KITP, April 17th (2006)

Spin Control Based on the Rashba Spin-orbit Interaction

- Rashba spin-orbit interaction
- Competition between Zeeman and Rashba
- Spin interference experiments
- Stern-Gerlach Spin Filter

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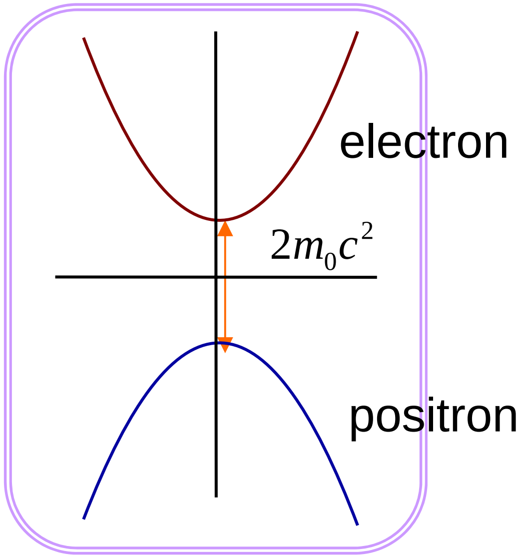
Enhancement of spin-orbit interaction

SOI in vacuum

$$H_{so} = -\mu_B \sigma \cdot \left(\frac{p \times E}{2m_0 c^2} \right) \rightarrow B_{eff}$$

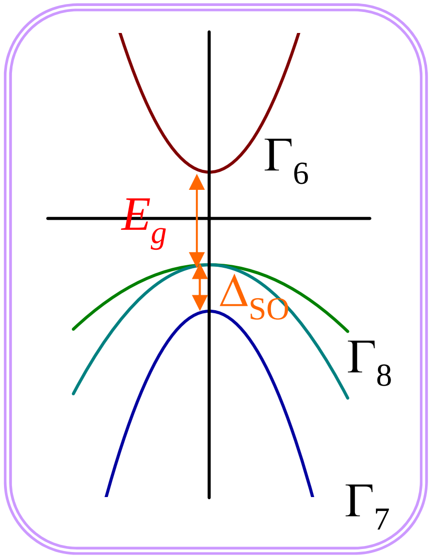
Dirac gap $2m_0c^2 \approx 1\,MeV$



Rashba SOI in semiconductors

$$H_R = \frac{eP^2}{3}\left[\frac{1}{E_g^2} - \frac{1}{(E_g + \Delta_{SO})^2}\right] \sigma \cdot k \times \langle E \rangle_v$$

Energy gap $E_g, \Delta_{SO} \approx 1\,eV$

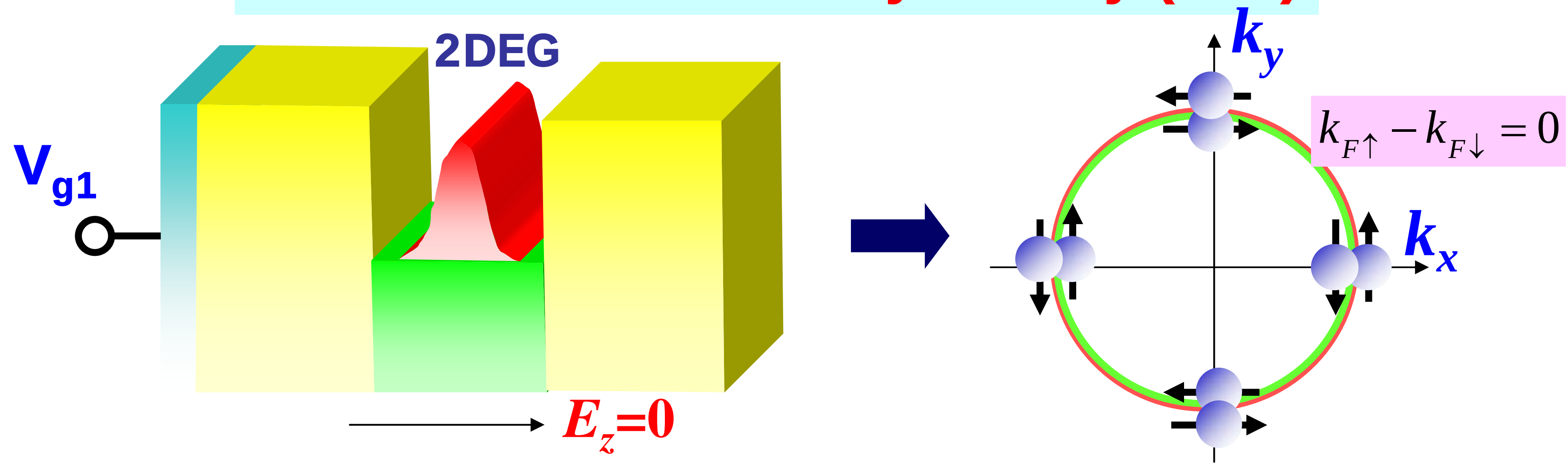


SOI

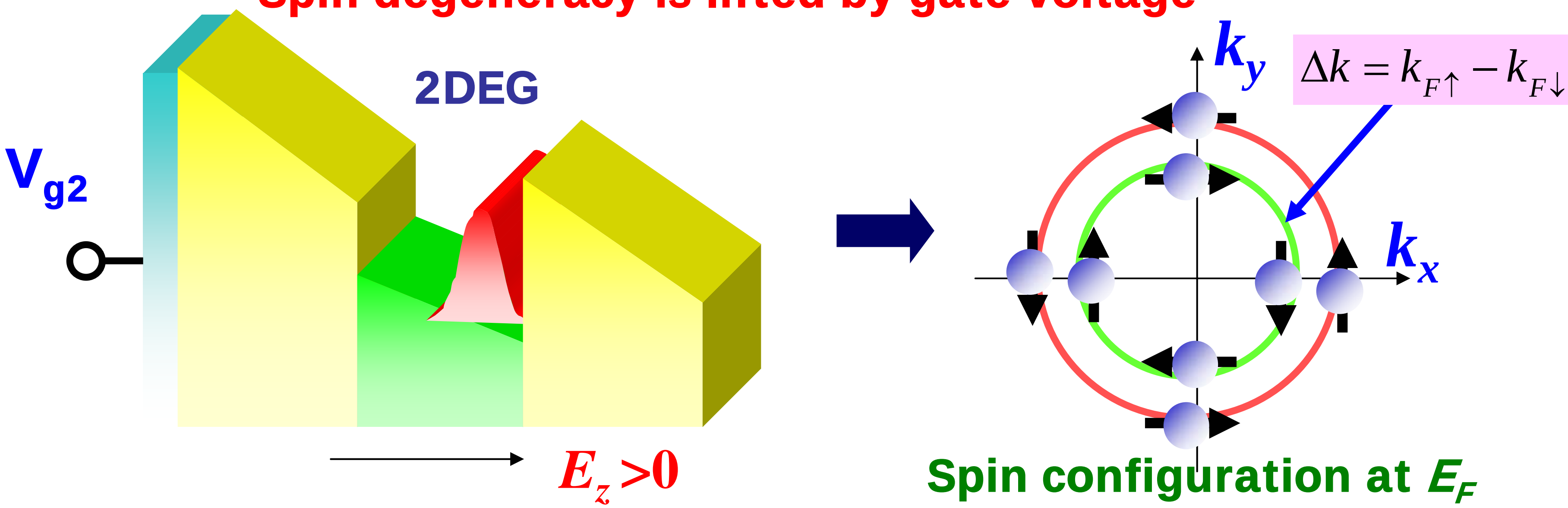
1. Narrow Gap semiconductor
2. Electric Field in QW

Rashba spin-orbit interaction in 2DEG

Structural inversion asymmetry (SIA)

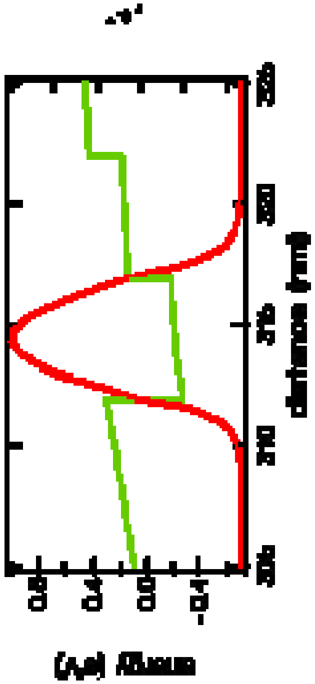


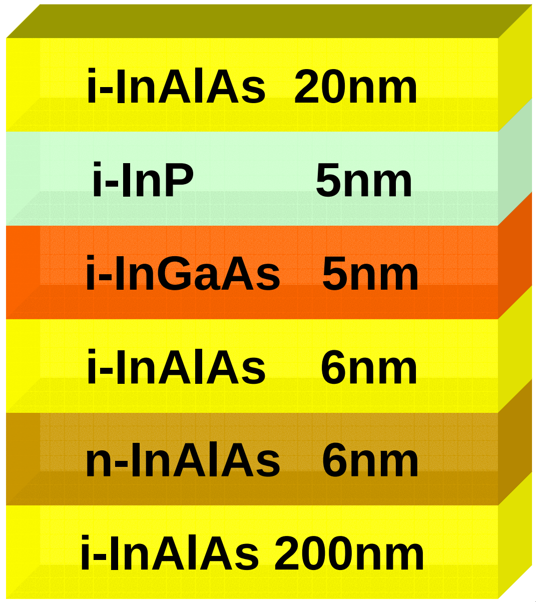
Spin degeneracy is lifted by gate voltage



