Spin Caloritronics

Thermoelectrics Meets Spintronics

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Collaborators:

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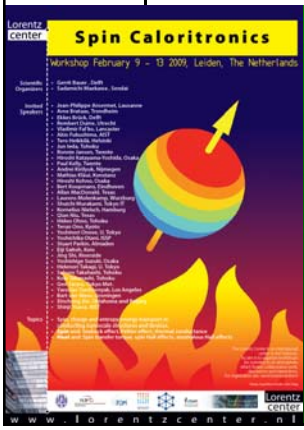
Sadamichi Maekawa 前川禎通 cum suis, Eiji Saitoh 齊藤英治 cum suis (Tohoku)

Workshops



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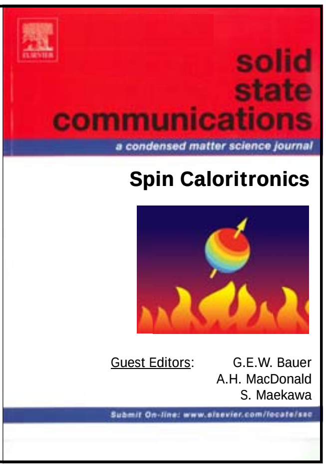
Potential contributors who wish to help defining the field are requested to contact the Editors.

Deadline for manuscripts: **October 1, 2009**

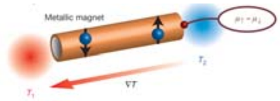


Motivation for Spin Caloritronics Research

- Save the Planet

- Get rich

- Do interesting physics



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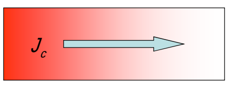
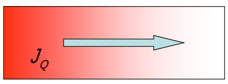
- Basics of (mesoscopic) thermoelectrics
- Experiments in spin caloritronics
- Spin caloritronic circuit theory
- Spin caloritonics in spin valves
- Spin-Seebeck effect
- Generalized Onsager reciprocity relations for magnetic domain walls

M. Hatami *et al.*, PRL **99**, 066603 (2007); PRB **79**, 174426 (2009).
J. Xiao (萧江) *et al.*, PRB **79**, 174415 (2009).
Y. Tserkovnyak *et al.*, Rev. Mod. Phys. **77**, 1375 (2005); A. Brataas *et al.*, Phys. Rep. **427**, 157 (2006), G.E.W. Bauer et al., Ch. 2 in Handbook of Magnetic Materials, Vol. 17, (2008); Y. Tserkovnyak *et al.*, JMMM **320**, 1282 (2008).

Metals

V_1  V_2

$$G = \left(\frac{J_c}{\Delta V}\right)_{\Delta T=0}$$

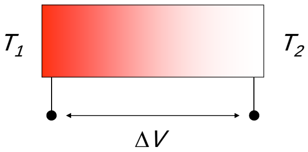
T_1  T_2

$$\kappa = -\left(\frac{J_Q}{\Delta T}\right)_{J_c=0}$$

Wiedemann-Franz Law: $\lim_{T\to 0}\frac{\kappa}{G} = L_0 T$

Lorenz number: $L_0 = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2$

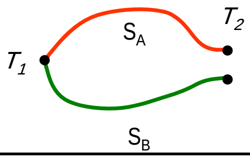
Thermoelectric power



$$S = \left(\frac{\Delta V}{\Delta T}\right)_{J_c=0}$$

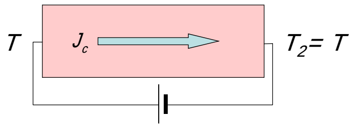
Seebeck coefficient

Thermocouple:



$$\Delta V = (S_B - S_A)\Delta T$$

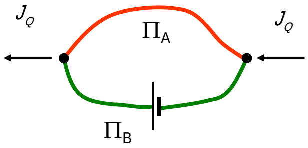
Peltier effect



$$\Pi = \left(\frac{J_Q}{J_c}\right)_{\Delta T=0}$$

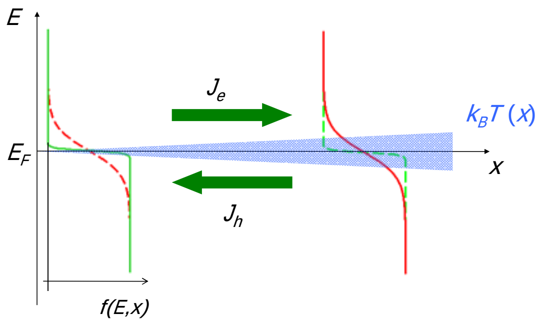
Peltier coefficient

Thermoelectric heat pump:

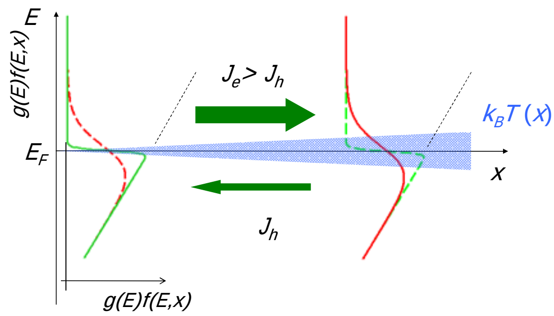


$$\Pi_{AB} = \Pi_A - \Pi_B$$

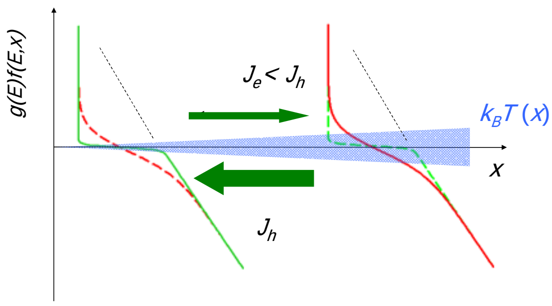
Heat transport in metals



Heat and charge transport (electron like)



Heat and charge transport (hole like)



Onsager reciprocity relations (de Groot)

X_i generalized forces

J_i generalized currents

$J_i = \sum_j L_{ij} X_j$ linear response

$L_{ij}(\mathbf{m}, \mathbf{H}_{ext}) = \varepsilon_i \varepsilon_j L_{ji}(-\mathbf{m}, -\mathbf{H}_{ext})$ Onsager relations

$\dot{S} = \sum_i X_i J_i$ entropy creation rate

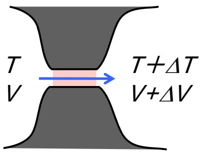
The Nobel Prize in Chemistry 1968:
"for the discovery of the reciprocal relations bearing his name, which are fundamental for the thermodynamics of irreversible processes"

Thermoelectrics

1st Law of thermodynamics:

$$dS = -\frac{\Delta V}{T}dq - \frac{dU}{T} + \frac{dU}{T+\Delta T}$$

$$\dot S = -\dot q\frac{\Delta V}{T} - \dot U\frac{\Delta T}{T^2}$$



$$\begin{pmatrix}\dot q\\ \dot U\end{pmatrix} = \begin{pmatrix}J_c\\ J_Q\end{pmatrix} = -\frac{1}{T}\begin{pmatrix}L_{11} & L_{21}\\ L_{12} & L_{22}\end{pmatrix}\begin{pmatrix}\Delta V\\ \frac{\Delta T}{T}\end{pmatrix}; \quad L_{12} = L_{21}$$

$$\begin{pmatrix}-\Delta V\\ J_Q\end{pmatrix} = \begin{pmatrix}R & S\\ \Pi & \kappa\end{pmatrix}\begin{pmatrix}J_c\\ -\Delta T\end{pmatrix}$$

