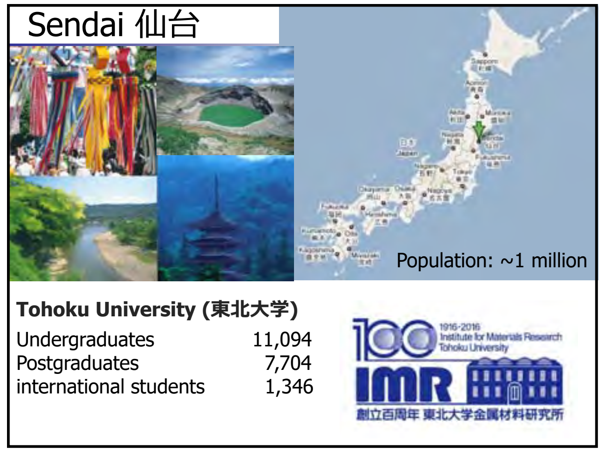
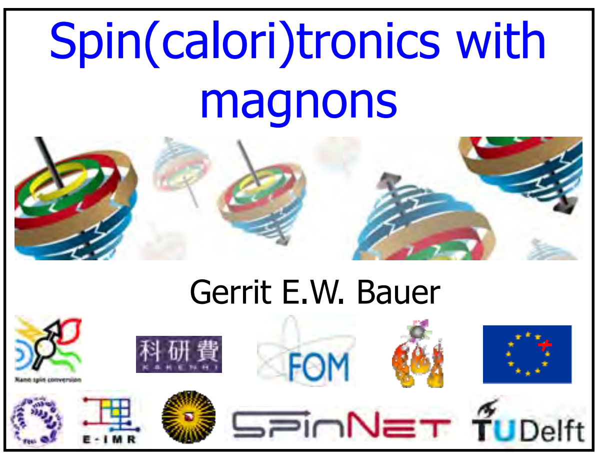
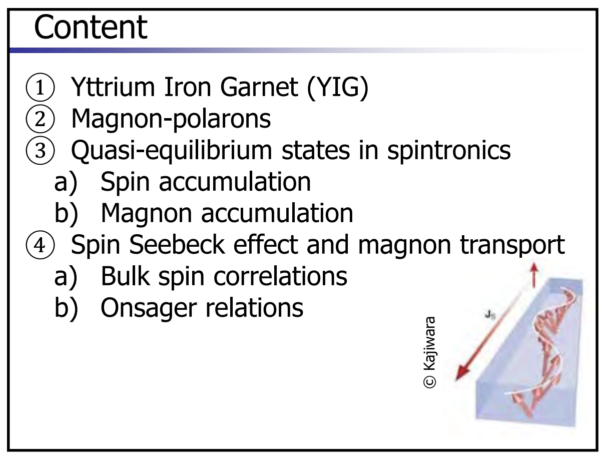

Spin Caloritronics VII, Utrecht
The Netherlands, 11-15 July 2016
SPINCALORITRONICS VI
Spin Caloritronics 4
SPIN CALORITRONICS V
NEW PERSPECTIVES FOR SPIN-CALORITRONICS
Spin Caloritronics 8, Regensburg, 12-15 June, 2017
Spin Caloritronics 9, Washington (DC) or Columbus (OH), 2018
Spin Currents and Spin Caloritronics


Sendai 仙台
Population: ~1 million
Tohoku University (東北大学)
Undergraduates 11,094
Postgraduates 7,704
international students 1,346
100 1916-2016 Institute for Materials Research Tohoku University
IMR
創立百周年 東北大学金属材料研究所


Spin(calori)tronics with magnons
Gerrit E.W. Bauer
科研費
FOM
E-IMR
SPINNET
TU Delft


Content
① Yttrium Iron Garnet (YIG)
② Magnon-polarons
③ Quasi-equilibrium states in spintronics
a) Spin accumulation
b) Magnon accumulation
④ Spin Seebeck effect and magnon transport
a) Bulk spin correlations
b) Onsager relations
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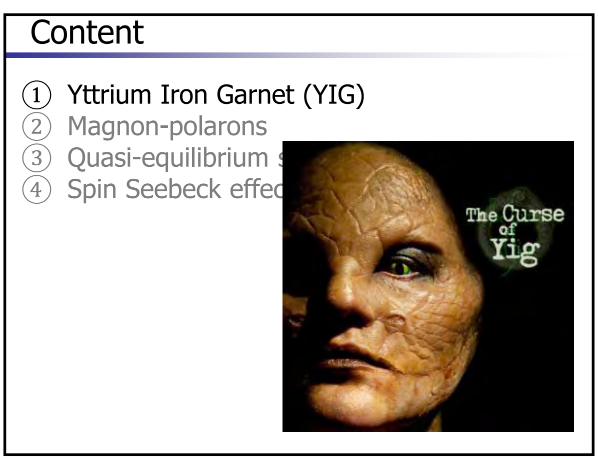
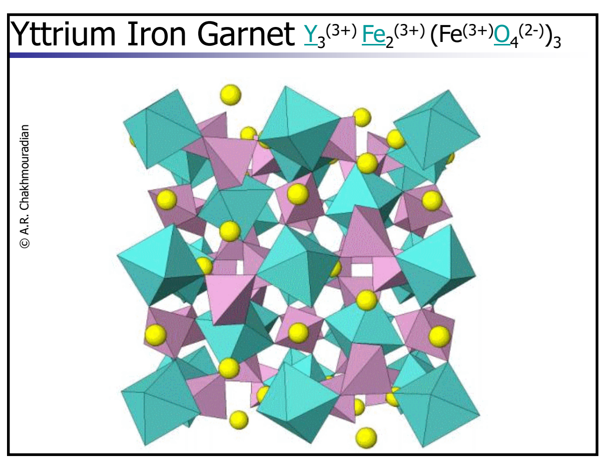
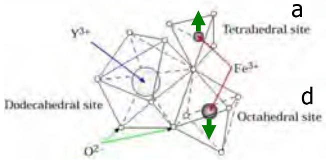

