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15. SUBJECT TERMS					
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a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 614-292-8439

RPPR Final Report

as of 06-Apr-2020

Agency Code:

Proposal Number: 63815MSMUR

Agreement Number: W911NF-14-1-0016

INVESTIGATOR(S):

Name: Roberto Correa Myers

Email: myers.1079@osu.edu

Phone Number: 6142928439

Principal: Y

Organization: **Ohio State University**

Address: 1960 Kenny Road, Columbus, OH 432101016

Country: USA

DUNS Number: 832127323

EIN: 316025986

Report Date: 31-Dec-2019

Date Received: 06-Apr-2020

Final Report for Period Beginning 16-Dec-2013 and Ending 30-Sep-2019

Title: Materials with Extraordinary Spin/Heat Coupling

Begin Performance Period: 16-Dec-2013

End Performance Period: 30-Sep-2019

Report Term: 0-Other

Submitted By: Roberto Myers

Email: myers.1079@osu.edu

Phone: (614) 292-8439

Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 15

STEM Participants: 22

Major Goals: The goal of this MURI was to establish the basic physics behind magnon thermal conductivity, spin Seebeck effect, and thermally-driven spin currents. The overarching goal was divided into several main objectives:

- Develop structure-property relationships for coupling heat and spin currents in materials;
- Synthesize magnetic materials with extraordinary and tunable thermal conductivity informed by theory;
- Understand non-equilibrium phonon-magnon transport and the mechanisms behind the spin-Seebeck effect;
- Measure and understand phonon-magnon drag and phonon-electron drag; and
- Combine materials for spin-thermal heat cycles, exceeding thermoelectric efficiency.

Accomplishments: During the course of the 5 year program, funded over the period 2014-2019 (the start date was delayed by the 2013 government shutdown), the team employed a diverse set of experimental techniques to systematically study the spin-heat conversion processes in both magnetic insulators and metals. These studies included dynamic, time-resolved measurements of the generation of spin current by heat currents and spatially-resolved measurements of spin diffusion lengths and spin lifetimes. A common thread in these studies is the non-equilibrium between energy carriers—magnons and phonons in magnetic insulators and magnons, phonons, and electrons in metals—and the importance of magnon transport for understanding the spin-Seebeck effect. In particular, the team developed a comprehensive understanding of spin-heat transport in YIG (Y₃Fe₅O₁₂), a prototypical magnetic insulator. These measurements guided the development of predictive theory of coupled spin-heat transport in magnetic insulators that provides a framework for designing materials and systems for enhanced spin/heat coupling.

A further consequence of the scientific advances of the MURI team is the evolution of the spin Seebeck effect into a metrology technique, capable of quantifying coupled spin/heat fluxes in a large number of systems. In electrical insulators, where magnons (i.e., spin waves) are the carriers of coupled entropy and spin, thermally driven measurements are the only transport measurements possible. Examples include future spin-Nernst and quantum-spin-Nernst systems.

The MURI team expanded the context of spin caloritronics to include linear momentum transfer between a thermally-driven current of magnons and the conduction electrons in a ferromagnetic metal. This effect, magnon-drag, is the dominant source of thermoelectric power in all ferromagnetic metals. Magnon-drag produces an order of magnitude stronger effect than the conventional thermoelectric effects that arise from the diffusion of charge carriers. Quantitative and predictive theories for magnon-drag in ferromagnetic and paramagnetic metals were developed by the MURI team.

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The MURI team also explored the materials properties governing giant magnon thermal conductivity in antiferromagnetic spin ladder compounds. Thermal transport measurements provide an understanding of the length scales of spin-lattice coupling in these systems enabling a quantitative and predictive understanding of thermal conductivity in these low dimensional antiferromagnetic materials. In addition, the MURI team has further explored a new area at the junction between spin caloritronics and the rapidly expanding research field of two-dimensional (2D) materials, especially 2D ferromagnetic and antiferromagnetic materials that have emerged in recent years due to large-scale federal supports that has followed another ARO MURI program.

The MURI team was able to develop the basic physics of spin/heat interactions in materials. Building on these foundations, new experiments, materials, and theory have been developed, including, all-optical thermometry using nitrogen-vacancy centers in diamond, ultrafast demagnetization across metallic interfaces, vortex-mediated transport between magnets and superconductors, and spin/heat coupling in disordered and low dimensional systems. This expansion of spin caloritronics theory and characterization techniques has strongly broadened the class of materials in which thermally-driven spin transport, and spin driven thermal transport can be developed for future applications in thermal management, waste-heat recovery, and spintronics. The thermally-pumped BEC agenda propelled by our MURI has impacted the developments in the broader spintronics/spin-caloritronics community, leading to novel magnon BEC realizations by other groups utilizing thermal/spin conversion processes.

Center-level funding related to MURI

- The NSF MRSEC at OSU was renewed in 2014 with an IRG (led by Heremans, MURI co-PI) largely inspired by work funded under the MURI
- NSF-MRSEC at U. of Illinois established in 2017 includes a research focus IRG-MAX (led by Cahill, MURI co-PI), about metallic antiferromagnetic materials. MURI support was instrumental in providing research development at U of I towards this research area
- Shortly after the MURI was funded, a DOE EFRC (SHINES, led by Prof. Jing Shi at UC Riverside) was established focused on spin/heat transport in nanoscale materials

Supported International Workshops

- 2015 Workshop on Non-linear spin-heat interactions, Columbus, OH
- 2017 Spin coherence, condensation, and superfluidity, Moorea, French Polynesia
- 2018 Spin Caloritronics IX, Columbus, OH

(see attached PDF for details)

Training Opportunities: Numerous graduate students, postdoctoral fellows, and visiting scientists participated in the MURI project. Many have gone on to obtain tenure-track faculty positions as a result of their research accomplishments and scientific developments associated with the MURI support.

(see attached PDF for details)

Results Dissemination: Dissemination of results was accomplished by publication of peer-reviewed articles and presentations at international conferences. Over the course of the MURI:

-115 papers and abstracts were published.

-1618 total citations to date

-h-index=23

(see attached PDF for details)

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Honors and Awards: Dr. Se Kwon Kim awarded Outstanding Young Researcher Award from Association of Korean Physicists in America in 2016. Obtained tenure-track assistant professor position in Physics at University of Missouri-Columbia

Professor David Cahill was awarded the Innovation in Materials Characterization Award, Materials Research Society 2018; citation: For developing transformative methods for characterizing the thermal transport properties of materials and their interfaces using time-domain thermoreflectance (TDTR) and related approaches. Prof. Cahill was also awarded the Yeram S. Touloukian Award, American Society of Mechanical Engineers 2015; citation: For sustained, pioneering contributions to heat conduction metrology including the 3-omega and optical pump-probe methods, which are pervasive in laboratories worldwide; and for landmark contributions on the minimum and ultralow thermal conductivity of solids.

Dr. Zhu Diao obtained a tenure-track assistant professor position at Florida A&M University.

Dr. Joseph Feser obtained a tenure-track assistant professor position at U. Delaware.

Dr. Gyung-Min Choi obtained a tenure-track assistant professor position at SKKU in Korea.

Dr. Richard Wilson obtained a tenure-track assistant professor position at UC Berkeley.

Dr. Xi Chen obtained a tenure-track assistant professor position at UC Riverside

Professor Li Shi was awarded the Heat Transfer Memorial Award in Science, American

(see attached PDF for details)

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI

Participant: Roberto Myers

Person Months Worked: 3.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Brandon Giles

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Zihao Yang

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

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Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Brelon May

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Kyongmo An

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Annie Weathers

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Sean Sullivan

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Mehta Devika

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Yimeng Wang

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

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National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Xi Chen

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Annie Weathers

Person Months Worked: 10.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Sean Sullivan

Person Months Worked: 7.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Ming Xie

Person Months Worked: 5.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Co PD/PI

Participant: Li Shi

Person Months Worked: 2.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Co-Investigator

Participant: Xiaoqin Li

Person Months Worked: 1.00

Funding Support:

Project Contribution:

International Collaboration:

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International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Co PD/PI
Participant: Emanuel Tutuc
Person Months Worked: 1.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: Co PD/PI
Participant: Allan MacDonald
Person Months Worked: 1.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Se Kwon Kim
Person Months Worked: 12.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: Graduate Student (research assistant)
Participant: Gyung-Min Choi
Person Months Worked: 12.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: Graduate Student (research assistant)
Participant: Richard Wilson
Person Months Worked: 12.00
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Funding Support:

Participant Type: Graduate Student (research assistant)
Participant: Qiye Zheng
Person Months Worked: 12.00
Project Contribution:

Funding Support:

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International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Hyein Jang

Person Months Worked: 12.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Ella Pek

Person Months Worked: 12.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Joseph Feser

Person Months Worked: 12.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Johannes Kimling

Person Months Worked: 12.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Judith Kimling

Person Months Worked: 12.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student

Participant: Michael Castells

Person Months Worked: 6.00

Funding Support:

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Staff Scientist (doctoral level)

Participant: Zhu Diao

Person Months Worked: 12.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Co PD/PI

Participant: David Cahill

Person Months Worked: 2.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: John Jamison

Person Months Worked: 12.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Paolo Andrich

Person Months Worked: 12.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Christopher Yale

Person Months Worked: 12.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Masaya Fukami

RPPR Final Report
as of 06-Apr-2020

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Masaya Fukami

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Paul Jerger

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Jonathan Karsch

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Joseph Heremans

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Brian Zhou

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Undergraduate Student

RPPR Final Report
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Participant: Hope Bretscher

Person Months Worked: 12.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Funding Support:

Participant Type: Co-Investigator

Participant: Paul Nealey

Person Months Worked: 12.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Funding Support:

Participant Type: Co PD/PI

Participant: David Awschalom

Person Months Worked: 1.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: Y

Other Collaborators:

Funding Support:

Participant Type: Co PD/PI

Participant: Joseph P Heremans

Person Months Worked: 2.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: Y

Other Collaborators:

Funding Support:

Participant Type: Co PD/PI

Participant: Yaroslav Tserkovnyak

Person Months Worked: 2.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Funding Support:

ARTICLES:

RPPR Final Report
as of 06-Apr-2020

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Nature

Publication Identifier Type:

Publication Identifier:

Volume: 14

Issue: 0

First Page #: 601

Date Submitted: 2/1/17 12:00AM

Date Published: 3/2/15 5:00AM

Publication Location:

Article Title: Phonon-induced Diamagnetism

Authors: Hyungyu Jin, Oscar D. Restrepo, Nikolas Antolin, Stephen R. Boona, Wolfgang Windl, Roberto C. Mye

Keywords: thermal conductivity, phonon scattering, anharmonicity, magnetic field

Abstract: Phonons are displacements of atoms around their rest positions in a crystalline solid; they carry sound and heat but are not classically associated with magnetism. Here we show that phonons in non-magnetic materials are, in fact, sensitive to magnetic fields. We do so by demonstrating experimentally that acoustic phonons in a diamagnetic semiconductor (InSb) scatter more strongly off one another when a magnetic field is applied. We attribute this observation to the magnetic field sensitivity of the anharmonicity of the interatomic bonds, which governs the probability of phonon-phonon interactions. The displacements of atoms locally affect the orbital motion of valence band electrons, which, in the presence of an external magnetic field, spatially modulates the orbital diamagnetism around the displaced atoms. The spatial gradient in magnetic moment results in an anharmonic magnetic force exerted on the displaced atom. The process is modeled by ab initio calculations that, without the us

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Acknowledged Federal Support: Y

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Physical Review B

Publication Identifier Type:

Publication Identifier:

Volume: 90

Issue: 0

First Page #: 94409

Date Submitted:

Date Published:

Publication Location:

Article Title: Dynamic phase diagram of dc-pumped magnon condensates

Authors:

Keywords: Bose Einstein Condensate, Magnon, Magnetization dynamics, Phonons

Abstract: We study the effects of nonlinear dynamics and damping by phonons on a system of interacting electronically pumped magnons in a ferromagnet. The nonlinear effects are crucial for constructing the dynamic phase diagram, which describes how "swasing" and Bose-Einstein condensation emerge out of the quasiequilibrated thermal cloud of magnons. We analyze the system in the presence of magnon damping and interactions, demonstrating the continuous onset of stable condensates as well as hysteretic transitions.

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nature Communications
Publication Identifier Type: DOI **Publication Identifier:** 10.1038/ncomms5334
Volume: 5 **Issue:** 0 **First Page #:** 4334
Date Submitted: **Date Published:**
Publication Location:

Article Title: Spin current generated by thermally driven ultrafast demagnetization

Authors:

Keywords: thermal demagnetization, spin current, ultrafast pump-probe, ferromagnetism

Abstract: Spin current is the key element for nanoscale spintronic devices. For ultrafast operation of such nano-devices, generation of spin current in picoseconds, a timescale that is difficult to achieve using electrical circuits, is highly desired. Here we show thermally driven ultrafast demagnetization of a perpendicular ferromagnet leads to spin accumulation in a normal metal and spin transfer torque in an in-plane ferromagnet. The data are well described by models of spin generation and transport based on differences and gradients of thermodynamic parameters. The temperature difference between electrons and magnons is the driving force for spin current generation by ultrafast demagnetization. On longer timescales, a few picoseconds following laser excitation, we also observe a small contribution to spin current by a temperature gradient and the spin-dependent Seebeck effect.

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Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nature Materials
Publication Identifier Type: DOI **Publication Identifier:** 10.1038/nmat4144
Volume: 14 **Issue:** 0 **First Page #:** 160
Date Submitted: 8/31/17 12:00AM **Date Published:**
Publication Location:

Article Title: Isolated electron spins in silicon carbide with millisecond-coherence times

Authors: David J. Christle, Abram L. Falk, Paolo Andrich, Paul V. Klimov, Jawad Ul Hassan, Nguyen T. Son, Erik

Keywords: Quantum spins, coherence, SiC

Abstract: The elimination of defects from SiC has facilitated its move to the forefront of the optoelectronics and power-electronics industries. Nonetheless, because the electronic states of SiC defects can have sharp optical and spin transitions, they are increasingly recognized as a valuable resource for quantum-information and nanoscale-sensing applications. Here, we show that individual electron spin states in highly purified monocrystalline 4HSiC can be isolated and coherently controlled. Bound to neutral divacancy defects, these states exhibit exceptionally long ensemble Hahn-echo spin coherence, exceeding 1 ms. Coherent control of single spins in a material amenable to advanced growth and microfabrication techniques is an exciting route to wafer-scale quantum technologies.

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Acknowledged Federal Support: Y

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Review of Scientific Instruments

Publication Identifier Type: DOI

Publication Identifier: 10.1063/1.4897622

Volume: 85

Issue: 0

First Page #: 104903

Date Submitted: 8/31/17 12:00AM

Date Published:

Publication Location:

Article Title: Pump-probe measurements of the thermal conductivity tensor for materials lacking in-plane symmetry

Authors: Joseph P. Feser, Jun Liu, David G. Cahill

Keywords: Time-domain thermorefectance, anisotropic thermal conductivity, magneto-optical Kerr effect

Abstract: We previously demonstrated an extension of time-domain thermorefectance (TDTR) which utilizes offset pump and probe laser locations to measure in-plane thermal transport properties of multilayers. However, the technique was limited to systems of transversely isotropic materials studied using axisymmetric laser intensities. Here, we extend the mathematics so that data reduction can be performed on non-transversely isotropic systems. An analytic solution of the diffusion equation for an N-layer system is given, where each layer has a homogenous but otherwise arbitrary thermal conductivity tensor and the illuminating spots have arbitrary intensity profiles. As a demonstration, we use both TDTR and time-resolved magneto-optic Kerr effect measurements to obtain thermal conductivity tensor elements of $\langle 110 \rangle$ α -SiO₂. We show that the out-of-phase beam offset sweep has full-width half-maxima that contains nearly independent sensitivity to the in-plane thermal conductivity corresponding to the

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Nature Materials

Publication Identifier Type:

Publication Identifier:

Volume: 0

Issue: 0

First Page #: 0

Date Submitted:

Date Published:

Publication Location:

Article Title: Phonon-induced diamagnetic force and its effect on the lattice thermal conductivity

Authors:

Keywords: lattice thermal conductivity, magnetism

Abstract: Phonons are displacements of atoms around their rest positions in a crystalline solid. They carry sound and heat, but are not classically associated with magnetism. Here, we show that phonons are, in fact, sensitive to magnetic fields, even in diamagnetic materials. We do so by demonstrating experimentally that acoustic phonons in a diamagnetic semiconductor (α -InSb) scatter more strongly from one another when a magnetic field is applied. We attribute this observation to the magnetic-field sensitivity of the anharmonicity of the interatomic bonds that govern the probability of phonon-phonon interactions. The displacements of atoms locally affect the orbital motion of valence band electrons, which, in the presence of an external magnetic field, spatially modulates the orbital diamagnetism around the displaced atoms. The spatial gradient in magnetic moment results in an anharmonic magnetic force exerted on the displaced atom. The process is modelled by ab initio calculations that, without

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nature Materials
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevB.92.224415
Volume: 92 **Issue:** 0 **First Page #:** 24415
Date Submitted: 8/31/17 12:00AM **Date Published:** 11/21/15 5:00AM
Publication Location:

Article Title: Long range pure magnon spin diffusion observed in a non-local spin-Seebeck geometry

Authors: Brandon L. Giles, Zihao Yang, John S. Jamison, Roberto C. Myers

Keywords: spin seebeck, magnon diffusion, spin transport

Abstract: The spin diffusion length for thermally excited magnon spins is measured by utilizing a nonlocal spin-Seebeck effect measurement. In a bulk single crystal of yttrium iron garnet (YIG) a focused laser thermally excites magnon spins. The spins diffuse laterally and are sampled using a Pt inverse spin Hall effect detector. Thermal transport modeling and temperature dependent measurements demonstrate the absence of spurious temperature gradients beneath the Pt detector and confirm the nonlocal nature of the experimental geometry. Remarkably, we find that thermally excited magnon spins in YIG travel over 120 μm at 23 K, indicating that they are robust against inelastic scattering. The spin diffusion length is found to be at least 47 μm and as high as 73 μm at 23 K in YIG, while at room temperature it drops to less than 10 μm . Based on this long spin diffusion length, we envision the development of thermally powered spintronic devices based on electrically insulating, but spin conducting mat

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Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review B
Publication Identifier Type: **Publication Identifier:**
Volume: 9.0E+001 **Issue:** 2.1E+001 **First Page #:** 214432
Date Submitted: **Date Published:**
Publication Location:

Article Title: Kerr rotation in Cu, Ag, and Au driven by spin accumulation and spin-orbit coupling

Authors:

Keywords: Time-resolved MOKE, spin transport, ultrafast demagnetization

Abstract: We measure transient spin accumulation in Cu, Ag, and Au by time-resolved magneto-optical Kerr effect. The transient spin current is generated by ultrafast demagnetization of a ferromagnetic [Co/Pt] layer, and spin accumulates in an adjacent normal metal, Cu, Ag, or Au by spin diffusion. The magnitude of the Kerr rotation is described by an off-diagonal conductivity tensor that is proportional to spin accumulation and spin-orbit coupling. From comparisons between observed Kerr rotations and calculated spin accumulations, we determine the strength of spin-orbit coupling of conduction electrons in Cu, Ag, and Au to be 0.02, 0.01, and 0.12eV, respectively.

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Journal: Review of Scientific Instruments

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Date Submitted: Date Published:

Publication Location:

Article Title: Pump-probe measurements of the thermal conductivity tensor for materials lacking in-plane symmetry

Authors:

Keywords: Thermal conductivity, Transducers, Tensor methods, Heat capacity, Multilayers

Abstract: We previously demonstrated an extension of time-domain thermorefectance (TDTR) which utilizes offset pump and probe laser locations to measure in-plane thermal transport properties of multilayers. However, the technique was limited to systems of transversely isotropic materials studied using axisymmetric laser intensities. Here, we extend the mathematics so that data reduction can be performed on non-transversely isotropic systems. An analytic solution of the diffusion equation for an N-layer system is given, where each layer has a homogenous but otherwise arbitrary thermal conductivity tensor and the illuminating spots have arbitrary intensity profiles. As a demonstration, we use both TDTR and time-resolved magneto-optic Kerr effect measurements to obtain thermal conductivity tensor elements of $\langle 110 \rangle$ α -SiO₂. We show that the out-of-phase beam offset sweep has full-width half-maxima that contains nearly independent sensitivity to the in-plane thermal conductivity corresponding to the

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Volume: 9.0E+001 Issue: 2.2E+001 First Page #: 224408

Date Submitted: Date Published:

Publication Location:

Article Title: Ultrafast demagnetization of FePt:Cu thin films and the role of magnetic heat capacity

Authors:

Keywords: ultrafast demagnetization, heat capacity, time-resolved MOKE

Abstract: The phenomenon of different time scales of ultrafast demagnetization has attracted much attention. This so-called diversity of ultrafast demagnetization has been explained by the microscopic three temperature model (M3TM) and by the Landau-Lifshitz-Bloch model (LLBM). Here, we revisit the basic three temperature model (3TM) and provide a general criterion for explaining the different time scales observed. We focus on the role of magnetic heat capacity, which we find mainly determines the slowing down of the demagnetization time with increasing ambient temperature and laser fluence. In this context, we clarify the role of magnetic heat capacity in the M3TM and compare the 3TM with the LLBM. To illustrate the role of magnetic heat capacity, we present a simulation of ultrafast demagnetization of Ni. Furthermore, we present time-resolved magneto-optic Kerr effect measurements of ultrafast demagnetization and specific heat of Fe₄₆Cu₆Pt₄₈ from 300 K to close to its Curie temperature. While

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Journal: Nature Physics

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Volume: 1.1E+001 Issue: 7.0E+000 First Page #: 576

Date Submitted: Date Published:

Publication Location:

Article Title: Thermal spin-transfer torque driven by the spin-dependent Seebeck effect in metallic spin-valves

Authors:

Keywords: spin-transfer torque, spin caloritronics, spin-valve, multilayers, time-resolved MOKE

Abstract: The coupling of spin and heat gives rise to new physical phenomena in nanoscale spin devices. In particular, spin-transfer torque (STT) driven by thermal transport provides a new way to manipulate local magnetization. We quantify thermal STT in metallic spin-valve structures using an intense and ultrafast heat current created by picosecond pulses of laser light. Our result shows that thermal STT consists of demagnetization-driven and spin-dependent Seebeck effect (SDSE)-driven components; the SDSE-driven STT becomes dominant after 3 ps. The sign and magnitude of the SDSE-driven STT can be controlled by the composition of a ferromagnetic layer and the thickness of a heat sink layer.

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Date Submitted: Date Published:

Publication Location:

Article Title: Spin-dependent thermal transport perpendicular to the planes of Co/Cu multilayers

Authors:

Keywords: Multilayers, thermal conductivity, time-domain thermoreflectance

Abstract: We report measurements of the cross-plane thermal conductivity of periodic Co/Cu multilayers using time-domain thermoreflectance. The cross-plane thermal conductivity increases from $\sim 18 \text{ W m}^{-1} \text{ K}^{-1}$ at remanence to $\sim 32 \text{ W m}^{-1} \text{ K}^{-1}$ at saturation fields. This giant magnetothermal resistance (GMTR) effect is consistent with predictions based on the Wiedemann-Franz law. We discuss the role of a spin-dependent temperature, known as spin heat accumulation, in GMTR experiments and develop a three-temperature model capable of predicting the time evolution of the temperatures of majority-spin electrons, minority-spin electrons, and phonons subsequent to pulsed laser heating.

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Volume: 9.1E+001 Issue: 4.0E+000 First Page #: 41121

Date Submitted: Date Published:

Publication Location:

Article Title: Spin and orbital magnetic response on the surface of a topological insulator

Authors:

Keywords: Topological insulators, magnetoelectric coupling, thermodynamic properties

Abstract: Coupling of the spin and orbital degrees of freedom on the surface of a strong three-dimensional insulator, on the one hand, and textured magnetic configuration in an adjacent ferromagnetic film, on the other, is studied using a combination of transport and thermodynamic considerations. Expressing exchange coupling between the localized magnetic moments and Dirac electrons in terms of the electrons' out-of-plane orbital and spin magnetizations, we relate the thermodynamic properties of a general ferromagnetic spin texture to the physics in the zeroth Landau level. Persistent currents carried by Dirac electrons endow the magnetic texture with a Dzyaloshinski-Moriya interaction, which exhibits a universal scaling form as a function of electron temperature, chemical potential, and the time-reversal symmetry breaking gap. In addition, the orbital motion of electrons establishes a direct magnetoelectric coupling between the unscreened electric field and local magnetic order, which furnishes

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Journal: Physical Review B, Rapid Communications

Publication Identifier Type: Publication Identifier:

Volume: 9.1E+001 Issue: 1.4E+001 First Page #: 140402

Date Submitted: Date Published:

Publication Location:

Article Title: Interfacial spin and heat transfer between metals and magnetic insulators

Authors:

Keywords: spin caloritronics, magnon transport, thermal transport, spin transport

Abstract: We study the role of thermal magnons in spin and heat transport across a normal-metal/insulating-ferromagnet interface, which is beyond an elastic electronic spin transfer. Using an interfacial exchange Hamiltonian, which couples spins of itinerant and localized orbitals, we calculate spin and energy currents for an arbitrary interfacial temperature difference and misalignment of spin accumulation in the normal metal relative to the ferromagnetic order. The magnonic contribution to spin current leads to a temperature-dependent torque on the magnetic order parameter; reciprocally, the coherent precession of the magnetization pumps spin current into the normal metal, the magnitude of which is affected by the presence of thermal magnons.

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Journal: Physical Review B

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Volume: 9.3E+001 Issue: 2.0E+000 First Page #: 0

Date Submitted: Date Published:

Publication Location:

Article Title: Thermally activated phase slips in superfluid spin transport in magnetic wires

Authors:

Keywords: theory, spin transport, superfluid, spin caloritronics

Abstract: We theoretically study thermally activated phase slips in superfluid spin transport in easy-plane magnetic wires within the stochastic Landau-Lifshitz-Gilbert phenomenology, which runs parallel to the Langer-Ambegaokar-McCumber-Halperin theory for thermal resistances in superconducting wires. To that end, we start by obtaining the exact solutions for free-energy minima and saddle points. We provide an analytical expression for the phase-slip rate in the zero spin-current limit, which involves a detailed analysis of spin fluctuations at the extrema of the free energy. An experimental setup for a magnetoelectric circuit is proposed, in which thermal phase slips can be inferred by measuring nonlocal magnetoresistance.

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Journal: Physical Review B, Rapid Communications

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Volume: 9.2E+001 Issue: 2.2E+001 First Page #: 220409

Date Submitted: Date Published:

Publication Location:

Article Title: Topological spin transport by Brownian diffusion of domain walls

Authors:

Keywords: spin caloritronics, spin transport, Brownian motion, domain wall

Abstract: We propose thermally populated domain walls (DWs) in an easy-plane ferromagnetic insulator as robust spin carriers between two metals. The chirality of a DW, which serves as a topological charge, couples to the metal spin accumulation via spin-transfer torque and results in the chirality-dependent thermal nucleation rates of DWs at the interface. After overpopulated DWs of a particular (net) chirality diffuse and leave the ferromagnet at the other interface, they reemit the spin current by spin pumping. The conservation of the topological charge supports an algebraic decay of spin transport as the length of the ferromagnet increases; this is analogous to the decaying behavior of superfluid spin transport but contrasts with the exponential decay of magnon spin transport. We envision that similar spin transport with algebraic decay may be implemented in materials with exotic spin phases by exploiting topological characteristics and the associated conserved quantities of their excitations

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Publication Location:

Article Title: Long-range pure magnon spin diffusion observed in a nonlocal spin-Seebeck geometry

Authors:

Keywords: magnon spin diffusion, spin transport, spin caloritronics

Abstract: The spin diffusion length for thermally excited magnon spins is measured by utilizing a nonlocal spin-Seebeck effect measurement. In a bulk single crystal of yttrium iron garnet (YIG) a focused laser thermally excites magnon spins. The spins diffuse laterally and are sampled using a Pt inverse spin Hall effect detector. Thermal transport modeling and temperature dependent measurements demonstrate the absence of spurious temperature gradients beneath the Pt detector and confirm the nonlocal nature of the experimental geometry. Remarkably, we find that thermally excited magnon spins in YIG travel over 120 μm at 23 K, indicating that they are robust against inelastic scattering. The spin diffusion length is found to be at least 47 μm and as high as 73 μm at 23 K in YIG, while at room temperature it drops to less than 10 μm . Based on this long spin diffusion length, we envision the development of thermally powered spintronic devices based on electrically insulating, but spin conducting mat

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Date Submitted:

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Publication Location:

Article Title: Effect of the magnon dispersion on the longitudinal spin Seebeck effect in yttrium iron garnets

Authors:

Keywords: spin caloritronics, spin-Seebeck effect, magnon dispersion

Abstract: We study the temperature dependence of the longitudinal spin Seebeck effect (LSSE) in an yttrium iron garnet Y₃Fe₅O₁₂ (YIG)/Pt system for samples of different thicknesses. In this system, the thermal spin torque is magnon driven. The LSSE signal peaks at a specific temperature that depends on the YIG sample thickness. We also observe freeze-out of the LSSE signal at high magnetic fields, which we attribute to the opening of an energy gap in the magnon dispersion. We observe partial freeze-out of the LSSE signal even at room temperature, where $k_B T$ is much larger than the gap. This suggests that a subset of the magnon population with an energy below $k_B T_C$ ($T_C \approx 40\text{K}$) contributes disproportionately to the LSSE; at temperatures above T_C , we label these magnons subthermal magnons. The T dependence of the LSSE at temperatures below the maximum is interpreted in terms of an empirical model that ascribes most of the temperature dependence to that of the thermally driven magnon flux, which is relat

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Date Submitted: Date Published:

Publication Location:

Article Title: Landau-Lifshitz theory of thermomagnonic torque

Authors:

Keywords: theory, spin caloritronics, spin torque, magnetic domains

Abstract: We derive the thermomagnonic torque associated with smooth magnetic textures subjected to a temperature gradient in the framework of the stochastic Landau-Lifshitz-Gilbert equation. Our approach captures on equal footing two distinct contributions: (i) a local entropic torque that is caused by a temperature dependence of the effective exchange field, the existence of which had been previously suggested based on numerics, and (ii) the well-known spin-transfer torque induced by thermally induced magnon flow. The dissipative components of two torques have the same structure, following a common phenomenology, but opposite signs, with the twice as large entropic torque leading to a domain-wall motion toward the hotter region. We compare the efficiency of the torque-driven domain-wall motion with the recently proposed Brownian thermophoresis.

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Date Submitted: Date Published:

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Article Title: Thermophoresis of an antiferromagnetic soliton

Authors:

Keywords: theory, antiferromagnets, spin caloritronics, domain wall motion

Abstract: We study the dynamics of an antiferromagnetic soliton under a temperature gradient. To this end, we start by phenomenologically constructing the stochastic Landau-Lifshitz-Gilbert equation for an antiferromagnet with the aid of the fluctuation-dissipation theorem. We then derive the Langevin equation for the soliton's center of mass by the collective coordinate approach. An antiferromagnetic soliton behaves as a classical massive particle immersed in a viscous medium. By considering a thermodynamic ensemble of solitons, we obtain the Fokker-Planck equation, from which we extract the average drift velocity of a soliton. The diffusion coefficient is inversely proportional to a small damping constant α , which can yield a drift velocity of tens of m/s under a temperature gradient of 1 K/mm for a domain wall in an easy-axis antiferromagnetic wire with $\alpha \approx 10^{-4}$.

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Date Submitted: Date Published:

Publication Location:

Article Title: Control and braiding of Majorana fermions bound to magnetic domain walls

Authors:

Keywords: Majorana fermions, domain walls

Abstract: Owing to the recent progress on endowing the electronic structure of magnetic nanowires with topological properties, the associated topological solitons in the magnetic texture—magnetic domain walls—appear as very natural hosts for exotic electronic excitations. Here, we propose to use the magnetic domain walls to engender Majorana fermions, which has several notable advantages compared to the existing approaches. First of all, the local tunneling density-of-states anomaly associated with the Majorana zero mode bound to a smooth magnetic soliton is immune to most of parasitic artifacts associated with the abrupt physical ends of a wire, which mar the existing experimental probes. Second, a viable route to move and braid Majorana fermions is offered by domain-wall motion. In particular, we envision the recently demonstrated heat-current induced motion of domain walls in insulating ferromagnets as a promising tool for nonintrusive displacement of Majorana modes. This leads us to propose

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Publication Location:

Article Title: Spin Seebeck effect through antiferromagnetic NiO

Authors: Arati Prakash, Jack Brangham, Fengyuan Yang, Joseph P. Heremans

Keywords: spin seebeck, NiO, antiferromagnet, spin transport

Abstract: We report temperature-dependent spin Seebeck measurements on Pt/YIG bilayers and Pt/NiO/YIG trilayers, where YIG (yttrium iron garnet, Y₃Fe₅O₁₂) is an insulating ferrimagnet and NiO is an antiferromagnet at low temperatures. The thickness of the NiO layer is varied from 0 to 10 nm. In the Pt/YIG bilayers, the temperature gradient applied to the YIG stimulates dynamic spin injection into the Pt, which generates an inverse spin Hall voltage in the Pt. The presence of a NiO layer dampens the spin injection exponentially with a decay length of 2 ± 0.6 nm at 180 K. The decay length increases with temperature and shows a maximum of 5.5 ± 0.8 nm at 360 K. The temperature dependence of the amplitude of the spin Seebeck signal without NiO shows a broad maximum of 6.5 ± 0.5 μ V/K at 20 K. In the presence of NiO, the maximum shifts sharply to higher temperatures, likely correlated to the increase in decay length. This implies that NiO is most transparent to magnon propagation near the paramagnet-a

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Article Title: Magnons and Phonons Optically Driven out of Local Equilibrium in a Magnetic Insulator

Authors: 7. Kyongmo An, Kevin S. Olsson, Annie Weathers, Sean Sullivan, Xi Chen, Xiang Li, Luke G. Marsh

Keywords: magnon-phonon coupling, YIG, laser heating, Raman, Brillouin scattering

Abstract: Magnons are the energy quanta of fundamental spin excitations, namely spin waves, and they can make a considerable contribution to energy transport in some magnetic materials in a similar manner as lattice vibration waves or phonons. The coupling and possible non-equilibrium between magnons and other energy carriers have been used to explain several recently discovered thermally driven spin transport and energy conversion phenomena. Here, we report experiments in which local non-equilibrium between magnons and phonons in a single crystalline bulk magnetic insulator, Y₃Fe₅O₁₂ (yttrium iron garnet, or YIG), has been created optically within a focused laser spot and probed directly with the use of micro-Brillouin light scattering (BLS). By analyzing the experimental results with a thermally induced magnon diffusion model, we obtain the magnon diffusion length of thermal magnons. By explicitly establishing non-equilibrium between magnons and phonons, our studies represent an important step

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Article Title: Optical-helicity-driven magnetization dynamics in metallic ferromagnets

Authors: Gyung-Min Choi, Andre Schleife, David G. Cahill

Keywords: optical control, magnetization dynamics, metallic ferromagnets

Abstract: We experimentally study magnetization dynamics of metallic ferromagnets (Co, Fe, Ni) driven by angular momentum of light. With a thin film ferromagnet/Au or ferromagnet/oxide structure, circularly polarized light imparts instantaneous torque on magnetization into the direction of the cross product of magnetization and the angular momentum of photons as well as parallel to the angular momentum of photons. The latter contribution increases significantly when the ferromagnetic layer is capped with a thin layer of Pt. We interpret these different behaviors in terms of inverse Faraday effect and optical spin transfer torque. Inverse Faraday effect is relatively insensitive to the composition of the ferromagnetic material or capping layer; the coefficient that relates the optomagnetic field to the intensity of the optical electric field is on the order of $10^{-18} \text{ T m}^2 \text{ V}^{-2}$. The optical spin transfer torque is significantly enhanced by the Pt capping layer, which produces a spin polarization

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Date Submitted: 8/30/16 12:00AM **Date Published:** 3/1/16 5:00AM
Publication Location:

Article Title: Bose-Einstein condensation of magnons pumped by the bulk spin Seebeck effect

Authors: Yaroslav Tserkovnyak, Scott A. Bender, Rembert A. Duine, Benedetta Flebus

Keywords: magnon BEC, YIG, thermal spin pumping

Abstract: We propose inducing Bose-Einstein condensation of magnons in a magnetic insulator by a heat flow oriented toward its boundary. At a critical heat flux, the oversaturated thermal gas of magnons accumulated at the boundary precipitates the condensate, which then grows gradually as the thermal bias is dialed up further. The thermal magnons thus pumped by the magnonic bulk (spin) Seebeck effect must generally overcome both the local Gilbert damping associated with the coherent magnetic dynamics as well as the radiative spin-wave losses toward the magnetic bulk, in order to achieve the threshold of condensation. We quantitatively estimate the requisite bias in the case of the ferrimagnetic yttrium iron garnet, discuss different physical regimes of condensation, and contrast it with the competing (so-called Doppler-shift) bulk instability.

