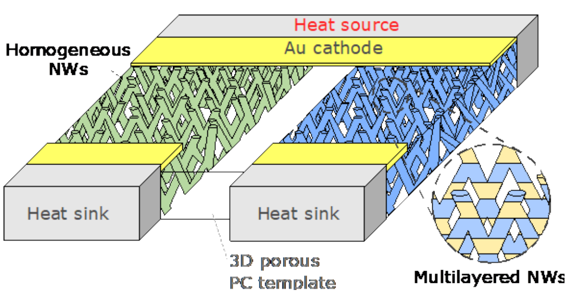

Figure 1: Magnetically activated flexible planar thermoelectric switches with one homogeneous leg and one multilayer leg connected electrically in series and thermally in parallel (left). Ideal switch where the “on” and “off” state are reached at zero and saturation magnetic field (right).

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Thermal Conductivity Study of Piezoelectric PZT Stack

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We present new data on tuning the thermal conductivity of a ferroelectric material, lead zirconium titanate (PZT), with an electric field; further, we analyze the results through the lens of a new theory claiming polarization waves can carry heat, much like magnons in ferromagnetic materials [1]. Hopkins and colleagues [2] report that piezoelectric materials have a thermal conductivity that is a function of the external electric field. They assert that the decrease as the field is applied is due to an increase in ferroelectric domain wall density, which increases the phonon scattering. While their experiment is conducted on a thin film, we investigate the field and temperature dependency of thermal conductivity on a PZT stack with interwoven electrodes. We measure the thermal conductivity and diffusivity to compare the Peltier coefficient, Π, defined as the ratio of heat produced by a change in polarization in the absence of a temperature gradient, in theory and that obtained through experiment. The values agree well, suggesting legitimacy to the theory. To tease apart the contributions to diffusivity from changes in phonon velocity and mean free path, we will also show results from resonant ultrasonic spectrometry.

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Thermal chiral anomaly in Weyl semimetal BiSb alloy

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Weyl semimetals (WSMs) are the family of topological insulator induced by strong spin-orbit coupling. WSMs have two pairs of Weyl points in momentum space which are the source and sink of Berry curvatures. At the Weyl points, electronic band structure is shown linear dispersion. Electron has no mass and only has velocity and chirality at Weyl Points. Also, WSMs have exotic thermal transport properties called thermal chiral anomaly[1,2], which is induced by energy imbalance between cold and hot sides when temperature gradient and magnetic field are applied parallel to Weyl points. Here, we observe very strong thermal chiral anomaly in ideal WSMs $Bi_{1-x}Sb_x$ alloy as a function of Sb concentration and doping level. $Bi_{1-x}Sb_x$ shows giant thermal chiral anomaly and thermal conductivity enhancement under magnetic field. It is maximized when Sb concentration is 11% because $Bi_{1-x}Sb_x$ turn into direct gap semiconductor with inverted bandgap at this concentration. Also, we study relationship between Fermi level and thermal chiral anomaly by doping $Bi_{1-x}Sb_x$ with P-type and N-type dopants Sn and Te, respectively. Very surprisingly, we observe maximum thermal chiral anomaly when Fermi level approaches to Weyl points. This giant thermal chiral anomaly and thermal conductivity enhancement in WSMs is promising tool to control heat flow actively without moving part.

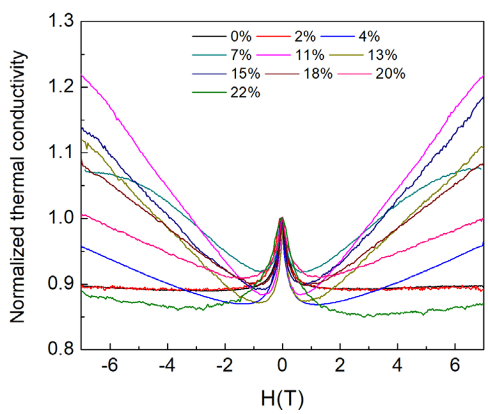

Figure. Thermal conductivity of $Bi_{1-x}Sb_x$ alloy from x=0 to x=0.22 under magnetic field at 75K