Spin configuration at E_F

Potential Profile in InGaAs Quantum Well



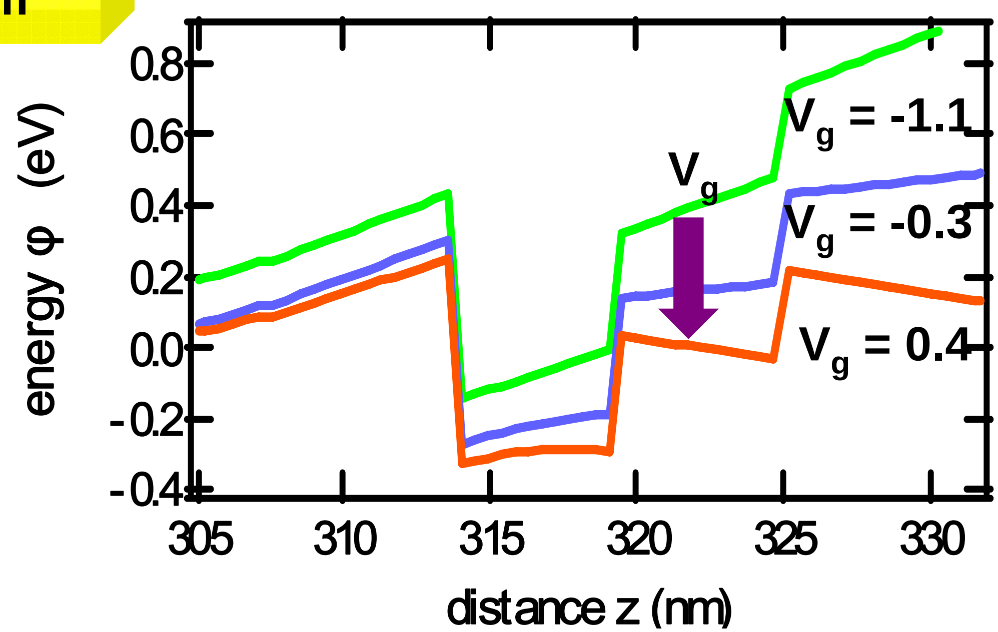


SOI depends on Vg

V_g	< E >	α
-1.1	large	large
-0.3	medium	medium
0.4	small	small

SOI is proportional to E

$$\alpha \propto \langle E \rangle = -\frac{\partial \phi(z)}{\partial z}$$



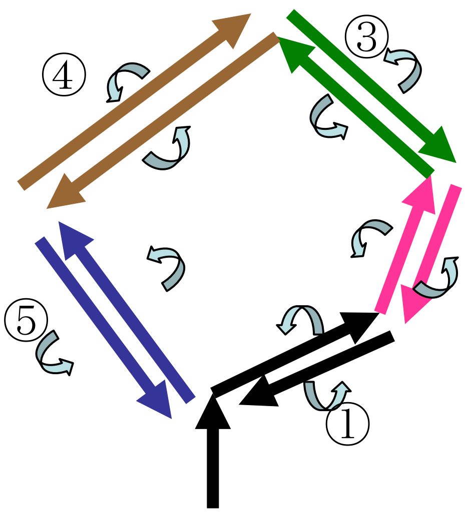
Spin states in Time Reversal Symmetry Paths

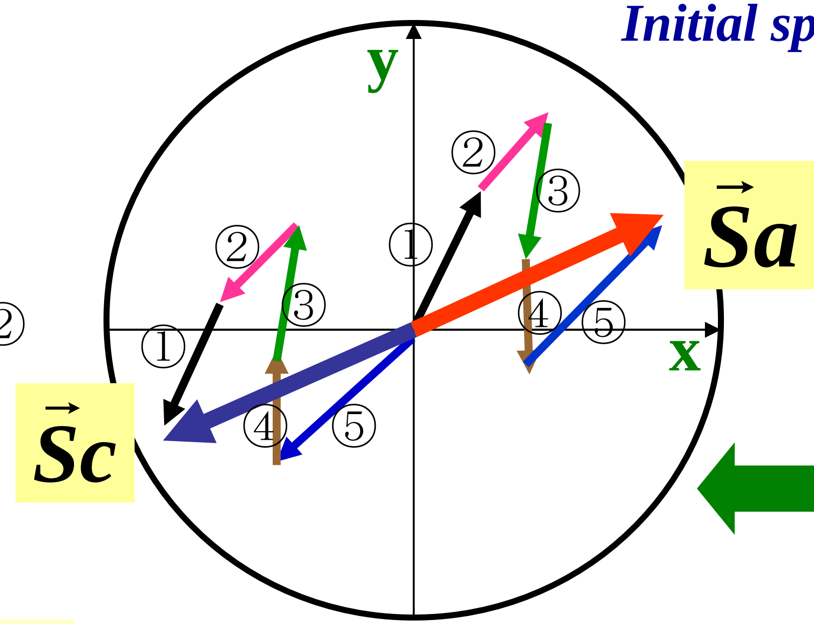
SOI does not break TRS

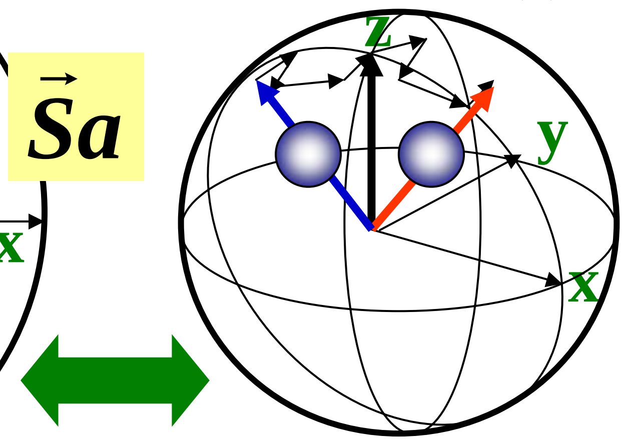
$$TRS \Rightarrow p \to -p,\ \sigma \to -\sigma,\ E \to E$$

$$H_{SO} = -\mu_B \sigma \cdot (p \times E)$$

Initial spin state $\left|\vec{S}i\right\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$







Real space trajectory in TRS paths

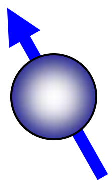
Top view of spin sphere

Spin sphere in TRS paths

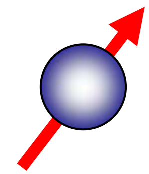
Final spin directions are exactly opposite

Destructive interference due to SOI

Final spin states → Exactly opposite



$$\left|\vec{S}c\right\rangle = R\left|\vec{S}i\right\rangle \quad \Longleftrightarrow \quad \left|\vec{S}a\right\rangle = R^{-1}\left|\vec{S}i\right\rangle$$



Clockwise — **Anti-clockwise**

$$R(\alpha,\beta,\gamma) = \begin{bmatrix} \cos\frac{\alpha}{2}e^{i(\beta+\gamma)/2} & i\sin\frac{\alpha}{2}e^{-i(\beta-\gamma)/2} \\ i\sin\frac{\alpha}{2}e^{i(\beta-\gamma)/2} & \cos\frac{\alpha}{2}e^{-i(\beta+\gamma)/2} \end{bmatrix}$$

Euler angle (α, β, γ)

Rotational operator

Many different paths with time reversal trajectories
(Final Spin states are statistical)

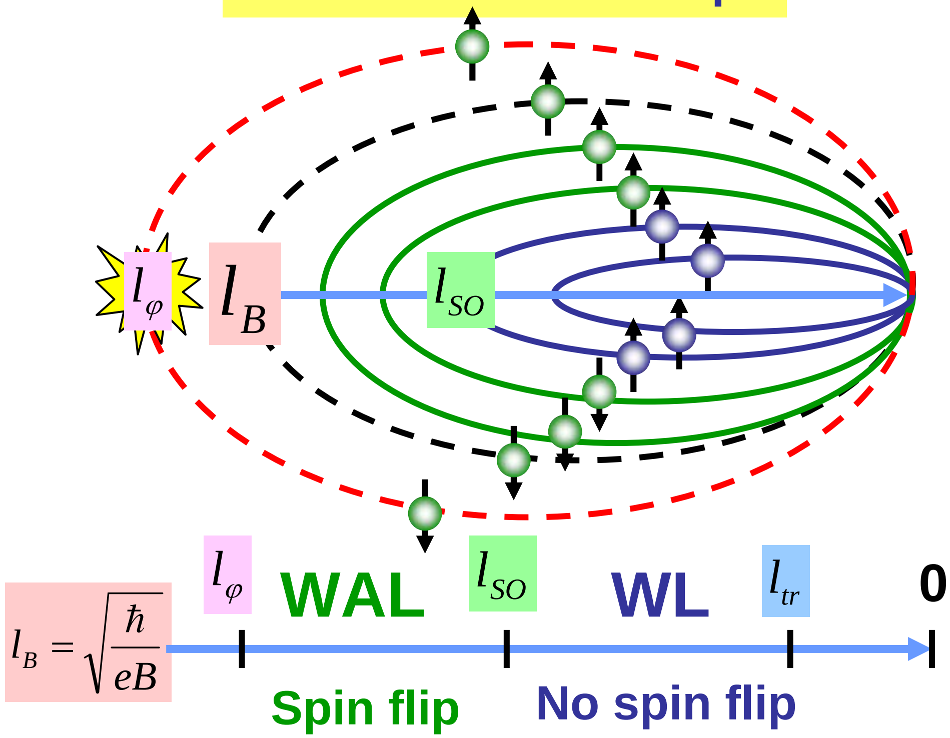
$$\left\langle \vec{S}a \middle| \vec{S}c \right\rangle = \left\langle \vec{S}i \middle| R^2 \middle| \vec{S}i \right\rangle = \cos^2\frac{\alpha}{2}\cdot e^{i(\beta+\gamma)} - \sin^2\frac{\alpha}{2} \approx 0 + \frac{\cos\alpha - 1}{2} \approx -\frac{1}{2}$$

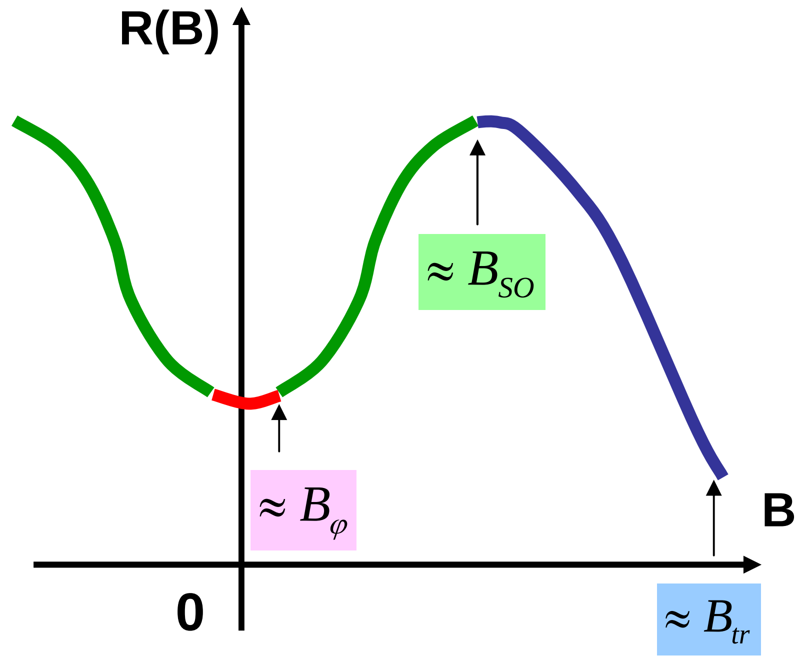
Initial spin state $\left|\vec{S}i\right\rangle = \begin{pmatrix}1\\0\end{pmatrix}$ *for simplicity*

WAL effect

Length scales in quantum interference

TRS interference loops → Related MR





l_φ; Maximum interference length → $B_\varphi = \hbar / 4e \cdot l_\varphi^2$

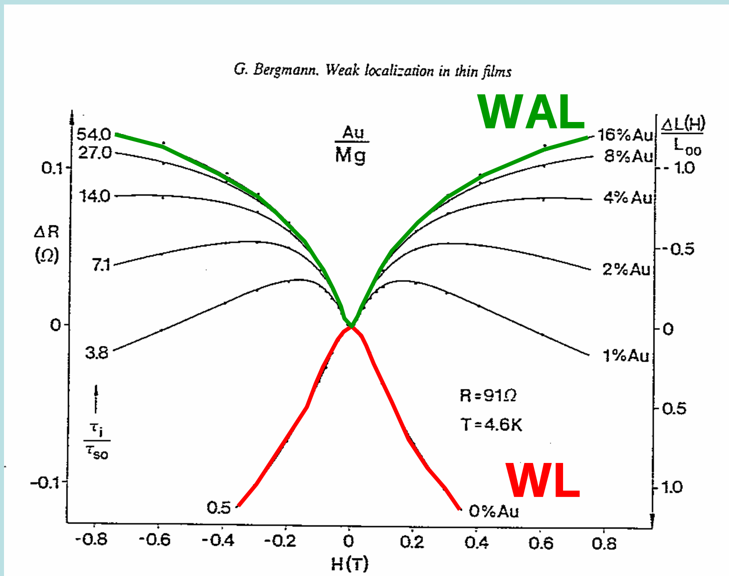
l_{SO}; Spin flip length → $B_{SO} = \hbar / 4e \cdot l_{SO}^2$

l_{tr}; Minimum interference length → $B_{tr} = \hbar / 4e \cdot l_{tr}^2$

l_B replaces l_φ as max. interference length when B is applied.

