Spintronics of Spin-Orbit Coupled Systems

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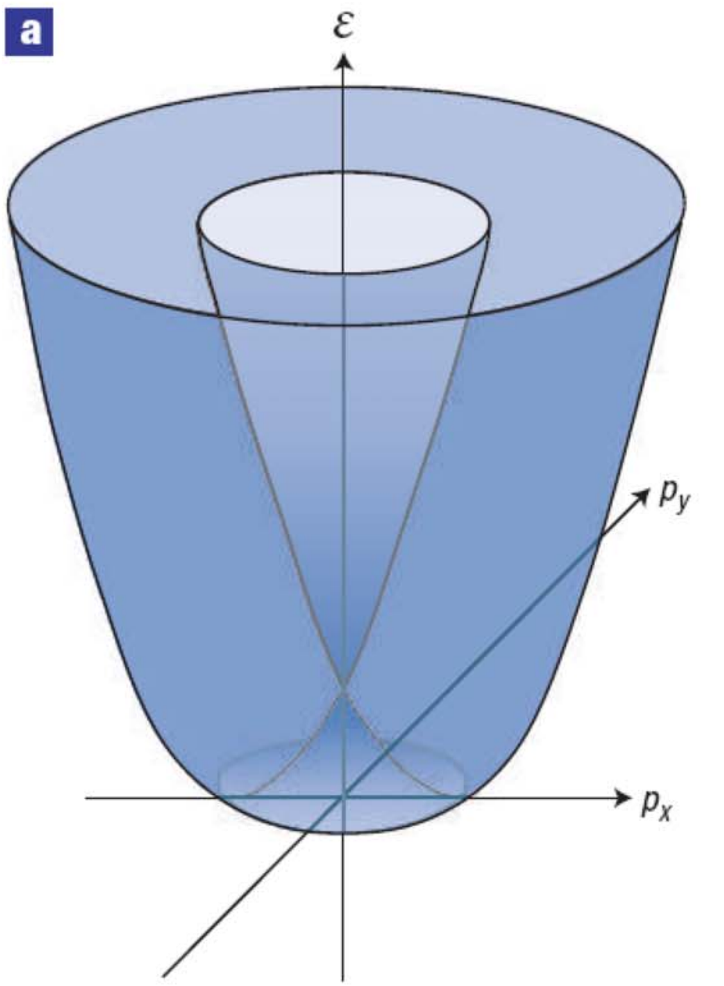
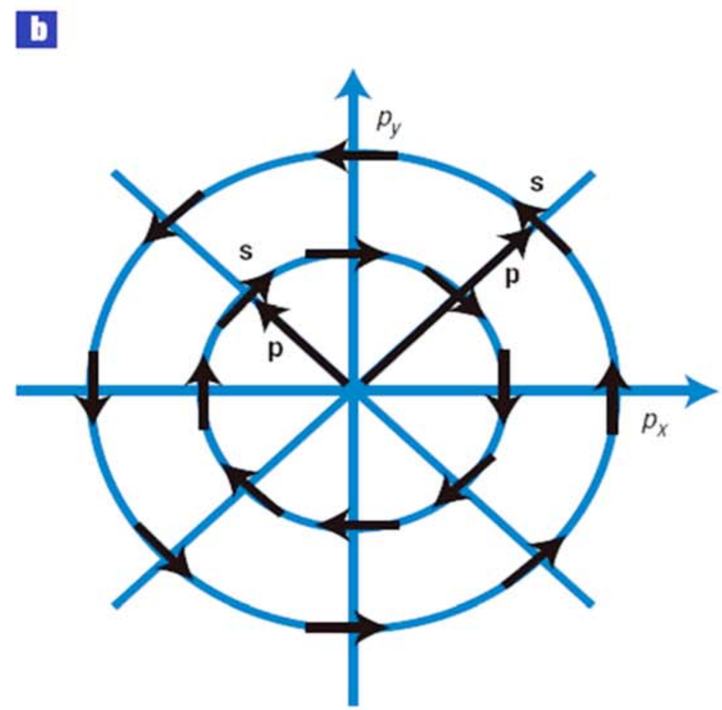
How spin-orbit coupling changes the spectrum of noncentrosymmetric systems?