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Designing efficient spin thermoelectric devices via engineering magnon-phonon thermal coupling

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The spin Seebeck effect (SSE) refers to a heat-to-electricity conversion via thermal spin current (or thermal magnon) in a ferromagnet (FM)/normal metal (NM) heterostructure. Recently, Prakash et al.[1] demonstrated that in thin-film yttrium iron garnet (YIG) with thickness less than 250 nm, the temperature difference between magnons and phonons and energy relaxation between them could play an important role in magnon transport, whereas magnon chemical potential dominates in micrometer scale. This result motivates designing an efficient SSE-based nm-scale-thermoelectric device by utilizing the “thermal coupling” between magnons and phonons.

Here, we report a novel method of engineering the interfacial magnon-phonon thermal coupling by introducing “magnon thermal fins” between a gadolinium gallium garnet (GGG) substrate and FM YIG. Analogous to that the conventional thermal fin increases the effective heat transfer between a “hot” source and a “cold” sink by its extended surface[2], the magnon thermal fin increases the interfacial energy transfer between “hot” magnon in FM and “cold” phonon in NM by the effective extended surface. By designing the size and density of the magnon thermal fins, the magnon current density can be systematically optimized, which results from the increased temperature difference between magnons in FM and electrons in NM. As a result, a magnon-thermal-fin-embedded YIG film obtained 250% enhanced magnon current density at 300 K compared to that of a reference FM sample without thermal fin. These results suggest that engineering interfacial magnon-phonon thermal coupling with thermal fins gives a new route to designing nanoscale high-efficient devices in spintronics and magnonics.

Acknowledgement
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Anomalous Nernst effect in the compensated ferrimagnets, Fe-Ln alloys (Ln = Gd, Tb, Dy, Ho, and Er)

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The anomalous Nernst effect (ANE) is the generation of the transverse electric field produced by a longitudinal thermal gradient in the presence of magnetization. While the effect has conventionally been correlated with the volume magnetization, it has recently been shown that large Berry curvature near the Fermi level generates large ANE beyond the scaling with the volume magnetization [1-3]. We note, however, that the sign of ANE, related to the direction of the magnetic moment of each atom [4], cannot be explained by neither the Berry curvature nor the volume magnetization. In this study, we examine a microscopic magnetic structure to establish the sign-determining mechanism of ANE.

To systematically study the correlation between the microscopic magnetic structure and ANE, we used a compensated ferrimagnetic Fe_3Ln (Ln = Gd, Tb, Dy, Ho, and Er) as the novel platform which can offer controllable magnetic ordering and magnetization by temperature [5]. Interestingly, the anomalous Nernst coefficient (ANC) of our Fe_3Ln showed temperature independence in amplitude and sudden change in the sign near the magnetic compensation point (Fig. 1 below). These unique behaviors of ANC were analyzed by transport properties and DFT calculations. The analyses revealed that the unique behaviors are caused by the magnetic moment flipping of Fe atom, which is located near the Fermi level in the band structure and contributes to thermal transport, rather than the net volume magnetization. Our work underscores the role of magnetic moment distribution near the Fermi level in determining the sign of ANE.

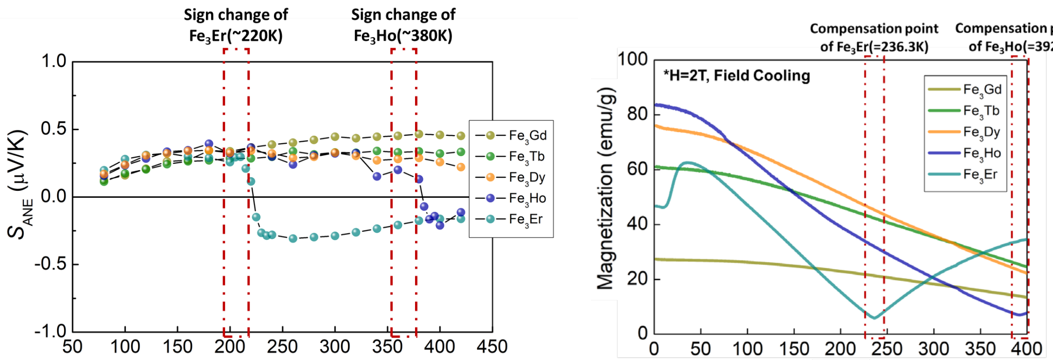

Fig. 1. *Temperature dependence of anomalous Nernst coefficient and magnetization of Fe_3Ln*

