# Spin-splitting in Rashba-Active Weak Links

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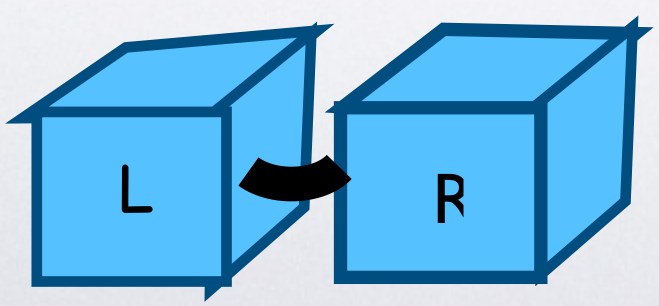
Ministry of Science and Technology

PAZY EXCELLING IN SCIENCE

הקרן הלאומית למדע




spin-orbit interaction confined to the weak link

Use of electrical currents (or fields) to generate spin current and polarization without magnetic fields or ferromagnets

* spins of mobile electrons can be manipulated by spin-orbit interactions —the spin of an electron moving through a spin-orbit active material (e.g., semiconductor heterostructures) rotates around an effective magnetic field generated by the spin-orbit interaction.

רבי שלמה בן אברהם

E Rashba

* Rashba spin-orbit interaction is significant at surfaces and interfaces due to strong internal uncompensated atomic electric fields (normal to surface) that appear since the surface potential breaks the symmetry of the atomic orbitals there (strong atomic fields no longer cancel as they do in the bulk). Electric fields generated by gates can then modulate the strength of the Rashba interaction.

*tunneling amplitude with spin-orbit interaction

and spin splitting by Rashba interaction

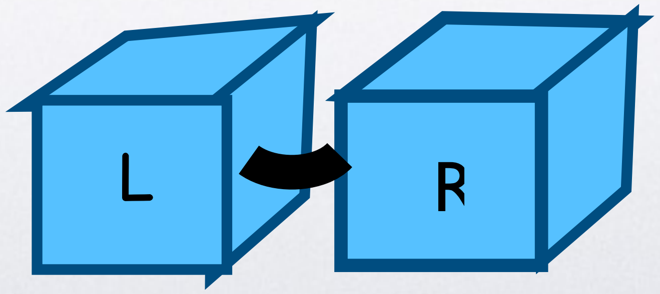
*Rashba splitting of Cooper pairs

*breaking time-reversal symmetry

—by a Zeeman field

—by an AC Rashba interaction created by a slowly-rotating electric field

spin-orbit interaction preserves time-reversal symmetry



## spin-orbit interaction

* Electron moving in an electric field experiences a ``magnetic” field in its rest-frame

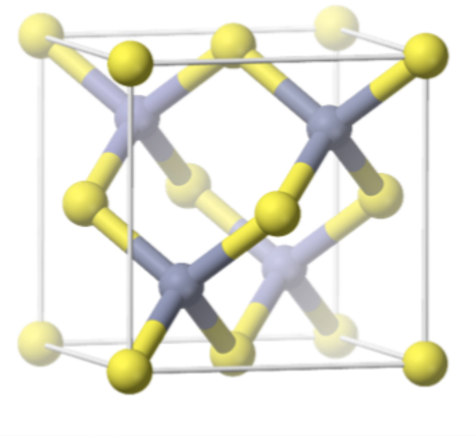
$$\mathbf{B}_{\rm eff} \sim \mathbf{E} \times \mathbf{p}/mc^2 \qquad \mathcal{H}_{\rm so} \sim \mu_{\rm B}\boldsymbol{\sigma} \cdot \mathbf{E} \times \mathbf{p}/mc^2$$

## Semiconductors

*In solids the electric field is the gradient of the crystal potential—>``magnetic field” odd in the momentum to preserve time-reversal symmetry
*In two-dimensions the interaction is integrated over the growth direction—>linear in the momentum

* bulk inversion asymmetry—>Dresselhaus

$$\mathcal{H}_{\rm D}^{2d} = \beta(-p_x\sigma_x + p_y\sigma_y)$$

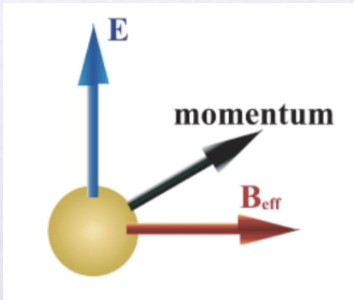


zinc-blende GaAs

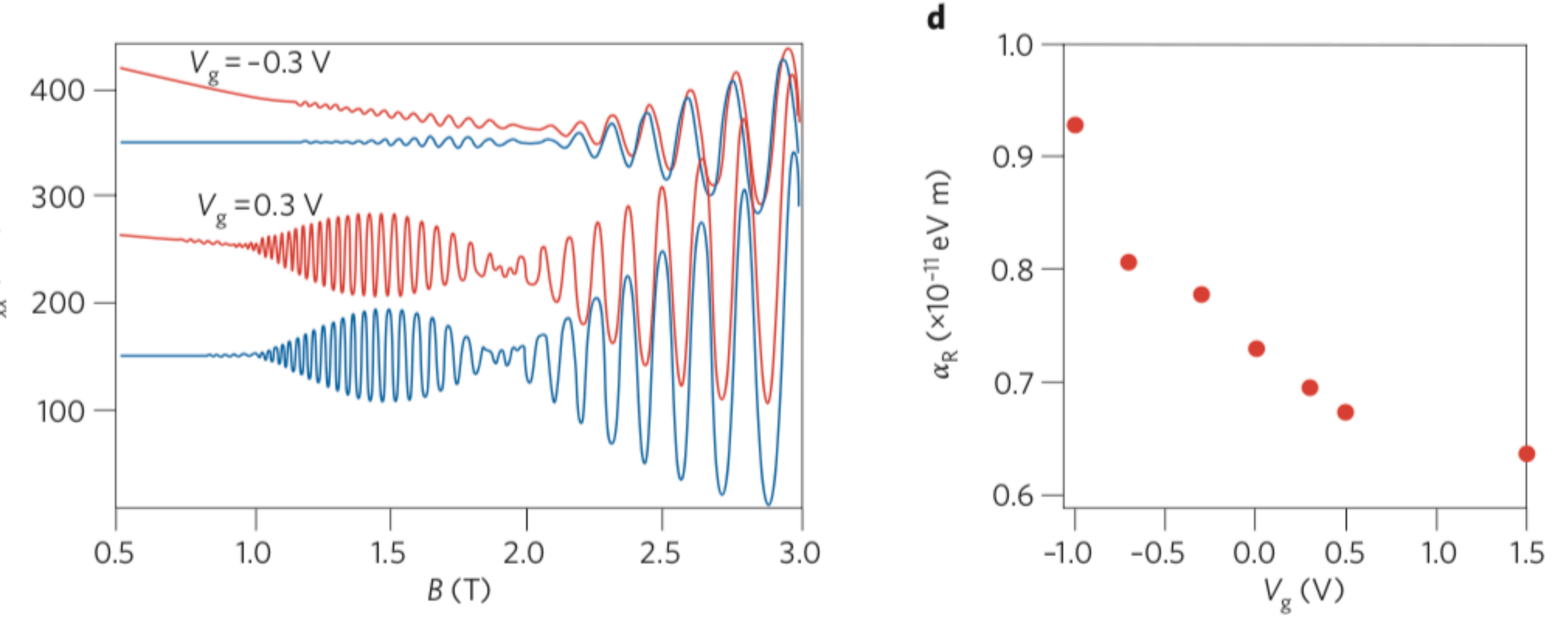
* structural inversion asymmetry—>Rashba

GaAs/AlGaAs

$$\mathcal{H}_{R}^{2d} = \alpha(p_x\sigma_y - p_y\sigma_x)$$



# Manipulating Rashba spin-orbit coupling




Nitta, Akazaki, Takayanagi, Enoki, Gate control of spin-orbit interaction in an inverted InGaAs/InAlAs heterostructures, PRL 78 (1997) as the electron moves ballistically a distance L, the angle by which the spin is rotated by the linear spin-orbit interaction is independent of the velocity, i.e., the rotation angle is determined by the spin-orbit coupling and by L

## experimental parameters

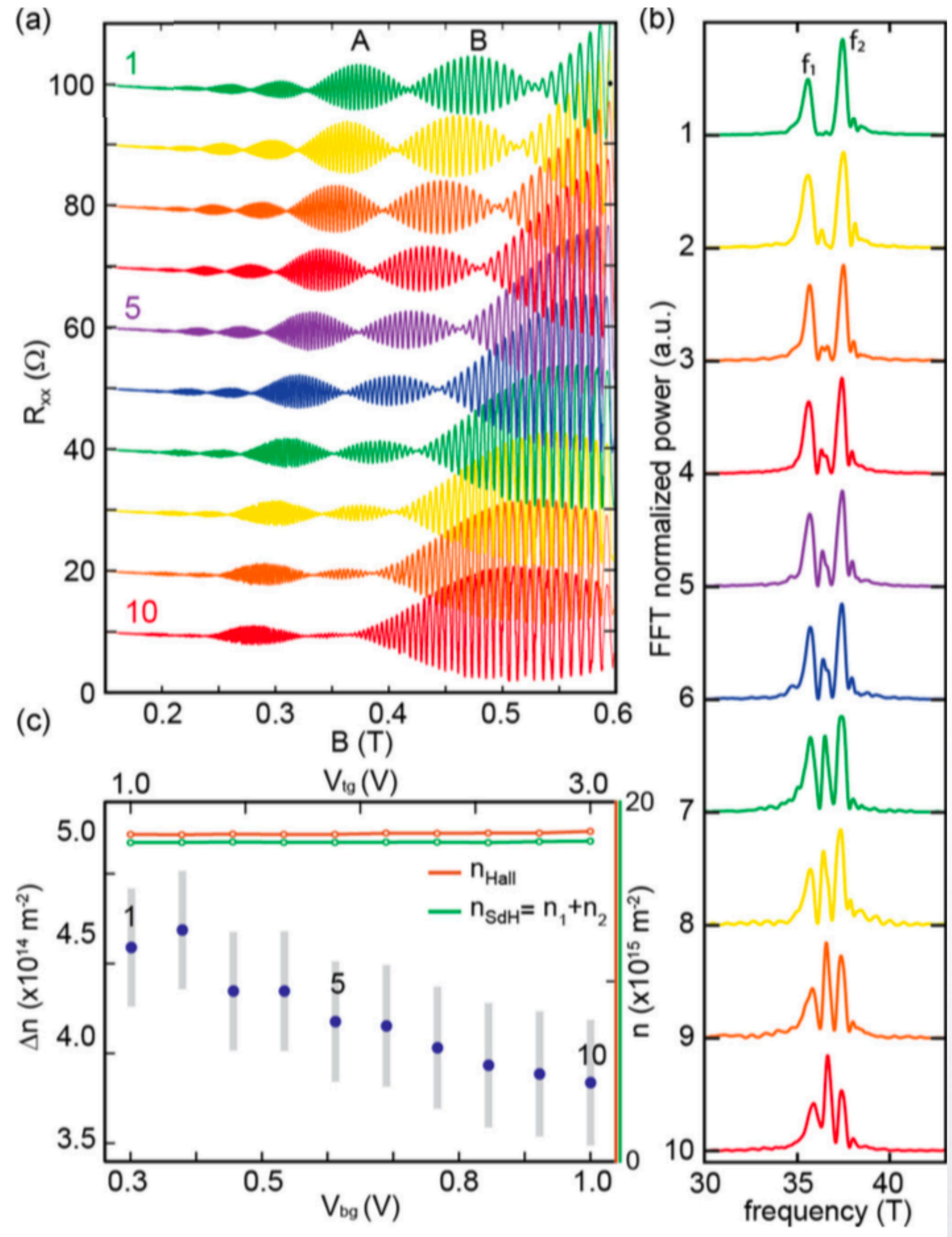
$$\ell_{\mathrm{so}} \Leftrightarrow \textit{rotation by } \pi$$

Dresselhaus spin-orbit parameter for GaAs $\ell_{\mathrm{so}} = \hbar^2/(\beta m^*) \sim 1 - 10\mu m$

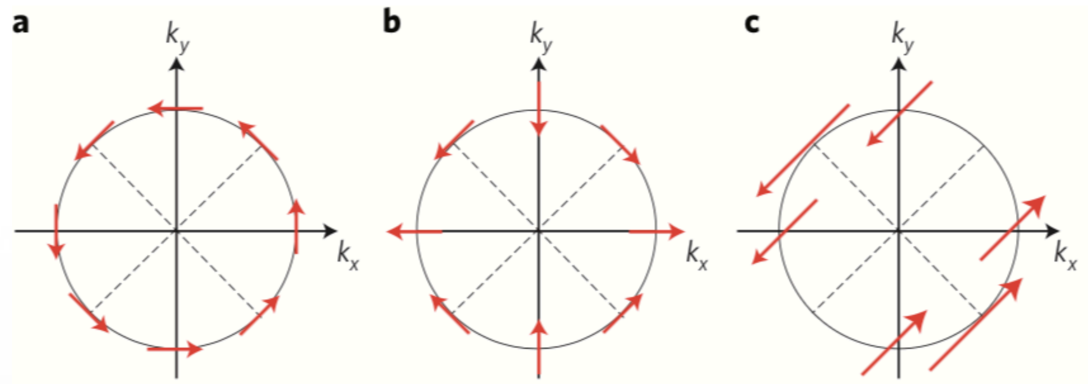
Dresselhaus spin-orbit parameter for dual-gated InAs/GaSb quantum well $\ell_{\mathrm{so}} \sim .5\mu m$ $(28.5 \text{ meV}\mathring{A})$

Rashba spin-orbit parameter for dual-gated InAs/GaSb quantum well $\ell_{\mathrm{so}} = \hbar^2/(\alpha m^*) \sim .125 - .25\mu m$ $(75 \sim 53 \text{ meV}\mathring{A})$

Rashba spin-orbit parameter for inversion layer of the heterostructure $\mathrm{In}_{0.75}\mathrm{Ga}_{0.25}As/\mathrm{In}_{0.75}\mathrm{Al}_{0.25}\mathrm{As}$ $\ell_{\mathrm{so}} \sim .06 - .125\mu m$




