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QUASILINEAR SPIN VOLTAGE PROFILES IN SPIN THERMOELECTRICS

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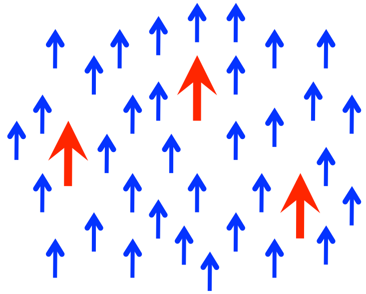
arXiv:1101.3277

Contribution of conduction electrons to Spin Seebeck effect
- ferromagnet with paramagnetic impurities ➔ inelastic spin-flip scattering
- diffusion contribution at low temperatures

Questions:
- quasilinear variation of spin voltage possible?
- relation of spin voltage to spin thermopower?

Model



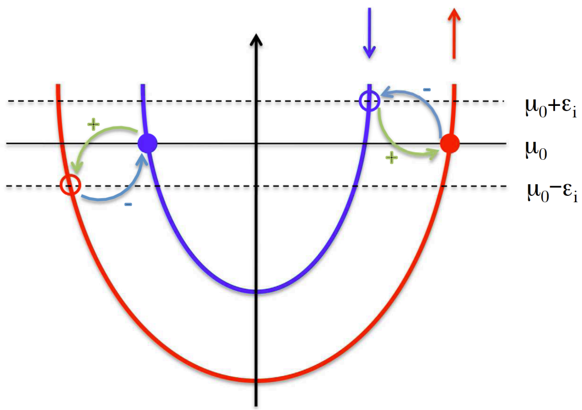
Itinerant ferromagnet: $\varepsilon_{p\sigma} = \varepsilon_p - \sigma h$
with paramagnetic impurities

Exchange interaction
➔ splitting of impurities S_z-levels by energy ε_i

Method: Kinetic equation ➔ derive continuity equations for currents $\mathbf{J}_\sigma$ and $\mathbf{J}_{Q\sigma}$
for weak ferromagnets at low temperatures

Relaxation mechanisms:

- Inelastic spin-flip scattering between electrons and impurity spins (rate Γ_σ^{sf})
  asymmetric for ↑ and ↓ spins at Fermi energy
  (finite $\Gamma_-^{sf} = N_\uparrow \Gamma_\uparrow^{sf} - N_\downarrow \Gamma_\downarrow^{sf}$)



- Direct spin relaxation of electrons (rate Γ_σ^{dir})
  (e.g. spin-orbit interaction)

- Direct spin relaxation of impurities (rate Γ_i^{dir})
  (e.g. spin-orbit interaction + phonons)

Spin-electric effects ($\nabla T = 0$)

For linear spin voltage μ_- need:

- Conservation law
- Chemical potential μ_+ as sink/source on right hand side

Continuity equations:

$$\nabla \cdot \mathbf{J} = -\frac{\sigma_+}{e^2}\nabla^2\mu_+ - \frac{\sigma_-}{e^2}\nabla^2\mu_- = 0$$

Conservation law

$$\nabla \cdot \mathbf{J}_{\text{spin}} = -\frac{\sigma_-}{e^2}\nabla^2\mu_+ - \frac{\sigma_+}{e^2}\nabla^2\mu_- = -2\alpha\Gamma_-^{\text{sf}}\mu_+ - 2(\alpha\Gamma_+^{\text{sf}} + \Gamma_+^{\text{dir}})\mu_-$$

direct spin relaxation of impurities

$$\alpha = \frac{\Gamma_i^{\text{dir}}}{\Gamma_i^{\text{sf}} + \Gamma_i^{\text{dir}}}$$

spin asymmetry of inelastic spin-flip scattering

$$\Gamma_-^{\text{sf}} = N_\uparrow\Gamma_\uparrow^{\text{sf}} - N_\downarrow\Gamma_\downarrow^{\text{sf}}$$

Linear charge voltage μ_+ ➔ linear spin voltage μ_-

$$\mu_- \simeq -\mu_+\frac{\alpha\Gamma_-^{\text{sf}}}{\alpha\Gamma_+^{\text{sf}} + \Gamma_+^{\text{dir}}}$$

Spin thermoelectrics – linear μ_-

Need to determine voltages μ_+ and μ_- and temperatures T_+ and T_-

➔ consider continuity equation for currents: **J**, $\mathbf{J}_{spin}$, $\mathbf{J}_Q$, $\mathbf{J}_{Qspin}$