Gate Controlled Spin-orbit Interaction(SOI)

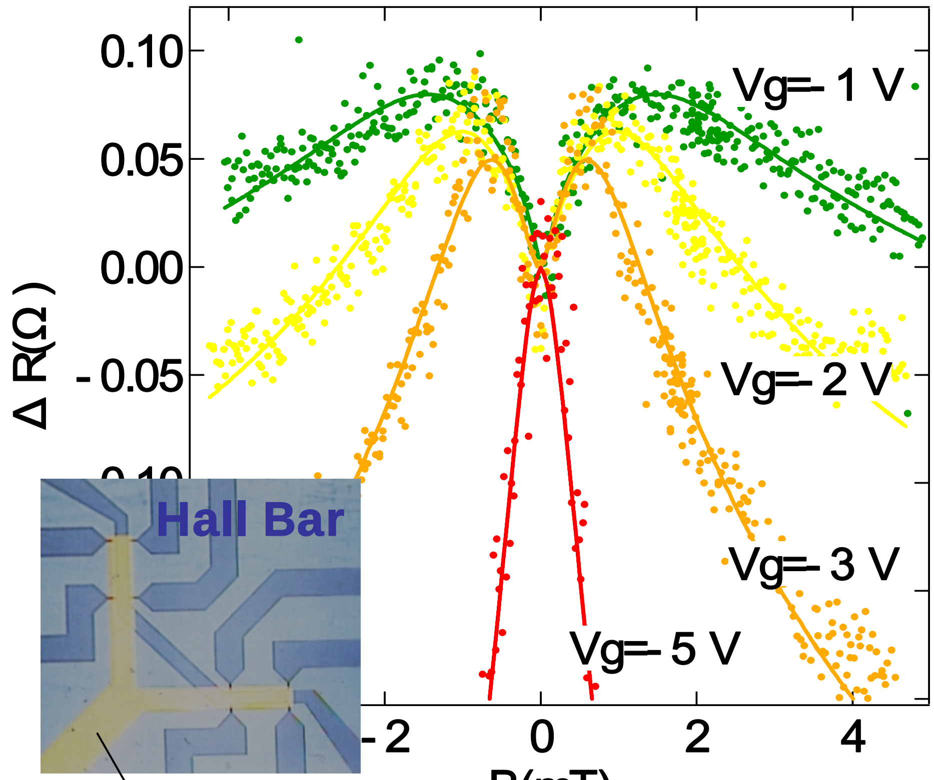
Mg thin film with Au



G.Bergmann,
Phys. Rev. Lett. 48, 1046 (1982)

Spin-orbit scattering is introduced by Au (Elliott spin relaxation)

Gate fitted InGaAs 2DEG Hall Bar

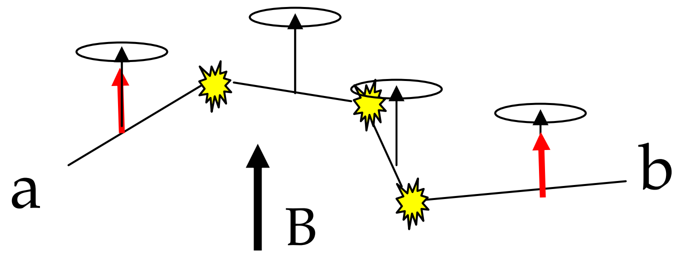


Gate Electrode

Gate voltage can control the Rashba SOI.

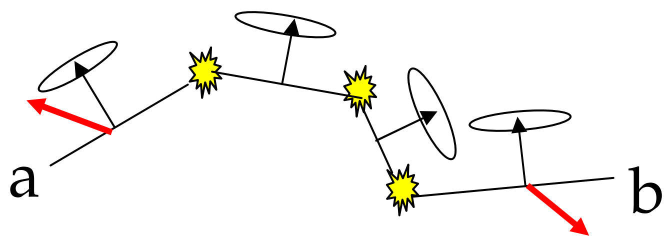
Spin dynamics in diffusive systems

Zeeman



Fixed
precession axis

Rashba SOI



Randomized
precession axis

⇓

$$H_R = \frac{\alpha}{\hbar}\cdot(p_x\sigma_y - p_y\sigma_x) \quad \Rightarrow \quad \vec{B}_{SOI} \propto \vec{p}\times\hat{z}$$

Rashba + scattering:
Spin relaxation (τ_s)

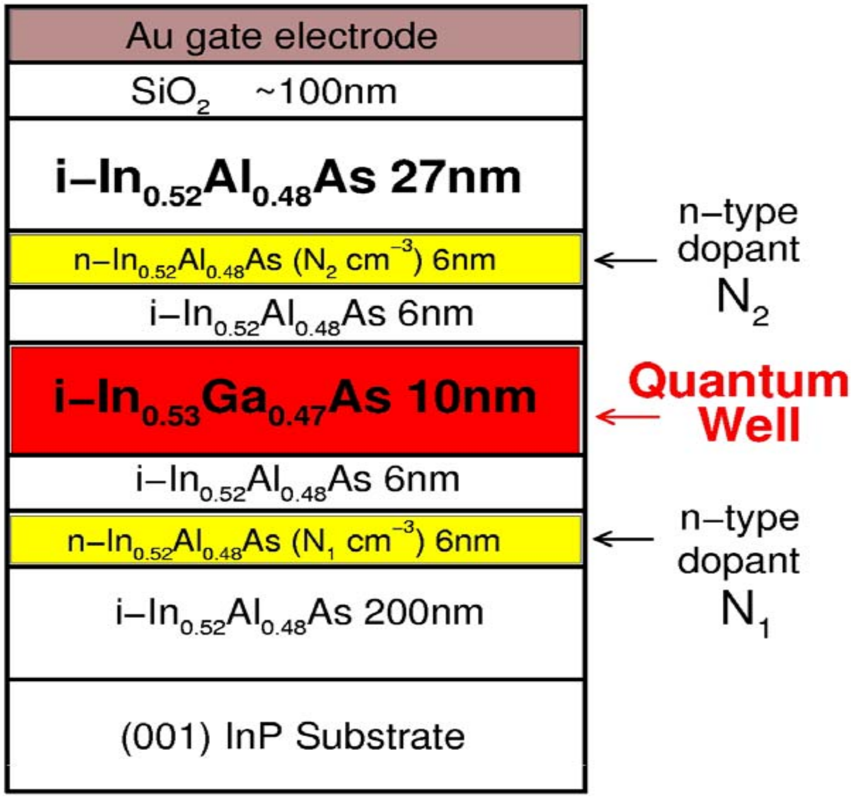
⇙

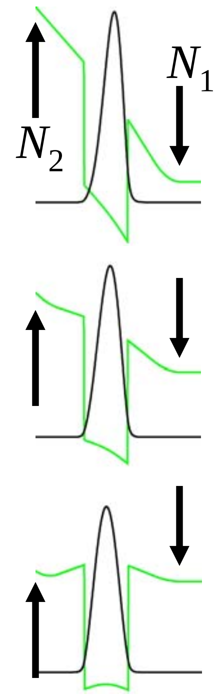
Competition Zeeman and Rashba:

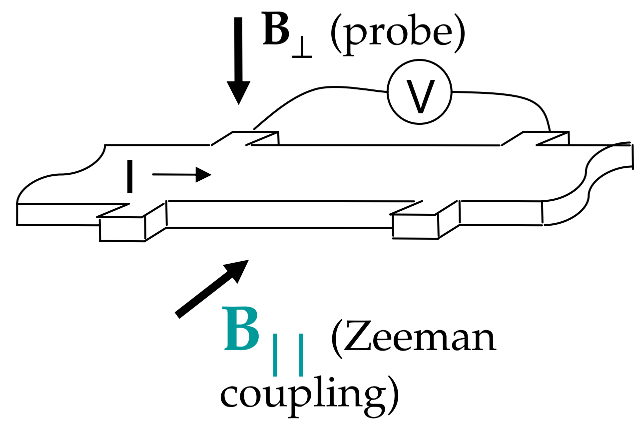
alignment ↔ randomization

$E_Z \leftrightarrow E_{SOI} \equiv \hbar/\tau_s$

Competition between Zeeman and Rashba







$N_1 + N_2 = 4 \times 10^{18}\ cm^{-3}$

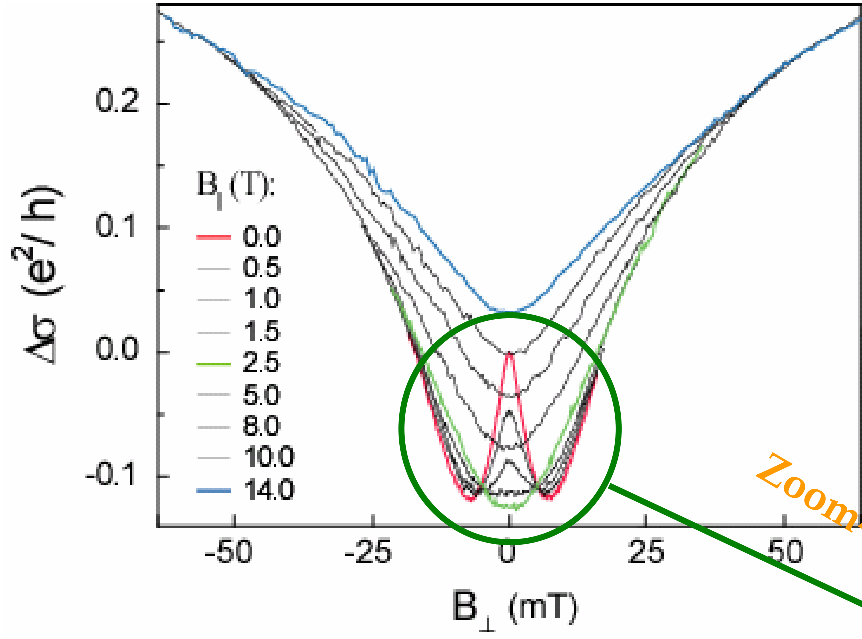
N_2/N_1:	0	1/3	1
Δ (meV):	≈2	≈1.5	≈0.5

Competition Zeeman and Rashba:

alignment ↔ randomization

$E_Z \leftrightarrow E_{SOI} \equiv \hbar/\tau_s$

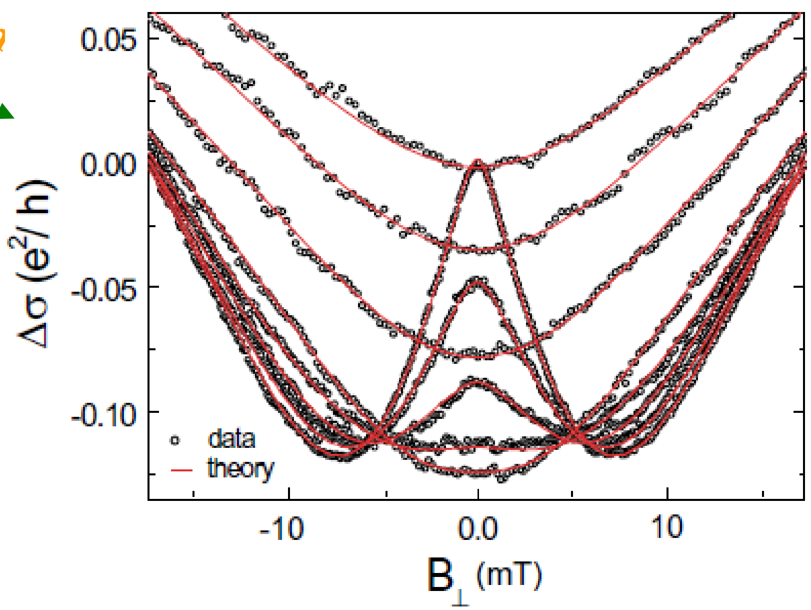
Weak anti-localization and data analysis



Good agreement with ILP theory

- $B_{||}$ (i.e. E_Z/E_{SOI})
- ne (i.e. τ)
- all samples

Zoom-in



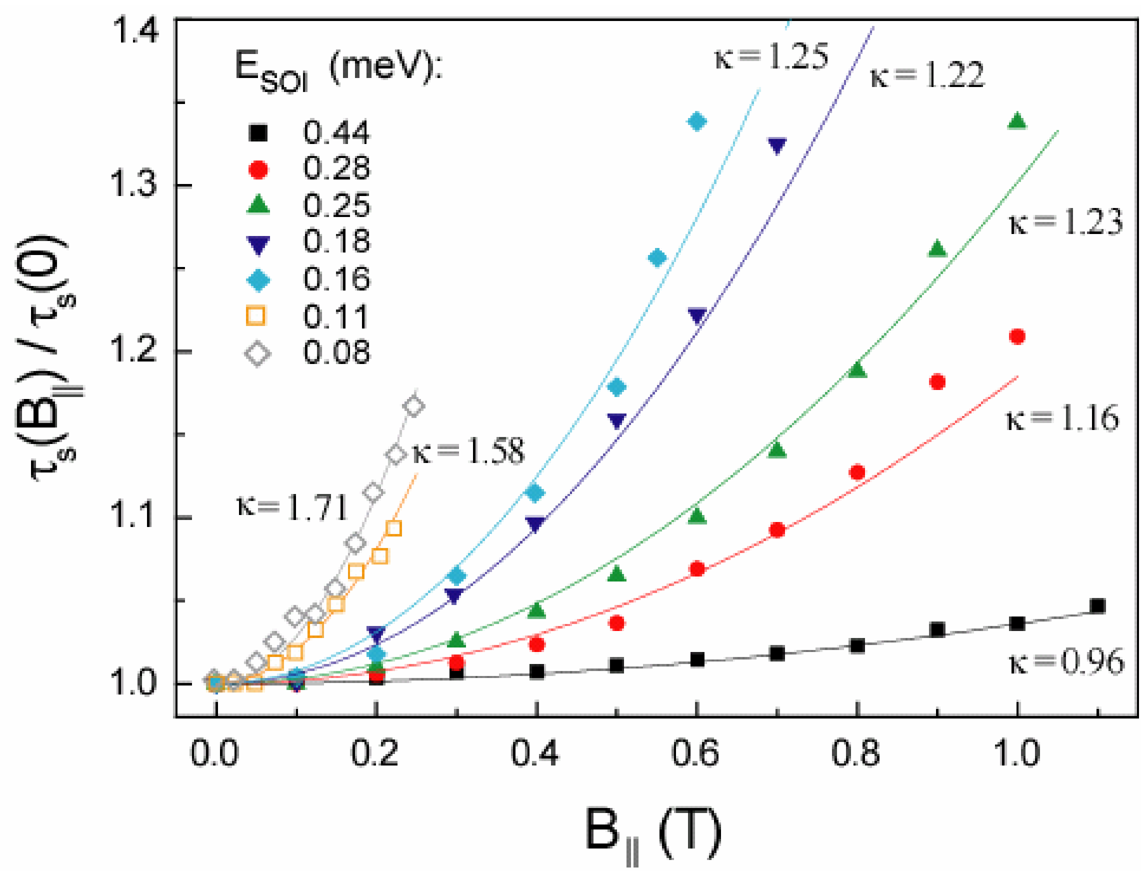
WAL data Analysis $\rightarrow \tau_s(B_{//}), \tau_\phi(B_{//})$

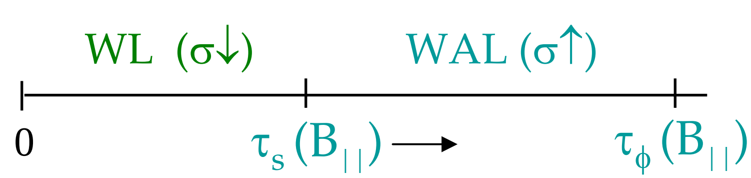
WL ($\sigma\downarrow$) **WAL** ($\sigma\uparrow$)

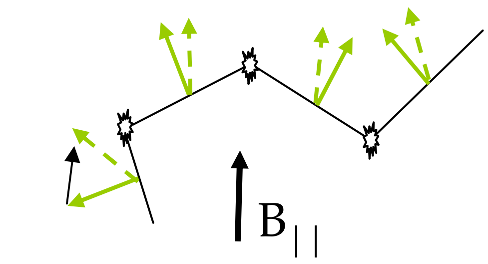
0 τ_s ($B_{||}$) $\rightarrow$ $\leftarrow$ τ_ϕ ($B_{||}$)

τ_s (E_z, E_{SOI}) TRS (E_z, E_{SOI})

Increase in spin relaxation time: $\tau_s(B_{||})$







Spin alignment $\Rightarrow \tau_s \uparrow$

Energy Scale:

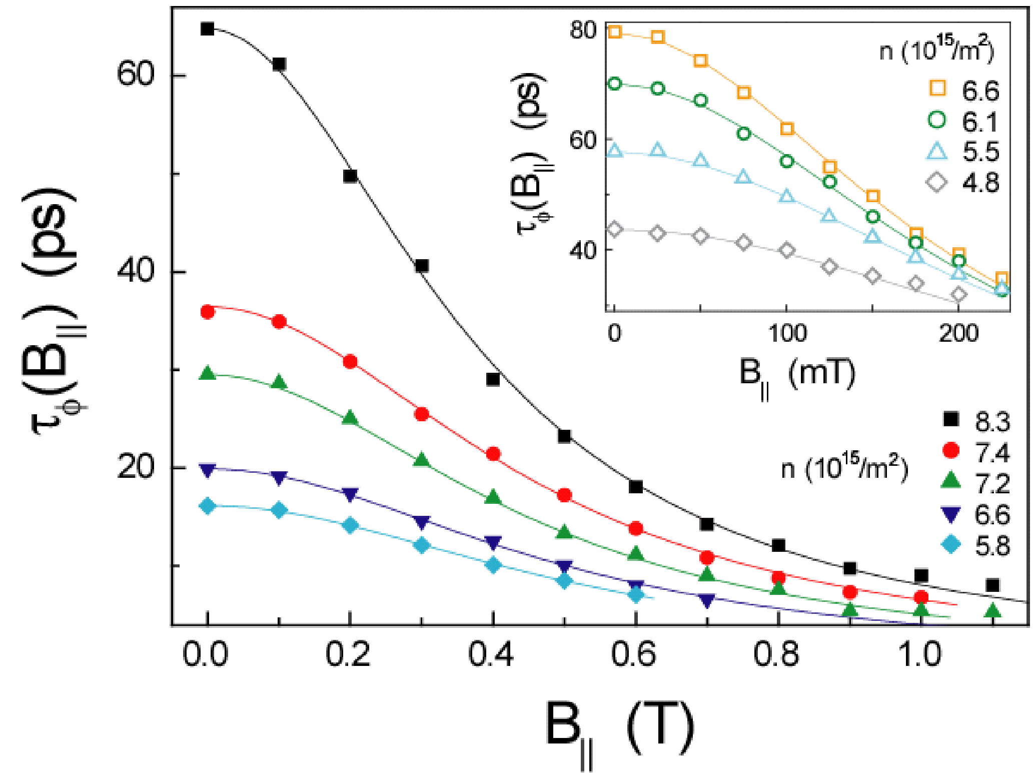
- **Zeeman** E_Z
- **Rashba** $E_{SOI} \equiv \hbar/\tau_s(0)$

Theory:

$$\frac{\tau_s(B_{||})}{\tau_s(0)} \approx 1 + \tfrac{1}{2}(E_Z / E_{SOI})^2$$

(V.A. Froltsov, PRB '01)

Decrease in dephasing time: $\tau_\phi (B_{||})$



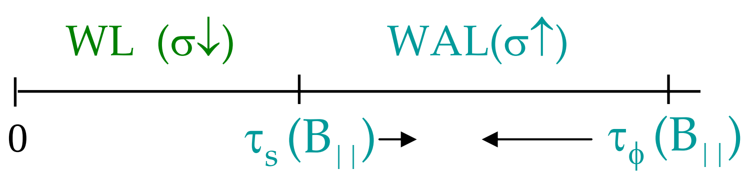
Theory ($E_Z/E_{SOI} << 1$) :

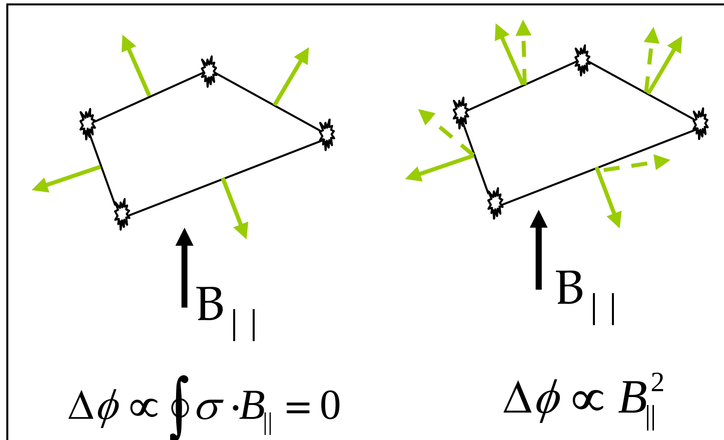
$$\frac{1}{\tau_\phi(B_{\|})} = \frac{1}{\tau_\phi(0)} + \frac{1}{T_\phi(B_{\|})}$$

