Long-Range Phonon Spin Transport

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Long-term motivation

\[ I = \frac{V}{R} \text{ with } R \text{ independent of } L \]
below room temperature \( T \)

? above room temperature \( T \)?

See e.g. Sonin (2010)
Non-local spin transport in metals/semi-conductors

Electron spin accumulation: \( \mu_s \propto e^{-x/\ell_s} \)

Non-local resistance: \( R_{NL} \sim \frac{V_{NL}}{I_{INJ}} \propto e^{-L/\ell_s} \)

Spin-diffusion length: \( \ell_s \sim \text{nm} - \mu\text{m} \)

From Wei Han et al., JMMM 324, 369 (2012)
Non-local spin transport though magnetic insulators

magnon spin accumulation: $\mu_m \propto e^{-x/\ell_m}$

non-local resistance: $R_{NL} \sim V/I \propto e^{-L/\ell_m}$

magnon spin diffusion length: $\ell_m \sim 10 \, \mu\text{m}$ YIG @ room T
General view

- Electrons (100’s nm)
- Magnons (10’s μm)
- This talk: phonons (mm’s)
Collaborators

Andreas Rueckriegel (Utrecht -> Frankfurt)
Simon Streib (Uppsala)
Gerrit Bauer (Sendai, Groningen)
Outline

• Phonon spin

• Role of phonons in Einstein-de Haas-like effects

• Long-range phonon spin currents
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• Long-range phonon spin currents
Circularly-polarized phonons carry spin angular momentum.

**PHONON SPIN**

S. V. Vonsovskii and M. S. Svirskii

Institute of Metal Physics, Academy of Sciences, USSR, Sverdlovsk; Chelyabinsk Pedagogical Institute


Original article submitted March 18, 1961

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Experimental detection phonon spin (I)

set-up:

dispersion relation:

Holanda et al, Nat. Phys (2018)
Experimental detection of phonon spin (II)

Set-up:

Magnon-phonon conversion:

Result:

- Excitation of magnon (spin $\approx \vec{h}$)
- Conversion to phonon
- Measurement of phonon polarization

Holanda et al, Nat. Phys (2018)
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Einstein, de Haas (1915); picture from Matsuo et al. (2015); modern experiments: detection of compensation point via Barnett effect & spin Seebeck mechanical force (Saitoh group, 2019); classical theory: Assmann/Novak (2019); see also Mentink et al. (2019).

**Einstein-de Haas effect**

\[ \frac{M_s V}{\gamma} \sim I \Omega \]

**conservation of angular momentum:**

\[ \mu_0 M_s B V \gg \Omega^2 / I \quad \text{because} \quad I \propto V^{5/3} \]

\[ \Omega \propto V^{-2/3} \]

Need reservoir = phonons & their spin!
Microscopic theory of Einstein-de Haas-like effects

- Starting point: rotation-invariant Hamiltonian for magnetic insulator
- Split mechanical motion into global rotation & translation + phonons
- Coupled Heisenberg equations for spins, lattice and global rotations
- Approximate as quantum-kinetic theory for magnons and phonons, coupled to magnetization dynamics and global rotation
- Solve by making ansatz in terms of phonon temperature & drift velocity: magnon temperature and chemical potential:

  $\delta T_\perp(t), \delta T_\parallel(t), \nu(t)$
  $\delta T_m(t), \mu(t)$

- From this, compute change in spin density, phonon spin density and global rotation:

  $\delta s(t), \delta l(t), \Omega_z(t)$

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Results (I)

- Initial condition: heating due to laser pulse, angular momentum conserved
- Magnons and longitudinal phonons equilibrate first
- Phonon spin and global rotation compensate for decrease in magnetization

See Schneider et al., Nature Nano. (2020), for a similar scenario to achieve BEC
Initial condition: parallel pumping, angular momentum conserved
- Magnons and longitudinal phonons equilibrate first
- Phonon spin and global rotation result due to equilibration with magnons
- Phonon spin large, global rotation changes sign
- Initial condition: (optical) spin injection into phonons
- Magnons and longitudinal phonons equilibrate first
- Magnon spin hardly changes, phonons and global rotation dominate
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Outline

• Phonon spin

• Role of phonons in Einstein-de Haas-like effects – conclusion: phonons & their spin important, but what can we do with them?

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• Long-range phonon spin currents
- Incoherently driven magnetic reservoirs
- Non-magnetic insulator
- Spin transfer due to magnetoelastic interactions
- Theoretical approach: coupled stochastic equations for magnetic and lattice dynamics
Spin-conductance & resonance condition

Spin current: 
\[ I_{L \rightarrow R} = \int \frac{d\omega}{2\pi} T_{L \rightarrow R}(\omega) \left[ f_B(\hbar \omega - \mu_L) - f_B(\hbar \omega - \mu_R) \right] \]

for small bias: 
\[ I_{L \rightarrow R} = \sigma(\mu_R - \mu_L) \]

resonance condition 
\[ \frac{L}{(\tilde{\lambda}/2)} + \frac{2d}{(\lambda/2)} = \text{integer} \]
Long-range phonon spin currents

- YIG and GGG parameters
- Decay length \( \sim 1 \text{ mm} \)
Phonon spin accumulation & spin current

- Same order of magnitude as spin density related to magnetization
- (Quasi-)equilibrium phonon spin accumulation and phonon spin currents
Experiments in coherent regime

FMR experiment, coherent coupling

Conclusion

- Electrons (100’s nm); limited by spin-orbit and disorder
- Magnons (10’s μm); limited by magnetic quality
- This talk: phonons (mm’s); limited by acoustic quality
- Experiments?!
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\[ I = \frac{V}{R} \text{ with } R \text{ independent of } L \]

below room \( T \)

above room \( T \)?
Superfluid transport of angular momentum without magnetization

Sonin (2010)
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