μ_+ and T_+ appear on right hand side of continuity equations due to finite Γ_-^{sf}

➔ decoupling of continuity equations impossible

Linear μ_- when additional conservation law (besides $\nabla \cdot \mathbf{J} = 0$) exists

- no direct spin relaxation for electrons and impurities $\nabla \cdot \mathbf{J}_{\text{spin}} = \nabla \cdot \mathbf{J}_Q = 0$
- no direct spin relaxation for impurities $\nabla \cdot \mathbf{J}_Q = 0$
- no direct spin relaxation for electrons $\nabla \cdot (\epsilon_i \mathbf{J}_{\text{spin}} + 2\mathbf{J}_Q) = 0$

Spin thermoelectrics – quasilinear μ_-

In general: direct spin relaxation exists for both electrons and impurities

➔ currents $\mathbf{J}_{spin}$, $\mathbf{J}_Q$, $\mathbf{J}_{Qspin}$ decay on length scales:

$$\frac{1}{\ell_1^2} = |e|^2 \frac{\Gamma_+^{\rm sf} + \Gamma_+^{\rm dir}}{\sigma_+}, \qquad \frac{1}{\ell_2^2} = \frac{1}{\ell_1^2} \frac{\alpha\Gamma_+^{\rm sf} + \Gamma_+^{\rm dir}}{\Gamma_+^{\rm sf} + \Gamma_+^{\rm dir}},$$

$$\frac{1}{\ell_3^2} = \frac{1}{\ell_1^2} \frac{\alpha\epsilon_i\Gamma_-^{\rm sf}\Gamma_+^{\rm dir}}{2(\Gamma_+^{\rm sf} + \Gamma_+^{\rm dir})(\alpha\Gamma_+^{\rm sf} + \Gamma_+^{\rm dir})} \left(\frac{e}{2\gamma}S_+ - \frac{\Gamma_-^{\rm sf\prime}}{\Gamma_-^{\rm sf}}\right)$$

- ℓ_1 ordinary spin diffusion length
- ℓ_2 of same order than ℓ_1 but diverges for $\Gamma_\sigma^{dir}=\Gamma_i^{dir}=0$
- ℓ_3 generically much longer than ℓ_1 and diverges for $\Gamma_\sigma^{dir}=0$ or for $\Gamma_i^{dir}=0$

$$\frac{\ell_3}{\ell_1} \quad \text{is of order} \quad \begin{cases} \frac{\epsilon_f}{\epsilon_i}\sqrt{\frac{\Gamma_+^{\rm dir}}{\Gamma_+^{\rm sf}}} \gg 1 & \text{for } \Gamma_+^{\rm dir} \gg \Gamma_+^{\rm sf} \\ \frac{\epsilon_f}{\epsilon_i}\sqrt{\frac{\Gamma_+^{\rm sf}}{\Gamma_+^{\rm dir}}} \gg 1 & \text{for } \Gamma_+^{\rm sf} \gg \Gamma_+^{\rm dir} \end{cases}$$

Spin voltage

Ferromagnet with constant temperature gradient:

T_0-ΔT  T_0+ΔT

No direct spin relaxation: $$\mu_- = -e\left(S_- T_+ + S_+ T_-\right)$$

➔ conventional expression

General case: direct spin relaxation exists for both electrons and impurities

$$\mu_- = \alpha \frac{\frac{e}{2} S_+ \Gamma_-^{\mathrm{sf}} - \gamma \Gamma_-^{\mathrm{sf}\prime}}{\alpha \Gamma_+^{\mathrm{sf}} + \Gamma_+^{\mathrm{dir}}} T_+ - \gamma \frac{\alpha \Gamma_+^{\mathrm{sf}\prime} + \Gamma_+^{\mathrm{dir}\prime}}{\alpha \Gamma_+^{\mathrm{sf}} + \Gamma_+^{\mathrm{dir}}} T_-$$

➔ spin thermopower S_- does not contribute

Outlook

Quasilinear contribution of conduction electrons to spin Seebeck effect in ferromagnets with paramagnetic impurities due to asymmetry of inelastic spin-flip scattering

So far: diffusion contribution to spin voltage at low temperatures

Future goal: extend theory to higher temperatures

➔ need to consider:

- Electron-electron interactions
- Scattering off phonons (phonon drag)
- Scattering off magnons (magnon drag)