Spin induced dephasing

$$\frac{1}{T_\phi(B_{\|})} \propto (E_Z / E_{SOI})^2$$

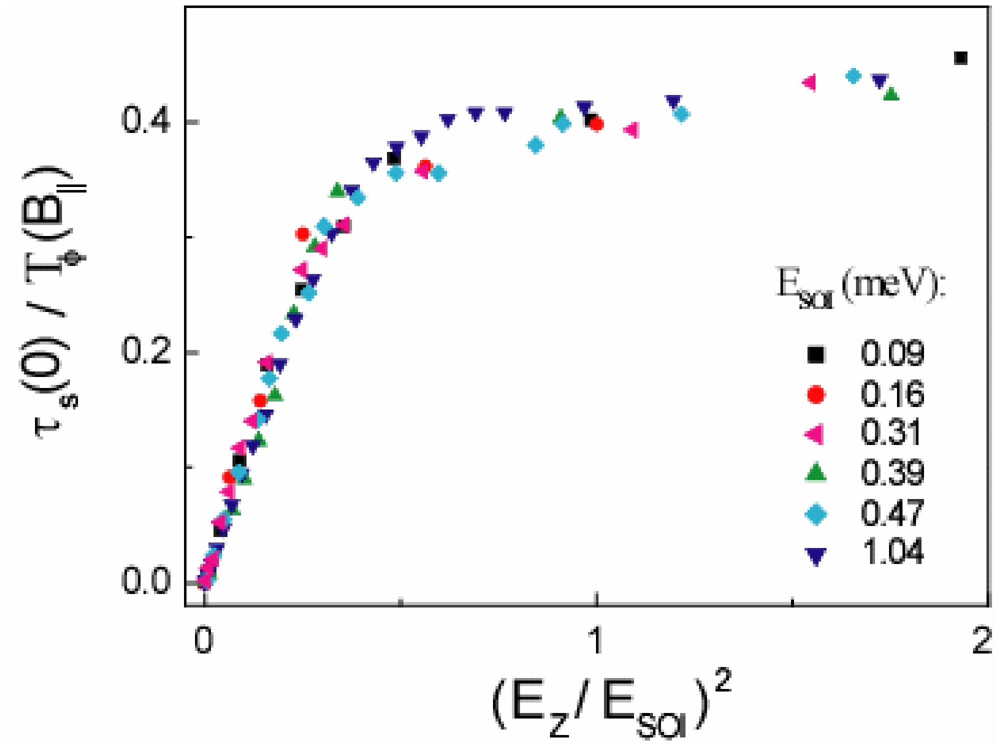
(A.G. Malshukov *et al.*, PRB '97)





Universal Spin-Induced Time Reversal Symmetry Breaking

Spin induced dephasing rate: $1/T_\phi(B)$



$$\frac{1}{T_\phi(B_\parallel)} = \frac{1}{\tau_\phi(B_\parallel)} - \frac{1}{\tau_\phi(0)}$$

Total dephasing rate

Inelastic scattering rate

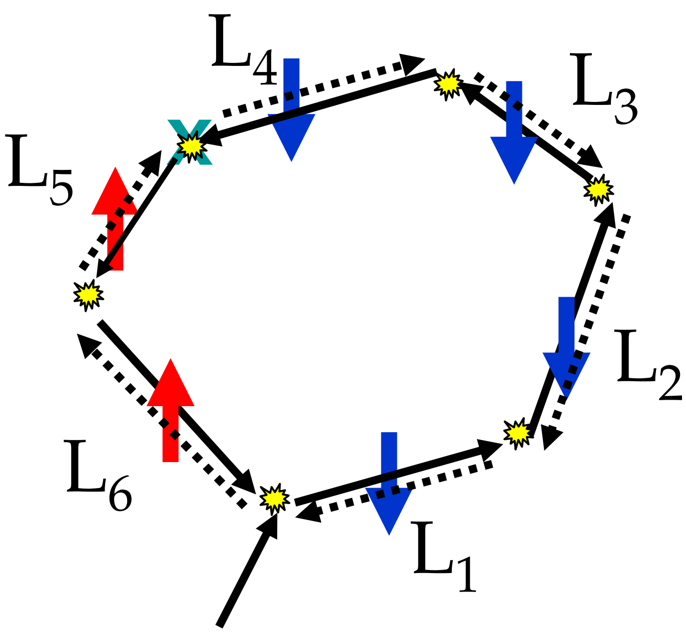
Upper limit ~ τ_s

- **Saturation ($E_Z/E_{SOI} >> 1$)**
- **Universal behavior**

$\Rightarrow$ **No available theory**

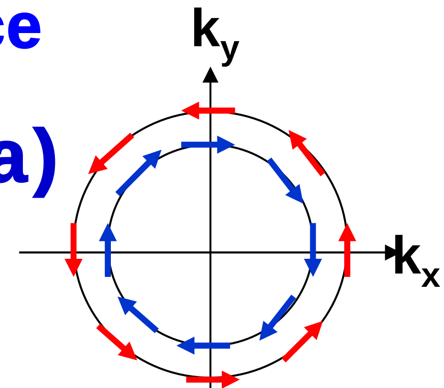
Spin-induced Time Reversal Symmetry Breaking

Time-Reversal Symmetric Interference



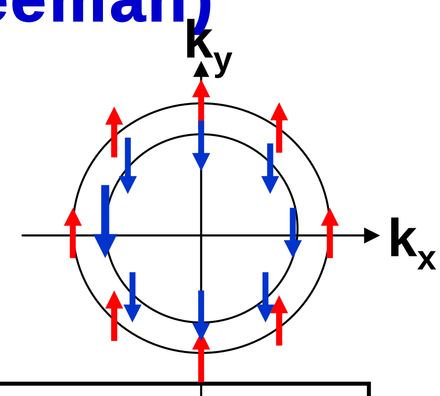
Spin flip (Rashba)

$E_{SOI} \Rightarrow \tau_S$



Difference in k_F (Zeeman)

$Ez \Rightarrow \left|k_{F\uparrow}\right| \neq \left|k_{F\downarrow}\right|$



Phase shift

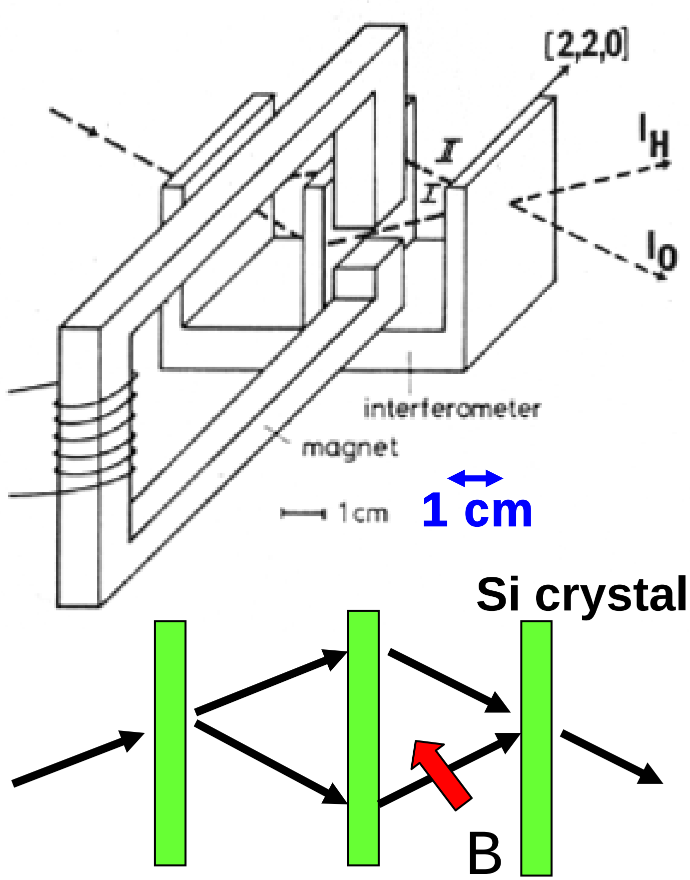
CW $\phi_c = k_{F\uparrow}(L_6 + L_5) + k_{F\downarrow}(L_4 + L_3 + L_2 + L_1)$

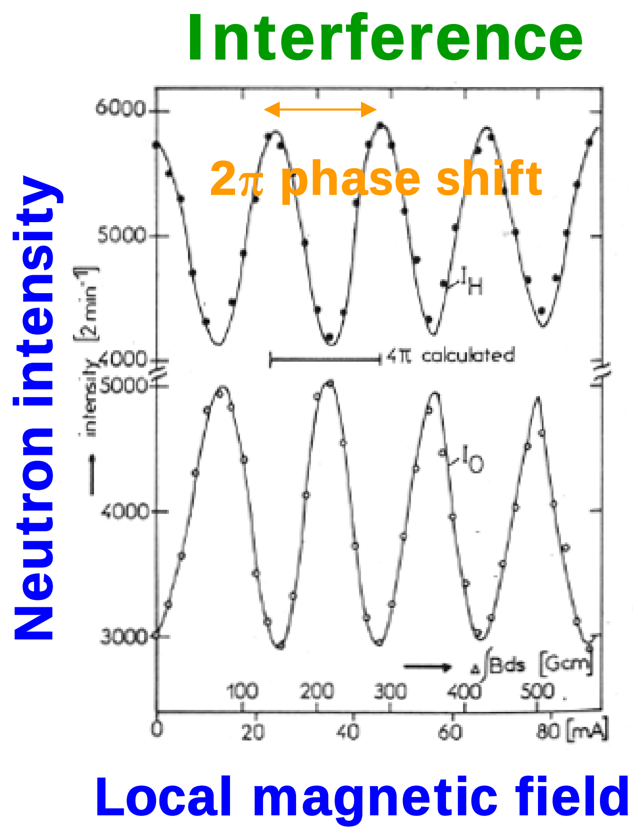
CCW $\phi_{ac} = k_{F\downarrow}(L_1 + L_2 + L_3 + L_4) + k_{F\uparrow}(L_5 + L_6)$

Breaking of interference $\Delta\phi = \phi_c - \phi_{ac} \approx 1 \quad \because \left|k_{F\uparrow}\right| \neq \left|k_{F\downarrow}\right|$

Neutron Spin-interference Exp.