It splits the paraboloid $E(p)=p^2/2m$ **into two sheets**



SO coupling establishes a strict connection between the direction of the momentum $\boldsymbol{p}$ and the direction of the spin $\boldsymbol{s}$

Oscillator Strength for a Bloch Electron

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

$$f_{n\leftarrow \ell} = i\{\langle \ell \,|\, k \,|\, n\rangle\langle n \,|\, x \,|\, \ell\rangle - \langle \ell \,|\, x \,|\, n\rangle\langle n \,|\, k \,|\, \ell\rangle\}$$

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

$$f_{n\leftarrow \ell} = 2\frac{\hbar^2}{m_0}\frac{|\langle \ell \,|\, k \,|\, n\rangle|^2}{E_n - E_\ell} \Leftarrow$$ typical terms of *k.p* - theory

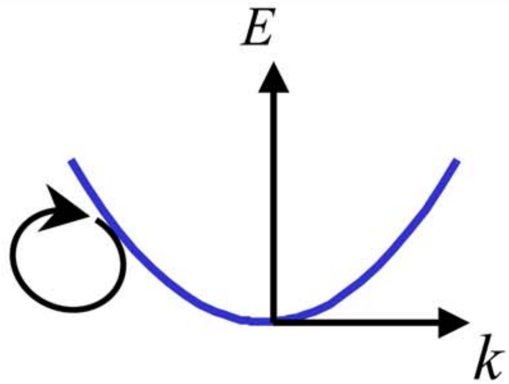
When the $n=\ell$ term survives in the TKR theorem

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

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

$f_{\ell\leftarrow \ell}$ is the oscillator strength of the cyclotron and Drude absorption

Where Spin Coupling to Electric Field comes from?

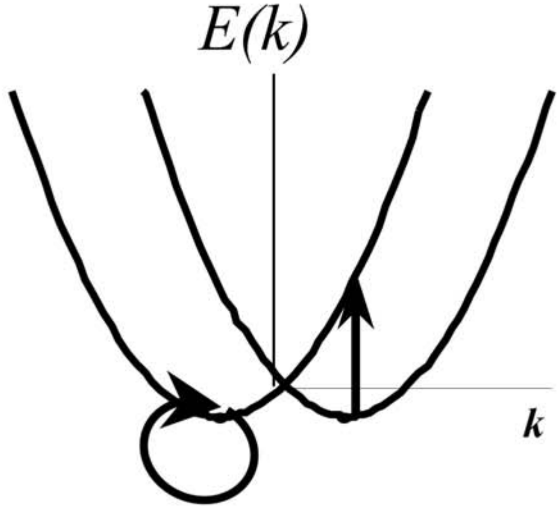


Oscillator strength for a free electron in a parabolic band:

$$f = m_0 / m$$

m - electron effective mass

m_0 - electron vacuum mass



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

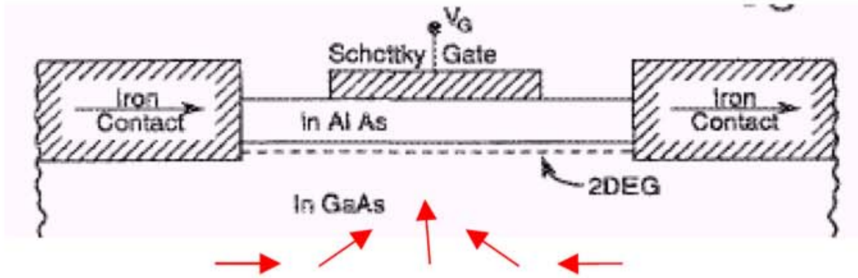
$$H_\alpha = \alpha(\boldsymbol{\sigma} \times \mathbf{k}) \cdot \hat{\mathbf{z}} = \alpha(\sigma_x k_y - \sigma_y k_x)$$