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Date Submitted: 8/30/16 12:00AM **Date Published:** 3/1/16 5:00AM
Publication Location:

Article Title: Topological Effects on Quantum Phase Slips in Superfluid Spin Transport

Authors: Se Kwon Kim, Yaroslav Tserkovnyak

Keywords: spin superfluid transport

Abstract: We theoretically investigate effects of quantum fluctuations on superfluid spin transport through easy-plane quantum antiferromagnetic spin chains in the large-spin limit. Quantum fluctuations result in the decaying spin supercurrent by unwinding the magnetic order parameter within the easy plane, which is referred to as phase slips. We show that the topological term in the nonlinear sigma model for the spin chains qualitatively differentiates the decaying rate of the spin supercurrent between the integer versus half-odd-integer spin chains. An experimental setup for a magnetoelectric circuit is proposed, in which the dependence of the decaying rate on constituent spins can be verified by measuring the nonlocal magnetoresistance.

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Date Submitted: 8/30/16 12:00AM

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Publication Location:

Article Title: Topological spin-transfer drag driven by skyrmion diffusion

Authors: Héctor Ochoa, Se Kwon Kim, Yaroslav Tserkovnyak

Keywords: spin-transfer drag, skyrmion, spin transport

Abstract: We study the spin-transfer drag mediated by the Brownian motion of skyrmions. The essential idea is illustrated in a two-terminal geometry, in which a thin film of a magnetic insulator is placed in between two metallic reservoirs. An electric current in one of the terminals pumps topological charge into the magnet via a spin-transfer torque. The charge diffuses over the bulk of the system as stable skyrmion textures. By Onsager's reciprocity, the topological charge leaving the magnet produces an electromotive force in the second terminal. The voltage signal decays algebraically with the separation between contacts, in contrast to the exponential suppression of the spin drag driven by nonprotected excitations like magnons. We show how this topological effect can be used as a tool to characterize the phase diagram of chiral magnets and thin films with interfacial Dzyaloshinskii-Moriya interactions.

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Article Title: Realization of the Haldane-Kane-Mele Model in a System of Localized Spins

Authors: Se Kwon Kim, Héctor Ochoa, Ricardo Zarzuela, Yaroslav Tserkovnyak

Keywords: spin-orbit coupling, ferromagnets, topological states, spin Nernst

Abstract: We theoretically study a spin Hamiltonian for spin-orbit-coupled ferromagnets on the honeycomb lattice. We find that the effective Hamiltonian for magnons, a quanta of spin-wave excitations from ordered states, is equivalent to the Haldane model for electrons in the honeycomb lattice, which indicates the nontrivial topology of the magnon bands and the existence of the associated edge state. We also take the Schwinger boson (or bosonic spinon) representations of spins that are applicable both to ordered and disordered phases. We show that the spinon bands within the mean-field treatment are topologically nontrivial, which causes a spin Nernst effect, by adopting the properties of the Kane-Mele model. A feasible experimental realization of the spin Hamiltonian is proposed.

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Article Title: Weak coupling of pseudoacoustic phonons and magnon dynamics in the incommensurate spin-ladder compound

Authors: Xi Chen, Dipanshu Bansal, Sean Sullivan, Douglas L. Abernathy, Adam A. Aczel, Jianshi Zhou, Olivier I

Keywords: Neutron scattering, magnon and phonon dispersions, chain and ladder cuprates

Abstract: Intriguing lattice dynamics have been predicted for aperiodic crystals that contain incommensurate substructures. Here we report inelastic neutron scattering measurements of phonon and magnon dispersions in Sr₁₄Cu₂₄O₄₁, which contains incommensurate one-dimensional (1D) chain and two-dimensional (2D) ladder substructures. Two distinct pseudoacoustic phonon modes, corresponding to the sliding motion of one sublattice against the other, are observed for atomic motions polarized along the incommensurate axis. In the long wavelength limit, it is found that the sliding mode shows a remarkably small energy gap of 1.7–1.9 meV, indicating very weak interactions between the two incommensurate sublattices. The measurements also reveal a gapped and steep linear magnon dispersion of the ladder sublattice. The high group velocity of this magnon branch and weak coupling with acoustic and pseudoacoustic phonons can explain the large magnon thermal conductivity in Sr₁₄Cu₂₄O₄₁ crystals.

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Publication Location:

Article Title: Spin Seebeck effect through antiferromagnetic NiO

Authors: Arati Prakash, Jack Brangham, Fengyuan Yang, Joseph P. Heremans

Keywords: spin Seebeck, antiferromagnets

Abstract: We report temperature-dependent spin Seebeck measurements on Pt/YIG bilayers and Pt/NiO/YIG trilayers, where YIG (yttrium iron garnet, Y₃Fe₅O₁₂) is an insulating ferrimagnet and NiO is an antiferromagnet at low temperatures. The thickness of the NiO layer is varied from 0 to 10 nm. In the Pt/YIG bilayers, the temperature gradient applied to the YIG stimulates dynamic spin injection into the Pt, which generates an inverse spin Hall voltage in the Pt. The presence of a NiO layer dampens the spin injection exponentially with a decay length of 2 ± 0.6 nm at 180 K. The decay length increases with temperature and shows a maximum of 5.5 ± 0.8 nm at 360 K. The temperature dependence of the amplitude of the spin Seebeck signal without NiO shows a broad maximum of 6.5 ± 0.5 μ V/K at 20 K. In the presence of NiO, the maximum shifts sharply to higher temperatures, likely correlated to the increase in decay length. This implies that NiO is most transparent to magnon propagation.

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Publication Location:

Article Title: Mechanical Actuation of Magnetic Domain-Wall Motion

Authors: Se Kwon Kim, Daniel Hill, Yaroslav Tserkovnyak

Keywords: domain wall, magnetization dynamics

Abstract: We theoretically study the motion of a magnetic domain wall induced by transverse elastic waves in a one-dimensional magnetic wire, which respects both rotational and translational symmetries. By invoking the conservation of the associated total angular and linear momenta, we are able to derive the torque and the force on the domain wall exerted by the waves. We then show how ferromagnetic and antiferromagnetic domain walls can be driven by circularly and linearly polarized waves, respectively. We envision that elastic waves may provide effective means to drive the dynamics of magnetic solitons in insulators.

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Article Title: Local thermomagnonic torques in two-fluid spin dynamics

Authors: Benedetta Flebus, Pramey Upadhyaya, Rembert A. Duine, Yaroslav Tserkovnyak

Keywords: spin Seebeck, spin superfluid

Abstract: We develop a general phenomenology describing the interplay between coherent and incoherent dynamics in ferromagnetic insulators. Using the Onsager reciprocity and Neumann's principle, we derive expressions for the local thermomagnonic torques exerted by thermal magnons on the order-parameter dynamics and the reciprocal pumping processes, which are in close analogy to the spin-transfer torque and the spin pumping at metallic interfaces. Our formalism is applicable to general long-wavelength dynamics and, although here we explicitly focus on ferromagnetic insulators possessing $U(1)$ symmetry, our approach can be easily extended to other classes of magnetic materials. As an illustrative example, we apply our theory to investigate a domain wall floating over a spin superfluid, whose dynamics are triggered thermally at the system's edge. Our results demonstrate that the local pumping of coherent spin dynamics by a thermal magnon gas offers an alternative route—with no need for conducting co

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Article Title: Optical-helicity-driven magnetization dynamics in metallic ferromagnets

Authors: Gyung-Min Choi, André Schleife, David G. Cahill

Keywords: magnetization dynamics

Abstract: Recent observations of switching of magnetic domains in ferromagnetic metals by circularly polarized light, so-called all-optical helicity dependent switching, has renewed interest in the physics that governs the interactions between the angular momentum of photons and the magnetic order parameter of materials. Here we use time-resolved-vectorial measurements of magnetization dynamics of thin layers of Fe, Ni and Co driven by picosecond duration pulses of circularly polarized light. We decompose the torques that drive the magnetization into field-like and spin-transfer components that we attribute to the inverse Faraday effect and optical spin-transfer torque, respectively. The inverse Faraday effect is approximately the same in Fe, Ni and Co, but the optical spin-transfer torque is strongly enhanced by adding a Pt capping layer. Our work provides quantitative data for testing theories of light-material interactions in metallic ferromagnets and multilayers.

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Article Title: Spin diffusion induced by pulsed-laser heating and the role of spin heat accumulation

Authors: Johannes Kimling, David G. Cahill

Keywords: thermal spin diffusion

Abstract: We present a model for describing spin diffusion in normal-metal/ferromagnetic-metal heterostructures induced by pulsed-laser heating. The model is based on the assumptions that electronic heat currents give rise to the spin-dependent Seebeck effect and that ultrafast demagnetization generates spin accumulation with a rate proportional to the demagnetization rate measured. Spin-diffusion currents are then driven by gradients in spin accumulation and electron temperature. The model considers spin-dependent thermal conductivity and electron-phonon coupling, which can give rise to different effective temperatures for majority and minority spins, known as spin heat accumulation. We find that spin heat accumulation can significantly enhance the spin-dependent Seebeck effect.

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Volume: 118 **Issue:** 5 **First Page #:** 057201
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Publication Location:
Article Title: Picosecond Spin Seebeck Effect
Authors: Johannes Kimling, Gyung-Min Choi, Jack T. Brangham, Tristan Matalla-Wagner, Torsten Huebner, Tim
Keywords: spin Seebeck effect
Abstract: We report time-resolved magneto-optic Kerr effect measurements of the longitudinal spin Seebeck effect in normal metal/Y3Fe5O12 bilayers driven by an interfacial temperature difference between electrons and magnons. The measured time evolution of spin accumulation induced by laser excitation indicates transfer of angular momentum across normal metal / Y3Fe5O12 interfaces on a picosecond time scale, too short for contributions from a bulk temperature gradient in an yttrium iron garnet. The product of spin-mixing conductance and the interfacial spin Seebeck coefficient determined is of the order of $10^8 \text{ A}^2 \text{ m}^2 \text{ K}^{-1}$.
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Publication Location:
Article Title: Effects of grain boundaries and defects on anisotropic magnon transport in textured
Authors: Xi Chen, Karalee Jarvis, Sean Sullivan, Yutao Li, Jianshi Zhou, Li Shi
Keywords: magnon transport, grain boundaries
Abstract: The strong spin-spin exchange interaction in some low-dimensional magnetic materials can give rise to a high group velocity and thermal conductivity contribution from magnons. Examples are the incommensurate layered compounds (Sr,Ca,La)14Cu24O41. The effects of grain boundaries and defects on quasi-one-dimensional magnon transport in these compounds are not well understood. Here we report the microstructural and anisotropic thermal transport properties of textured Sr14Cu24O41, which is prepared by solid-state reaction followed by spark plasma sintering. Transmission electron microscopy clearly reveals nanolayered grains and the presence of dislocations and planar defects. The thermal conductivity contribution and mean free paths of magnons in the textured samples are evaluated with the use of a kinetic model for one-dimensional magnon transport and found to be suppressed significantly compared to single crystals at low temperatures. The experimental results can be explained by a one-dim
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Date Submitted: 8/31/17 12:00AM **Date Published:** 12/1/16 5:00AM
Publication Location:
Article Title: Interaction between a domain wall and spin supercurrent in easy-cone magnets
Authors: Se Kwon Kim, Yaroslav Tserkovnyak
Keywords: domain wall, spin supercurrent
Abstract: A domain wall and spin supercurrent can coexist in magnets with easy-cone anisotropy owing to simultaneous spontaneous breaking of Z2 and U(1) symmetries. Their interaction is theoretically investigated in quasi-one-dimensional ferromagnets within the Landau-Lifshitz-Gilbert phenomenology. Specifically, the spin supercurrent can exert the torque on a domain wall and thereby drive it. We also show, as a reciprocal phenomenon, a field-induced motion of a domain wall can generate spin supercurrent.
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Article Title: Magnetic Domain Wall Floating on a Spin Superfluid

Authors: Pramey Upadhyaya, Se Kwon Kim, Yaroslav Tserkovnyak

Keywords: domain wall, spin superfluid

Abstract: We theoretically investigate the transfer of angular momentum between a spin superfluid and a domain wall in an exchange coupled easy-axis and easy-plane magnetic insulator system. A domain wall in the easy-axis magnet absorbs spin angular momentum via disrupting the flow of a superfluid spin current in the easy-plane magnet. Focusing on an open geometry, where the spin current is injected electrically via a nonequilibrium spin accumulation, we derive analytical expressions for the resultant superfluid-mediated motion of the domain wall. The analytical results are supported by micromagnetic simulations. The proposed phenomenon extends the regime of magnon-driven domain-wall motion to the case where the magnons are condensed and exhibit superfluidity. Furthermore, by controlling the pinning of the domain wall, we propose a realization of a reconfigurable spin transistor. The long-distance dissipationless character of spin superfluids can thus be exploited for manipulating soliton-based

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Article Title: Self-focusing skyrmion racetracks in ferrimagnets

Authors: Se Kwon Kim, Kyung-Jin Lee, Yaroslav Tserkovnyak

Keywords: skyrmion, ferrimagnets, dynamics

Abstract: We theoretically study the dynamics of ferrimagnetic skyrmions in inhomogeneous metallic films close to the angular momentum compensation point. In particular, it is shown that the line of the vanishing angular momentum can be utilized as a self-focusing racetrack for skyrmions. To that end, we begin by deriving the equations of motion for the dynamics of collinear ferrimagnets in the presence of a charge current. The obtained equations of motion reduce to those of ferromagnets and antiferromagnets at two special limits. In the collective coordinate approach, a skyrmion behaves as a massive charged particle moving in a viscous medium subjected to a magnetic field. Analogous to the snake orbits of electrons in a nonuniform magnetic field, we show that a ferrimagnet with nonuniform angular momentum density can exhibit the snake trajectories of skyrmions, which can be utilized as racetracks for skyrmions.

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Article Title: Spin analogs of superconductivity and integer quantum Hall effect in an array of spin chains

Authors: Daniel Hill, Se Kwon Kim, Yaroslav Tserkovnyak

Keywords: spin superconductivity

Abstract: Motivated by the successful idea of using weakly coupled quantum electronic wires to realize the quantum Hall effects and the quantum spin Hall effects, we theoretically study two systems composed of weakly coupled quantum spin chains within the mean-field approximations, which can exhibit spin analogs of superconductivity and the integer quantum Hall effect. First, a certain bilayer of two arrays of interacting spin chains is mapped, via the Jordan-Wigner transformation, to an attractive Hubbard model that exhibits fermionic superconductivity, which corresponds to spin superconductivity in the original spin Hamiltonian. Secondly, an array of spin-orbit-coupled spin chains in the presence of a suitable external magnetic field is transformed to an array of quantum wires that exhibits the integer quantum Hall effect, which translates into its spin analog in the spin Hamiltonian. The resultant spin superconductivity and spin integer quantum Hall effect can be characterized by their ability

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Article Title: Gauge fields and related forces in antiferromagnetic soliton physics

Authors: Sayak Dasgupta, Se Kwon Kim, Oleg Tchernyshyov

Keywords: soliton dynamics, antiferromagnets

Abstract: We derive equations of motion for topological solitons in antiferromagnets under the combined action of perturbations such as an external magnetic field and torque-generating electrical current. Aside from conservative forces, such perturbations generate an effective “magnetic field” exerting a gyrotropic force on the soliton and an induced “electric field” if the perturbation is time-dependent. We apply the general formalism to the cases of a domain wall and of a vortex. An antiferromagnetic vortex can be effectively moved by combined applications of a magnetic field and an electric current.

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Article Title: Fast vortex oscillations in a ferrimagnetic disk near the angular momentum compensation point

Authors: Se Kwon Kim, Yaroslav Tserkovnyak

Keywords: magnetic vortices, ferrimagnetism

Abstract: We theoretically study the oscillatory dynamics of a vortex core in a ferrimagnetic disk near its angular momentum compensation point, where the spin density vanishes but the magnetization is finite. Due to the finite magnetostatic energy, a ferrimagnetic disk of suitable geometry can support a vortex as a ground state similar to a ferromagnetic disk. In the vicinity of the angular momentum compensation point, the dynamics of the vortex resemble those of an antiferromagnetic vortex, which is described by equations of motion analogous to Newton's second law for the motion of particles. Owing to the antiferromagnetic nature of the dynamics, the vortex oscillation frequency can be an order of magnitude larger than the frequency of a ferromagnetic vortex, amounting to tens of GHz in common transition-metal based alloys. We show that the frequency can be controlled either by applying an external field or by changing the temperature. In particular, the latter property allows us to detect the

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Date Submitted: 8/31/17 12:00AM **Date Published:** 7/1/17 4:00AM
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Article Title: Gyrotropic elastic response of skyrmion crystals to current-induced tensions

Authors: Hector Ochoa, Se Kwon Kim, Oleg Tchernyshyov, Yaroslav Tserkovnyak

Keywords: Current-induced magnetization dynamics

Abstract: We theoretically study the dynamics of skyrmion crystals in electrically insulating chiral magnets subjected to current-induced spin torques by adjacent metallic layers. We develop an elasticity theory that accounts for the gyrotropic force engendered by the nontrivial topology of the spin texture, tensions at the boundaries due to the exchange of linear and spin angular momentum with the metallic reservoirs, and dissipation in the bulk of the film. A steady translation of the skyrmion crystal is triggered by the current-induced tensions and subsequently sustained by dissipative forces, generating an electromotive force on itinerant spins in the metals. This phenomenon should be revealed as a negative drag in an open two-terminal geometry, or equivalently, as a positive magnetoresistance when the terminals are connected in parallel. We propose nonlocal transport measurements with these salient features as a tool to characterize the phase diagram of insulating chiral magnets.

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Article Title: Magnetic Domain Walls as Hosts of Spin Superfluids and Generators of Skyrmions

Authors: Se Kwon Kim, Yaroslav Tserkovnyak

Keywords: Spin Superfluid, Skyrmions

Abstract: A domain wall in a magnet with easy-axis anisotropy is shown to harbor spin superfluid associated with its spontaneous breaking of the $U(1)$ spin-rotational symmetry. The spin superfluid is shown to have several topological properties, which are absent in conventional superfluids. First, the associated phase slips create and destroy Skyrmions to obey the conservation of the total Skyrmion charge, which allows us to use a domain wall as a generator and detector of Skyrmions. Second, the domain wall engenders the emergent magnetic flux for magnons along its length, which are proportional to the spin supercurrent flowing through it, and thereby provides a way to manipulate magnons. Third, the spin supercurrent can be driven by the magnon current traveling across it owing to the spin transfer between the domain wall and magnons, leading to the magnonic manipulation of the spin superfluid. The theory for superfluid spin transport within the domain wall is confirmed by numerical simulations.

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Article Title: Chiral Edge Mode in the Coupled Dynamics of Magnetic Solitons in a Honeycomb Lattice

Authors: Se Kwon Kim, Yaroslav Tserkovnyak

Keywords: Magnetic Solitons, Topological Transport

Abstract: Motivated by a recent experimental demonstration of a chiral edge mode in an array of spinning gyroscopes, we theoretically study the coupled gyration modes of topological magnetic solitons, vortices and magnetic bubbles, arranged as a honeycomb lattice. The soliton lattice under suitable conditions is shown to support a chiral edge mode like its mechanical analogue, the existence of which can be understood by mapping the system to the Haldane model for an electronic system. The direction of the chiral edge mode is associated with the topological charge of the constituent solitons, which can be manipulated by an external field or by an electric-current pulse. The direction can also be controlled by distorting the honeycomb lattice. Our results indicate that the lattices of magnetic solitons can serve as reprogrammable topological metamaterials.

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Article Title: Spin caloritronic nano-oscillator
Authors: C. Safranski, I. Barsukov, H. K. Lee, T. Schneider, A. A. Jara, A. Smith, H. Chang, K. Lenz, J. Lindner, Y
Keywords: spin caloritronics, nano-oscillator
Abstract: Energy loss due to ohmic heating is a major bottleneck limiting down-scaling and speed of nano-electronic devices, and harvesting ohmic heat for signal processing is a major challenge in modern electronics. Here, we demonstrate that thermal gradients arising from ohmic heating can be utilized for excitation of coherent auto-oscillations of magnetization and for generation of tunable microwave signals. The heat-driven dynamics is observed in Y3Fe5O12/Pt bilayer nanowires where ohmic heating of the Pt layer results in injection of pure spin current into the Y3Fe5O12 layer. This leads to excitation of auto-oscillations of the Y3Fe5O12 magnetization and generation of coherent microwave radiation. Our work paves the way towards spin caloritronic devices for microwave and magnonic applications.
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Article Title: Eu²⁺–Eu³⁺ valence transition in double, Eu-, and Na-doped PbSe from transport, magnetic, and electronic structure studies
Authors: Bartłomiej Wiendlocha, SunPhil Kim, Yeseul Lee, Bin He, Gloria Lehr, Mercouri G. Kanatzidis, Donald T
Keywords: Magnetic structure, Electronic structure, Transport
Abstract: The Eu atoms in Pb_{1-x}EuxSe have long been assumed to be divalent. We show that p-type doping of this magnetic semiconductor alloy with Na can modify the effective Eu valence: a mixed, Eu²⁺–Eu³⁺ state appears in Pb_{1-x}yEuxNaySe at particular values of y. Magnetization, carrier concentration, resistivity, and thermopower of Pb_{1-x}yEuxNaySe are reported for a number of samples with different x and y. A pronounced increase in thermopower at a given carrier concentration was identified and attributed to the presence of enhanced ionized impurity scattering. A strong decrease in the hole concentration is observed in Pb_{1-y}NaySe when Eu is added to the system, which we attribute to a Eu²⁺–Eu³⁺ self-ionization process. This is evidenced by magnetization measurements, which reveal a significant reduction of the magnetic moment of Pb_{1-x}EuxSe upon alloying with Na. Further, a deviation of magnetization from a purely paramagnetic state, described by a Brillouin function, identifies antiferromagnetic
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Article Title: Long-range spin wave mediated control of defect qubits in nanodiamonds

Authors: Paolo Andrich, Charles F. de las Casas, Xiaoying Liu, Hope L. Bretscher, Jonson R. Berman, F. Joseph

Keywords: Spin wave coherence, quantum control

Abstract: Hybrid architectures that combine nitrogen-vacancy centers in diamond with other materials and physical systems have been proposed to enhance the nitrogen-vacancy center's capabilities in many quantum sensing and information applications. In particular, spin waves in ferromagnetic materials are a promising candidate to implement these platforms due to their strong magnetic fields, which could be used to efficiently interact with the nitrogen-vacancy centers. Here, we develop an yttrium iron garnet-nanodiamond hybrid architecture constructed with the help of directed assembly and transfer printing techniques. Operating at ambient conditions, we demonstrate that surface confined spin waves excited in the ferromagnet can strongly amplify the interactions between a microwave source and the nitrogen-vacancy centers by enhancing the local microwave magnetic field by several orders of magnitude. Crucially, we show the existence of a regime in which coherent interactions between spin waves and

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Article Title: Thermally driven long-range magnon spin currents in yttrium iron garnet due to intrinsic spin Seebeck effect

Authors: Brandon L. Giles, Zihao Yang, John S. Jamison, Juan M. Gomez-Perez, Saül Vélez, Luis E. Hueso, Fèli

Keywords: spin-Seebeck

Abstract: The longitudinal spin Seebeck effect refers to the generation of a spin current when heat flows across a normal metal/magnetic insulator interface. Most explanations of the spin Seebeck effect use the interfacial temperature difference as the conversion mechanism between heat and spin fluxes. However, recent theoretical and experimental works claim that a magnon spin current is generated in the bulk of a magnetic insulator even in the absence of an interface. This is the so-called intrinsic spin Seebeck effect. Here, by utilizing a nonlocal spin Seebeck geometry, we provide additional evidence that the total magnon spin current in the ferrimagnetic insulator yttrium iron garnet (YIG) actually contains two distinct terms: one proportional to the gradient in the magnon chemical potential (pure magnon spin diffusion), and a second proportional to the gradient in magnon temperature (T_m). We observe two characteristic decay lengths for magnon spin currents in YIG with distinct temperat

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Article Title: Microscale-Resolution Thermal Mapping Using a Flexible Platform of Patterned Quantum Sensors

Authors: Paolo Andrich, Jiajing Li, Xiaoying Liu, F. Joseph Heremans, Paul F. Nealey, David D. Awschalom

Keywords: Thermal mapping, NV-center

Abstract: Temperature sensors with micro- and nanoscale spatial resolution have long been explored for their potential to investigate the details of physical systems at an unprecedented scale. In particular, the rapid miniaturization of transistor technology, with its associated steep boost in power density, calls for sensors that accurately monitor heating distributions. Here, we report on a simple and scalable fabrication approach, based on directed self-assembly and transfer-printing techniques, to constructing arrays of nanodiamonds containing temperature-sensitive fluorescent spin defects. The nanoparticles are embedded within a low-thermal-conductivity matrix that allows for repeated use on a wide range of systems with minimal spurious effects. Additionally, we demonstrate access to a wide spectrum of array parameters ranging from sparser single-particle arrays, with the potential for quantum computing applications, to denser devices with $98 \pm 0.8\%$ yield and stronger photoluminescence sign

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Publication Location:

Article Title: Theory of the magnon-mediated tunnel magneto-Seebeck effect

Authors: Benedetta Flebus, Gerrit E. W. Bauer, Rembert A. Duine, Yaroslav Tserkovnyak

Keywords: magneto-Seebeck effect

Abstract: The tunnel magneto-Seebeck effect is the dependence of the thermopower of magnetic tunnel junctions on the magnetic configuration. It is conventionally interpreted in terms of a thermoelectric generalization of the tunnel magnetoresistance. Here, we investigate the heat-driven electron transport in these junctions associated with electron-magnon scattering, using stochastic Landau-Lifshitz phenomenology and quantum kinetic theory. Our findings challenge the widely accepted single-electron picture of the tunneling thermopower in magnetic junctions.

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Date Submitted: 10/9/18 12:00AM

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Publication Location:

Article Title: Fast domain wall motion in the vicinity of the angular momentum compensation temperature of ferrimagnets

Authors: Kab-Jin Kim, Se Kwon Kim, Yuushou Hirata, Se-Hyeok Oh, Takayuki Tono, Duck-Ho Kim, Takaya Okur

Keywords: domain wall dynamics, ferrimagnets

Abstract: Antiferromagnetic spintronics is an emerging research field which aims to utilize antiferromagnets as core elements in spintronic devices. A central motivation towards this direction is that antiferromagnetic spin dynamics is expected to be much faster than its ferromagnetic counterpart³. Recent theories indeed predicted faster dynamics of antiferromagnetic domain walls (DWs) than ferromagnetic DWs. However, experimental investigations of antiferromagnetic spin dynamics have remained unexplored, mainly because of the magnetic field immunity of antiferromagnets. Here we show that fast field-driven antiferromagnetic spin dynamics is realized in ferrimagnets at the angular momentum compensation point TA. Using rare earth–3d-transition metal ferrimagnetic compounds where net magnetic moment is nonzero at TA, the field-driven DW mobility is remarkably enhanced up to 20?km?s⁻¹?T⁻¹. The collective coordinate approach generalized for ferrimagnets⁸ and atomistic spin model simulations

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Date Submitted: 10/9/18 12:00AM

Date Published: 5/1/18 4:00AM

Publication Location:

Article Title: Magnon-induced non-Markovian friction of a domain wall in a ferromagnet

Authors: Se Kwon Kim, Oleg Tchernyshyov, Victor Galitski, Yaroslav Tserkovnyak

Keywords: Domain wall dynamics

Abstract: Motivated by the recent study on the quasiparticle-induced friction of solitons in superfluids, we theoretically study magnon-induced intrinsic friction of a domain wall in a one-dimensional ferromagnet. To this end, we start by obtaining the hitherto overlooked dissipative interaction of a domain wall and its quantum magnon bath to linear order in the domain-wall velocity and to quadratic order in magnon fields. An exact expression for the pertinent scattering matrix is obtained with the aid of supersymmetric quantum mechanics. We then derive the magnon-induced frictional force on a domain wall in two different frameworks: time-dependent perturbation theory in quantum mechanics and the Keldysh formalism, which yield identical results. The latter, in particular, allows us to verify the fluctuation-dissipation theorem explicitly by providing both the frictional force and the correlator of the associated stochastic Langevin force. The potential for magnons induced by a domain wall is ref

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Journal: Physical Review Letters
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevLett.121.037202
Volume: 121 **Issue:** 3 **First Page #:** 037202
Date Submitted: 10/9/18 12:00AM **Date Published:** 7/1/18 12:00AM
Publication Location:

Article Title: Spin-Torque-Biased Magnetic Strip: Nonequilibrium Phase Diagram and Relation to Long Josephson Junctions

Authors: Daniel Hill, Se Kwon Kim, Yaroslav Tserkovnyak

Keywords: Spin-Torque, Superconductor

Abstract: Spin-torque-biased magnetic dynamics in an easy-plane ferromagnet (EPF) is theoretically studied in the presence of a weak in-plane anisotropy. While this anisotropy spoils U(1) symmetry, thereby quenching the conventional spin superfluidity, we show that the system instead realizes a close analog of a long Josephson junction (LJJ) model. The traditional magnetic-field and electric-current controls of the latter map, respectively, onto the symmetric and antisymmetric combinations of the out-of-plane spin torques applied at the ends of the magnetic strip. This suggests an alternative route towards realizations of superfluidlike transport phenomena in insulating magnetic systems. We study a spin-torque-biased phase diagram, providing an analytical solution for static multidomain phases in the EPF. We adapt an existing self-consistency method for the LJJ to develop an approximate solution for the EPF dynamics. The LJJ-EPF mapping has the potential for producing applications with supercond

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Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nature Communications
Publication Identifier Type: DOI **Publication Identifier:** 10.1038/s41467-018-06059-7
Volume: 9 **Issue:** 1 **First Page #:** 3612
Date Submitted: 10/9/18 12:00AM **Date Published:** 9/1/18 4:00AM
Publication Location:

Article Title: Role of dimensional crossover on spin-orbit torque efficiency in magnetic insulator thin films

Authors: Qiming Shao, Chi Tang, Guoqiang Yu, Aryan Navabi, Hao Wu, Congli He, Junxue Li, Pramey Upadhyay

Keywords: spin-orbit torque

Abstract: Magnetic insulators (MIs) attract tremendous interest for spintronic applications due to low Gilbert damping and the absence of Ohmic loss. Spin-orbit torques (SOTs) on MIs are more intriguing than magnetic metals since SOTs cannot be transferred to MIs through direct injection of electron spins. Understanding of SOTs on MIs remains elusive, especially how SOTs scale with the MI film thickness. Here, we observe the critical role of dimensionality on the SOT efficiency by studying the MI layer thickness-dependent SOT efficiency in tungsten/thulium iron garnet (W/TmIG) bilayers. We show that the TmIG thin film evolves from twodimensional to three-dimensional magnetic phase transitions as the thickness increases. We report the significant enhancement of the measured SOT efficiency as the TmIG thickness increases, which is attributed to the increase of the magnetic moment density. We demonstrate the current-induced SOT switching in the W/TmIG bilayers with a TmIG thickness up to 15 nm.

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Volume: 7

Issue: 9

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Date Submitted: 10/9/18 12:00AM

Date Published: 9/1/17 8:00AM

Publication Location:

Article Title: Scalable Nernst thermoelectric power using a coiled galfenol wire

Authors: Zihao Yang, Emilio A. Codecido, Jason Marquez, Yuanhua Zheng, Joseph P. Heremans, Roberto C. My

Keywords: Nernst effect, thermoelectric

Abstract: The Nernst thermopower usually is considered far too weak in most metals for waste heat recovery. However, its transverse orientation gives it an advantage over the Seebeck effect on non-flat surfaces. Here, we experimentally demonstrate the scalable generation of a Nernst voltage in an air-cooled metal wire coiled around a hot cylinder. In this geometry, a radial temperature gradient generates an azimuthal electric field in the coil. A Galfenol (Fe_{0.85}Ga_{0.15}) wire is wrapped around a cartridge heater, and the voltage drop across the wire is measured as a function of axial magnetic field. As expected, the Nernst voltage scales linearly with the length of the wire. Based on heat conduction and fluid dynamic equations, finite-element method is used to calculate the temperature gradient across the Galfenol wire and determine the Nernst coefficient. A giant Nernst coefficient of $-2.6 \text{ } \mu\text{V/KT}$ at room temperature is estimated, in agreement with measurements on bulk Galfenol. We expect that the

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Volume: 97

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Date Submitted: 10/9/18 12:00AM

Date Published: 1/1/18 5:00AM

Publication Location:

Article Title: Evidence for the role of the magnon energy relaxation length in the spin Seebeck effect

Authors: Arati Prakash, Benedetta Flebus, Jack Brangham, Fengyuan Yang, Yaroslav Tserkovnyak, Joseph P. H

Keywords: spin-Seebeck

Abstract: Temperature-dependent spin Seebeck effect data on Ptluttrium iron garnet (YIG) [gadolinium gallium garnet (GGG)] are reported for YIG films of various thicknesses. The effect is reported as a spin Seebeck resistivity (SSR), the inverse spin-Hall field divided by the heat flux, to circumvent uncertainties about temperature gradients inside the films. The SSR is a nonmonotonic function of YIG thickness. A diffusive model for magnon transport demonstrates how these data give evidence for the existence of two distinct length scales in thermal spin transport, a spin-diffusion length, and a magnon energy relaxation length.

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Volume: 96

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Date Submitted: 10/9/18 12:00AM

Date Published: 9/1/17 4:00AM

Publication Location:

Article Title: Coherent terahertz spin-wave emission associated with ferrimagnetic domain wall dynamics

Authors: Se-Hyeok Oh, Se Kwon Kim, Dong-Kyu Lee, Gyungchoon Go, Kab-Jin Kim, Teruo Ono, Yaroslav Tserk

Keywords: THz, spin-waves, domain dynamics

Abstract: We theoretically study the dynamics of ferrimagnetic domain walls in the presence of a Dzyaloshinskii-Moriya interaction. We find that an application of a dc magnetic field can induce terahertz spin-wave emission by driving ferrimagnetic domain walls, which is not possible for ferromagnetic or antiferromagnetic domain walls. The Dzyaloshinskii-Moriya interaction is shown to facilitate terahertz spin-wave emission in a wide range of the net angular momentum by increasing the Walker breakdown field. Moreover, we show that spin-orbit torque combined with the Dzyaloshinskii-Moriya interaction also drives fast ferrimagnetic domain wall motion by emitting terahertz spin waves in a wide range of the net angular momentum.

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Date Submitted: 10/9/18 12:00AM

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Publication Location:

Article Title: Exploiting Coherence in Nonlinear Spin-Superfluid Transport

Authors: Yaroslav Tserkovnyak, Mathias Kläui

Keywords: coherence, spin-superfluid

Abstract: We show how the interference between superfluid spin currents can endow spin circuits with coherent logic functionality. While the hydrodynamic aspects of the linear-response collective spin transport obviate interference features, we focus on the nonlinear regime, where the critical supercurrent is sensitive to the phase accumulated by the condensate in a loop geometry. We propose to control this phase by electrical gating that tunes the spin-condensate coherence length. The nonlinear aspects of the spin superfluidity thus naturally lend themselves to the construction of logic gates, uniquely exploiting the coherence of collective spin currents. Vice versa, this functionality can be used to reveal the fundamental properties of spin superfluids.

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Volume: 96

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Date Submitted: 10/9/18 12:00AM

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Publication Location:

Article Title: Magnonic topological insulators in antiferromagnets

Authors: Kouki Nakata, Se Kwon Kim, Jelena Klinovaja, Daniel Loss

Keywords: topological insulator, magnons

Abstract: Extending the notion of symmetry protected topological phases to insulating antiferromagnets (AFs) described in terms of opposite magnetic dipole moments associated with the magnetic Neel order, we establish a bosonic counterpart of topological insulators in semiconductors. Making use of the Aharonov-Casher effect, induced by electric field gradients, we propose a magnonic analog of the quantum spin Hall effect (magnonic QSHE) for edge states that carry helical magnons. We show that such up and down magnons form the same Landau levels and perform cyclotron motion with the same frequency but propagate in opposite direction. The insulating AF becomes characterized by a topological Z_2 number consisting of the Chern integer associated with each helical magnon edge state. Focusing on the topological Hall phase for magnons, we study bulk magnon effects such as magnonic spin, thermal, Nernst, and Ettinghausen effects, as well as the thermomagnetic properties of helical magnon transport.

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Date Submitted: 10/9/18 12:00AM

Date Published: 1/1/18 5:00AM

Publication Location:

Article Title: Magnetoelectric antiferromagnets as platforms for the manipulation of solitons

Authors: Ricardo Zarzuela, Se Kwon Kim, Yaroslav Tserkovnyak

Keywords: magneto-electric, soliton dynamics

Abstract: We study the magnetic dynamics of magnetoelectric antiferromagnetic thin films, where an unconventional boundary ferromagnetism coexists with the bulk Néel phase below the Néel temperature. The spin exchange between the two order parameters yields an effective low-energy theory that is formally equivalent to that of a ferrimagnet. Dynamics of domain walls and skyrmions are analyzed within the collective-variable approach, from which we conclude that they behave as massive particles moving in a viscous medium subjected to a gyrotropic force. We find that the film thickness can be used as a control parameter for the motion of these solitons. In this regard, it is shown that an external magnetic field can drive the dynamics of domain walls, whose terminal velocity is tunable with the sample thickness. Furthermore, the classification of the skyrmion dynamics is sensitive to the spatial modulation of the sample thickness, which can be easily engineered with the present (thin-film) deposition.

