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14. ABSTRACT The conference was organized with the sole support by the Army Research Office, which covered all the venue-related expenses, including meals and coffee breaks, as well as offset the housing costs for the participants. The goals set forward in the original proposal have been met, making the conference a success.					
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Report Title

Final Report: Conference on Spin Coherence, Condensation and Superfluidity

ABSTRACT

The conference was organized with the sole support by the Army Research Office, which covered all the venue-related expenses, including meals and coffee breaks, as well as offset the housing costs for the participants. The goals set forward in the original proposal have been met, making the conference a success.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations:

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received

Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:.....

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:.....

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):.....

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:.....

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME PERCENT SUPPORTED
FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

We had 28 participants in total (plus the chairperson), who all gave 40-min invited talks, in the course of the 5-day meeting. The final program is appended at the end of this document. The scientific program was divided into 11 sessions on

- Spin/magnon torques
- NV imaging and horizons
- Magnon condensate dynamics
- Spin superfluidity
- Soliton dynamics
- Quantum Hall/topology
- Spin magneto(hydro)dynamics
- Thermal transport in spin chains
- Thermal magnons
- Quantum dynamics
- Competing orders and dynamics

Out of the 28 speakers, 9 were junior (either at the PhD or postdoc level), including 4 female participants. The full list of the speakers, in the alphabetical order, along with their affiliations and talk titles follows. All the talk slides have been uploaded at <https://muri.engineering.osu.edu/meetings/spin-coherence-condensation-and-superfluidity> and are available to the public.

Technology Transfer

REPORT FOR THE CONFERENCE

**SPIN COHERENCE, CONDENSATION, AND
SUPERFLUIDITY**

February 13-17, 2017

University of California Gump Station, Moorea, French Polynesia

Chairperson: Yaroslav Tserkovnyak (UCLA)

The conference was organized with the sole support by the Army Research Office, which covered all the venue-related expenses, including meals and coffee breaks, as well as offset the housing costs for the participants. The goals set forward in the original proposal have been met, making the conference a success. We had 28 participants in total (plus the chairperson), who all gave 40-min invited talks, in the course of the 5-day meeting. The final program is appended at the end of this document. The scientific program was divided into 11 sessions on

1. Spin/magnon torques
2. NV imaging and horizons
3. Magnon condensate dynamics
4. Spin superfluidity
5. Soliton dynamics
6. Quantum Hall/topology
7. Spin magneto(hydro)dynamics
8. Thermal transport in spin chains
9. Thermal magnons
10. Quantum dynamics
11. Competing orders and dynamics

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1. Johan Åkerman (Gothenburg/KTH) *Magnetodynamical solitons in spin torque and spin Hall nano-oscillators*

2. Wei Chen (ETH Zurich) *Dissipationless multiferroic magnonics*
3. Sasha Chernyshev (UC Irvine) *Heat transport in spin chains: The good, the bad, and the realistic*
4. Matthieu Dartiailh (ENS Paris) *Mesoscopic cQED with carbon nanotubes*
5. Rembert Duine (Utrecht) *New horizons for spintronics*
6. Benedetta Flebus (Utrecht) *Local thermomagnonic torques in two-fluid spin dynamics*
7. Victor Galitski (Maryland) *Quantum friction and Brownian motion of solitons*
8. Tero T. Heikkilä (Jyväskylä) *Spin pumping and torque statistics in the quantum noise limit*
9. Joseph P. Heremans (OSU) *Magnon drag and bulk spin-Seebeck*
10. Ezio Iacocca (Boulder) *Dispersive hydrodynamic formulation of thin film ferromagnets*
11. Andrew D. Kent (NYU) *Spin Transfer Torque Induced Magnon Condensates*
12. Se Kwon Kim (UCLA) *Soliton diffusion, thermophoresis, and information transport*
13. Mathias Kläui (Mainz) *Spin Transport from diffusion to spin-superfluidity?*
14. Olivier Klein (Grenoble) *Spin conductance of YIG thin films driven from thermal to subthermal magnons*
15. Allan MacDonald (UT Austin) *Electron-hole pair condensates*
16. Shuichi Murakami (TIT) *Berry curvature and topology in dipolar-exchange magnons*
17. Kouki Nakata (Basel) *Magnonic quantum Hall effect and Wiedemann-Franz law in magnetic insulators*
18. Arati Prakash (OSU) *Spin Seebeck effect: Problems and parameterization*
19. Christina Psaroudaki (Basel) *Quantum dynamics of skyrmions in chiral magnets*
20. Masahiro Sato (Ibaraki) *Spinon spin Seebeck effect in 1D gapless quantum spin liquids*
21. Oleksandr Serha (Kaiserslautern) *Kinetic instability, Bose-Einstein condensation, and magnon supercurrents in YIG films*
22. Juan Shan (Groningen) *Electrically and thermally driven magnon transport in magnetic insulators*
23. Andrei Slavin (Oakland) *Avoiding collapse in an untrapped BEC of quasiparticles with attractive interaction*