Content
① Yttrium Iron Garnet (YIG)
② Magnon-polarons
③ Quasi-equilibrium s
④ Spin Seebeck effec
The Curse of Yig


Yttrium Iron Garnet $Y_3^{(3+)} Fe_2^{(3+)} (Fe^{(3+)}O_4^{(2-)})_3$
© A.R. Chakhmouradian

Yttrium Iron Garnet $Y_3^{(3+)}\,Fe_2^{(3+)}\,(Fe^{(3+)}O_4^{(2-)})_3$



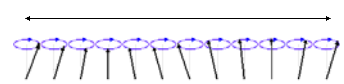
80 atoms & 20 magnetic moments/unit cell

- electrical insulator (band gap 2.8 eV)
- Curie temperature 550 K
- low acoustic damping
- high magnetic quality factor Q=10^5
- large Faraday effect (by doping)
- tunable magnetic anisotropy (by doping)

Spin waves (magnons)

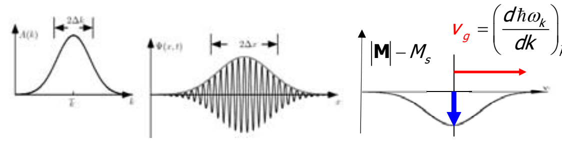
Landau-Lifshitz equation: $\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M}\times\mathbf{B}$

Linearized solution (exchange magnons):



$\lambda = 2\pi/k$

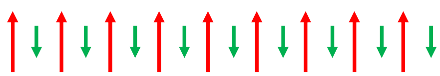
$\hbar\omega_k = \hbar\omega_0 + Ak^2$



$v_g = \left(\frac{d\hbar\omega_k}{dk}\right)_{\bar{k}}$

Planck (Rayleigh-Jeans) distribution: $n_k^{(\text{magnon})} = \frac{1}{e^{\frac{\hbar\omega_k}{k_BT}}-1} \rightarrow \frac{k_BT}{\hbar\omega_k}$

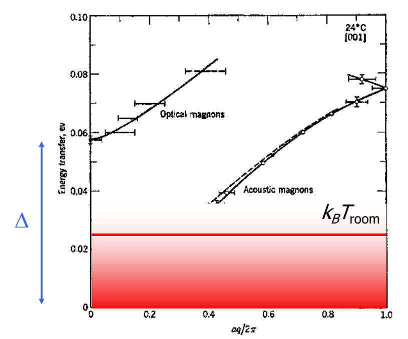
Sublattice model for ferrimagnets



Acoustic (FMR) mode in eff. magnetic field:

Optical (AFM) mode in eff. exchange field:

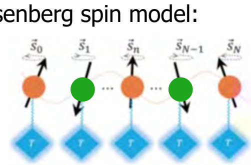
Spin waves in magnetite Fe_3O_4



Acoustical and optical magnon dispersion relations in magnetite, as determined from inelastic neutron scattering by Brockhouse and Watanabe (IAEA Symposium, Chalk River, Ontario, 1962).

Atomistic spin simulations (J. Barker)

Classical Heisenberg spin model:



Stochastic Landau-Lifshitz-Gilbert equation:

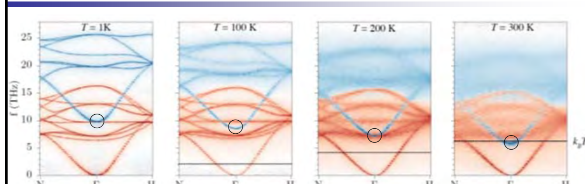
$$\frac{d\vec{s}_n}{dt} = -\vec{s}_n \times \left(\vec{H}_{\text{eff}} + \vec{h}_n\right) + \alpha \vec{s}_n \times \frac{d\vec{s}_n}{dt}$$

$$\left\langle h_n^i(t)\, h_{n'}^j(t')\right\rangle = 2\alpha k_B T_n \delta_{nn'}\delta_{ij}\delta(t-t')$$

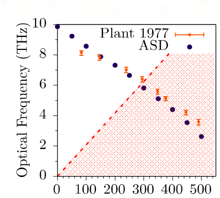
J_{ad} = -30.0 meV
J_{dd} = -10.1 meV
J_{aa} = -2.9 mev
α = 0.002

Output: $\vec{s}_n(t)$ for a large system and time interval.

Temperature dependence and chirality

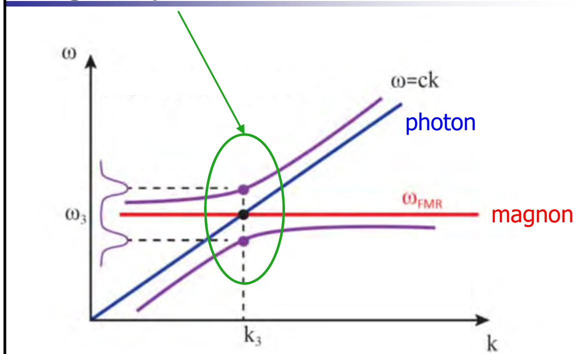


red: + chirality
blue: - chirality



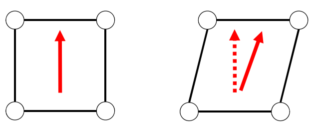
Contents

Magnon-polaritons



Spin mechanics

Magnetic anisotropy couples magnetic and lattice order

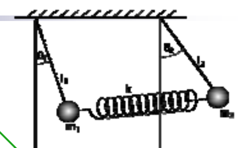


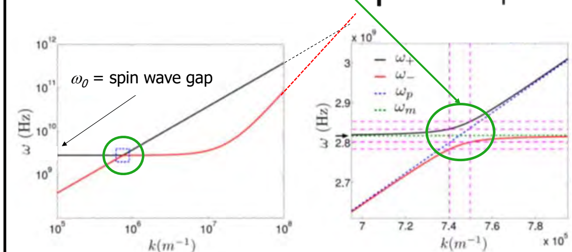
Dynamics

- thermalization of lattice and spin
- magnon-phonon drift
- hybridized states (Kittel, 1958)

