Spin Mechanics of Ferromagnets

Gerrit E.W. Bauer

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1. Spin Mechanics
   a) Einstein-de Haas & Barnett effect
   b) Magnetoelastic coupling
2. Spin mechanics of magnetic nanoparticles
3. Spin mechanics in optics
4. Spin mechanics in transport

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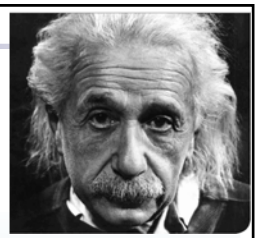

1. Spin Mechanics
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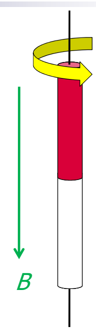
4. Spin mechanics in optics
5. Spin mechanics in transport

Einstein's only experiment

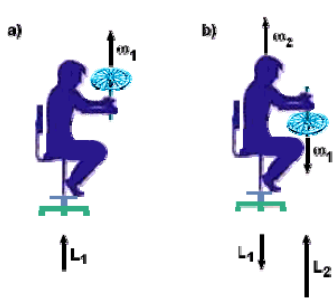
http://www.ptb.de/

Einstein-de Haas effect (1916)

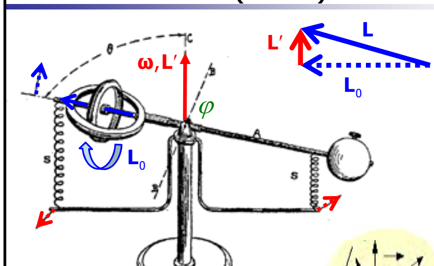


$\mathbf{M} = \gamma \mathbf{L}$

Mechanics of Einstein-de Haas effect

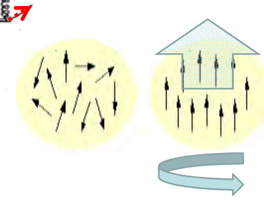


Barnett effect (1915)

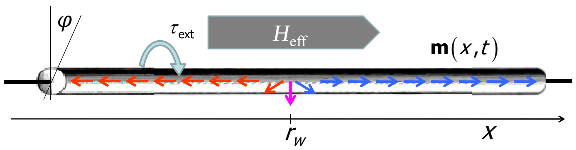


$$\mathbf{H}_{Barnett} = -\frac{\boldsymbol{\omega}}{\gamma}$$

$$|\boldsymbol{\omega}| = \dot{\varphi}$$



Freely suspended magnetic wire



Landau-Lifshitz-Gilbert & Newton equations:

$$\dot{\mathbf{m}} = -\gamma \mathbf{m} \times \left(\mathbf{H}_{eff} - \frac{\dot{\varphi}}{\gamma} \mathbf{e}_x \right) + \alpha \mathbf{m} \times \dot{\mathbf{m}}$$

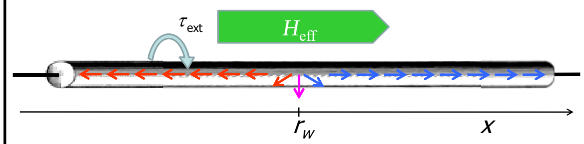
$$I \ddot{\varphi} + \beta_{mech} \dot{\varphi} = \tau_{ext} + \tau_{mag}(\dot{\mathbf{m}})$$

$\mathbf{H}_{eff}$ external and internal magnetic fields

α magnetic friction

β_{mech} mechanical friction

Collective coordinate approximation



	spin	mass
force	$-2AM_sH_{eff}$	τ_{ext}
response	$v_w = \partial r_w / \partial t$	$\omega = \partial \varphi / \partial t$

A wire cross section

M_s magnetization

$$\begin{pmatrix} \omega \\ v_w \end{pmatrix} = \begin{pmatrix} L_{\omega\omega} & L_{\omega W} \\ L_{W\omega} & L_{WW} \end{pmatrix} \begin{pmatrix} \tau_{ext} \\ -2AM_sH_{ext} \end{pmatrix}$$

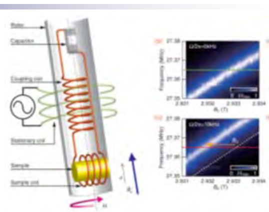
Onsager:

$$L_{\omega W} = -L_{W\omega}$$

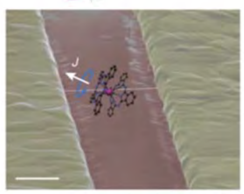
$EdH = Barnett$

Recent experiments

Chudo et al. (2014): Barnett-field detection by NMR of rapidly rotating samples.