$R = 1/G$	electrical resistance
κ	thermal conductance
S	Seebeck coefficient
$\Pi = ST$	Peltier coefficient

Landauer-Büttiker formalism (Butcher, 1990)

$$G = -\frac{2e^2}{h}\int dE\,\frac{\partial f}{\partial E}g(E)$$

$$g(E) = \sum_{nm}^{\varepsilon_n,\varepsilon_m=E}|t_{nm}|^2$$

$$GS = \frac{2e^2}{h}\frac{k_B}{e}\int dE\,\frac{\partial f}{\partial E}g(E)\frac{E-E_F}{k_BT}$$

$$\frac{\kappa}{T} = S^2G + \frac{2e^2}{h}\left(\frac{k_B}{e}\right)^2\int dE\,\frac{\partial f}{\partial E}g(E)\left(\frac{E-E_F}{k_BT}\right)^2$$

Sommerfeld expansion:

$$G = \frac{2e^2}{h}g(E_F)$$

$$S = -L_0eT\left.\frac{\partial \log g(E)}{\partial E}\right|_{E_F}$$

$$\frac{\kappa}{T} = (S^2 + L_0T)G$$

Experiments:
Molenkamp *et al.* (1993)

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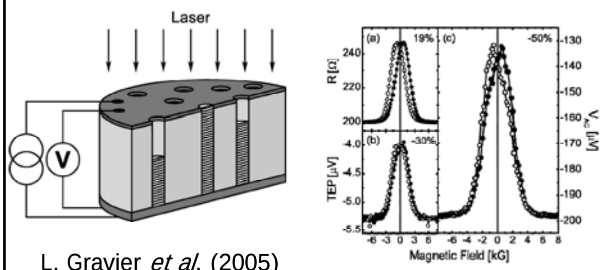
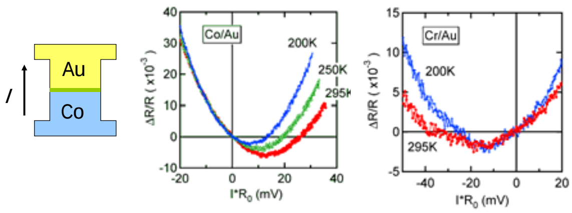
Magneto-thermoelectric voltage in MML



L. Gravier *et al.* (2005)

M. Johnson and R.H. Silsbee (1987);
J.P. Wegrowe (2000)

Metallic nanopillars (Fukushima *et al.*, 2005)



$$\Delta R \sim \Delta T \sim W = RI_c^2 - \Pi I_c$$

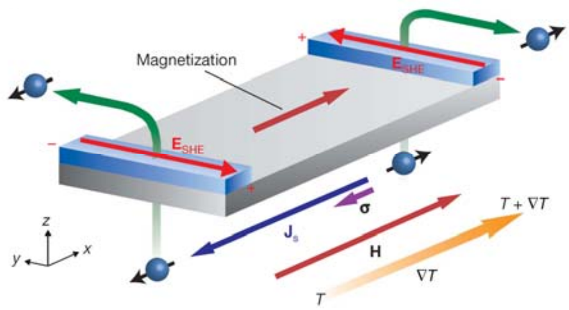
$$\Delta R(I_{c,p}) = 0$$

$$\Pi = RI_{c,p}$$

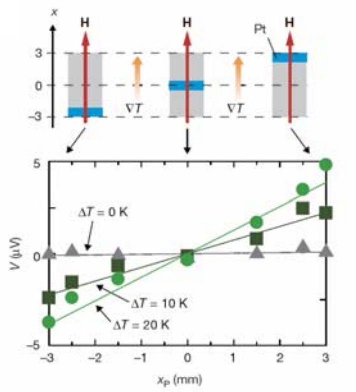
+ Gravier *et al.* (2006)

