Spin relaxation in graphene

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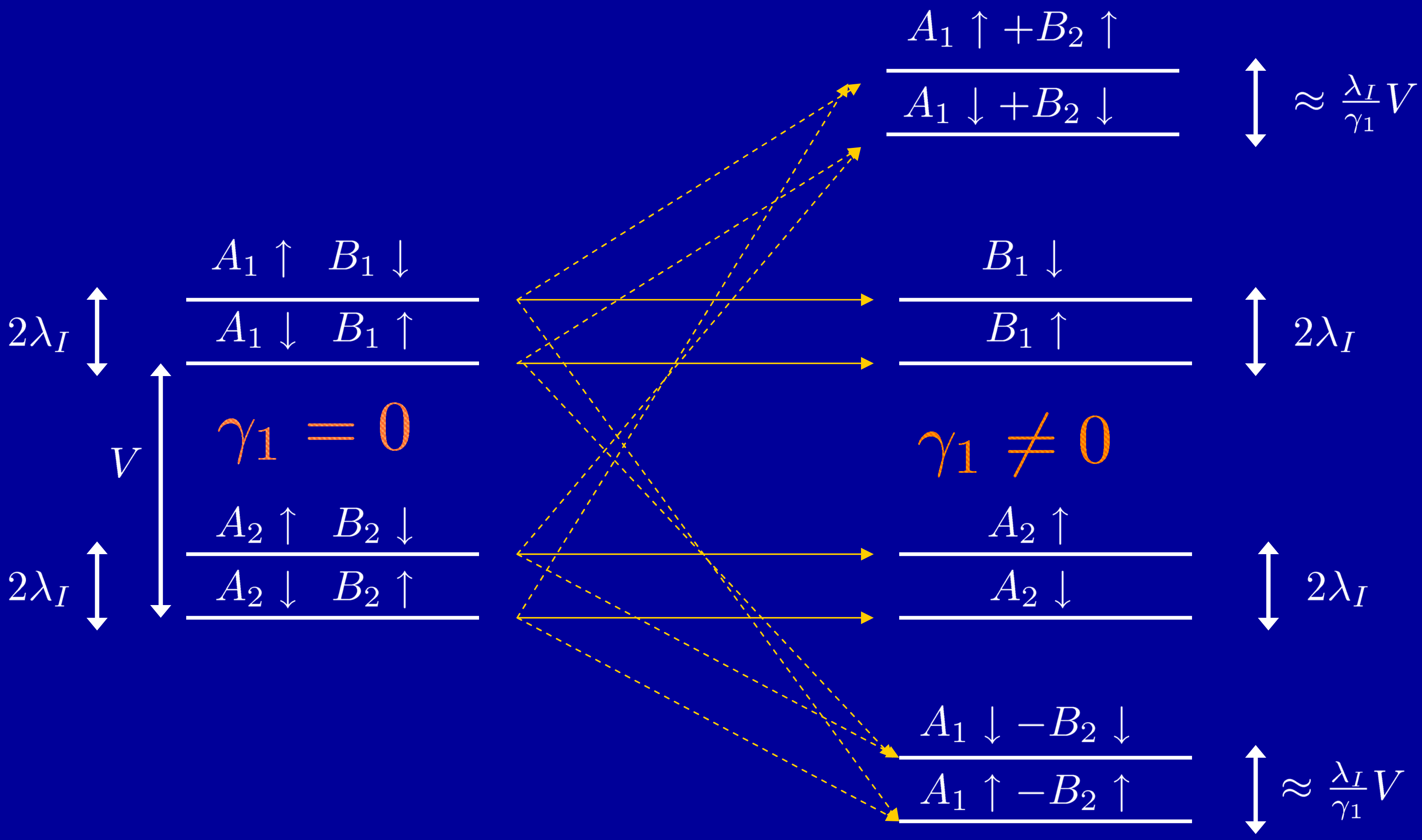
spectrum (K) of bilayer graphene with SOC

