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Axial current driven by magnetization dynamics in Dirac semimetals

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We theoretically study the axial current $\boldsymbol{j}_5$ (defined as the difference between the charge current with opposite helicity) in the magnetic insulator/doped Dirac semimetal using microscopic theory. In the Dirac semimetal, the axial current is induced by the magnetization dynamics, which is produced from the proximity effect of the magnetization of the magnetic insulator. We find that the induced axial current can be detected by using ferromagnetic resonance or the inverse spin Hall effect and can be converted into charge current with no accompanying energy loss. These properties make the Dirac semimetal advantageous for application to low-consumption electronics with new functionality.

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Mohammad Alidoust

Axial current:

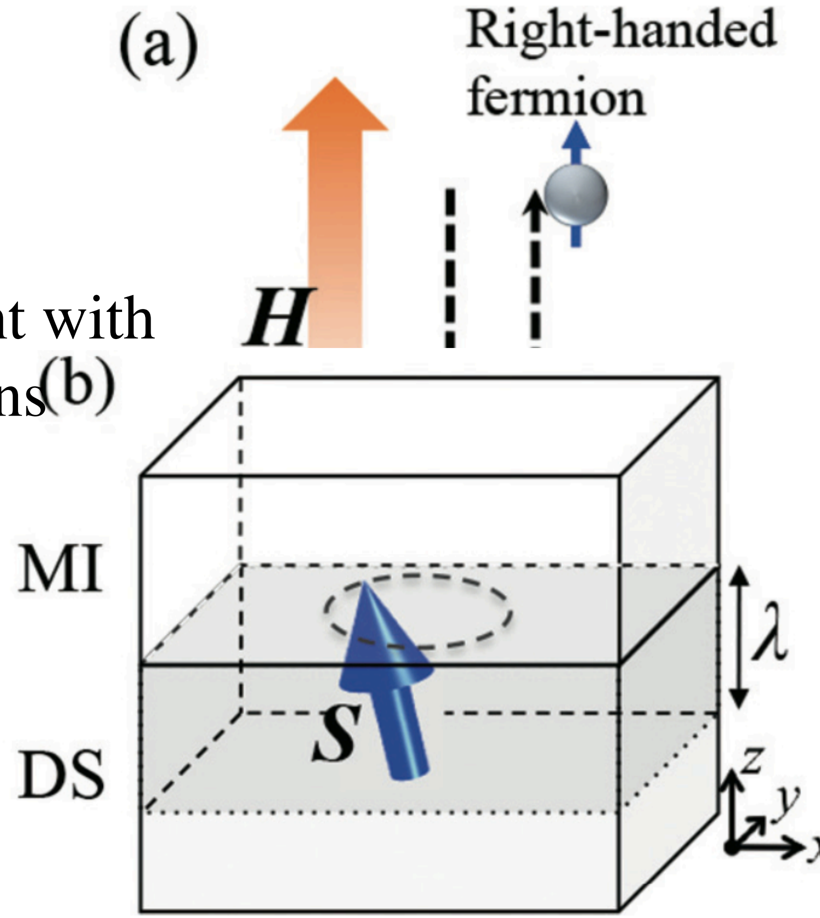
difference between the charge current with right-handed and left-handed fermions

A stationary axial current exists in the presence of an applied static magnetic field (the chiral separation effect)

Proposed configuration

Origin: different helicities

helicity $\gamma = \hat{\boldsymbol{\sigma}} \cdot \hat{\boldsymbol{p}}$



$$\mathcal{H} = \mathcal{H}_{\mathrm{D}} + \mathcal{H}_{\mathrm{ex}} + V_{\mathrm{i}}$$

$$\mathcal{H}_{\mathrm{D}} = \sum_{\gamma=\pm} \mathcal{H}_{\mathrm{D},\gamma}$$

$$\mathcal{H}_{\mathrm{D},\gamma} = \int d\boldsymbol{x}\, \psi_{\gamma}^{\dagger}[-i\hbar v_{\mathrm{F},\gamma} \boldsymbol{\nabla} \cdot \hat{\boldsymbol{\sigma}} - \epsilon_{\mathrm{F}}]\psi_{\gamma}$$

$$v_{\mathrm{F},\gamma} = \gamma v_{\mathrm{F}}$$

$$\mathcal{H}_{\mathrm{ex},\gamma} = -\int d\boldsymbol{x}\, J_{\mathrm{ex}} \psi_{\gamma}^{\dagger} \boldsymbol{S} \cdot \hat{\boldsymbol{\sigma}}\, \psi_{\gamma}$$

$$V_{\mathrm{i}} = u_{\mathrm{i}} \sum_{\gamma} \sum_{j=1}^{N_i} \int d\boldsymbol{x}\, \delta(\boldsymbol{x} - \boldsymbol{r}_j) \psi_{\gamma}^{\dagger} \psi_{\gamma}$$