It splits spectrum into two spin branches

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

f_{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

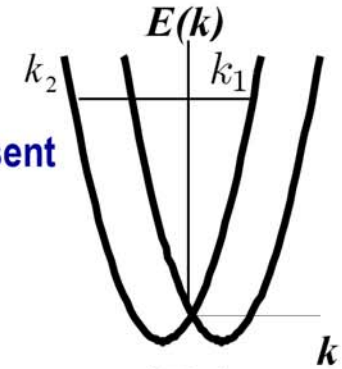


$$H_\alpha = g(\boldsymbol{\sigma}\cdot\mathbf{B}_{\text{in}})/2,\ \mathbf{B}_{\text{in}} = 2\alpha(\mathbf{k}\times\hat{\mathbf{z}})/g$$

2. electron spin $\mathbf{s}\,||\,\mathbf{k}$ precesses in the effective magnetic field $\mathbf{B}_{\text{in}}(\mathbf{k})$

Two equivalent pictures:

$$H_\alpha = \alpha(\sigma_x k_y - \sigma_y k_x)$$



1. two Fermi momenta represent two beams that interfere

$$P = \cos^2[(k_1 - k_2)L/2]$$

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

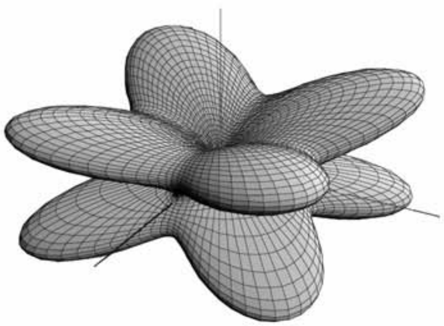
EDSR – Electric Dipole Spin Resonance

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

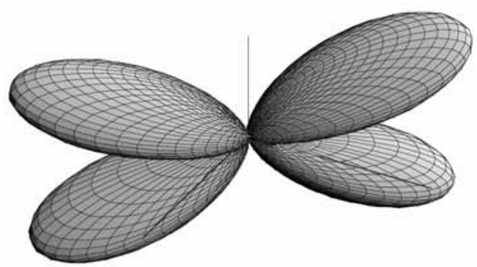
$H_1(\boldsymbol{k},\sigma)$ mechanism well known in 3D:

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

$$H_1(\mathbf{k},\boldsymbol{\sigma}): H_\alpha = \alpha(\sigma_x k_y - \sigma_y k_x) \text{ SIA, } H_\beta = \beta(\sigma_x k_x - \sigma_y k_y) \text{ BIA}$$

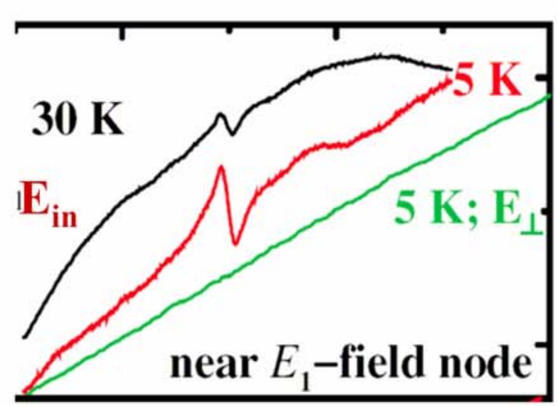


SIA $\tilde{\mathbf{E}} \parallel \hat{\mathbf{z}}$



BIA and SIA $\tilde{\mathbf{E}} \parallel \hat{\mathbf{z}}$

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



Schulte et al. (2005) AlAs

In narrow QWs, EDSR with in-plane *E* dominates

$$I_{\mathrm{EDSR}} \approx 10^4\, I_{\mathrm{EPR}}$$

$$H_2(\mathbf{r},\boldsymbol{\sigma}) = \mu_B(\boldsymbol{\sigma}\,\hat{\mathbf{g}}(\mathbf{r})\mathbf{B}(\mathbf{r}))/2$$

