Spin motive force in the presence of spin-orbit interaction

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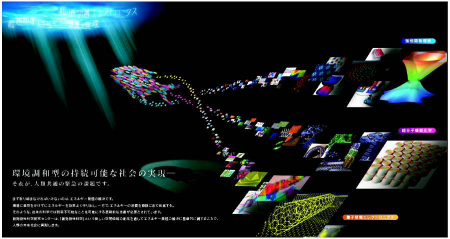

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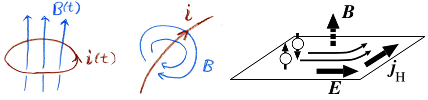
Electromagnetism for charge and spin

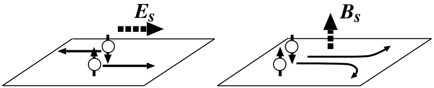
- Electromagnetism

$$\nabla \times E + \dot{B} = 0$$
$$\nabla \times B = \mu j + \epsilon\mu \dot{E}$$
$$j_{\mathrm{Hall}} = \sigma_{\mathrm{H}}(E \times B)$$



- Spin electromagnetism   Ferromagnetic metals   *Volovik'87*
  - Drives conduction electron spin
  - sd exchange interaction

$$\nabla \times E_{\mathrm{s}} + \dot{B}_{\mathrm{s}} = 0$$
$$\nabla \times B_{\mathrm{s}} = \mu_{\mathrm{s}} j + \epsilon_{\mathrm{s}}\mu_{\mathrm{s}} \dot{E}_{\mathrm{s}}$$
$$j_{\mathrm{Hall}} = \sigma_{\mathrm{SH}}(E \times B_{\mathrm{s}})$$



- E_{s} : Spin motive force, B_{s} : Spin Berry's phase

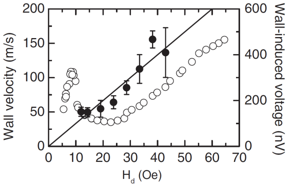
Berger'86,Stern'92,Barnes&Maekawa'07

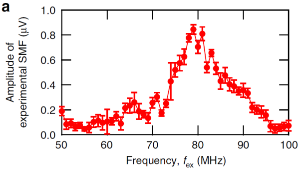
- Real field   Detectable by electric measurements

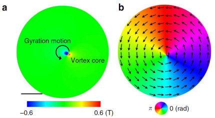
$j_{\mathrm{s}} = Pj$ in ferromagnetic metals $P \sim O(1)$

Spin electromagnetic field

- E_s from motion of domain wall, vortex $V \sim \mu\mathrm{V} \propto E_\mathrm{s} \propto v_\mathrm{dw}$



