Spin Hall effect in graphene

Patrick Lee
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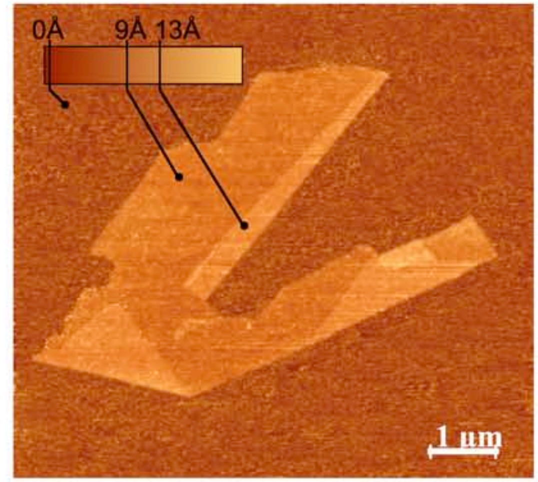
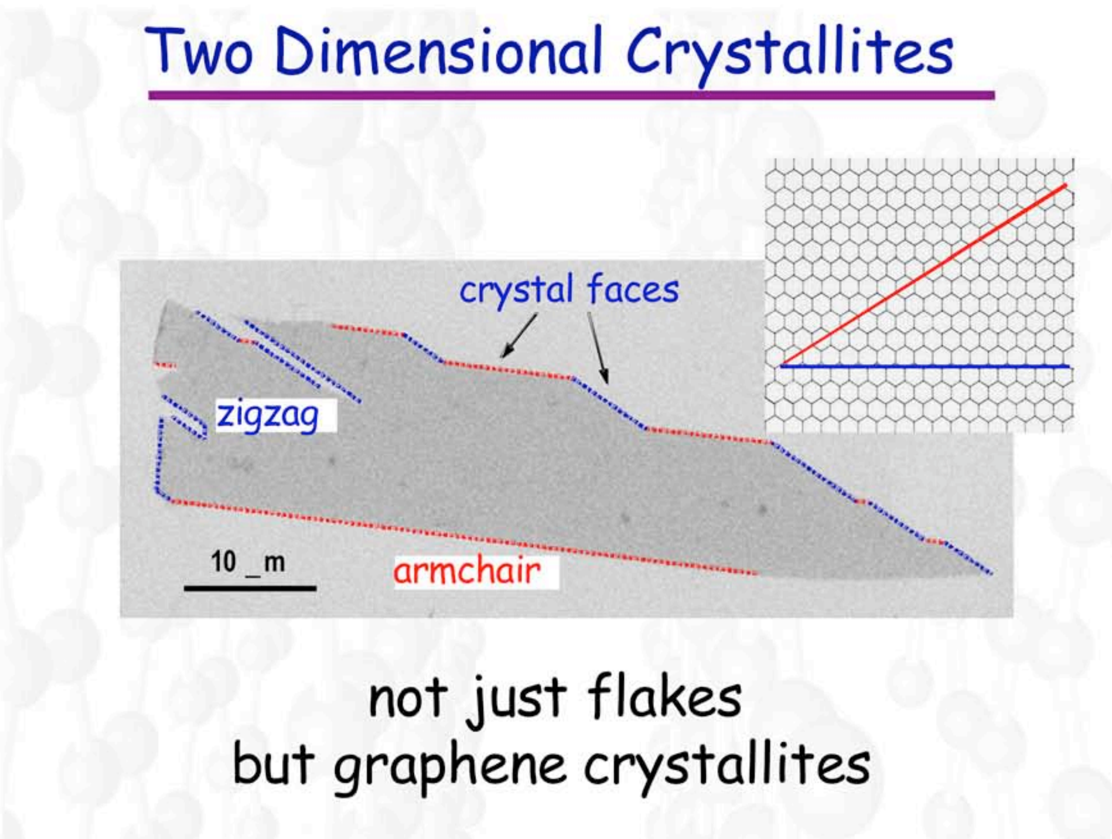
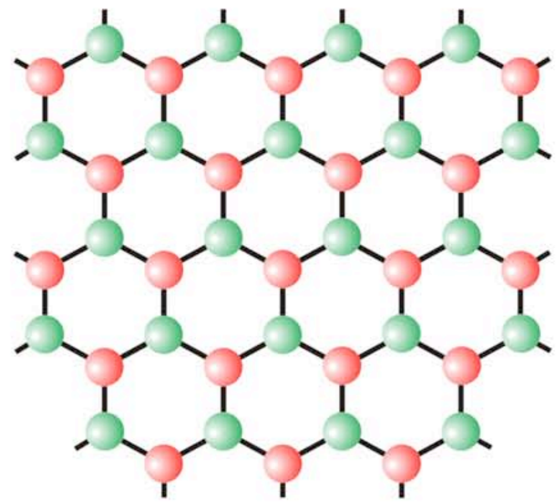
Dimitri Abanin, PAL, Leonid Levitov, cond-mat 07 and Solid State Communications, to appear.

