# EFRC FINAL TECHNICAL REPORT
# Spins and Heat in Nanoscale Electronic Systems (SHINES)

## I. COVER PAGE

**Project Title:** Spins and Heat in Nanoscale Electronic Systems (SHINES)

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**Organization:** Office of Basic Energy Sciences

**Recipient Award Identification Number:** DE-SC0012670

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## II. ACCOMPLISHMENTS

**What are the major goals of the project?**

This project covers the funding period of 08/01/2014-07/31/2020. The project received a no-cost extension for 6 months which ended on 01/31/2021. The overall project is divided into two periods: full funding of $3 million/year with the total of $12 million for the first four years (08/01/2014-07/1/2018); and $1.9 million for the two-year extension (08/01/2018-07/31/2020). During the first four-year period, SHINES supported 14 PIs plus two UCR seed PIs (internally funded). During the 2-year extension, only 7 PIs were involved, and 8 UCR seed PIs were supported using UCR internal funds.

**Four-year period** (08/01/2014-07/31/2018):

The four-year **objectives** include (1) better understanding of and significant improvement in pure spin current effects in nanoscale electronic devices, including magnonic switching, spin-torque oscillations, spin-orbit torques, and spin Seebeck effect through novel materials and heterostructures; (2) engineering of acoustic phonon and magnon transport in nano-structured materials via controlling their dispersions and interactions; and (3) exploration of spin-orbit coupling for low energy effects and spin superconducting condensate for dissipationless spin and energy transport.

The SHINES EFRC team consists of 11 experimentalists and 3 theorists from 7 institutions initially (9 institutions after relocation of two PIs). The 14 PIs are: Alexander Balandin (UCR), Tingyong Chen (ASU), Chia-Ling Chien (JHU), Javier Garay (UCR and moved to UCSD), Alexander Khitun (UCR), Ilya Krivorotov (UCI), Roger Lake (UCR), Chun-Ning (Jeanie) Lau (UCR and moved to OSU), Elaine (Xiaoqin) Li (UT Austin), Allan MacDonald (UT Austin), Jing Shi (UCR), Kang L. Wang (UCLA), Mingzhong Wu (Colorado State), and Ruqian Wu (UCI). The team was organized under three interactive themes:

(1) Pure Spin Currents in Metals and Insulators;
(2) Phonon/Magnon Transport and Phonon/Magnon Engineering in Nanostructured Materials; and
(3) Spin-Orbit Coupling Heterostructures and Highly Correlated Spin Materials.

SHINES supported two seed projects led by UCR investigators (Nathaniel Gabor and Jianlin Liu) using UCR internal funds. The focus of the seed projects was on the spin-phenomena in excitonic systems.

**Two-year extension period** (08/01/2018-07/31/2020):

In 2018, SHINES was granted a two-year extension by DOE/BES to complete the work in progress. The scope of the research was revised accordingly. As a result, SHINES' new focus is on "Antiferromagnetic Spintronics", one of the three themes proposed in the 2018 renewal proposal, which was also one of the research topics pursued in the four-year award period. The revised SHINES scope of research is centered on the understanding of the fundamental physics and materials science related to antiferromagnetic spintronics.

The two-year **objectives** include discovering or demonstrating new spintronic phenomena in antiferromagnetic heterostructures, developing an in-depth understanding of these phenomena, and controlling interactions such as magnetic anisotropy, exchange coupling, and damping.

Building on the progress made in the four-year period, in the two-year period, SHINES actively worked on the following research topics:

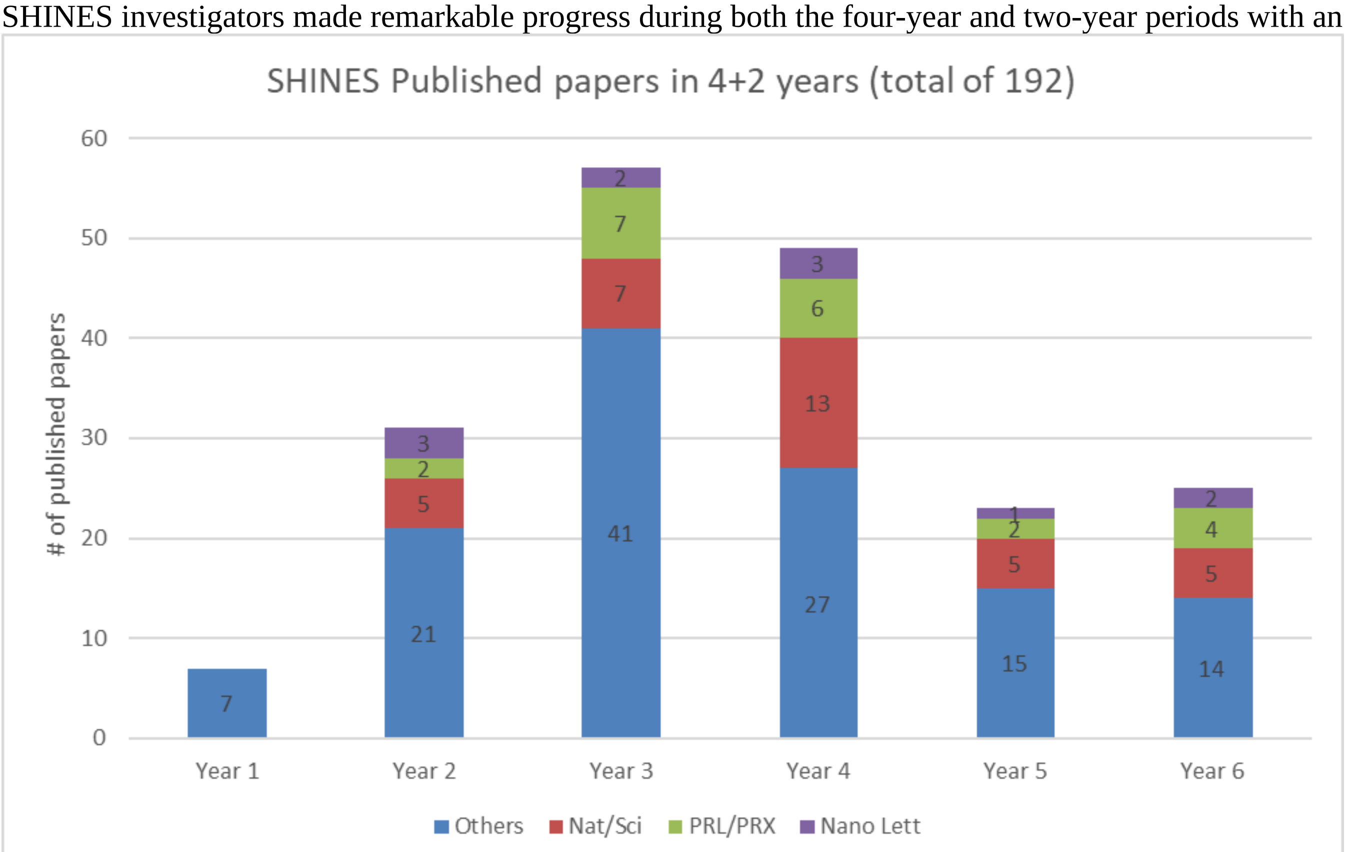
(1) Growth and experimental study of structural and magnetic properties of high-quality antiferromagnetic insulator thin films and heterostructures;

(2) Spin current generation, transport, and detection in antiferromagnetic insulator thin film and heterostructure devices;
(3) Enhanced spin current transmission through antiferromagnetic thin films and spin-orbit torques in ferromagnetic/antiferromagnetic heterostructures;
(4) High-frequency spin dynamics and antiferromagnetic resonances in antiferromagnetic insulator crystals and thin films;
(5) Control of non-trivial spin textures and spin dynamics via interfacial exchange coupling in antiferromagnetic heterostructures;
(6) Spin-lattice and magnon-phonon interactions in antiferromagnetic insulators.

