Journal Club

# New Spin Mechanism for Negative Magnetoresistance in Hopping Regime

*PRB 89, 100201(R) 2014*

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# Outline

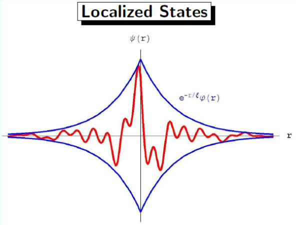
1. Overview of Magnetoresistance (MR) in Hopping Regime
   - ♠ Orbital Mechanism
   - ♠ Spin Mechanism
2. New Spin Mechanism
   - ♠ Qualitative picture
   - ♠ Simple Model

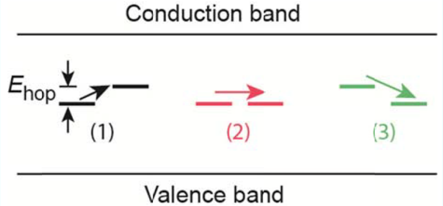
# Overview of Magnetoresistance in Hopping Regime

# Hopping Conduction

## Strongly localized systems at low temperature

The main contribution to electrical conductivity comes from electrons hopping between impurities (tunneling).



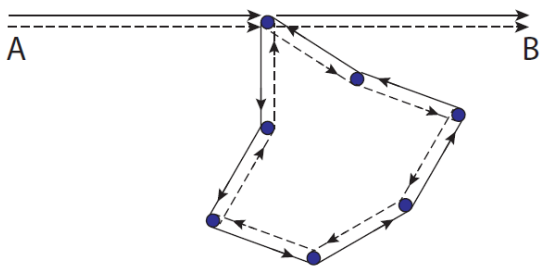

**MR in hopping regime** NOT well understood.

Orbital-related mechanisms

Spin-related mechanisms

# Orbital Mechanism

**Metallic regime**: Negative MR is explained by weak localization theory (back-scattering).

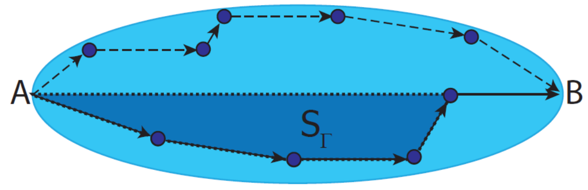



$$\propto \frac{1}{k_F l}$$

# Orbital Mechanism

**Hopping regime**: anomalously large negative MR[1].

$\propto B^{4/5}$



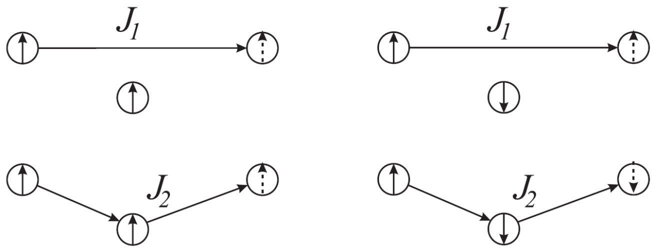

**Characteristics**

- field: $H_0 \sim \Phi_0/S = \hbar c/eS$.
- ANISOTROPY in two dimension.

[1] Ioffe & Spivak, JETP 117, 551 (2013)

## Absence of interference effects for free spins[2]

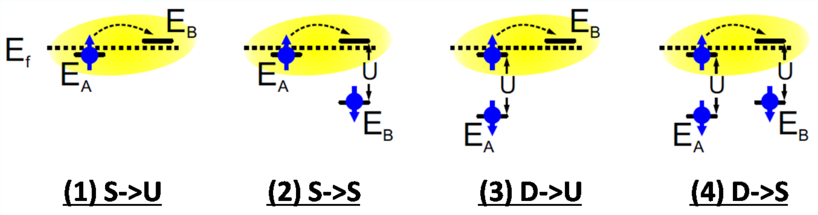
(more on Shumilin and Kozub, PRB 85,115203 (2012))




[2]Shklovskii & Spivak, in *Hopping Transport in Solid*, 1991

# Spin Mechanism

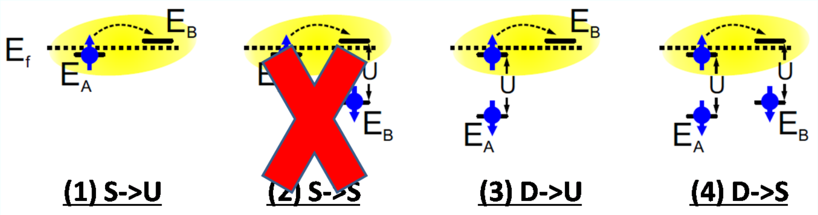
{ISOTROPIC + POSITIVE} Magnetoresistance [3]




[3] Kamimura et. al, 1985

# Spin Mechanism

{ISOTROPIC + POSITIVE} Magnetoresistance [3]