With $g \approx 0$, the mechanism proved to be efficient in AlGaAs QWs with $\mathbf{E}\parallel\mathbf{z}$

Kato et al. (2003)

Charge Transport *vs* Spin Transport

Maxwellian equations include:

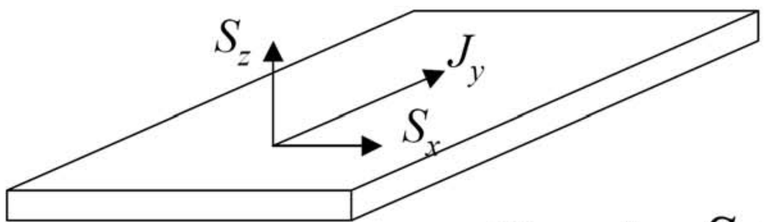
$\boldsymbol{E}$, $\boldsymbol{D}$, ρ, and $\boldsymbol{J}$ for electric charge and current

$\boldsymbol{B}$ and $\boldsymbol{H}$, or $\boldsymbol{M}=(\boldsymbol{B}-\boldsymbol{H})/4\pi$ for magnetization

Spin magnetization $\boldsymbol{S}$ is the only observable quantity.

There is no magnetic charges and currents.

Spin nonconservation makes theory highly sophisticated, cf. AHE



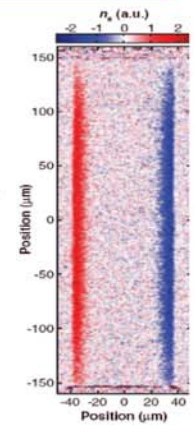
Observing $\boldsymbol{S_x}$: Kato et al. (2004),

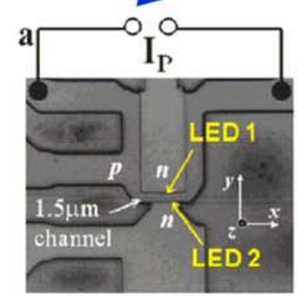
Silov et al. (2004), Ganichev et al. (2004)

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)

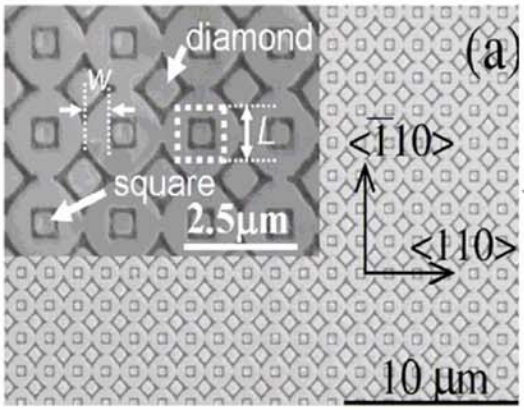


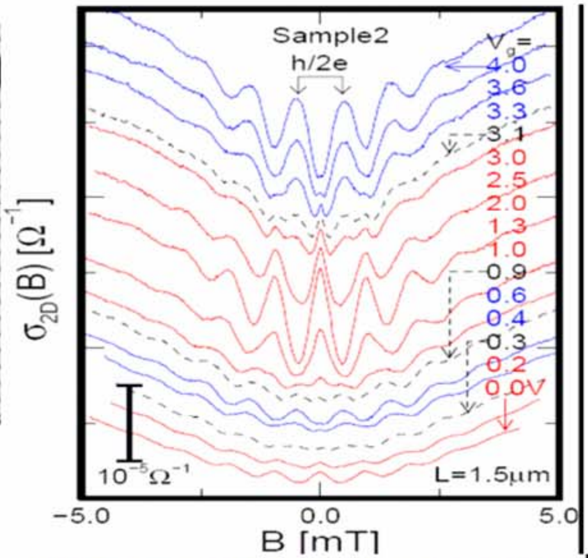


All these observations: generating spin magnetization by electric current due to central symmetry violation