# Rashba interaction and Dresselhaus interaction can add up—(110) direction




Manchon, Koo, Nitta, Frolov, Duine, Perspectives for Rashba spin-orbit coupling, Nat. Materials, 14 (2015)

Beukman, de Vries, van Veen, Skolasinski, Wimmer, Qu, de Vries, Nguyen, Yi, Kiselev, Sokolich, Manfra, Nichele, Marcus, Kouwenhoven, Spin-orbit interaction in dual gated InAs/GaSb quantum well, PRB 96 (2017)

# Effective magnetic field

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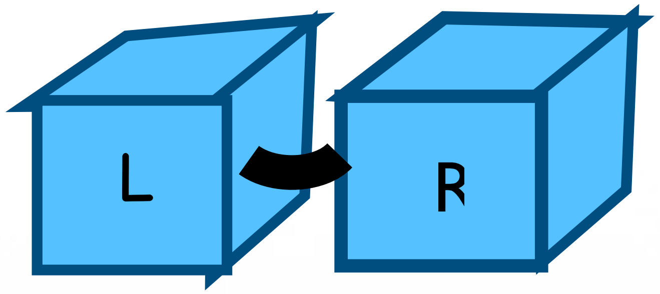
DOI: 10.1038/ncomms2584

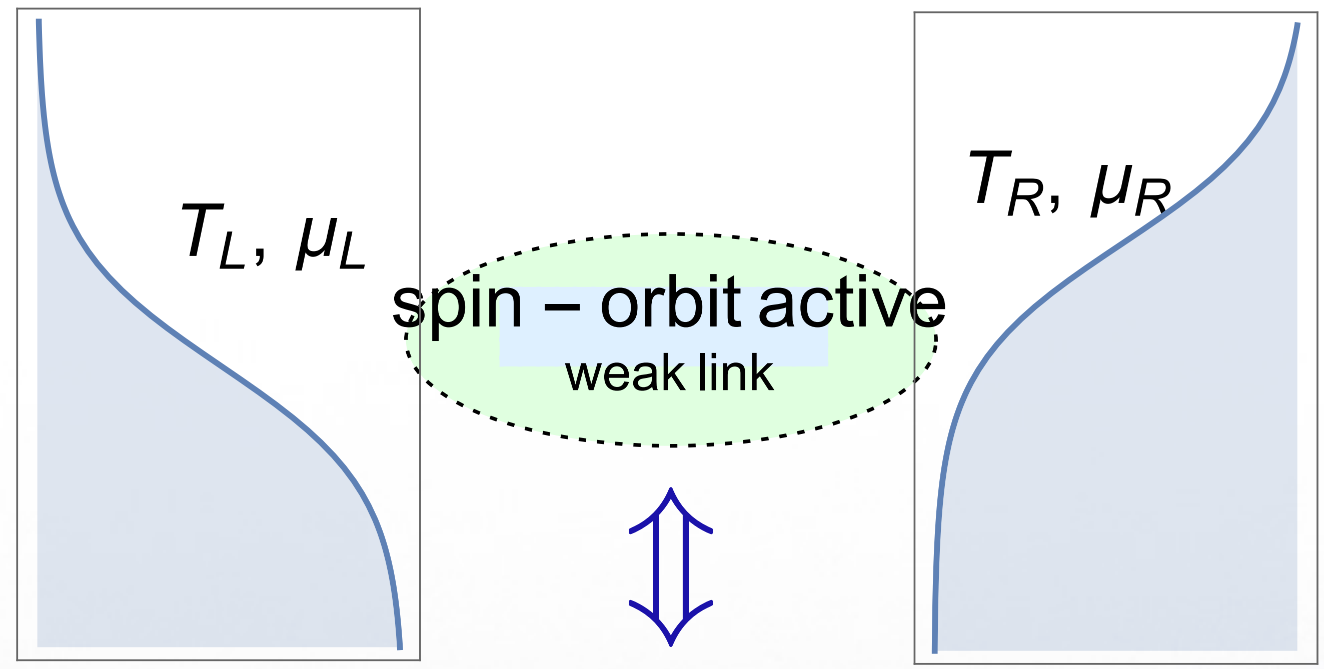
# Large spin-orbit coupling in carbon nanotubes

G.A. Steele[1], F. Pei[1], E.A. Laird[1], J.M. Jol[1], H.B. Meerwaldt[1] & L.P. Kouwenhoven[1]

It has recently been recognised that the strong spin-orbit interaction present in solids can lead to new phenomena, such as materials with non-trivial topological order. Although the atomic spin-orbit coupling in carbon is weak, the spin-orbit coupling in carbon nanotubes can be significant due to their curved surface. Previous works have reported spin-orbit couplings in reasonable agreement with theory, and this coupling strength has formed the basis of a large number of theoretical proposals. Here we report a spin-orbit coupling in three carbon nanotube devices that is an order of magnitude larger than previously measured. We find a zero-field spin splitting of up to 3.4 meV, corresponding to a built-in effective magnetic field of 29 T aligned along the nanotube axis. Although the origin of the large spin-orbit coupling is not explained by existing theories, its strength is promising for applications of the spin-orbit interaction in carbon nanotubes devices.

# propagation through a ``Rashba-effective" link




$$\Updownarrow$$

$$\mathcal{H}_R = \alpha_R(\mathbf{E} \times \mathbf{p}) \cdot \boldsymbol{\sigma}$$

$$\Updownarrow$$

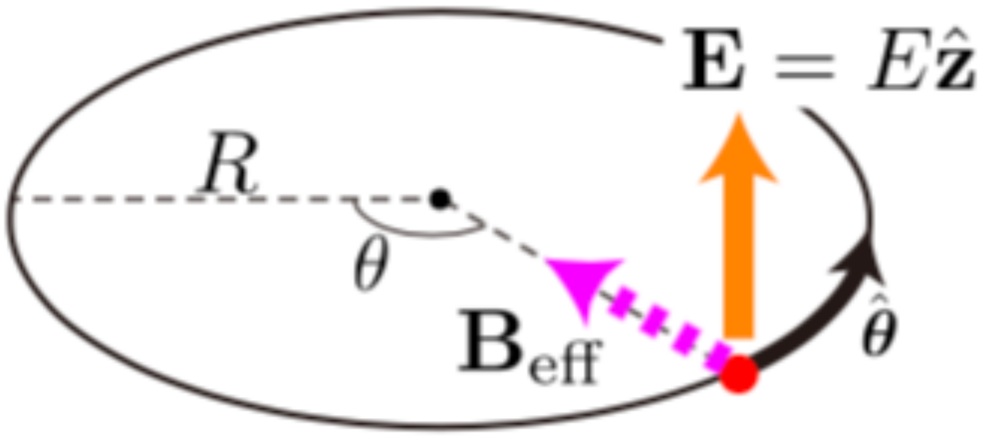
Tunneling matrix element?

Bychkov and Rashba, Oscillatory effects and the magnetic susceptibility of carriers in invention layers, J. Phys. C 17 (1984)

phenomenological Hamiltonian for spin-orbit coupling in uniaxial-symmetric systems lacking inversion symmetry (heterostructures, surfaces)

# propagation through a "Rashba-effective" link

The Schrodinger equation for an electron moving on a ring, subjected to the Rashba interaction




$$\Big[-i\frac{d}{d\theta}+k_{\rm so}\hat{\mathbf{n}}(\theta)\cdot\boldsymbol{\sigma}\Big]^2\psi(\theta)=\epsilon\psi(\theta)\ ,$$

$$\hat{\mathbf{n}}(\theta)=[\cos(\theta),\sin(\theta),0] \qquad \hat{\mathbf{n}}\parallel\mathbf{B}_{\rm eff}$$

$$\psi(\theta)=P(\theta)\widetilde{\psi}(\theta)\ ,$$

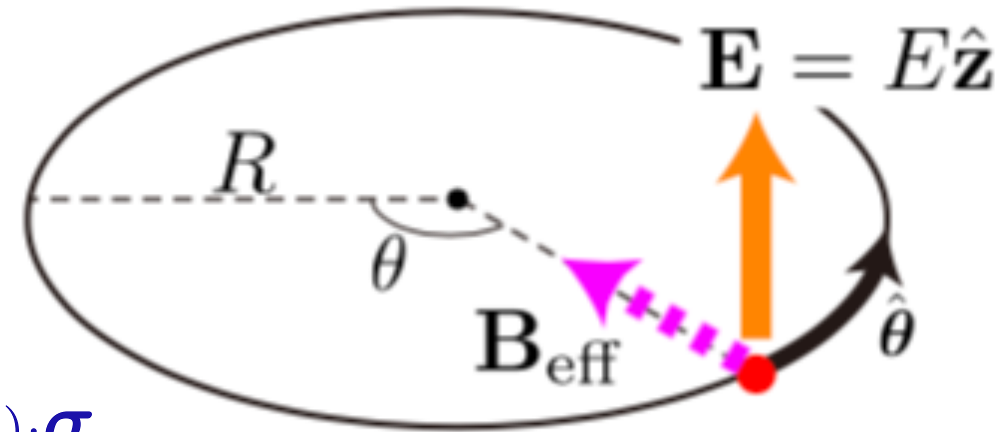
Gauge transformation:

$$i\frac{d}{d\theta}P(\theta)=k_{\rm so}\hat{\mathbf{n}}(\theta)\cdot\boldsymbol{\sigma}$$

# propagation through a "Rashba-effective" link

Electron moving through infinitesimal $d\theta$
acquires phase factor

$$\psi(\theta + d\theta) = \exp[ik_{\rm so}\hat{\mathbf{n}}(\theta)\cdot\boldsymbol{\sigma}d\theta]\psi(\theta)\ ,$$
$$\hat{\mathbf{n}}(\theta) = \hat{\mathbf{x}}\cos(\theta) + \hat{\mathbf{y}}\sin(\theta)$$

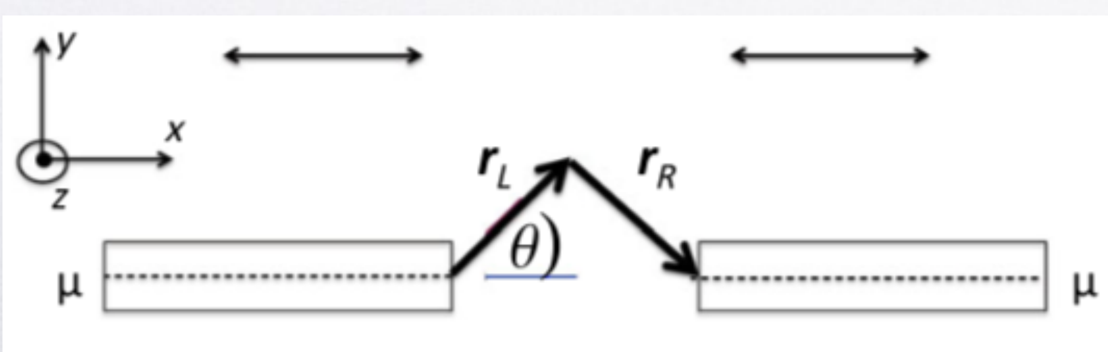



$\hat{\mathbf{n}} \parallel \mathbf{B}_{\rm eff}$

but: $e^{ik_{\rm so}\hat{\mathbf{n}}(\theta_1)\cdot\boldsymbol{\sigma}}e^{ik_{\rm so}\hat{\mathbf{n}}(\theta_2)\cdot\boldsymbol{\sigma}} \neq e^{ik_{\rm so}\hat{\mathbf{n}}(\theta_2)\cdot\boldsymbol{\sigma}}e^{ik_{\rm so}\hat{\mathbf{n}}(\theta_1)\cdot\boldsymbol{\sigma}}$

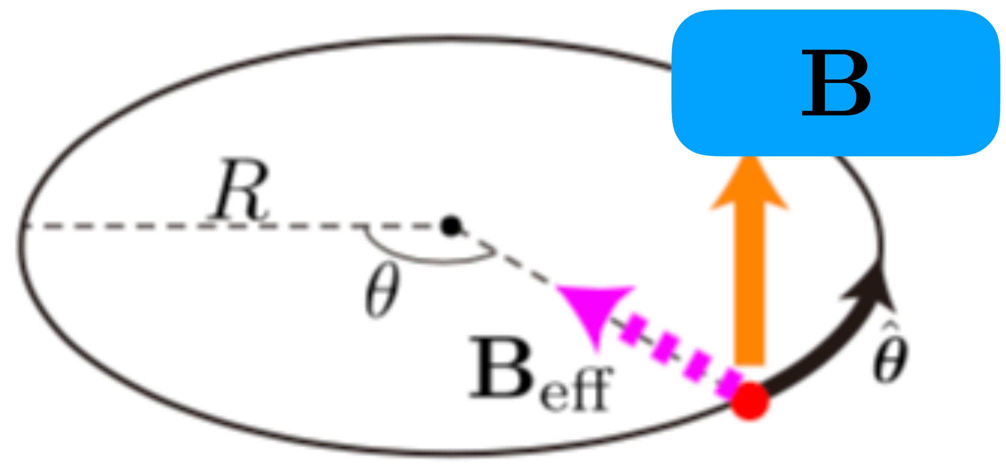
there appears effective magnetic field along $\hat{\mathbf{z}}$