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# Spin Mechanism

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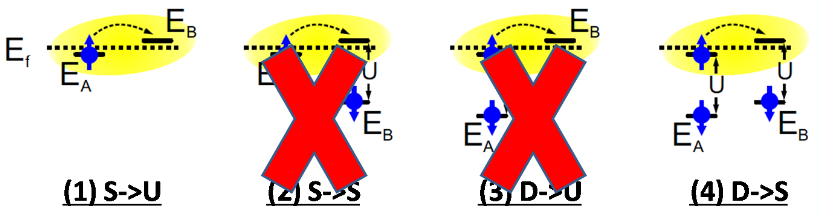


[3] Kamimura et. al, 1985

# Summary

## Orbital Mechanism

- Negative

$$\propto B^{4/5}$$

- Anisotropy

## Spin Mechanism

- Positive

$$\propto B^2$$

- Isotropy

# New Spin Mechanism

# New Spin Mechanism

RAPID COMMUNICATION

PHYSICAL REVIEW B **89**, 100201(R) (2014)

**Spin-memory effect and negative magnetoresistance in hopping conductivity**

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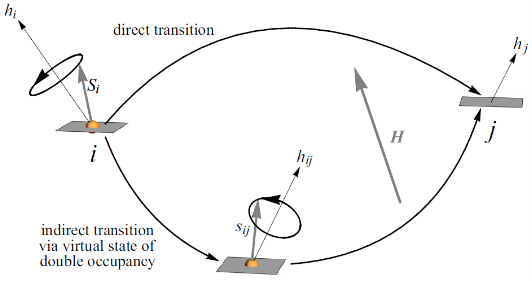
- Characters: NEGATIVE + ISOTROPIC
- Ingredients: fluctuation of $g$ factor in space; long memory of non-equilibrium spin correlation.

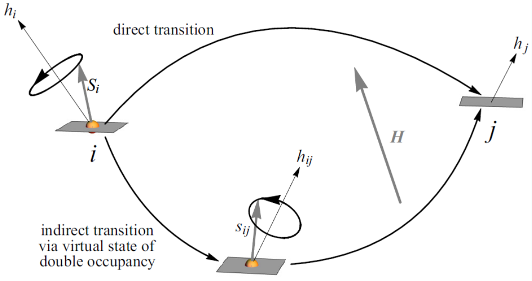
# Qualitative Picture

Hopping rate of an electron $i \to j$ depends on the relative spin configuration of hoping electron and a spin nearby.



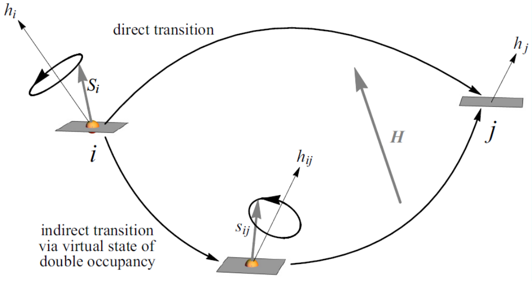
# Qualitative Picture

1. Spin-memory $\longleftarrow$ nonequilibrium electric current: decreases conductivity for $H = 0$



# Qualitative Picture

1. Spin-memory $\longleftarrow$ nonequilibrium electric current: decreases conductivity for $H = 0$
2. Strong disordered system: random $g$ factor: increases conductivity.



# Qualitative Picture

1. Spin-memory $\longleftarrow$ nonequilibrium electric current
2. Strong disordered system: random $g$ factor

Characteristic field:

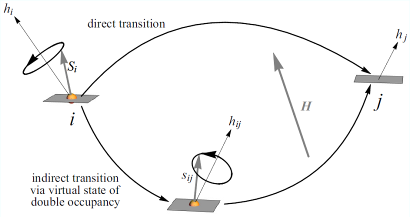
$$\delta g \mu_B H^* \tau \sim 1$$

with $\tau \ll \tau_s$

Estimation: $R \sim 10^{-9}\Omega, \delta g \sim 0.01 \longrightarrow \mu_B \overline{n} H^*/T \sim 10^{-4}$, i.e

field of order of gauss at $T \sim 1K$.