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Volume: 100

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Date Submitted: 1/13/20 12:00AM

Date Published: 10/2/19 4:00AM

Publication Location:

Article Title: Long lifetime of thermally-excited magnons in bulk yttrium iron garnet

Authors: John S. Jamison, Zihao Yang, Brandon L. Giles, Jack T. Brangham, Guanzhong Wu, P. Chris Hammel,

Keywords: magnon lifetime, YIG

Abstract: Spin currents are generated within the bulk of magnetic materials due to heat flow, an effect called intrinsic spin Seebeck. This bulk bosonic spin current consists of a diffusing thermal magnon cloud, parametrized by the magnon chemical potential, with a diffusion length of several microns in yttrium iron garnet (YIG). Transient optothermal measurements of the spin-Seebeck effect (SSE) as a function of temperature reveal the time evolution due to intrinsic SSE in YIG. The interface SSE develops at times < 2 ns while the intrinsic SSE signal continues to evolve at times > 500 ns, dominating the temperature dependence of SSE in bulk YIG. Time-dependent SSE data are fit to a multitemperature model of coupled spin/heat transport using the finite-element method (FEM), where the magnon spin lifetime and magnon-phonon thermalization time are used as fit parameters. These results demonstrate that the thermal magnon cloud in YIG contains extremely low-frequency magnons.

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Publication Type: Journal Article

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Journal: Physical Review Letters

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Volume: 121

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Date Submitted: 1/13/20 12:00AM

Date Published: 10/16/18 4:00AM

Publication Location:

Article Title: Cooper-Pair Spin Current in a Strontium Ruthenate Heterostructure

Authors: S. B. Chung, S. K. Kim, K. H. Lee, and Y. Tserkovnyak

Keywords: spin-current, superconductor, heterostructure

Abstract: It has been recognized that the condensation of spin-triplet Cooper pairs requires not only the broken gauge symmetry but also the spin ordering as well. One consequence of this is the possibility of the Cooper-pair spin current analogous to the magnon spin current in magnetic insulators, the analogy also extending to the existence of the Gilbert damping of the collective spin-triplet dynamics. The recently fabricated heterostructure of the thin film of the itinerant ferromagnet SrRuO₃ on the bulk Sr₂RuO₄, the best-known candidate material for the spin-triplet superconductor, offers a promising platform for generating such spin current. We will show how such heterostructure allows us to not only realize the long-range spin valve but also electrically drive the collective spin mode of the spin-triplet order parameter. Our proposal represents both a new realization of the spin superfluidity and a transport signature of the spin-triplet superconductivity.

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CONFERENCE PAPERS:

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Publication Status: 1-Published

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Date Received: 15-Jan-2020

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Date Published:

Conference Location: Baltimore, Maryland, United States

Paper Title: BiSb and spin-related thermoelectric phenomena

Authors: Joseph P. Heremans, Hyungyu Jin, Yuanhua Zheng, Sarah J. Watzman, Arati Prakash

Acknowledged Federal Support: Y

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DISSERTATIONS:

Publication Type: Thesis or Dissertation

Institution: University of Illinois at Urbana-Champaign

Date Received: 30-Aug-2016

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Title: ULTRAFAST LASER DRIVEN SPIN GENERATION IN METALLIC FERROMAGNETS

Authors: GYUNG-MIN CHOI

Acknowledged Federal Support: **Y**

Publication Type: Thesis or Dissertation

Institution: The Ohio State University

Date Received: 15-Jan-2020

Completion Date: 7/10/17 8:00AM

Title: Opto-thermal measurements of thermally generated spin current in Yttrium Iron Garnet

Authors: Brandon L. Giles

Acknowledged Federal Support: **Y**

Publication Type: Thesis or Dissertation

Institution: The Ohio State University

Date Received: 01-Sep-2017

Completion Date: 8/30/17 4:00AM

Title: Magneto and spin transport in magnetically doped semiconductors and magnetic insulators

Authors: Zihao Yang

Acknowledged Federal Support: **N**

Publication Type: Thesis or Dissertation

Institution: Ohio State University

Date Received: 15-Jan-2020

Completion Date: 8/31/18 8:00AM

Title: Magneto Thermal Coupling in Solid State Transport

Authors: Arati Prakash

Acknowledged Federal Support: **Y**

Publication Type: Thesis or Dissertation

Institution: University of Illinois, Urbana Champaign

Date Received: 15-Jan-2020

Completion Date: 5/1/15 8:00AM

Title: Phonon thermal transport at the nanoscale

Authors: Richard Wilson

Acknowledged Federal Support: **Y**

WEBSITES:

URL: <http://muri.engineering.osu.edu/>

Date Received: 30-Aug-2016

Title: Materials with Extraordinary Spin/Heat Coupling: MURI

Description: MURI website with links to meetings, publications, and related news

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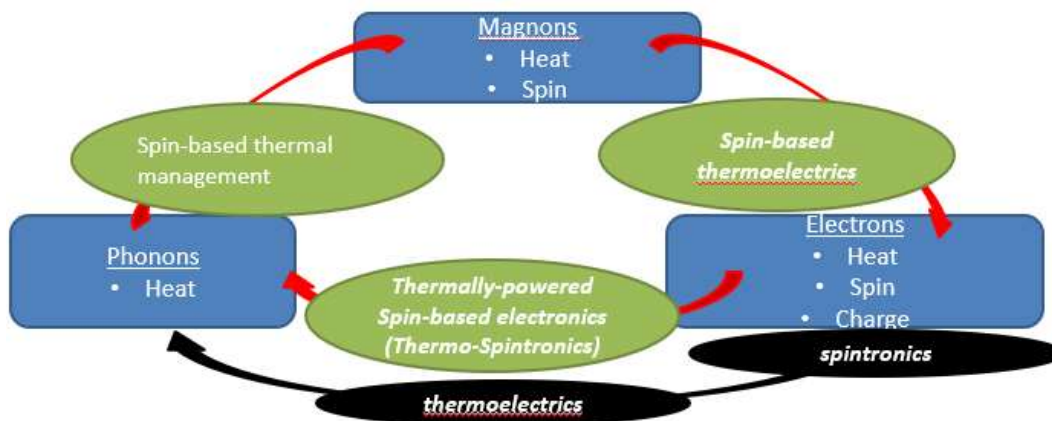
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Project Background

The discovery of a fundamentally new energy conversion process is a rare event. Ten years ago, experimentalists demonstrated a new thermodynamic effect where the flow of heat in a material generates a flow of electron spin, essentially a flow of magnetic moments. These observations took the name “spin-Seebeck effect” in analogy with the well-known coupling between heat and electricity that underlies the operation of thermocouples and thermoelectric generators. The spin-Seebeck effect promised new avenues for manipulating magnetism, and a new approach for generating electrical power from a temperature difference. Theoretical understanding of the spin-Seebeck effect and related phenomena, collectively referred to as “spin caloritronics”, developed slowly. The community of scientists studying spin caloritronics effects consisted predominately of physicists from the field of magnetic devices who were less well-versed in measurement and understanding of heat transport.

Project Vision

To accelerate progress in this emerging field, the MURI team formed in 2012 under the leadership of Professor Roberto Myers at Ohio State University and brought together experts in the physics of spin and heat transport in materials. The members of the MURI team experimentally discovered or theoretically predicted several of the key spin-heat conversion effects. The vision of the MURI team was to develop a fundamental understanding of spin-heat coupling in solids through coordinated research in theory, experiment, measurement science, and new materials. Before the MURI team was established, the conversion of heat to electrical power by the spin-Seebeck effect was known to be a three-stage process: i) generation of spin currents by temperature gradients; ii) transport of spin across an interface between a ferromagnetic insulator and a normal metal; and iii) conversion between spin and charge currents by the relativistic effects of spin-orbit coupling. The ultimate goal of the MURI team was to understand the properties of materials that govern each stage of this energy conversion process. The team also targeted materials where large useful energy conversion might be realized, for example giant spin-Seebeck signals on order $\sim 10 \text{ mV K}^{-1}$ (100 times larger than typical Seebeck effects in thermoelectric materials) and giant magnon thermal conductivities as large as the thermal conductivity of metal alloys. Applications that emerge from understanding the relationship between the quasi-particles transporting heat and spin in solids are schematically shown below:



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Project Activities

During the course of the 5 year program, funded over the period 2014-2019 (the start date was delayed by the 2013 government shutdown), the team employed a diverse set of experimental techniques to systematically study the spin-heat conversion processes in both magnetic insulators and metals. These studies included dynamic, time-resolved measurements of the generation of spin current by heat currents and spatially-resolved measurements of spin diffusion lengths and spin lifetimes. A common thread in these studies is the non-equilibrium between energy carriers—magnons and phonons in magnetic insulators and magnons, phonons, and electrons in metals—and the importance of magnon transport for understanding the spin-Seebeck effect. In particular, the team developed a comprehensive understanding of spin-heat transport in YIG ($\text{Y}_3\text{Fe}_5\text{O}_{12}$), a prototypical magnetic insulator. These measurements guided the development of predictive theory of coupled spin-heat transport in magnetic insulators that provides a framework for designing materials and systems for enhanced spin/heat coupling.

A further consequence of the scientific advances of the MURI team is the evolution of the spin Seebeck effect into a metrology technique, capable of quantifying coupled spin/heat fluxes in a large number of systems. In electrical insulators, where magnons (i.e., spin waves) are the carriers of coupled entropy and spin, thermally driven measurements are the only transport measurements possible. Examples include future spin-Nernst and quantum-spin-Nernst systems.

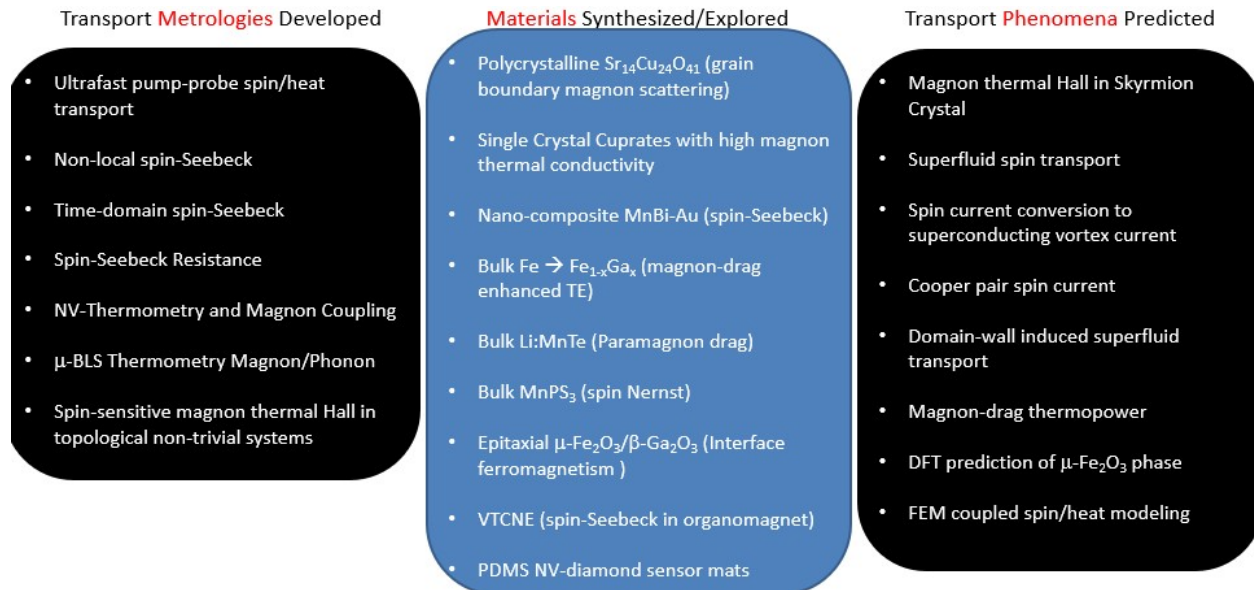
The MURI team expanded the context of spin caloritronics to include linear momentum transfer between a thermally-driven current of magnons and the conduction electrons in a ferromagnetic metal. This effect, magnon-drag, is the dominant source of thermoelectric power in all ferromagnetic metals. Magnon-drag produces an order of magnitude stronger effect than the conventional thermoelectric effects that arise from the diffusion of charge carriers. Quantitative and predictive theories for magnon-drag in ferromagnetic and paramagnetic metals were developed by the MURI team.

The MURI team also explored the materials properties governing giant magnon thermal conductivity in antiferromagnetic spin ladder compounds. Thermal transport measurements provide an understanding of the length scales of spin-lattice coupling in these systems enabling a quantitative and predictive understanding of thermal conductivity in these low dimensional antiferromagnetic materials. In addition, the MURI team has further explored a new area at the junction between spin caloritronics and the rapidly expanding research field of two-dimensional (2D) materials, especially 2D ferromagnetic and antiferromagnetic materials that have emerged in recent years due to large-scale federal supports that has followed another ARO MURI program.

Project Outcomes

The MURI team was able to develop the basic physics of spin/heat interactions in materials. Building on these foundations, new experiments, materials, and theory have been developed, including, all-optical thermometry using nitrogen-vacancy centers in diamond, ultrafast demagnetization across metallic interfaces, vortex-mediated transport between magnets and superconductors, and spin/heat coupling in disordered and low dimensional systems. This expansion of spin caloritronics theory and characterization techniques has strongly broadened the class of materials in which thermally-driven spin transport, and spin driven thermal transport can be developed for future applications in thermal management, waste-heat recovery, and spintronics. The thermally-pumped BEC agenda propelled by our MURI has impacted the developments in the broader spintronics/spin-caloritronics community, leading to novel magnon BEC realizations by other groups utilizing thermal/spin conversion processes.

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Center-level funding related to MURI

- The NSF MRSEC at OSU was renewed in 2014 with an IRG (led by Heremans, MURI co-PI) largely inspired by work funded under the MURI
- NSF-MRSEC at U. of Illinois established in 2017 includes a research focus IRG-MAX (led by Cahill, MURI co-PI), about metallic antiferromagnetic materials. MURI support was instrumental in providing research development at U of I towards this research area
- Shortly after the MURI was funded, a DOE EFRC (SHINES, led by Prof. Jing Shi at UC Riverside) was established focused on spin/heat transport in nanoscale materials

Supported International Workshops

- 2015 Workshop on Non-linear spin-heat interactions, Columbus, OH
- 2017 Spin coherence, condensation, and superfluidity, Moorea, French Polynesia
- 2018 Spin Caloritronics IX, Columbus, OH

Student and postdoctoral fellow notable outcomes

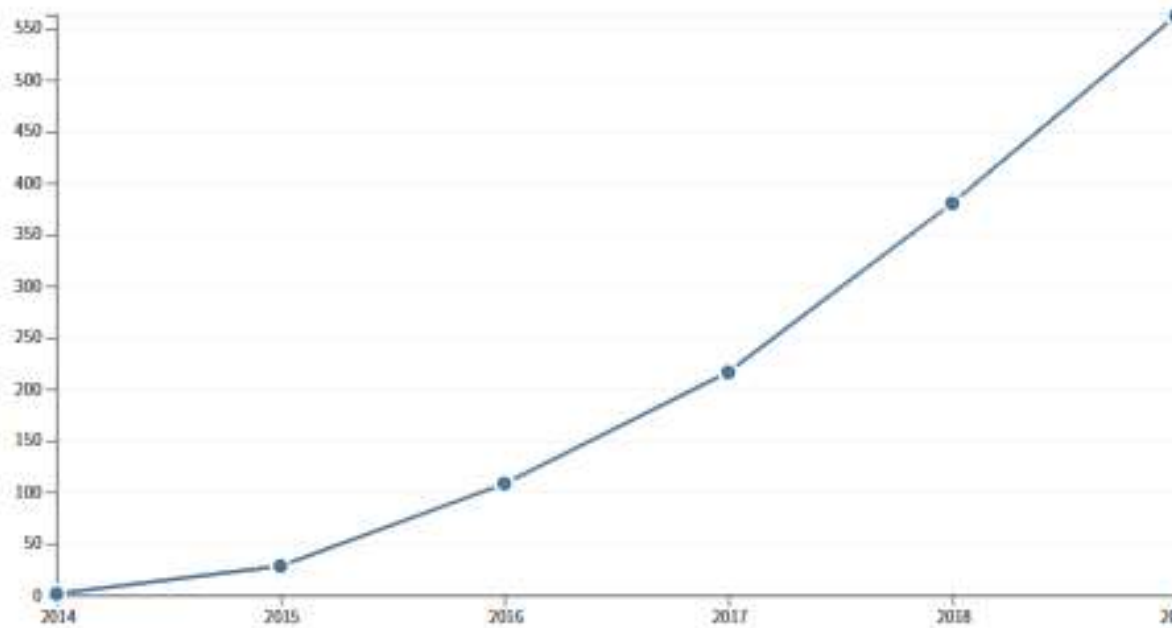
- Former postdoctoral fellow Se Kwon Kim now Assistant Professor at University of Missouri, Outstanding Young Researcher Award from Association of Korean Physicists in America in 2016
- Former graduate student Kyongmo An, now postdoctoral fellow at EPFL
- Former graduate student Annie Weathers, now Technical Staff Member at MIT Lincoln Laboratory, won Ben Streetman Junior Award 2017, and Caltech Young Investigator Lecturer in Engineering and Applied Science
- Former graduate student Sean Sullivan, now postdoctoral fellow out Argonne National Lab
- Former graduate student Bin He, now postdoc at the Max Planck Institute, Dresden
- Former postdoctoral fellow Koen Vandaele, now research staff at Johnson & Matthey, London UK
- Former postdoctoral fellow Steve Boona, now research staff (Research Associate 2-Engineer) at CEMAS, OSU
- Former postdoctoral fellow Joseph Heremans, now research staff scientist, Argonne National Laboratory
- Brian Zhou, now assistant professor of physics, Boston College

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Scholarship and Impact

The detailed technical activity and accomplishments are articulated in detail within the peer-reviewed publications,¹⁻⁷⁸ meeting abstracts, and dissertations associated with the MURI. The impact of these works can be roughly gauged by the number of citations per year associated with MURI publications graphed below based on citation data from Web of Science:

Sum of Times Cited per Year



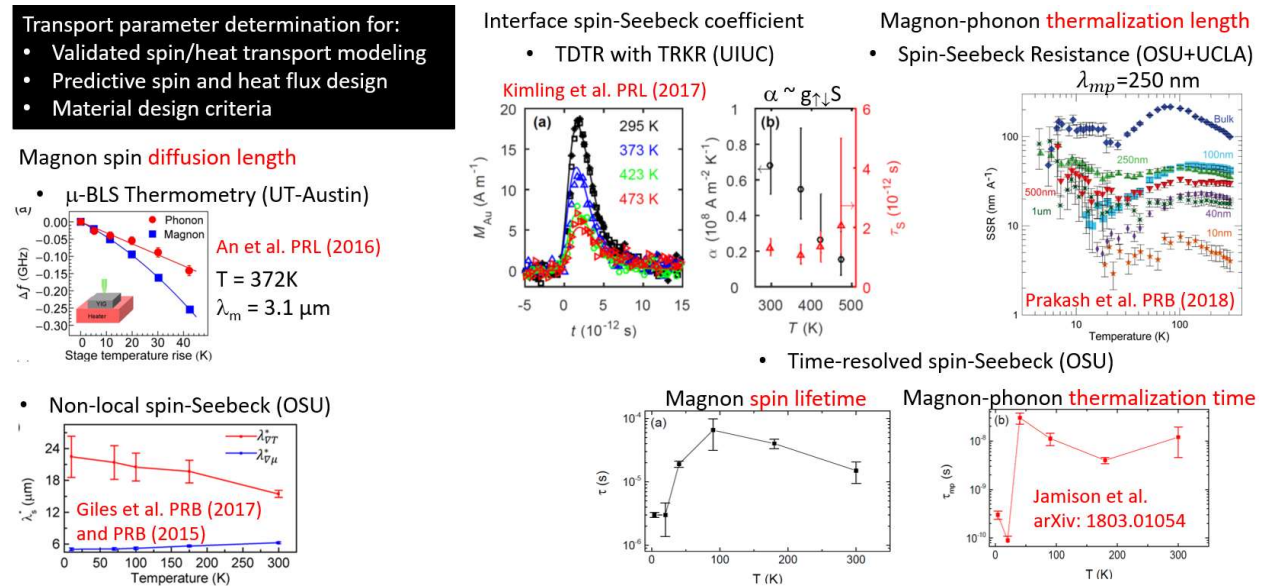
Additional citation metrics are listed below:

- 115 papers and abstracts published
- h-index 23 (google scholar)
- total cites = 1618 (google scholar)
- Many publications in high profile journals including in: Science,⁷⁴ Nature journals,^{10,28-31,46,57,63-65} Phys. Rev. Lett.,^{19-22,47-50,58-61,70-72} Nano Letters,⁵² Phys. Rev. X,⁷³ Phys. Rev. Appl.⁶⁶

Technical Highlights

Comprehensive spin-heat transport in YIG

Within the field of magnonics and spin caloritronics, yttrium iron garnet (YIG) represents the standard system on which to examine coupled spin-heat transport, as well as to isolate and spectrally resolve magnon transport. Due to its insulating nature, measurement artifacts associated with charge transport phenomena are absent. The MURI team set a goal of developing measurement methods to determine the magnon, phonon, and coupled magnon-phonon thermal and spin transport characteristics of YIG in order to explain and understand phenomena including the spin-Seebeck effect in this magnetic insulator. Several new experimental tools were developed to probe this physics including: μ -Brillouin Light Scattering (BLS) using focused laser heating,¹⁹ Non-local spin-Seebeck measurement,^{37,77} time-resolved spin-Seebeck,⁶⁷ time-resolved Kerr rotation (TRKR) and thermo-reflectance (TDTR) of YIG,⁵⁰ as well as spin-Seebeck resistance.⁵⁴ The combined view of coupled spin-heat transport in YIG provides the transport parameters necessary to perform valid spin/heat modeling for designing spin and heat fluxes. It also provides insight to the materials parameters necessary to engineer in other materials systems to enhance spin-thermal phenomena. These results are briefly illustrated in the figure below:



Magnon Thermal Conductivity in Cuprates

Part of the MURI team, led by UT Austin and UIUC, combined synthesis and experimental techniques to explore giant magnon thermal conductivity in cuprates. Developing single crystals of various classes of cuprate spin-chain and spin-ladder compounds allowed the precise determination of the magnon enhanced thermal conductivity in these materials using both TDTR and bulk thermo-transport. Inelastic neutron scattering was used to map the phonon and magnon modes in $\text{Sr}_{14}\text{Cu}_{24}\text{O}_{41}$ which provide spectral insight to the origin of giant magnon thermal conductance.¹⁷ In Ca_2CuO_3 , the materials science of spinon-phonon transport was probed by exploring the thermal transport of bulk crystals as it relates to defect scattering.⁷¹

Spin-Enhanced Thermopower

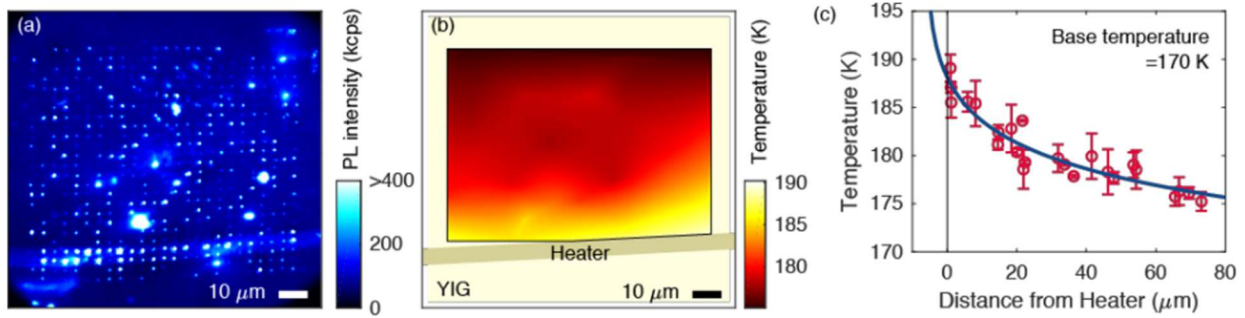
The MURI team combined theoretical and experimental expertise to explore the possibility to enhance thermopower phenomena in materials by taking advantage of electron-magnon interactions. The two most important findings were: (1) the development of two quantitative and predictive theories for magnon drag,

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in particular establishing that magnon drag enables magnetic solids to have the thermoelectric power far in excess of that of ordinary metals. The physical basis for this is that electrons, as Fermions, are subject to the Mott relation, which dictates that the thermoelectric power must decrease as the density of electrons increases. Magnons, being Bosons, are not subject to that limitation. (2) The discovery of a strong enhancement to the thermopower of metals and semiconductors due to paramagnons in paramagnetic solids: paramagnons are thermally driven local fluctuations of the magnetization, and can drag electrons just like magnons can. This is technologically relevant, as there are no FM semiconductors at room temperature, but there are plenty of paramagnetic ones. This discovery identifies entirely new classes of paramagnetic semiconductors as potential high- zT thermoelectrics. For example, spin-enhanced thermopower was demonstrated in bulk nanocomposites of Ni-Pt and MnBi-Au,¹⁰ magnon-electron drag was found to play a dominate role in the thermopower of elemental 3d ferromagnetic metals (Fe, Ni, Co),¹¹ which was supported by theoretical framework explaining the transport physics.⁹ Magnon-drag was more recently observed in disorderd magnetic systems including large $zT > 1$ in Li:MnTe paramagnetic semiconductor,⁷⁴ and large spin-Seebeck resistance in the amorphous ferromagnet V(TCNE)₂.

Magnon-NV coupling, thermometry, and thermal imaging

As one of the central goals of the MURI was to measure coupled heat-spin transport, the development of new magnetometric and thermometric techniques at short length scales was a central activity. An ambitious aspect of the proposed work was to develop NV-centers for thermal imaging and mapping⁶⁶ as well as for local magnetometers for probing magnon transport (see figure below).

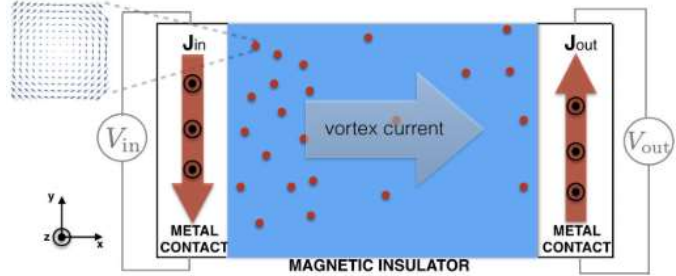


(a) Spatial PL scan of NV centers in NDs in the array. (b) Two-dimensional temperature imaging of the YIG surface using NV centers in the array of NDs embedded on the surface of the PDMS sheet measured by the all-optical thermometry technique. An 80-mA current is applied to the resistive heater. The base temperature was set to $T = 170$ K. (c) YIG surface temperature as a function of the distance from the resistive heater. Fit with a logarithmic function is shown. From Fukami et al. (2019).

Microwave magnon transport in YIG was observed using NV-centers as local sensors. This also led to the unexpected observation of enhanced microwave-spin interactions providing a means to couple magnon coherence and NV-spin coherence.³¹

Vorticity Transport and Conversion

Another example of an unexpected development in the course of MURI work was the realization that interface conversion processes between magnetic insulators and normal metals, at the heart of the theory for electron-spin magnon conversion processes in spin-Seebeck and other spin caloritronics phenomena, could also be expanded to include the conversion of magnon spins to superconducting vortices. As Cooper pairs carry no net spin and flux lines cannot penetrate a perfect superconductor, one imagines that magnon spin should perfectly reflect at the interface of a magnetic material and a superconductor. However, in type-II superconductors, fluxes are quantized in topological vortices that exhibit transport through the superconductors. The MURI theory team led by Tserkovnyak collaborated with Myers to develop a theory for magnon-vortex conversion.⁶⁰ This is providing a new concept of topologically protected transport via vortices in insulating ferromagnets (see figure on right).⁶⁹

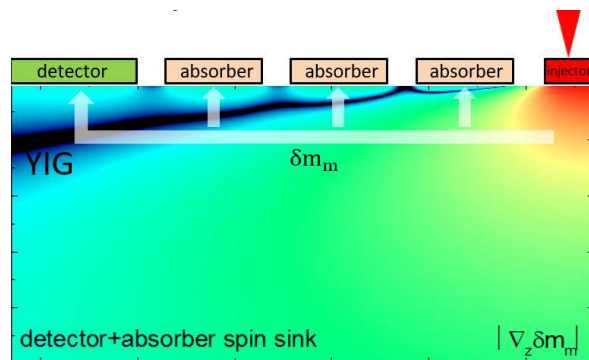


Detailed Research Report

The MURI activities led by individual PIs are summarized below.

Opto-thermal measurement of magnon spin currents: length and time scales (OSU-Myers)

Myers group developed a scanning laser based technique to thermally excite local populations of magnons in magnetic insulators, and measure their diffusion lengths, and lifetimes. The technique was developed under the support of the MURI as the first so-called non-local transport measurement of magnons in YIG revealing for the first time the existence of very long-range magnon transport from thermally driven spin currents.⁷⁷ Temperature dependence combined with theoretical modeling of the coupled spin-heat diffusion led to precise measurement of the spin diffusion length of thermal magnons in YIG.³⁷ This revealed that thermally excited magnons in YIG can diffuse over 100 μm lengthscales, far longer than previously expected. In order to understand the details of coupled spin-heat transport in terms of transport coefficients,

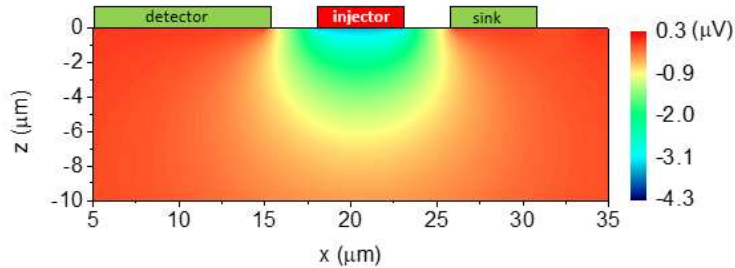


Myers group devoted significant effort to developing reliable finite-element-method (FEM) modeling of spin currents in YIG. Initially, coupled spin-heat transport was modeled using the spin diffusion equations derived by Zhang and Zhang,⁷⁷ before the spin caloritronics community had derived the coupled spin-heat transport parameters. These models enabled a first view of the dependence of the magnon chemical potential on the sample and experimental geometry (boundary conditions) on thermal spin-diffusion in YIG (see figure on left). Accurate quantitative

modeling of the magnon chemical potential was an essential step to understand the necessary conditions to achieve functional magnonics in YIG, such as lateral devices coupled through non-local spin currents⁷⁹. Additionally, the expectation of magnon BEC formation based on the Tserkovnyak's team's theories also motivated the modeling work to optimize device geometry to be able to drive magnon condensation.

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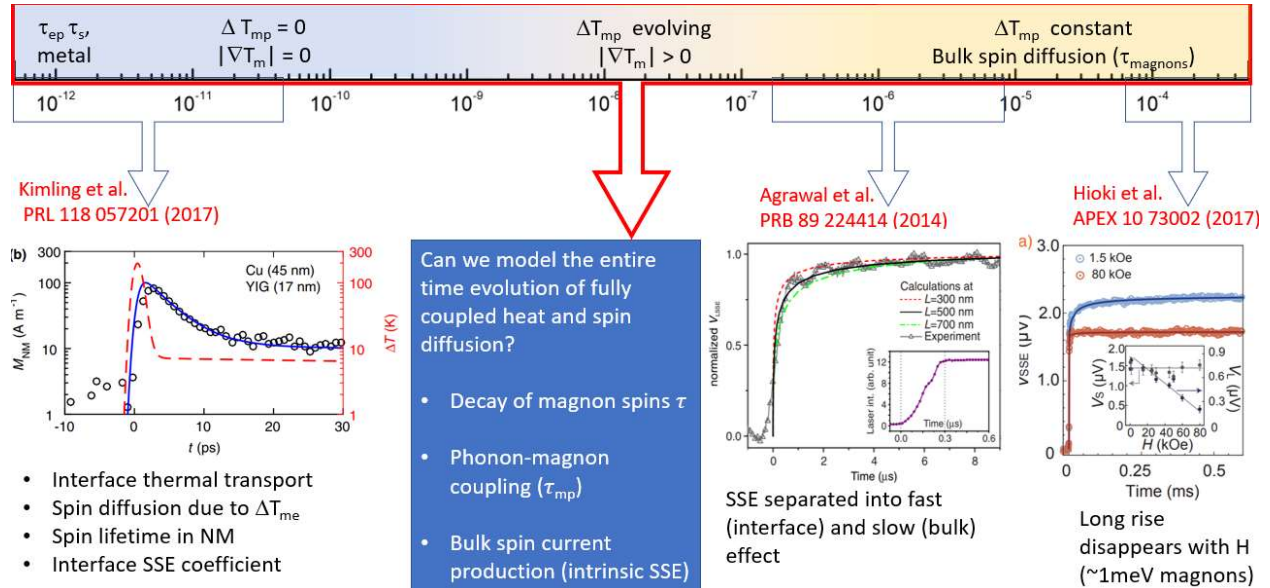
The theory arm of the MURI team led by Tserkovnyak's team understood the importance of the transport equations and in-turn derived the mathematical framework to understand the diffusion of thermal and condensed magnons⁷⁶. Applying this framework, Myers' team was able to refine the non-local spin-Seebeck modeling to accurately extract the magnon diffusion lengths and model the magnon chemical potential profile (see figure below).³⁷



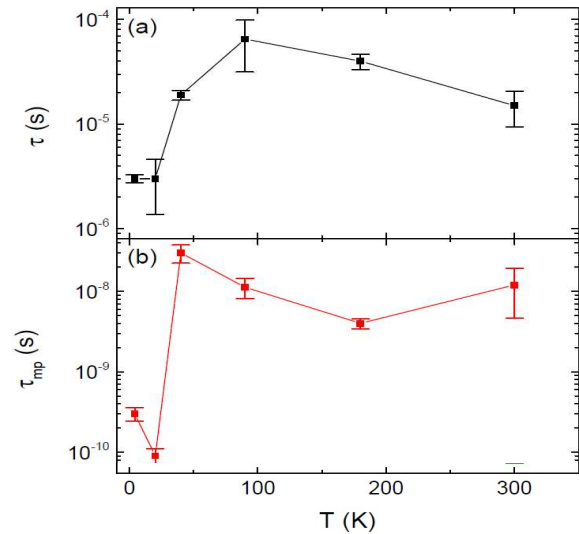
The long range transport of these magnons hints at their spectral nature, that is especially low energy magnons near the bottom of the magnon dispersion exhibit especially long lifetimes, and are thereby able to obtain quite long diffusion lengths.

This motivated the next phase of the

experiments focused on exploring the time-domain of the thermal magnon generation and diffusion process in YIG. Cahill's group as part of the MURI team, explored the ultrafast timescale confirming the interface temperature difference as a driving force for spin-Seebeck in YIG coated with a normal metal in the $\sim$ ps regime.⁵⁰ However, those time scales are too short to explain previously experiments carried out at longer timescale revealing spin-Seebeck signal evolution on the $\sim$ ms timescale. The overarching motivation then was to model spin-heat transport over the entire time range over which the system (electrons, magnons, phonons) diffuse and equilibrate. Therefore we devised a time-domain spin-Seebeck experiment spanning from $\sim$ 1ns to $\sim$ 1ms time range that would be sensitive to both the interface spin-Seebeck effect, thought to dominate the system, and the bulk or intrinsic spin-Seebeck effect thought to be a small correction to the overall signal (see figure below).



By measuring the temporal evolution of the spin-Seebeck signal, Myers' group was able to fit the highly non-linear signal over four orders of magnitude in the time domain spanning from interface dominated spin transport, to bulk (intrinsic) spin Seebeck dominated transport. The results of the fits provide the magnon spin lifetimes (previously unmeasured), the magnon-phonon equilibration time, and the ratio of the interface to the bulk spin-Seebeck coefficients all as a function of temperature.⁶⁷ It was found that the magnon spin lifetime peaks at around 60 μ s at 90 K in YIG. Converting the lifetimes into spin conductivities using the Einstein relations, the data could be compared to results obtained in a completely different experiment (non-local spin injection in YIG) from van Wees group in the Netherlands, which is in close agreement. These results demonstrate the level of understanding to complex transport phenomena that can be obtained with support of MURI funding together with multidisciplinary expertise and close collaboration of the team. Although the publications are not co-authored by all team members, the scientific advising between team members was critical to the outcome of this and other similar MURI projects.

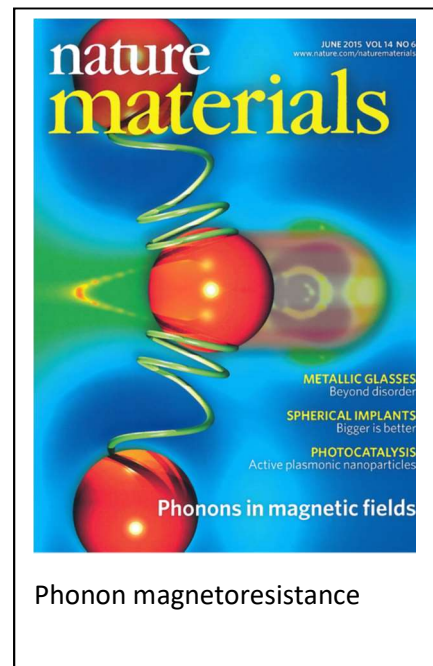


Temperature dependence of the (a) magnon spin lifetime and (b) magnon-phonon thermalization time in YIG.