Magnon-polar~~it~~ons

Kittel (1958)
⋮
Rückriegel *et al.* (2014)
Kamra *et al.* (2015)

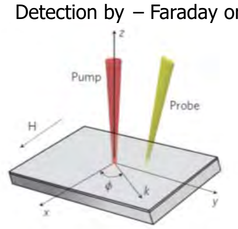


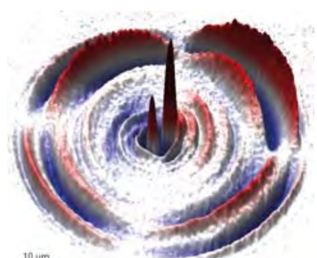


Pump & probe spectrosocpy

Femto-second optical excitation

Excitation by – Inverse Faraday effect
– Heat
Detection by – Faraday or Kerr rotation





Ogawa *et al.* (2015)
Satoh *et al.* (2012)
Hashimoto *et al.* (unpublished).

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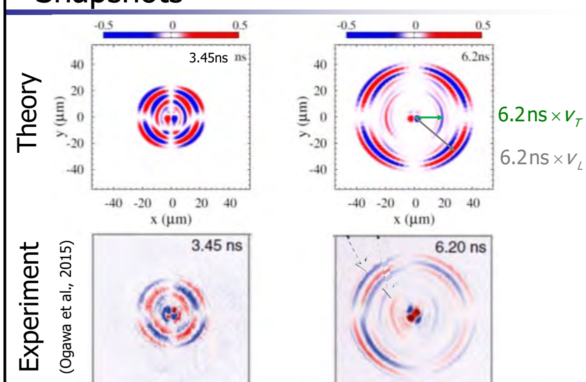
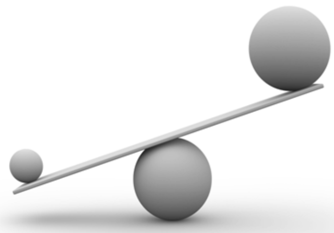
Snapshots

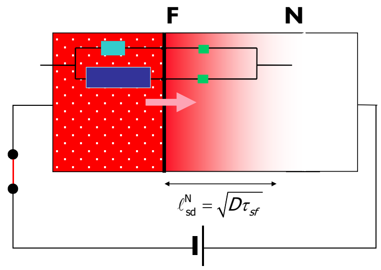


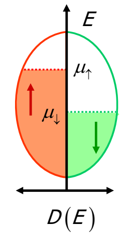
Shen & GB (2015)

Contents



Spin-accumulation and spin-current





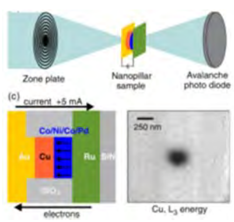
ℓ_{sd}^{N} spin-flip diffusion length

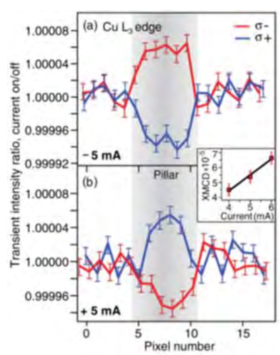
D diffusion constant

τ_{sf} spin-flip relaxation time

$$\mu_\uparrow(\mathbf{r}) - \mu_\downarrow(\mathbf{r}) = eV_s(\mathbf{r})$$

Current-induced spin accumulation by XMCD



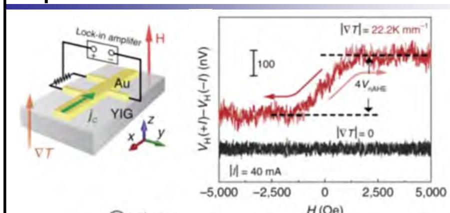


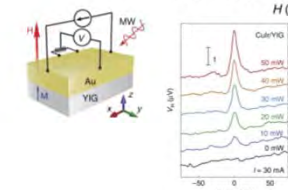
Kukreja et al., PRL (2015)

[Also: Li et al., PRL (2016)]

Spin accumulation AHE

D. Hou et al. (2016)





$$R_{AHE} = -\frac{\rho_0^2 \mu_s}{2d} \frac{\partial \sigma_{SHE}}{\partial \varepsilon}\bigg|_{\varepsilon_F}$$

closely related to spin Nernst effect

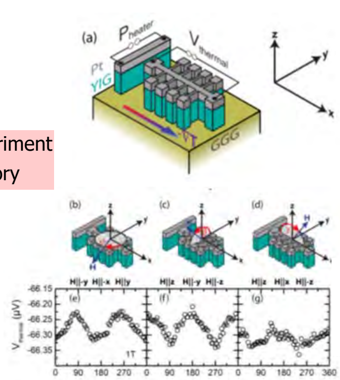
Spin Nernst effect

S. Meyer et al. (2016)

$$J_{s,SH} = \theta_{\text{spin Hall}} J_c|_{\nabla T=0}$$

$$J_{s,SN} = \theta_{\text{spin Nernst}} J_c|_{\nabla V=0}$$

$$\frac{\theta_{\text{spin Hall}}}{\theta_{\text{spin Nernst}}} = \begin{cases} -0.5 & \text{experiment} \\ -0.9 & \text{theory} \end{cases}$$