24. Oleg Starykh (Utah) *Emergent Ising orders of frustrated magnets*
25. So Takei (CUNY) *Macroscopic quantum spintronics devices*
26. Mircea Trif (Tsinghua) *Dynamical Shiba states and bands in s-wave superconductors*
27. Ronald Walsworth (Harvard) *Nanoscale magnetic imaging using NV-diamond: Techniques & applications*
28. Amir Yacoby (Harvard) *Imaging skyrmions and spin chemical potential using nitrogen vacancy centers in diamond*

This list of presentations, many based on the ongoing unpublished work, illustrates the rapidly expanding agenda in the field. The main focus is on the emergent nonlinear dynamic phenomena in the magnonic and spin systems that are strongly driven out of equilibrium. Magnon condensation and spin superfluidity provide the central notions and the key experimental objectives. Several experimental groups (cf. talks 11, 13, 14, and 21) have reported on the preliminary (tentative) signatures of these collective phenomena. Another experimental highlight (talks 27 and 28) concerns the development of the diamond NV-center relaxometry technique to measure the chemical potential of a nonequilibrium magnonic system driven either coherently (by microwave field) or incoherently (by spin Hall or spin Seebeck effects). This promises to be a versatile and powerful tool to study collective spin transport in magnetic insulators, including possibly antiferromagnets.

The central topics, along with the key issues, discussed at the workshop included:

- Magnonic condensates: Coherence, transport, and dynamics. The stability and dynamics of several types of magnetic condensates, induced by parametric microwave instabilities, electrical, or thermomagnonic torques, have been discussed. These are possible both in insulators and metals, ferromagnets and antiferromagnets, as has been experimentally demonstrated (with the antiferromagnets being only in the preliminary stages of research; see talk 13).
- Spin superfluidity: Pinning, dissipation, and nonlinearities. This is among the most interesting topics going forward in this field. Demonstration of a versatile and robust spin superfluid. Both room- and low-temperature regimes should in principle be possible, with different scenarios of dissipation (including the omnipresent magnetic Gilbert damping and phase slips that are common of all superfluids and superconductors).
- Thermal control of diffusive and collective spin transport in insulators. This primarily concerns the improved understanding of the standard spin Seebeck physics (particularly in regard to the pertinent microscopic lengthscales), extending it towards more unconventional and exotic materials and heterostructures (see, e.g., talk 20).
- Macroscopic quantum phenomena and mesoscopic effects, based on spin superfluids and topological solitons. This is very early and adventurous at this stage, but is certain to

grow in the years to come. Talks 4, 7, 25, and 26 pushed the most into the (macroscopic) quantum realm.

- Progress on the nonferromagnetic materials: From antiferromagnets to spin liquids (as talk 20). Much more work on antiferromagnets and frustrated quantum magnets without net magnetism (or even a long-ranged order) is anticipated.
- Classical and quantum device concepts: Nonvolatile memories, spin interconnects, and low-dissipation integrated circuits. As the field is maturing, new functionalities and device ideas will be emerging, as presented in talks 6 (a spin transistor based on the interplay of magnetic domain walls and spin superfluids) and 25 (quantum qubits and circuits quantum annealing based on superfluid droplets).

As a summary of the open questions and outlook for future work, the conference raised the following set of key issues:

- Stability, coherence of the driven condensates
- Collective heat transport
- (Mesoscopic) quantum regimes
- Novel (insulating?) materials for spin condensates and superfluids
- Other emergent dynamic phenomena and the associated spin/heat/topological transport
- Useful spintronic devices: memory, communication, logic, heat harvesting

Finally, I close this report with my own (subjective) opinion on the heat-driven spin phenomena in spin-active materials. The most interesting thrust there is the understanding of the coupling of heat fluxes in magnetic materials (mostly insulators, but also metals; ferromagnets to antiferromagnets to spin glasses and frustrated quantum materials) with the relevant collective spin degrees of freedom. Simply measuring the spin Seebeck effect in the standard linear-response Nernst geometry (i.e., heat flux in, transverse voltage out) is not particularly compelling anymore, although it could of course still be a useful first step for characterizing spin/heat properties in new magnetic/spin materials. It is more interesting (and maybe ultimately more useful) to shift the focus towards the interplay of heat fluxes and dynamics of solitons, helical (superfluid) textures, skyrmionic lattices etc. (particularly, where a hydrodynamic theory can be developed in terms of topological texture densities, such as chiral winding and skyrmionic textures; this is relevant not only for ferro- and antiferromagnets, but also even for completely disordered materials). New ideas on how to probe such collective textures directly, both spectroscopically and electrically, exploit interconversions between different topological properties (such as 1D magnetic winding, 2D skyrmions, and 3D Bloch points), and utilize their thermoelectric signatures, all in

response to large heat fluxes, are called for. Nonlinear physics and dissipation (Gilbert damping vs collective effects such as “phase slips”) need to be explored further, along with the dynamic phase transitions (essentially, coherent instabilities) of strongly-heat-driven magnetic heterostructures.