The experimental techniques employed for this team research include molecular beam epitaxy and pulsed laser deposition for high-quality material growth, structural characterization, magnetic domain imaging, non-local transport, terahertz spectroscopy, antiferromagnetic resonance, spin pumping, spin Seebeck effect measurements, Raman and Brillouin light scattering, etc. The seven PI team for the two-year period is composed of six PIs who were the PIs in the four-year period: Alex Balandin (UCR), Chia-Ling Chen (JHU), Roger Lake (UCR), Allan MacDonald (UT Austin), Jing Shi (UCR, Director), and Kang Wang (UCLA), and a new investigator, Igor Barsukov (UCR), who was involved in SHINES research as a postdoc in the previous four-year period. The seven PIs all have expertise in the area of antiferromagnetic spintronics and have proven records of closely working with each other.

**No-cost extension period** (08/01/2020-01/31/2021):
The objective is for PIs to finish up their ongoing projects and prepare for the closeout.

**What was accomplished under these goals?**
SHINES investigators made remarkable progress during both the four-year and two-year periods with an




unusually high productivity as evidenced by the large number of published papers, especially high-impact papers (as shown in the chart above; one book chapter included), patents and invention disclosures (in a separate Excel document). Among 191 published papers, 35 are in the *Science/Nature* family of journals, 19 in *Physical Review Letters/Physical Review X*, and in other high-impact journals such as *Nano Letters*, *Advanced Materials*, etc. The average output is 2.3 and 3.4 papers per PI per year during the four-year period, and the two-year period, respectively (no double counting for co-authored papers). As a whole, SHINES produced 36 papers per year during the four-year period, and 24 papers per year during the two-year period with a much reduced budget. Scaled by the funding amount, the productivity is translated to an average of 1.2 papers per $100,000 per year in the four-year funding period, and 2.9 papers per $100,000 per year in the two-year funding period. These numbers together with the high-impact journals the papers were published compared very well against most EFRCs according to the published data on the EFRC Community website. Major progress in both periods is briefly summarized below.

<u>Representative research breakthroughs</u>

- Discovered the chiral Majorana modes in quantum anomalous Hall insulator(QAHI)/superconductor(SC) heterostructures through unique quantized conductance due to chiral edge channels (Wang, *Science*, 2017). The discovery has laid an important foundation for both exploring Majorana fermion physics in the solid state and for advancing topological spintronics, quantum information science, and topological computing using the QAHI/SC heterostructure platform.
- Discovered zero-field half-quantum flux in superconducting $\beta$-$Bi_2Pd$ (Chien, *Science*, 2019) and $\alpha$-BiPd (Chien, *Physical Review Letters*, 2020) rings via the Little-Park effect. These phase-sensitive experimental data offer stronger evidence of triplet superconductivity than existing amplitude-sensitive results on other triplet superconducting material candidates. Triplet superconductors are expected to carry Majorana fermions which can be used for fault-tolerant topological quantum computing.
- Realized sub-terahertz spin pumping in $Cr_2O_3$, a uniaxial antiferromagnetic (AFM) insulator (Shi, *Nature*, 2020). The generation and electrical detection of spin currents in ferromagnets have played a important role in spintronics. Such spin currents had not been shown by any researcher for antiferromagnets. This topic had been vigorously pursued by the spintronics community without success. This work has generated a great deal of excitement in basic science research as well as potential applications.
- Demonstrated enhanced Curie temperature of magnetic topological insulator (TI) by tailoring the exchange coupling to a high-Néel temperature AFM, which effectively initiated a subfield, “topological antiferromagnetic spintronics” (Wang, *Nature Materials*, 2017). A giant enhancement (a factor of three) in the Curie temperature of magnetic TI is found to be due to strong interfacial exchange interaction with the uncompensated spins of the AFM.
- Demonstrated proximity-induced ferromagnetism in non-magnetic TI with drastically enhanced Curie temperature (> 400 K) in TI/ferrimagnetic insulator (FMI) heterostructures (Shi, *Science Advances*, 2017). This work opens up a promising route to tailor acquired strong exchange interaction in TI surface states via proximity coupling, which provides a pathway to realize the quantum anomalous Hall effect (QAHE) without resorting to random magnetic doping in TI.
- Demonstrated highly efficient spin-orbit torques (SOTs) delivered by TI such as $Bi_2Se_3$ and $SmB_6$ thin films in novel heterostructures (Wang, *Nature Nanotechnology*, 2016; Chien, *Science Advances*, 2018). When the heavy metal is replaced by TI, e.g., $Bi_2Se_3$ or $SmB_6$, it exerts extraordinarily large SOTs, offering a clear advantage over heavy metals for spintronics. In $Bi_2Se_3$, the torques can be controlled by electrical fields as shown in the *Nature Nanotechnology*, 2016 paper.
- Directly observed interaction-induced anomalies by inelastic neutron scattering and spin Seebeck effect in a ferrimagnetic material (Shi, *Physical Review B RC*, 2017) and by spin Seebeck effect in an antiferromagnetic (Shi, *Physical Review Letters*, 2020) material. In the presence of magnon-phonon interaction, a new hybridized mode, “magnon-polaron”, appears and modifies both quasiparticle