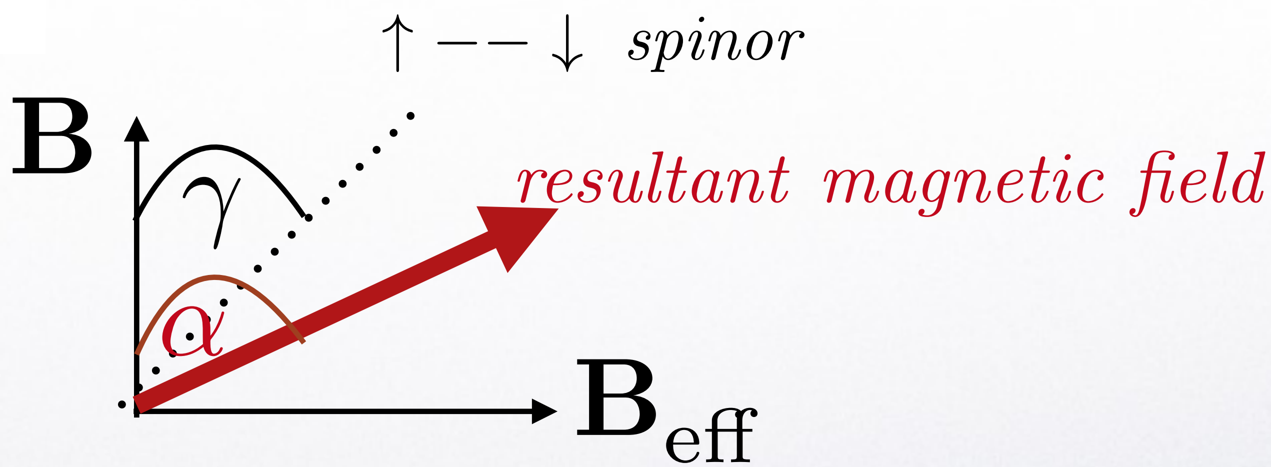
**example:**




$$e^{-ik_{\rm so}d\hat{\mathbf{n}}_L\cdot\boldsymbol{\sigma}}e^{-ik_{\rm so}d\hat{\mathbf{n}}_R\cdot\boldsymbol{\sigma}}$$
$$= 1 - 2\sin^2(k_{\rm so}d)\cos^2(\theta)$$
$$+ i\sin(2k_{\rm so}d)\cos(\theta)\sigma_y - i\sin^2(k_{\rm so}d)\sin(2\theta)\sigma_z$$

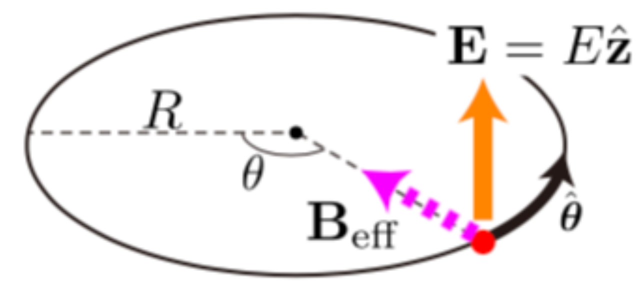
# Berry phase—Ubiquitous explanation




$\gamma \Rightarrow \alpha$ *in the adiabatic limit*

## propagation through a "Rashba-effective" finite arc NO etxternal magnetic field




$$\psi(\theta) = \begin{bmatrix} P_{11}(\theta) & P_{12}(\theta) \\ P_{21}(\theta) & P_{22}(\theta) \end{bmatrix} \psi(0)$$

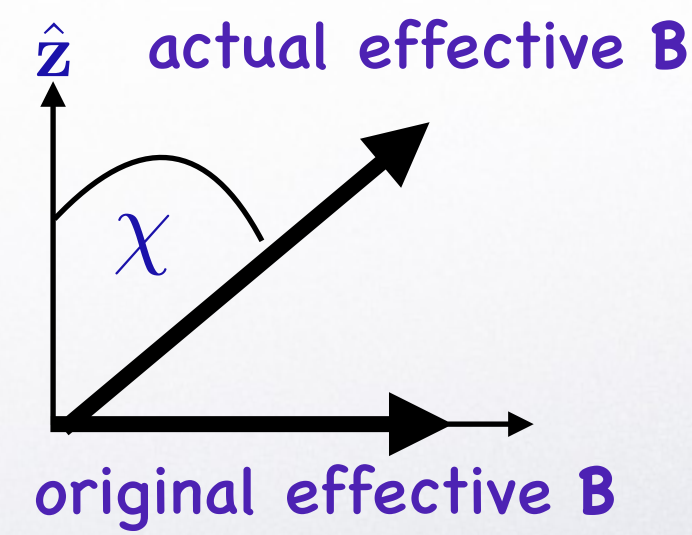
$$P_{11}(\theta) = P_{22}^*(\theta) = e^{-i\frac{\theta}{2}}\left(\cos[(a-\frac{1}{2})\theta] - i\cos(\chi)\sin[(a-\frac{1}{2})\theta]\right)$$

$$P_{12}(\theta) = P_{21}^*(\theta) = -ie^{-i\frac{\theta}{2}}\sin(\chi)\sin[(a-\frac{1}{2})\theta]$$

$$a = \frac{1-\cos(\chi)}{2} + k_{\rm so}\sin(\chi) \quad [\textit{dimensionless } k_{\rm so}]$$

Aharonov-Anandan (Berry) phase

Dynamical phase




$$\tan(\chi) = -2k_{\rm so} \;\Rightarrow\; a = [1 - 1/\cos(\chi)]/2$$

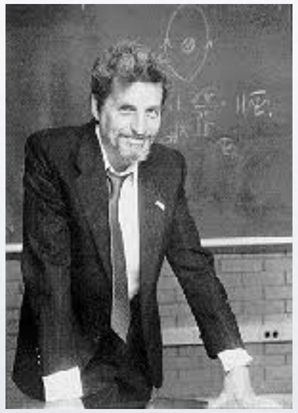
*Aharonov and Casher, Topological quantum effects for neutral particles, PRL 53, (1984)

*Aharonov and Anandan, Phase change during a cyclic quantum evolution, PRL 58, (1987)

*Qian and Su, Spin-orbit interaction and Aharonov-Anandan phase in mesoscopic rings, PRL 72, (1994)

* Avishai, Totsuka, and Nagaosa, Non-abelian Aharonov-Casher phase factor in mesoscopic systems, arXiv: 1904.01751

A. Casher



Y. Aharonov

J. Anandan

## tunneling amplitude— the propagator

Shabhazyan and Raikh, Low-field anomaly in 2D hopping magnetoresistance caused by spin-orbit term in the energy spectrum, PRL 73, (1994)

propagation of a plane wave (wave vector k) along a straight segment of length s

$$P(E) = \int dk e^{iks} [E_{\mathrm{F}} - \mathcal{H}(k)]^{-1}$$

$$\mathcal{H} = \frac{1}{2m^*}\Big(-i\frac{d}{d\mathbf{s}} - \frac{e}{c}\mathbf{A}\Big)^2 + \frac{\widetilde{k}_{\mathrm{so}}}{m^*}\hat{\mathbf{n}}\cdot\boldsymbol{\sigma}\times\Big(-i\frac{d}{d\mathbf{s}} - \frac{e}{c}\mathbf{A}\Big) - \mathbf{B}\cdot\boldsymbol{\sigma}$$

$$\Longrightarrow \quad \mathcal{H}(k) = \frac{k^2}{2m^*} + \frac{k k_{\mathrm{so}}}{m^*}(\hat{\mathbf{n}}\times\hat{\mathbf{s}})\cdot\boldsymbol{\sigma}$$

omit Aharonov-Bohm phase due to **A**, ignore Zeeman interaction due to **B**, assume **n||E** normal to plane where **k** is

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$$\Longrightarrow \mathcal{H}(k) = \frac{k^2}{2m^*} + \frac{kk_{\mathrm{so}}}{m^*}(\hat{\mathbf{n}}\times\hat{\mathbf{s}})\cdot\boldsymbol{\sigma}$$

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omit Aharonov-Bohm phase due to **A**, ignore Zeeman interaction due to **B**, assume **n||E** normal to plane where **k** is

propagation of a plane wave (wave vector k) along a straight segment of length s

$$P(E) = \int dk e^{iks}[E_{\rm F} - \mathcal{H}(k)]^{-1}$$

Cauchy integration $\Downarrow$

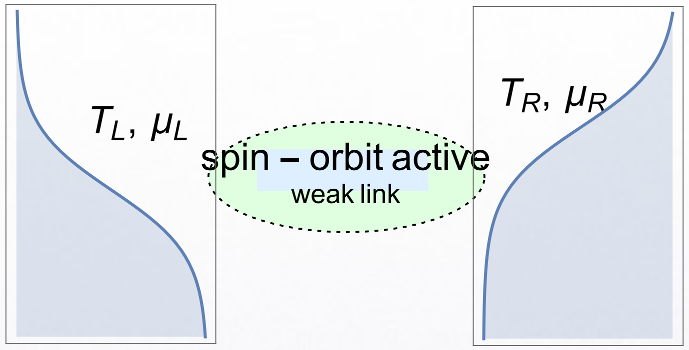
propagation amplitude is a unitary matrix in the Hilbert space of the spin

$$= -i\pi m^* \frac{e^{is\sqrt{k_{\rm F}^2+k_{\rm so}^2}}}{\sqrt{k_{\rm F}^2+k_{\rm so}^2}} \exp[ik_{\rm so}\hat{\mathbf{n}}\times\hat{\mathbf{s}}\cdot\boldsymbol{\sigma}]$$

Tunneling amplitude

also a unitary matrix

$$E_{\rm F} < \mu$$

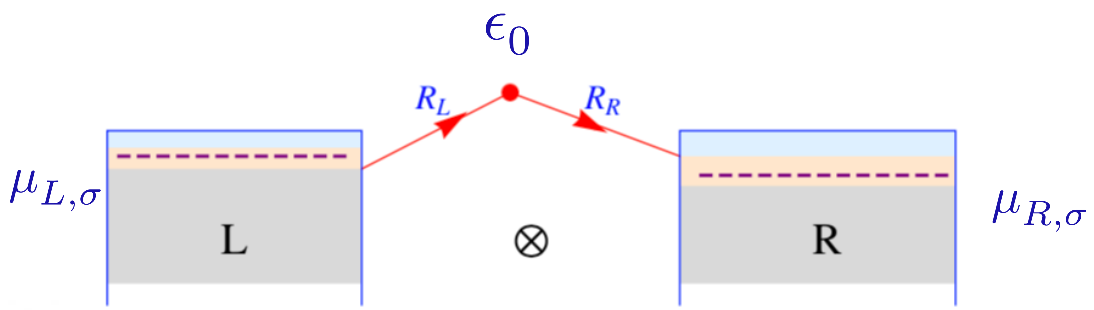


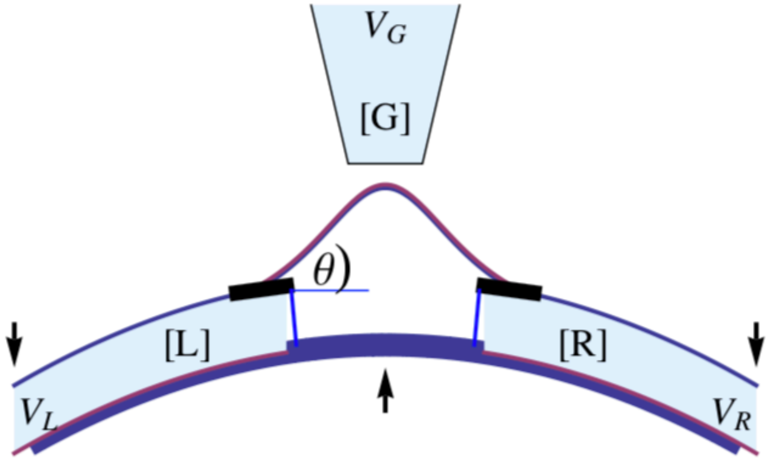

$$P(E) = -\pi m^* \frac{e^{-s\sqrt{(1/a^2)-k_{\rm so}^2}}}{\sqrt{(1/a^2)-k_{\rm so}^2}} \exp[ik_{\rm so}\hat{\mathbf{n}}\times\hat{\mathbf{s}}\cdot\boldsymbol{\sigma}]$$

time-reversal symmetry -> no spin polarization in two-terminal junctions

Bardarson, a proof of Kramers degeneracy of transmission eigenvalues from antisymmetry of the scattering matrix, J. Phys. A 41 (2008)

# Mechanically controlled Rashba spin splitter




The model exploited in the calculations: the location of the quantum dot vibrates normal to the wire in the junction plane

Shekhter, OEW, and Aharony, Suspended nanowires as mechanically-controlled Rashba spin filters, PRL 111 (2013)

The spin-orbit interaction in the bent wire can be modulated mechanically by loads and electrically, by biasing the STM

$$I_{L,\sigma} = \frac{\Gamma_L \Gamma_R}{2\pi\epsilon_0^2} \sum_{\sigma'} \sum_{n,n'=0}^{\infty} P(n) |\langle n|[e^{-i\psi_R} e^{-i\psi_L}]_{\sigma'\sigma}|n'\rangle|^2$$

$$\times\, (1 - e^{\beta(\mu_{L,\sigma} - \mu_{R,\sigma'})}) \frac{\mu_{L,\sigma} - \mu_{R,\sigma'} + (n'-n)\omega}{e^{\beta[\mu_{L,\sigma} - \mu_{R,\sigma'} + (n'-n)\omega]} - 1}$$

$$P(n) = (1 - e^{-\beta\omega}) e^{-n\beta\omega}$$

Shekhter, Gorelik, Glazman, and Jonson, Electronic Aharonov-Bohm effect induced by quantum vibrations, PRL 97 (2006)

Electrons tunneling through the weak link (e.g., SWNT) excite flexural vibrations in the presence of Aharonov-Bohm type magnetic field

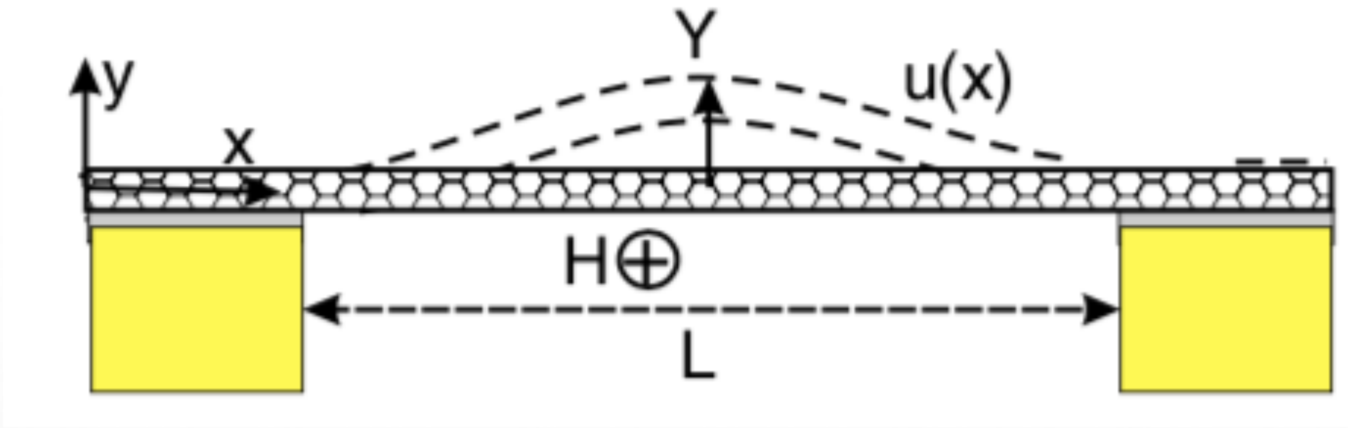



FIG. 2 (color online). Nanoelectromechanical system proposed to show the coherent coupling between quantum electron transport and quantum flexural vibrations discussed in the text. Electrons tunneling through a doubly clamped SWNT excite quantized vibrations of the SWNT in the presence of a magnetic field, *H*. The resulting effective multiconnectivity of the system leads to a negative magnetoconductance (see text).