Bulk-thermal measurement of magnon, phonon, and electron coupling (OSU-Heremans)

In 2015, we discovered the influence of magnetic fields on phonon transport.⁴⁶ We reported how magnetic fields affect the distribution of valence electrons inside the unit cells of semiconductors, creating local variations of the diamagnetic permeability. This in turn adds a magnetic-field dependent anharmonicity to the interatomic forces, which leads to field-dependent anharmonic phonon scattering. The final result is a magnetoresistance observed in phonon thermal conductivity. This made the cover of the journal Nature Materials.

Throughout the MURI, we concentrated on thermal transport of spins through spin-Seebeck measurements. We identify the propagation of thermally activated magnons from a FM, yttrium iron garnet (YIG), into AFM NiO by means of a spin-Seebeck measurement.¹⁴ We identified the length of the magnon-phonon interaction to be on the order of 250 nm in YIG.⁵⁴ Heaters and thermometers couple to the phonon system in the material studied for any spin-thermal device. The magnon system thus receives a transfer of the thermal energy from the phonon system. Although magnon-phonon coupling can be quite strong in various coupled magnon-phonon modes that have



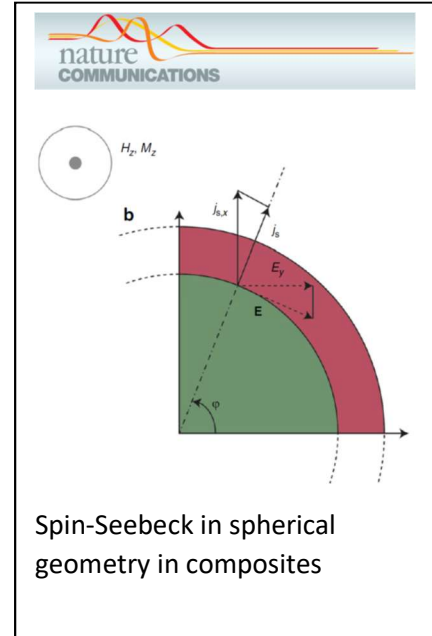
been identified, this is not always the case. We have identified the magnon-phonon interaction length at 250 nm by measuring the spin-Seebeck value in a series of experiments on YIG as a function of YIG thickness. This is an important identification, as this length is significantly shorter than the 10 μm magnon diffusion length.

We extrapolated and applied the spin-Seebeck geometry to a bulk nanocomposite geometry. Typically, the spin-Seebeck geometry consists of a NM thin-film with high spin-orbit coupling deposited onto a FM insulator.¹⁰ This geometry is vital to the practical applications of the spin-Seebeck effect in energy conversion as, generally, 1 g of material is needed per Watt of electrical energy.

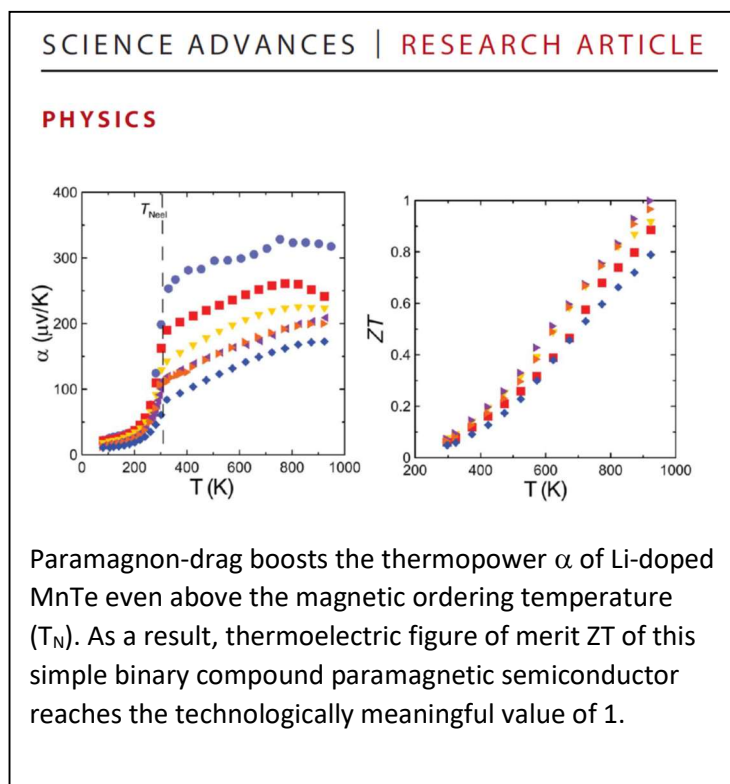
In double-doped $\text{Pb}_{1-x-y}\text{Eu}_x\text{Na}_y\text{Se}$ we studied for its electronic transport, magnetic properties, and electronic structure.³² We reported results for a number of samples with different x and y , providing resistivity, thermopower, carrier concentration, and magnetization measurements. We found that at given carrier concentrations, there were pronounced increases in thermopower because of ionized impurity scattering. Unexpectedly, a mixed, Eu^{2+} - Eu^{3+} state in $\text{Pb}_{1-x-y}\text{Eu}_x\text{Na}_y\text{Se}$ was found to result from a Eu valence transition was in Na-doped $\text{Pb}_{1-x}\text{Eu}_x\text{Se}$. We conclude this by observing significant reductions in the carrier concentration, with increasing Eu content, x , and the magnetization, with increasing Na content, y . The electronic structure calculations support this conclusion by showing the 4f7 configuration instability in the Eu^{2+} ion with Na doping. The importance of AFM interactions between the nearest-neighbor Eu atoms is shown by magnetization measurements, and an exchange coupling parameter value of $J_{\text{ex}} = -0.35$ kB was found.

A major effort then went into studying the bulk analog to the spin-Seebeck effect, namely magnon-drag. In 2016-2019, we focused on magnon drag in metals and semiconductors. Magnon drag is a form of advective transport whereby a temperature gradient excites a gradient in magnon concentration, and thus in magnon chemical potential, the same mechanism that gives rise to the spin-Seebeck effect. The ratio of the magnon chemical potential gradient to the temperature gradient is the magnonic thermopower, shown to be the specific heat per magnon.²⁷ While the classical diffusion thermopower of electrons decreases with an increasing electron density, importantly, the magnonic thermopower does not. Where magnons cross an interface between a FM and a NM, they spin-polarize the conduction electrons in the NM by conserving spin-angular momentum. If the NM has a strong spin-orbit coupling, an inverse spin-Hall electric field arises, producing the spin-Seebeck effect. Where magnons interact directly with the charge carriers in a FM or AFM conductor, they impel these electrons by conserving linear momentum. This is the magnon-drag effect.

We showed that magnon drag is the dominant mechanism that produces a thermoelectric power in ferromagnetic Fe, Co, and Ni.¹¹ This thermoelectric power is quite significant, as it is one order of magnitude larger than the traditional diffusion thermopower, and is therefore the only known case where a spin-based effect produces a much larger signal than a charge-based effect. Magnon drag has also been styled as a form of self-spin-Seebeck effect. The theory was proven to be predictive, in that it enabled the design of magnon-drag-enhanced thermopower in Fe-Co alloys.⁷⁵ With the Myers group, we measured the Nernst coefficient of Galfenol (Fe-Ga alloys). We developed a Nernst-effect-based coiled thermomagnetic power generator from this work, and the generator output confirms the materials properties well.²⁵



Since magnons also exist in AFMs, we extended the study to AFM metals and semiconductors. This is more challenging to accomplish because isolating drag in these materials (e.g., by applying an external magnetic field) is much more difficult than it is for FMs, due to their lack of a net magnetic moment. However, the current interest of the scientific community in the magnonics of AFMs coincides with this research direction. Furthermore, as there are many more AFM materials than FM materials, the choice of possible materials is greatly broadened by this avenue of study. Specifically, we extended our work on magnon drag to MnTe, a semiconducting AFM with a Néel temperature of $T_N = 307$ K and a band gap of 1.2 eV, with Prof. Daryoosh Vashaee, North Carolina State University; Prof. Huaizhou Zhao, Institute of Physics, Chinese Academy of Sciences; and Dr. Raphael Hermann, Oak Ridge National Laboratory. We prepared several sets of Li-doped MnTe samples (Li is an aliovalent acceptor) by spark-plasma sintering, and studied their thermoelectric properties from 2 to 1000 K. Magnon drag is proven to dominate thermopower in the AFM state. Surprisingly, a very large excess thermopower persists in the paramagnetic regime, up to temperatures three times the ordering temperature. Neutron scattering from 250 to 450 K confirms the existence of magnon modes at $T < T_N$, with lifetimes of the order of 250 fs. Interestingly, the magnon features visible below T_N persist to the maximum measurement temperature, 450 K. These are “paramagnons.” Paramagnon lifetime and spin-spin coherence length measurements give a temperature-independent lifetime of 25-30 fs and a coherence length of 2.5 nm. The scattering time for electron transport is an order of magnitude shorter. The electron de Broglie wavelength and effective Bohr radius are also shorter than the spin-spin correlation length. As such, we posit that paramagnons look like magnons to electrons, thus exerting drag. This can explain the excess thermopower.



The result is technologically relevant in that optimally doped samples reach a thermoelectric figure of merit $ZT=1$ at $T > 850$ K, simply due to the excess thermopower in paramagnetic semiconductors. This is the first example of a spin-based effect resulting in a high ZT . This was published in *Science Advances*,⁷⁴ and is possibly the most important advance in the field of thermoelectrics research of the last decade. It shows how spin-based thermoelectrics can boost the figure of merit of even a simple binary compound semiconductor to technologically relevant values. It also opens the field of thermoelectric semiconductor research to explore the great many paramagnetic semiconductors that have been ignored to date. Indeed, there are no known FM semiconductors with ordering temperatures above about 100 K, so that magnon drag was never before considered

for thermoelectric applications at room temperature or above. Further, up to now, commonsense reasoning in the field of thermoelectrics research was that magnetic scattering of electrons on magnetic impurities in paramagnetic semiconductors lower ZT by lowering the electron mobility. Nobody previously envisioned

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that it could also boost the thermopower, to such an extent as to overcome the mobility loss and boost the ZT.

Ultrafast spin caloritronics (Cahill group)

Our research activities on ultrafast spin caloritronics encompassed the following sub-topics.

Spin-dependent Seebeck effect and spin Seebeck effect. The spin-dependent Seebeck effect (SDSE) refers to the generation of a spin current by a temperature gradient applied to a metallic ferromagnet. We were the first to accurately quantify the SDSE by taking advantage of the enormous heat fluxes that can be generated on short time scales by picosecond laser pulses.³³ We used two independent methods to measure the thermally generated spin currents: magneto-optic detection of spin accumulation in Cu and Au; and the spin transfer torque exerted on a second ferromagnetic layer. Magneto-optic detection of spin accumulation in a normal metal with picosecond time resolution is a significant research accomplishment on its own and enabled our measurements of the interfacial contribution to the spin Seebeck effect that is generated by the interactions of magnons in $\text{Y}_3\text{Fe}_5\text{O}_{12}$ (YIG) with the electronic excitations of an adjacent non-magnetic metal.⁵⁰

Magnetic tunnel junctions and multilayers. We quantified for the first time the effective thermal conductivity of 2 nm MgO layers that are typical of magnetic tunnel junctions (MTJ) in spintronic devices through a combination of time-domain thermoreflectance (TDTR) and time-resolved magneto-optic Kerr effect (TR-MOKE) measurements.⁵⁷ These new insights enable better understanding of the magnetization-dependent Seebeck signal that is generated by MTJ subjected to a heat current. In closely-related experiments, we used TR-MOKE to measure the strength of electron-phonon coupling in transition metals, Pt in particular, and thereby enable new tests of computational models of electron-phonon interactions and new approaches for studying thermal transport at the nanoscale when electrons and phonons are out-of-equilibrium.¹³

Thermal conductivity of magnetic insulators. Our research activities on magnetic insulators encompassed *magnon thermal conductivity in low-dimensional antiferromagnetic materials*; and *the thermal conductivity and magnon-phonon coupling in $\text{Y}_3\text{Fe}_5\text{O}_{12}$ (YIG)*. Our emphasis for low-dimensional antiferromagnetic materials was in quantifying the high temperature behavior of the magnon thermal conductivity. Conventional techniques for small samples are typically not suitable at temperature above room temperature. Using TDTR, we measured the thermal conductivity of several anti-ferromagnetic cuprates to temperatures as high as 800 K to better understand the role of magnetic disorder and magnon-phonon coupling on the thermal conductivity. Measurements of the heat capacity of YIG at high frequencies set a lower limit to the strength of magnon-phonon coupling in YIG and provides constraints on models for the spin Seebeck effect.

Magnon and spinon thermal conductivity (UT Austin)

The team members at the University of Texas (UT) at Austin have investigated magnon and spinon contributions to the thermal conductivity in spin ladder and spin chain compounds, magnon-phonon coupling at the interface between a heavy metal and a magnetic insulator, and magnetism and spin/heat coupling in two-dimensional (2D) and moiré structures. They have employed the optical floating zone technique, chemical vapor transport, and solid-state reaction to grow incommensurate spin ladder and spin chain compounds, yttrium iron garnet (YIG) ferromagnetic insulator, and ferromagnetic and antiferromagnetic 2D crystals.

- (i) Inelastic light scattering measurements of pseudoacoustic phonons and magnon dynamics in incommensurate spin ladder compounds¹⁷

Intriguing lattice dynamics have been predicted for aperiodic crystals that contain incommensurate substructures. In this work, we have used inelastic neutron scattering measurements to measure phonon and magnon dispersions in $\text{Sr}_{14}\text{Cu}_{24}\text{O}_{41}$, which contains incommensurate one-dimensional (1D) chain and two-dimensional (2D) ladder substructures (Fig. 1a). Two distinct pseudoacoustic phonon modes, corresponding to the sliding motion of one sublattice against the other, are observed for atomic motions polarized along the incommensurate axis (Fig. 1b, c). In the long wavelength limit, it is found that the sliding mode shows a remarkably small energy gap of 1.7–1.9 meV, indicating very weak interactions between the two incommensurate sublattices. The measurements also reveal a gapped and steep linear magnon dispersion of the ladder sublattice (Fig. 1b). The high group velocity of this magnon branch and weak coupling with acoustic and pseudoacoustic phonons can explain the large magnon thermal conductivity in $\text{Sr}_{14}\text{Cu}_{24}\text{O}_{41}$ crystals. In addition, the magnon specific heat is determined from the measured total specific heat and phonon density of states and exhibits a Schottky anomaly due to gapped magnon modes of the spin chains (Fig. 1d). These findings offer new insights into the phonon and magnon dynamics and thermal transport properties of incommensurate magnetic crystals that contain low-dimensional substructures.

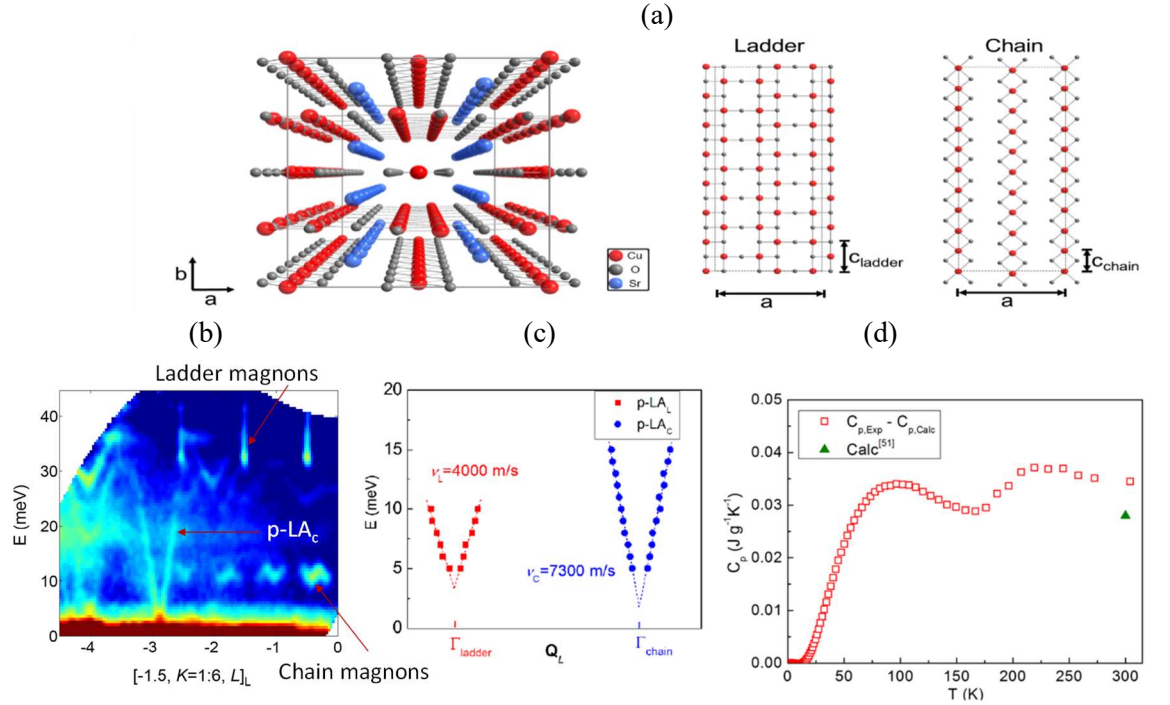


Figure 1: (a) Crystal structure of incommensurate $\text{Sr}_{14}\text{Cu}_{24}\text{O}_{41}$. (b) Measured dispersions of pseudo longitudinal acoustic (p-LA) phonons and magnons of the ladder (L) and chain (C) sublattices. (c) Measured and fitted dispersions of the p-LA phonon dispersions. Reproduced from X. Chen, D. Bansal, S. Sullivan, D. L. Abernathy, A. Aczel, J. S. Zhou, O. Delaire, L. Shi, *Phys. Rev. B* 94, 134309, (2016)

(ii) Thermal transport measurements of spinon coupling with defects and phonons in a spin chain compound⁷¹

Extrinsic spinon scattering by defects and phonons instead of intrinsic spinon-spinon coupling is responsible for resistive magnetic heat transport in one-dimensional (1D) quantum magnets. Here we report an investigation of the elusive extrinsic effect in the 1D Heisenberg $S = 1/2$ spin chain compound Ca_2CuO_3 , where the defect concentration is determined from the measured specific heat and first-principles calculations are used to separate the lattice component of the measured thermal conductivity to isolate a large magnetic contribution (κ_m , Fig.2a, b, c) The obtained temperature-dependent spinon-defect and spinon-phonon mean free paths (Fig. 2d) can enable a quantitative understanding of both κ_m and the spinon induced spin Seebeck effect.

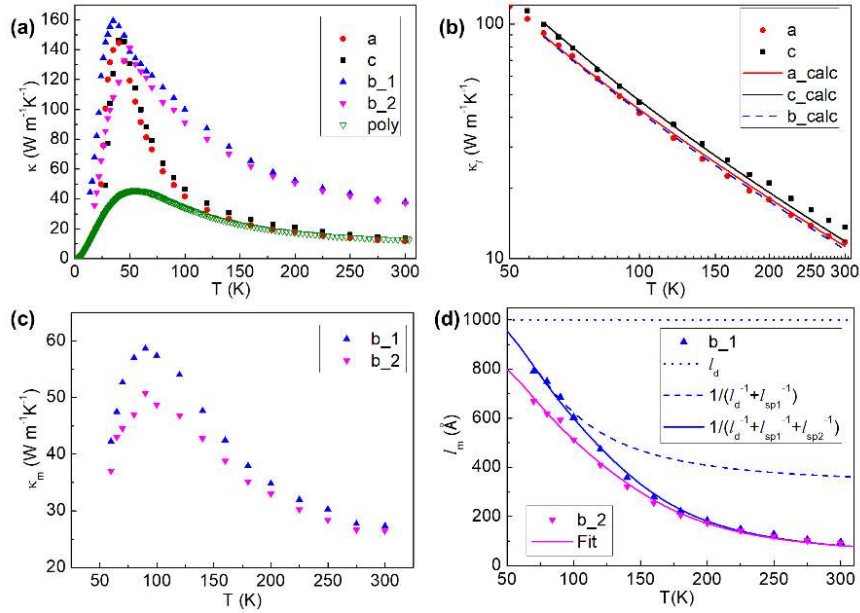


Figure 2. (a) Thermal conductivity of Ca_2CuO_3 crystals measured along the three principal crystal axes, in comparison with the κ of a Ca_2CuO_3 polycrystalline sample. (b) Fit to the κ along a and c axes. The blue dashed line is the calculated κ_l along the b axis. (c) The extracted κ_m of Ca_2CuO_3 along the b axis. (d) Calculated spinon MFP of Ca_2CuO_3 along the b axis. The solid and dashed lines are the fits according to theoretical models. Reproduced from X. Chen, J. Carrete, S. Sullivan, A. Roekeghem, Z. Li, X. Li, J. Zhou, N. Mingo, L. Shi, *Phys. Rev. Lett.* 122, 185901 (2019)

(iii) Brillouin light scattering (BLS) detection of magnon spin relaxation length¹⁹

The coupling and possible nonequilibrium between magnons and other energy carriers have been used to explain several recently discovered thermally driven spin transport and energy conversion phenomena. Here, we report experiments in which local nonequilibrium between magnons and phonons in a single crystalline bulk magnetic insulator, yttrium iron garnet (YIG, $\text{Y}_3\text{Fe}_5\text{O}_{12}$), has been created optically within a focused laser spot and probed directly via micro-Brillouin light scattering. Through analyzing the deviation in the magnon number density from the local equilibrium value, we obtain the diffusion length of thermal magnons to be $3.1 \pm 0.9 \mu\text{m}$ in YIG at about 327 K. By explicitly establishing and observing local nonequilibrium between magnons and phonons, our studies represent an important step toward a quantitative understanding of various spin-heat coupling phenomena.

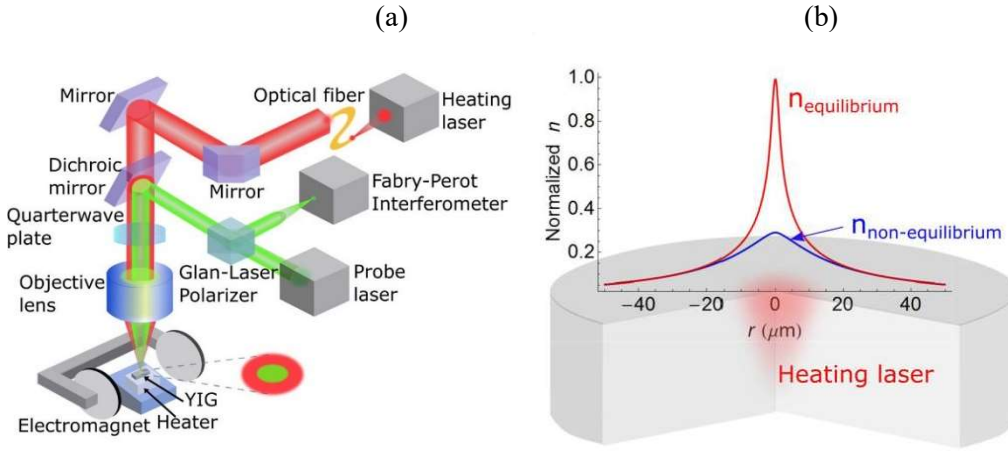


Figure 3: (a) Schematic illustration of the micro-Brillouin light scattering (BLS) set up that uses a heating laser to generate localized heating and use a probe laser to detect phonon and magnon peaks in a YIG sample. (b) Calculated equilibrium and non-equilibrium magnon density (n) distribution at the heated spot. Reproduced from K. An, K. S. Olsson, A. Weathers, S. Sullivan, X. Chen, X. Li, L. G. Marshall, X. Ma, N. Klimovich, J. S. Zhou, L. Shi, X. Q. Li, *Phys. Rev. Lett.* 117, 107202 (2016)

(iv) Lock-in BLS measurements of spin Hall injection of magnons from a heavy metal into a ferrimagnetic insulator

The ability of a magnetic insulator (MI) to transport a pure spin current offers new approaches to information processing and energy conversion. A fundamental challenge for the emerging MI-based spintronics centers on the detection of the spin current injected into the MI. Here we introduce lock-in Brillouin light scattering (BLS) measurements to detect spin injection from a heavy metal, platinum (Pt), into a MI, yttrium iron garnet (YIG), as shown in Fig. 4. This sensitive measurements allow for the direct measurements of the interface transmission and the diffusion length of the injected pure spin current.

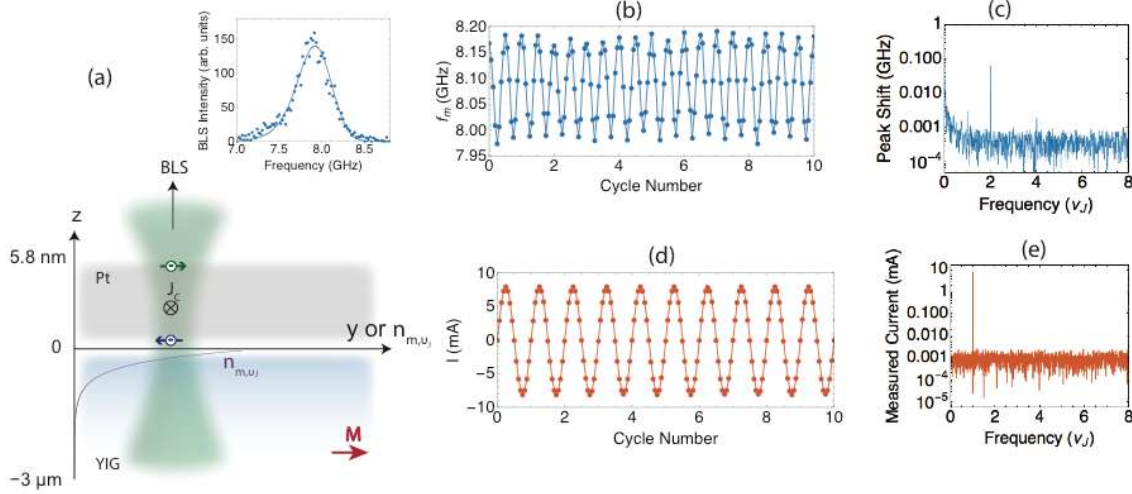


Figure 4: (a) Schematic illustration of YIG magnon frequency measurement, in which the measured BLS intensity peak position is used to detect the magnon population (n_{m,v_j}) injected by the spin Hall effect (SHE) from Pt into YIG. (b) Measured magnon frequency modulation and (c) the amplitude spectrum when a discretized sinusoidal electrical current flows in the Pt line, as shown in (d) the measured charge current modulation and (e), the amplitude spectrum of the current. The SHE signal is the first harmonic peak in (c). Reproduced from A. Weathers, S. Sullivan, H. Lee, L. Shi.

(v) Detection of Spin Peltier Magnetoresistance

A panoply of magnetoresistive effects have emerged in heterostructures between a heavy metal (HM) and a ferromagnetic metal or insulator (FM or FI). HM/FM bi-layers exhibit a unidirectional magnetoresistance (UMR) that varies upon the reversal of the magnetization direction of the FM. This breaking of the time reversal symmetry has been attributed to the spin Hall effect (SHE) in the HM in conjunction with spin-dependent electron-electron and electron-magnon scattering mechanisms. Here, we show similar UMR exists in a prototypical HM/FI heterostructure (Fig. 5a) where the electron-magnon scattering mechanism is singled out. The observed UMR (Fig. 5b) is much larger than existing theories that have not accounted for phonons. Instead, both the UMR magnitude and the magnetization direction dependence support the presence of a spin Peltier magnetoresistance (SPMR) caused by electron-phonon coupling and spin Peltier cooling and heating of the HM phonons (Fig. 5c, d). This SPMR can serve as a sensitive probe of spin-mediated heat transport processes.

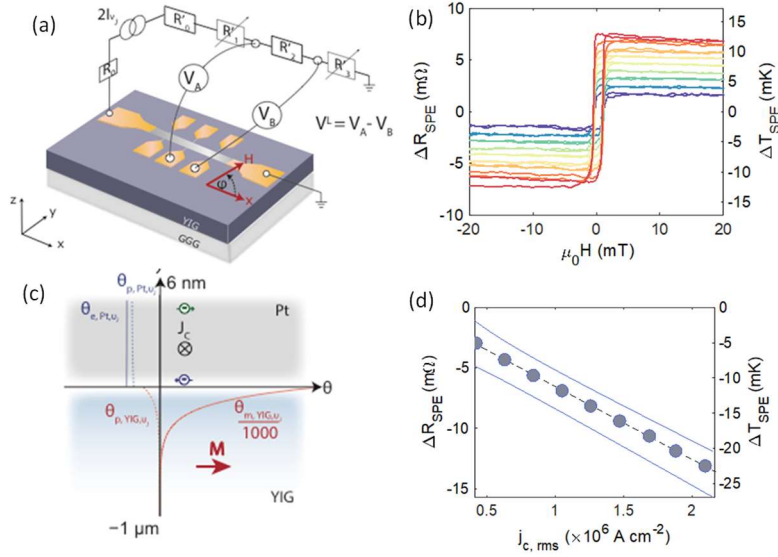


Figure 5: (a) Schematic illustration of the longitudinal measurement configuration of a Pt/YIG sample, where a balanced circuit is used to nullify the first harmonic component of the two bridge voltages, V_A and V_B . (b) The resistance change and equivalent temperature change due to the SPE as a function of magnetic field for rms current levels from 1 mA (purple) to 5 mA (red). (c) Calculated first harmonic temperature modulations due to the SPE for Pt electrons (ϑ_{e,Pt,v_J}), Pt and YIG phonons (ϑ_{p,Pt,v_J} and ϑ_{p,YIG,v_J}), and YIG magnons (ϑ_{m,YIG,v_J}) based on an analytical solution. (d) The resistance change (left axis) and equivalent phonon temperature change (right axis) in the Pt arising from the spin Peltier effect as a function of the current density in the Pt and a negative H filed at $\varphi = 90^\circ$. The shaded band represents the measurement uncertainty. The dashed line is a fit of the measurement data (symbol) with a slope -1.0×10^{-12} K m ^{2} A $^{-1}$. Reproduced from S. Sullivan, A. Weathers, L. Shi.

(vi) Resonant magnetic optical Kerr effect (MOKE) measurement of the magnon spin Nernst effect in an two-dimensional honeycomb antiferromagnetic insulator

A recent theory has predicted the presence of a magnon spin Nernst effect in a honeycomb antiferromagnet in the presence of Dzyaloshinski-Moriya interaction. Here we report the detection of this magnon spin Nernst effect in two-dimensional (2D) MnPS $_3$ flakes subject to a large longitudinal temperature gradient applied by a micro-heater device. Sensitive resonant magnetic optical Kerr effect (MOKE) measurements found opposite spin accumulation at the two transverse edges of the flake. The experiment demonstrates an approach to generate a pure transverse spin current in an antiferromagnetic insulator with an applied longitudinal temperature gradient.

- (vii) Flat bands, and correlated insulators in moiré patterns of transition metal dichalcogenide or graphene twisted homobilayers

The experimental observation of correlated insulators and superconductivity in magic-angle twisted bilayer graphene has led to tremendous interest in the properties of electrons in flat bands that may be experimentally realized in graphene or transition metal dichalcogenide (TMD) moiré patterns. Recently, the **MacDonald** group has shown that flat bands and tunable topological insulators can be realized in twisted transition metal dichalcogenide homobilayers (Wu *et al.*, Phys. Rev. Lett. **122**, 086402 (2019)). Motivated by these predictions, and leveraging previously introduced techniques the **Tutuc** group has realized twisted WSe₂ homobilayers, and probed the moiré bands in this system with transport, and scanning probe techniques (Fig. 6).

Thanks to a recent dilution refrigerator acquisition made possible through the MURI support, we will be able to probe the magnetic properties of correlated insulators experimentally observed in graphene and TMD-based moiré patterns.

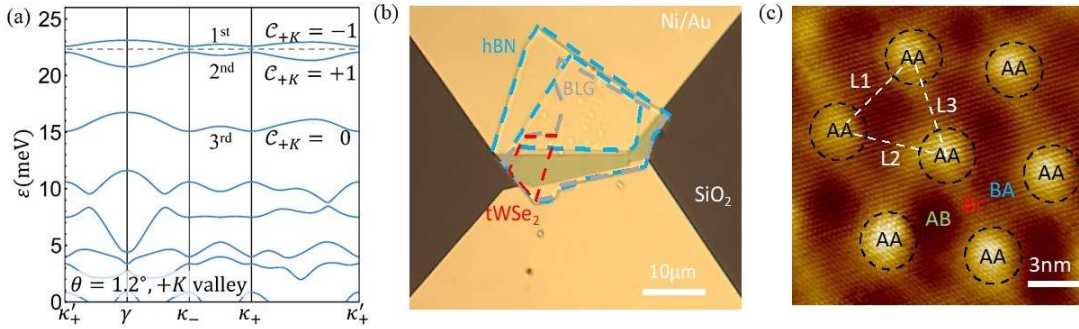
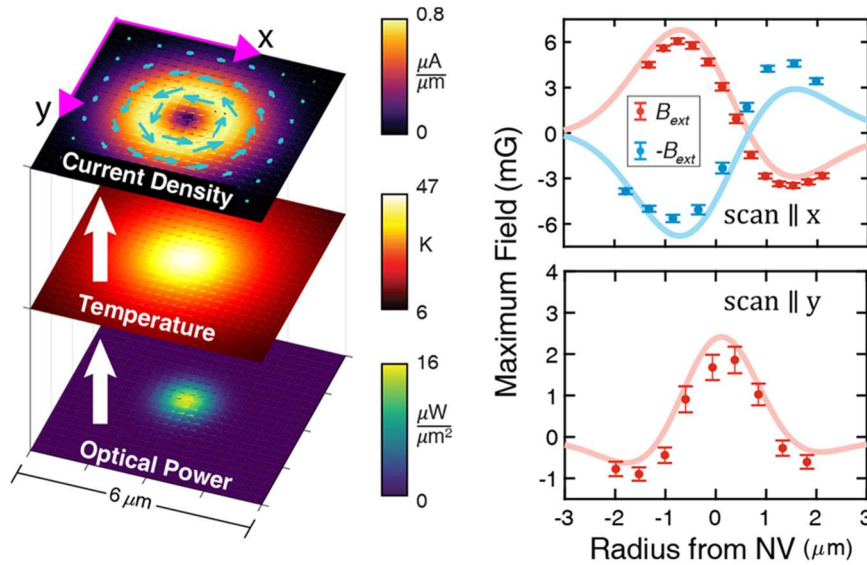


Figure 6. (a) Moiré band structure calculated for a twisted TMD bilayer at twist angle 1.2°. The system is a topological insulator when the chemical potential (black dashed line) is in the gap between the first and the second bands. The Chern numbers for the first three moiré subbands are indicated. (b) Optical micrograph of a twisted WSe₂ (tWSe₂) homobilayer, with a bottom bilayer graphene (BLG) contact, on a hexagonal boron-nitride (hBN) substrate. The blue and gray dashed lines highlight the hBN and BLG flakes, and the red dashed lines mark the tWSe₂ region. (c) Moiré pattern probed by scanning tunneling microscopy in twisted WSe₂ bilayer with a 3° twist angle. The different stacking configurations: AA, AB, BA are marked.

Spatiotemporal Mapping of a Photocurrent Vortex in Monolayer MoS₂ Using Diamond Quantum Sensors (Awschalom group)

Photocurrents are central to understanding and harnessing the interaction of light with matter and are particularly important when probing magnetic structures. Within the MURI program, we have developed a contact-free method to spatially resolve photocurrent distributions using proximal quantum magnetometers. As a demonstration of its potential, we interfaced monolayer MoS₂ with a near-surface ensemble of nitrogen-vacancy centers in diamond and map the generated photothermal current distribution through its magnetic-field profile. By synchronizing pulsed photoexcitation with dynamical decoupling of the sensor spin, we extend the sensor's quantum coherence and resolve time-dependent, two-dimensional current densities as small as 20 nA/ μm , with a projected sensitivity of 200 nA/($\mu\text{m}\sqrt{\text{Hz}}$). Our spatially resolved measurements reveal that optical excitation can generate micron-sized photocurrent vortices in MoS₂, manifesting a photo-Nernst effect exceeding that of gate-tuned graphene at comparable magnetic fields. The technique can produce fields exceeding 10 mG and currents exceeding 1.3 microamps. We further probe the rise time of the photocurrents and show that thermal diffusion determines its spatial variation. These spatiotemporal capabilities establish an optically accessed, local probe for optoelectronic phenomena, ideally suited to the emerging class of two-dimensional materials, for which making contacts is challenging and can alter the intrinsic material properties. In short, this discovery enables local, contact-free measurement that resolves currents invisible to transport studies, and also provides “stick-on” sources of ac magnetic fields.