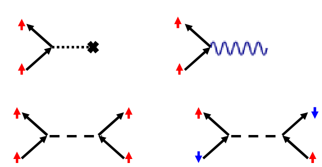


spin Nernst magnetothermo-power

Scattering in metals

Legenda	
electrons	⟶
magnons	∿∿∿
phonons	∿∿∿
impurities	·········✖
photon	- - - -

spin conserving

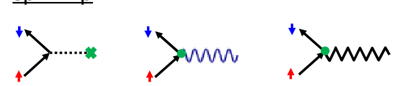


diffusion

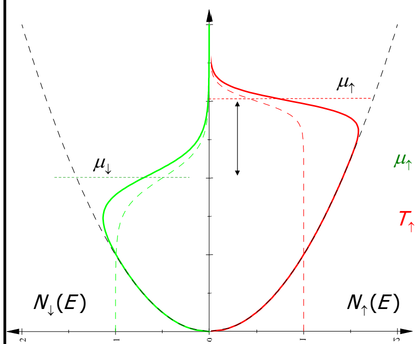
thermalization

dissipation

spin-flip



Spin and heat accumulation

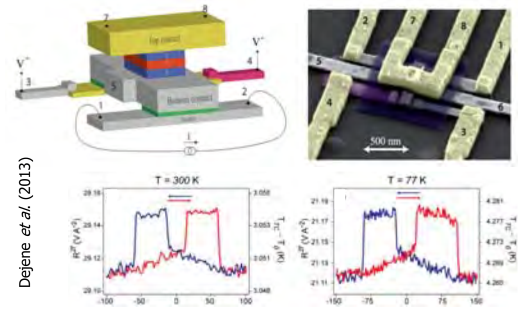


$$N_\uparrow(E) = \frac{D_\uparrow(E)}{e^{\frac{E-\mu_\uparrow}{k_B T_\uparrow}}+1}$$

$\mu_\uparrow - \mu_\downarrow$ spin particle accumulation

$T_\uparrow - T_\downarrow$ spin heat accumulation

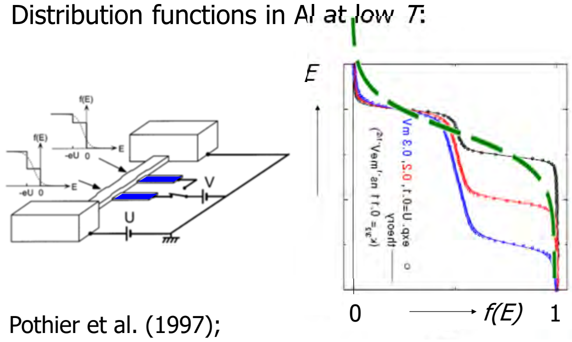
Spin temperature and heat accumulation



$\ell_{sp}(300\text{K}) = 60$ nm $\qquad \ell_{sp}(77\text{K}) = 150$ nm

Weakly interacting limit

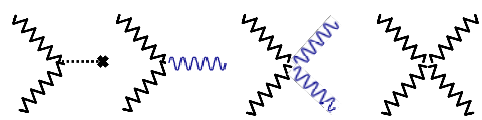
Distribution functions in Al at low *T*:



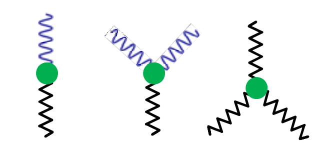
Pothier et al. (1997);
Pierre et al. (2000)

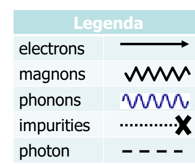
Magnon scattering in insulators

magnon conserving

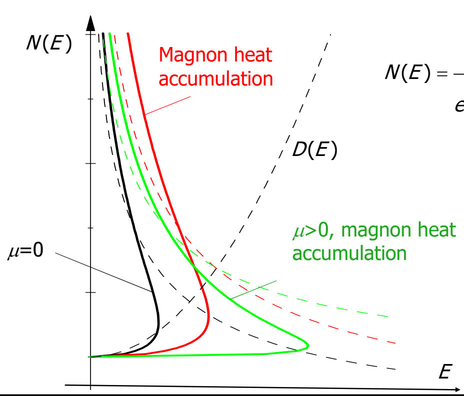


magnon non-conserving (~α)





Magnon accumulation



$$N(E) = \frac{D(E)}{e^{\frac{E-\mu}{k_B T}}-1}$$

Quantum statistics

$\lambda_T = \sqrt{\frac{4\pi A}{k_B T}}$ magnon thermal wave length

quantum statistics when

$$n_{\text{equil.}}^{(\text{magnon})} = \sum_k \frac{1}{e^{\frac{\hbar\omega_k}{k_B T}}-1} \geq \frac{1}{\lambda_T^3}$$

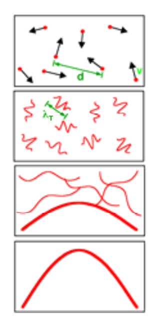
Pumped system: $n_{\text{excited}}^{(\text{magnon})} > n_{\text{equil.}}^{(\text{magnon})}$

$$n_{\text{excited}}^{(\text{magnon})} \approx \sum_k \frac{1}{e^{\frac{\hbar\omega_k-\mu_m}{k_B T}}-1} + n_c$$