Ganzhorn et al. (2016): Einstein-de Haas effect suppresses quantum tunneling of spin in molecular magnets (cf. theory by Kovalev et al., 2011)



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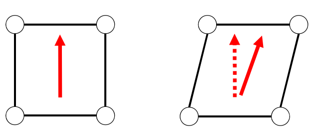
Spin mechanics

Magnetic anisotropy couples magnetic and lattice order

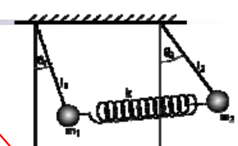


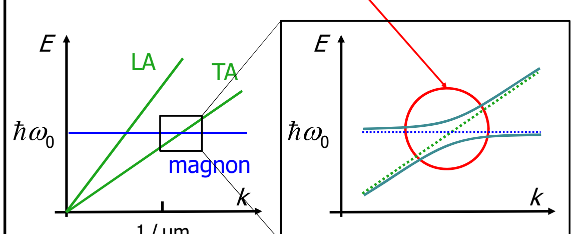
Dynamics

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

Magnon-polaritons

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





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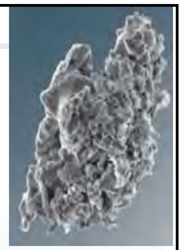


Cf. poster by
Hedyeh Keshtgar and Simon Streib

Magnetomechanics of nanoparticles

Total angular momentum:

$$\mathbf{J} = \mathbf{L} - \frac{\mathbf{M}}{\gamma}$$

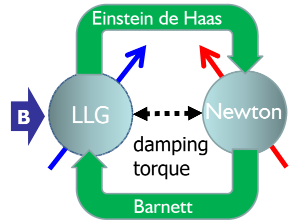
Einstein-de Haas:

$$\frac{d\mathbf{L}}{dt} = \frac{\dot{\mathbf{M}}}{\gamma} + \mathbf{M}\times\mathbf{B}$$

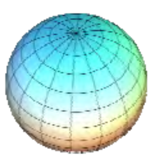
Barnett:

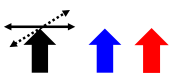
$$\frac{d\mathbf{M}}{dt} = -\gamma\mathbf{M}\times\mathbf{B} + \frac{\alpha}{M_s}\mathbf{M}\times\left(\frac{d\mathbf{M}}{dt} + \mathbf{M}\times\boldsymbol{\omega}\right)$$

instantaneous rotation axis in lab frame



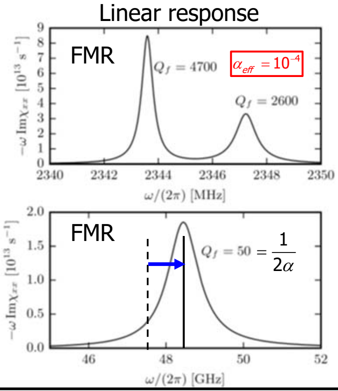
Fe sphere with cubic anisotropy



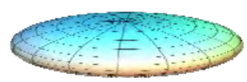


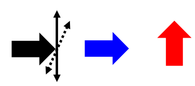
d = 2 nm
α = 0.01

Linear response



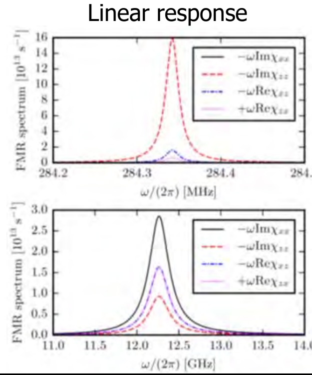
Fe disk





D = 15 nm, d = 2 nm
α = 0.01

Linear response



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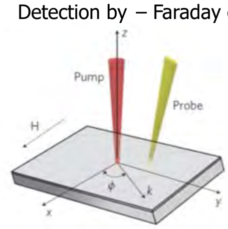
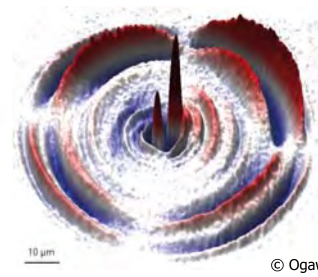
Pump & probe spectrosocpy