Our demonstration broaches wide-ranging opportunities for investigating fascinating opto-electronic phenomena in materials. Highlighted by our mapping of a photo-Nernst vortex, the ability to spatially resolve photocurrent flow could more clearly characterize phenomena obscured in transport-based techniques, including chiral photocurrents localized at edges, directional currents controlled by coherent optical injection, and the scattering of valley-polarized, Weyl-point, or Dirac-point photocurrents from disorder. Beyond fundamental interests, nano-engineering of the diamond surface into pillared arrays would reduce the thermal interface conductance and possibly extend the results here to room temperature. This result, in conjunction with the use of wide-field imaging techniques and isotopically purified samples that prolong the NV's quantum coherence, could enable ultrasensitive, large-area photodetector arrays

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using our technique. Moreover, the optical generation of ac magnetic fields that are spatially localized, but also available on demand anywhere across the area covered by MoS₂, provides simplified, stick-on alternatives for fabricating devices to manipulate solid-state spins. Adding to capabilities such as electrical spin readout, spontaneous emission tuning, and 2D ferromagnetism, our demonstration of spin-photocurrent interaction widens the perspective for integrated quantum technologies based on the quantum emitter-2D material platform.

Spin-Thermal Transport Theory (UCLA)

Throughout the MURI, we have investigated novel spin and heat transport by considering various types of materials including magnets and superconductors. Understanding the physics of transport by coherent order-parameter dynamics as well as transport by incoherent thermal excitations have been studied thoroughly by focusing on the interplay of spin and heat transport by the UCLA group. The three highlights of our accomplishments can be summarized as follows.

The fundamental properties and the practical utilities of highly efficient superfluid spin transport and accompanying heat transport has been theoretically studied. We have studied superfluid spin transport in various materials such as quantum spin chains and strontium ruthenate, which allows for low-dissipation spin transport similar to charge transport in superconductors. Based on the theoretical results, we have contrived several energy efficient devices such as field-effect transistors and domain-wall racetrack memory exploiting the dissipationless nature of spin superfluids, which has the potential of solving the energy problem of the traditional electronic devices.

In addition, we have been pioneering the research on new class of magnetic materials, ferrimagnets. We have developed a general phenomenological theory for the dynamics of ferrimagnets for the first time and made a new prediction that topological solitons therein such as domain walls and skyrmions can move very fast at the angular momentum compensation point due to vanishing spin density. The theoretical prediction on a domain wall has been confirmed experimentally and published in Nature Materials in 2017. Our research has introduced ferrimagnets to researchers in spintronics as promising platforms for spin devices with easy controllability and high operating speed, spawning the emergent field of ferrimagnetic spintronics. The developed theory for the dynamics of ferrimagnets has been providing a suitable framework for researchers to understand the dynamics of ferrimagnets ever since.

Lastly, we have identified new types of spin and heat transport in several types of materials that are realized by hydrodynamics of topological charges, namely topological hydrodynamics. This is enabled by the topological properties of certain collective order- parameter textures, which can give rise to conservation laws that are not based on any specific symmetries. The emergent continuity relations are thus robust against structural imperfections and anisotropies, which would be detrimental to the conventional spin currents (that rely on approximate spin-rotational symmetries). The underlying fluxes thus supersede the notion of spin flow in insulators, setting the stage for nonequilibrium phenomena termed topological hydrodynamics. Specifically, we showed that spin and heat can be transported with little dissipation by topological solitons in solid state systems, which include domain walls in easy-axis magnets, skyrmions in chiral magnets, and vortices in superconductors. These results are detailed in the following pages.

The *tunnel magneto-Seebeck effect* is the dependence of the thermopower of magnetic tunnel junctions on the magnetic configuration. It is conventionally interpreted in terms of a thermoelectric generalization of the tunnel magnetoresistance. Here, we investigate the heat-driven electron transport in these junctions associated with electron-magnon scattering, using stochastic Landau-Lifshitz phenomenology and quantum kinetic theory. Our findings challenge the widely accepted single-electron picture of the tunneling thermopower in magnetic junctions.⁴⁰

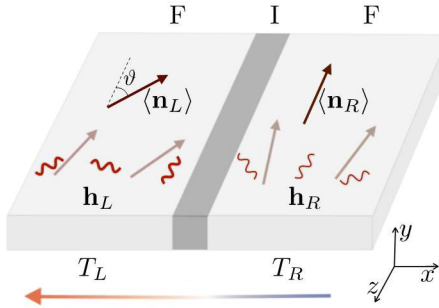


FIG. 2. Schematic of a thermally-biased F|I|F junction. Stochastic fluctuations around the equilibrium orientations of the spin-density order parameters, $\langle \mathbf{n}_R \rangle \parallel -\mathbf{z}$ and $\langle \mathbf{n}_L \rangle$ (tilted by an angle ϑ), are induced by the Langevin fields $\mathbf{h}_R$ and $\mathbf{h}_L$ (wiggly lines), whose intensity is greater in the left lead when its temperature $T_L > T_R$.

Antiferromagnetic spintronics is an emerging research field which aims to utilize antiferromagnets as core elements in spintronic devices. A central motivation toward this direction is that antiferromagnetic spin dynamics is expected to be much faster than ferromagnetic counterpart because antiferromagnets have higher resonance frequencies than ferromagnets. Recent theories indeed predicted faster dynamics of antiferromagnetic domain walls (DWs) than ferromagnetic DWs. However, experimental investigations of antiferromagnetic spin dynamics have remained unexplored mainly because of the immunity of antiferromagnets to magnetic fields. Furthermore, this immunity makes field-driven antiferromagnetic DW motion impossible despite rich physics of field-driven DW dynamics as proven in ferromagnetic DW studies. Here we show that *fast field-driven antiferromagnetic spin dynamics is realized in ferrimagnets at the angular momentum compensation point T_A* .³⁰ Using rare-earth-3d-transition metal ferrimagnetic

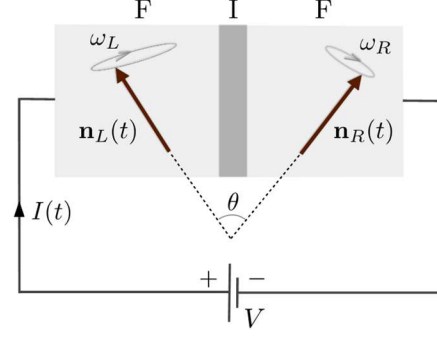


FIG. 1. An F|I|F junction circuit, subjected to an applied voltage and coherent microwave dynamics of the monodomain order parameters, $\mathbf{n}_L(t)$ and $\mathbf{n}_R(t)$. The ensuing time-dependent electric current, Eq. (1), consists of an Ohmic, $\propto G$, and adiabatically pumped, $\propto \eta$, contributions.

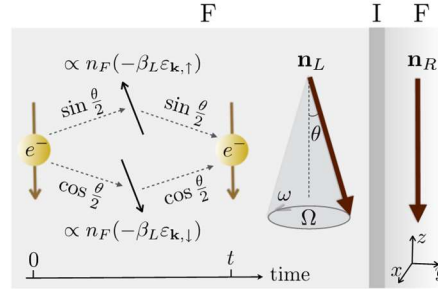


FIG. 3. A F|I|F junction biased by a macrospin precession in the left lead. The two leads have the same volume V : The size of the right lead is expanded only for the sake of illustration. In the left ferromagnet, the order parameter $\mathbf{n}_L$ precesses with constant frequency ω around the $-\mathbf{z}$ axis with cone angle θ . $\mathbf{n}_R \rightarrow -\mathbf{z}$ in the right ferromagnet is fixed. Ω is the solid angle subtended by a cycle of precession of $\mathbf{n}_L$. On the left, we sketch the process encoded in the Green function $G_{\mathbf{k},\downarrow,L}^>(\varepsilon)$. In the adiabatic limit, a spin-down electron, injected at time 0 and extracted at time t , is a linear combination of instantaneous spin eigenstates pointing along $\pm \mathbf{n}_L$. Both components acquire different phases when following rigidly the precessing order parameter, leading to probabilities proportional to $\cos^2 \frac{\theta}{2}$ ($\sin^2 \frac{\theta}{2}$) and to the number of available states, $1 - n_F(\beta_L \varepsilon_{\mathbf{k},\downarrow(t)}) \equiv n_F(-\beta_L \varepsilon_{\mathbf{k},\downarrow(t)})$.

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compounds where net magnetic moment is nonzero at TA, the field-driven DW mobility remarkably enhances up to $20 \text{ km s}^{-1} \text{T}^{-1}$. The collective coordinate approach generalized for ferrimagnets and atomistic spin model simulations show that this remarkable enhancement is a consequence of antiferromagnetic spin dynamics at T_A . Our finding allows us to investigate the physics of antiferromagnetic spin dynamics and highlights the importance of tuning of the angular momentum compensation point of ferrimagnets, which could be a key towards ferrimagnetic spintronics.

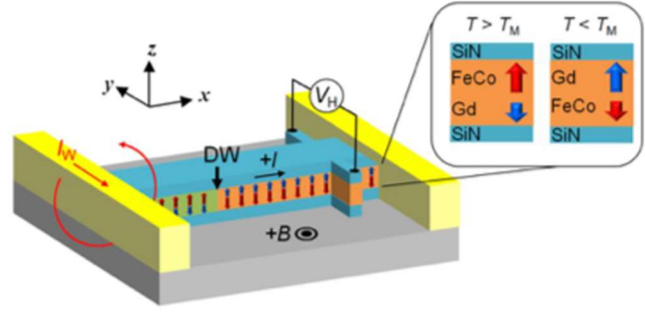


Fig.1

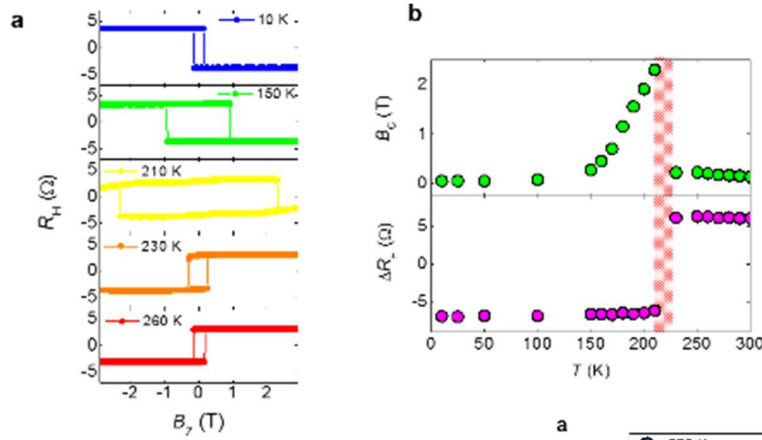


Fig.2

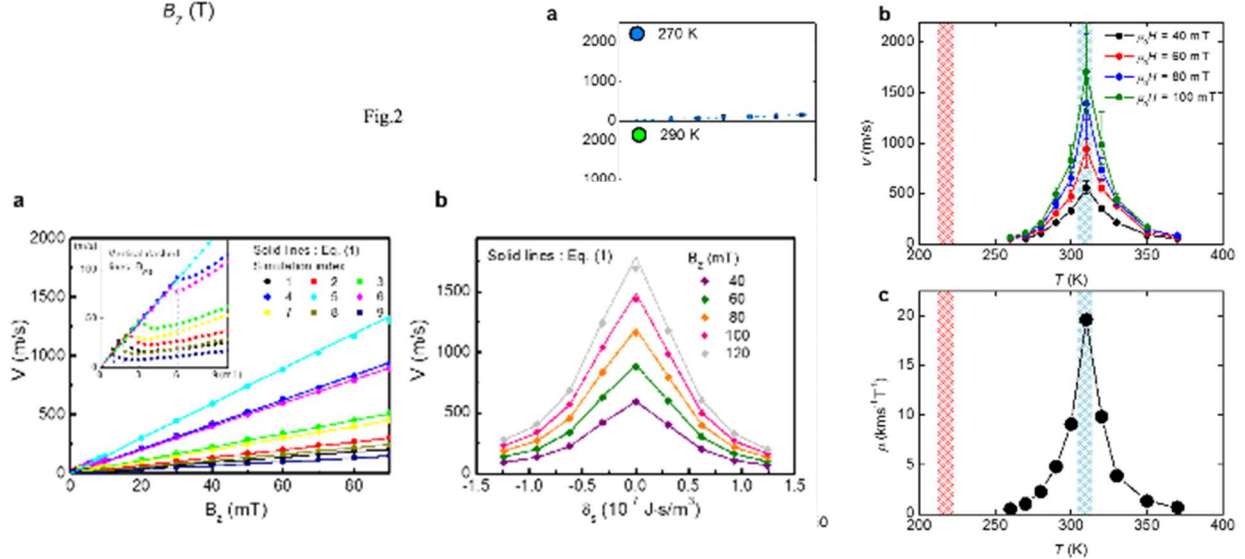


Fig.3

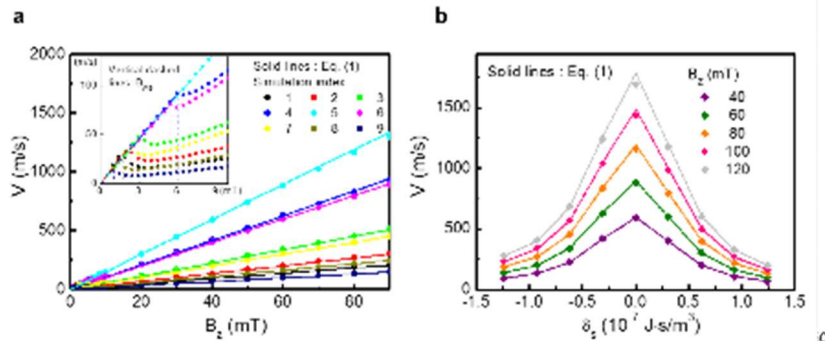


Fig.4

We theoretically study the *dynamics of ferrimagnetic domain walls* in the presence of Dzyaloshinskii-Moriya interaction. We find that an application of a DC magnetic field can induce terahertz spin-wave emission by driving ferrimagnetic domain walls, which is not possible for ferro- magnetic or antiferromagnetic domain walls. Dzyaloshinskii-Moriya interaction is shown to facilitate the terahertz spin-wave emission in wide ranges of net angular momentum by increasing the Walker- breakdown field.⁴² Moreover, we show that spin-orbit torque combined with Dzyaloshinskii-Moriya interaction also drives a fast ferrimagnetic domain wall motion with emitting terahertz spin-waves in wide ranges of net angular momentum.

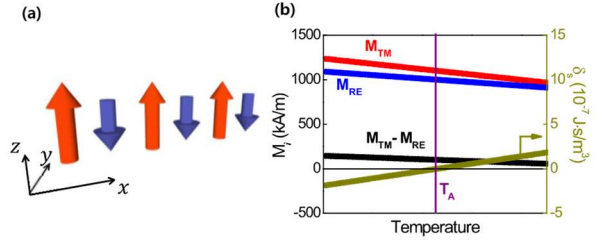


FIG. 1. (a) A schematic illustration of a ferrimagnet in which neighboring spins are coupled antiferromagnetically. (b) The assumed magnetic moments of TM (red) and RE (blue) elements as a function of the temperature T . Black symbols represent the net magnetic moment ($= M_{TM} - M_{RE}$), and dark yellow symbols represent the net angular momentum δ_s . Zero δ_s corresponds to the angular momentum compensation temperature T_A (purple).

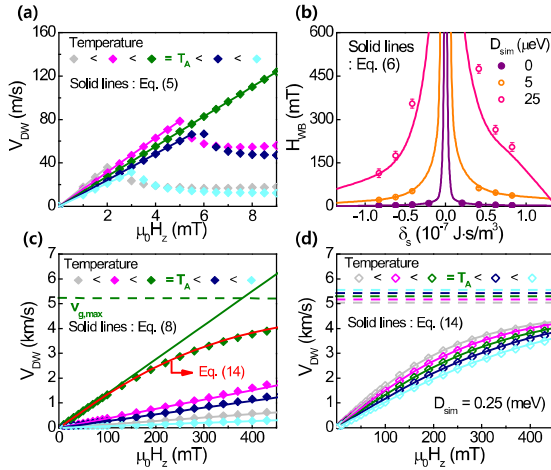


FIG. 2. (a) Domain wall velocity as a function of the external field H in the low-field regime ($\mu_0 H < 10$ mT). Symbols indicate the calculation results and solid lines indicate Eq. (5). (b) Walker breakdown field H_{WB} as a function of net angular momentum δ_s at various DMI constants D_{sim} . Domain wall velocity in the high-field regime for (c) $D_{sim} = 0$ and (d) $D_{sim} = 0.25$ meV. Solid straight lines in (c) indicate Eq. (8). The red solid line in (c) and solid curved lines in (d) represent Eq. (14). Horizontal dashed lines in (c) and (d) represent $v_{g,max}$ [Eq. (12)].

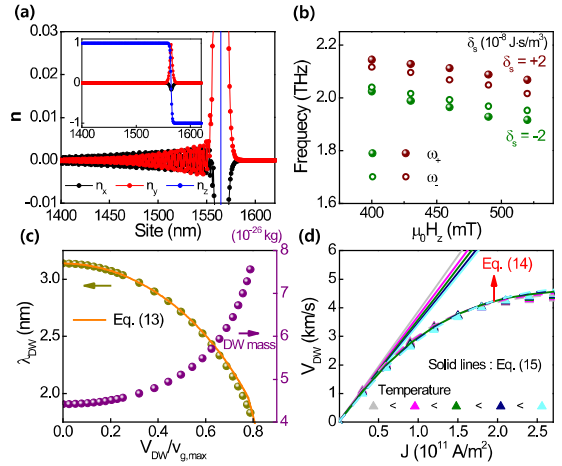


FIG. 3. (a) Configuration of domain wall and spin waves for the staggered vector $\mathbf{n}$. The inset shows the overall shape of the domain wall. (b) The frequency of emitted spin waves as a function of H with finite δ_s . (c) Domain wall width and mass as a function of $V_{DW}/v_{g,max}$ at T_A . The orange solid line indicates Eq. (13). (d) Domain wall velocity as a function of the current density J at several temperatures. Symbols represent calculation results and solid lines represent Eq. (15). Dashed lines represent relativistic modified solutions, Eq. (14).

We show how the interference between *superfluid spin currents* can endow spin circuits with coherent logic functionality. While the hydrodynamic aspects of the linear-response collective spin transport obviate interference features, we focus on the nonlinear regime, where the critical super-current is sensitive to the phase accumulated by the condensate in a loop geometry. *We propose to control this phase by electrical gating, tuning the spin-condensate coherence length.*⁸⁰ The nonlinear aspects of the spin superfluidity thus naturally lend themselves to the construction of logic gates, uniquely exploiting the coherence of collective spin currents. Vice versa, this functionality can be used to reveal the fundamental properties of spin superfluids.

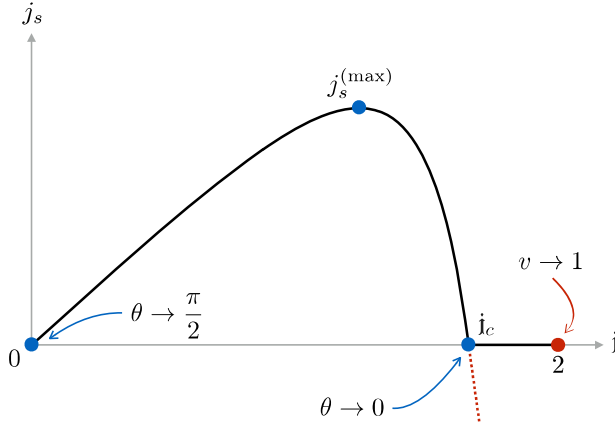


FIG. 2. Spin current (17), which governs the detected motive force $\epsilon = \vartheta j_s / g$, in the case of $p = 0$ and choosing $\mathbf{g} = 2$. Note that the picture would simply flip for the opposite bias, $\mathbf{j} < 0$.

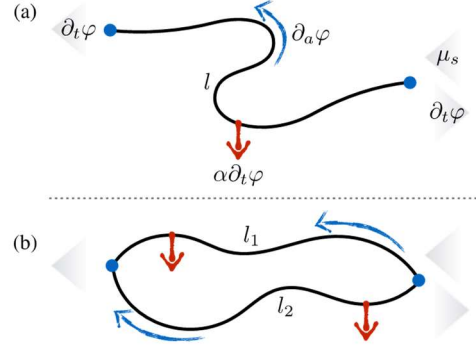


FIG. 1. Hydrodynamic spin transport in linear response. (a) Single channel of length l collectively transmitting spin current $\propto \partial_a \varphi$, which is injected on the right at the rate $\propto \mu_s$. Spin pumping $\propto \partial_t \varphi$ ejects spin currents at both ends, and along the length of the conduits Gilbert damping α leads to an attenuation. (b) Superposition of two similar spin flows in a loop geometry composed of two branches of lengths $l_{1(2)}$. φ here is the azimuthal angle of easy-plane magnetic dynamics.

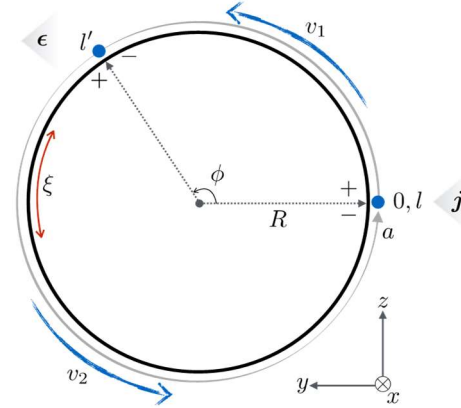


FIG. 3. Schematic of the circular configuration to exhibit interference of two (nonlinear) spin superfluids. The critical current is maximized at special relative angles ϕ between the injector and detector leads, which are determined by ξ/R according to Eq. (24).

Extending the notion of symmetry protected topological phases to insulating antiferromagnets (AFs) described in terms of opposite magnetic dipole moments associated with the magnetic Néel order, we establish a *bosonic counterpart of topological insulators in semiconductors*.⁴⁵ Making use of the Aharonov-Casher effect, induced by electric field gradients, we propose a magnonic analog of the quantum spin Hall effect (magnonic QSHE) for edge states that carry helical magnons. We show that such up and down magnons form the same Landau levels and perform cyclotron motion with the same frequency but propagate in opposite direction. The insulating AF becomes characterized by a topological Z_2 number consisting of the Chern integer associated with each helical magnon edge state. Focusing on the topological Hall phase for magnons, we study bulk magnon effects such as magnonic spin, thermal, Nernst, and Ettinghausen effects, as well as the thermomagnetic properties of helical magnon transport both in topologically trivial and nontrivial bulk AFs and establish the magnonic Wiedemann-Franz law. We show that our predictions are within experimental reach with current device and measurement techniques.

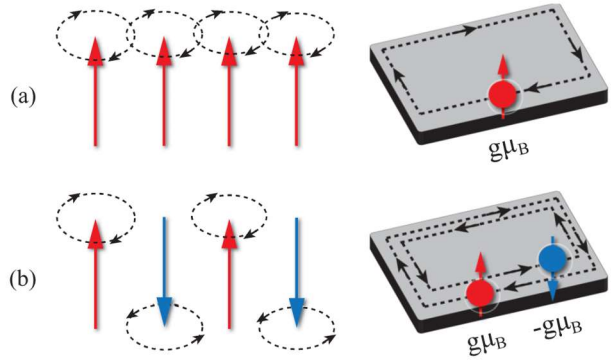


FIG. 1. (Left) Schematic representation of spin excitations in (a) a FM with the uniform ground-state magnetization and (b) an AF with classical magnetic Néel order. (Right) Schematic representation of edge magnon states in a two-dimensional topological (a) FM and (b) AF. (a) Chiral edge magnon state where magnons with a magnetic dipole moment $g\mu_B \mathbf{e}_z$ propagate along the edge of a finite sample in a given direction. (b) Helical edge magnon state where up and down magnons ($\sigma = \pm 1$) with opposite magnetic dipole moments $\sigma g\mu_B \mathbf{e}_z$ propagate along the edge in opposite directions. The AF thus forms a bosonic analog of a TI characterized by two edge modes with opposite chiralities and can be identified with two independent copies (with opposite magnetic moments) of single-layer FMs shown in (a).

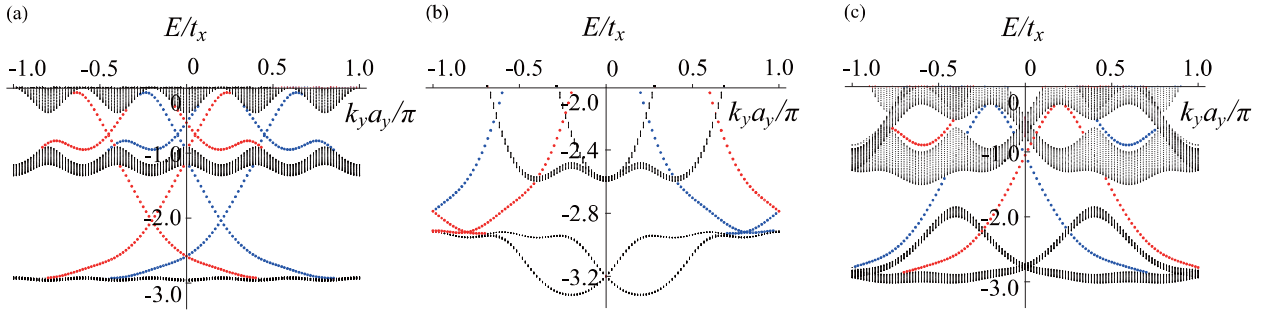


FIG. 2. Plots of the magnonic energy spectrum, rescaled energy E/t_x , as a function of the rescaled wave vector $k_y a_y / \pi$ obtained by numerically solving the tight-binding model (24) for a strip with width of 115 lattice sites, for $t_x = t_y = 1$ and $\theta_1 = 2\pi/5$, showing the first and partially the second Landau levels (black). The up magnon edge states ($\sigma = 1$) are in red while down magnon edge states ($\sigma = -1$) are in blue. The periodicity of the vector potential is (a) $q \gg 1$, (b) $q = 7$, and (c) $q = 4$. (a) shows a band structure characteristic for a TI with a well-developed gap in an almost flat band and with helical edge states formed by the up and down magnons. (b) Qualitatively the same as in (a). (c) For each given value of k_y there are well-defined edge states with a gap in the spectrum, but they coexist with bulk states at different momenta.

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Temperature-dependent spin Seebeck effect data on Pt|yttrium iron garnet (YIG) |gallium gadolinium garnet (GGG) are reported for YIG films of various thicknesses. The effect is reported as a spin Seebeck resistivity (SSR), the inverse spin-Hall field divided by the heat flux, to circumvent uncertainties about temperature gradients inside the films. The SSR is a nonmonotonic function of YIG thickness. A *diffusive model for magnon transport* demonstrates how these data give evidence for the existence of two distinct length scales in thermal spin transport, a spin-diffusion length, and a magnon energy relaxation length.⁵⁴

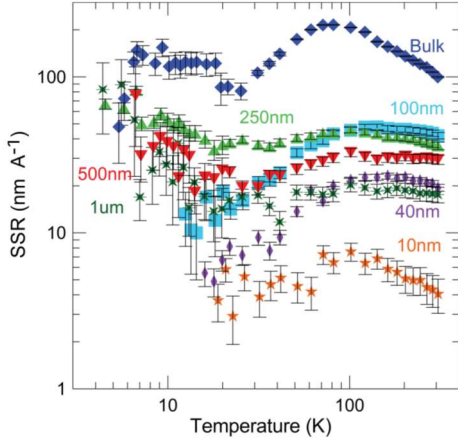


FIG. 1. Temperature dependence of the SSR for various YIG film thicknesses and bulk YIG.

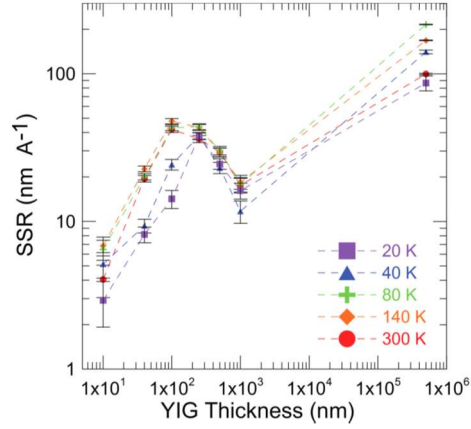


FIG. 2. Thickness dependence of the SSR at the various temperatures indicated on the graph.

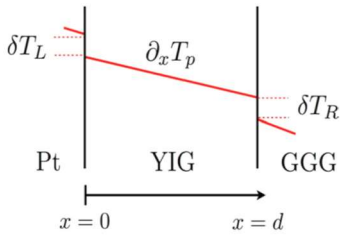


FIG. 3. Qualitative illustration of the phonon temperature profile in a Pt|YIG|GGG heterostructure.

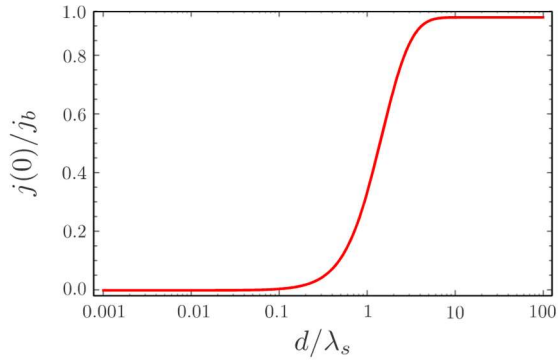


FIG. 4. Thickness dependence of the spin current $j(0)$ injected at the Pt|YIG interface in the far regime, i.e., where the thickness is represented on the scale of the magnon spin-diffusion length λ_s . Here, spin transport is dominated by the mechanisms leading to relaxation of the magnon chemical potential. The spin current is normalized by the thermal spin current in the bulk $j_b = -\zeta \partial_x T_p$.

We study the magnetic dynamics of magnetoelectric antiferromagnetic thin films, where an unconventional boundary ferromagnetism coexists with the bulk Néel phase below the Néel temperature. The spin exchange between the two order parameters yields an effective low-energy theory that is formally equivalent to that of a ferrimagnet. *Dynamics of domain walls and skyrmions* are analyzed within the collective variable approach, from which we conclude that they behave as massive particles moving in a viscous medium subjected to a gyrotropic force. We find that the film thickness can be used as a control parameter for the motion of these solitons. In this regard, it is shown that an external magnetic field can drive the dynamics of domain walls, whose terminal velocity is tunable with the sample thickness. Furthermore, the classification of the skyrmion dynamics is sensitive to the spatial modulation of the sample thickness, which can be easily engineered with the present (thin-film) deposition techniques. *Current-driven spin transfer can trigger drifting orbits of skyrmions*,⁵³ which can be utilized as racetracks for these magnetic textures.

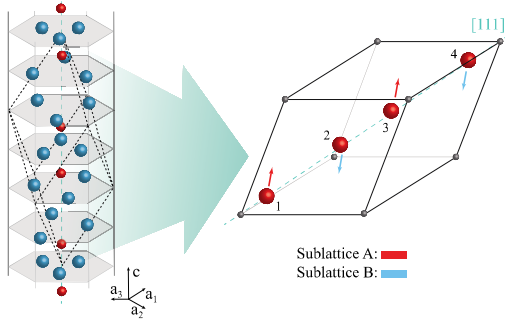


FIG. 1. Corundum-type crystal structure of eskolaite (mineral form of $\alpha\text{-Cr}_2\text{O}_3$). The inset depicts the corresponding unit cell. The parameters of the rhombohedral crystal lattice are $a = 4.95 \text{ \AA}$ and $c = 13.58 \text{ \AA}$ (referred to the hexagonal frame). Red (blue) spheres represent Cr^{3+} (O^{2-}) ions. Red (blue) spheres (sublattice A) and blue (sublattice B) arrows illustrate a spin arrangement of the Cr^{3+} ions corresponding to the antiferromagnetic phase: $s_1 = -s_2 = s_3 = -s_4$.

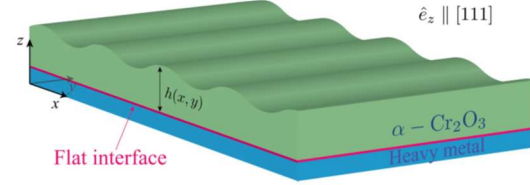


FIG. 2. Schematic of the heterostructure: A film made of chromia ($\alpha\text{-Cr}_2\text{O}_3$) is deposited on top of a flat heavy-metal substrate. The film is grown along the $[111]$ direction of its rhombohedral crystal lattice, and its thickness varies over the interface, which is described by the profile $h(x, y)$. This figure illustrates the example of a periodically modulated thickness along the x axis.

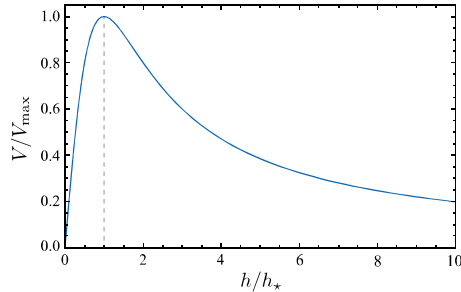


FIG. 3. Dependence of the field-driven terminal velocity of the domain wall on the thickness of the ME-AFM film. Both quantities have been normalized to the maximum velocity $V_{\max} = g\delta H_z/2$ and the length scale $h_* = s/\alpha$. The dashed line illustrates the maximum of the terminal velocity reached at the value $h = h_*$ of the film thickness.

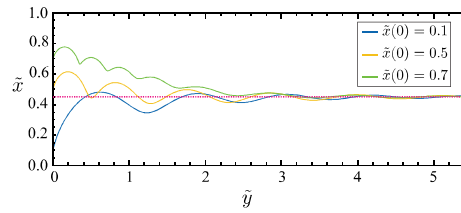


FIG. 4. Driftinglike orbits of skyrmions with topological charge $Q = 1$ subjected to the current-induced force $\vec{F}_J = 0.8(4\pi\delta_x + \mathcal{K}\delta_y)$ for the hyperbolic thickness profile $h(\tilde{x})/T = 1 + 0.7 \tanh[10(\tilde{x}_c - \tilde{x})]$, with $\tilde{x}_c = 0.45$. These trajectories are calculated by numerical integration of the dimensionless equations of motion (14) with the following values of the parameters: $\mathcal{K} = 0.9\pi$ and $4\pi s/\alpha s T = 4\pi$. In the calculations we have taken the initial velocity $\dot{\tilde{x}}(0) = \dot{\tilde{y}}(0) = 0$ and initial position along the x axis [$\tilde{y}(0) = 0$]: $\tilde{x}(0) = 0.1$ (blue), $\tilde{x}(0) = 0.5$ (yellow), and $\tilde{x}(0) = 0.7$ (green). The magenta dashed line at $\tilde{x} = \tilde{x}_c$ depicts the (attractive) racetrack for the skyrmion dynamics.

Motivated by the recent study on the quasiparticle-induced friction of solitons in superfluids, we theoretically study *magnon-induced intrinsic friction of a domain wall in a one-dimensional ferromagnet*.⁵⁶ To this end, we start by obtaining the hitherto overlooked dissipative interaction of a domain wall and its quantum magnon bath to linear order in the domain-wall velocity and to quadratic order in magnon fields. An exact expression for the pertinent scattering matrix is obtained with the aid of supersymmetric quantum mechanics. We then derive the magnon-induced frictional force on a domain wall in two different frameworks: time-dependent perturbation theory in quantum mechanics and the Keldysh formalism, which yield identical results. The latter, in particular, allows us to verify the fluctuation-dissipation theorem explicitly by providing both the frictional force and the correlator of the associated stochastic Langevin force. The potential for magnons induced by a domain wall is reflectionless, and thus the resultant frictional force is non-Markovian similar to the case of solitons in superfluids. They share an intriguing connection to the Abraham-Lorentz force that is well known for its causality paradox. The dynamical responses of a domain wall are studied under a few simple circumstances, where the non-Markovian nature of the frictional force can be probed experimentally. Our work, in conjunction with the previous study on solitons in superfluids, shows that the macroscopic frictional force on solitons can serve as an effective probe of the microscopic degrees of freedom of the system.

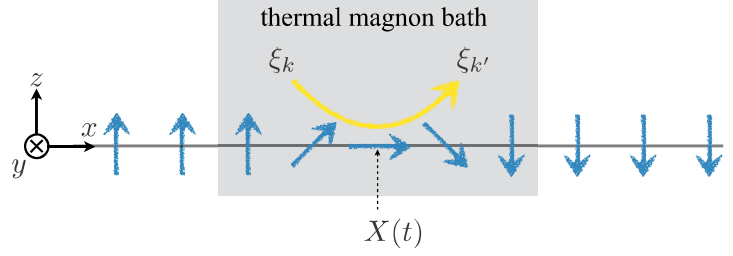


FIG. 1. Schematic illustration of a ferromagnetic domain wall and its thermal magnon bath, which induces a non-Markovian frictional force and a colored stochastic Langevin force on the domain wall. $X(t)$ represents the position of the domain wall; ξ_k parametrizes the amplitude of magnon fluctuations. See the main text for details.