distributions. These studies provided the first direct experimental evidence of the magnon-polarons in ferrimagnets and antiferromagnets.

Other representative significant works include

- Demonstrated highly efficient spin-charge conversion in FMI/TI heterostructures revealed by greatly enhanced spin Seebeck effect (Shi & MacDonald, *Nature Commun*, 2016); Observed long-distance magnon transport across canted insulating AFM quantum Hall graphene channel (Lau, Lake, & MacDonald, *Nature Physics*, accepted); Realized heat current driven auto-oscillations in nano-oscillators (Krivorotov, *Nature Commun.*, 2017); Experimentally established electrical signal transmission across FMI via magnon-mediated current drag (Shi & Lake, *Nature Commun.*, 2016); Discovered photo-spin-voltaic effect in FMI/heavy metal heterostructures (M.Z. Wu & R.Q. Wu, *Nature Physics*, 2016); Experimentally uncovered the roles of damping in spin Seebeck effect in FMI/heavy metal heterostructures (Shi, *Science Advances*, 2017); Demonstrated switching of magnetization of FMI with perpendicular magnetic anisotropy by spin-orbit torques (M.Z. Wu, *Nature Commun.*, 2016; Shi, *PRBRC*, 2017); Observed spin Hall magnetoresistance enhancement due to spin current backflow through AFM fluctuations (Chien, *Physical Review Letters*, 2017); Observed acoustic phonon confinement effect in individual nanowires (*Nature Commun.*, 2016); Quantified interfacial Dzyaloshinskii-Moriya interaction (Li & Wang, DMI) in FM/AFM heterostructures (Li & Wang, *Physical Review Letters*, 2017); Elucidated spectroscopic features of phonon, magnon, and spin-phonon interaction in NiO AFM crystals using Raman and Brillouin light scattering (Balandin, Shi, & Lake, two *Applied Physics Letters*, 2017); Demonstrated the incoherent magnon mechanism for the spin Seebeck effect in $FeF_2$ uniaxial antiferromagnetic insulator (Shi, *Physical Review Letters*, 2019).

Intellectual property

- US patent (No. 9,929,338): "Spin Current Devices and Method of Fabrication Thereof" (issued in March 2018) by *Shi* and *Lake*. It is based on the findings reported in two papers (*Nature Communications*, 2016) and (*Applied Physics Letters*, 2016).
- US patent (No. 9,899,071 B2): "Heavy Metal Multilayers for Switching of Magnetic Unit via Electrical Current without Magnetic Field, Method and Applications" (issued in Feb. 2018) by *Chien*.
- US patent (No. 10,559,747 B1): "Topological Insulator-Based High Efficiency Switching of Magnetic Unit, Method and Applications"(issued in Feb. 2020) by *Chien*.
- US patent application (Publication No. 0109172 A1): "Spin-Based Detection of Terahertz and Sub-terahertz electromagnetic radiation" (filed on Sept. 14, 2020 and published on April 15, 2021) by *Shi*.
- US provisional patent application (No. 62/522,357): "Method of Inducing Robust High-Temperature Ferromagnetism in Topological Insulator by Coupling to Magnetic Insulators in Heterostructures" (filed in 2017). The invention is based on the findings reported in a paper by *Shi* (*Science Advances*, 2017).
- US patent application (No. 16/562,171): "Magnetometer Based on Spin Wave Interferometer" (filed in September 2019) by *Khitun*.
- US provisional patent application (No. 62/847,028): "Qubit Devices Comprising One or More Polycrystalline or Single Crystalline Spin-Triplet Superconductors" (filed in September 2020) by *Chien*.