## Unpolarized leads

$$\mu_{L(R),\sigma} = \mu_{L(R)}$$

$$I_{L,\sigma} = \frac{\Gamma_L \Gamma_R}{2\pi\epsilon_0^2} \sum_{\sigma'} \sum_{n,n'=0}^{\infty} P(n) |\langle n| [e^{-i\psi_R} e^{-i\psi_L}]_{\sigma'\sigma} |n'\rangle|^2$$

$$\times (1 - e^{\beta(\mu_{L,\sigma} - \mu_{R,\sigma'})}) \frac{\mu_{L,\sigma} - \mu_{R,\sigma'} + (n'-n)\omega}{e^{\beta[\mu_{L,\sigma} - \mu_{R,\sigma'} + (n'-n)\omega]} - 1}$$

$$P(n) = (1 - e^{-\beta\omega}) e^{-n\beta\omega}$$

Summing over spin indices (to obtain the charge current) implies

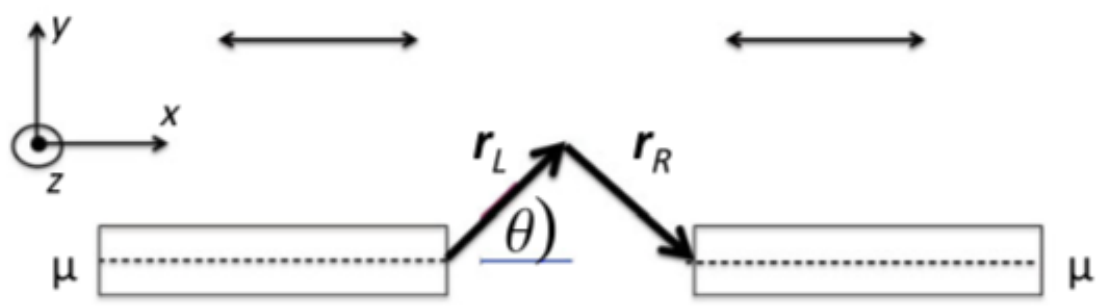
$$\delta_{n,n'}$$

leading to the Landauer formula (particle current)

(almost) no effect of Rashba interaction on the tunneling conductance

$$I = (\mu_R - \mu_L) \frac{\Gamma_L \Gamma_R}{\pi \epsilon_0^2}$$

## Details of the spin-orbit interaction




$$e^{-i\psi_L} e^{-i\psi_R}$$

$$e^{-ik_{\mathrm{so}} d\hat{\mathbf{n}}_L\cdot\boldsymbol{\sigma}} e^{-ik_{\mathrm{so}} d\hat{\mathbf{n}}_R\cdot\boldsymbol{\sigma}}$$
$$= 1 - 2\sin^2(k_{\mathrm{so}} d)\cos^2(\theta)$$
$$+ i\sin(2k_{\mathrm{so}} d)\cos(\theta)\sigma_y - i\sin^2(k_{\mathrm{so}} d)\sin(2\theta)\sigma_z$$

$$\theta = \theta_0 + \frac{a_0\cos(\theta_0)}{d}(b + b^\dagger)$$

## Rashba scatterer as a spin source

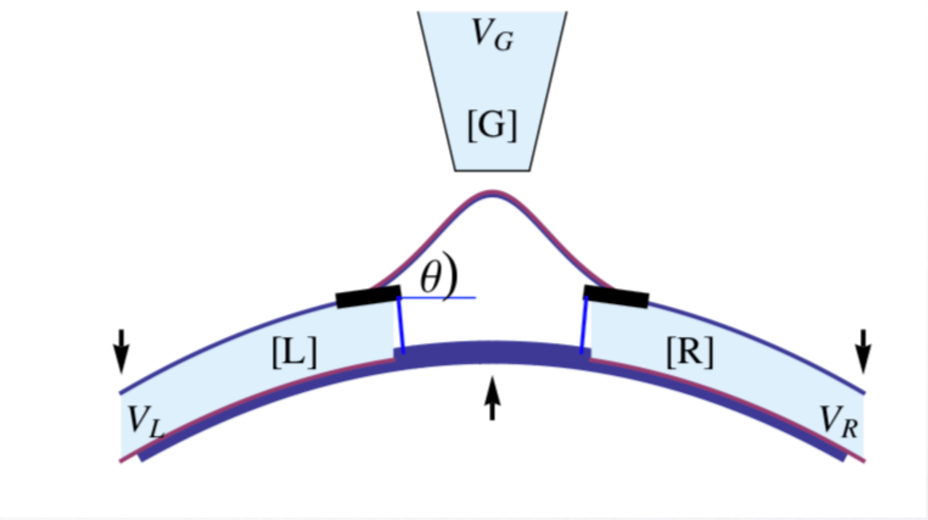
$$\mu_{L(R)\sigma} = \mu + \sigma\frac{U_{L(R)}}{2}$$
$$U = \frac{U_L + U_R}{2}$$

For a certain spin component:

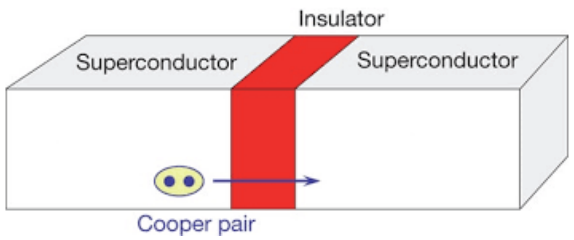
$$I_{L,\sigma} + I_{R,\sigma} = U\frac{\Gamma_L\Gamma_R}{\pi\epsilon_0^2}\sin^2(2k_{\mathrm{so}} d)$$
$$\times\sum_{n=0}^{\infty}\sum_{\ell=1}^{\infty} P(n)|\langle n|\cos(\theta)|n+\ell\rangle|^2\frac{2\beta\ell\omega}{e^{\beta\ell\omega}-1}$$

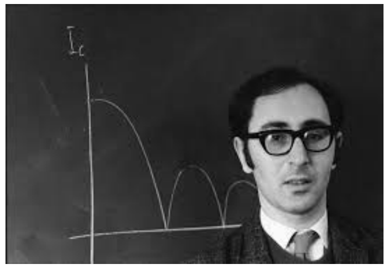
# Rashba spin splitter

Dynamic of the spin is deterministic (i.e., not random as from magnetic impurities) $\Rightarrow$ interference of spins in nanostructures with spatially localized spin-orbit interaction induces spin currents in unpolarized conductors, currents which are not associated with charge transportation. The Rashba spin splitter can be designed by mechanically tuning the nanowire.



# Rashba splitting of Cooper pairs
# Josephson current



Splitting of the spin state of paired electrons (that carry the Josephson current) $\Rightarrow$ interference between the channel where $\uparrow\downarrow$ and the channel where $\uparrow\uparrow$

$\Downarrow$

interference pattern in the amplitude of the Josephson current (not there in the normal conductance)

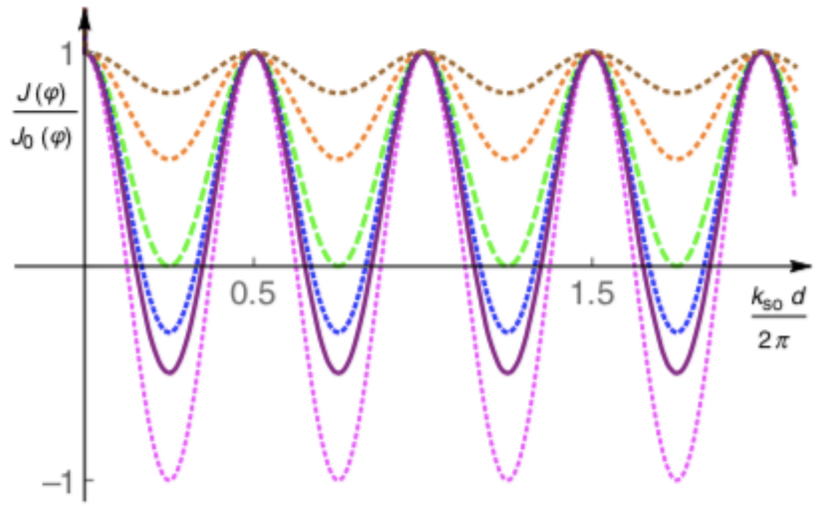



FIG. 3. The Josephson current $J(\varphi)$ divided by its value without the SO interaction, $J_0(\varphi)$, for the genuine Rashba configuration [Eqs. (7) and (8)] as a function of $k_{so}d/(2\pi)$. The largest amplitude is for the zero bending angle, $\theta = 0$, decreasing gradually for $\theta = \pi/6, \pi/5, \pi/4, \pi/3, \pi/2.5$ [Fig. 2(b)]. Relevant values of $k_{so}$ are estimated in the text.

Shekhter, OEW, Aharony, Jonson, Rashba splitting of Cooper pairs, PRL 116, (2016)

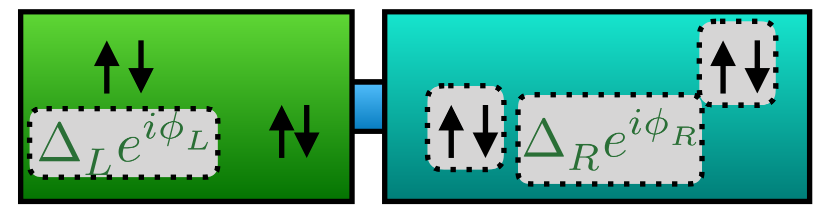
# Josephson equilibrium current

*electrons in the source are paired in time-reversed states in which their spins are antiparallel
*supercurrent carried by Cooper pairs flows in the non-superconducting link when there is a (order-parameter) phase difference across the weak link
*the electrons tunnel one-by-one but the Cooper pairs maintain superconducting coherence (link shorter than the coherence length)
*when reaching the drain the electrons are paired again

# Josephson equilibrium current

*Supercurrent is proportional to the superconducting phase difference

$$I(\varphi) = I_0 \sin(\varphi)$$
$$\varphi = \phi_L - \phi_R$$



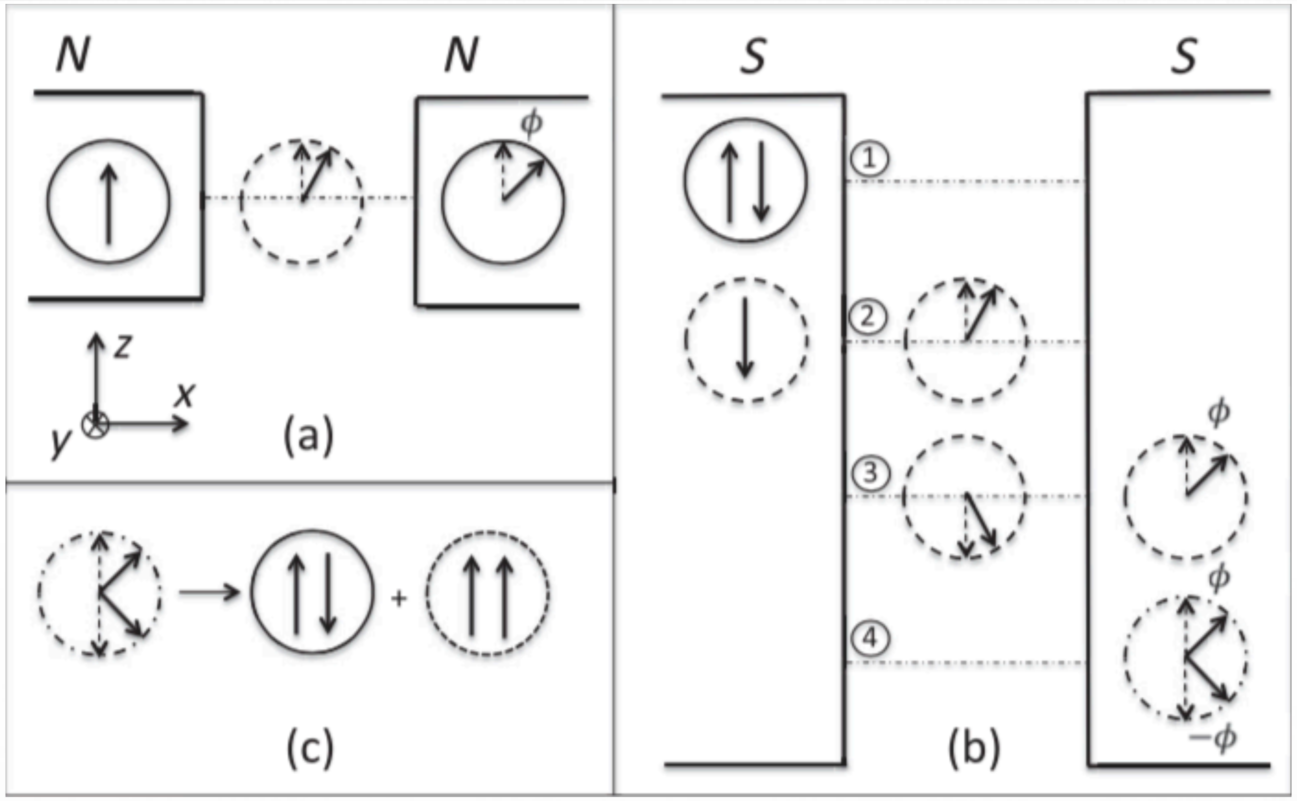

*the critical current for a junction with identical superconductors $I_0 = \dfrac{\pi \Delta}{2e} G_n$