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The Effect of Spin-orbital Entropy on Anomalous Nernst Effect

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The anomalous Nernst effect (ANE) is an emerging research topic in 'spin caloritronics'. The ANE offers an alternative approach towards efficient thermoelectric (TE) generation, since it can overcome the Wiedemann-Franz law. Accordingly, active research to search for highly efficient ANE materials has recently been made [1-2]; the intrinsically large Berry curvature has been considered an essential factor for achieving a large ANE. However, from an engineering perspective, it is also imperative to develop strategies to increase ANE performance of materials by manipulating extrinsic conditions, beyond using a naturally good material. In that regard, we report how one of such extrinsic factors, the spin-orbital entropy, affects ANE using a hopping semiconductor as our experimental platform. Here, we synthesized four Co-rich strontium cobalt oxide $Sr_3YCo_4O_{10+d}$ (SYCO) polycrystals, a promising TE ferromagnet [3], and closely observed their anomalous Nernst voltages near the Curie temperature. The ANE coefficients of our samples significantly increase with the temperature and record a maximum near the Curie temperature, resembling the temperature dependence of magnetization. In particular, the slope of ANE coefficient increases for the Co-richer sample due to thermal activation of its many intermediate- and high-spin states. Such fascinating result provides evidence for an increase of spin-orbital entropy from the excessive amount of $Co^{2+/3+}$ ions. In addition, the maximum ANE coefficient of the Co-richest sample is nearly twice that of the pristine. This immense increase results from the increase of spin-orbital entropy which can strengthen the total Seebeck currents following the linear response theory. In this report, we attempt to examine the dependence of ANE signal on the extrinsic contribution of spin-orbital entropy, and thus provide useful insight into artificially tunable ANE in hopping semiconductors.

Acknowledgements

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Spin-orbit Torques in Magnetron-Sputtered $MoTe_2$

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Weyl semimetals can generate large current-induced spin-orbit torques (SOT) that can manipulate the magnetization dynamics in adjacent ferromagnetic materials, and thus play an important role in spintronic devices. Due to their reduced symmetries, Weyl semimetals are also promising for generating novel SOT that may be able to switch perpendicular magnetic anisotropy magnetic thin films. Large spin-orbit torque efficiencies have already been reported for exfoliated and sputtered WTe_2 films [1]. Here we investigate magnetron-sputtered $MoTe_2$ films that are theoretically predicted to have even larger SOT efficiencies than WTe_2. We studied the effects of processing conditions on the stoichiometry and crystal structure of the magnetron-sputtered $MoTe_2$ films by using Rutherford backscattering and X-ray diffraction. Furthermore, we verified the 1T' semimetal phase from Raman spectroscopy. SOT efficiencies of the $MoTe_2$ thin films were measured via spin-torque ferromagnetic resonance on $MoTe_2/Ni_{80}Fe_{20}$ heterostructures and we observed a large novel SOT efficiency (ξ_{DL}= 16% and ξ_{FL}= 27%) in symmetric and anti-symmetric components of the mixing voltage signals.

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Magneto-optical detection of spin-orbit torque vector with first order Kerr effects

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When spin polarized currents diffuse into a ferromagnetic (FM) material, they induce spin-orbit torques (SOTs): a powerful mechanism for magnetic order manipulation, with applications in magnetic recording, logic devices and neuro-morphing computing [1].

To the date, detection SOTs have relied almost exclusively on measuring electrical voltages arising from the device under excitation. In this line, techniques such as second harmonic generation, spin transfer torque ferromagnetic resonance (STT-FMR) and spin pumping, have dominated the scenario. In these techniques, signals are often contaminated by unwanted thermo-electric voltages and the sensitivity depends critically on magneto-electric coefficients that can show large variations among even for typical 3d ferromagnetic materials [2].