Meritorious honors and awards

- Chia-Ling Chien and Kang L. Wang received the prestigious "Magnetism Award and Néel Medal" prizes of the International Union of Pure and Applied Physics (IUPAP) in 2015 and 2018, respectively.

- Allan H. MacDonald received the prestigious Wolf Prize for Physics in 2020.
- Nathaniel Gabor received a NSF CAREER award, a Cottrell Scholar award, and an Azrieli Global Scholar award of the Canadian Institute for Advanced Research (CIFAR).

**What opportunities for training and professional development has the project provided?**

SHINES provided excellent opportunities for young investigators to grow scientifically and professionally which is critical to the success of their careers. All postdocs and students in SHINES have actively participated in center-wide collaborative research projects. In addition, they took responsibility in managing center activities including maintaining and updating SHINES webpages, running teleconference meetings, organizing weekly and annual in-person meetings, etc. These skills are extremely useful for their career development and would have not been possible without the SHINES EFRC platform. Specifically, the project has provided the following training and professional development opportunities:

**1. Junior faculty researchers**

SHINES EFRC has a large number of junior faculty member participants including both full members as well as the UCR participants supported by UCR internal funds. In the four-year period, the junior faculty members were Mingzhong Wu, Tingyong Chen, Elaine Li, Nathaniel Gabor (seed); in the two-year period, they were Igor Barsukov, and eight seed PIs including Nathaniel Gabor, Peng Wei, Ran Cheng, Richard Wilson, Chen Li, Boniface Fokwa, Yongtao Cui, and Sinisa Coh. There were charged with leading or coordinating collaborative projects, representing SHINES at DOE reviews and PI meetings, and presenting talks in SHINES internal meetings as well as international conferences/workshops. For example, Nathaniel Gabor, an assistant professor at UCR during the four-year period, worked closely with Elaine Li at UT Austin, Jing Shi at UCR, Roger Lake at UCR and others in the areas of transition metal dichalcogenide (TMD) materials, van der Waals heterostructure devices, and spin Seebeck effect excited by scanning local heating source, etc. The productive collaborations yielded high-profile publications in *Physical Review Letters*, *Nature Nanotechnology*, *Nature Photonics*, etc. This would have not been possible with the SHINES platform. For his excellent research work, Gabor was named as a Scialog Advanced Energy Storage Fellow by the Research Corporation for Science Advancement and a CIFAR Azieli Global Scholar within the Canadian Institute for Advanced Research. His multi-disciplinary research focus has led to his being named a National Academy of Sciences Kavli Frontiers Fellow. The ideas inspired by the SHINES collaborative research helped him win his NSF Early Career award. In 2018, Gabor received an early tenure and promotion for his outstanding research achievements, many of which were attributed to SHINES, along with his excellence in teaching and service. Since August 1, 2018, SHINES took advantage of the UCR costsharing funds and supported seven additional UCR junior faculty for their collaborative research with the full SHINES members. The expertise of these researchers ranges from inelastic neutron/X-ray scattering (Li), crystal growth (Fokwa), ultrafast optical switching of magnetization (Wilson), molecular beam epitaxial growth of TMD materials (Wei), scanning microwave impedance microscopy and magnetic force microscopy (Cui), DFT calculations of electron and phonon properties (Coh), antiferromagnetic spintronics theory (Cheng). They and their relevant group members were invited to attend weekly SHINES meetings at UCR, and attend and give oral or poster presentations at the 2019 SHINES annual meeting. In the weekly meetings, these faculty members and students take turns to make Powerpoint presentations, which provided unique opportunities for the junior faculty as well as their postdocs and students to develop critical communication and presentation skills needed for their careers.