μ_m magnon chemical potential

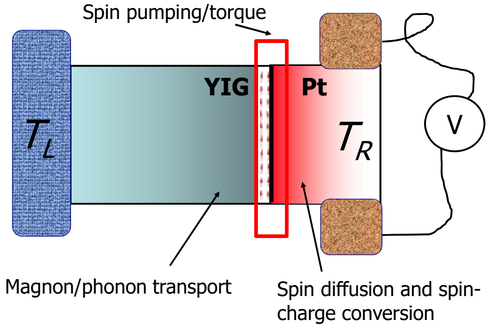
magnon condensate fraction $n_c \neq 0$ when

$$\frac{k_B T}{A} < 6.626\, n_{\text{excited}}^{(\text{magnon})}$$



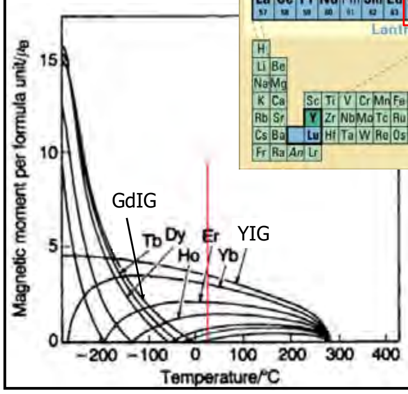
① Yttrium Iron Garnet
② Magnon-polarons
③ Quasi-equilibrium
  a) Spin accumulation
  b) Magnon accumulation
④ Spin Seebeck effect and magnon transport

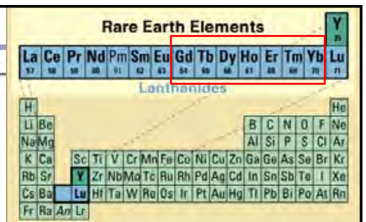
Standard Spin Seebeck model



$$V = C(T, \theta_{SHE}, d_N, d_F, \cdots)(T_L - T_R)\, g_{\uparrow\downarrow} \int d\omega\, \omega \sum_{\mathbf{k}} \mathrm{Im}\, \mathscr{S}_{xy}(\mathbf{k}, \omega)$$

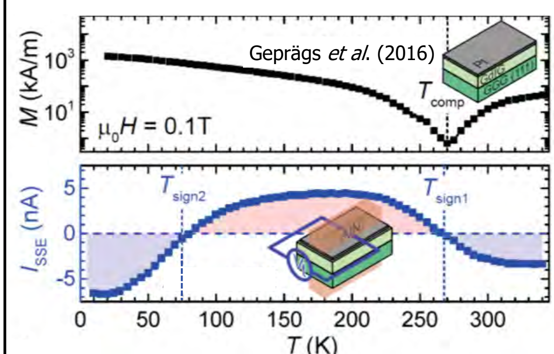
RE-IG



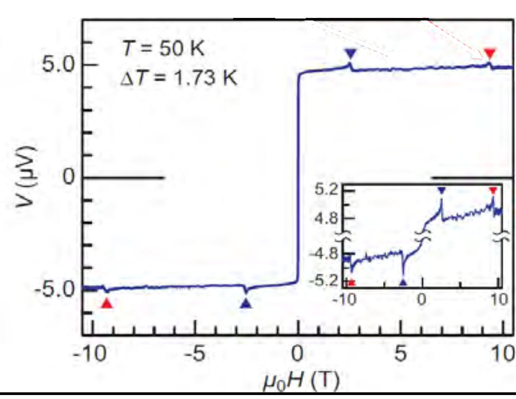


Electroceramics: Materials, Properties, Applications, by A.J. Moulson & J. M. Herbert (Wiley, 2003).

SSE of Gadolinium Iron Garnet

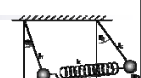


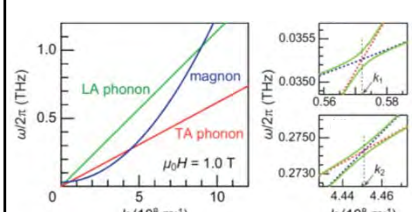
Glitches in the SSE (Kikkawa et al., 2016)



Magnon-polarons & SSE

T. Kikkawa & E. Saitoh: experiments
K. Shen & B. Flebus: Boltzmann theory



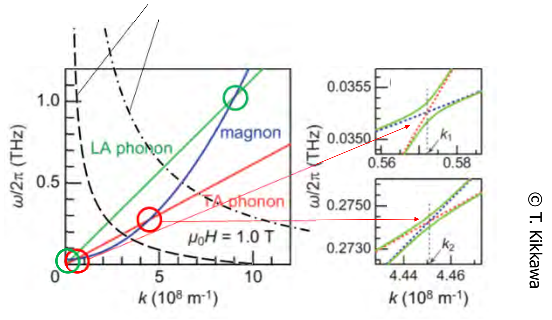


incl. magnetostatics & defect scattering

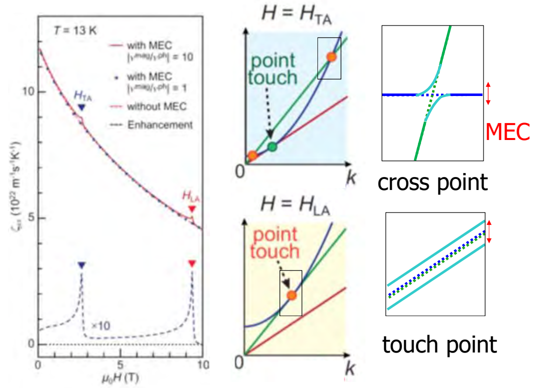
$$\partial_t f_{i\mathbf{k}} + \nabla_{\mathbf{r}} f_{i\mathbf{k}} \cdot \nabla_{\mathbf{k}} \Omega_{i\mathbf{k}} = -(f_{i\mathbf{k}} - f_{i\mathbf{k}}^{(0)})/\tau_{i\mathbf{k}}$$