(irrespective of detailed mechanisms)

Spin interference in transport experiments



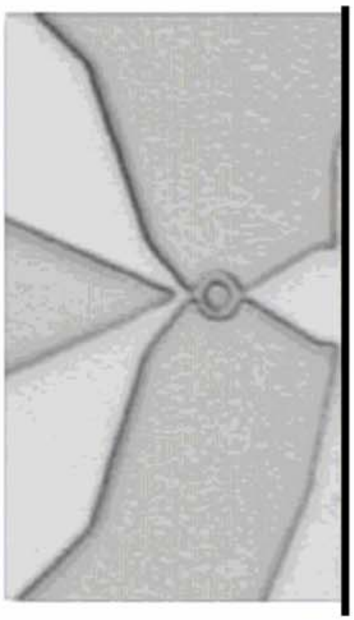


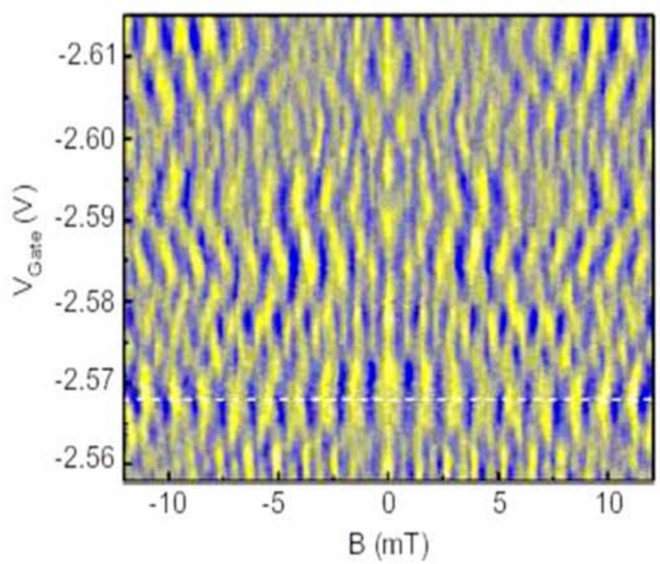
Spin interferometer with square loop array

(follow *B*=0 vertical)

InGaAs

Koga et al. (2005)





←α=0

Conductance of a ring controlled by gate voltage

(follow vertical sections)

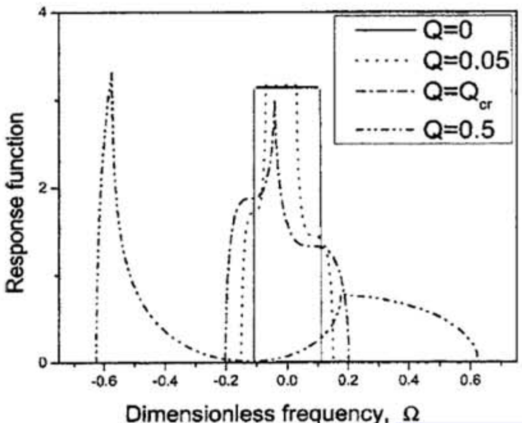
HgTe/HgCdTe

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 $\ell_\alpha = \hbar^2 / m\alpha \approx L_{\rm sd}, k_\alpha = m\alpha / \hbar^2$

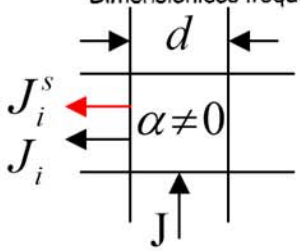


Response of $\sigma_x(\mathbf{q},\omega)$ to $\mathbf{E}(\mathbf{r},t) = E\exp[i(\mathbf{qr} - \omega t)]$