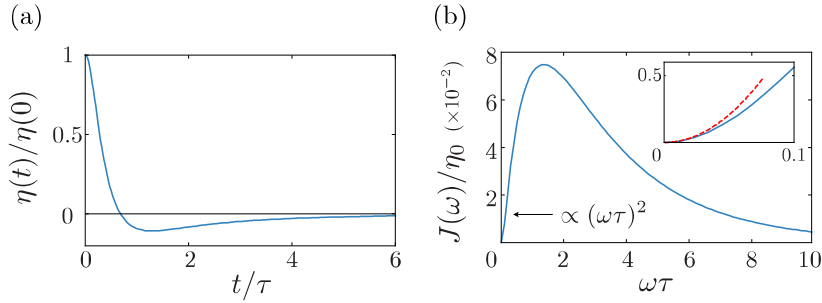


FIG. 2. Plots of a response kernel in (a) the time domain $\eta(t)$, and (b) the frequency domain $J(\omega) = \text{Re } \eta[\omega]$ at temperature $T = \epsilon_0/10$. The solid blue lines show the numerical evaluations of Eqs. (30) and (31). The dashed red line in the inset shows the analytical expression for the low-frequency limit of $J(\omega)$ in Eq. (32).

Spin-torque-biased magnetic dynamics in an easy-plane ferromagnet (EPF) is theoretically studied in the presence of a weak in-plane anisotropy.⁶¹ While this anisotropy spoils U(1) symmetry, thereby quenching the conventional spin superfluidity, we show that the system instead realizes a close analog of a long Josephson junction (LJJ) model. The traditional magnetic-field and electric-current controls of the latter map, respectively, onto the symmetric and antisymmetric combinations of the out-of-plane spin torques applied at the ends of the magnetic strip. This suggests an alternative route towards realizations of superfluidlike transport phenomena in insulating magnetic systems. We study a spin-torque-biased phase diagram, providing an analytical solution for static multidomain phases in the EPF. We adapt an existing self-consistency method for the LJJ to develop an approximate solution for the EPF dynamics. The LJJ-EPF mapping has the potential for producing applications with superconductor-based circuit functionality at elevated temperatures. The results apply equally to antiferromagnets with suitable effective free energy in terms of the Néel order instead of in-plane magnetization.

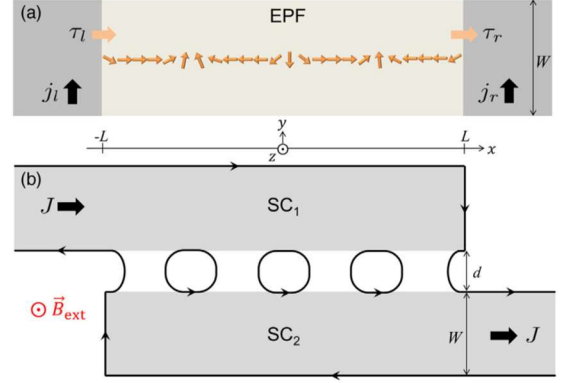


FIG. 1. (a) EPF with spin injection from metal contacts on two sides. The spin polarization of the current is along the z axis, while the spin-current flow is oriented along the x axis. The ferromagnet is sufficiently narrow in the transverse dimensions to treat it as quasi-one-dimensional. (b) Diagram of the inline LJJ, with W much smaller than L as well as the depth of the structure in the z direction. We assume two conventional superconductors (SCs) much larger than the London penetration depth in all dimensions. The magnetic-field screening currents as well as the circulating vortices are schematically depicted with black oriented lines. The vortices in the junction map onto the domain walls depicted in (a).

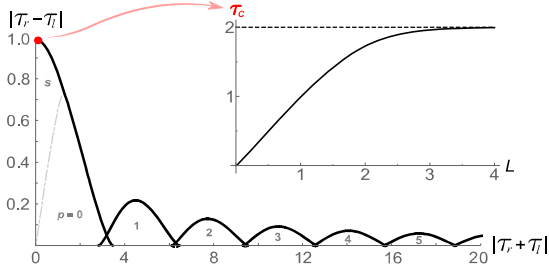


FIG. 2. The regions of stability for equilibrium p -vortex solutions of the LJJ boundary-value problem, for $L/\lambda = 1$. The spin torques $\tau_{r,l}$ are in units of A/λ . Overlapping regions can have either solution. Outside of these regions, i.e., in the high $|\tau_r - \tau_l|$ limit, there are no stable time-independent solutions. Inset: The dependence of the critical torque τ_c , for which $\tau_r + \tau_l = 0$, on the length L in units of λ .

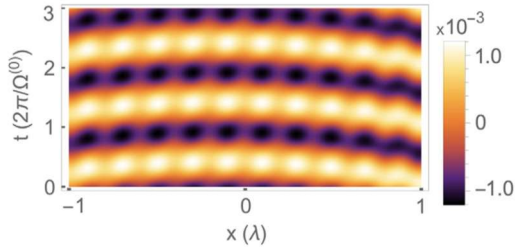


FIG. 3. Plot of the approximate modulation of the superfluid phase solution, $e^{(0)}(x, t)$, resulting from a weak in-plane anisotropy, with $L = 1$, $\beta_d = 0.1$, $\gamma = 0.01$, $\tau_l = 1.5$, and $\tau_r = -2$.

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It has been recognized that the condensation of spin-triplet Cooper pairs requires not only the broken gauge symmetry but also the spin ordering as well. One consequence of this is the possibility of the *Cooper-pair spin current analogous to the magnon spin current in magnetic insulators*, the analogy also extending to the existence of the Gilbert damping of the collective spin-triplet dynamics. The recently fabricated heterostructure of the thin film of the itinerant ferromagnet SrRuO₃ on the bulk Sr₂RuO₄, the best-known candidate material for the spin-triplet superconductor, offers a promising platform for generating such spin current. We will show how such heterostructure allows us to not only realize the long-range spin valve but also electrically drive the collective spin mode of the spin-triplet order parameter.⁵⁸ Our proposal represents both a new realization of the spin superfluidity and a transport signature of the spin-triplet superconductivity.

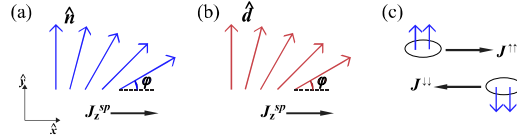


FIG. 1. Schematic illustration of the analogy between the magnetic insulator and the spin-triplet superconductor. (a) The planar spiraling of the magnetic order parameter $\hat{\mathbf{n}}$ leads to spin current. (b) The same phenomena occurs for that of the spin component $\hat{\mathbf{d}}$ of the spin-triplet superconductor order parameter, (c) the dual picture of which is the counterflow of the spin up-up and down-down pairs.

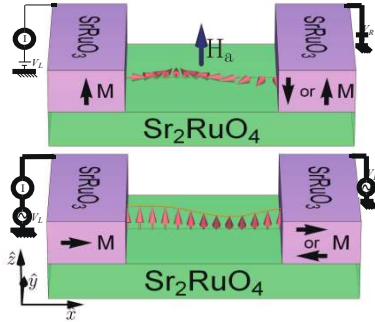


FIG. 2. The setup for the DC voltage bias for the spin valve (upper) and the AC bias voltage for the spin-wave detection (lower), where $\hat{x}, \hat{y}, \hat{z}$ coincide with the crystalline a, b, c -axes, respectively. For the upper figure, the lead magnetization is along the c -axis, with the applied magnetic field $H_a \geq 200$ G along the c -axis giving us the easy plane d -vector configuration on the ab -plane, hence the spiraling in the ab -plane. For the lower figure, the lead magnetization is along the a -axis; as the easy-axis d -vector anisotropy favors the alignment along the c -axis, in the absence of an applied field, the AC bias voltage gives us the low-frequency standing wave of the d -vector oscillating around the c -axis in the bc -plane.

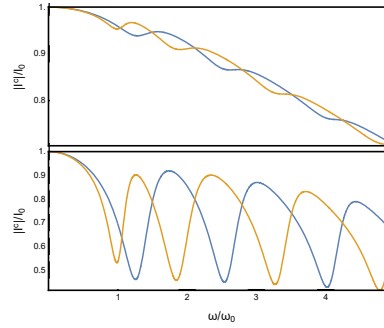


FIG. 3. Charge current versus frequency plotted for $\hat{g} = 0.5$, $\hat{L} = 2$, $\Gamma/\omega_0 = 0.1$ and $\hat{A} = 0.2$, with the orange curve representing $p_L = p_R = p$ and the blue $p_L = -p_R = p$. Note that $p = 0.2$ for the top plot and $p = 0.8$ for the bottom plot.

We theoretically study the *thermal Hall effect by magnons in skyrmion crystal phases* of ferrimagnets in the vicinity of the angular momentum compensation point (CP).⁷⁰ To this end, we start by deriving the equation of motion for magnons in the background of an arbitrary equilibrium spin texture, which gives rise to the fictitious electromagnetic field for magnons. As the net spin density varies, the resultant equation of motion interpolates between the relativistic Klein-Gordon equation at CP and the nonrelativistic Schrödinger-like equation away from it. In skyrmion crystal phases, the right- and the left-circularly polarized magnons with respect to the order parameter are shown to form the Landau levels separately within the uniform skyrmion-density approximation. For an experimental proposal, we predict that the magnonic thermal Hall conductivity changes its sign when the ferrimagnet is tuned across CP, providing a way to control heat flux in spin-caloritronic devices on the one hand and a feasible way to detect CP of ferrimagnets on the other hand.

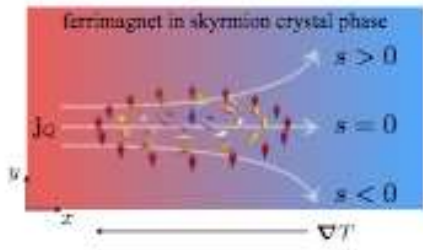


FIG. 1. Schematic illustration of the magnonic heat flux j_Q through a ferrimagnet in its skyrmion crystal phase subjected to a temperature gradient ∇T . The colored small arrows depict a single skyrmion texture of the order parameter $\mathbf{n}$. Magnons can exhibit the thermal Hall effect since the skyrmion crystal gives rise to the fictitious magnetic field, which magnons of left and right circular polarization (with respect to the order parameter) experience as if they carry the positive and the negative charge, respectively. The induced transverse heat flux changes its direction as the net spin density s along $\mathbf{n}$ varies across 0.

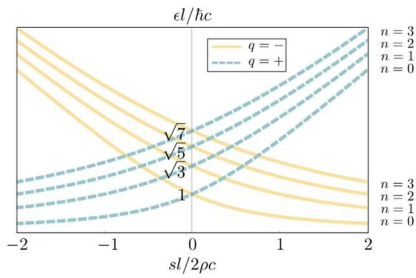


FIG. 2. The plot of the Landau levels [Eq. (11)] of magnon bands in ferrimagnetic skyrmion crystals in terms of the rescaled energy el/hc and the rescaled spin density $sl/2pc$. The solid gold and the dashed blue lines represent the right-circularly polarized ($q = +$) and the left-circularly polarized ($q = -$) magnon bands, respectively.

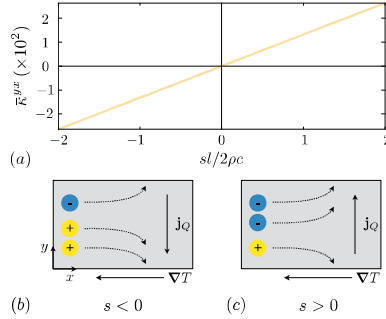


FIG. 3. (a) The plot of the rescaled thermal Hall conductivity $\bar{\kappa}^{yx} \equiv (2\pi\hbar t/k_B^2 T)\kappa^{yx}$, which parametrizes the ratio of the induced transverse heat flux j_Q^y to the applied longitudinal temperature gradient $\partial_x T$ for the ferrimagnet film of thickness t . (b) and (c) the schematic illustrations of the positive-chirality (+) and the negative-chirality (-) magnon motions subjected to a temperature gradient $\nabla T = (\partial_x T)\hat{x}$ and the resultant transverse energy flux $\mathbf{j}_Q = j_Q^y \hat{y}$.

Departing from the conventional view on superconducting vortices as a parasitic source of dissipation for charge transport, *we propose to use mobile vortices as topologically-stable information carriers for spin transport.*⁶⁰ To this end, we start by constructing a phenomenological theory for the interconversion between spin and vorticity, a topological charge carried by vortices, at the interface between a magnetic insulator and a superconductor, by invoking the interfacial spin Hall effect therein. We then show that a vortex liquid in superconductors can serve as a spin-transport channel between two magnetic insulators by encoding spin information in the vorticity. The vortex-mediated nonlocal signal between the two magnetic insulators is shown to decay algebraically as a function of their separation, contrasting with the exponential decay of the quasiparticle-mediated spin transport. We envision that hydrodynamics of topological excitations, such as vortices in superconductors and domain walls in magnets, may serve as a universal framework to discuss long-range transport properties of ordered materials.



FIG. 1. (a) A schematic of spin-vorticity transmutation at the interface between a magnetic insulator and a superconductor. The blue arrow represents spin in a magnetic insulator and the red arrows depict the phase of a superconducting vortex. (b) A schematic of the mean-field phase diagram of bulk type-II superconductors [2], which comprises the Meissner phase at low magnetic fields $H < H_{c1}$ with complete expulsion of the magnetic flux, the mixed phase at intermediate fields $H_{c1} < H < H_{c2}$, where the magnetic flux penetrates into a superconductor in the form of vortices, and the normal-metal phase at high fields $H > H_{c2}$, where superconductivity is destroyed. T_c is the critical temperature for the onset of superconductivity. Vortices in the mixed phase can form several states of matter, including vortex liquid.

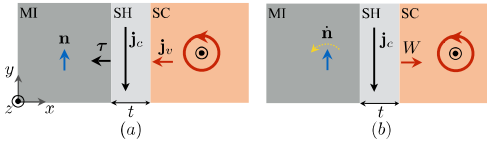


FIG. 3. (a) The vorticity-current density $\mathbf{j}_v$ induces the charge-current density $\mathbf{j}_c$ [Eq. (3)] in SH via the Josephson effect, which in turn exerts the torque $\boldsymbol{\tau}$ [Eq. (4)] on the MI via the spin Hall effect. (b) The dynamics of the MI $\mathbf{\hat{n}}$ induces the normal charge-current density $\mathbf{j}_c$ [Eq. (5)] in SH via the inverse spin Hall effect. The counter-propagating supercurrent then performs the vorticity-dependent work W [Eq. (6)] on a vortex via the Lorentz force.

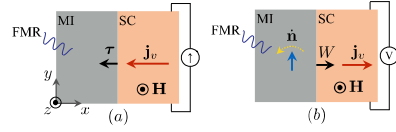


FIG. 2. Schematics of experimental setups for probing spin-vorticity transmutation at the interface between a magnetic insulator (MI) and a superconductor (SC) subjected to an external magnetic field $\mathbf{H}$. (a) The torque $\boldsymbol{\tau}$ [Eq. (2a)] on MI exerted by the vorticity flux $\mathbf{j}_v$ in SC can be probed by performing ferromagnetic resonance (FMR) measurements on MI, while applying a transverse current to SC, which generates a longitudinal vorticity flux $\mathbf{j}_v$ via the Lorentz force [13]. (b) The vorticity-dependent work W [Eq. (2b)] performed by magnetic dynamics $\mathbf{\hat{n}}$ on vortices creates the nonequilibrium vorticity accumulation at the interface and thereby induces a diffusive vorticity flux $\mathbf{j}_v$. The vorticity flux $\mathbf{j}_v$ can be probed by measuring a transverse voltage drop across the SC, which is induced by $\mathbf{j}_v$ via the Josephson effect [13], while driving FMR dynamics in the MI. In addition, the energy dissipation through vortex generation suggests a new channel for Gilbert damping of MI, which can be manifested through the enhancement FMR linewidth [14].

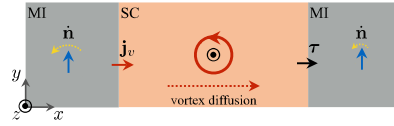
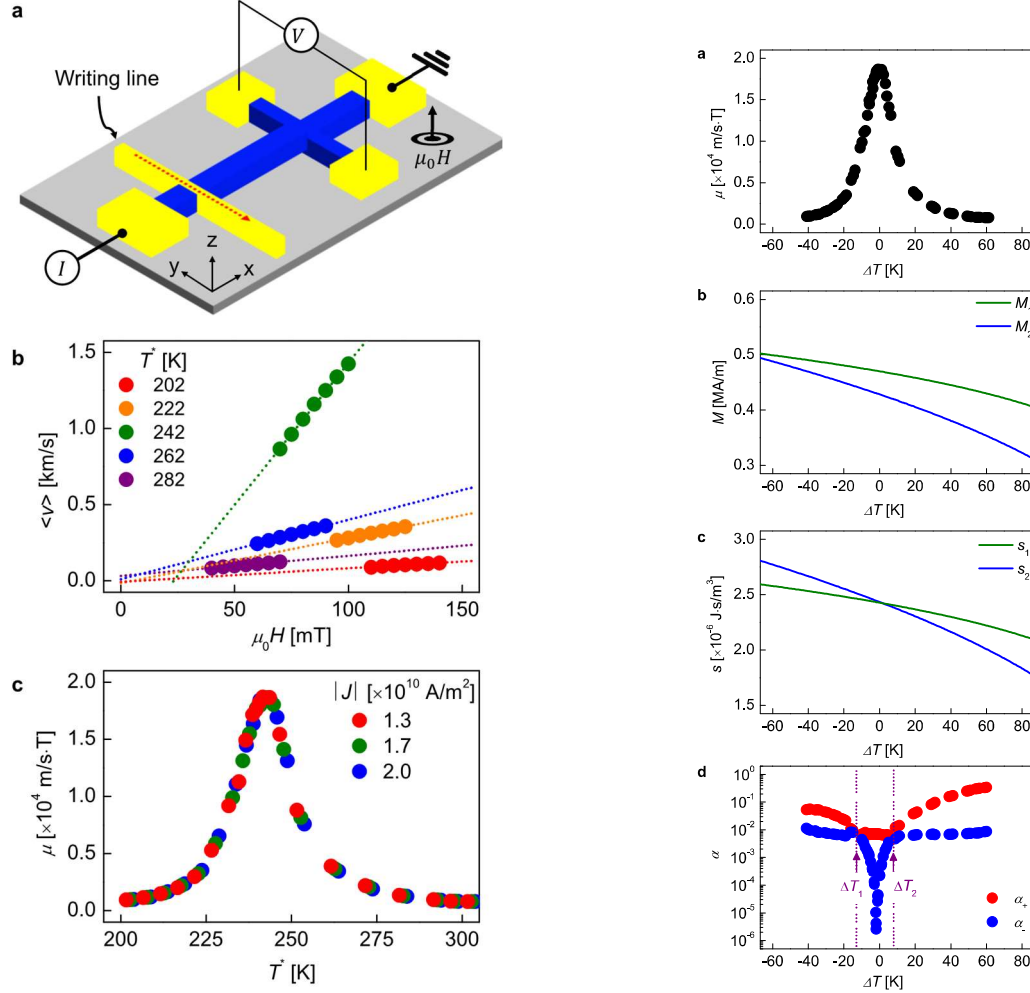


FIG. 4. A schematic of the nonlocal spin transport between two MIs mediated by a vortex liquid in the interconnecting SC. The dynamics of the magnetization $\mathbf{n}$ of the left MI pumps the vorticity current $\mathbf{j}_v$ into the SC. Some of the pumped vortices travel across the SC by thermal diffusion and reach the interface to the right MI, exerting the torque $\boldsymbol{\tau}$ to it. The width of the SC needs to be much larger than the length to prevent vortices from escaping through sides.

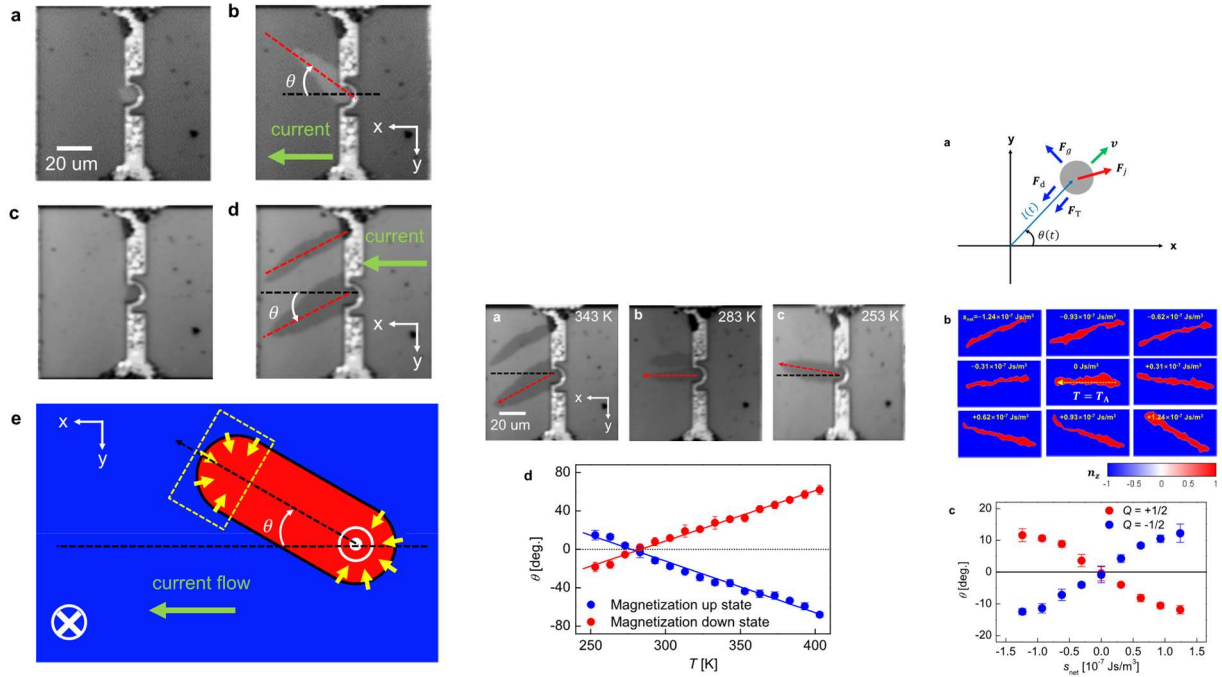
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We investigate the *Gilbert damping parameter for rare earth (RE)– transition metal (TM) ferrimagnets over a wide temperature range*.⁷² Extracted from the field-driven magnetic domain-wall mobility, was as low as 7.2×10^{-3} and was almost constant across the angular momentum compensation temperature T_A , starkly contrasting previous predictions that should diverge at T_A due to vanishing total angular momentum. Thus, magnetic damping of RE-TM ferrimagnets is not related to the total angular momentum but is dominated by electron scattering at the Fermi level where the TM has a dominant damping role.



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Charged particles exhibit the Hall effect in the presence of magnetic fields. Analogously, ferromagnetic skyrmions with non-zero topological charges and finite fictitious magnetic fields exhibit the skyrmion Hall effect, which is detrimental for applications. The *skyrmion Hall effect has been theoretically predicted to vanish for antiferromagnetic skyrmions* because the fictitious magnetic field, proportional to net spin density, is zero.⁶⁵ We experimentally confirm this prediction by observing current-driven transverse elongation of pinned ferrimagnetic bubbles. Remarkably, the skyrmion Hall effect, estimated with the angle between the current and bubble elongation directions, vanishes at the angular momentum compensation temperature where the net spin density vanishes. This study establishes a direct connection between the fictitious magnetic field and spin density, offering a pathway towards the realization of skyrmionic devices.



We have studied a *spin Hamiltonian for spin-orbit-coupled ferromagnets on the honeycomb lattice*.²¹ At sufficiently low temperatures supporting the ordered phase, the effective Hamiltonian for magnons, the quanta of spin-wave excitations, is shown to be equivalent to the Haldane model for electrons, which indicates the nontrivial topology of the band and the existence of the associated edge state as shown in Fig. 1. At high temperatures comparable to the ferromagnetic-exchange strength, we take the Schwinger-boson representation of spins, in which the mean-field spinon band forms a bosonic counterpart of the Kane-Mele model. The nontrivial geometry of the spinon band, which is shown in Fig. 2, can be inferred by detecting the spin Nernst effect. The spin Nernst conductivity is shown in Fig. 3 as a function of a temperature.

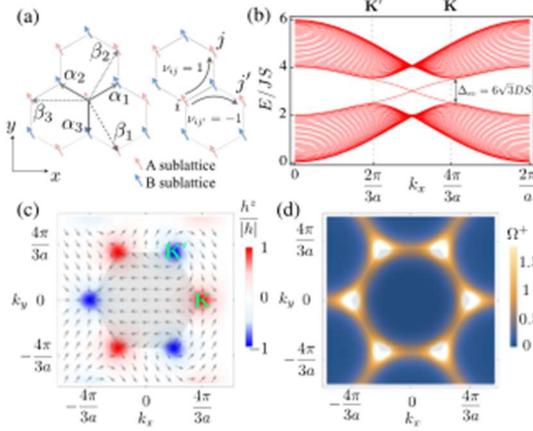


FIG. 1. (a) The honeycomb lattice structure and the relative sign ν_{ij} of the DM interaction. (b) One-dimensional projection of the magnon bands [Eq. (5)], which are calculated with a ribbon geometry with zigzag terminations and 30 unit cells width. (c) The direction of the vector field $\mathbf{h}(\mathbf{k})$ [Eq. (4)]. (d) The Berry curvature of the upper band, Ω^+ . For (b)–(d), the parameters $D = 0.1J$ and $B = 0$ are used. The shaded honeycomb in (c) is the first Brillouin zone. Two Dirac points, $\mathbf{K}$ and $\mathbf{K}'$ are denoted in (b) and (c). See the main text for detailed discussions.

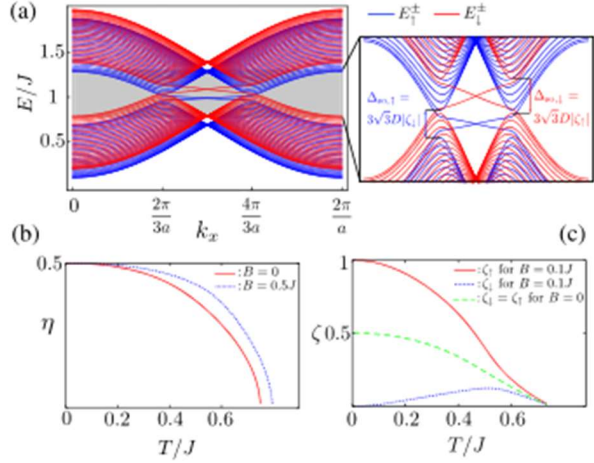


FIG. 2. (a) One-dimensional projection of the spinon bands [Eq. (10)] at the temperature $T = 0.6J$ for the parameters $S = 1/2$, $D = 0.1J$, $B = 0.1J$. A zoom of the middle sector is shown in the right. The band structure calculation corresponds to a ribbon geometry with zigzag terminations and 30 unit cells. (b), (c) The dependence of the mean fields η , $\zeta_\uparrow$, and $\zeta_\downarrow$ on the temperature for the parameters $S = 1/2$ and $D = 0.1J$. See the main text for detailed discussions.

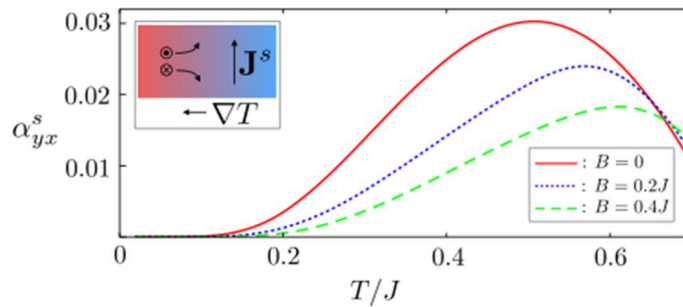


FIG. 3. The spin Nernst conductivity α^s_{yx} as a function of temperature. The inset schematically shows a setup of an experiment and motions of spinons therein.

We have studied the motion of a magnetic domain wall induced by transverse elastic waves in a one-dimensional magnetic wire, which respects both rotational and translational symmetries. See Fig. 1 for an illustration. By invoking the conservation of the associated total angular and linear momenta, we are able to derive the torque (Fig. 2) and the force (Fig. 3) on the domain wall exerted by the waves. We then show how *ferromagnetic and antiferromagnetic domain walls can be driven by circularly- and linear-polarized waves*, respectively.²⁰ We envision that elastic waves may provide effective means to drive the dynamics of magnetic solitons in insulators.

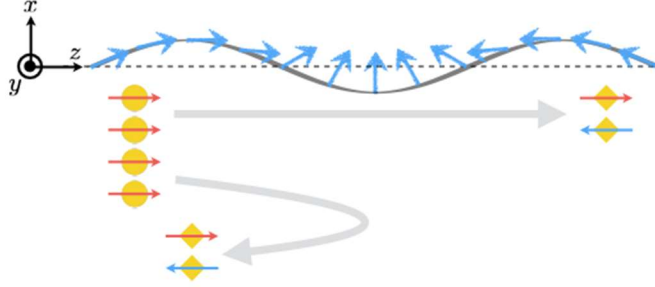


FIG. 1. A schematic illustration of a ferromagnetic wire with a magnetic domain wall (shown by blue thick arrows) and a transverse elastic deformation. The yellow circles represent incoming phonons, quanta of elastic waves; the yellow diamonds represents transmitted and reflected phonons. The red (blue) arrows on circles represent phonons' angular momentum in the positive (negative) z direction. Phonons are injected from the left; some of them are reflected by the domain wall and thereby exert the force on it; some of the transmitted and reflected phonons change their angular momentum and thereby exert the torque on the wall

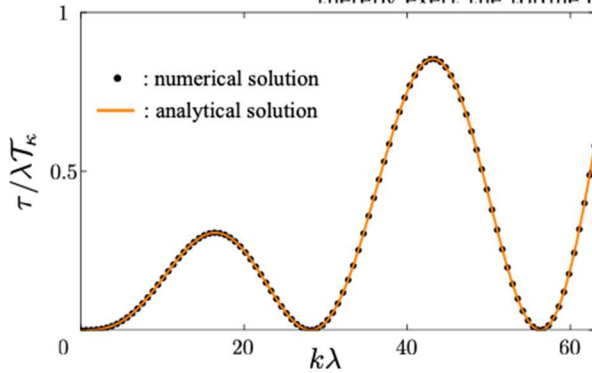


FIG. 2. The torque τ on the domain wall by the circularly-polarized waves as a function of the wavenumber $k\lambda$ for the parameters $\kappa = 0.2$ and $a = \lambda/10$. The solid line is obtained with the analytical expression for τ in Eq. (5); the dots are obtained with τ in Eq. (13) calculated from numerical solutions of the differential equations (7).

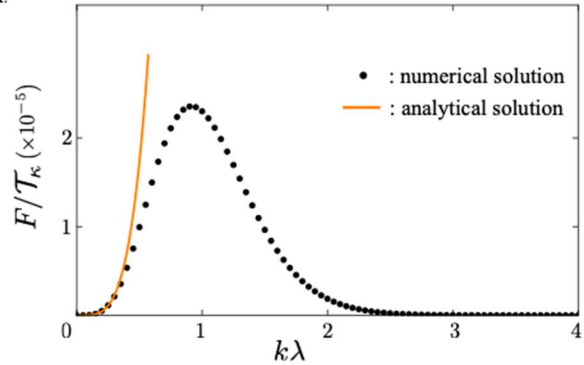


FIG. 3. The force F on the domain wall exerted by the linearly-polarized waves perpendicular to the wall plane for the parameters $\kappa = 0.2$ and $a = \lambda/10$. The solid line is obtained with the analytical expression for F in Eq. (6); the dots are obtained with F in Eq. (14) calculated from numerical solutions of the differential equations (7).

A domain wall and spin supercurrent can coexist in magnets with easy-cone anisotropy owing to simultaneous spontaneous breaking of Z_2 and $U(1)$ symmetries. Their interaction is theoretically investigated in quasi-one-dimensional ferromagnets within the Landau-Lifshitz-Gilbert phenomenology. Specifically, the spin supercurrent can exert the torque on a domain wall and thereby drive it. We also show, as a reciprocal phenomenon, *a field-induced motion of a domain wall can generate spin supercurrent*.¹²

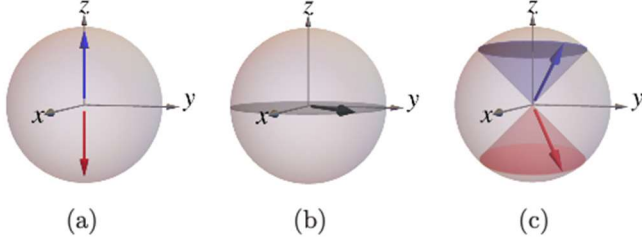


FIG. 1. (a) Two arrows represent two ground states of easy-axis magnets. (b) The unit circle in the xy plane represents continuously degenerate ground states of easy-plane magnets; one exemplary spin direction is shown as an arrow. (c) Two cones represent the ground-state manifold of easy-cone magnets; two example spin directions are depicted as arrows.

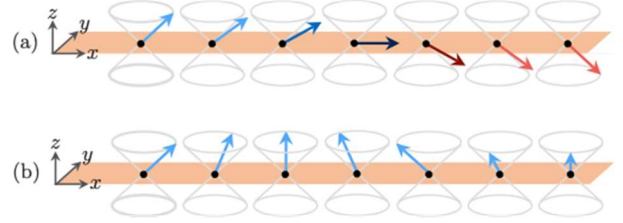


FIG. 2. Schematic illustrations of (a) a domain wall and (b) spiraling spin texture within the upper cone, which carries finite spin supercurrent.

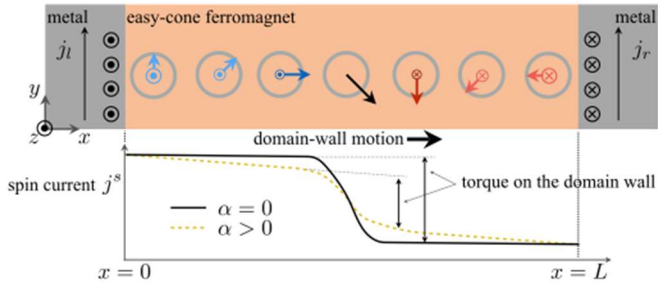


FIG. 3. A schematic geometrical setup for a domain-wall motion driven by spin supercurrent. Blue and red colors represent positive and negative spin components projected onto the z axis, respectively. The black arrow is the spin direction at the center of the domain wall. The charge currents through two adjacent heavy metals inject spin current into the magnet via spin Hall effect. The polarization directions of injected spin are depicted as circles in the metals. The spin is transported to the domain wall by spin supercurrent in the form of spiraling spin texture. The domain wall moves by absorbing the transported spin.

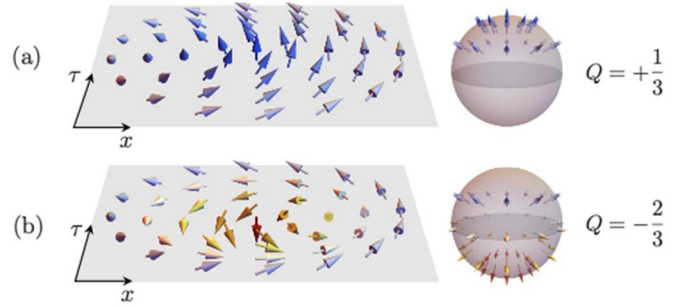


FIG. 4. Schematic illustrations of two types of vortices. Spins are in the upper cone away from the vortex centers. Q is the skyrmion charge of a vortex. See the main text for discussions.

We theoretically investigate the transfer of angular momentum between a spin superfluid and a domain wall in an exchange coupled easy-axis and easy-plane magnetic insulator system.⁴⁸ A domain wall in the easy-axis magnet absorbs spin angular momentum via disrupting the flow of a superfluid spin current in the easy-plane magnet. Focusing on an open geometry, where the spin current is injected electrically via a nonequilibrium spin accumulation, we derive analytical expressions for the resultant *superfluid-mediated motion of the domain wall*. The analytical results are supported by micromagnetic simulations. The proposed phenomenon extends the regime of magnon-driven domain-wall motion to the case where the magnons are condensed and exhibit superfluidity. Furthermore, by controlling the pinning of the domain wall, we propose a realization of a reconfigurable spin transistor. The long-distance dissipationless character of spin superfluids can thus be exploited for manipulating soliton-based memory and logic devices.

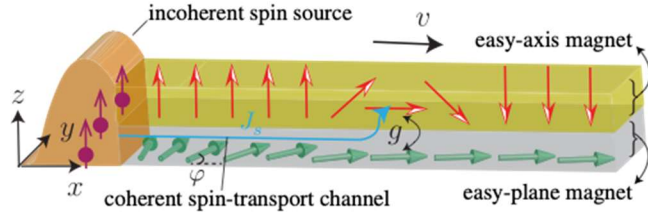


FIG. 1. A bilayer of an easy-z-axis magnet exchange coupled (with the coupling strength g) to an easy-x-y-plane magnet. A z-polarized spin current is injected from an incoherent spin source and propagates as a superfluid spin current through the easy-plane magnet. This spin current is $\propto \nabla\varphi$, where φ is the azimuthal angle of the spin order parameter within the x-y plane. This spin current is interrupted and absorbed by a domain wall in the easy-axis magnet, where it is converted into its sliding motion at speed v .