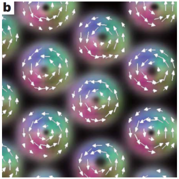


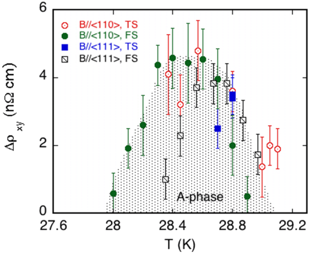


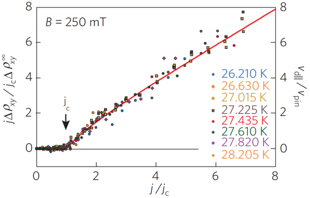
Domain wall *Yang'09*

Vortex *Tanabe'12*

- Skyrmion lattice $\rho_{xy} \sim 4\mathrm{n\Omega cm} \propto B_\mathrm{s}$







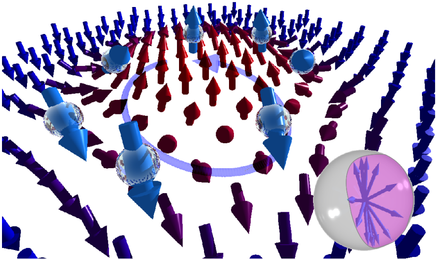
Topological Hall effect B_s

Voltage , $E_\mathrm{s} \propto v_\mathrm{skym}$

Yu'10 *Neubauer'09* *Schulz'12*

Spin electromagnetic field

Volovik'87, Stern'92, Barnes&Maekawa'07



Adiabatic limit

- Electron spin rotation

$\Rightarrow$ Phase $e^{i\varphi}$

$$\varphi = \int_C d\boldsymbol{r} \cdot \boldsymbol{A}_{\mathrm{s}}$$

$$\boldsymbol{A}_{\mathrm{s}} = \frac{1}{2}(1 - \cos\theta)\partial\phi$$

- Spin magnetic field

$$\varphi = \int_S d\boldsymbol{S} \cdot \boldsymbol{B}_{\mathrm{s}}$$

- Spin electric field (dynamics)

$$\dot{\varphi} = -\int_C d\boldsymbol{r} \cdot \boldsymbol{E}_{\mathrm{s}}$$

- Faraday's law is satisfied

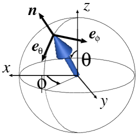
$$\nabla \times \boldsymbol{E}_{\mathrm{s}} = -\frac{\partial \boldsymbol{B}_{\mathrm{s}}}{\partial t}$$

Electromagnetic field coupled to spin

Topological spin electromagnetic field (Adiabatic limit)

- Effective U(1) gauge field   Adiabatic limit

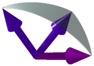
$$A^z_{\mathbf{s},\mu} = \frac{1}{2}(1 - \cos\theta)\partial_\mu \phi$$



- Spin electromagnetic fields

$$E_{\mathbf{s},i} = -\nabla_i A^z_{\mathbf{s},0} + \partial_t A^z_{\mathbf{s},i} = -\frac{1}{2}\boldsymbol{n}\cdot(\dot{\boldsymbol{n}} \times \nabla_i \boldsymbol{n})$$

$$B_{\mathbf{s},i} = (\nabla \times A^z_{\mathbf{s}})_i = \frac{1}{4}\sum_{jk}\epsilon_{ijk}\boldsymbol{n}\cdot(\nabla_j \boldsymbol{n} \times \nabla_k \boldsymbol{n})$$



$B_{\mathbf{s}}$: Spin Berry's phase

$E_{\mathbf{s}}$: Spin motive force

$E_{\mathbf{s}}$ and $B_{\mathbf{s}}$ couple spin structure and electron transport

Effects of spin-orbit interaction

- Inverse (and direct) spin Hall effects
  - Spin-orbit $\Rightarrow$ No longer in the adiabatic limit
  - Spin relaxation effects
- Spin relaxation effects on $\boldsymbol{E}_{\mathbf{s}}$
  - Spin relaxation $\boldsymbol{\beta}$ *Duine PRB'08*

$$\boldsymbol{n} \cdot (\dot{\boldsymbol{n}} \times \boldsymbol{\nabla}_i \boldsymbol{n}) \Rightarrow \boldsymbol{\beta} \boldsymbol{n} \cdot (\dot{\boldsymbol{n}} \times (\boldsymbol{n} \times \boldsymbol{\nabla}_i \boldsymbol{n})) = \boldsymbol{\beta} (\dot{\boldsymbol{n}} \boldsymbol{\nabla}_i \boldsymbol{n})$$

  - Onsager relation *Saslow PRB'07, Tserkovnyak PRB'08*
- Rashba effects
  - Weak $\boldsymbol{sd}$ Transport (Diagrams) *Takeuchi&GT J.Phys.Soc.Jpn'12*
  - Strong $\boldsymbol{sd}$ "Chiral derivative" *Kim PRL'12*
  - Strong $\boldsymbol{sd}$ Transport (Diagrams) *GT PRB'13, Nakabayashi&GT'13*

Rashba-induced spin electromagnetic field

- Strong sd coupling Δ_{sd} + Rashba interaction α_R

$$H = \int d^3 r c^\dagger \left[\left(\frac{\hbar^2}{2m} \nabla^2 + \epsilon_F \right) + \Delta_{sd} (n \cdot \sigma) - \frac{i}{2} \alpha_R \cdot \left(\overleftrightarrow{\nabla} \times \sigma \right) \right] c$$