**2. Postdoctoral researchers**

Over the entire award period, SHINES involved excellent postdoctoral researchers, either as SHINES Center Postdocs jointly supported by the center and individual PIs, or 100% supported by individual PIs.

Igor Barsukov, who is one of the 7 PIs in the two-year period, was previously a postdoc of a SHINES PI (Ilya Krivorotov at UCI) during the four-year period and was involved in various SHINES research projects on magnon condensate and spin superfluidity in nanomagnets. He was hired by the Department of Physics and Astronomy of UCR in 2017 as an assistant professor to work on the GHz-THz spin dynamics in magnetic materials. Clearly, the SHINES project prepared him very well for his academic career.
SHINES supported three Center Postdocs, Gen Yin at UCLA, Yafis Barlas at UCR, and Eric Montoya at UCI. SHINES empowered them to lead the center-wide multi-PI group collaborative projects. In addition to their own research, they were charged to work with other groups including PIs, students, and postdocs, act as liaisons between the center director and the research groups, and present progress report in monthly WebEx meetings and annual meetings. The leadership skills they acquired are a very important asset to their academic job search as they entered the job market. Most of them have already become junior faculty members or engineers/researchers in industry. Gen Yin is an assistant professor at Georgetown University; Yafis Barlas, an assistant professor at the University of Nevada at Reno; Junxue Li, a former postdoc of Jing Shi at UCR, now an assistant professor at the Southern University of Science and Technology in China; Weiwei Lin, a former postdoc of Chia-Ling Chien at JHU, now an assistant professor at Southeast University in China; Peng Li, a former postdoc of Mingzhong Wu at Colorado State University, now an assistant professor at Auburn University; Xin Ma, a former postdoc of Elaine Li at UT Austin, is now working for Google.

### 3. Graduate and undergraduate students

The SHINES EFRC has supported a large number of students through various collaborative projects. Many of the graduate students were assigned as lead coordinators of center-wide collaborative projects, or group lead coordinators representing their groups. Their responsibilities include communicating with their peers in other research groups, initialing new ideas and projects, reporting the status of their research, and making presentations in internal meetings or DOE PI meetings.

The overall DOE EFRC program provided great opportunities for students to develop important skills through the DOE Early Career Network (ECN), the Energy Frontier Community Newsletters, various competitions (e.g., Team Science competition, video) at the PI meetings which SHINES postdocs and students actively took part in. Gen Yin and Rudy Rodriguez represented SHINES as ECN members. Max Grossnickle served as a reporter/writer for the EFRC Community Newsletters for two terms.

Several graduate students who previously worked on SHINES projects have already become faculty members or scientists in academic institutions. Qiming Shao, a former student of Kang Wang at UCLA, is an assistant professor at Hong Kong University of Science and Technology. Pramey Upadhyaya, a former student of Kang Wang at UCLA, now an assistant professor at Purdue University. Mohammed Aldosary, a former student of Jing Shi at UCR, now is an assistant professor at King Saud University. Fariborz Kargar, a former student of Alex Balandin, is a project scientists at UCR. Many more have joined the workforce in industry (e.g., Chi Tang employed at Google, Yawen Liu at Google, Ece Aytan at Intel, Chris Safranski at IBM, Houchen Chang at Western Digital, Yadong Xu at Intel, Maxwell Grossnickle at Applied Materials, Gejian Zhao at ASM, Mojtaba Ranjbar at Western Digital, Bishwajit Debnath at Intel, Aleksey Volodchenkov at SpaceX, Mohammad Suja at Intel) or are currently working as postdoctoral researchers (e.g., Victor Ortiz at UCR, Yabin Fan at MIT, Petr Stepanov at ICFO Institute of Photonic Sciences, Kevin Olsson at Univ. of Maryland, Danru Qu at the Institute of Physics of Academia Sinica).