CPP-A/B	Π_{bulk} (mV)	Π_{MJ}(mV)
Co/Au	9.8	31 ±5
Cr/Au	-6.0	-28 ±8
Co/Cr	15.8	41 ±5
Cr/Cr	0	~0

Spin Seebeck effect [Uchida *et al.* (2008)]



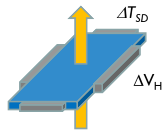
Spin-Seebeck effect [Uchida et al. (2008)]

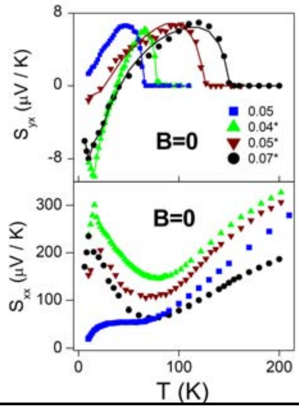


Anomalous Nernst effect [Pu *et al.* (2008)]

$GaMn_xAs_{1-x}$

perp. magnetization





Seki *et al.* (2008):
ANE in FePt

Our interest and strategy

Search for: New spin-related (static and dynamic) thermoelectric effects in magnetic metallic nanostructures.

Approximation: (spin)-diffusion equation in bulk layers, quantum mechanical treatment of interfaces, adiabatic magnetization dynamics.

Implementation: extension of magnetoelectronic circuit and spin diffusion theory (Brataas *et al.*, 2000, 2006).

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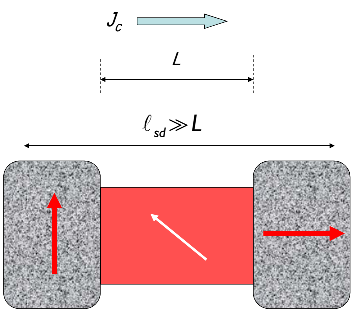
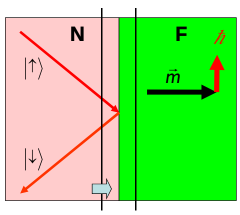
Non-collinear F|N|F spin valves



Slonczewski's spin-transfer torque



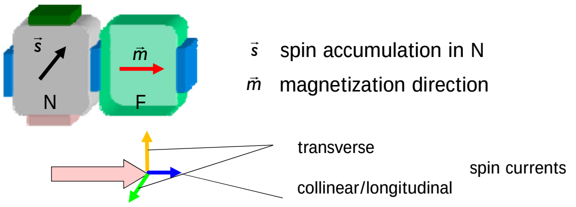
$J_S^N \quad J_S^F = 0$

Absorbed spin current = magnetization torque

$$\vec{L} = \vec{J}_S^N = \frac{g^{\uparrow\downarrow}}{4\pi}\left(\mu_N^{\uparrow} - \mu_N^{\downarrow}\right)$$

$g^{\uparrow\downarrow}$ spin-mixing conductance

Spin-currents and conductances



$$g_s = \sum_{nm} \left|t^s_{nm}\right|^2 = N - \sum_{nm} \left|r^s_{nm}\right|^2$$

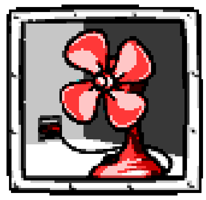
$s=\uparrow,\downarrow$ spin-dependent Landauer conductances for charge and collinear spin current

$$g_{\uparrow\downarrow} = N - \sum_{nm} r^{\uparrow}_{nm}\left(r^{\downarrow}_{nm}\right)^*$$

complex spin-mixing conductance for transverse spin current (torque + exchange field)

Onsager relations for magnetization dynamics

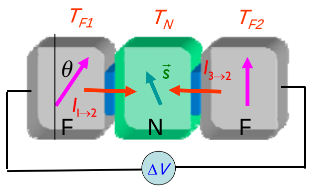
Spin currents cause magnetization motion (spin transfer torque).