- Diagram calculation

Nakabayashi&GT,arXiv:1308.0152

- Result
  - Electromagnetic field description works

Linear order of α_R

$$\begin{aligned} \nabla \times E_R + \dot{B}_R &= 0 \\ \nabla \times B_R - \epsilon_R \mu_R \dot{E}_R &= \mu_R j \\ j_{Hall} &= \sigma_R (E \times B_R) \end{aligned}$$

$$E_R = -\frac{m}{e\hbar} (\alpha_R \times \dot{n})$$

$$B_R = \frac{m}{e\hbar} [\nabla \times (\alpha_R \times n)]$$

  - Spin vector potential Linear order

$$A_R = -\frac{m}{e\hbar} (\alpha_R \times n)$$

Kim'12, Nakabayashi&GT,arXiv

Total effective electromagnetic field

- Ferromagnetic metals
- Charge + Spin electromagnetic fields

$$\boldsymbol{E}_{\mathbf{eff}} = \boldsymbol{E} + \boldsymbol{E}_{\mathbf{s}}, \qquad \boldsymbol{E}_{\mathbf{s}} = \boldsymbol{E}_{\mathbf{s,top}} + \boldsymbol{E}_{\mathbf{R}}$$

$$\boldsymbol{B}_{\mathbf{eff}} = \boldsymbol{B} + \boldsymbol{B}_{\mathbf{s}}, \qquad \boldsymbol{B}_{\mathbf{s}} = \boldsymbol{B}_{\mathbf{s,top}} + \boldsymbol{B}_{\mathbf{R}}$$

- Ampère's law
  - $\boldsymbol{\nabla} \times (\boldsymbol{B} + \boldsymbol{B}_{\mathbf{s}}) - \dfrac{\partial}{\partial t}(\boldsymbol{\epsilon\mu E} + \boldsymbol{\epsilon}_{\mathbf{s}}\boldsymbol{\mu}_{\mathbf{s}}\boldsymbol{E}_{\mathbf{s}}) = \boldsymbol{\mu j}$

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- Ampère's law

- $\nabla \times (B + B_{\mathbf{s}}) - \frac{\partial}{\partial t}(\epsilon\mu E + \epsilon_{\mathbf{s}}\mu_{\mathbf{s}} E_{\mathbf{s}}) = \mu j$
- $\boxed{\nabla \times B - \epsilon\mu \frac{\partial E}{\partial t} = \mu(j + j^{(\mathbf{SEMF})})}$

$$\begin{aligned} j^{(\mathbf{SEMF})} &\equiv -\frac{1}{\mu}\left(\nabla \times B_{\mathbf{s}} - \epsilon_{\mathbf{s}}\mu_{\mathbf{s}}\frac{\partial E_{\mathbf{s}}}{\partial t}\right) \\ &= -\frac{1}{\mu}(\nabla \times B_{\mathbf{s}}) + \sigma_{\mathbf{s}} E_{\mathbf{s}} \qquad (\omega\tau \ll 1) \end{aligned}$$

Electric current induced by spin electromagnetic field

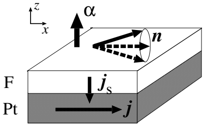
Rashba-induced spin electromagnetic field

- Rashba-induced current

$$j^{(\mathbf{SEMF})} = -\frac{1}{\mu}(\nabla \times B_{\mathbf{R}}) + \sigma_{\mathbf{s}} E_{\mathbf{R}}$$
$$= -\frac{1}{\mu}(\nabla \times (\nabla \times (\alpha_{\mathbf{R}} \times n))) + \frac{m}{e\hbar}\sigma_{\mathbf{s}}(\alpha_{\mathbf{R}} \times \dot{n})$$

- Dynamic part
  - Spin pumping + Inverse spin Hall by Rashba (?)

$$j_x = \alpha_{\mathbf{R}} j^y_{\mathbf{s},z},\ j_{\mathbf{s},z} \propto \dot{n}$$



☐ Present model is not directly applicable
  - Rashba interaction
  - Uniform system (Rashba and sd coexist)