**How have the results been disseminated to communities of interest?**

SHINES PIs took every opportunity to disseminate the research results to the communities of spintronics, materials science and engineering, and condensed matter physics by the following means:

1. Holding workshops and seminars. In January 2017, the SHINES EFRC held a two-day workshop on Spins and Heat at the UCR Palm Desert Campus. The workshop was advertised on various UCR websites. Over 10 leading scientists from overseas and the US were invited as external speakers. The workshop was open to the public and well attended by SHINES PIs, postdocs and students, especially UCR graduate and undergraduate students. SHINES held seminars on UCR campus regularly. The seminars were live streamed to all off-site SHINES participants. Speakers from universities, national labs, and industrial labs from all over the world (Germany, Japan, China, Taiwan, etc.) were invited. Lunchtime discussions were especially arranged between the speakers and students during these visits.

2. Giving presentations at international conferences and workshops. SHINES has strong presence in major international conferences on the research topics relevant to SHINES. For example, SHINES PIs, Mingzhong Wu, Allan MacDonald, and Jing Shi were three speakers (out of five speakers) in an invited symposium on "Topological Spintronics" at the 2019 American Physical Society March Meeting in Boston. Igor Barsukov and Jing Shi were invited speakers at the Spin Caloritronics IX Conference held at OSU in 2018. Mingzhong Wu gave an invited talk at the 2019 MMM-Intermag Joint Conference, a major international conference in the magnetism and magnetic materials community. Chia-Ling Chien, Ilya Krivorotov, and Jing Shi are invited speakers at the Spin Caloritronics X Conference at Groningen in Netherlands in 2019. Alex Balandin is a plenary speaker at the 25th International Conference on Noise and Fluctuations to be held in Neuchâtel (Switzerland) in 2019. Jing Shi is an invited speaker at the Gordon Research Conference on Spin Dynamics in Nanostructures in Switzerland in July 2019. In addition to invited talks, most PIs and graduate students from all groups have given contributed talks in conferences including the Materials Research Society (MRS) meetings, American Physical Society (APS) March Meetings, Conferences on Magnetism and Magnetic Materials (MMM), Intermag, and ICM.

3. Publishing research papers in scholarly journals. Over the entire period, SHINES published 191 papers in peer-reviewed journals and one book chapters. These papers include review articles (e.g., MacDonald's 2018 *Nature Physics* on Topological Antiferromagnetic Spintronics), which reach out to even a broader research community than regular papers.

4. Publishing press releases. Several press releases were published to publicize SHINES PIs' research results. The following press releases are representatives for major research breakthroughs.

   a. Mingzhong Wu's Colorado State University press release on his Nature Communication article in September 2016 (https://source.colostate.edu/making-the-switch-this-time-with-an-insulator/);
   b. Jing Shi's press release in UCR Today on the record high Curie temperature in induced ferromagnetism on the surface of topological insulators in June 2017 (https://www.eurekalert.org/pub_releases/2017-06/uoc--raq062317.php);
   c. Kang Wang's UCLA press release on the chiral Majorana work in July 2017 (https://newsroom.ucla.edu/releases/ucla-led-research-offers-clearest-evidence-yet-of-long-sought-majorana-particle);
   d. Alex Balandin's press release in UCR Today on the noise study of magnonic devices in March 2019 (https://news.ucr.edu/articles/2019/03/04/magnonic-devices-can-replace-electronics-without-much-noise);

e. article published in the Highlander, UCR's newspaper, on Nathaniel Gabor's study of an exotic electron liquid in February 2019 (https://www.highlandernews.org/34863/ucr-physics-researchers-produce-electron-liquid-shows-potential-nanotechnological-advancement/);
f. Chia-Ling Chien's press release at Johns Hopkins on his half quantum flux work (https://releases.jhu.edu/2019/10/10/johns-hopkins-researchers-discover-superconducting-material-that-could-someday-power-quantum-computer/);
g. Jing Shi's press release in UCR Today on his terahertz antiferromagnetic spin pumping in January 2020 (https://news.ucr.edu/articles/2020/01/27/detection-very-high-frequency-magnetic-resonance-could-revolutionize).

## III. PRODUCTS

### 1. Publications

The published papers have been entered to the energyfrontier.us website. A list of the published papers is generated from the website and appended to this document.

### 2. Intellectual Property

A separate Excel spreadsheet is provided.

### 3. Technologies or Techniques

None.

### 4. Other Products

None.