Spintronics of Spin-Orbit Coupled Systems

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How spin-orbit coupling changes the spectrum of noncentrosymmetric systems?

It splits the paraboloid $E(p) = \frac{p^2}{2m}$ into two sheets.

SO coupling establishes a strict connection between the direction of the momentum $p$ and the direction of the spin $S$. 
Oscillator Strength for a Bloch Electron

\[ i[k, x] = 1, \quad \sum_n f_{n \leftarrow \ell} = 1 \quad \text{TKR theorem} \]

\[ f_{n \leftarrow \ell} = i\{\langle \ell | k | n \rangle \langle n | x | \ell \rangle - \langle \ell | x | n \rangle \langle n | k | \ell \rangle\} \]

\[ \langle n | x | \ell \rangle (E_{\ell} - E_n) = i \frac{\hbar^2}{m_0} \langle n | k | \ell \rangle \]

\[ f_{n \leftarrow \ell} = 2 \frac{\hbar^2}{m_0} \frac{|\langle \ell | k | n \rangle|^2}{E_n - E_{\ell}} \quad \text{typical terms of } k.p \text{- theory} \]

When then \( n = \ell \) term survives in the TKR theorem:

\[ \sum_{n \neq \ell} f_{n \leftarrow \ell} = 1 \quad \text{for local states} \]

\[ \frac{m_0}{m_\ell} + \sum_{n \neq \ell} f_{n \leftarrow \ell} = 1, \quad f_{\ell \leftarrow \ell} = \frac{m_0}{m_\ell} \quad \text{for band states} \]

\[ f_{\ell \leftarrow \ell} \text{ is the oscillator strength of the cyclotron and Drude absorption} \]
Where Spin Coupling to Electric Field comes from?

Oscillator strength for a free electron in a parabolic band:

\[ f = \frac{m_0}{m} \]

- \( m \) - electron effective mass
- \( m_0 \) - electron vacuum mass

Simplest spin-orbit coupling in non-centrosymmetric uniaxial crystals and in quantum wells:

\[ H_\alpha = \alpha (\sigma \times k) \cdot \hat{z} = \alpha (\sigma_x k_y - \sigma_y k_x) \]

It splits spectrum into two spin branches

Near the spectrum bottom the oscillator strength is divided equally between the intra- and interbranch transitions

\( f_{\text{inter}} \) results in spin coupling to ac electric field, and in EDSR (electric dipole spin resonance) in a strong magnetic field
Spin transistor: Ideas encoded

Two equivalent pictures:

\[ H_\alpha = \frac{g(\sigma \cdot B_{in})}{2}, \quad B_{in} = 2\alpha(k \times z)/g \]

1. two Fermi momenta represent two beams that interfere

\[ P = \cos^2 \left[ \frac{(k_1 - k_2)L}{2} \right] \]

Gate controlled birefringence

\[ \alpha = \alpha(E_g) \]

Basic ideas underlying the device:

(i) Spin injection from ferromagnetic electrodes,
(ii) Gate control of electron spin (SO),
(iii) Spin precession in internal magnetic field (SO),
(iv) Spin interference (SO).

Spintronics without magnetic elements:

generating nonequilibrium spin populations electrically via SO coupling
EDSR – Electric Dipole Spin Resonance

\[ H_{so} = H_1(k, \sigma) + H_2(r, \sigma), \quad g\mu_B B >> \alpha k_F \]

\( H_1(k, \sigma) \) mechanism well known in 3D:

Bell (1962), McCombe et al. (1967), Dobrowolska et al. (1984)

\[ H_1(k, \sigma) : H_\alpha = \alpha(\sigma_x k_y - \sigma_y k_x) \text{ SIA}, \quad H_\beta = \beta(\sigma_x k_x - \sigma_y k_y) \text{ BIA} \]

\[ \tilde{E} \parallel \hat{z} \quad \text{SIA} \quad \tilde{E} \parallel \hat{z} \quad \text{BIA and SIA} \]

Ratio of matrix elements: \( \ell_\perp / \ell_\parallel \approx \omega_c \omega_s / \omega_0^2 \)

\[ H_2(r, \sigma) = \mu_B (\sigma \cdot g(r)B(r)) / 2 \]

With \( g \approx 0 \), the mechanism proved to be efficient in AlGaAs QWs with \( E\parallel z \)

Schulte et al. (2005) AlAs

In narrow QWs, EDSR with in-plane \( E \) dominates

\[ I_{\text{EDSR}} \approx 10^4 I_{\text{EPR}} \]

Kato et al. (2003)
Maxwellian equations include:

- $E$, $D$, $\rho$, and $J$ for electric charge and current
- $B$ and $H$, or $M=(B-H)/4\pi$ for magnetization

Spin nonconservation makes theory highly sophisticated, cf. AHE

Spin magnetization $S$ is the only observable quantity.
There is no magnetic charges and currents.