In this work we present a new and powerful method for the detection of SOTs based on Magneto-Optical Kerr Effect (MOKE). Whit it, we can quantify both the damping-like and field-like SOT effective fields ($\mathbf{h}_{DL}$ and $\mathbf{h}_{FL}$ respectively) of SOTs, employing a simple and low-cost set-up that has been already widely employed in MOKE magnetometry (Fig. 1).

We tested our method in NiFe/Pt, NiFe/Pd, Ta/CoFeB bilayers, obtaining a damping-like SOT efficiency (ξ_{DL}) equal to 0.08 ± 0.01, 0.034 ± 0.004 and -0.15 ± 0.01 respectively. On the other side, we obtained $\mathbf{h}_{FL}\backslash\mathbf{h}_{DL}$ ratio equal to 0.24 ± 0.03 and 0.11 ± 0.03, in the samples with 4 nm thick NiFe and CoFeB, respectively. The results for ξ_{DL} are close to the most accepted values reported in the literature for the studied materials. On the other side, the $\mathbf{h}_{FL}\backslash\mathbf{h}_{DL}$ ratios fit well inside the diffusive model of spin accumulation in the ferromagnetic layer [4], with a finite spin dephasing length. This effect has been often disregarded in STT-FMR works.

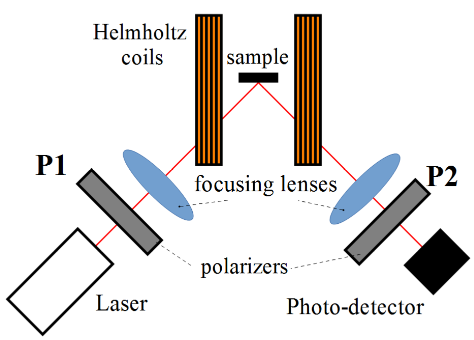

Figure 1: Schematic diagram of theset-up employed for magneto-optical detection of SOTs

Acknowledgments

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Spin Hall magnetoresistance effect from a disordered interface

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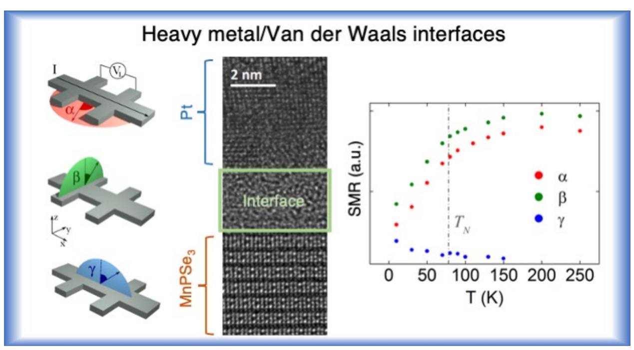
The spin Hall magnetoresistance (SMR) arises in heavy metal (HM)/magnetic compound interfaces, from the interaction between the magnetization and the spin currents generated in the HM layer by spin Hall effect. The SMR allows the magnetization of thin films and surfaces to be probed with an all-electrical set-up and, therefore, could represent a valuable tool to characterize the magnetization of van der Waals magnetic materials.
For this purpose, we have studied the SMR response of heterostructures combining a platinum (Pt) thin film with the van der Waals antiferromagnet $MnPSe_3$. The bilayers are fabricated by sputtering of the heavy metal on top of exfoliated flakes of the van der Waals compound.
We observe a robust SMR effect in the system, which we measure both below and above the Néel temperature of $MnPSe_3$. By taking advantage of transmission electron microscopy (TEM), we characterize the Pt/$MnPSe_3$ bilayers, revealing the presence of a nanometers-thick platinum-chalcogen amorphous layer at the interface, whose formation we ascribe to the sputtering deposition process. From our analysis of the transport and TEM data, we conclude that the SMR signal arises from a disordered magnetic system formed at the Pt/$MnPSe_3$ interface because of the sputtering induced damage. Our results show that damaged interfaces can yield an important contribution to SMR, questioning a widespread assumption on the role of disorder in such measurements[1].
This work was supported by the European Union H2020 under the Marie Sklodowska-Curie Actions (796817-ARTEMIS and 748971-SUPER2D) and by the Spanish MICINN under project nos. RTI2018-094861-B-I00, PID2019-108153GA-I00, and the Maria de Maeztu Units of Excellence Programme (MDM-2016-0618 and CEX2020- 001038-M).