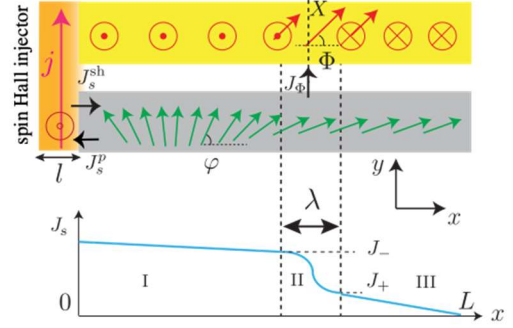


FIG. 2. The model of a domain wall of width λ coupled to a spin superfluid. The domain wall divides the bilayer into three regions: (I) up domain, (III) down domain, and (II) the domain wall. A spin current, J_s^{sh} , is injected on the left by converting a charge current, j , into a spin accumulation via the spin Hall effect. Upon reaching the domain-wall region, a portion of this spin current, J_ϕ , is absorbed from the easy-plane magnet by the domain wall. The resultant dynamics of the domain wall is characterized by the generalized coordinates X and Φ , parametrizing its position and the associated azimuthal angle. The dynamics of the spin superfluid pumps a spin current, J_s^p , back to the contact. (Bottom panel) The corresponding superfluid spin current flowing in the easy-plane magnet, as obtained by plotting $-At\partial_x\phi$.

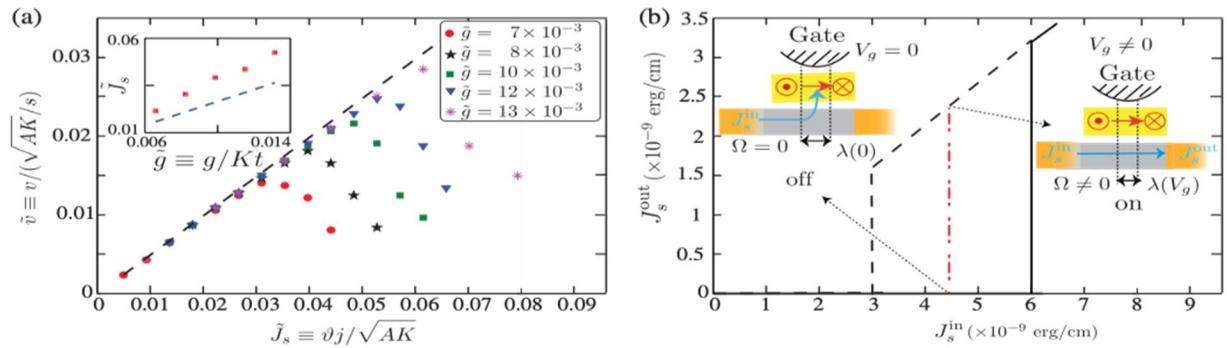


FIG. 3. (a) For a given exchange coupling $\tilde{g} \equiv g/Kt$, two regimes for domain-wall motion are obtained. A steady-state regime with linearly increasing velocity ($\tilde{v}$) and oscillatory motion above a critical value of the injected spin current $\tilde{J}_s$. The broken line plots the analytical result from Eq. (7). (Inset) The critical $\tilde{J}_s$ increases linearly with $\tilde{g}$. The broken line shows the analytical result from Eq. (9). (b) The spin current detected at the right end of the bilayer (J_s^{out}) exhibits nonlinear behavior in the presence of a pinned domain wall. When the injected spin current, J_s^{in} , is below (above) a critical breakdown current, $J_s^{\text{out}} = 0$ ($J_s^{\text{out}} \neq 0$). Solid and broken curves plot the nonlinear characteristics for $\lambda = 10$ and 5 nm, respectively. The nonlinearity can be used to construct a transistor, as indicated by the vertical dashed-dotted line. Fixing J_s^{in} and changing λ by an external gate switches the device from an *off* ($J_s^{\text{out}} = 0$) to an *on* ($J_s^{\text{out}} \neq 0$) state. These *off* and *on* states are depicted schematically in the insets.

We theoretically study the dynamics of ferrimagnetic skyrmions in inhomogeneous metallic films close to the angular momentum compensation point. In particular, it is shown that *the line of the vanishing angular momentum can be utilized as a self-focusing racetrack for skyrmions*.³⁴ To that end, we begin by deriving the equations of motion for the dynamics of collinear ferrimagnets in the presence of a charge current. The obtained equations of motion reduce to those of ferromagnets and antiferromagnets at two special limits. In the collective coordinate approach, a skyrmion behaves as a massive charged particle moving in a viscous medium subjected to a magnetic field. Analogous to the snake orbits of electrons in a nonuniform magnetic field, we show that a ferrimagnet with nonuniform angular momentum density can exhibit the snake trajectories of skyrmions, which can be utilized as racetracks for skyrmions.

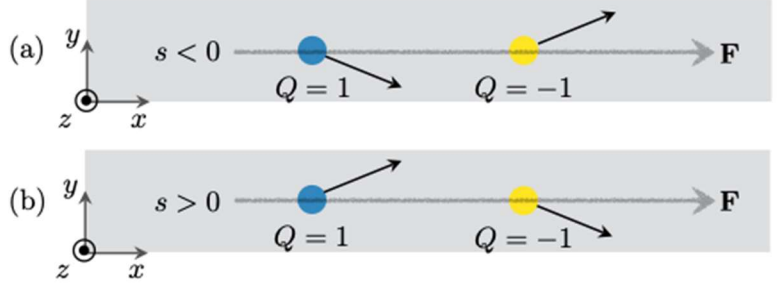


FIG. 1. Schematic illustrations of a steady-state skyrmion motion [Eq. (5)] in the presence of a current-induced force $\mathbf{F} = F\hat{\mathbf{x}}$. Four possible types are classified by its skyrmion charge Q and the sign of the net spin density s . See the main text for discussions.

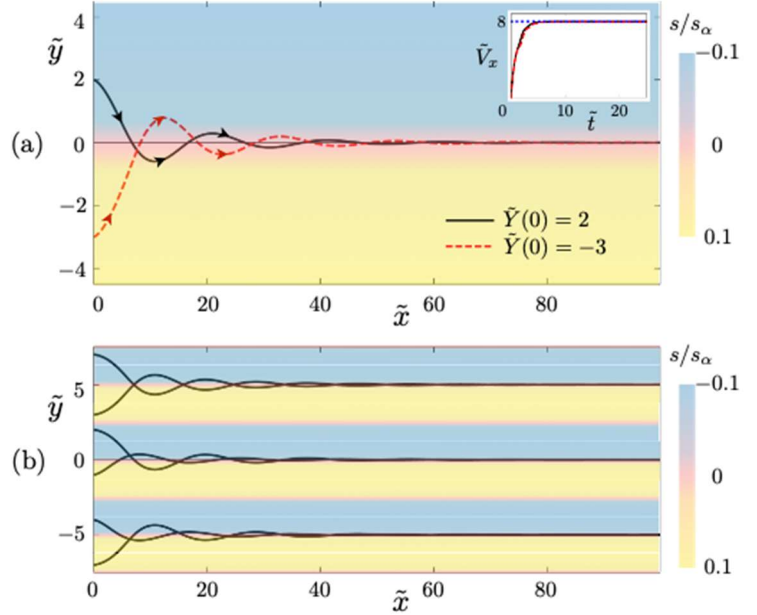


FIG. 2. Trajectories of skyrmions with the topological charge $Q = 1$ in the presence of a current-induced force $\mathbf{F} = F\hat{\mathbf{x}}$, which are obtained by numerically solving the dimensionless equations of motion for the dynamics of skyrmions in Eq. (6). (a) Two trajectories for the monotonic net angular momentum density s . The inset shows the convergence of the skyrmion velocities. (b) Multiple trajectories for the periodic net angular momentum density s . See the main text for detailed discussions.

Motivated by the successful idea of using weakly coupled quantum electronic wires to realize the quantum Hall effects and the quantum spin Hall effects, we theoretically study two systems composed of weakly coupled quantum spin chains within the mean-field approximations, which can exhibit *spin analogs of superconductivity and the integer quantum Hall effect*.⁴¹ First, a certain bilayer of two arrays of interacting spin chains is mapped, via the Jordan-Wigner transformation, to an attractive Hubbard model that exhibits fermionic superconductivity, which corresponds to spin superconductivity in the original spin Hamiltonian. Secondly, an array of spin-orbit-coupled spin chains in the presence of a suitable external magnetic field is transformed to an array of quantum wires that exhibits the integer quantum Hall effect, which translates into its spin analog in the spin Hamiltonian. The resultant spin superconductivity and spin integer quantum Hall effect can be characterized by their ability to transport spin without any resistance.

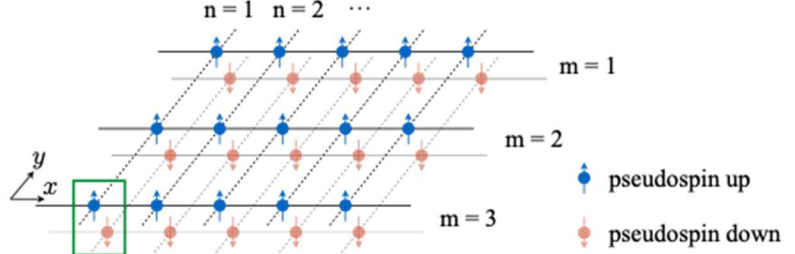


FIG. 1. Schematic of a bilayer of two arrays of weakly coupled spin chains (shown as the solid lines indexed by m), each of which can be represented by a one-dimensional system of (spinless) Jordan-Wigner fermions. The top and bottom layer indices serve as the pseudospin up and down for the fermions, respectively. The green box represents a pseudospin-singlet Cooper pair of two fermions established by an Ising interlayer interaction.

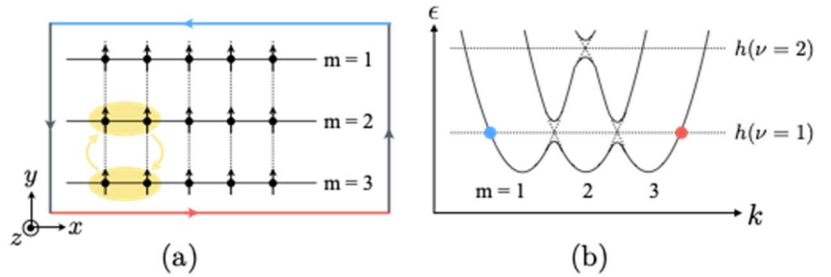


FIG. 2. (a) Schematic of an array of spin-orbit-coupled spin-1/2 spin chains, which can support chiral edge modes of the Jordan-Wigner fermions. The coupling of four spins (colored by yellow) illustrates the interchain interaction $\mathcal{O}$ [Eq. (2)]. (b) A schematic plot showing how the interchain interaction gives rise to chiral edge modes with the gapped bulk. At the external magnetic field h corresponding to the filling factor $\nu = 1$, the JW fermion can flow in the left direction on the top chain (colored by blue) and in the right direction on the bottom chain (colored by red) in (a), which are represented by the blue (left) and red (right) dots in (b), respectively. The particle current in the JW representation corresponds to the spin current polarized along the z axis.

We derive equations of motion for topological solitons in antiferromagnets under the combined action of perturbations such as an external magnetic field and torque-generating electrical current.⁴³ Aside from conservative forces, such perturbations generate an effective “magnetic field” exerting a gyrotropic force on the soliton and an induced “electric field” if the perturbation is time-dependent. We apply the general formalism to the cases of a domain wall and of a vortex. *An antiferromagnetic vortex can be effectively moved by combined applications of a magnetic field and an electric current.*

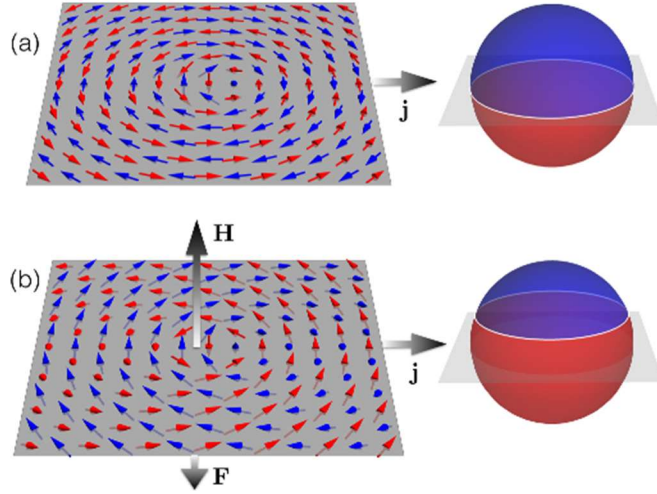


FIG. 1. A vortex in an easy-plane antiferromagnet in zero magnetic field (a) and in a field $\mathbf{H}$ pointing along the hard axis normal to the plane (b). A combination of the field and an in-plane electric current $\mathbf{j}$ gives rise to a Magnus force $\mathbf{F} \propto \mathbf{j} \times \mathbf{H}$. Sublattice magnetizations $\mathbf{m}_1$ and $\mathbf{m}_2$ are shown in blue and red. Right panels show portions of the unit sphere covered by the magnetization fields $\mathbf{m}_1(\mathbf{r})$ and $\mathbf{m}_2(\mathbf{r})$.

We theoretically study the oscillatory dynamics of a vortex core in a ferrimagnetic disk near its angular momentum compensation point, where the spin density vanishes but the magnetization is finite.²⁶ Due to the finite magnetostatic energy, a ferrimagnetic disk of suitable geometry can support a vortex as a ground state similar to a ferromagnetic disk. In the vicinity of the angular momentum compensation point, the dynamics of the vortex resemble those of an antiferromagnetic vortex, which is described by equations of motion analogous to Newton's second law for the motion of particles. Owing to the antiferromagnetic nature of the dynamics, the vortex oscillation frequency can be an order of magnitude larger than the frequency of a ferromagnetic vortex, amounting to tens of GHz in common transition-metal based alloys. We show that the frequency can be controlled either by applying an external field or by changing the temperature. In particular, the latter property allows us to detect the angular momentum compensation temperature, at which the lowest eigenfrequency attains its maximum, by performing ferromagnetic resonance measurements on the vortex disk. Our work proposes a *ferrimagnetic vortex disk as a tunable source of fast magnetic oscillations and a useful platform to study the properties of ferrimagnets*.

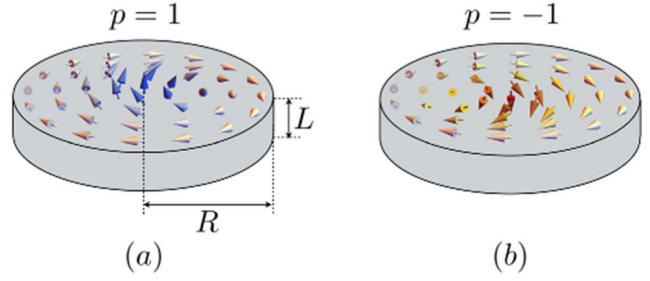


FIG. 1. Schematic illustrations of the magnetization of ferrimagnetic disks harboring (a) a vortex with polarization $p = 1$ and (b) a vortex with polarization $p = -1$. The thickness and the radius of disks are denoted by L and R , respectively.

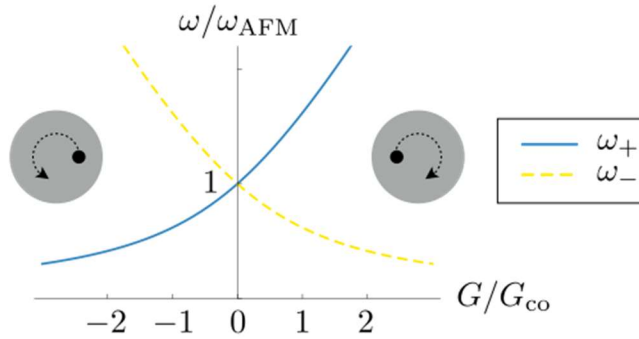


FIG. 2. The eigenfrequencies $\omega_{\pm}/\omega_{\text{AFM}}$ as functions of the gyrotropic coefficient G/G_{CO} . The solid and dashed lines show the eigenfrequencies for the counter-clockwise (ω_+) and clockwise (ω_-) rotations of the core. See the main text for discussions.

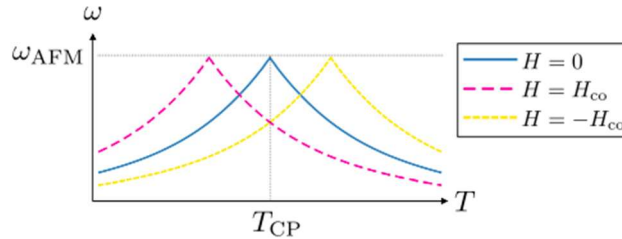


FIG. 3. Schematic illustrations of the lowest eigenfrequency ω of the vortex-core oscillation as a function of temperature T , in the vicinity of the angular momentum CP (T_{CP}) subjected to an external field, $\mathbf{H} = H\hat{z}$. The vortex with polarization $p = 1$ is considered. For CoTb disks, the maximum eigenfrequency and the crossover field are estimated as $\omega_{\text{AFM}} \approx 2\pi \times 30$ GHz and $H_{\text{CO}} \approx 2$ T, respectively. See the main text for discussions.

We theoretically study the dynamics of skyrmion crystals in electrically insulating chiral magnets subjected to current-induced spin torques by adjacent metallic layers.⁸¹ We develop an elasticity theory that accounts for the gyrotropic force engendered by the nontrivial topology of the spin texture, tensions at the boundaries due to the exchange of linear and spin angular momentum with the metallic reservoirs, and dissipation in the bulk of the film. A steady translation of the skyrmion crystal is triggered by the current-induced tensions and subsequently sustained by dissipative forces, generating an electromotive force on itinerant spins in the metals. This phenomenon should be revealed as a negative drag in an open two-terminal geometry, or equivalently, as a positive magnetoresistance when the terminals are connected in parallel. *We propose nonlocal transport measurements with these salient features as a tool to characterize the phase diagram of insulating chiral magnets.*

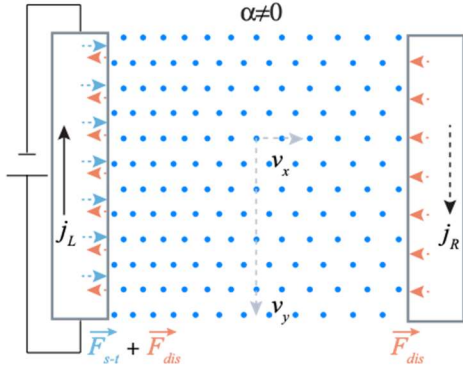


FIG. 1. Two-terminal geometry considered in the text. A current supplied by an external source in one of the metal contacts exerts a tension $\vec{F}_{s-t}$ over the skyrmion crystal (the blue points represent the center of mass of the skyrmions). In the absence of Gilbert damping α , the crystal moves collectively parallel to the electrical current. The damping deflects the trajectory, pushing the skyrmions from one contact to the other and generating an electromotive force in the second terminal. The red arrows represent the viscous force $\vec{F}_{dis}$ due to the enhanced (effective) Gilbert damping near the interface.

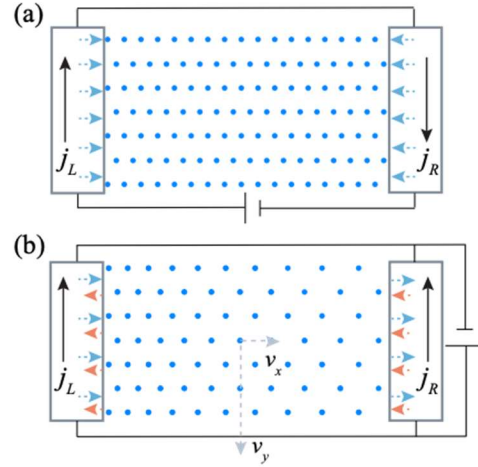


FIG. 2. Closed circuit in series (a) and parallel (b) configurations. In the former case, the skyrmion crystal is compressed but remains static, whereas in the parallel circuit the dynamics of the skyrmions enhances the resistivity of the external circuit, reflecting the negative drag in the open geometry.

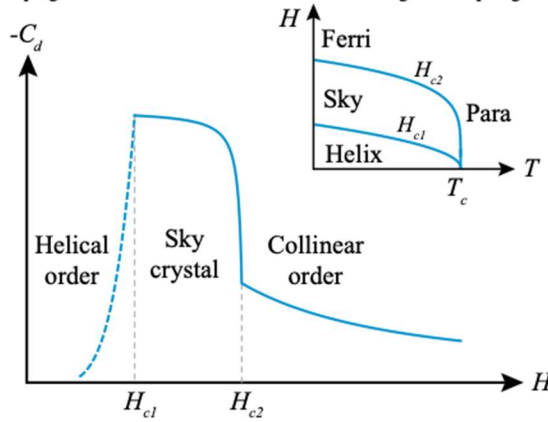


FIG. 3. Drag coefficient as a function of applied magnetic field H at temperatures well below T_c . The inset shows the schematic magnetic phase diagram in thin films of Cu_2OSeO_3 as deduced from transmission electron microscopy and magnetic susceptibility measurements [13].

A domain wall in a magnet with easy-axis anisotropy is shown to harbor spin superfluid associated with its spontaneous breaking of the $U(1)$ spin-rotational symmetry.⁴⁹ The spin superfluid is shown to have several topological properties, which are absent in conventional superfluids. First, the associated phase slips create and destroy Skyrmions to obey the conservation of the total Skyrmion charge, which allows us to use a domain wall as a generator and detector of Skyrmions. Second, the domain wall engenders the emergent magnetic flux for magnons along its length, which are proportional to the spin supercurrent flowing through it, and thereby provides a way to manipulate magnons. Third, the spin supercurrent can be driven by the magnon current traveling across it owing to the spin transfer between the domain wall and magnons, leading to the magnonic manipulation of the spin superfluid. The theory for superfluid spin transport within the domain wall is confirmed by numerical simulations.

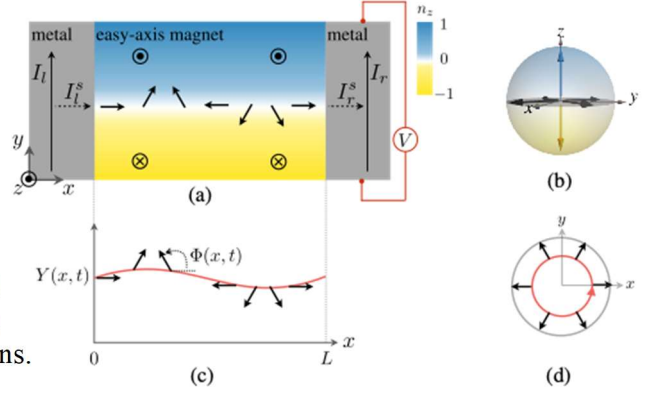


FIG. 1. (a) An illustration of a DW stretched along the x direction, which is carrying a spin supercurrent. (b) Mapping of the spin texture in (a) onto the unit sphere, characterized by its Skyrion charge $Q = 1$. (c) An illustration for the simplified description of the DW using its vertical position $Y(x, t)$ and in-plane angle $\Phi(x, t)$. (d) Mapping of the DW state in (c) onto the unit circle, characterized by its winding number $w = 1$.

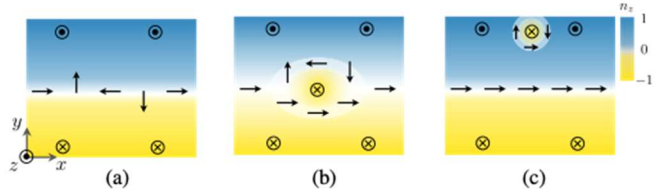


FIG. 2. A schematic illustration of a phase slip that decreases the winding number w from 1 in the initial state (a) to 0 in the final state (c) via the intermediate state (b), in which w is not well defined. (c) An isolated Skyrion with the Skyrion charge $Q = \Delta w = 1$ leaves the ferromagnet through the boundary.

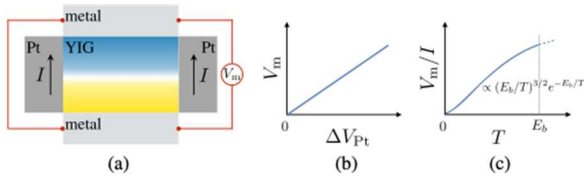


FIG. 3. (a) An experimental setup for probing phase slips. (b) The linear relationship between the two phase-slip-induced voltages, ΔV_{Pt} in the platinum and V_m in the metals. (c) The temperature dependence of V_m/I induced by thermally activated phase slips with the energy barrier E_b .

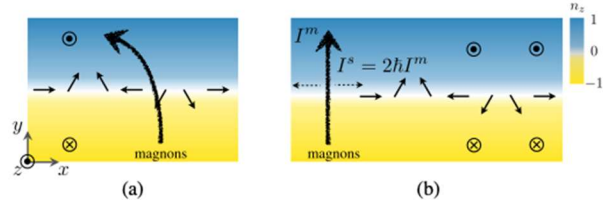


FIG. 4. (a) Magnons are deflected by the emergent magnetic field engendered by the spin supercurrent in the DW. (b) The magnon current I^m flowing across the DW injects the spin supercurrent $I^s = 2\hbar I^m$ into the wall via the magnonic spin-transfer torque.

Motivated by a recent experimental demonstration of a chiral edge mode in an array of spinning gyroscopes, we theoretically study the coupled gyration modes of topological magnetic solitons, vortices and magnetic bubbles, arranged as a honeycomb lattice.⁴⁷ The soliton lattice under suitable conditions is shown to support a chiral edge mode like its mechanical analogue, the existence of which can be understood by mapping the system to the Haldane model for an electronic system. The direction of the chiral edge mode is associated with the topological charge of the constituent solitons, which can be manipulated by an external field or by an electric-current pulse. The direction can also be controlled by distorting the honeycomb lattice. Our results indicate that the *lattices of magnetic solitons can serve as reprogrammable topological metamaterials*.

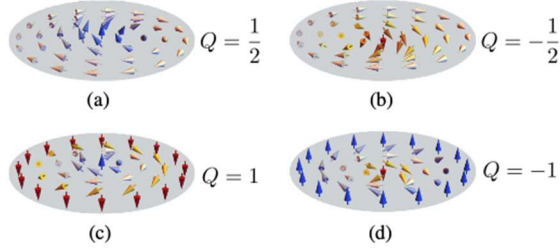


FIG. 1. Schematic illustrations of (a) a vortex with the topological charge $Q = 1/2$, (b) a vortex with $Q = -1/2$, (c) a magnetic bubble with $Q = 1$, and (d) a magnetic bubble with $Q = -1$.

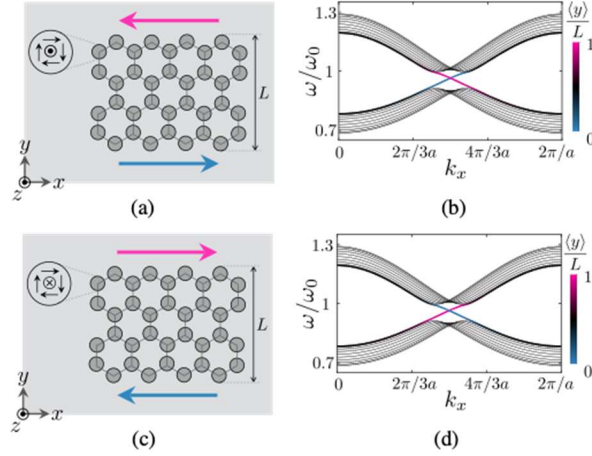


FIG. 2. (a) A schematic illustration of physically separated ferromagnetic disks (drawn as circles) in a honeycomb lattice with zigzag edges; vortices in disks have the polarity $p = 1$ and thus the topological charge $Q = 1/2$. The gray lines between circles represent the magnetostatic interactions between vortices. The arrows along the edges represent the directions of the chiral mode. (b) The one-dimensional dispersion for the coupled gyration modes of the system shown in (a), which is obtained by solving Eq. (4) numerically. The symbol a represents the distance between the second-nearest neighbors. The color represents the average vertical position $\langle y \rangle$ weighted by the amplitude squared corresponding to each mode. (c),(d) Analogous figures for vortices with the polarity $p = -1$, corresponding to the topological charge $Q = -1/2$.

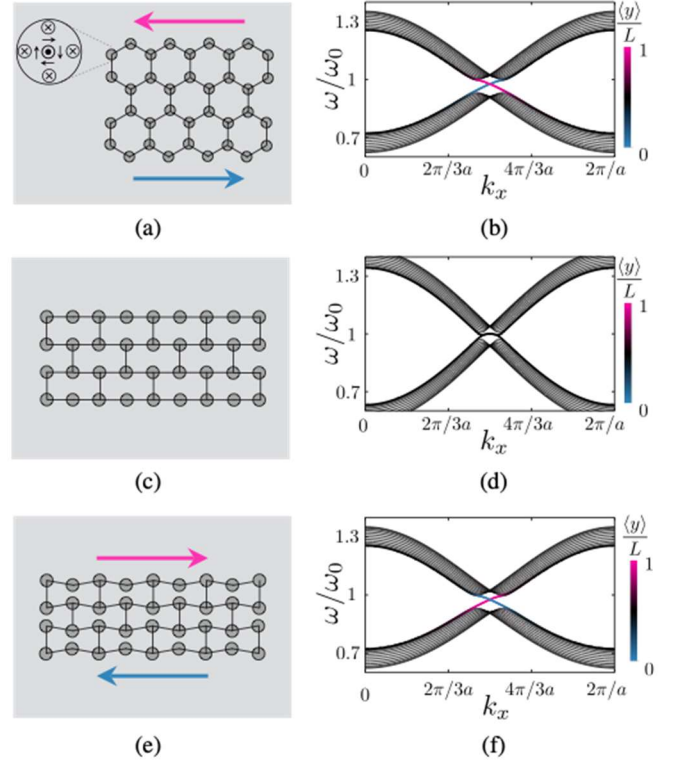


FIG. 3. (a) A schematic illustration of magnetic bubbles with the topological charge $Q = 1$ (drawn as circles) in a honeycomb lattice with zigzag edges. The black lines between circles represent the exchange-coupled interactions between magnetic bubbles connected by the magnetic strips. (b) The one-dimensional dispersion for the coupled gyration modes for the system shown in (a). (c), (d) Analogous figures when the angles between nearest bonds are multiples of $\pi/2$, for which the dispersion for the bulk is gapless and thus the topological edge mode is not supported. (e), (f) Analogous figures for the system exhibiting the chiral edge mode in the opposite direction to (a) and (b).

Energy loss due to ohmic heating is a major bottleneck limiting down-scaling and speed of nano-electronic devices, and harvesting ohmic heat for signal processing is a major challenge in modern electronics. Here, *we demonstrate that thermal gradients arising from ohmic heating can be utilized for excitation of coherent auto-oscillations of magnetization and for generation of tunable microwave signals.*²⁸ The heat-driven dynamics is observed in $\text{Y}_3\text{Fe}_5\text{O}_{12}/\text{Pt}$ bilayer nanowires where ohmic heating of the Pt layer results in injection of pure spin current into the $\text{Y}_3\text{Fe}_5\text{O}_{12}$ layer. This leads to excitation of auto-oscillations of the $\text{Y}_3\text{Fe}_5\text{O}_{12}$ magnetization and generation of coherent microwave radiation. Our work paves the way towards spin caloritronic devices for microwave and magnonic applications.

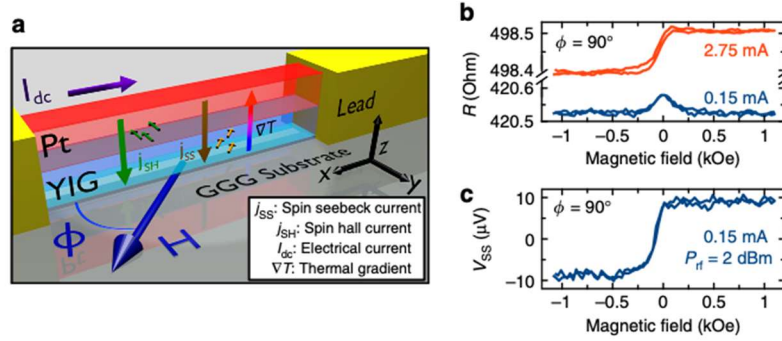


Fig. 1 YIG/Pt nanowire magnetoresistance. **a** Sketch of the YIG/Pt nanowire spin torque oscillator. Arrows across the YIG/Pt interface illustrate the flow of spin Hall j_{SH} and spin Seebeck j_{SS} currents with corresponding smaller arrows representing the spin current polarization. The directions of the temperature gradient ∇T perpendicular to the YIG/Pt interface, the direct current I_{dc} , and the magnetic field H are depicted by arrows. **b** Magnetoresistance R of the YIG/Pt nanowire measured at low ($I_{\text{dc}} = 0.15$ mA) and high ($I_{\text{dc}} = 2.75$ mA) direct current bias for a magnetic field applied in the sample plane at the field angle $\phi = 90^\circ$ with respect to the wire axis. **c** Spin Seebeck voltage V_{SS} induced in the nanowire by a large microwave current (microwave power $P_{\text{rf}} = 2$ dBm) as a function of magnetic field

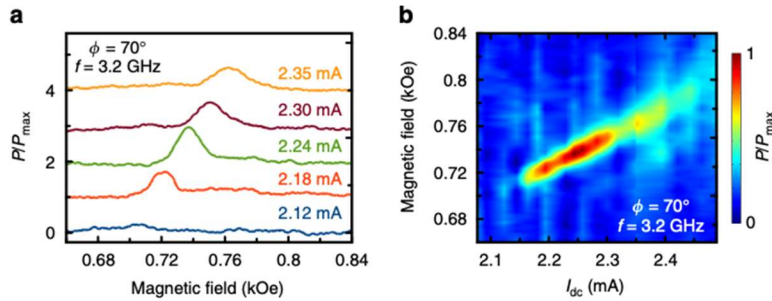


Fig. 2 YIG/Pt nanowire microwave signal generation. **a** Spectra of normalized microwave power P/P_{max} generated by the nanowire at the frequency $f = 3.2$ GHz and magnetic field angle $\phi = 70^\circ$ as a function of magnetic field at several direct current biases (vertically offset for clarity). **b** Color plot of microwave power generated by the nanowire at 3.2 GHz as a function of magnetic field and direct current bias

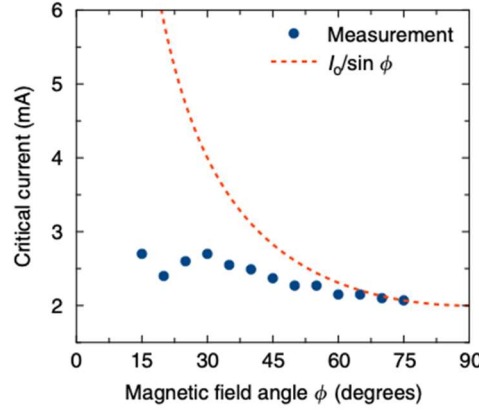


Fig. 3 Angular dependence of the critical current. Critical current for the onset of auto-oscillations as a function of in-plane magnetic field direction ϕ . The line shows the expected behavior due to only a spin Hall current (with a fitting parameter I_0) in the absence of a spin Seebeck current

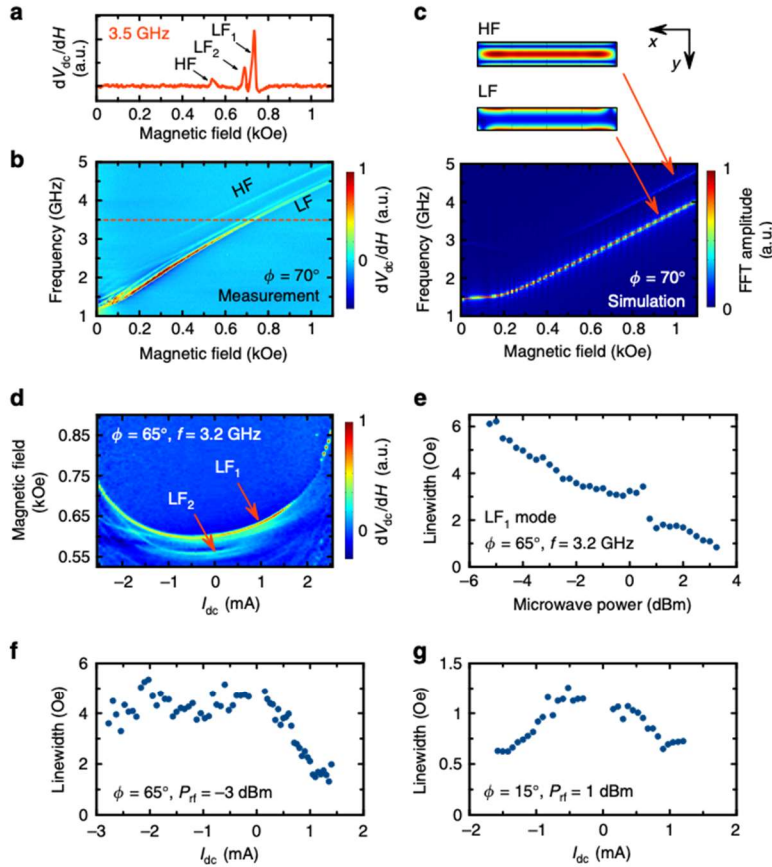


Fig. 4 ST-FMR measurements. **a** A single spin torque ferromagnetic resonance spectrum measured at a microwave frequency $f = 3.5$ GHz and magnetic field angle $\phi = 70^\circ$. Low-frequency (LF) and high-frequency (HF) modes are observed. **b** ST-FMR spectra of the YIG/Pt nanowire measured as a function of magnetic field and drive frequency at the field angle $\phi = 70^\circ$. **c** Micromagnetic simulation of the spin wave eigenmode spectra in the YIG/Pt nanowire with a top view of the spatial dependence of the LF and HF mode amplitudes. **d** ST-FMR spectra measured as a function of magnetic field and direct current bias current I_{dc} for microwave power $P_{rf} = -3$ dBm. **e** Linewidth of the LF_1 mode as a function of the microwave drive power P_{rf} . **f** Linewidth of the LF_1 mode as a function of direct current I_{dc} for $\phi = 65^\circ$ and $P_{rf} = -3$ dBm. **g** Linewidth of the LF_1 mode as a function of direct current for $\phi = 15^\circ$ and $P_{rf} = 1$ dBm

We have studied *thermally activated phase slips in superfluid spin transport in easy-plane magnetic wires within the stochastic Landau-Lifshitz-Gilbert phenomenology*.¹⁵ To that end, we start by obtaining the exact solutions for free-energy minima and saddle points, which are schematically shown in Fig. 1. We provide an analytical expression for the phase-slip rate in the zero spin-current limit, which involves a detailed analysis of spin fluctuations at the extrema of the free energy. An experimental setup for a magnetoelectric circuit is shown in Fig. 2, in which thermal phase slips can be inferred by measuring nonlocal magnetoresistance.