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

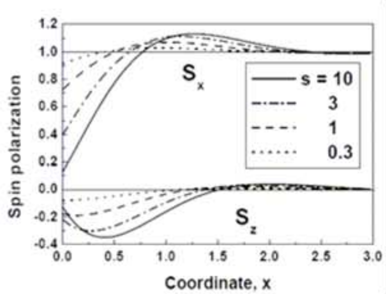
Response diverges for $q \to 2k_\alpha$

(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 α=0 regions



Spin currents in $\alpha \neq 0$ regions

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

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

$j_\ell^i \sim e/2\pi\hbar$ in 2D (Sinova et al

$j_\ell^i \sim (e/2\pi\hbar) k_F$ in 3D (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:**

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

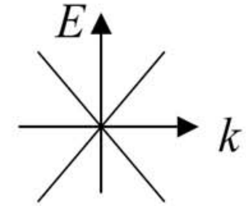
$$j_{\mathrm{sH}}(k_{so}) \sim eE/2\pi\hbar, \quad S(k_{so})/\hbar \sim k_{so}\tau eE/2\pi\hbar$$

For small device sizes and high operation frequencies,
large α and Δ_F are needed

Nontraditional systems: from graphene to metal surfaces

Dispersion law and magnetic quantization in graphene:

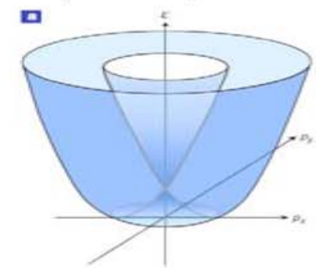
$$E(k)=\hbar v_F k,\ E_n=\mathrm{sign}\{n\}\sqrt{2\hbar v_F^2 B|n|/c},\ -\infty<n<\infty$$



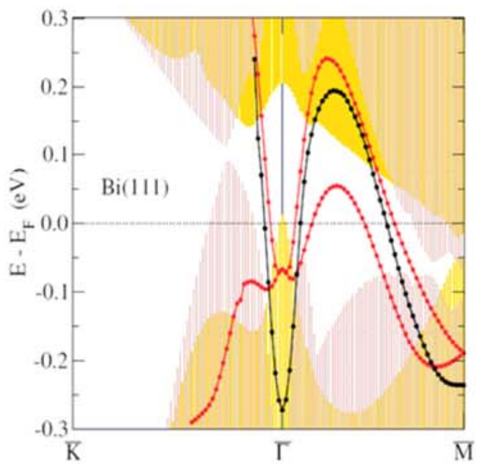
Magnetic quantization with *k*-linear SO term:

$$E_0=\hbar\omega_c\delta,\ E_n^{\pm}=\hbar\omega_c\left(n\pm\sqrt{\delta^2+2(k_\alpha \ell_B)^2 n}\right),\ n\le 1$$

$$\omega_c=eB/\hbar c,\ \delta=(1-gm/2m_0)/2,\ k_\alpha=m\alpha/\hbar^2,\ \ell_B^2=c\hbar/eB$$



Giant SO coupling near surfaces of semimetals and metals



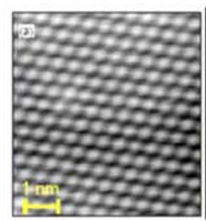
Surface states Bi (111)

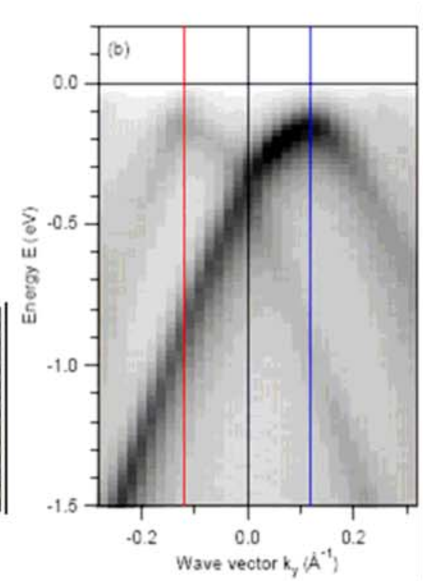
Black: without SO coupling

Red: with SO coupling

Koroteev et al. (2004)

Bi/Ag(111) monolayer alloy





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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