From the left to the right: sketch of the measurements set-up; TEM image of the Pt/$MnPSe_3$ interface; temperature dependence of the SMR signal.

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Temperature-dependent optical and magneto-optical spectra of ferromagnetic BCC Fe: First-principles study

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Temperature dependence of optical and magneto-optical spectra from magnetic materials has been widely utilized to characterize their magnetic features. Optical pump-probe measurements induce temperature excursions and observe spin dynamics such as ferromagnetic resonance[1] and magnetic domain wall motion.[2] In computational research, optical and magneto-optical properties of magnetic materials have been popularly investigated by first-principles density functional theory,[3-4] but the introduction of temperature effect is limited even for non-magnetic materials such as silicon.[5-6] In this work, we expand the William-Lax theory[7-8] to magnetic materials and calculate optical and first-order magneto-optical conductivity spectra at finite temperature. Lattice and magnetic temperatures are modeled using supercells with perturbed atomic structure from the stochastic sampling of mean displacement at each phonon mode and perturbed magnetic structure from classical atomistic spin dynamics simulations, respectively. Both temperatures provoke surging signals of imaginary optical conductivity below 1.5 eV, caused by phonon and magnon-assisted intraband transitions. This phenomenon does not originate from changes of energy states, but modified dipole transition matrix elements. In addition, magnetic temperature uniquely induces a red shift of the peak near 2.8 eV in the imaginary part of optical conductivity, solving the discrepancy between calculated optical spectrum at 0 K and measured spectrum at 300 K. Unfolded band structure at finite magnetic temperature explains that this red shift comes from the reduction of exchange splitting by thermal demagnetization. Furthermore, unfolded band structure at finite magnetic temperature captures the anomalous band kinks, which are the feature of electron-magnon scattering observed in photoemission measurement[9] and *GW*+*T* method[10]. Finally, calculated optical conductivity and first-order magneto-optical conductivity spectra at 300 K show good agreement with measured spectra at 300 K. This method might be expanded to investigate any temperature-dependent property of magnetic materials such as transport and magnetic properties, and it might also enable the study of paramagnetic states above the critical temperature.

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Scanning tunneling microscopy platform for low-temperature, vector magnetic field spin-caloritronic studies

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Much progress has been made in spin-caloritronics in recent years, with rapidly growing interest from the research community [1, 2]. A major limiting factor in further progress is the availability of precise and reproducible experimental platforms, which can rapidly and consistently create the demanding conditions required to test the already extensive body of theoretical work.

Building on our previous work measuring the tunneling magneto-Seebeck effect using scanning tunneling microscopy (STM) [3, 4], we have developed a microscope combining ultra-high vacuum (<1E-10 mbar) and cryogenic (<20 K) conditions, with a controllable base temperature and reversible temperature gradient across the tunneling junction. A vector-field magnet is capable of applying up to 6 T out-of-plane and 2 T in-plane fields, and optical access to the scanning tip enables higher frequency temperature gradient modulation, while avoiding perturbative effects from oscillating electrical heating currents.

The use of STM for spin-caloritronic studies allows for atomically precise replication of tunneling conditions. This instrument will enable and support our atomic-scale studies of thermal spin-transfer torque, as well as on-going investigations of magneto-Seebeck tunneling in diverse sample systems. Knowledge of these effects in the ideal environment of vacuum tunneling gaps, ultra-high vacuum, and known atomic species can also serve as a benchmark reference, in support of investigations of planar junctions and novel sample systems.