S. Konschuh, M. Gmitra, D. Kochan, and J. Fabian,
Theory of spin-orbit coupling in bilayer graphene, arXiv: 1111.7223



$A_1 \uparrow \quad B_1 \downarrow$

$2\lambda_I$

$A_1 \downarrow \quad B_1 \uparrow$

V

$\gamma_1 = 0$

$A_2 \uparrow \quad B_2 \downarrow$

$2\lambda_I$

$A_2 \downarrow \quad B_2 \uparrow$

$A_1 \uparrow + B_2 \uparrow$

$A_1 \downarrow + B_2 \downarrow$

$\approx \frac{\lambda_I}{\gamma_1} V$

$B_1 \downarrow$

$B_1 \uparrow$

$2\lambda_I$

$\gamma_1 \neq 0$

$A_2 \uparrow$

$A_2 \downarrow$

$2\lambda_I$

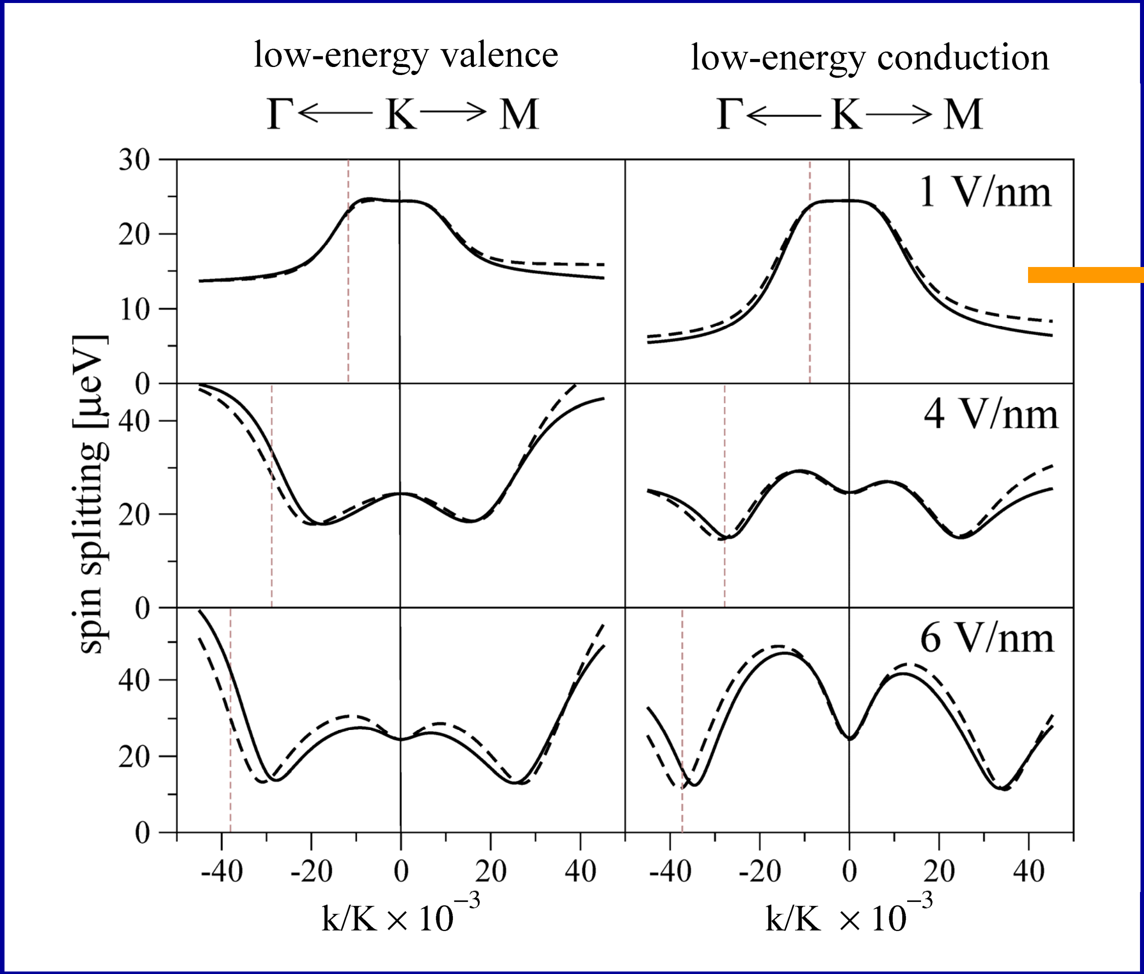
$A_1 \downarrow - B_2 \downarrow$

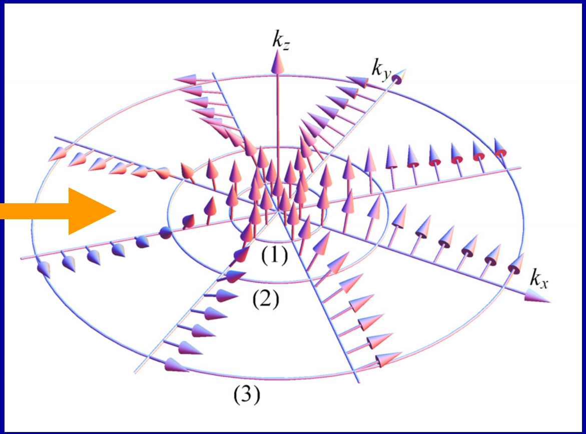
$A_1 \uparrow - B_2 \uparrow$

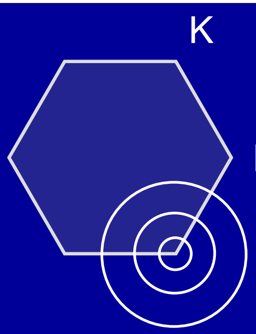
$\approx \frac{\lambda_I}{\gamma_1} V$

:spin splittings in AB bilayer:

low-energy bands







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Theory of spin-orbit coupling in bilayer graphene, arXiv: 1111.7223

:spin splittings in AB bilayer:

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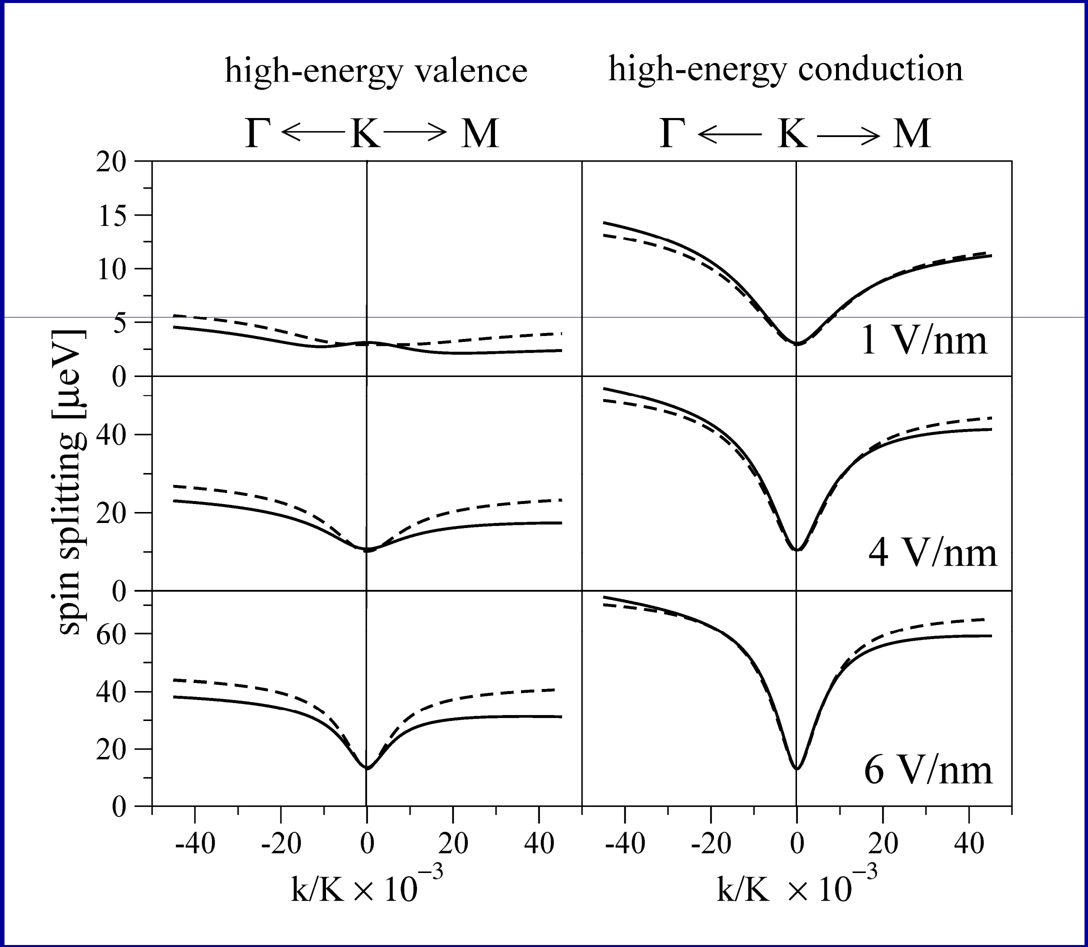

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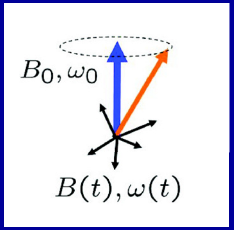
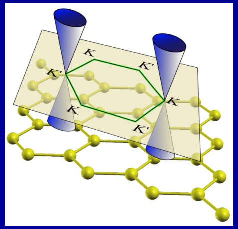
Theory of spin-orbit coupling in bilayer graphene, arXiv: 1111.7223

- spin relaxation in graphene



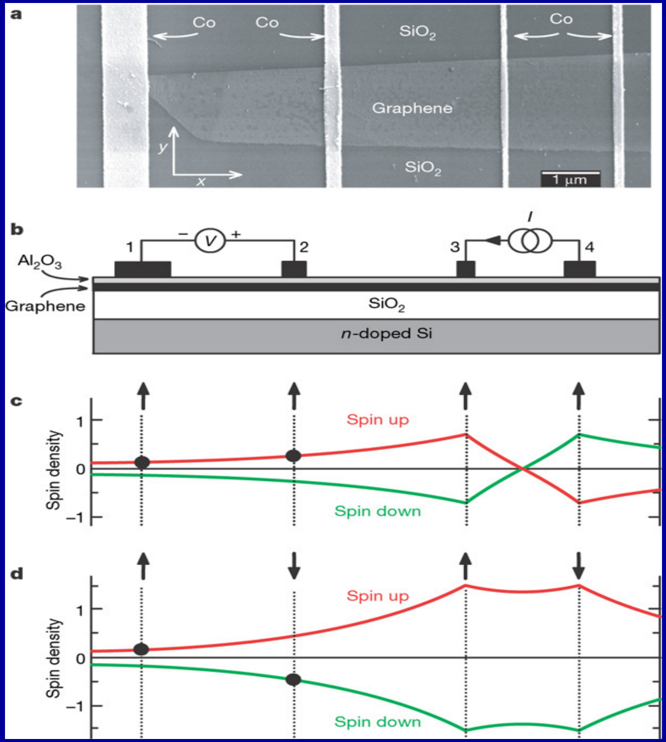
:spin relaxation in graphene:

experimental facts



non-local spin injection/detection scheme

single-layer on a SiO_2 substrate



surprisingly small

- spin relaxation time

$$\tau_s \approx 100\ \text{ps},\quad L_s = \sqrt{D\tau_s} \approx 1\,\mu\text{m}$$

see also K. Pi et al., Phys. Rev. Lett. 104, 187201 (2010)