Magnetization motion causes spin currents (spin pumping).

$$\vec{I}^{F\to N}_{pump} = \frac{\hbar}{4\pi} g_{\uparrow\downarrow} \vec{m} \times \frac{d\vec{m}}{dt}$$

Extended circuit theory of spin valves



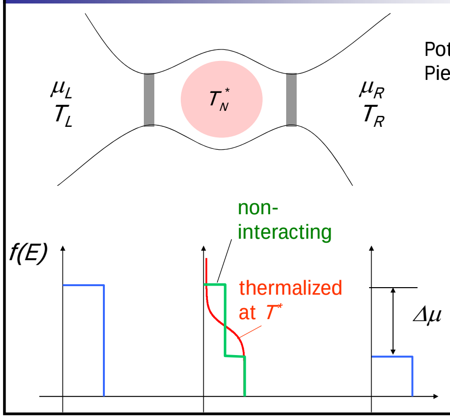
Charge, spin, and heat current conservation:

$$J^c_{3\to2} + J^c_{1\to2} = 0$$
$$\vec{J}^s_{3\to2} + \vec{J}^s_{1\to2} = \vec{s} / \tau_{sf}$$
$$J^E_{3\to2} + J^E_{1\to2} = 0$$

Parameters: $\hat{g}(E_F),\ \frac{\partial}{\partial E}\hat{G}(E)\Big|_{E_F}$

Non-interacting/strongly interacting limit

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



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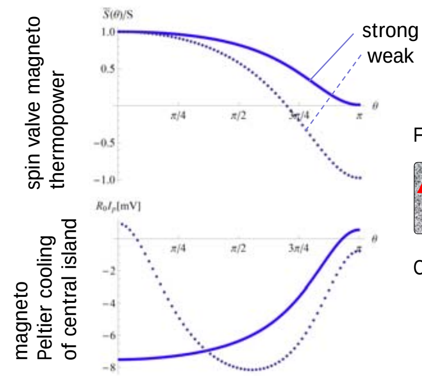
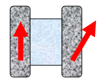
Magneto-Peltier and -Seebeck effects

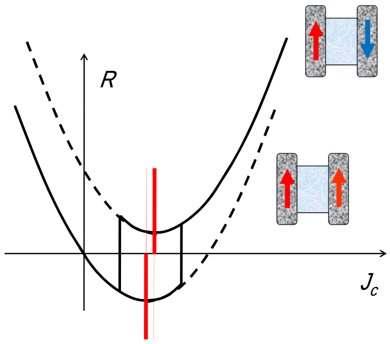


Fe|Cr|Fe



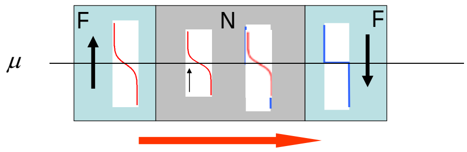
Co|Cr|Fe

Magneto-Peltier effect in spin valves



Heat conductance of halfmetallic spin valve

Antiparallel configuration:



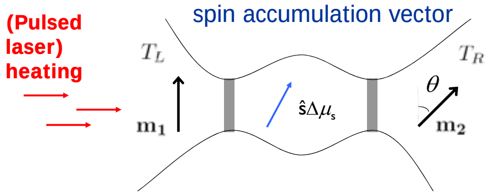
Non-interacting: $\kappa_{F|N|F}(\pi) = L_0 T G_{F|N|F}(\pi) = 0$

Strongly interacting: $\kappa_{F|N|F}(\pi) = L_0 T G/2$

$G_{F|N|F}(\pi) = 0$

Giant violation of Wiedemann-Franz Law !