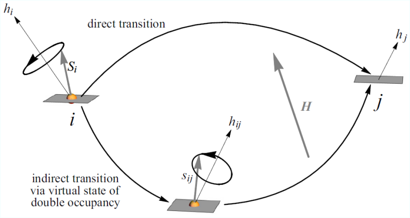
# Simple model




- Main assumptions:
  - ◇ indirect transition rate: $\gamma_{ij} \ll 1$ – perturbation parameter.
  - ◇ link spins are rare.
- Parametrize states: $P_i^0 + \mathrm{Tr}\hat{P}_i^1 = 1$

$$n_i = \mathrm{Tr}\hat{P}_i^1, \qquad \mathbf{S}_i = \mathrm{Tr}(\boldsymbol{\sigma}\hat{P}_i^1)$$

# Simple model




$$\frac{d\langle n_i\rangle}{dt} = -\sum_j \left[\frac{\langle n_i\rangle + \gamma_{ij}\left(\langle n_i\rangle - \langle \mathbf{S}_i \cdot \mathbf{s}_{ij}\rangle\right)}{\tau_{i\to j}} - (i \leftrightarrow j)\right]$$

$$\frac{d\langle \mathbf{S}_i\rangle}{dt} = \mathbf{h}_i \times \langle \mathbf{S}_i\rangle - \sum_j \left[\frac{\langle \mathbf{S}_i\rangle + \gamma_{ij}\left(\langle \mathbf{S}_i\rangle - \langle n_i \mathbf{s}_{ij}\rangle\right)}{\tau_{i\to j}} - (i \leftrightarrow j)\right]$$

$$\frac{d\langle s_{ij}\rangle}{dt} = \mathbf{h}_{ij} \times \langle \mathbf{s}_{ij}\rangle$$

# Simple model

Non-equilibrium variables:

$$\langle n_i \rangle \to n_i^{eq} \left(1 + \psi_i\right), \qquad \mathbf{S}_i \to n_i^{eq} \tilde{\mathbf{S}}_i, \qquad \mathbf{s}_{ij} \to \mathbf{s}_{ij}$$

$$\Longrightarrow \begin{Bmatrix} n_i^{eq} \dfrac{d\psi_i}{dt} = \displaystyle\sum_j \frac{1}{\tau_{ij}} \left[\psi_j - \psi_i - \gamma_{ij} \left\langle \left(\tilde{\mathbf{S}}_j - \tilde{\mathbf{S}}_i\right) \cdot \mathbf{s}_{ij} \right\rangle\right] \\ n_l^{eq} \left[\left(\dfrac{\mathrm{d}}{\mathrm{dt}} + \dfrac{1}{\tau_s}\right) C_{l;ij}^{\alpha\beta} - \epsilon_{\alpha\gamma\delta} h_l^{\gamma} C_{l;ij}^{\alpha\beta} - \epsilon_{\beta\gamma\delta} h_{ij}^{\gamma} C_{l;ij}^{\alpha\delta}\right] \\ \qquad = -\displaystyle\sum_{k \neq l} \frac{C_{l;ij}^{\alpha\beta} - C_{k;ij}^{\alpha\beta}}{\tau_{lk}} + \gamma_{ij} \delta_{\alpha\beta} \left(\delta_{il} - \delta_{jl}\right) \frac{\psi_i - \psi_j}{\tau_{ij}} \end{Bmatrix}$$

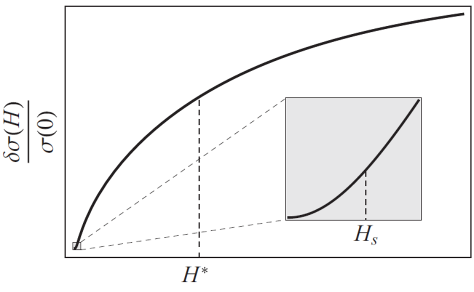
$$\gamma_{ij} \left\langle \left(\tilde{\mathbf{S}}_j - \tilde{\mathbf{S}}_i\right) \cdot \mathbf{s}_{ij} \right\rangle = Q_{ij}\left(H\right)\left(\psi_j - \psi_i\right)$$

$$G_{ij} = \frac{e^2}{T\tau_{ij}} \left[1 - Q_{ij}\left(H\right)\right]$$

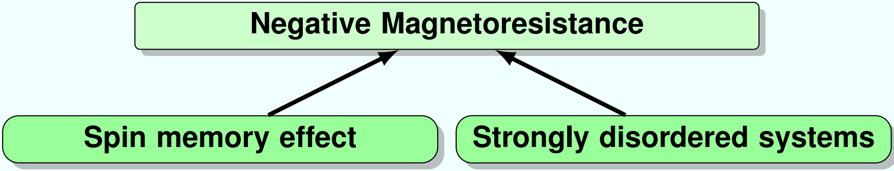
# Simple model: Result

$$\frac{\sigma(H \to \infty) - \sigma(0)}{\sigma(0)} \sim A = \rho\overline{\gamma_{ij}^2}$$ !Small

$$\frac{\delta\sigma(H)}{A\sigma(0)} \sim -\Gamma\left(-\frac{d_s}{2}\right) \sum_{l=-1}^{1} \left[ \left( \frac{ilH}{H^*} + \frac{\tau}{\tau_s} \right)^{d_s/2} + \left( \frac{\tau}{\tau_s} \right)^{d_s/2} \right]$$



# Conclusion




Thanks for Your Attention!