Ambegaokar and Baratoff, tunneling between superconductors, PRL 10, (1963)

* $G_n$ is the normal-state conductance

# Illustration (semi-classical description)

$\phi \propto$ spin – orbit coupling $(k_{so}d)$




sequential transfer

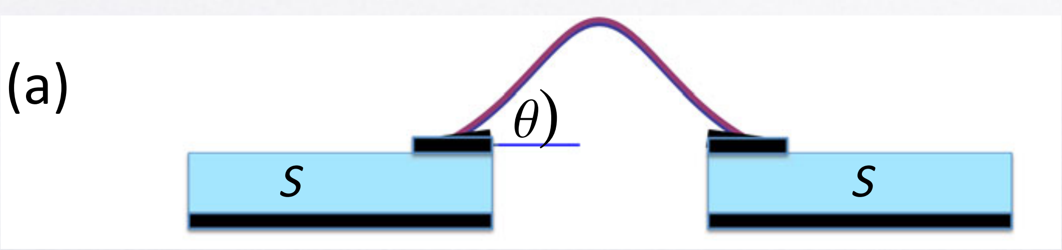
Evolution of spin states of electrons moving between two bulk leads via link in which they are subjected to Rashba interaction (effective magnetic field directed along **y**)

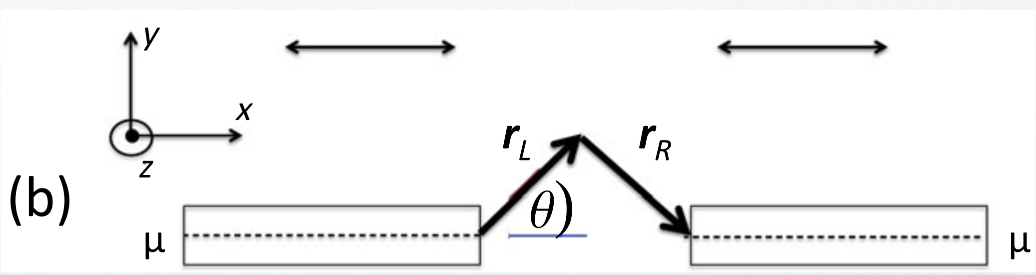
N-N: if the spin in left is along **z**, the spin at right is in a coherent superposition of $\uparrow,\downarrow$

Cooper pair S-S (Coulomb-blockade-no double occupancy on the link) two electrons in time-reversed quantum states, their spins are reversed wrt one another, rotation angles have opposite signs.
Final state is a coherent mixture of spin-singlet and spin-triplet state, but only the former can enter into the second S, leading to a reduction in the amplitude of the Josephson current.

# Transfer of Cooper pairs through a weak link

*Cooper pairs are transferred between superconducting leads via virtual localized states
*Coulomb blockade-the members of the pair are transferred sequentially
*short weak link-dependence of the matrix element for a single-electron transfer on electron energy in the virtual state can be ignored $d < \hbar v_{\mathrm{F}}/|\Delta|$
*conservation of longitudinal momentum

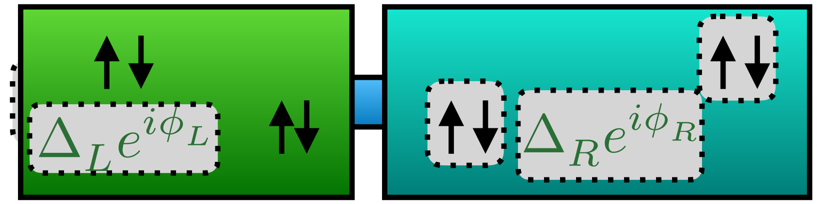


# Josephson tunneling

$$\mathcal{H} = \mathcal{H}_L + \mathcal{H}_R + \mathcal{H}_T$$

$$\mathcal{H}_L = \sum_{\mathbf{k}} \sum_{\sigma} (\epsilon_k - \mu) c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \left( \Delta_L e^{i\phi_L} \sum_{\mathbf{k}} c^\dagger_{\mathbf{k}\uparrow} c^\dagger_{-\mathbf{k}\downarrow} + \text{H.c.} \right)$$




Single-electron tunneling

$$\mathcal{H}_T = \sum_{\mathbf{k},\mathbf{p}} \sum_{\sigma,\sigma'} \left( c^\dagger_{\mathbf{p}\sigma'} [W_{\mathbf{pk}}]_{\sigma'\sigma} c_{\mathbf{k}\sigma} + \text{H.c.} \right)$$

Time-reversal symmetry

$$[W_{\mathbf{pk}}]_{\sigma\sigma'} = \left( [W_{-\mathbf{p}-\mathbf{k}}]_{-\sigma-\sigma'} \right)^*$$

## Josephson current

For $W_{\mathbf{kp}} = W_0 \mathcal{W}$

calculation of the current
(second-order in the tunneling)

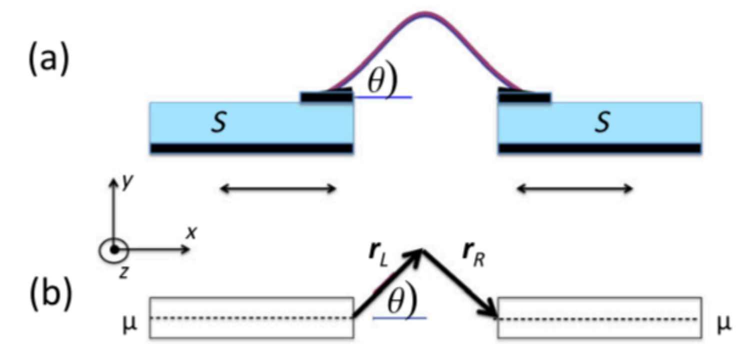
$$I_L = -e\langle \dot{N}_L \rangle = -ie\langle [\mathcal{H}, \sum_{\mathbf{k}\,\sigma} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma}] \rangle$$

gives for the equilibrium (no bias) Josephson current

$$\frac{I(\varphi)}{I_0(\varphi)} = \frac{1}{2} \sum_{\sigma} ([\mathcal{W}]_{\sigma\sigma} - [\mathcal{W}]_{\sigma -\sigma})$$

Without the spin-orbit interaction $\mathcal{W}_{\sigma\sigma}$ is diagonal in spin space

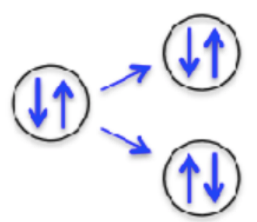
# Rashba splitting of Cooper pairs (in the Coulomb blockade regime)




## equilibrium (no bias) Josephson current

$$\frac{I(\varphi)}{I_0(\varphi)} = \frac{1}{2}\sum_{\sigma}[|\mathcal{W}_{\sigma\sigma}|^2 - |\mathcal{W}_{\sigma\overline{\sigma}}|^2] \;= 1 - 2\cos^2(\theta)\sin^2(k_{\rm so}d)$$

Josephson tunneling $\pi$ shift



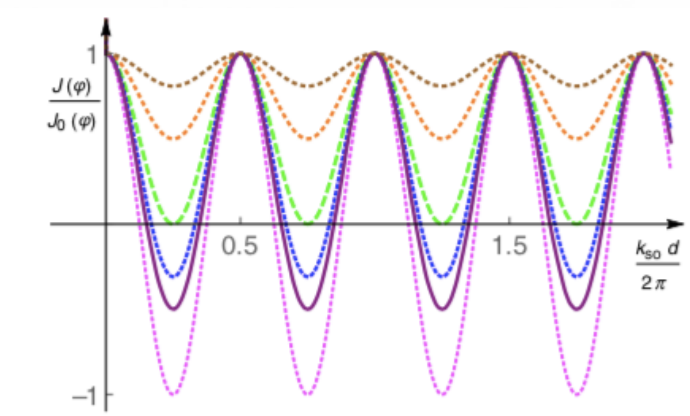


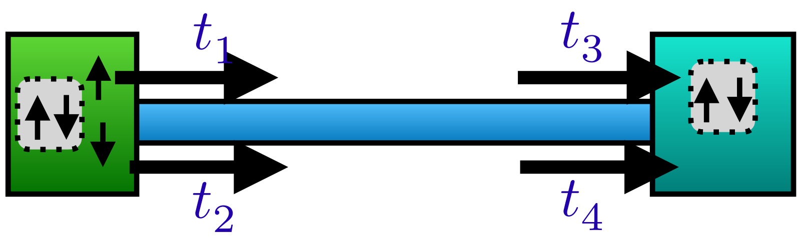

FIG. 3. The Josephson current $J(\varphi)$ divided by its value without the SO interaction, $J_0(\varphi)$, for the genuine Rashba configuration [Eqs. (7) and (8)] as a function of $k_{so}d/(2\pi)$. The largest amplitude is for the zero bending angle, $\theta = 0$, decreasing gradually for $\theta = \pi/6, \pi/5, \pi/4, \pi/3, \pi/2.5$ [Fig. 2(b)]. Relevant values of $k_{so}$ are estimated in the text.

special cases :

$\theta = 0\ ,\ \ k_{\rm so}d = \pi/4\ ,\pi/2$

## Normal-state conductance is unchanged

# Lifting the Coulomb blockade
## (will this destroy the coherent spin precession)




1st electron comes into the link at $t_1$ leaves at $t_3$

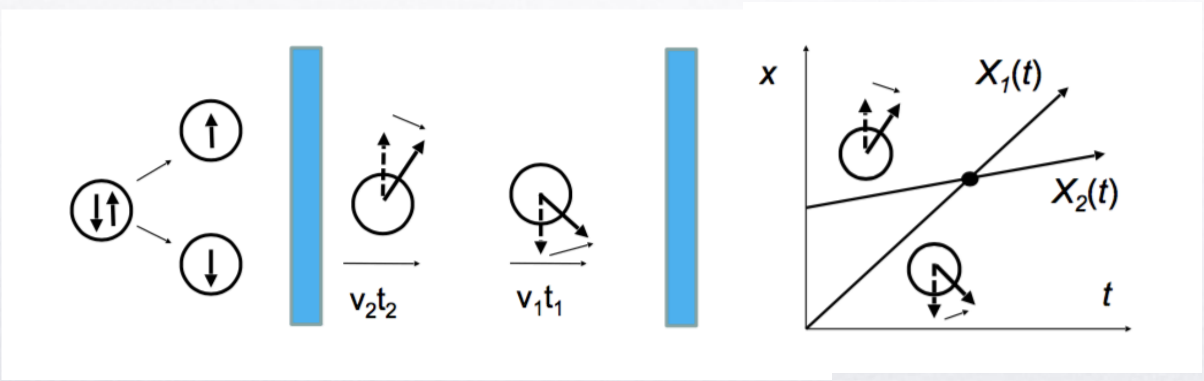
2nd electron comes into the link at $t_2$ leaves at $t_4$

``single-electron tunneling channel" $t_1 < t_3 < t_2 < t_4$

electrons tunnel sequentially one by one

``double-electron tunneling channel" $t_1 < t_2 < t_3 < t_4$

Coulomb interaction comes into play

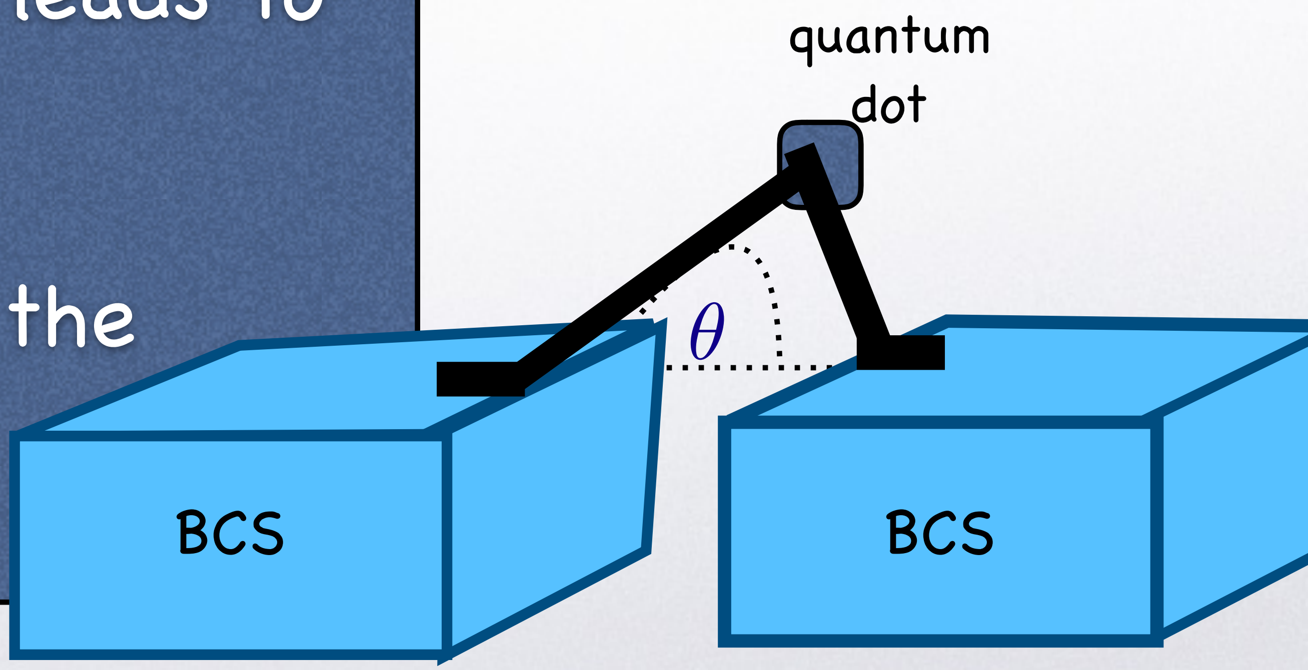



conflict with

Pauli principle

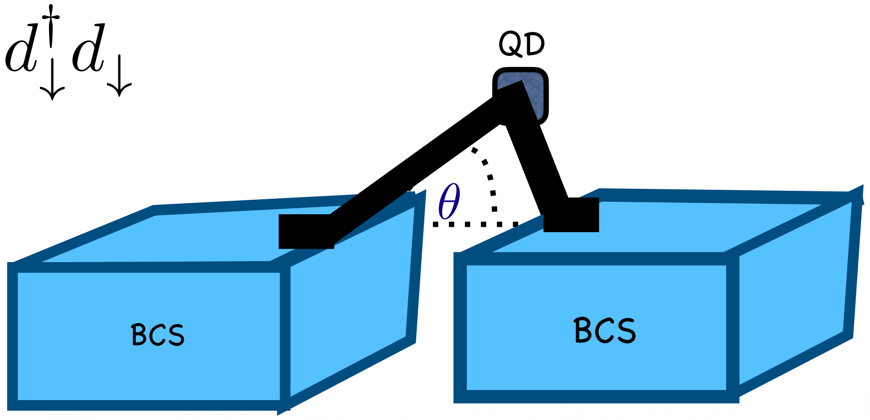
# modeling spin precession of Cooper pairs