Thermally induced transfer torque (thermalized regime)



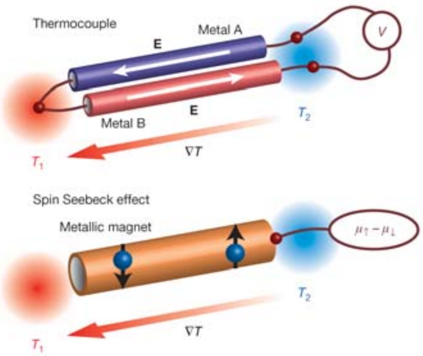
$$\tau_{F|N|F}(\theta) = \frac{G}{2}\frac{\eta\sin\theta}{1-\cos\theta+\eta(1+\cos\theta)}(P\Delta V + P'S\Delta T)$$

$$P'S \sim \frac{\mu V}{K}$$

Slonczewski criterion for thermal spin-transfer induced magnetization reversal: ΔT~100K

Contents

Spin-Seebeck effect [Uchida et al. (2008)]



Extended (Valet-Fert) diffusion theory

Boltzmann equation in relaxation time approximation:

$$v_{\mathbf{k}}^{\alpha}\cdot\frac{\partial}{\partial\mathbf{r}}f^{\alpha}(\mathbf{k},\mathbf{r}) + \frac{\mathbf{F}^{\alpha}}{\hbar}\cdot\frac{\partial}{\partial\mathbf{k}}f_0^{\alpha}(\varepsilon,\mathbf{r}) = -\frac{f^{\alpha}(\mathbf{k},\mathbf{r}) - f_0^{\alpha}(\varepsilon,\mathbf{r})}{\tau^{\alpha}(\varepsilon)} - \frac{f_0^{\alpha}(\varepsilon,\mathbf{r}) - f_0^{-\alpha}(\varepsilon,\mathbf{r})}{\tau_{sf}^{\alpha}(\varepsilon)}$$

Weak spin flip: $f^{\alpha}(\mathbf{k},\mathbf{r}) - f_0^{\alpha}(\varepsilon,\mathbf{r}) = \tau^{\alpha}(\varepsilon)v_{\mathbf{k}}^{\alpha}\cdot\frac{\partial}{\partial\mathbf{r}}f_0^{\alpha}(\varepsilon,\mathbf{r})$

$$\partial_{\mathbf{r}}^2 f_c(\varepsilon,\mathbf{r}) + P(\varepsilon)\partial_{\mathbf{r}}^2 f_s(\varepsilon,\mathbf{r}) = 0 \qquad \partial_{\mathbf{r}}^2 f_s(\varepsilon,\mathbf{r}) = \frac{1}{l_{sf}(\varepsilon)^2}f_s(\varepsilon,\mathbf{r})$$

Sommerfeld approximation:

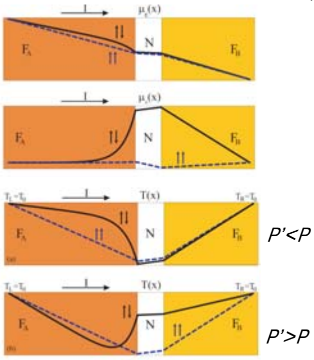
$$\partial_x^2\mu_s = \mu_s/l_{sf}^2(\varepsilon_F)$$

Spin-flip as heat source

$$\mathcal{L}_0\partial_x^2 T + \left((1-P^2)\frac{S^{\uparrow}-S^{\downarrow}}{2e}\right)\partial_x^2\mu_s = 0$$