Acknowledgements

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Local Thermoelectric Response from a Single Néel Domain Wall

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Spatially resolved thermoelectric detection of magnetic systems provides a unique platform for the investigation of spintronic and spin caloritronic effects. This has furthered understanding of magnetic phenomena at length scales comparable with the domain size. We investigate the separate individual nanoscopic spin caloritronic signatures of a domain-wall pinned in an ultra-thin Pt/CoFeB/Pt trilayer, with perpendicular magnetic anisotropy, by localized scanning thermoelectric microscopy (sThEM, Fig. 1(a)). Figure 1(b-c) presents the sThEM micrographs of the wire when saturated and with a domain wall pinned at the notch, respectively. We measure a large thermoelectric response when the probe is near the domain wall (Fig. 1(d)), which is not seen in the saturated state. This improvement in nanoscopic thermoelectric imaging using a highly localized heat source is dissected with micromagnetic modeling employing the Landau–Lifshitz–Bloch (LLB) equation, which provides new insights into spin caloritronic responses at nanometer length-scales.

We show how the highly localized generation of non-equilibrium spin polarized currents in the vicinity of novel spin textures results in a significant and specific thermoelectric response. The ability to directly resolve the nanoscale magnetization is important to address the under-constrained problem of determining the spin texture, where a manifold of potential solutions can exist.

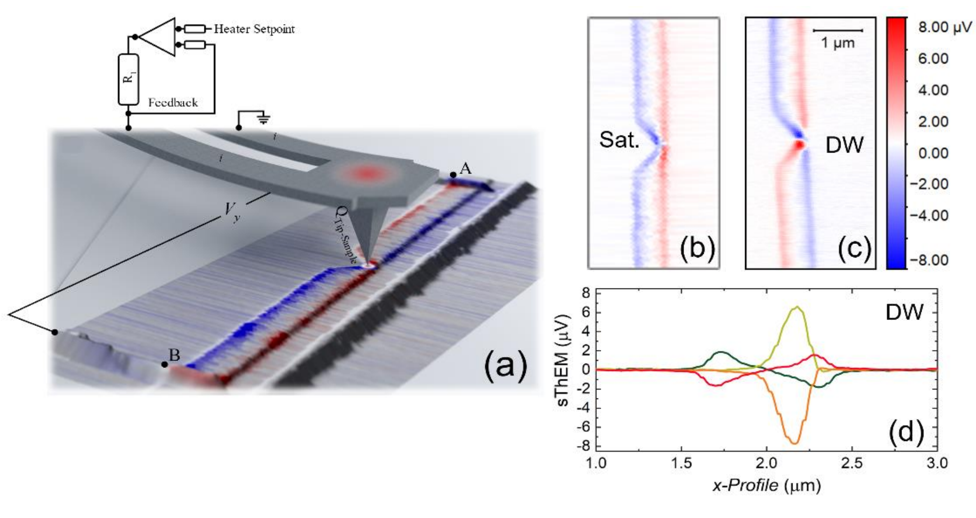

Fig. 1. (a) Schematic of the sThEM measurement setup showing the heated AFM probe used to apply the local thermal gradient. A voltage measurement is made along the device (y) and the integrated response is mapped pixelwise. **(b-c)** sThEM micrographs on the same color-scale for saturated and domain wall pinned configurations, respectively. **(d)** Line profiles taken from the domain wall state in saturated regions above and below the notch (red and dark-green, respectively) and through the signal maxima and minima (orange and light-green, respectively).

Magnetization Dynamics of Spintronic Materials Enabled by Ultrafast Optical Metrology

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In this work, we report the study of magnetization dynamics of materials with perpendicular magnetic anisotropy (PMA) using the ultrafast laser-based time-resolved magneto-optical Kerr effect (TR-MOKE) metrology. With optical excitation and detection, 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) approaches. The first representative sample system is $L1_0$-FePd, as a promising candidate for energy-efficient and non-volatile spintronic devices with large areal densities (down to 10-nm pitch sizes or even lower). To better address the technological viability of $L1_0$-FePd for spintronic applications, we systematically examine the impacts of buffer layers (Cr/Pt, Cr/Ru, Cr/Rh, Cr/Ir, and Ir) on the PMA and Gilbert damping of $L1_0$-FePd during the operating temperature range for spintronic devices (from room temperature to 150°C). Secondly, we demonstrate the spin-strain coupling in Co/Pd multilayers with a strong PMA, which holds promise in strain-assisted magnetic switching. Lastly, we study the magnetization dynamics of synthetic antiferromagnets (SAFs), which has been proposed as a building block in magnetic tunnel junctions (MTJs) to achieve fast and energy-efficient switching. Combining modeling analysis and experimental investigation, we successfully extract detailed information about the cone angles, directions, and phases of spin precession in individual ferromagnetic layers for both high-frequency and low-frequency modes with varying magnetic fields. The structure-property relationships of these technologically important materials established by TR-MOKE open up opportunities of tailoring material properties by structural engineering for applications in spintronic devices with low energy consumption, high thermal stability, and fast switching.