*the ``meeting point" is modeled by a quantum dot with spin-up and spin-down states; injection into these states obeys the Pauli principle (breaking the coherent evolution of spin states before and after the meeting)
*single-electron tunneling from leads to the quantum dot
*Coulomb repulsion on the dot
*the results are averaged over the location of the quantum dot



# System's Hamiltonian

$$\mathcal{H} = \mathcal{H}_L + \mathcal{H}_R + \mathcal{H}_{\rm tun} + \sum_\sigma \epsilon d^\dagger_\sigma d_\sigma + U d^\dagger_\uparrow d_\uparrow d^\dagger_\downarrow d_\downarrow$$




Tunneling through dot:

$$\mathcal{H}_{\rm tun} = \mathcal{H}_{LD} + \mathcal{H}_{RD} + \mathcal{H}_{DL} + \mathcal{H}_{DR}$$

$$\mathcal{H}_{LD} = \sum_{\mathbf{k},\sigma,\sigma'} [t_{\mathbf{k}}]_{\sigma\sigma'} c^\dagger_{\mathbf{k}\sigma} d_{\sigma'}$$

1. Going from the time-reversed state of $\sigma'$, *i.e.*, $|\overline{\sigma'}\rangle = (i\sigma_y)|\sigma'\rangle$ to state $|-\mathbf{k},\overline{\sigma}\rangle$

$\mathbf{T} = K(i\sigma_y)$ requires $\bar{\mathbf{t}}_{\mathbf{k}} = \mathbf{T}\mathbf{t}_{\mathbf{k}}\mathbf{T}^{-1}$

$$[\bar{\mathbf{t}}_{\mathbf{k}}]_{\overline{\sigma\sigma'}} = [\mathbf{t}^*_{\mathbf{k}}]_{\sigma\sigma'}$$


Shekhter, OEW, Jonson, Aharony, Spin precession in spin-orbit coupled weak links: Coulomb repulsion and Pauli quenching, PRB(R), 96 (2017)

$$I_L = -e\langle \dot{N}_L \rangle = -ie\langle [\mathcal{H}, \sum_{\mathbf{k}\,\sigma} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma}] \rangle$$

2. Terms in the perturbation theory

One particle on the link

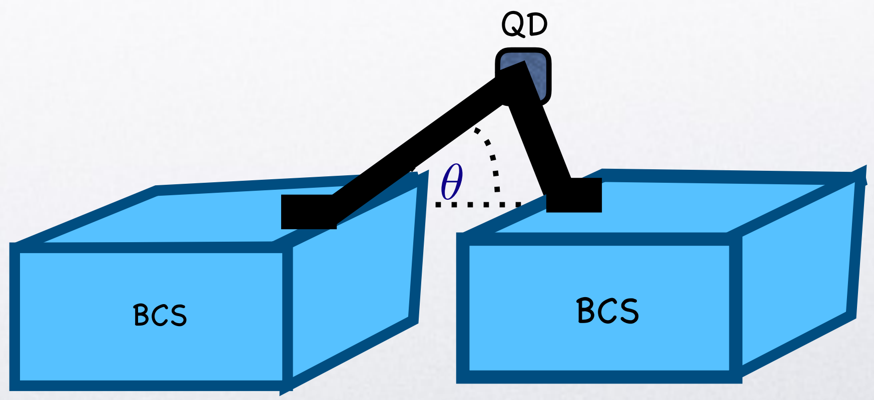
$$\langle \mathcal{H}_{LD}(t)\mathcal{H}_{DR}(t_1)\mathcal{H}_{LD}(t_2)\mathcal{H}_{DR}(t_3)\rangle$$
$$[t \geq t_1 \geq t_2 \geq t_3]$$

two particles on the link

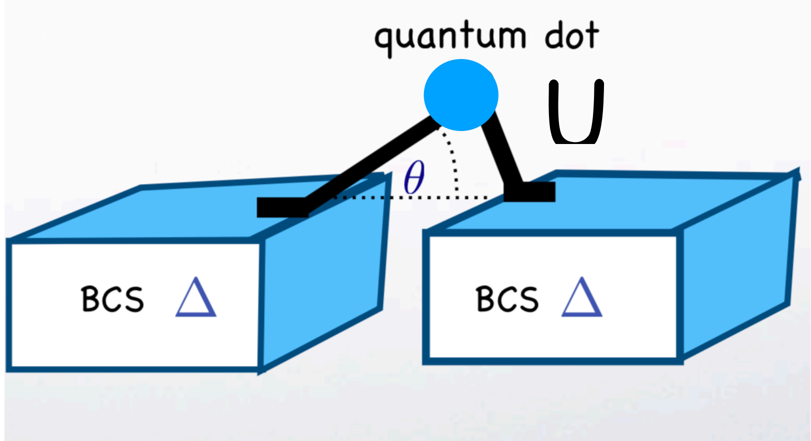
$$\langle \mathcal{H}_{LD}(t)\mathcal{H}_{LD}(t_1)\mathcal{H}_{DR}(t_2)\mathcal{H}_{DR}(t_3)\rangle$$

3. In the first scenario the tunneling amplitudes can be grouped to yield an effective L<->R amplitude, $V_{LR}$;

In the second they cannot.



4. Spin dependent transmission




One particle on the link

$$\mathcal{T}_1 = \frac{1}{2}\sum_\sigma (|V_{LR}V^\dagger_{LR}]_{\sigma\sigma} - [V_{LR}V^\dagger_{LR}]_{\sigma-\sigma})$$

two particles on the link

$$\mathcal{T}_2 = \left(|[V_{DR}]_{\uparrow\uparrow}|^2 - |[V_{DR}]_{\uparrow\downarrow}|^2\right)\left(|[V_{LD}]_{\uparrow\uparrow}|^2 - |[V_{LD}]_{\uparrow\downarrow}|^2\right)$$

Loss of coherence at the quantum dot due to the Pauli principle

5. ``energy denominator'' due to quantum dot

$$F_1(\frac{\epsilon}{\Delta}) = \int_{-\infty}^{\infty} \frac{dx_1 dx_2}{\pi^2}\left[[\cosh(x_1) + \frac{\epsilon}{\Delta}][\cosh(x_1) + \cosh(x_2)][\cosh(x_2) + \frac{\epsilon}{\Delta}]\right]^{-1}$$

$$F_2(\frac{\epsilon}{\Delta}, \frac{U}{\Delta}) = \int_{-\infty}^{\infty} \frac{dx_1 dx_2}{\pi^2}\left[[\cosh(x_1) + \frac{\epsilon}{\Delta}][2\frac{\epsilon}{\Delta} + \frac{U}{\Delta})][\cosh(x_2) + \frac{\epsilon}{\Delta}]\right]^{-1}$$

Glazman and Matveev, Resonant Josephson current through Kondo impurities in a tunnel barrier, JEPT Lett., 49 (1989)

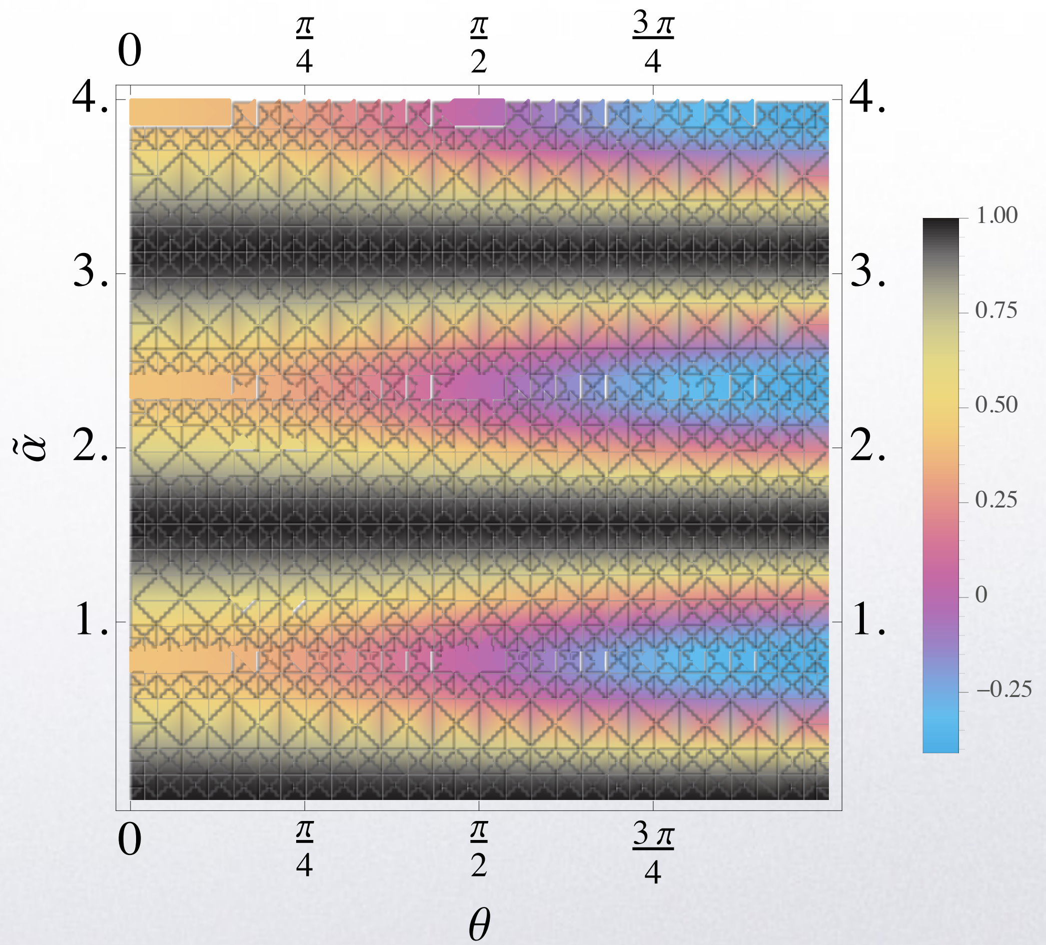
# mechanical and electric manipulation of the supercurrent in the Coulomb-blockade regime

$$\frac{I(\varphi)}{I_0(\varphi)} = F_1\left(\frac{\epsilon}{\Delta}\right)\mathcal{T}_1 + 2F_2\left(\frac{\epsilon}{\Delta}, \frac{U}{\Delta}\right)\mathcal{T}_2$$

Single Double

$$I_0(\varphi) = e\frac{\Gamma_L\Gamma_R}{\Delta}\sin(\varphi)$$

FIG. 3: (Color online) A density plot of the normalized Josephson current, Eq. (18), as a function of the angle $\theta$ between $\hat{\mathbf{v}}_L$ and $\hat{\mathbf{v}}_R$ and the spin-orbit coupling constant, $\tilde{\alpha}$ [see Eqs. (35)]. The parameters that determine Eqs. (15) and (16) are $\epsilon/\Delta = 0$ and $U/\Delta = 5$.