$$\boldsymbol{j}_\gamma = -ev_{\mathrm{F},\gamma}\langle\psi_\gamma^\dagger\boldsymbol{\sigma}\psi_\gamma\rangle \qquad \rho_\gamma \equiv -e\langle\psi_\gamma^\dagger\psi_\gamma\rangle$$

$$\dot{\rho}_\gamma = -\boldsymbol{\nabla}\cdot\boldsymbol{j}_\gamma$$

$$G_\gamma^< = \langle\psi_\gamma^\dagger\psi_\gamma\rangle/(-i\hbar)$$

$$j_{i,\gamma}(\boldsymbol{x},t) = i\hbar ev_{\mathrm{F},\gamma}\mathrm{tr}[\hat{\sigma}_i G_\gamma^<(\boldsymbol{x},t:\boldsymbol{0},0)]$$

$$j_{i,\gamma} = \frac{-i\hbar J_{\mathrm{ex}}ev_{\mathrm{F},\gamma}}{V}\sum_{\boldsymbol{q},\Omega} e^{-i(\boldsymbol{q}\cdot\boldsymbol{x}-\Omega t)}\Pi_{ij,\gamma}(\boldsymbol{q},\Omega)S^j_{\boldsymbol{q},\Omega}$$

S varies slowly in space and time

$$q\ell \ll 1 \qquad \Omega\tau \ll 1$$

convolution of $\boldsymbol{S}$

$$\langle \boldsymbol{S} \rangle_{\mathrm{D}} \equiv \int_{-\infty}^{\infty} dt' \int d\boldsymbol{x}' \mathcal{D}(\boldsymbol{x}-\boldsymbol{x}', t-t') \boldsymbol{S}(\boldsymbol{x}', t')$$

diffusive propagation function

$$\mathcal{D}(\boldsymbol{x}, t) \equiv \frac{1}{V} \sum_{\boldsymbol{q},\Omega} e^{-i(\boldsymbol{q}\cdot\boldsymbol{x}-\Omega t)} [\tfrac{3}{2} D q^2 + i\Omega]^{-1}$$

$$\boldsymbol{j}_\gamma = \frac{e v_{\mathrm{F},\gamma} J_{\mathrm{ex}} \nu_e \tau}{2} \partial_t \boldsymbol{S} - \frac{3}{2} D \nabla \rho_\gamma$$

$$\rho_\gamma = -\frac{1}{2} e v_{\mathrm{F},\gamma} J_{\mathrm{ex}} \nu_e \tau \nabla \cdot \partial_t \langle \boldsymbol{S} \rangle_{\mathrm{D}}$$

$$\boldsymbol{j}_+ + \boldsymbol{j}_- = 0, \quad \rho_+ + \rho_- = 0$$

$$\boldsymbol{j}_5 \equiv \boldsymbol{j}_+ - \boldsymbol{j}_- \quad \rho_5 \equiv \rho_+ - \rho_-$$

$$\boldsymbol{j}_5 = e v_{\mathrm{F}} J_{\mathrm{ex}} \nu_e \tau \partial_t \boldsymbol{S} - \frac{3}{2} D \boldsymbol{\nabla} \rho_5$$

$$\rho_5 = -e v_{\mathrm{F}} J_{\mathrm{ex}} \nu_e \tau \boldsymbol{\nabla} \cdot \partial_t \langle \boldsymbol{S} \rangle_{\mathrm{D}}.$$

$$\boldsymbol{j}_5 \equiv \boldsymbol{j}_5^{\mathrm{L}} + \boldsymbol{j}_5^{\mathrm{D}}$$

$$\lambda \gg \ell \quad \lambda \ll \ell$$

Experimental detection:

(a)- half-width value of the ferromagnetic resonance

$$\partial_t \boldsymbol{M} = \gamma \mu \boldsymbol{H} \times \boldsymbol{M} + \frac{\alpha_{\mathrm{G}}}{M} \boldsymbol{M} \times \partial_t \boldsymbol{M} + \boldsymbol{\mathcal{T}}_{\mathrm{e}}$$

$$\boldsymbol{\mathcal{T}}_{\mathrm{e}} = \frac{2J_{\mathrm{ex}}}{\hbar} \boldsymbol{M} \times \boldsymbol{s}$$

$$\boldsymbol{\mathcal{T}}_{\mathrm{e}} = \frac{-J_{\mathrm{ex}}}{\hbar e v_{\mathrm{F}}} (\boldsymbol{M} \times \boldsymbol{j}_5^{\mathrm{L}} + \boldsymbol{M} \times \boldsymbol{j}_5^{\mathrm{D}})$$

$$\boldsymbol{\mathcal{T}}_{\mathrm{e}} = \frac{J_{\mathrm{ex}}^2 \nu_e \tau S}{\hbar M} \left[\boldsymbol{M} \times \partial_t \boldsymbol{M} + \frac{3}{2} D \boldsymbol{M} \times \boldsymbol{\nabla} \left(\boldsymbol{\nabla} \cdot \partial_t \langle \boldsymbol{M} \rangle_{\mathrm{D}} \right) \right]$$