We gratefully acknowledge the funding support from the Advanced Storage Research Consortium (ASRC) and the C-SPIN, one of six centers of STARnet, a Semiconductor Research Corporation program, sponsored by MARCO and DARPA. Parts of the work were carried out in the Characterization Facility of the University of Minnesota, which receives partial support from NSF through the MRSEC program (DMR-2011401) and the Minnesota Nano Center, which is supported by NSF through the National Nanotechnology Coordinated Infrastructure (NNCI) under Award Number ECCS-2025124. In addition, we would like to thank all the scientific contributions from our collaborators, primarily involving members from the research groups of Prof. Jian-Ping Wang, Prof. Randall Victora, and Prof. Paul Crowell at the University of Minnesota, Twin Cities, and Dr. Gopman from NIST.

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Deformation Induced Skyrmion Rotation and Orbital Motion

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Skyrmions are topological spin textures with interesting properties that may make them useful in advanced computing architectures. In this work, we studied the dynamics of magnetic skyrmions using micromagnetic simulations. We observe novel rotational and orbital motion of skyrmions when a time-varying out-of-plane magnetic field is applied to skyrmions in confined systems and excites their breathing modes. This phenomenon can be explained by the redistribution of topological charge as skyrmions expand and contract in a confined environment. An example of this behavior can be seen below. As skyrmions expand from application of an out-of-plane field, they begin moving around the center of the system. Decreasing the magnetic field causes the skyrmions to shrink but maintain their individual rotation. Increasing the magnetic field again causes the cycle to repeat. This motion illustrates how the topological properties and the spontaneous emergence of chirality in skyrmions can result in unexpected complex behavior. Furthermore, it may have practical relevance to applications of skyrmions to neuromorphic and reservoir computing, where information may be encoded in the positions of different skyrmions. Previous groups have also observed skyrmion rotation, but have explained this with the presence of a thermal gradient.[1] Our work demonstrates a similar rotation but without having to introduce disorder into the system, possibly making the system more realizable in a practical setting.

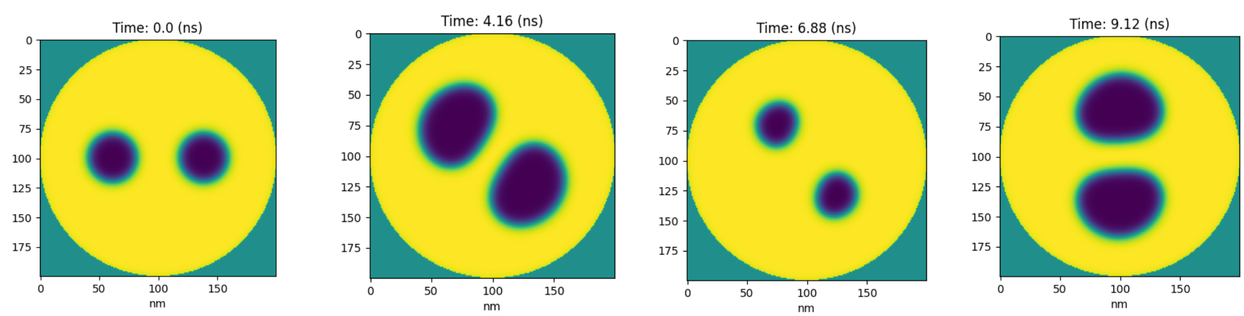

Fig. 1: Snapshots of different magnetic configurations of two skyrmions in a confined disc structure upon excitation with time varying out-of-plane fields.

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