Diffusion theory

Current-driven distributions for $S_A > S_B$

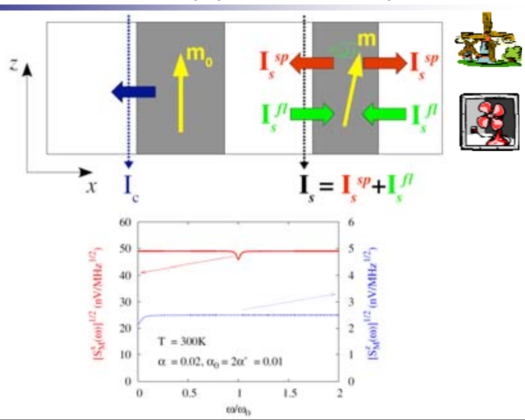


chemical potential

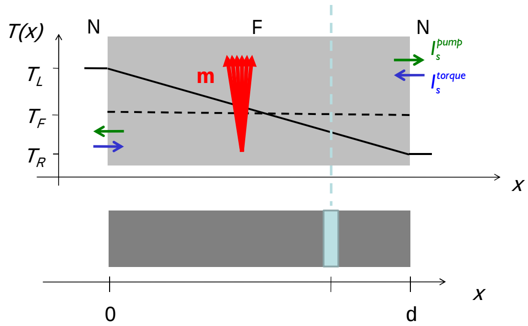
spin accumulation

temperature profile

Magnetic Johnson-Nyquist noise in spin valves



Macro-spin model)



$$\langle I_z \rangle = \frac{2\alpha' k_B}{1+\alpha^2}(T_F^m - T_N) \simeq \frac{\gamma \hbar g_r k_B}{2\pi M_s V}(T_F^m - T_N)$$

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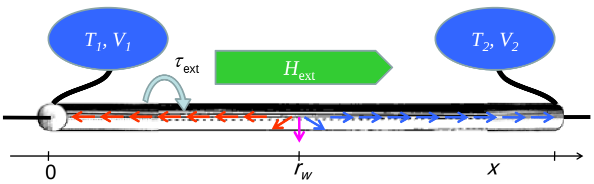
Suspended magnetic wire

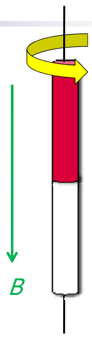


tail-to-tail domain wall centered at r_w

Einstein's only experiment

http://www.ptb.de/

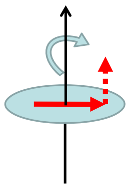
Einstein-de Haas effect (1915)



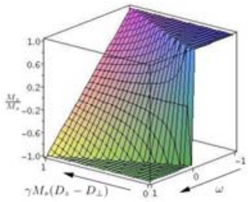
$\vec{M} = \gamma \vec{L}$

Modern developments see: Kovalev *et al.* (2003,2005,2007), Wallis *et al.* (2006), Zolfagharkhani *et al.* (2008).

Barnett effect (1915)

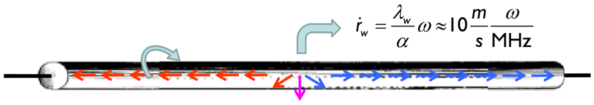


$\vec{B}_{rot} = -\gamma^{-1}\vec{\omega}$

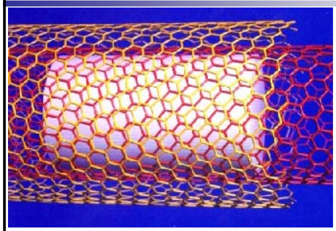


Bretzel *et al.* (unpublished)

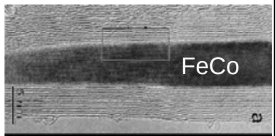
$\dot{r}_w = \frac{\lambda_w}{\alpha}\omega \approx 10\frac{m}{s}\frac{\omega}{MHz}$

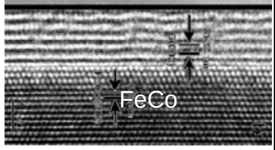


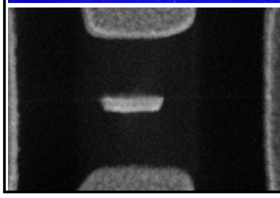
Carbon nanotubes



Elias *et al.* (2005)







Fennimore *et al.* (2003)

Conclusion

Spintronics: Spin degree added to conventional electronics offers new physics and applications.

↓

Spin Caloritronics: Spin degree added to conventional thermoelectrics offers new physics and applications.