Femto-second optical excitation

Excitation by – Inverse Faraday effect
– Heat

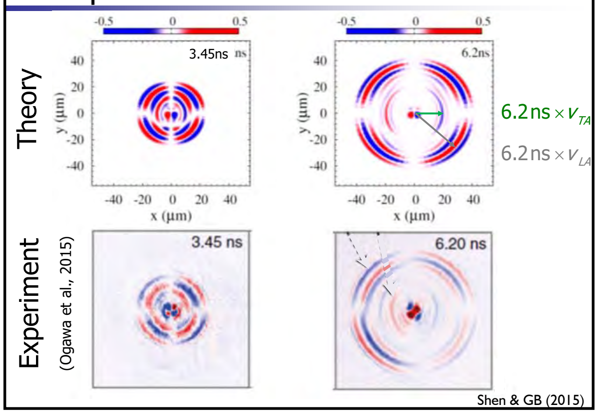
Detection by – Faraday or Kerr rotation





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

Snapshots



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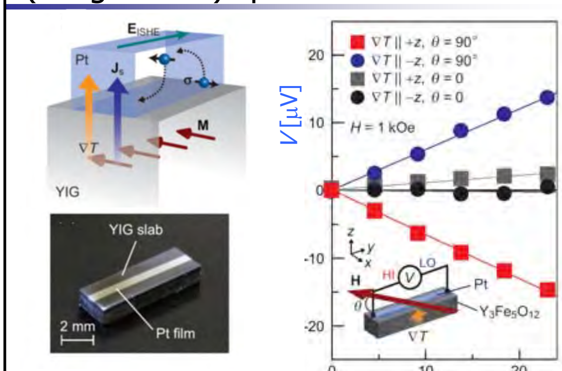
(Longitudinal) spin Seebeck effect

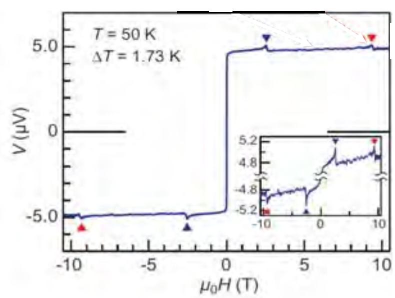


Uchida *et al.* (2010/2011)

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

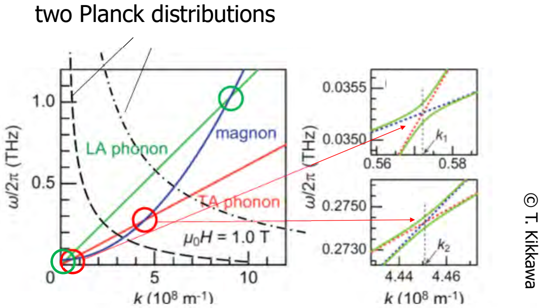
T. Kikkawa & E. Saitoh: experiments

B. Flebus & K. Shen: Boltzmann theory



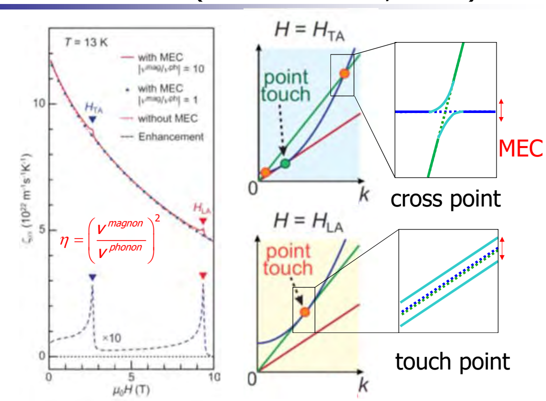
Magnon-polaron occupation

two Planck distributions

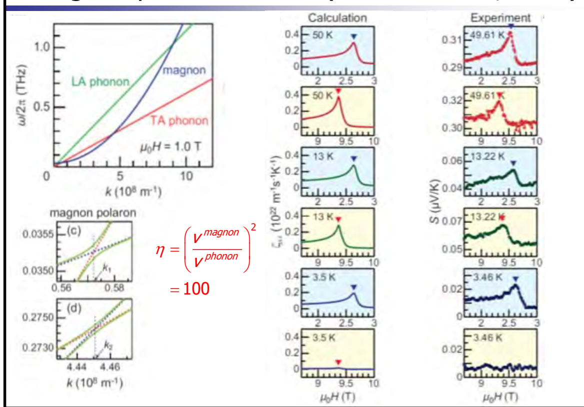


$$\partial_t f_{\mathbf{ik}} + \nabla_{\mathbf{r}} f_{\mathbf{ik}} \cdot \nabla_{\mathbf{k}} \Omega_{\mathbf{ik}} = -(f_{\mathbf{ik}} - f^{(0)}_{\mathbf{ik}})/\tau_{\mathbf{ik}}$$

Cross vs. touch (Kikkawa et al., 2016)



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



Take-home messages

① The FMR of magnetic nanoparticles show should have very sharp low frequency satellites.
② Spin transport in YIG induced by focused lasers is dominated by phonons.
③ The magnon-polaron anomaly in the spin Seebeck effect indicates better mechanical than magnetic quality of YIG films.

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