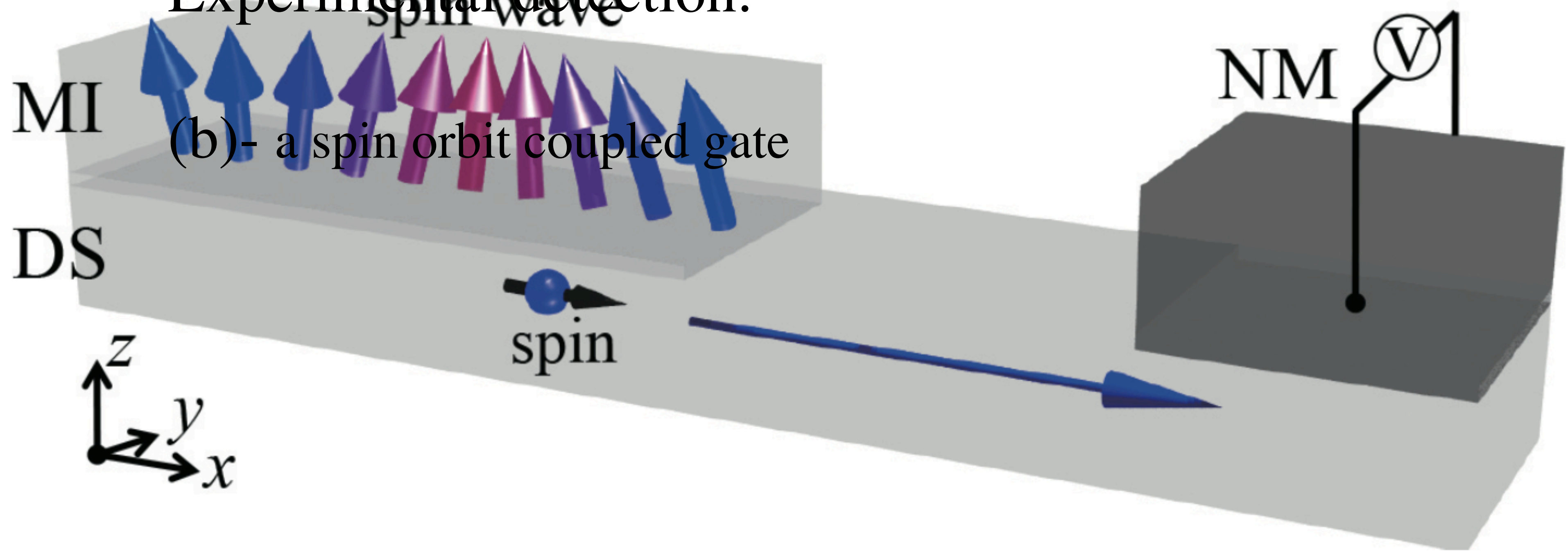
$$\boldsymbol{M} \times \boldsymbol{j}_5^{\mathrm{L}} \quad \Longrightarrow \quad \alpha_{\mathrm{G}} + J_{\mathrm{ex}}^2 \nu_e \tau S / \hbar$$

$$\Delta H = 2\omega_0\left(\alpha_{\mathrm{G}} + J_{\mathrm{ex}}^2 \nu_e \tau S/\hbar\right)$$

This equation means that before and after the generation of $\boldsymbol{j}_5^{\mathrm{L}}$, the half-width value changes from $2\omega_0\alpha_{\mathrm{G}}$ by $2\omega_0 J_{\mathrm{ex}}^2 \nu_e \tau S/\hbar$, where ω_0 is the resonance frequency. When we choose the parameters $J_{\mathrm{ex}}/\epsilon_{\mathrm{F}} = 0.01$, $\tau = 6 \times 10^{-14}$ s, $\epsilon_{\mathrm{F}}\nu_e = 1$, and $S = 5/2$, the change in damping is estimated as $J_{\mathrm{ex}}^2 \nu_e \tau S/\hbar \sim 2 \times 10^{-3}$. The order of α_{G} is reported as 10^{-3} in ferromagnets

Experimental detection:

(b)- a spin orbit coupled gate



$\propto j_5$

flow of spin $\boldsymbol{I}_s \| \boldsymbol{z}$ and $\boldsymbol{s}^{\mathrm{D}} \| \boldsymbol{x}$

$$\boldsymbol{j} \propto \boldsymbol{s}^{\mathrm{D}} \times \boldsymbol{I}_s$$

Conclusions:

-The magnetization dynamic of a ferromagnetic layer coupled to a diffusive Dirac semimetal layer can induce axial currents

-The components of axial current may be detected through FMR experiments and spintronics methods

-The axial currents are conserve (unlike the usual spin currents), carry no charge, and may be converted to charge currents in MI/DS/NM junctions

Thank you