Magnon-polaron occupation

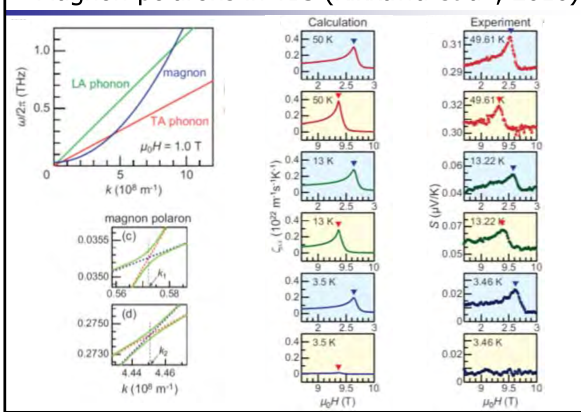
Planck distributions



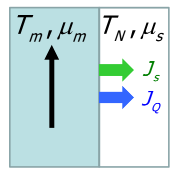
Cross versus touch (Kikkawa et al. 2016)



Magnon-polarons in YIG (Kikkawa et al., 2016)



Interface response matrix



spin conductance

spin Seebeck effect

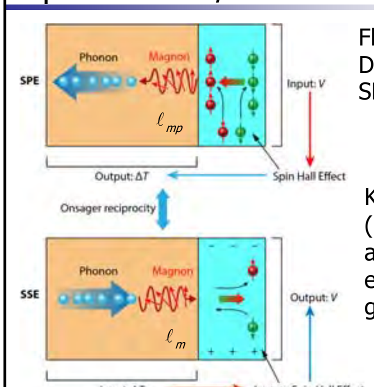
$$\begin{pmatrix} J_s \\ J_Q \end{pmatrix} = \begin{pmatrix} L_{ss} & L_{sQ} \\ L_{Qs} & L_{QQ} \end{pmatrix} \begin{pmatrix} (\mu_s - \mu_m)/2e \\ (T_m - T_N)/T \end{pmatrix}$$

heat conductance

spin Peltier effect

Xiao *et al.* (2015)
Duine *et al.* (2015)

Spin Seebeck/Peltier diffuse regime



Flipse et al. (2014), Daimon et al. (2016): SPE governed by ℓ_{mp}.

Kehlberger et al. (2015); Boona et al. (2015), Kikkawa et al. (2015) : governed by ℓ_m.

© Heremans & Boona (2014)

RT (Duine et al., 2015; Cornelissen et al., 2016)

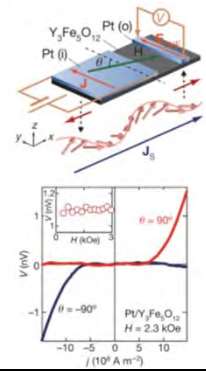
thermal wave length	$\lambda_T = \sqrt{4\pi A/(k_B T)} \approx 1\,\mathrm{nm}$	@RT
thermalization length	$\ell_{mm} \sim T^{-3.5} \approx 1-10\,\mathrm{nm}$	
heat relaxation length	$\ell_{mp} \sim T^{-3} \approx 1-10\,\mathrm{nm}$	
spin relaxation length	$\ell_m \sim 1/\sqrt{\alpha} \approx 1-10\,\mu\mathrm{m}$	

$d_F < \lambda_T$	wave interference	Yan et al. (2016)
$d_F < \ell_{mm}$	non-interacting magnons	
$\lambda_T < d_F$	Boltzmann equation	
$\ell_{mm}, \lambda_T < d_F$	diffusion equation	
$\lambda_T, \ell_{mm} < d_F < \ell_{mp}, \ell_m$	constant distribution	Cornelissen et al. (2016)
$\ell_{mp}, \ell_m < d_F$	diffuse bulk transport	

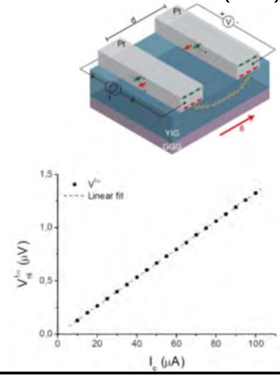
Electrical magnon injection

Self-oscillation vs. magnon injection

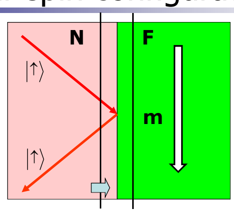
Kajiwara et al. (2010)



Cornelissen et al. (2015)

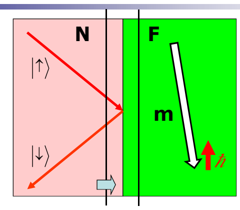


Collinear spin configuration



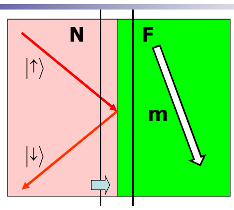
$I_s^N = 0 \quad I_s^F = 0$

Spin current conversion

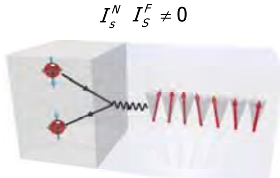


$I_s^N \quad I_s^F \neq 0$

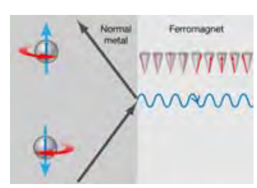
Spin current conversion



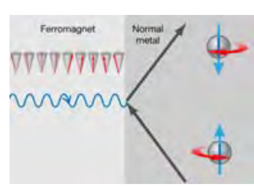
$I_s^N \quad I_s^F \neq 0$



Small angle spin transfer

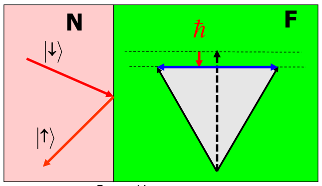


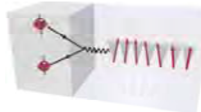
magnon injection



magnon detection

Magnon injection





$$I_s^F = I_s^N$$

$$I_s^N = \frac{\hbar}{2e} G_s \left[\left(V_\uparrow - V_\downarrow \right) - \frac{\mu_m}{e} \right]$$