- longer in *bilayer*

T. Yang et al., arXiv:1012.1156 (up to 2 ns in low mobility samples)

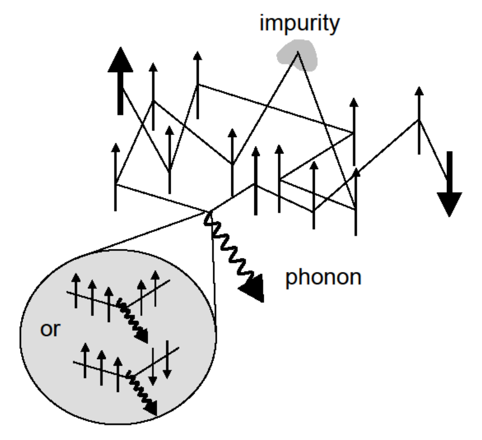
W. Han and R. Kawakami, arXiv:1012.3435 (up to 6 ns)

AG D. Weiss/J. Eroms (200-350ps)

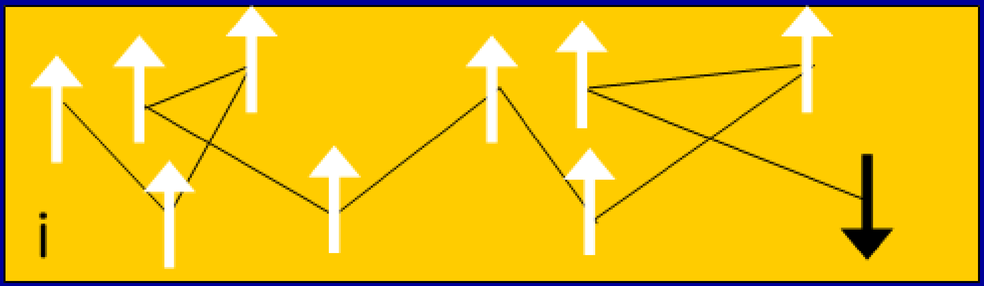
N. Tombros, C. Jozsa, M. Popinciuc, H. T. Jonkman, and B. J. van Wees
Electronic spin transport and spin precession in single graphene layers at room temperature,
Nature 448, 571 (2007)
See also W. Han et al, *Tunneling spin injection into single layer graphene*,
Phys. Rev. Lett. 105, 167202 (2010).

:spin relaxation in graphene:

Elliott-Yafet mechanism



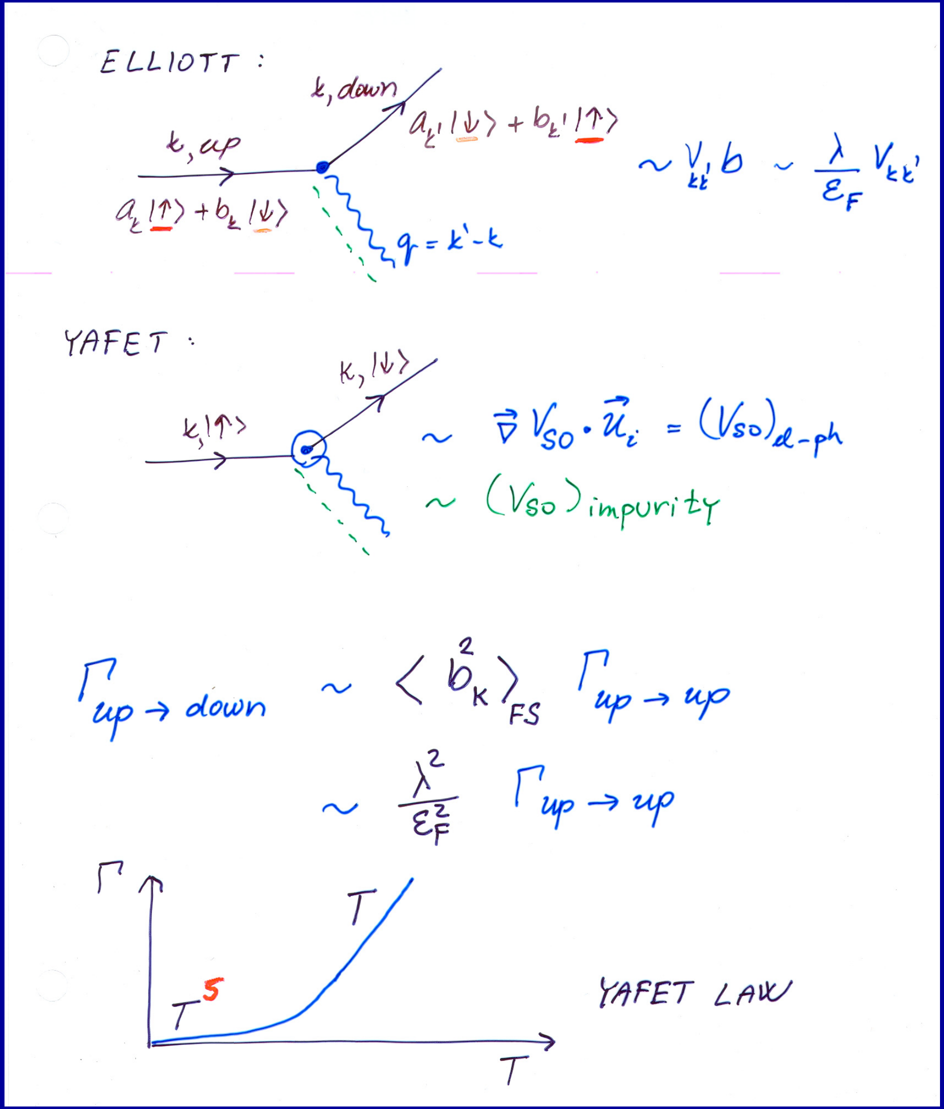
$$1/\tau_s \approx (\lambda_{so}/E_F)^2/\tau$$