# Breaking time-reversal symmetry by time-dependent electric fields

Spin-orbit interaction created by slowly-rotating electric field perpendicularly to the (one-dimensional) weak link

$\Downarrow$

Even though the leads are non magnetic, and there is no bias, the rotating electric field creates DC spin current and transverse spin components which rotate around the link, flowing into the leads

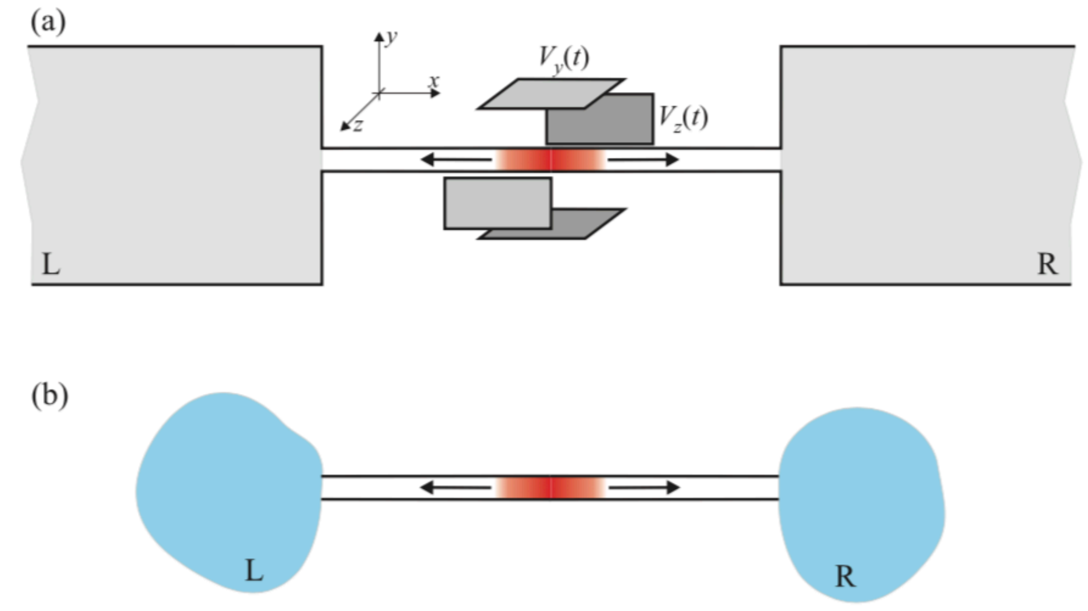


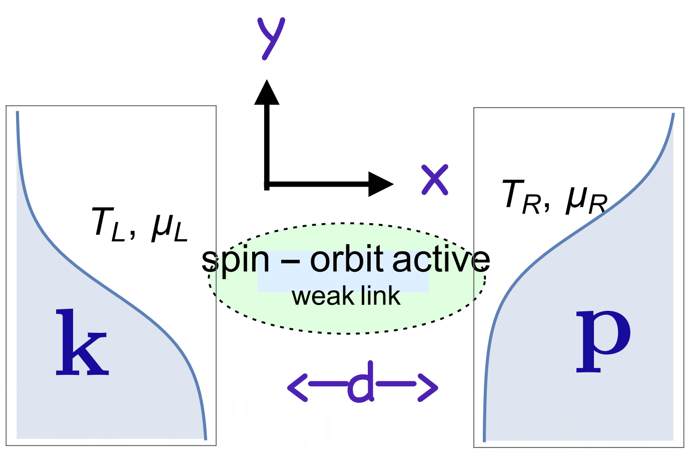

FIG. 1: Schematic visualizations of devices proposed in the text. (a) A spin-orbit-active weak link connects two contacts, $L$ and $R$, to form a closed circuit. The time-dependent spin-orbit interaction is generated by two perpendicular gates, whose potentials $V_y(t)$ and $V_z(t)$ oscillate slowly in time with frequency $\Omega$. The arrows within the weak link indicate the directions in which polarized electron-spins are flowing. (b) An open-circuit version of (a) where spin is accumulated in two terminals leading to a magnetization that can be measured.

Jonson, Shekhter, OEW, Aharony, Park, Radic, DC spin generation by junctions with Ac driven spin-orbit interaction, arXiv:1903.03321

## Time-dependent Rashba Hamiltonian (adiabatic approximation)

$$\mathcal{H}_{\rm tun}(t) = \sum_{\mathbf{k},\mathbf{p}} \sum_{\sigma,\sigma'} ([W_{LR}(t)]_{\sigma\sigma'} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{p}\sigma'} + \text{H.c.})$$

$$W_{LR}(t) = J\exp[i\varphi_{\rm AC}(t) = J\exp[k_{\rm so} d[\hat{\mathbf{x}}\times\hat{\mathbf{n}}(t)]\cdot\boldsymbol{\sigma}]$$




Circularly-rotating electric field $\quad \hat{\mathbf{n}}(t) = \cos(\Omega t)\hat{\mathbf{z}} - \sin(\Omega t)\hat{\mathbf{y}}$

elliptically-rotating electric field $\quad \hat{\mathbf{n}}(t) = [\cos(\Omega t)\hat{\mathbf{z}} - \gamma\sin(\Omega t)\hat{\mathbf{y}}]/\sqrt{\cos^2(\Omega t) + \gamma^2\sin^2(\Omega t)}$

Validity of the adiabatic limit: $\quad \Omega \ll [\textit{dwell time on link}]^{-1}$

$$\hbar\Omega \lesssim \frac{G}{G_0}\frac{\hbar v_{\rm F}}{d}$$

$$\text{transparency}: \frac{G}{G_0} \sim 0.5$$

$$v_{\rm F} \sim \frac{\ell_e e}{m^* \mu_e} \sim 10^8 \text{cm/s for InAs nanowire}$$

$$\hbar\Omega \lesssim 3\text{meV} \Rightarrow \quad \hbar\Omega \approx 0.1\text{meV}$$

$$\text{for } \Omega = 2\pi\times 20\text{GHz}$$

**Details**

System's Hamiltonian:

$$\mathcal{H} = \mathcal{H}_{\text{leads}} + \mathcal{H}_{\text{tun}}(t)\ ,$$

$$\mathcal{H}_{\text{tun}}(t) = \sum_{\mathbf{k},\mathbf{p}} \sum_{\sigma,\sigma'} ([W_{LR}(t)]_{\sigma\sigma'} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{p}\sigma'} + \text{H.c.})$$

$$\mathcal{H}_{\text{leads}} = \sum_{\mathbf{k},\sigma} \epsilon_k c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_{\mathbf{p},\sigma} \epsilon_p c^{\dagger}_{\mathbf{p}\sigma} c_{\mathbf{p}\sigma}$$

"rate": $$[R_L(t)]_{\sigma\sigma'} = \frac{d}{dt} \sum_{\mathbf{k}} \langle c^{\dagger}_{\mathbf{k}\sigma}(t) c_{\mathbf{k}\sigma'}(t) \rangle$$

Particle current (left lead): $$I_L(t) = \sum_{\sigma} [R_L(t)]_{\sigma\sigma}$$

Rate of change of the total spin (left lead):

$$\dot{\mathbf{M}}_L(t) = \frac{d}{dt} \sum_{\sigma,\sigma'} \sum_{\mathbf{k}} \langle c^{\dagger}_{\mathbf{k}\sigma}(t) \boldsymbol{\sigma}_{\sigma\sigma'} c_{\mathbf{k}\sigma'}(t) \rangle$$

$$= \sum_{\sigma,\sigma'} [R_L(t)]_{\sigma\sigma'} \boldsymbol{\sigma}_{\sigma\sigma'}$$

example:

$$\dot{M}^x_L(t) = \frac{d}{dt} \sum_{\mathbf{k}} \langle c^{\dagger}_{\mathbf{k}\uparrow}(t) c_{\mathbf{k}\downarrow}(t) + c^{\dagger}_{\mathbf{k}\downarrow}(t) c_{\mathbf{k}\uparrow}(t) \rangle$$

$$\dot{M}^z_L(t) = \frac{d}{dt} \sum_{\mathbf{k}} \langle c^{\dagger}_{\mathbf{k}\uparrow}(t) c_{\mathbf{k}\uparrow}(t) - c^{\dagger}_{\mathbf{k}\downarrow}(t) c_{\mathbf{k}\downarrow}(t) \rangle$$

in units of: $g\mu_{\text{B}}/2$

Details

System's Hamiltonian:

$$\mathcal{H} = \mathcal{H}_{\rm leads} + \mathcal{H}_{\rm tun}(t)\ ,$$

$$\mathcal{H}_{\rm tun}(t) = \sum_{\mathbf{k},\mathbf{p}}\sum_{\sigma,\sigma'}([W_{LR}(t)]_{\sigma\sigma'}c^{\dagger}_{\mathbf{k}\sigma}c_{\mathbf{p}\sigma'} + \text{H.c.})$$

$$\mathcal{H}_{\rm leads} = \sum_{\mathbf{k},\sigma}\epsilon_k c^{\dagger}_{\mathbf{k}\sigma}c_{\mathbf{k}\sigma} + \sum_{\mathbf{p},\sigma}\epsilon_p c^{\dagger}_{\mathbf{p}\sigma}c_{\mathbf{p}\sigma}$$

"rate": $$[R_L(t)]_{\sigma\sigma'} = \frac{d}{dt}\sum_{\mathbf{k}}\langle c^{\dagger}_{\mathbf{k}\sigma}(t)c_{\mathbf{k}\sigma'}(t)\rangle$$

$$[R_L(t)]_{\sigma\sigma'} = \sum_{\mathbf{k},\mathbf{p}}[f_R(\epsilon_p) - f_L(\epsilon_k)]\int_{-\infty}^{t} dt_1 e^{\eta t_1}$$

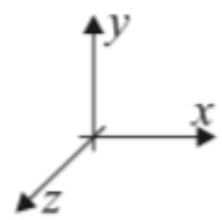
$$\times\left(e^{i(\epsilon_k-\epsilon_p)(t-t_1)}[W_{LR}(t)W^{\dagger}_{LR}(t_1)]_{\sigma'\sigma} + \text{H.c.}\right)\ ,\quad \eta\to 0^+$$

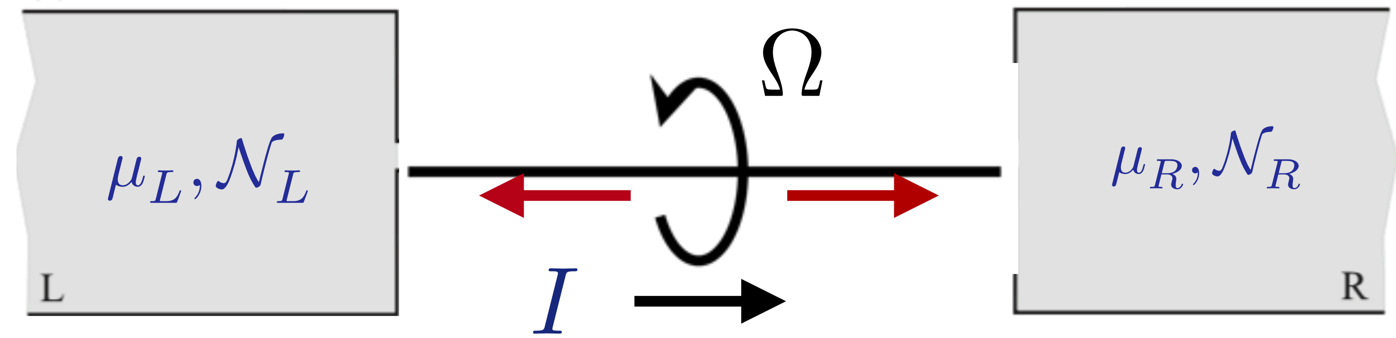
$$f_L(\epsilon_k) = \left(\exp[\frac{\epsilon_k-\mu_L}{k_{\rm B}T}] + 1\right)^{-1}$$

## Results:

Particle current is conserved: $I_L + I_R = 0$

spin currents are not: $\dot{\mathbf{M}}_L(t) = \dot{\mathbf{M}}_R(t)$




Particle current:

$$I = \left(4\pi |W_0|^2 \mathcal{N}_L \mathcal{N}_R\right)(\mu_R - \mu_L)$$

junction conductance/e

$$\dot{M}_L^x = \frac{G}{G_0}\mathcal{F}(\Omega)\sin^2(k_{\rm so} d)$$

$$\mathcal{F}(\Omega) = \int \frac{d\omega d\omega'}{2\pi}[f_L(\omega) - f_R(\omega')][\delta(\omega - \omega' + \Omega) - \delta(\omega - \omega' - \Omega)]$$

junction conductance (units of quantum conductance) $G/G_0$

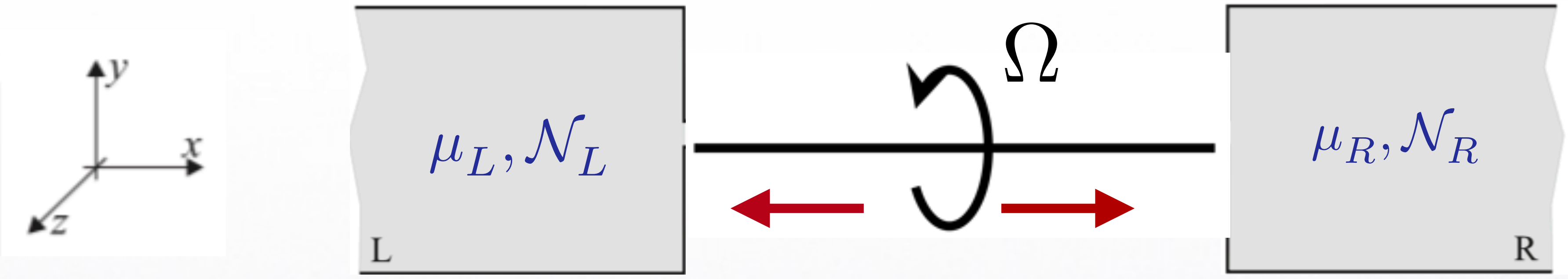
DC longitudinal spin generated by AC electric field

## Transversed magnetization:

The sum of the two transversed spin component is along the vector

$$[0, \sin(\Omega t), -\cos(\Omega t)]$$

$$\dot{\mathbf{M}}_L^{\mathrm{tr}}(t) = \frac{G}{G_0}\frac{\mathcal{F}(\Omega)}{2}\sin(2k_{\mathrm{so}}d)[0, \sin(\Omega t), -\cos(\Omega t)]$$



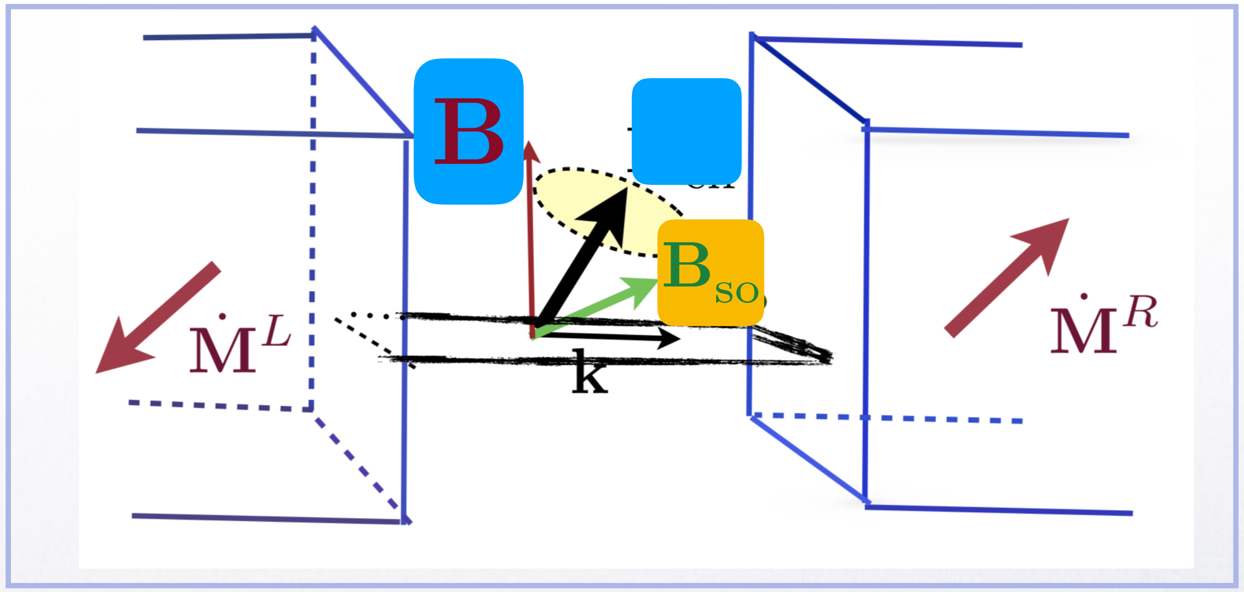

$$\mathcal{F}(\Omega) = \int \frac{d\omega d\omega'}{2\pi}[f_L(\omega) - f_R(\omega')][\delta(\omega - \omega' + \Omega) - \delta(\omega - \omega' - \Omega)]$$

junction conductance (units of quantum conductance) $G/G_0$

An un-biased weak link between two terminals, which is subjected to a Rashba spin-orbit interaction caused by an AC electric field that rotates periodically in the plane perpendicular to the link, injects spin polarized electrons into the terminals. The DC component of the polarization vanishes for a linearly-polarized electric field.