spin current not absorbed but conserved at interface

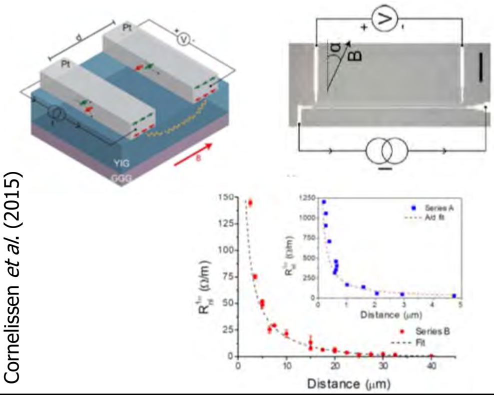
$G_s \sim TG^{\uparrow\downarrow}$ spin conductance

$\approx 0.1\, g^{\uparrow\downarrow}$ YIG at RT

Xiao *et al.* (2015)
Duine *et al.* (2015)

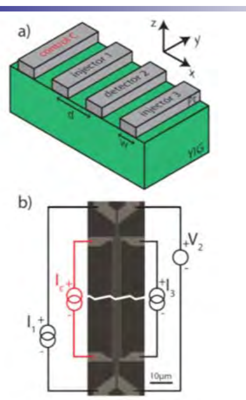
Long distance magnon transport

Cornelissen *et al.* (2015)

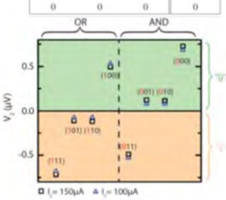


Magnon based logic in a multi-terminal YIG|Pt nanostructure

Ganzhorn *et al.* (2016)



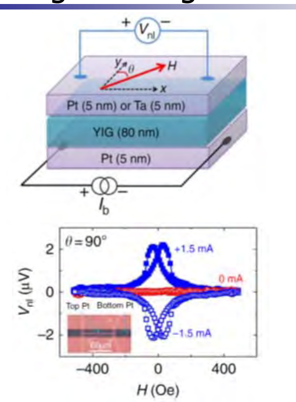
Control C	Injector 1	Injector 3	Detector 2
1	1	1	1
1	0	1	1
1	1	0	1
1	0	0	0
0	1	1	1
0	0	1	0
0	1	0	0
0	0	0	0



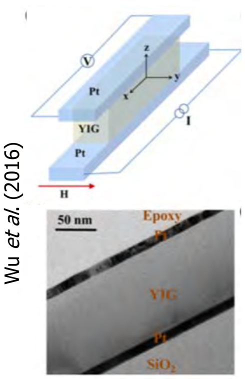
4-strip majority gate
Input: (I_c, I_1, I_3)
Output: V_2

"Magnon drag"

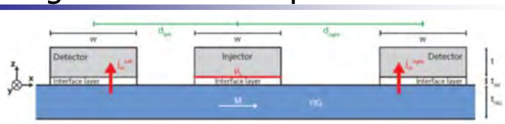
Li *et al.* (2016)



Wu *et al.* (2016)



Magnon diffusion equations



Cornelissen *et al.* (2016)

$$\begin{pmatrix} j_s^{\mathrm{int}} \\ j_Q^{\mathrm{int}} \end{pmatrix} = \frac{3\hbar g^{\uparrow\downarrow}}{4e^2 \pi s \Lambda^3} \begin{pmatrix} e\,\zeta(3/2) & \frac{5}{2} k_B \zeta(5/2) \\ \frac{5}{2}\frac{e k_B T}{\hbar}\zeta(5/2) & \frac{35}{4}\frac{k_B^2 T}{\hbar}\zeta(7/2) \end{pmatrix} \begin{pmatrix} \mu_z - \mu_m \\ T_e - T_m \end{pmatrix}$$

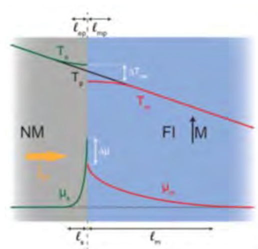
$$\begin{pmatrix} e & \alpha_p k_B \\ e\alpha_T / k_B & 1 \end{pmatrix} \begin{pmatrix} \nabla^2 \mu_m \\ \nabla^2 T_m \end{pmatrix} =$$