more scattering, more spin relaxation

J. Fabian, A. Matos-Abiague, C. Ertler, and P. Stano, *Semiconductor spintronics*, Acta Phys. Slov. 57, 565 (2007)

:the Elliott-Yafet mechanism:



ELLIOTT :

$$\sim V_{kk'}\, b \sim \frac{\lambda}{\varepsilon_F} V_{kk'}$$

YAFET :

$$\sim \vec{\nabla} V_{SO} \cdot \vec{u}_i = (V_{SO})_{el-ph}$$

$$\sim (V_{SO})_{impurity}$$

$$\Gamma_{up \to down} \sim \langle b_K^2 \rangle_{FS}\, \Gamma_{up \to up}$$

$$\sim \frac{\lambda^2}{\varepsilon_F^2}\, \Gamma_{up \to up}$$

YAFET LAW

electronic band structure
with spin-orbit coupling

+

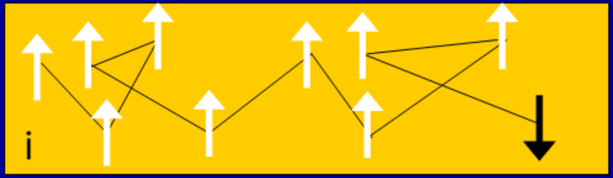
phonon band structure

+

electron-phonon coupling

+

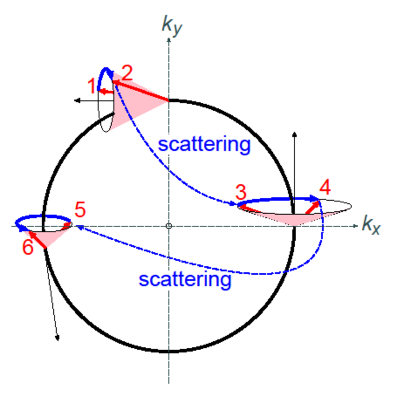
accurate summation in k-space



more scattering, more spin relaxation

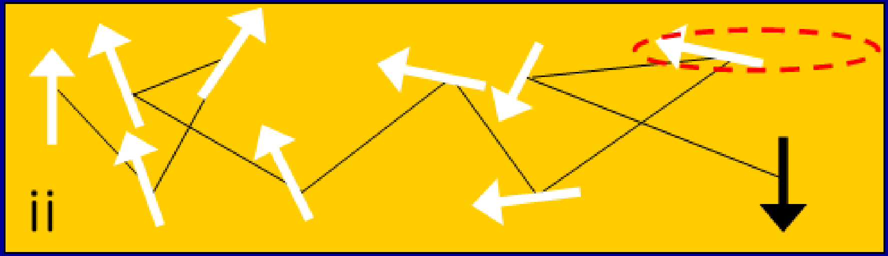
:spin relaxation in graphene:

Dyakonov-Perel mechanism



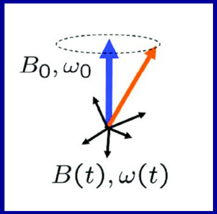
$$1/\tau_s \approx \Omega_{BR}^2 \tau$$

Picture courtesy of Phivos Mavropoulos



more scattering, less spin relaxation

spin in a random fluctuating magnetic field



J. Fabian, A. Matos-Abiague, C. Ertler, and P. Stano, *Semiconductor spintronics*, Acta Phys. Slov. 57, 565 (2007)

:the actual equation to be solved looks like this:

spin density matrix at each k

$$\frac{\partial \rho_{\mathbf{k}}}{\partial t} - \overbrace{\frac{1}{i\hbar}[H_1(\mathbf{k}), \rho_{\mathbf{k}}]}^{\textit{Dyakonov-Perel}} + \frac{\partial \rho_{\mathbf{k}}}{\partial \hbar \mathbf{k}} \cdot \mathbf{F}_{\mathbf{k}} + \frac{\partial \rho_{\mathbf{k}}}{\partial \mathbf{r}} \cdot \mathbf{v}_{\mathbf{k}} = \overbrace{\left(\frac{\partial \rho_{\mathbf{k}}}{\partial t}\right)_{\text{coll}}}^{\textit{Elliott-Yafet here}}$$