4π-spin precession = 2π-phase shift





Spin precession: Local magnetic field

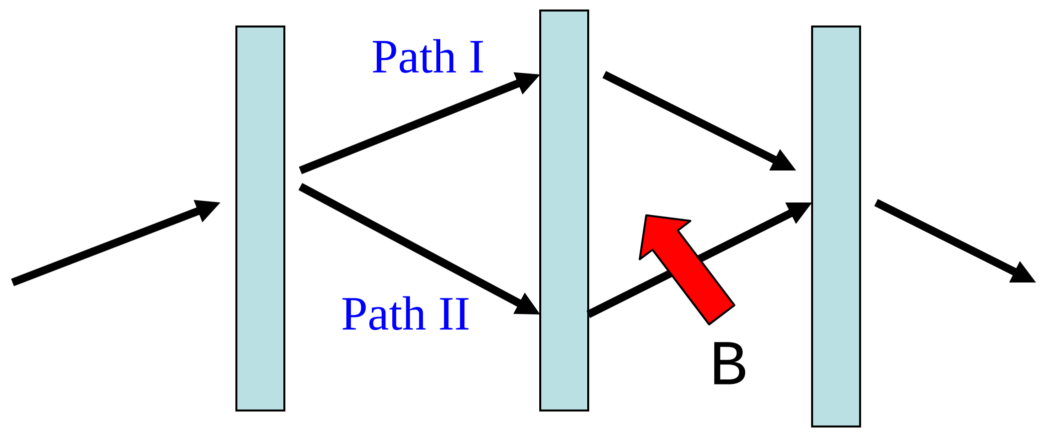
H. Rauch *et al* Phys. Lett. 54A (1975)

Operational Principle of Spin Interferometer

Non-spin polarized beam

Path I

$$\begin{pmatrix}\alpha\\ \beta\end{pmatrix} \to \begin{pmatrix}\alpha\\ \beta\end{pmatrix}$$



Path II

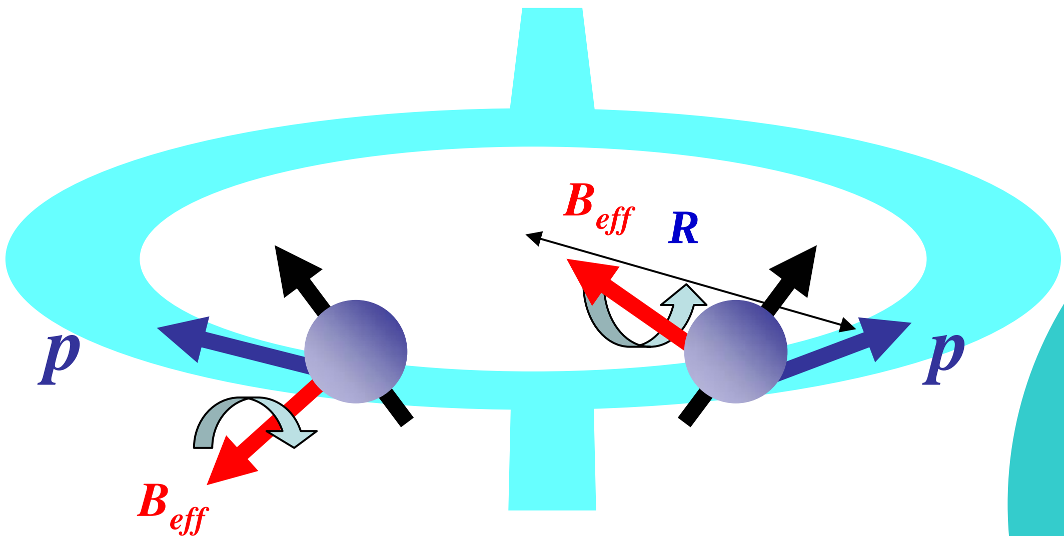
$$\begin{pmatrix}\alpha\\ \beta\end{pmatrix} \to \begin{pmatrix}e^{i\phi/2} & 0\\ 0 & e^{-i\phi/2}\end{pmatrix}\begin{pmatrix}\alpha\\ \beta\end{pmatrix} = \begin{pmatrix}\alpha e^{i\phi/2}\\ \beta e^{-i\phi/2}\end{pmatrix}$$

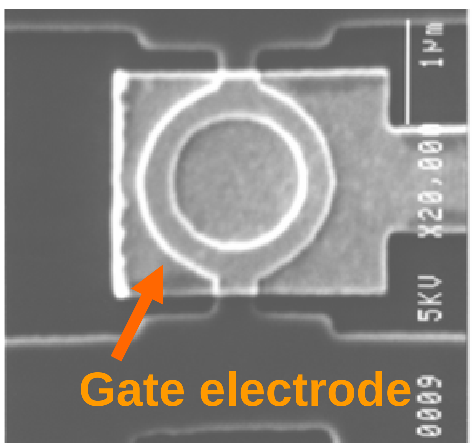
$$\phi = \gamma \boldsymbol{B} \tau$$

Interference

$$\frac{\left|\begin{pmatrix}\alpha e^{i\phi/2}\\ \beta e^{-i\phi/2}\end{pmatrix} + \begin{pmatrix}\alpha\\ \beta\end{pmatrix}\right|^2}{\left|\begin{pmatrix}\alpha\\ \beta\end{pmatrix} + \begin{pmatrix}\alpha\\ \beta\end{pmatrix}\right|^2} = \frac{(1+\cos\phi/2)}{2}$$

Spin interferometer by the Rashba SOI



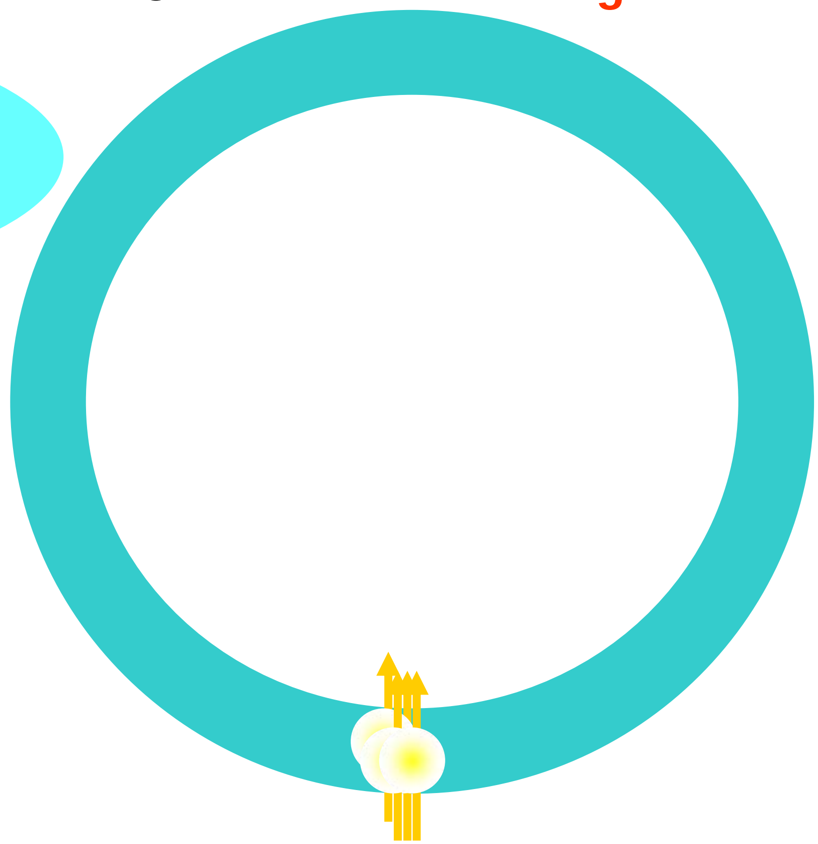


Spin interference device

Appl. Phys. Lett. 75, 695 (1999)

Vg= 0 V

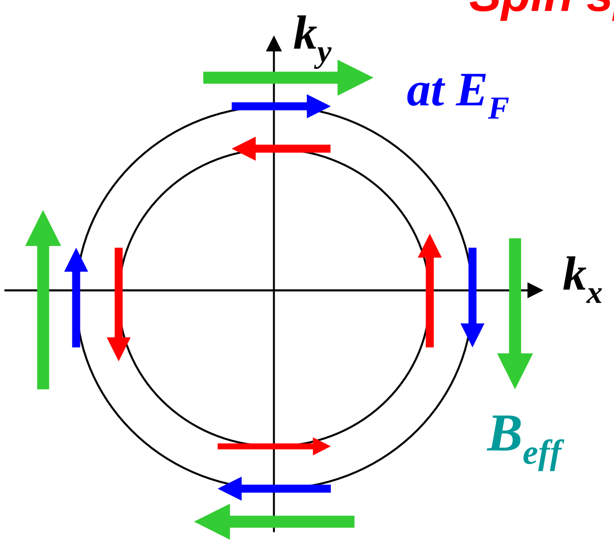
Vg= 1 V



Ring conductance depends on the precession angle

Spin precession by the Rashba SOI

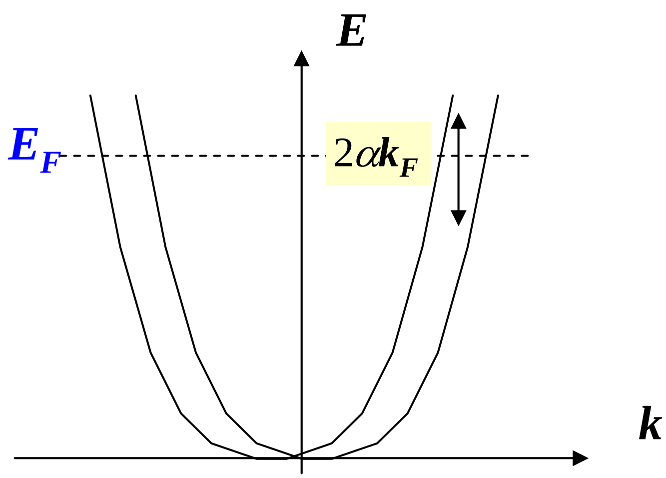
Spin splitting as if a spin feels an effective magnetic field perpendicular to it momentum direction



$$E(\boldsymbol{k}) = \frac{\hbar^2 \boldsymbol{k}^2}{2\boldsymbol{m}^*} \pm \alpha \boldsymbol{k}$$

$$\frac{\hbar^2 \boldsymbol{k}_\uparrow^2}{2\boldsymbol{m}^*} + \alpha \boldsymbol{k}_\uparrow = \frac{\hbar^2 \boldsymbol{k}_\downarrow^2}{2\boldsymbol{m}^*} - \alpha \boldsymbol{k}_\downarrow \quad \therefore \boldsymbol{k}_\downarrow - \boldsymbol{k}_\uparrow = \frac{2\alpha \boldsymbol{m}^*}{\hbar^2}$$

$$\boldsymbol{k}_\downarrow \approx \boldsymbol{k}_F + \frac{\alpha \boldsymbol{m}^*}{\hbar^2}, \quad \boldsymbol{k}_\uparrow \approx \boldsymbol{k}_F - \frac{\alpha \boldsymbol{m}^*}{\hbar^2}$$