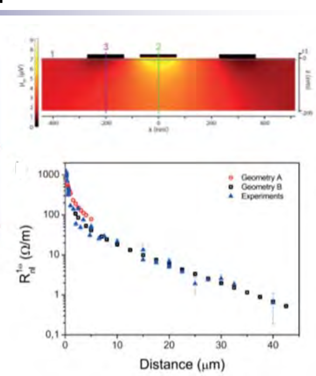
$$\begin{pmatrix} e/\ell_m^2 & k_B / (\ell_{\mu T} T^2) \\ e/(k_B \ell_{Q\mu} \mu_m^2) & 1/\ell_{mp}^2 \end{pmatrix} \begin{pmatrix} \mu_m \\ T_m - T_p \end{pmatrix}$$

at **room** temperature

since $\ell_m \gg \ell_{mp}$

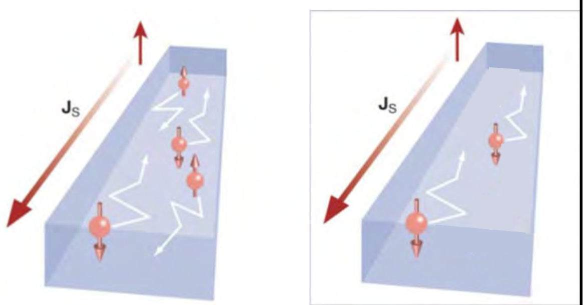
Magnon diffusion



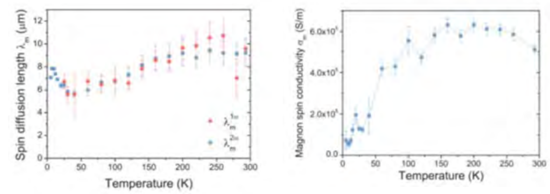


Cornelissen *et al.* (2016)

How to interpret magnon spin currents?



Low temperature



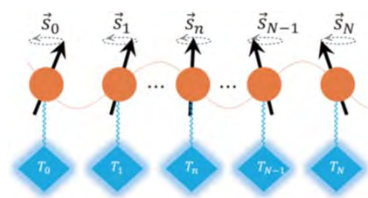
Cornelissen & van Wees (2016)

However: $\ell_{mm} \sim T^{-3.5}$, $\ell_{mp} \sim T^{-3}$

Magnons become non-interacting and ballistic at (not so) low T …

Ballistic (but not quantum) magnons

Atomistic spin model (P. Yan, 2016)



Heisenberg spin model

lattice temperature profile

$$\frac{d\vec{s}_n}{dt} = -\vec{s}_n \times \left(\vec{H}_{\text{eff}} + \vec{h}_n\right) + \alpha \vec{s}_n \times \frac{d\vec{s}_n}{dt}$$

stochastic LLG equation

$$\left\langle h_n^i(t)\, h_{n'}^j(t')\right\rangle = 2\alpha k_B T_n \delta_{nn'} \delta_{ij} \delta(t-t')$$

classical FDT

Linearized LLG equation

Fluctuating diffusion equation: (trigonal matrix)

$$(i+\alpha)\frac{d\psi_n}{dt} = -\sum_{m=0}^{N}\left(JQ_{nm} + H\delta_{nm}\right)\psi_m + h_n(t)$$

$$\phi_k = \sum_{n=0}^{N} P_{kn}^{-1}\psi_n$$

P_{kn} amplitude of free magnon k at site n.

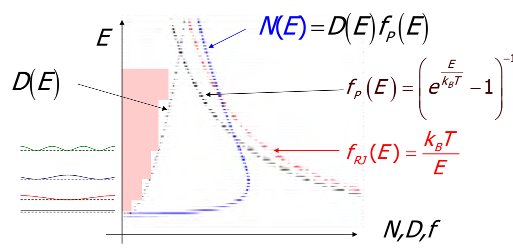
$$(i+\alpha)\frac{d\phi_k}{dt} + \omega_k \phi_k = \eta_k(t)$$

$$\left\langle \eta_k^*(t)\,\eta_{k'}(t')\right\rangle = 4\alpha k_B \mathcal{T}_{kk'}\delta(t-t')$$

$$\mathcal{T}_{kk'} = \sum_{n=0} P_{nk} P_{nk'} T_n$$

temperature matrix

Equilibrium magnon distribution



magnon density: $\rho_{M,n} = \sum_k \left|P_{k,n}\right|^2 \frac{k_B T}{\hbar\omega_k}$

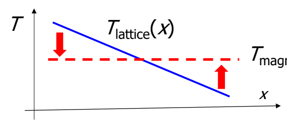
$\langle \varepsilon_k \rangle = k_B T$

Non-equilibrium steady state

$\rho_{M,n} = \frac{1}{2}\langle \psi_n \psi_n^* \rangle$ magnon density at site n

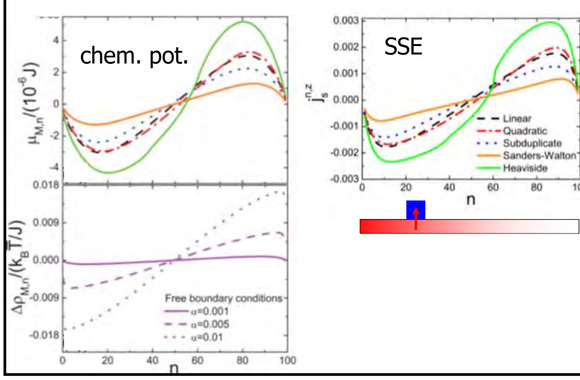
$$= 2\sum_{kk'} P_{nk}P_{nk'}k_B \mathcal{T}_{kk'} \frac{\alpha^2(\omega_k+\omega_{k'})}{\alpha^2(\omega_k+\omega_{k'})^2+(\omega_k-\omega_{k'})^2}$$

$\mathcal{T}_{kk} = \bar{T}$ magnon temperature constant to leading order in α for antisymmetric (linear) T_n.



$$\rho_{M,n} \equiv \sum_k (P_{nk})^2 k_B \mathcal{T}_{kk}/(\omega_k - \mu_{M,n})$$

Transverse SSE and chemical potential



Take-home messages

① Ferromagnets ≠ ferrimagnets at temperatures possibly much below T_{curie}
② Magnons can be strongly coupled to phonons and photons.
③ Phonons can be important for magnon transport.
④ The magnon chemical potential describes the spin accumulation in magnetic insulators not only in the diffuse regime.

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