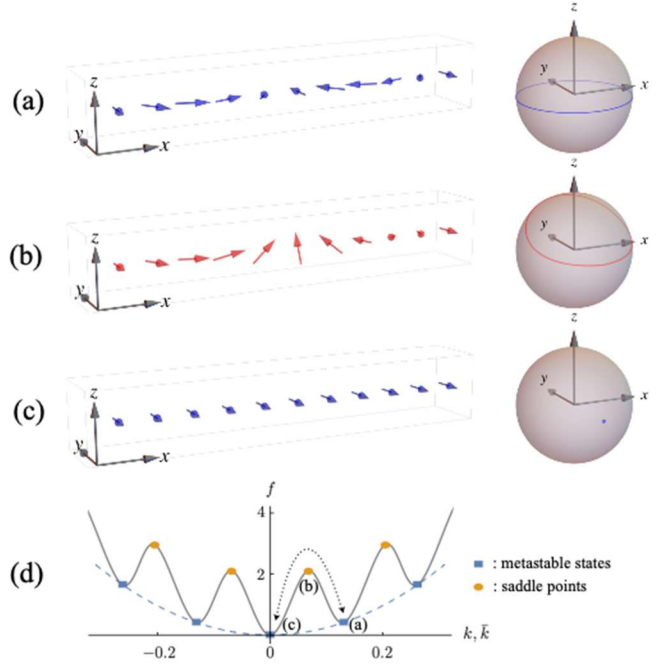


FIG. 1. (a)–(c) Extrema of the free energy f [Eq. (1)] for an easy- xy -plane magnetic wire with periodic boundary conditions. The metastable state (a) that winds in the easy plane once will decay to the ground state (c) via TAPS passing over the saddle point (b), where a few spins localized within the magnetic coherence length develop significant out-of-easy-plane components. (d) A plot of the free energy f as a function of spin current k (metastable states) and $\bar{k}$ (saddle points) for the wire length $l = 48$. The solid line is a guide to the eye. The dashed line shows the free energy of the metastable states for an infinitely long wire: $f = k^2 l / 2$. Points corresponding to the three configurations, (a)–(c), are denoted accordingly. The dotted line illustrates transitions between nearby metastable states (a) and (c).

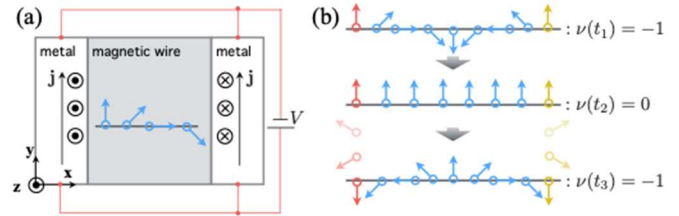


FIG. 2. (a) Schematics of an experimental setup for detecting TAPS, in which two identical metals, parallel in the electric circuit, are connected by a magnetic insulator supporting superfluid spin transport. (b) Schematics illustrating the origin of an electromotive force in the metals. TAPS unwind the equilibrium spiraling structure (at $t = t_1$), resulting in a uniform state (at $t = t_2$). As the magnet returns to the equilibrium spiraling structure, the magnetization at the left (right) interface rotates counterclockwise (clockwise), which in turn induces a detectable electromotive force in the metals.

For quantum version of phase slips, we have investigated effects of quantum fluctuations on superfluid spin transport through easy-plane quantum antiferromagnetic spin chains in the large-spin limit.²² Quantum fluctuations result in the decaying spin supercurrent by unwinding the magnetic order parameter within the easy plane, which is referred to as phase slips. These phase slips are vortices in the Euclidean spacetime as shown in Fig. 1. We show that the topological term in the nonlinear sigma model for the spin chains qualitatively differentiates the decaying rate of the spin supercurrent between the integer versus half-odd-integer spin chains, as shown in Fig. 2. An experimental setup (Fig. 3) for a magnetoelectric circuit is proposed, in which the dependence of the decaying rate on constituent spins can be verified by measuring the nonlocal magnetoresistance.

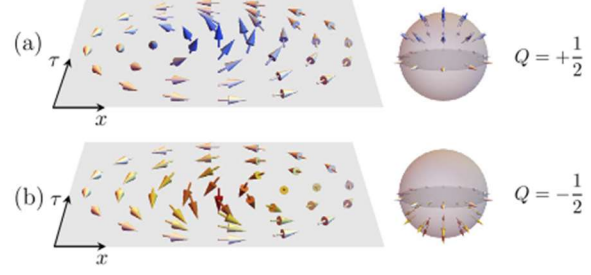


FIG. 1. Vortex configurations of the local Néel order parameter in the Euclidean spacetime (x, τ) with Skymion charges (a) $Q = 1/2$ and (b) $Q = -1/2$.

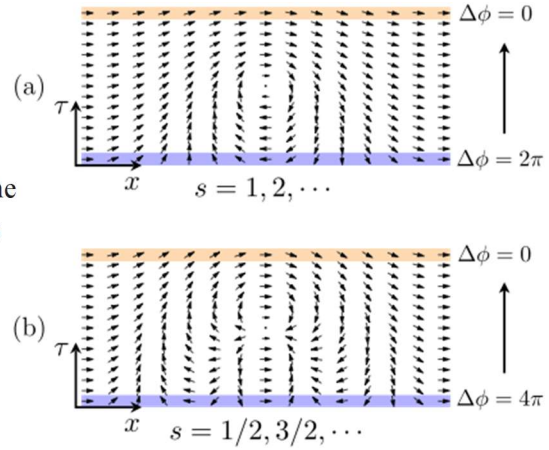


FIG. 2. Elementary vortices, which control the winding number $\Delta\phi$, with Skymion charges (a) $Q = 1/2$ and (b) $Q = 1$. For half-odd-integer spin chains, 2π phase slips are prohibited by destructive interference between vortices with Skymion charges $Q = \pm 1/2$. See the main text for a detailed discussion.

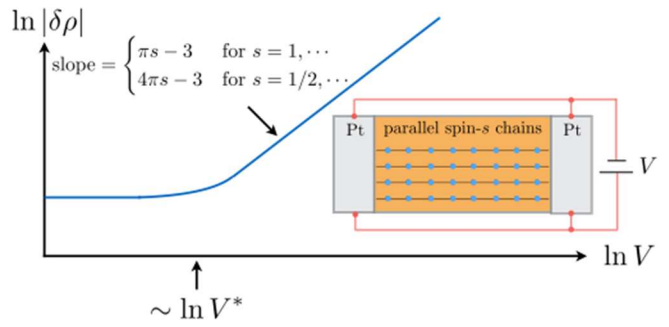


FIG. 3. A change in the electrical resistance $|\delta\rho|$ of the magnetoelectric circuit as a function of an applied voltage V on a logarithmic scale. The circuit consists of a quasi-one-dimensional antiferromagnet (a 3D stack of parallel spin chains) and two platinum layers. See the main text for a detailed discussion.

We have studied the *spin-transfer drag mediated by the Brownian motion of skyrmions*.¹⁶ The essential idea is illustrated in a two-terminal geometry, in which a thin film of a magnetic insulator is placed in between two metallic reservoirs (see Fig. 1). An electric current in one of the terminals pumps topological charge into the magnet via a spin-transfer torque. The charge diffuses over the bulk of the system as stable skyrmion textures. By Onsager's reciprocity, the topological charge leaving the magnet produces an electromotive force in the second terminal. The voltage signal decays algebraically with the separation between contacts, in contrast to the exponential suppression of the spin drag driven by nonprotected excitations like magnons. We show how this topological effect can be used as a tool to characterize the phase diagram of chiral magnets and thin films with interfacial Dzyaloshinskii-Moriya interactions.

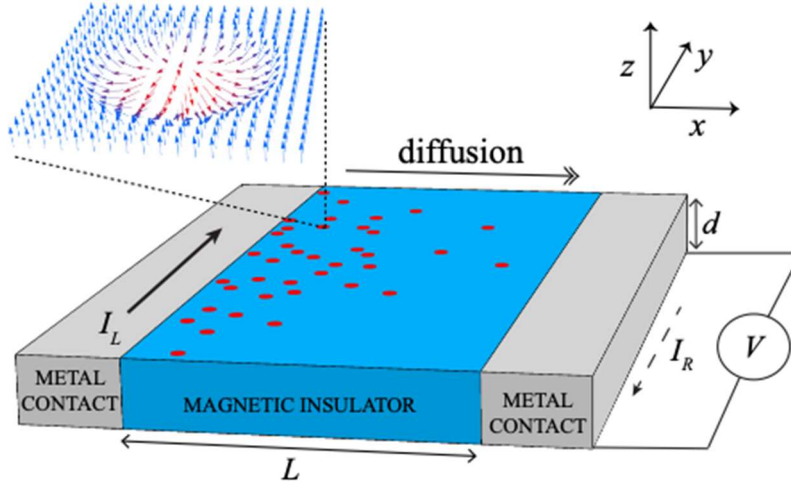


FIG. 1. Scheme for electrical injection and detection of skyrmions. The electric current in the left terminal pumps skyrmion charge into the magnet, which diffuses as stable solitons over the system. The skyrmion charge leaving the system sustains a voltage signal in the second terminal.

References

1. "Dynamic phase diagram of dc-pumped magnon condensates," S. A. Bender, R. A. Duine, A. Brataas, & Y. Tserkovnyak, *Phys. Rev. B*, **90**, 094409, 2014
<http://doi.org/10.1103/PhysRevB.90.094409>
2. "Ultrafast demagnetization of FePt:Cu thin films and the role of magnetic heat capacity," J. J. Kimling, J. J. Kimling, R. B. Wilson, B. Hebler, M. Albrecht, & D. G. Cahill, *Phys. Rev. B*, **90**, 224408, 2014 <http://doi.org/10.1103/PhysRevB.90.224408>
3. "Control and braiding of Majorana fermions bound to magnetic domain walls," S. K. Kim, S. Tewari, & Y. Tserkovnyak, *Phys. Rev. B - Condens. Matter Mater. Phys.*, **92**, 020412, 2015
<http://doi.org/10.1103/PhysRevB.92.020412>
4. "Spin-dependent thermal transport perpendicular to the planes of Co/Cu multilayers," J. J. Kimling, R. B. Wilson, K. Rott, J. J. Kimling, G. Reiss, & D. G. Cahill, *Phys. Rev. B - Condens. Matter Mater. Phys.*, **91**, 144405, 2015 <http://doi.org/10.1103/PhysRevB.91.144405>
5. "Landau-Lifshitz theory of thermomagnonic torque," S. K. Kim, & Y. Tserkovnyak, *Phys. Rev. B - Condens. Matter Mater. Phys.*, **92**, 020410, 2015 <http://doi.org/10.1103/PhysRevB.92.020410>
6. "Topological spin transport by Brownian diffusion of domain walls," S. K. Kim, S. Takei, & Y. Tserkovnyak, *Phys. Rev. B - Condens. Matter Mater. Phys.*, **92**, 220409, 2015
<http://doi.org/10.1103/PhysRevB.92.220409>
7. "Thermophoresis of an antiferromagnetic soliton," S. K. Kim, O. Tchernyshyov, & Y. Tserkovnyak, *Phys. Rev. B - Condens. Matter Mater. Phys.*, **92**, 020402, 2015
<http://doi.org/10.1103/PhysRevB.92.020402>
8. "Effect of the magnon dispersion on the longitudinal spin Seebeck effect in yttrium iron garnets," H. Jin, S. R. Boona, Z. Yang, R. C. Myers, & J. P. Heremans, *Phys. Rev. B - Condens. Matter Mater. Phys.*, **92**, 054436, 2015 <http://doi.org/10.1103/PhysRevB.92.054436>
9. "Landau-Lifshitz theory of the magnon-drag thermopower," B. Flebus, R. A. Duine, & Y. Tserkovnyak, *EPL*, **115**, 57004, 2016 <http://doi.org/10.1209/0295-5075/115/57004>
10. "Observation of spin Seebeck contribution to the transverse thermopower in Ni-Pt and MnBi-Au bulk nanocomposites," S. R. Boona, K. Vandaele, I. N. Boona, D. W. McComb, & J. P. Heremans, *Nat. Commun.*, **7**, 13714, 2016 <http://doi.org/http://dx.doi.org/10.1038/ncomms13714>
11. "Magnon-drag thermopower and Nernst coefficient in Fe, Co, and Ni," S. J. Watzman, R. A. Duine, Y. Tserkovnyak, S. R. Boona, H. Jin, A. Prakash, Y. Zheng, & J. P. Heremans, *Phys. Rev. B*, **94**, 144407, 2016 <http://doi.org/10.1103/PhysRevB.94.144407>
12. "Interaction between a domain wall and spin supercurrent in easy-cone magnets," S. K. Kim, & Y. Tserkovnyak, *Phys. Rev. B*, **94**, 220404, 2016 <http://doi.org/10.1103/PhysRevB.94.220404>
13. "Kerr rotation in Cu, Ag, and Au driven by spin accumulation and spin-orbit coupling," G. M. Choi, & D. G. Cahill, *Phys. Rev. B - Condens. Matter Mater. Phys.*, **90**, 214432, 2014
<http://doi.org/10.1103/PhysRevB.90.214432>
14. "Spin Seebeck effect through antiferromagnetic NiO," A. Prakash, J. Brangham, F. Yang, & J. P. Heremans, *Phys. Rev. B*, **94**, 014427, 2016 <http://doi.org/10.1103/PhysRevB.94.014427>
15. "Thermally activated phase slips in superfluid spin transport in magnetic wires," S. K. Kim, S. Takei, & Y. Tserkovnyak, *Phys. Rev. B*, **93**, 020402, 2016

- <http://doi.org/10.1103/PhysRevB.93.020402>
16. "Topological spin-transfer drag driven by skyrmion diffusion," H. Ochoa, S. K. Kim, & Y. Tserkovnyak, *Phys. Rev. B*, **94**, 024431, 2016 <http://doi.org/10.1103/PhysRevB.94.024431>
 17. "Weak coupling of pseudoacoustic phonons and magnon dynamics in the incommensurate spin-ladder compound Sr_2CuO_4 ," X. Chen, D. Bansal, S. Sullivan, D. L. Abernathy, A. A. Aczel, J. Zhou, O. Delaire, & L. Shi, *Phys. Rev. B*, **94**, 134309, 2016 <http://doi.org/10.1103/PhysRevB.94.134309>
 18. "Bose-Einstein condensation of magnons pumped by the bulk spin Seebeck effect," Y. Tserkovnyak, S. A. Bender, R. A. Duine, & B. Flebus, *Phys. Rev. B*, **93**, 100402, 2016 <http://doi.org/10.1103/PhysRevB.93.100402>
 19. "Magnons and Phonons Optically Driven out of Local Equilibrium in a Magnetic Insulator," K. An, K. S. Olsson, A. Weathers, S. Sullivan, X. Chen, X. X. Li, L. G. Marshall, X. Ma, N. Klimovich, J. Zhou, L. Shi, & X. X. Li, *Phys. Rev. Lett.*, **117**, 107202, 2016 <http://doi.org/10.1103/PhysRevLett.117.107202>
 20. "Mechanical Actuation of Magnetic Domain-Wall Motion," S. K. Kim, D. Hill, & Y. Tserkovnyak, *Phys. Rev. Lett.*, **117**, 237201, 2016 <http://doi.org/10.1103/PhysRevLett.117.237201>
 21. "Realization of the Haldane-Kane-Mele Model in a System of Localized Spins," S. K. Kim, H. H. Ochoa, R. Zarzuela, & Y. Tserkovnyak, *Phys. Rev. Lett.*, **117**, 227201, 2016 <http://doi.org/10.1103/PhysRevLett.117.227201>
 22. "Topological Effects on Quantum Phase Slips in Superfluid Spin Transport," S. K. Kim, & Y. Tserkovnyak, *Phys. Rev. Lett.*, **116**, 127201, 2016 <http://doi.org/10.1103/PhysRevLett.116.127201>
 23. "BiSb and spin-related thermoelectric phenomena," J. P. Heremans, H. Jin, Y. Zheng, S. J. Watzman, & A. Prakash, in *spiedigitallibrary.org*, (eds. Epstein, R. I., Andresen, B. F., Hehlen, M. P., Heremans, J. P., Rühlich, I. N. & Sheik-Bahae, M.) 98210I, 2016 <http://doi.org/10.1117/12.2228758>
 24. "Pump-probe measurements of the thermal conductivity tensor for materials lacking in-plane symmetry," J. P. Feser, J. Liu, & D. G. Cahill, *Rev. Sci. Instrum.*, **85**, 104903, 2014 <http://doi.org/10.1063/1.4897622>
 25. "Scalable Nernst thermoelectric power using a coiled galferol wire," Z. Yang, E. A. Codecido, J. Marquez, Y. Zheng, J. P. Heremans, & R. C. Myers, *AIP Adv.*, **7**, 095017, 2017 <http://doi.org/10.1063/1.5003611>
 26. "Fast vortex oscillations in a ferrimagnetic disk near the angular momentum compensation point," S. K. Kim, & Y. Tserkovnyak, *Appl. Phys. Lett.*, **111**, 032401, 2017 <http://doi.org/10.1063/1.4985577>
 27. "Thermal spin transport and energy conversion," K. Vandaele, S. J. Watzman, B. Flebus, A. Prakash, Y. Zheng, S. R. Boona, & J. P. Heremans, *Mater. Today Phys.*, **1**, 39–49, 2017 <http://doi.org/10.1016/j.mtphys.2017.05.003>
 28. "Spin caloritronic nano-oscillator," C. Safranski, I. Barsukov, H. K. Lee, T. Schneider, A. A. Jara, A. Smith, H. Chang, K. Lenz, J. Lindner, Y. Tserkovnyak, M. Wu, & I. N. Krivorotov, *Nat. Commun.*, **8**, 117, 2017 <http://doi.org/10.1038/s41467-017-00184-5>
 29. "Optical-helicity-driven magnetization dynamics in metallic ferromagnets," G. M. Choi, A. Schleife, & D. G. Cahill, *Nat. Commun.*, **8**, 1–7, 2017 <http://doi.org/10.1038/ncomms15085>

MURI: Materials with Extraordinary Spin/Heat Coupling Final Report

30. "Fast domain wall motion in the vicinity of the angular momentum compensation temperature of ferrimagnets," K. J. Kim, S. K. Kim, Y. Hirata, S. H. Oh, T. Tono, D. H. Kim, T. Okuno, W. S. Ham, S. Kim, G. Go, Y. Tserkovnyak, A. Tsukamoto, T. Moriyama, K. J. Lee, & T. Ono, *Nat. Mater.*, **16**, 1187–1192, 2017 <http://doi.org/10.1038/nmat4990>
31. "Long-range spin wave mediated control of defect qubits in nanodiamonds," P. Andrich, C. F. de las Casas, X. Liu, H. L. Bretscher, J. R. Berman, F. J. Heremans, P. F. Nealey, & D. D. Awschalom, *npj Quantum Inf.*, **3**, 28, 2017 <http://doi.org/10.1038/s41534-017-0029-z>
32. "Eu 2+ –Eu 3+ valence transition in double, Eu-, and Na-doped PbSe from transport, magnetic, and electronic structure studies," B. Wiendlocha, S. Kim, Y. Lee, B. He, G. Lehr, M. G. Kanatzidis, D. T. Morelli, & J. P. Heremans, *Phys. Chem. Chem. Phys.*, **19**, 9606–9616, 2017 <http://doi.org/10.1039/C7CP00358G>
33. "Spin diffusion induced by pulsed-laser heating and the role of spin heat accumulation," J. Kimling, & D. G. Cahill, *Phys. Rev. B*, **95**, 1–16, 2017 <http://doi.org/10.1103/PhysRevB.95.014402>
34. "Self-focusing skyrmion racetracks in ferrimagnets," S. K. Kim, K.-J. Lee, & Y. Tserkovnyak, *Phys. Rev. B*, **95**, 140404, 2017 <http://doi.org/10.1103/PhysRevB.95.140404>
35. "Moving spins with heat: Prospects for thermally powered spintronics," R. C. Myers, B. Giles, Z. Yang, & J. Jamison, in *2015 73rd Annu. Device Res. Conf.*, **2015-Augus**, 47–48, IEEE, 2015 <http://doi.org/10.1109/DRC.2015.7175546>
36. "Direct observation of magnon-phonon coupling in yttrium iron garnet," H. Man, Z. Shi, G. Xu, Y. Xu, X. Chen, S. Sullivan, J. Zhou, K. Xia, J. Shi, P. Dai, J. Z.-P. R. B, & undefined 2017, *Phys. Rev. B*, **96**, 100406, 2017 <http://doi.org/10.1103/PhysRevB.96.100406>
37. "Thermally driven long-range magnon spin currents in yttrium iron garnet due to intrinsic spin Seebeck effect," B. L. Giles, Z. Yang, J. S. Jamison, J. M. Gomez-Perez, S. Vélez, L. E. Hueso, F. Casanova, & R. C. Myers, *Phys. Rev. B*, **96**, 180412, 2017 <http://doi.org/10.1103/PhysRevB.96.180412>
38. "Gauge fields and related forces in antiferromagnetic soliton physics," S. Dasgupta, S. K. Kim, & O. Tchernyshyov, *Phys. Rev. B*, **95**, 220407, 2017 <http://doi.org/10.1103/PhysRevB.95.220407>
39. "Thermally driven long-range magnon spin currents in yttrium iron garnet due to intrinsic spin Seebeck effect," B. L. Giles, Z. Yang, J. S. Jamison, J. M. Gomez-Perez, S. Vélez, L. E. Hueso, F. Casanova, & R. C. Myers, *Phys. Rev. B*, **96**, 180412, 2017 <http://doi.org/10.1103/PhysRevB.96.180412>
40. "Theory of the magnon-mediated tunnel magneto-Seebeck effect," B. Flebus, G. E. W. Bauer, R. A. Duine, & Y. Tserkovnyak, *Phys. Rev. B*, **96**, 094429, 2017 <http://doi.org/10.1103/PhysRevB.96.094429>
41. "Spin analogs of superconductivity and integer quantum Hall effect in an array of spin chains," D. Hill, S. K. Kim, & Y. Tserkovnyak, *Phys. Rev. B*, **95**, 180405, 2017 <http://doi.org/10.1103/PhysRevB.95.180405>
42. "Coherent terahertz spin-wave emission associated with ferrimagnetic domain wall dynamics," S.-H. Oh, S. K. Kim, D.-K. Lee, G. Go, K.-J. Kim, T. Ono, Y. Tserkovnyak, & K.-J. Lee, *Phys. Rev. B*, **96**, 100407, 2017 <http://doi.org/10.1103/PhysRevB.96.100407>
43. "Gauge fields and related forces in antiferromagnetic soliton physics," S. Dasgupta, S. K. Kim, & O. Tchernyshyov, *Phys. Rev. B*, **95**, 1–5, 2017 <http://doi.org/10.1103/PhysRevB.95.220407>

MURI: Materials with Extraordinary Spin/Heat Coupling Final Report

44. "Effects of grain boundaries and defects on anisotropic magnon transport in textured Sr₁₄Cu₂₄O₄₁," X. Chen, K. Jarvis, S. Sullivan, Y. Li, J. Zhou, & L. Shi, *Phys. Rev. B*, **95**, 1–8, 2017 <http://doi.org/10.1103/PhysRevB.95.144310>
45. "Magnonic topological insulators in antiferromagnets," K. Nakata, S. K. Kim, J. Klinovaja, & D. Loss, *Phys. Rev. B*, **96**, 1–13, 2017 <http://doi.org/10.1103/PhysRevB.96.224414>
46. "Phonon-induced diamagnetic force and its effect on the lattice thermal conductivity," H. Jin, O. D. Restrepo, N. Antolin, S. R. Boona, W. Windl, R. C. Myers, & J. P. Heremans, *Nat. Mater.*, **14**, 601–606, 2015 <http://doi.org/10.1038/nmat4247>
47. "Chiral Edge Mode in the Coupled Dynamics of Magnetic Solitons in a Honeycomb Lattice," S. K. Kim, & Y. Tserkovnyak, *Phys. Rev. Lett.*, **119**, 077204, 2017 <http://doi.org/10.1103/PhysRevLett.119.077204>
48. "Magnetic Domain Wall Floating on a Spin Superfluid," P. Upadhyaya, S. K. Kim, & Y. Tserkovnyak, *Phys. Rev. Lett.*, **118**, 097201, 2017 <http://doi.org/10.1103/PhysRevLett.118.097201>
49. "Magnetic Domain Walls as Hosts of Spin Superfluids and Generators of Skyrmions," S. K. Kim, & Y. Tserkovnyak, *Phys. Rev. Lett.*, **119**, 1–6, 2017 <http://doi.org/10.1103/PhysRevLett.119.047202>
50. "Picosecond Spin Seebeck Effect," J. Kimling, G.-M. M. Choi, J. T. Brangham, T. Matalla-Wagner, T. Huebner, T. Kuschel, F. Yang, & D. G. Cahill, *Phys. Rev. Lett.*, **118**, 057201, 2017 <http://doi.org/10.1103/PhysRevLett.118.057201>
51. "Perspective: (Beyond) spin transport in insulators," Y. Tserkovnyak, *J. Appl. Phys.*, **124**, 190901, 2018 <http://doi.org/10.1063/1.5054123>
52. "Microscale-Resolution Thermal Mapping Using a Flexible Platform of Patterned Quantum Sensors," P. Andrich, J. Li, X. Liu, F. J. Heremans, P. F. Nealey, & D. D. Awschalom, *Nano Lett.*, **18**, 4684–4690, 2018 <http://doi.org/10.1021/acs.nanolett.8b00895>
53. "Magnetoelectric antiferromagnets as platforms for the manipulation of solitons," R. Zarzuela, S. K. Kim, & Y. Tserkovnyak, *Phys. Rev. B*, **97**, 014418, 2018 <http://doi.org/10.1103/PhysRevB.97.014418>
54. "Evidence for the role of the magnon energy relaxation length in the spin Seebeck effect," A. Prakash, B. Flebus, J. Brangham, F. Yang, Y. Tserkovnyak, & J. P. Heremans, *Phys. Rev. B*, **97**, 020408, 2018 <http://doi.org/10.1103/PhysRevB.97.020408>
55. "Magnetoelectric antiferromagnets as platforms for the manipulation of solitons," R. Zarzuela, S. K. Kim, & Y. Tserkovnyak, *Phys. Rev. B*, **97**, 014418, 2018 <http://doi.org/10.1103/PhysRevB.97.014418>
56. "Magnon-induced non-Markovian friction of a domain wall in a ferromagnet," S. K. Kim, O. Tchernyshyov, V. Galitski, & Y. Tserkovnyak, *Phys. Rev. B*, **97**, 174433, 2018 <http://doi.org/10.1103/PhysRevB.97.174433>
57. "Thermal spin-transfer torque driven by the spin-dependent Seebeck effect in metallic spin-valves," G. M. Choi, C. H. Moon, B. C. Min, K. J. Lee, & D. G. Cahill, *Nat. Phys.*, **11**, 576–581, 2015 <http://doi.org/10.1038/nphys3355>
58. "Cooper-Pair Spin Current in a Strontium Ruthenate Heterostructure," S. B. Chung, S. K. Kim, K. H. Lee, & Y. Tserkovnyak, *Phys. Rev. Lett.*, **121**, 167001, 2018 <http://doi.org/10.1103/PhysRevLett.121.167001>

MURI: Materials with Extraordinary Spin/Heat Coupling Final Report

59. "Cooper-Pair Spin Current in a Strontium Ruthenate Heterostructure," S. B. Chung, S. K. Kim, K. H. Lee, & Y. Tserkovnyak, *Phys. Rev. Lett.*, **121**, 167001, 2018
<http://doi.org/10.1103/PhysRevLett.121.167001>
60. "Nonlocal Spin Transport Mediated by a Vortex Liquid in Superconductors," S. K. Kim, R. Myers, & Y. Tserkovnyak, *Phys. Rev. Lett.*, **121**, 187203, 2018
<http://doi.org/10.1103/PhysRevLett.121.187203>
61. "Spin-Torque-Biased Magnetic Strip: Nonequilibrium Phase Diagram and Relation to Long Josephson Junctions," D. Hill, S. K. Kim, & Y. Tserkovnyak, *Phys. Rev. Lett.*, **121**, 037202, 2018
<http://doi.org/10.1103/PhysRevLett.121.037202>
62. "Ferromagnetic Epitaxial μ -Fe₂O₃ on β -Ga₂O₃: A New Monoclinic Form of Fe₂O₃," J. S. Jamison, B. J. May, J. I. Deitz, S.-C. Chien, D. W. McComb, T. J. Grassman, W. Windl, & R. C. Myers, *Cryst. Growth Des.*, **19**, 4205–4211, 2019 <http://doi.org/10.1021/acs.cgd.9b00029>
63. "Topological Hall effect at above room temperature in heterostructures composed of a magnetic insulator and a heavy metal," Q. Shao, Y. Liu, G. Yu, S. K. Kim, X. Che, C. Tang, Q. L. He, Y. Tserkovnyak, J. Shi, & K. L. Wang, *Nat. Electron.*, **2**, 182–186, 2019
<http://doi.org/10.1038/s41928-019-0246-x>
64. "Spin-transfer torques for domain wall motion in antiferromagnetically coupled ferrimagnets," T. Okuno, D.-H. Kim, S.-H. Oh, S. K. Kim, Y. Hirata, T. Nishimura, W. S. Ham, Y. Futakawa, H. Yoshikawa, A. Tsukamoto, Y. Tserkovnyak, Y. Shiota, T. Moriyama, K.-J. Kim, K.-J. Lee, & T. Ono, *Nat. Electron.*, **2**, 389–393, 2019 <http://doi.org/10.1038/s41928-019-0303-5>
65. "Vanishing skyrmion Hall effect at the angular momentum compensation temperature of a ferrimagnet," Y. Hirata, D.-H. Kim, S. K. Kim, D.-K. Lee, S.-H. Oh, D.-Y. Kim, T. Nishimura, T. Okuno, Y. Futakawa, H. Yoshikawa, A. Tsukamoto, Y. Tserkovnyak, Y. Shiota, T. Moriyama, S.-B. Choe, K.-J. Lee, & T. Ono, *Nat. Nanotechnol.*, **14**, 232–236, 2019
<http://doi.org/10.1038/s41565-018-0345-2>
66. "All-Optical Cryogenic Thermometry Based on Nitrogen-Vacancy Centers in Nanodiamonds," M. Fukami, C. G. Yale, P. Andrich, X. Liu, F. J. Heremans, P. F. Nealey, & D. D. Awschalom, *Phys. Rev. Appl.*, **12**, 014042, 2019 <http://doi.org/10.1103/PhysRevApplied.12.014042>
67. "Long lifetime of thermally excited magnons in bulk yttrium iron garnet," J. S. Jamison, Z. Yang, B. L. Giles, J. T. Brangham, G. Wu, P. C. Hammel, F. Yang, & R. C. Myers, *Phys. Rev. B*, **100**, 134402, 2019 <http://doi.org/10.1103/PhysRevB.100.134402>
68. "Spin and orbital magnetic response on the surface of a topological insulator," Y. Tserkovnyak, D. A. Pesin, & D. Loss, *Phys. Rev. B*, **91**, 041121, 2015 <http://doi.org/10.1103/PhysRevB.91.041121>
69. "Topological transport of vorticity in Heisenberg magnets," J. Zou, S. K. Kim, & Y. Tserkovnyak, *Phys. Rev. B*, **99**, 180402, 2019 <http://doi.org/10.1103/PhysRevB.99.180402>
70. "Tunable Magnonic Thermal Hall Effect in Skyrmion Crystal Phases of Ferrimagnets," S. K. Kim, K. Nakata, D. Loss, & Y. Tserkovnyak, *Phys. Rev. Lett.*, **122**, 057204, 2019
<http://doi.org/10.1103/PhysRevLett.122.057204>
71. "Coupling of Spinons with Defects and Phonons in the Spin Chain Compound Ca₂CuO₃," X. Chen, J. Carrete, S. Sullivan, A. van Roekeghem, Z. Li, X. Li, J. Zhou, N. Mingo, & L. Shi, *Phys. Rev. Lett.*, **122**, 185901, 2019 <http://doi.org/10.1103/PhysRevLett.122.185901>
72. "Low Magnetic Damping of Ferrimagnetic GdFeCo Alloys," D.-H. Kim, T. Okuno, S. K. Kim, S.-H. Oh, T. Nishimura, Y. Hirata, Y. Futakawa, H. Yoshikawa, A. Tsukamoto, Y. Tserkovnyak, Y.

MURI: Materials with Extraordinary Spin/Heat Coupling Final Report

- Shiota, T. Moriyama, K.-J. Kim, K.-J. Lee, & T. Ono, *Phys. Rev. Lett.*, **122**, 127203, 2019
<http://doi.org/10.1103/PhysRevLett.122.127203>
73. "Spatiotemporal Mapping of a Photocurrent Vortex in Monolayer MoS₂ Using Diamond Quantum Sensors," B. B. Zhou, P. C. Jerger, K.-H. Lee, M. Fukami, F. Mujid, J. Park, & D. D. Awschalom, *Phys. Rev. X*, **10**, 011003, 2020 <http://doi.org/10.1103/PhysRevX.10.011003>
74. "Paramagnon drag in high thermoelectric figure of merit Li-doped MnTe," Y. Zheng, T. Lu, M. M. H. Polash, M. Rasoulianboroujeni, N. Liu, M. E. Manley, Y. Deng, P. J. Sun, X. L. Chen, R. P. Hermann, D. Vashaee, J. P. Heremans, & H. Zhao, *Sci. Adv.*, **5**, eaat9461, 2019
<http://doi.org/10.1126/sciadv.aat9461>
75. "Magnon drag effect in Fe-Co alloys," Y. Zheng, E. J. Weiss, N. Antolin, W. Windl, & J. P. Heremans, *J. Appl. Phys.*, **126**, 125107, 2019 <http://doi.org/10.1063/1.5117165>
76. "Local thermomagnonic torques in two-fluid spin dynamics," B. Flebus, P. Upadhyaya, R. A. Duine, & Y. Tserkovnyak, *Phys. Rev. B*, **94**, 1–6, 2016
<http://doi.org/10.1103/PhysRevB.94.214428>
77. "Long-range pure magnon spin diffusion observed in a nonlocal spin-Seebeck geometry," B. L. Giles, Z. Yang, J. S. Jamison, & R. C. Myers, *Phys. Rev. B*, **92**, 224415, 2015
<http://doi.org/10.1103/PhysRevB.92.224415>
78. "Interfacial spin and heat transfer between metals and magnetic insulators," S. A. Bender, & Y. Tserkovnyak, *Phys. Rev. B*, **91**, 140402, 2015 <http://doi.org/10.1103/PhysRevB.91.140402>
79. "Proposal for an all-spin logic device with built-in memory," B. Behin-Aein, D. Datta, S. Salahuddin, & S. Datta, *Nat Nano*, **5**, 266–270, 2010
http://www.nature.com/nnano/journal/v5/n4/supinfo/nnano.2010.31_S1.html
80. "Exploiting Coherence in Nonlinear Spin-Superfluid Transport," Y. Tserkovnyak, & M. Kläui, *Phys. Rev. Lett.*, **119**, 1–6, 2017 <http://doi.org/10.1103/PhysRevLett.119.187705>
81. "Gyrotropic elastic response of skyrmion crystals to current-induced tensions," H. Ochoa, S. K. Kim, O. Tchernyshyov, & Y. Tserkovnyak, *Phys. Rev. B*, **96**, 1–5, 2017
<http://doi.org/10.1103/PhysRevB.96.020410>