Observing $S_x$:
- Kato et al. (2004),
- Silov et al. (2004), Ganiev et al. (2004)

Observing $S_z$ by optical techniques:
- in $n$-GaAs by Kerr rotation (Kato et al. 2004)
- in $p$-GaAs by polarized emission (Wunderlich et al. 2005)

All these observations: generating spin magnetization by electric current due to central symmetry violation (irrespective of detailed mechanisms)
Spin interference in transport experiments

Spin interferometer with square loop array
(follow $B=0$ vertical)

InGaAs
Koga et al. (2005)

Conductance of a ring
controlled by gate voltage
(follow vertical sections)

$\alpha=0$  HgTe/HgCdTe
Koenig et al. (2005)
Formalism, spatial scales, and spin currents

Two analytical models: (I) ballistic transport in rings and (ii) diffusive transport

Both result in characteristic length $\ell_\alpha = \hbar^2 / m\alpha \approx L_{sd}, k_\alpha = m\alpha / \hbar^2$

Response of $\sigma_x(q, \omega)$ to $E(r, t) = E \exp[i(qr - \omega t)]$

$Q = q / 2k_\alpha, \omega = 2v_F k_\alpha, \Omega = m(\omega - \sigma) / 2\hbar k_F k_\alpha$

Response diverges for $q \to 2k_\alpha$
(breakdown when two Fermi surfaces touch)

$\alpha \neq 0$ island as spin emitter into $\alpha = 0$ leads; maximum effect at $d \approx \ell_\alpha$

Such spin currents are well defined because they are conserved in $\alpha = 0$ regions

Spin currents in $\alpha \neq 0$ regions

$j_i^l = \frac{1}{2} \langle \sigma_l v_i + v_i \sigma_l \rangle$ or $j_i^l = \langle \frac{d}{dt} \sigma_l x_i \rangle$

A beautiful playground for different SO coupling mechanisms, but they physical meaning and relation to spin accumulation remain obscure yet

In systems with $j_i^z = 0$, $S_z \neq 0$ develops when spin leak at or across the edge

Conjecture: spin currents with $q \approx ik_\alpha$ seem more relevant than $q = 0$ currents
Universality Conjecture

Spin currents at $q = 0$ and $\omega = 0$ are of the scale

$$j^i_\ell \sim e/2\pi\hbar \text{ in 2D} \quad \text{(Sinova et al)}$$

$$j^i_\ell \sim (e/2\pi\hbar)k_F \text{ in 3D} \quad \text{(Murakami et al.)}$$

Exact quantization only when spin is conserved

(2D channels in graphene)

Conjecture: at the spin-precession momentum $q \sim 2k_\alpha$ universality is achieved:

$$k_{so} \sim m\alpha/\hbar^2 \sim \Delta_F / \hbar$$

$$j_{sH}(k_{so}) \sim eE/2\pi\hbar, \quad S(k_{so})/\hbar \sim k_{so} eE/2\pi\hbar$$

For small device sizes and high operation frequencies, large $\alpha$ and $\Delta_F$ are needed
Nontraditional systems: from graphene to metal surfaces

Dispersion law and magnetic quantization in graphene:
\[ E(k) = \hbar v_F k, \quad E_n = \text{sign} \{n\} \sqrt{2\hbar v_F^2 B|n|/c}, \quad -\infty < n < \infty \]

Magnetic quantization with \( k \)-linear SO term:
\[ E_0 = \hbar \omega_c \delta, \quad E_n^\pm = \hbar \omega_c (n \pm \sqrt{\delta^2 + 2(k_\alpha \ell_B^2)^2 n}), \quad n \leq 1 \]
\[ \omega_c = eB/\hbar c, \quad \delta = (1-gm/2m_0)/2, \quad k_\alpha = m\alpha/\hbar^2, \quad \ell_B^2 = c\hbar/eB \]

Giant SO coupling near surfaces of semimetals and metals

Surface states Bi (111)
Black: without SO coupling
Red: with SO coupling
Koroteev et al. (2004)

Large SO results in ultra-short spin precession lengths
Conclusions:

1. Effect of SO on energy spectrum
2. Ideas underlying SO devices,
3. EDSR in 2D,
4. Electrical generation of spin populations,
5. Discovery of spin interference,
6. Theory: status, characteristic scales, challenges,
7. Nontraditional systems and surfaces
Spintronics of Spin-Orbit coupled Systems: Achievements and Challenges

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