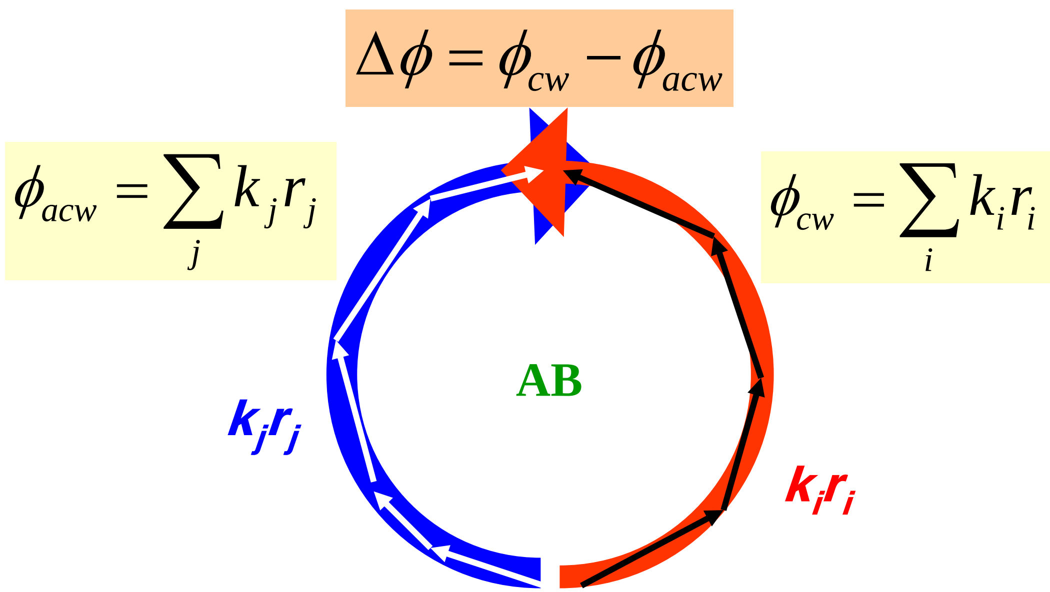


Spin precession and precession angle

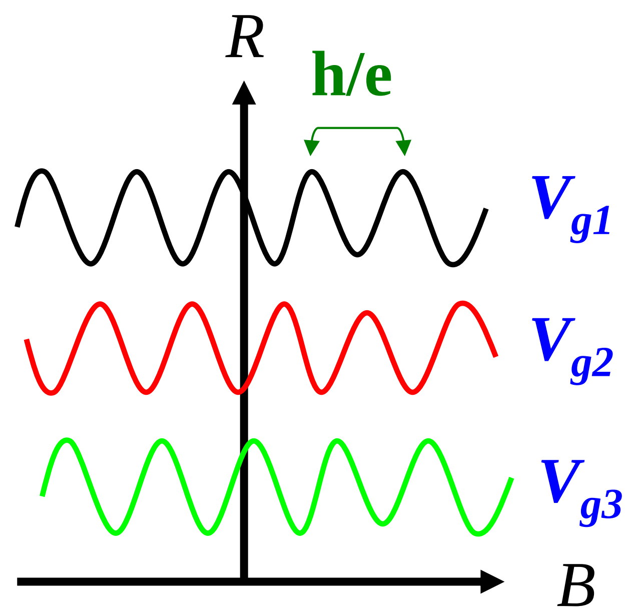
$$\psi(r) = \frac{1}{\sqrt{2}} e^{ik_F r} \begin{pmatrix} e^{-\frac{\alpha m^*}{\hbar^2} r} \\ e^{\frac{\alpha m^*}{\hbar^2} r} \end{pmatrix} \qquad \theta = \frac{2\alpha \boldsymbol{m}^* \boldsymbol{L}}{\hbar^2}$$

Aharonov-Bohm Oscillations
Sample specific feature

Detail of the trajectory and k_F affect the interference



h / e period oscillations

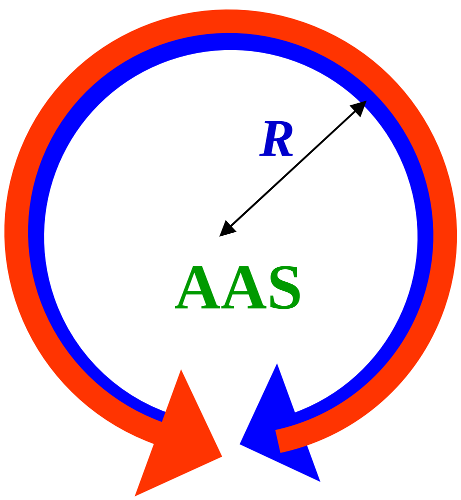


AB oscillations

Gate voltage changes k_F, and its interference pattern !

AAS effect; Time-reversal symmetry interference

AAS oscillation does not depend on wave-vector k_F
But it depends on spin precession angle



h/2e period oscillations

Trajectory: Same length between cw and anti-cw

Wave-function

$$\Phi_{k\sigma} = \frac{1}{\sqrt{2}} e^{ikx} \begin{pmatrix} e^{-\frac{i\alpha m^* x}{\hbar^2}} \\ e^{\frac{i\alpha m^* x}{\hbar^2}} \end{pmatrix}$$

Orbital phase	Spin phase
$\phi_{cw} = \sum_{i=1}^{n} k_i r_i = \phi_{acw}$ Phase difference= 0 $\Delta\phi = \phi_{cw} - \phi_{acw} = 0$ Always constructive	$\varphi_{cw} = \frac{2\pi\alpha m^* R}{\hbar^2} = -\varphi_{acw}$ Phase difference≠ 0 $\Delta\varphi = \varphi_{cw} - \varphi_{acw} = \frac{4\pi\alpha m^* R}{\hbar^2}$ Constructive/Destructive

Ensemble averaging of AB oscillations

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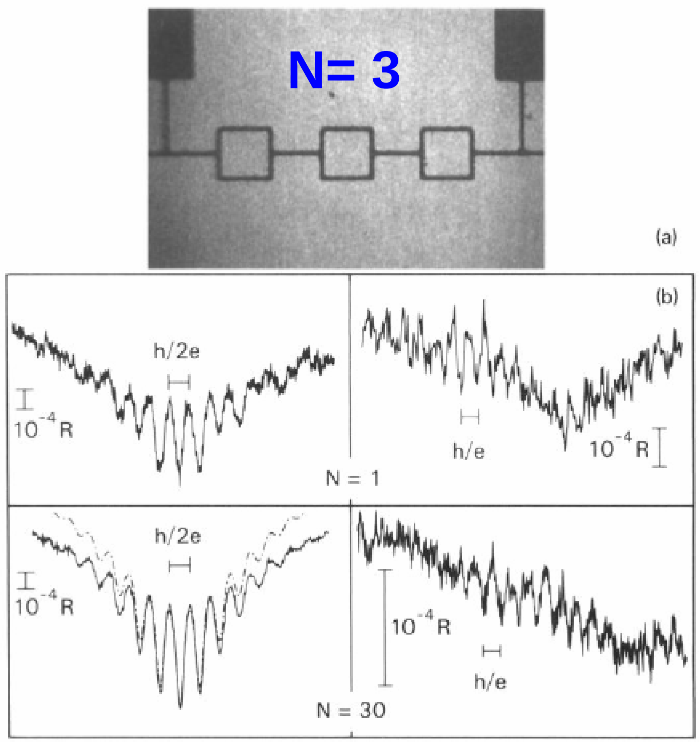
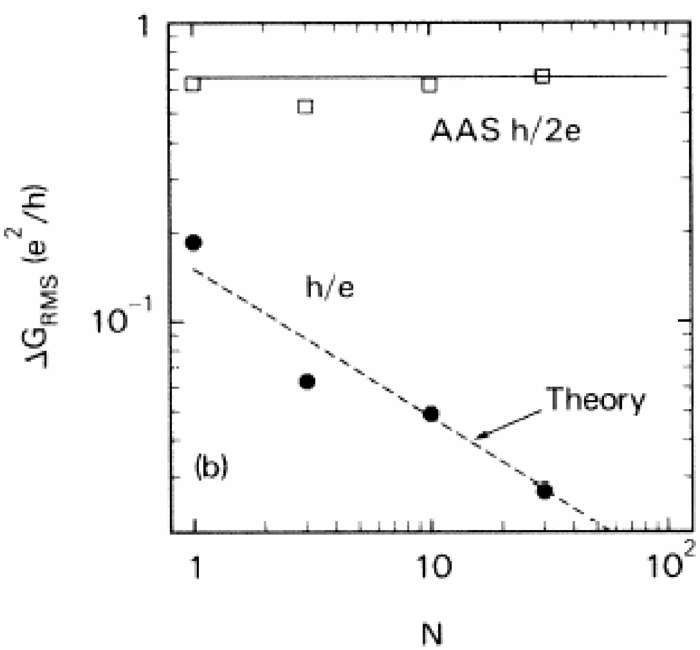
Direct Observation of Ensemble Averaging of the Aharonov-Bohm Effect in Normal-Metal Loops

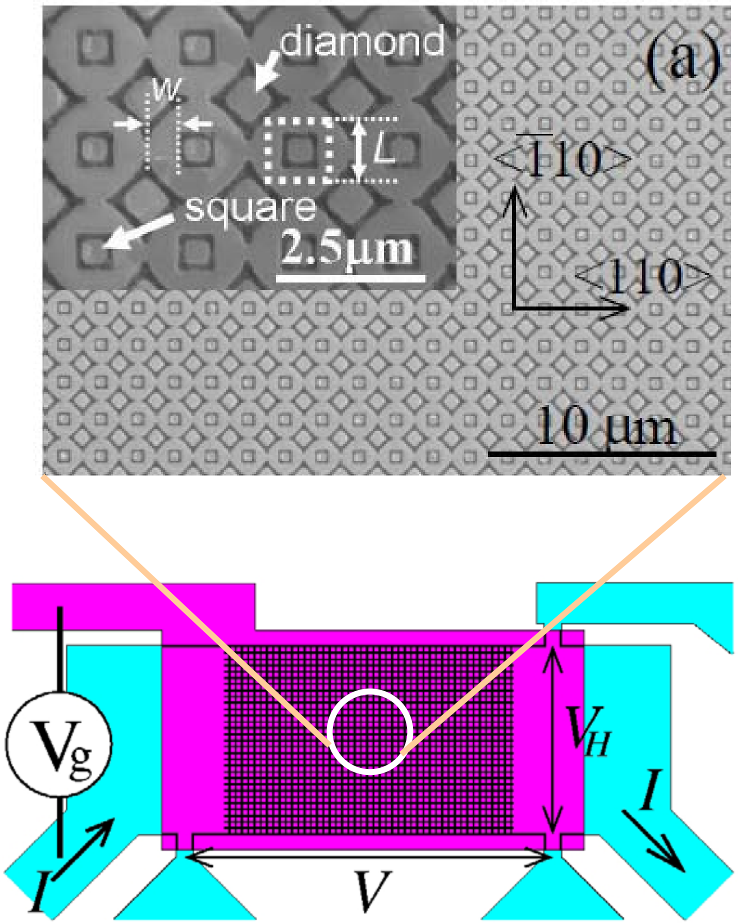
C. P. Umbach, C. Van Haesendonck,[a] R. B. Laibowitz, S. Washburn, and R. A. Webb
IBM T.J. Watson Research Center, Yorktown Heights, New York 10598
(Received 6 November 1985)