Junction is argued by including electron diffusion

Rashba-induced spin electromagnetic field

- Where is essential spin pumping contribution ?
  - Include spin relaxation

$$\boldsymbol{E}_{\mathbf{R}} = \frac{m}{e\hbar}\left[(\boldsymbol{\alpha}_{\mathbf{R}} \times \dot{\boldsymbol{n}}) + \beta_{\mathbf{R}}[\alpha_{\mathbf{R}} \times (n \times \dot{n})]\right]$$

$\beta_{\mathbf{R}}$ Spin relaxation rate

$$\Downarrow$$

$$\boxed{j^{(\mathbf{SEMF})} = -\frac{m}{\mu e\hbar}\sigma_{\mathbf{s}}\alpha_{\mathbf{R}} \times [\dot{n} + \beta_{\mathbf{R}}(n \times \dot{n})]}$$

- Looks more like Spin pumping + Inverse spin Hall

$$j_{\mathbf{s},z} = g_{\uparrow\downarrow}(n \times \dot{n}) + g'_{\uparrow\downarrow}\dot{n} \qquad g_{\uparrow\downarrow} \simeq \frac{m}{\mu e\hbar}\sigma_{\mathbf{s}}\beta_{\mathbf{R}}$$

  - No undefined quantity

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$$\boldsymbol{E}_{\mathbf{R}} = \frac{m}{e\hbar}\left[(\boldsymbol{\alpha}_{\mathbf{R}} \times \dot{\boldsymbol{n}}) + \beta_{\mathbf{R}}[\boldsymbol{\alpha}_{\mathbf{R}} \times (\boldsymbol{n} \times \dot{\boldsymbol{n}})]\right]$$

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Rashba-induced spin electromagnetic field

- Rashba-induced spin electric field

$$\boldsymbol{E}_{\mathbf{R}} = \frac{m}{e\hbar}\left[(\boldsymbol{\alpha}_{\mathbf{R}} \times \dot{\boldsymbol{n}}) + \beta_{\mathbf{R}}[\boldsymbol{\alpha}_{\mathbf{R}} \times (\boldsymbol{n} \times \dot{\boldsymbol{n}})]\right]$$

$$\Downarrow$$

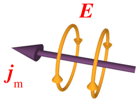
$$\boxed{\nabla \times \boldsymbol{E}_{\mathbf{s}} + \dot{\boldsymbol{B}}_{\mathbf{s}} = \boldsymbol{j}_{\mathbf{m}} \neq 0}$$

- Emergence of spin damping monopole from spin relaxation

Takeuchi, J. Phys.Soc.Japan '12

$$\boldsymbol{j}_{\mathbf{m}} = \beta_{\mathbf{R}} \nabla \times (\boldsymbol{\alpha}_{\mathbf{R}} \times \boldsymbol{N})$$

$\boldsymbol{N} \equiv \boldsymbol{n} \times \dot{\boldsymbol{n}}$: Spin damping vector



- Non-conservation of spin (dissipation) $\Rightarrow$ Monopole (?)
- No topological meaning (?)
- But is physical

$$\boxed{\boldsymbol{n} \times \dot{\boldsymbol{n}}} \Rightarrow \boldsymbol{j}_{\mathbf{m}} \Rightarrow \nabla \times \boldsymbol{E}_{\mathbf{R}} = \boldsymbol{j}_{\mathbf{m}} \Rightarrow \boxed{\boldsymbol{E}}$$

Monopole current converts spin damping to electric voltage

Summary

- Strong sd + Rashba spin-orbit system
- Effective electromagnetic field description
  - Beautiful   Physicists' job is to seek beauty ..?
  - No undefined parameters
  - More works necessary (junction, diffusion)

    Post docs, good students

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    Post docs, good students

RIKEN positions

- Postdoc/researcher positions available in Spin Physics Theory Grou[p]

  gen.tatara@riken.jp

- Positions offered by RIKEN   http://www.riken.jp/en/careers/programs/
  - Postdocs, Graduate school students (PhD candidates)

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