# Breaking time-reversal symmetry with a Zeeman field

Due to the Zeeman field, both charge and spin current exhibit oscillations with the link's length in conjunction with the spin-orbit coupling. This can be used to measure the strength of the spin-orbit interaction




Aharony, OEW, Jonson, Shekhter, Electric and magnetic gating of Rashba-active weak links, PRB(R) 97, (2018)

## tunneling amplitude— the propagator

Shabhazyan and Raikh, Low-field anomaly in 2D hopping magnetoresistance caused by spin-orbit term in the energy spectrum, PRL 73, (1994)

propagation of a plane wave (wave vector k) along a straight segment of length s

$$P(E) = \int dk e^{iks}[E_{\mathrm{F}} - \mathcal{H}(k)]^{-1}$$

$$\mathcal{H} = \frac{1}{2m^*}\Big(-i\frac{d}{ds} - \frac{e}{c}\mathbf{A}\Big)^2 + \frac{\widetilde{k}_{\mathrm{so}}}{m^*}\hat{\mathbf{n}}\cdot\boldsymbol{\sigma}\times\Big(-i\frac{d}{ds} - \frac{e}{c}\mathbf{A}\Big) - \mathbf{B}\cdot\boldsymbol{\sigma}$$

$$\Longrightarrow \mathcal{H}(k) = \frac{k^2}{2m^*} + \frac{kk_{\mathrm{so}}}{m^*}(\hat{\mathbf{n}}\times\hat{\mathbf{s}})\cdot\boldsymbol{\sigma} - \mathbf{B}\cdot\boldsymbol{\sigma}$$

omit Aharonov-Bohm phase due to A, ~~ignore Zeeman interaction due to B~~, assume **n||E** normal to plane where **k** is

## propagator without time-reversal symmetry

$$\mathbf{H}_{\rm eff}(\mathbf{k}) = \frac{k k_{\rm so}}{m^*}\hat{\mathbf{n}} \times \hat{\mathbf{s}} - \mathbf{B}$$

$E \to k_{\rm F}^2/(2m^*)$

$$G(s;E) = \int dk e^{iks} \frac{E + i0^+ - \frac{k^2}{2m^*} - \mathbf{H}_{\rm eff}(\mathbf{k}) \cdot \boldsymbol{\sigma}}{(E + i0^+ - \frac{k^2}{2m^*})^2 - H_{\rm eff}^2(\mathbf{k})}$$

Cauchy integration leads to two poles $k_\pm^2 - k_{\rm F}^2 = \pm 2m^* H_{\rm eff}(k_\pm)$ two residues $A_\pm$

$\Rightarrow$ two polarizations $\Rightarrow$ Interference in spin space due to Aharonov Casher phase $\Rightarrow$ Tunneling amplitude is no more unitary (no more a simple rotation)

$$G(s;E) \propto e^{ik_+ s} A_+ (1 + \hat{\mathbf{q}}_+ \cdot \boldsymbol{\sigma}) + e^{ik_- s} A_- (1 - \hat{\mathbf{q}}_- \cdot \boldsymbol{\sigma})$$

$$\hat{\mathbf{q}}_\pm = \mathbf{H}_{\rm eff}(k_\pm)/H_{\rm eff}(k_\pm)$$

$$\mathbf{B} = 0 \Rightarrow \hat{\mathbf{q}}_+ = \hat{\mathbf{q}}_- = \hat{\mathbf{n}} \times \hat{\mathbf{s}}$$

propagator without time-reversal symmetry

$$G(s;E) \propto e^{ik_+ s} A_+ (1 + \hat{\mathbf{q}}_+ \cdot \boldsymbol{\sigma}) + e^{ik_- s} A_- (1 - \hat{\mathbf{q}}_- \cdot \boldsymbol{\sigma})$$

$$\hat{\mathbf{q}}_\pm = \mathbf{H}_{\rm eff}(k_\pm)/H_{\rm eff}(k_\pm)$$

The two terms correspond to waves with wave numbers $k_+$ and $k_-$ (small Zeeman energy compared to Fermi energy). The corresponding tunneling amplitudes contain the spin projection matrices $1 \pm \hat{\mathbf{q}}_\pm \cdot \boldsymbol{\sigma}$

The transmitted electrons are fully polarized along $q_+$ and $q_-$

The non-unitarity of the propagator is due to the Zeeman field. Then a bias voltage between the leads generates charge and spin currents.

## Hamiltonian

$$\mathcal{H} = \mathcal{H}_{\rm leads} + \mathcal{H}_{\rm tun}$$

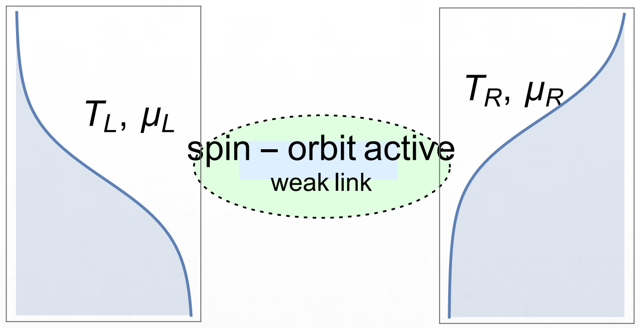
$$\mathcal{H}_{\rm leads} = \sum_{\mathbf{k},\sigma} \epsilon_k c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_{\mathbf{p},\sigma} \epsilon_p c^\dagger_{\mathbf{p}\sigma} c_{\mathbf{p}\sigma}$$

$$\mathcal{H}_{\rm tun} = \sum_{\mathbf{k},\mathbf{p}} \sum_{\sigma\sigma'} ([V_{\mathbf{kp}}]_{\sigma\sigma'} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{p}\sigma'} + \mathrm{H.c.})$$

rate: $$R^L_{\sigma\sigma'} = \frac{d}{dt} \sum_{\mathbf{k}} \langle c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma'} \rangle$$

$$= 2\pi \sum_{\mathbf{k},\mathbf{p}} [V_{\mathbf{kp}} V^\dagger_{\mathbf{kp}}]_{\sigma'\sigma} \delta(\epsilon_k - \epsilon_p) [f_L(\epsilon_k) - f_R(\epsilon_p)]$$

Both generated by the bias




Particle current $$I_L = \sum_\sigma R^L_{\sigma\sigma}$$

Spin current $$\dot{\mathbf{M}}_L = \sum_{\sigma,\sigma'} R^L_{\sigma\sigma'} \boldsymbol{\sigma}_{\sigma\sigma'}$$

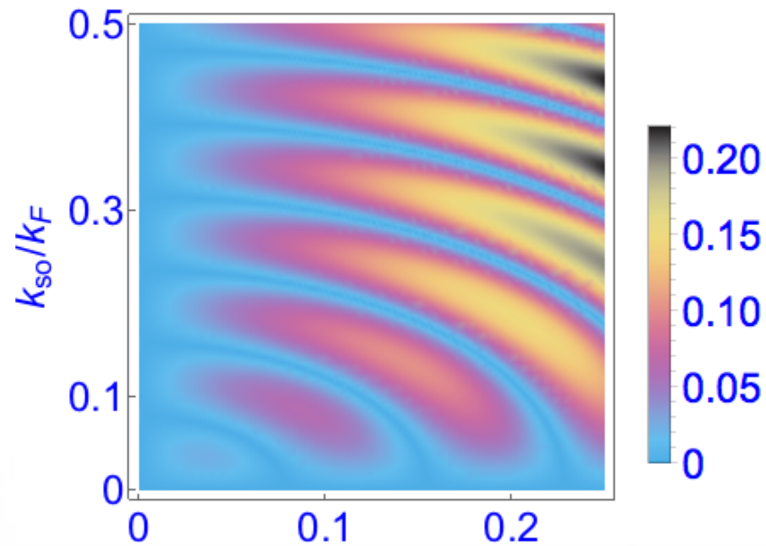
$$\mathcal{T}_{\sigma'\sigma} = \mathcal{T}_0 (U \delta_{\sigma,\sigma'} + \mathbf{W} \cdot [\boldsymbol{\sigma}]_{\sigma'\sigma})$$

charge current

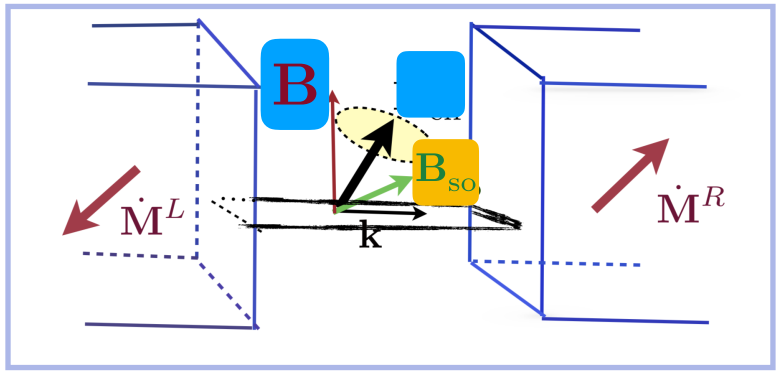
spin current

# $\mathbf{B} \perp \mathbf{B}_{\mathrm{so}}$

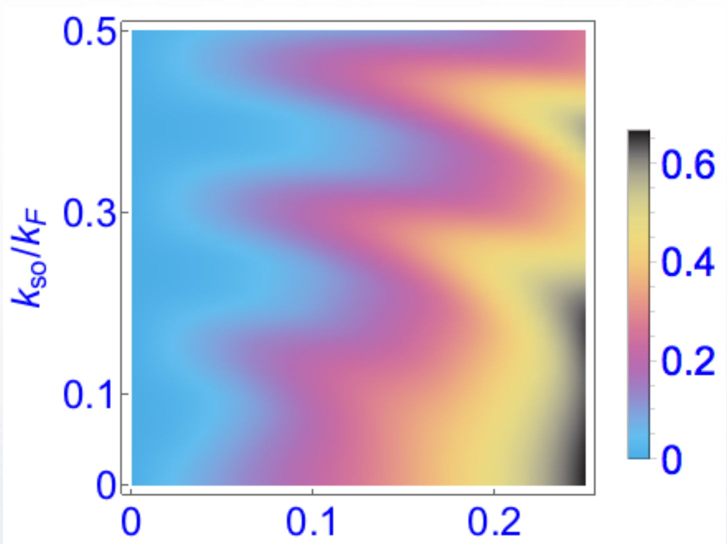
spin current




*in* $\{\mathbf{B}_{\mathrm{so}}, \mathbf{B}\}$ *− plane*




magnetoconductance oscillates with the length of the weak link




*normal to* $\{\mathbf{B}_{\mathrm{so}}, \mathbf{B}\}$ *− plane*

charge current

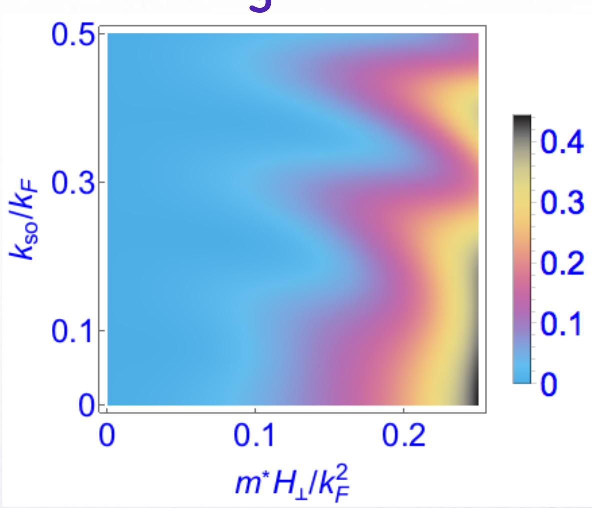



FIG. 2: (Color online.) The magnetoconductance difference, $U_{ii} - U_i$, calculated for $k_{\mathrm{F}}d = 20$, as function of the spin-orbit coupling ($k_{\mathrm{so}}$) measured in units of the Fermi wave vector, and the Zeeman energy, measured in units of $k_{\mathrm{F}}^2/m^*$. The oscillations shown are due to the term $\propto \cos(\alpha)$ of $U_{ii}$; $\alpha = (k_+ - k_-)d$.

*net amount of charge and magnetic moment per unit time is transferred through a biased, spin-orbit active, week link;

*oscillations as function of $(k_{+}-k_{-})d$;

*the injected magnetization can be measured by a properly-positioned superconducting quantum interference device, or by a magnetic-resonance force microscope.

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