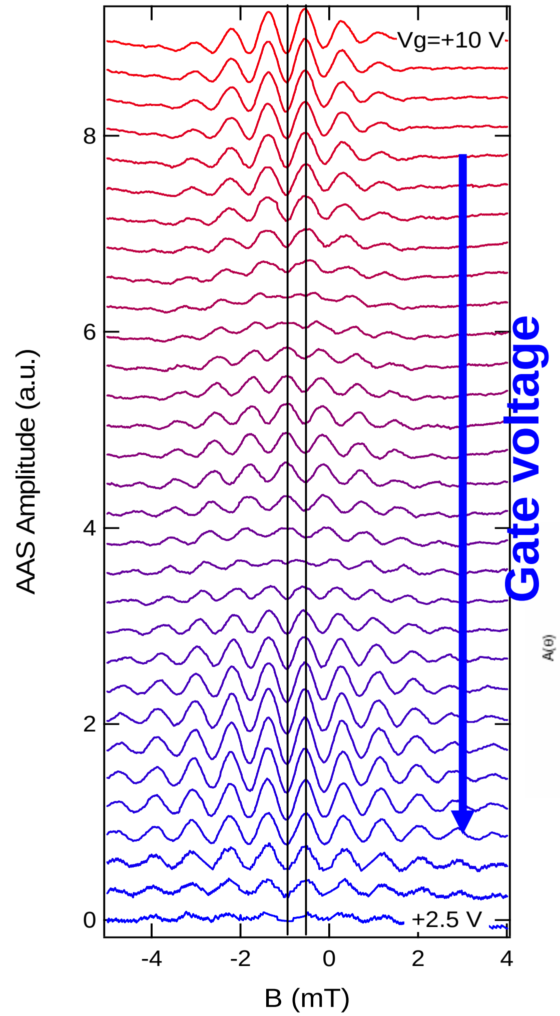


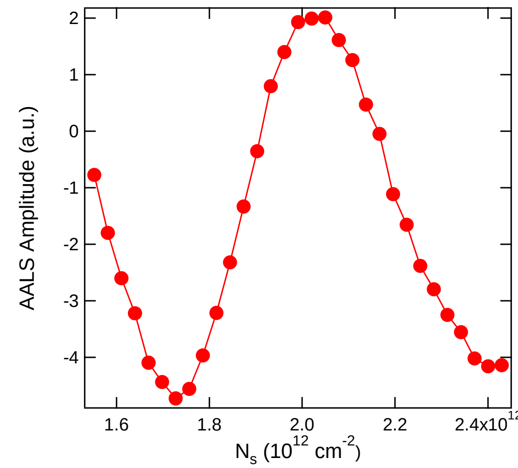


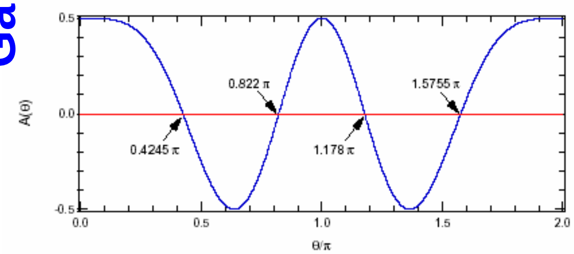
Vg dependence of AAS oscillations

Array of 7700 loops







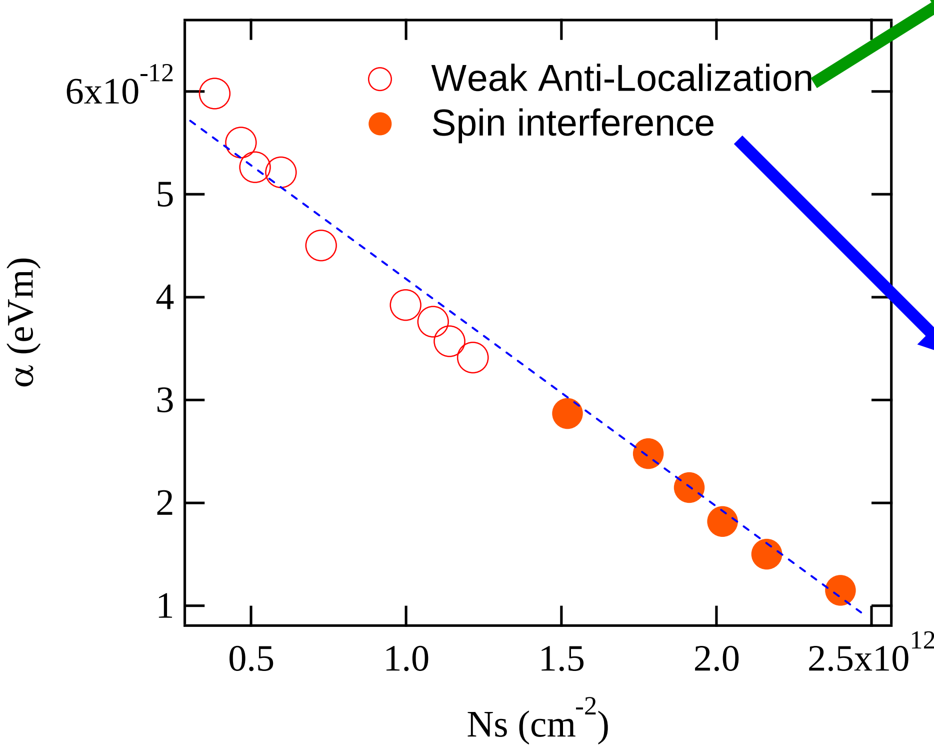


$$\alpha = \frac{\hbar^2 \theta}{2m^* L}$$

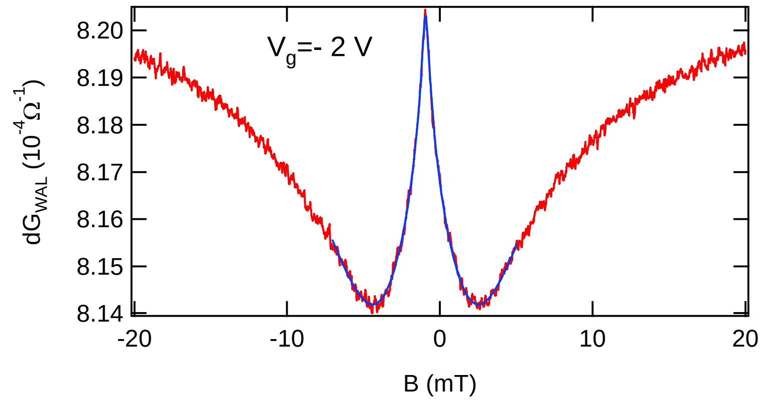
Array of loops is covered with gate to control SOI

Gate controlled SOI and spin precession

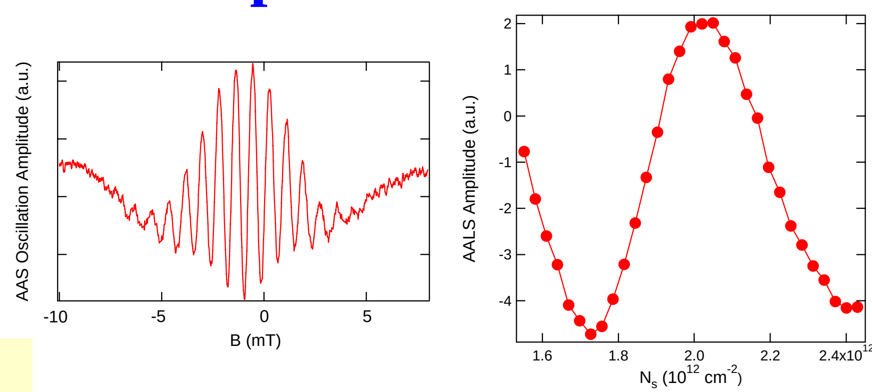
Gate voltage dependence of SOI



Weak anti-localization



Spin interference



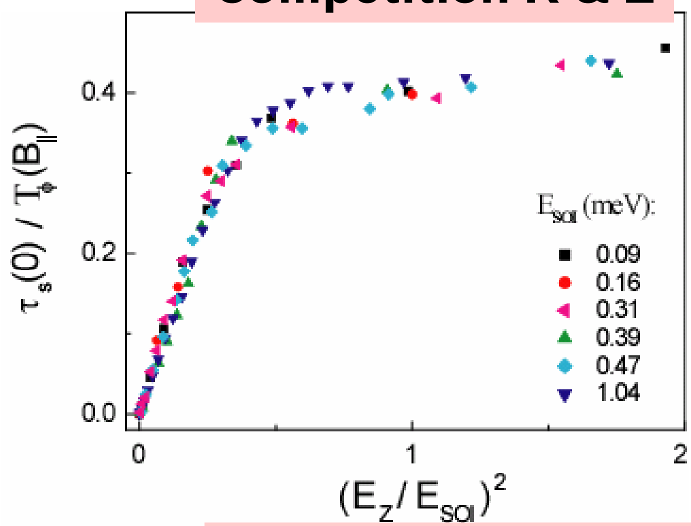
Experimental demonstration of Aharanov-Casher Effect

Cond-mat/0504743

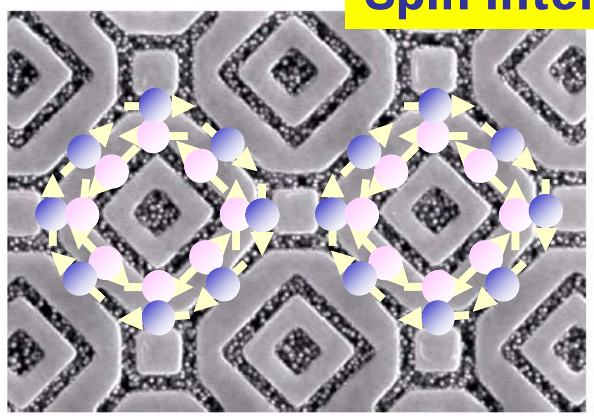
Summary

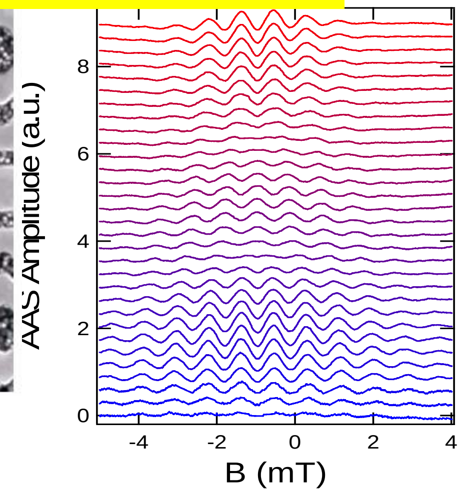
1. The origin of Rashba SOI and gate control
2. Competition between Zeeman and Rashba
3. Spin interference device

Competition R & Z



Spin interference Exp.





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