:spin relaxation in graphene:

Theoretical interest:

D. Huertas-Hernando, F. Guinea, and A. Brataas, EPJ Spec. Top. 148, 177 (2007)

C. Ertler, S. Konschuh, M. Gmitra, and J. Fabian, Phys. Rev. B **80**, 041405(R) (2009)

D. Huertas-Hernando, F. Guinea, and A. Brataas, PRL 103, 146801 (2009)

Y. Zhou and M. W. Wu, arXiv:1004.0638

F. Simon, F. Muranyi, and B. Dora, arXiv:1004.0210

Simple estimates (exp: 100 ps, anisotropy 0.8):

Elliott-Yafet:

$$1/\tau_s \approx (\lambda_{so}/E_F)^2(1/\tau) \approx (10^{-5}eV/10^{-1}eV)^2/10^{-13}s = 10^5/s$$

anisotropy $\tau_{s,\perp}/\tau_{s,||} \rightarrow \infty$

Dyakonov-Perel:

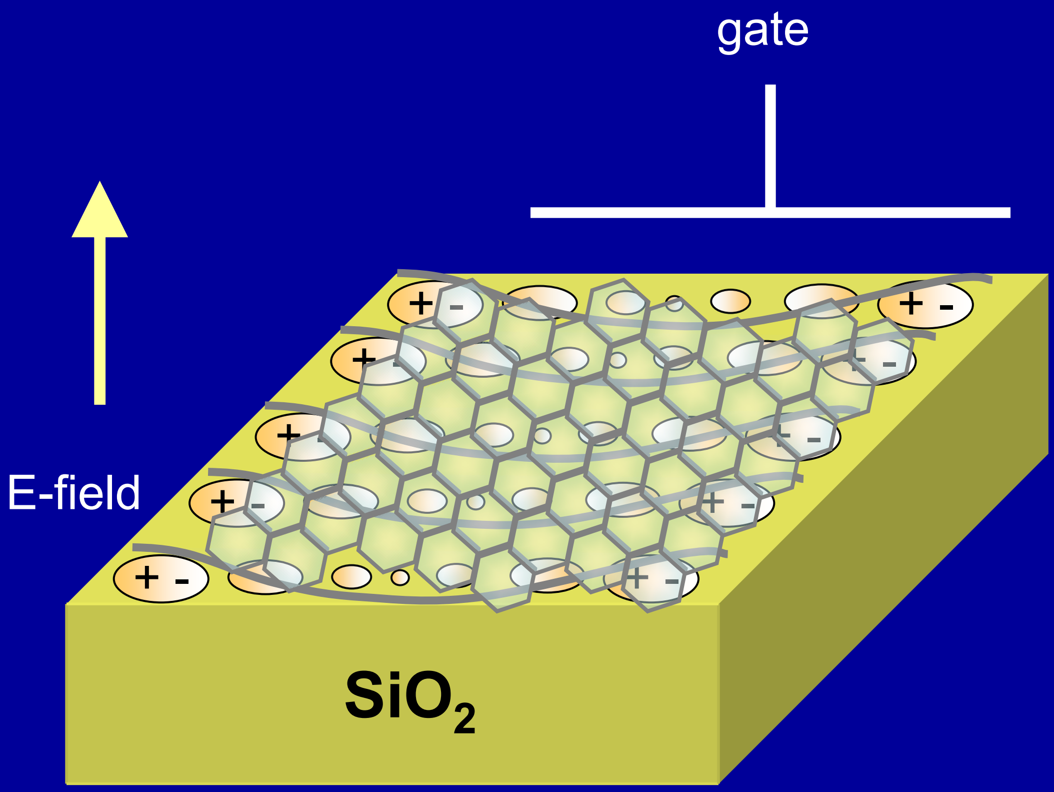
$$1/\tau_s \approx \Omega^2\tau \approx (10^{-6}eV/\hbar)^2 10^{-13}s \approx 10^5/s$$

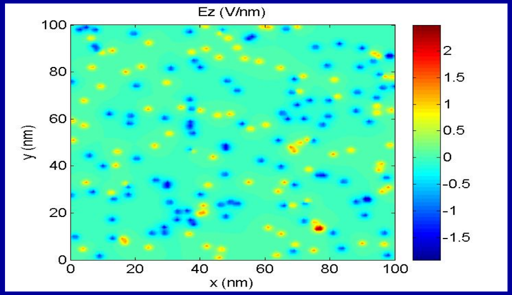
anisotropy $\tau_{s,\perp}/\tau_{s,||} \rightarrow 0.5$

:spin relaxation in graphene:

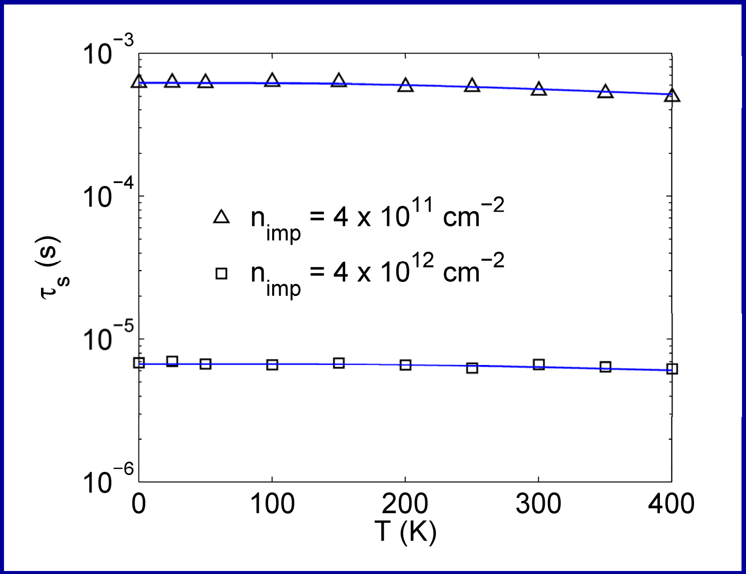
Dyakonov-Perel mechanism

C. Ertler, S. Konschuh, M. Gmitra, and J. Fabian, Phys. Rev. B **80**, 041405(R) (2009)

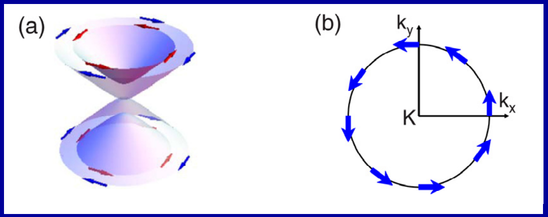




Momentum scattering: *Das Sarma group model*
Adam et al, Proc. Nat. Acad. Sci. USA 104, 18392 (2007)



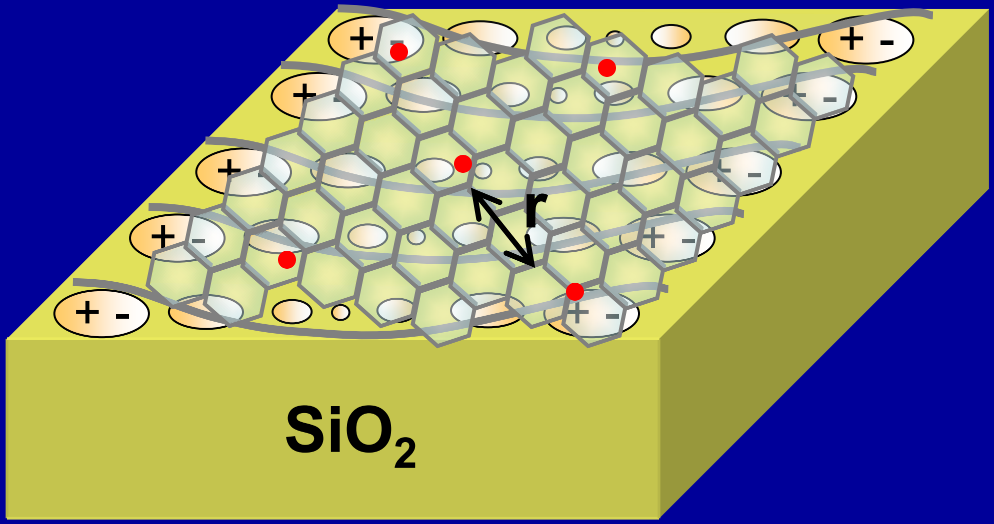
substrate: random charges, surface polaritons



:spin relaxation in graphene:

the role of adatoms

C. Ertler, S. Konschuh, M. Gmitra, and J. Fabian, Phys. Rev. B **80**, 041405(R) (2009)



:spin relaxation in graphene:

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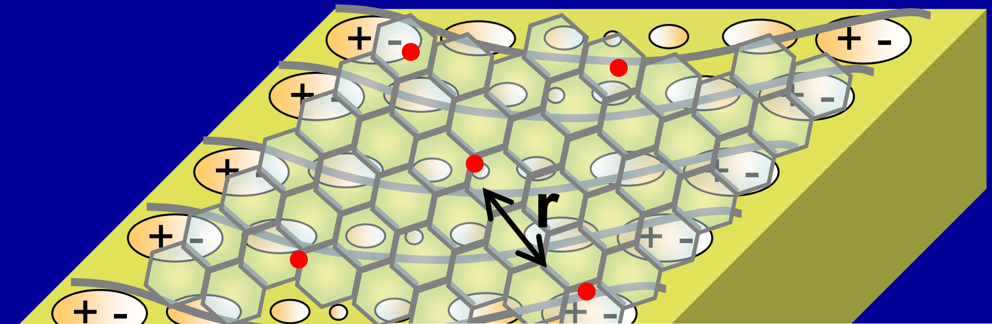
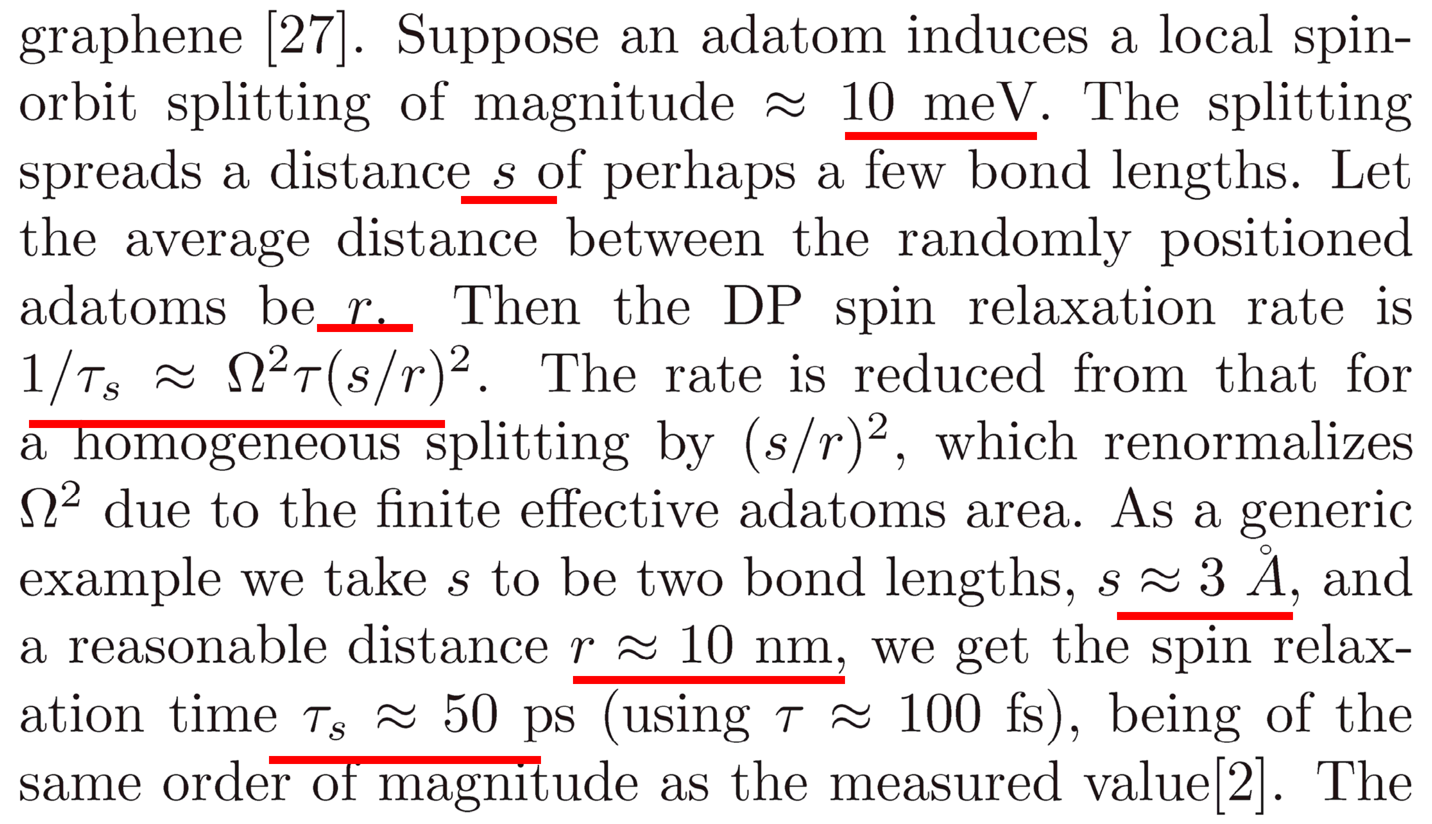
C. Ertler, S. Konschuh, M. Gmitra, and J. Fabian, Phys. Rev. B **80**, 041405(R) (2009)

A. Castro-Neto and F. Guinea, PRL 103, 026804 (2009)

M. Grandhand, D. Fedorov, et al. (Mertig group), JF, *ab initio treatment of spin relaxation in graphene caused by adatoms,* poster MA 63.21

Exp: K. Pi et al., Phys. Rev. Lett. 104, 187201 (2010)
T. Yang et al., arXiv:1012.1156




graphene [27]. Suppose an adatom induces a local spin-orbit splitting of magnitude ≈ 10 meV. The splitting spreads a distance s of perhaps a few bond lengths. Let the average distance between the randomly positioned adatoms be r. Then the DP spin relaxation rate is $1/\tau_s \approx \Omega^2 \tau (s/r)^2$. The rate is reduced from that for a homogeneous splitting by $(s/r)^2$, which renormalizes Ω^2 due to the finite effective adatoms area. As a generic example we take s to be two bond lengths, $s \approx 3$ Å, and a reasonable distance $r \approx 10$ nm, we get the spin relaxation time $\tau_s \approx 50$ ps (using $\tau \approx 100$ fs), being of the same order of magnitude as the measured value[2]. The