Novoselov et al, Science **306**, 666 (2004)

Key: optical detection.





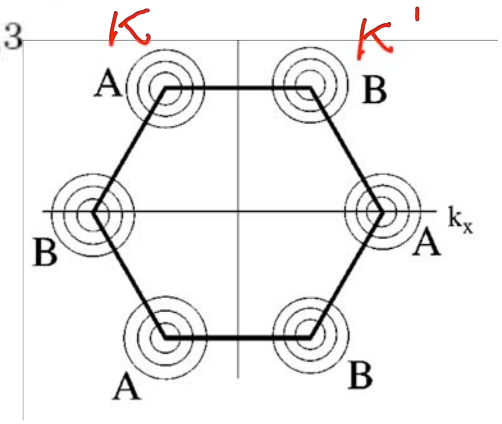


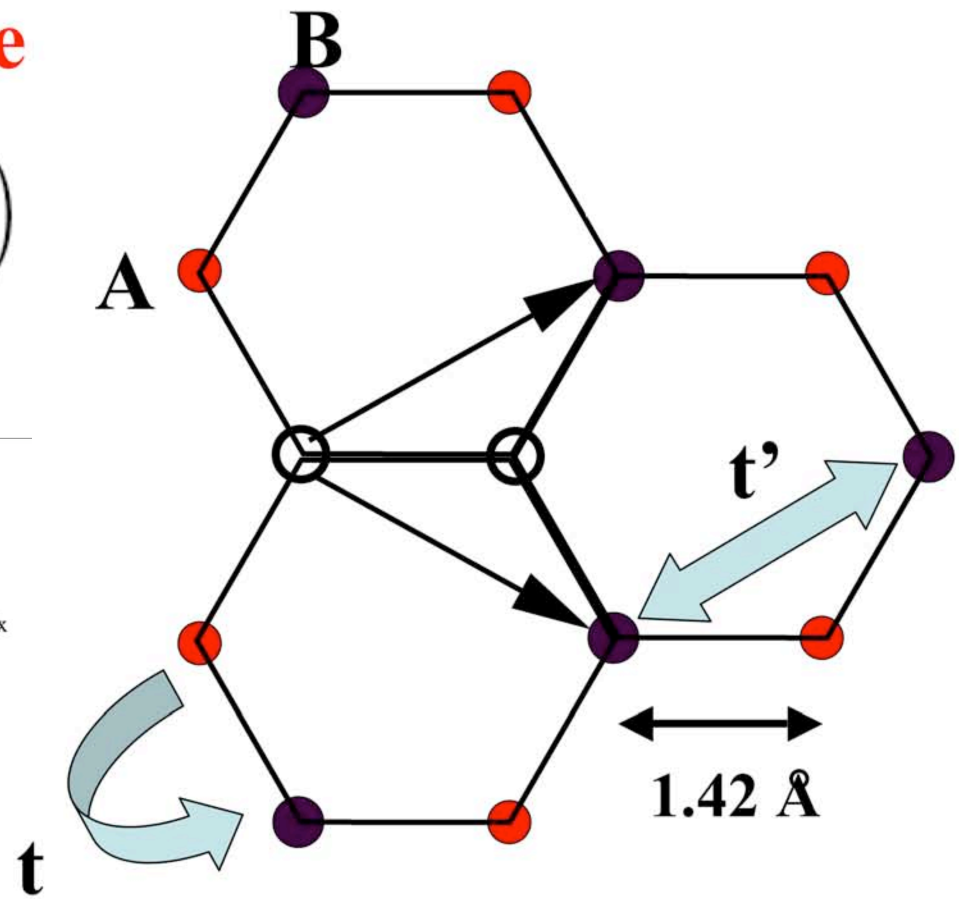
Single layer graphene

$$\begin{bmatrix} 0 & \tau(\mathbf{q}) \\ \tau^*(\mathbf{q}) & 0 \end{bmatrix} \begin{pmatrix} u \\ v \end{pmatrix} = \varepsilon \begin{pmatrix} u \\ v \end{pmatrix}$$

$$\tau(\mathbf{q}) = \sum_{i=1,2,3} t_i e^{i\mathbf{q}.\mathbf{e}_i}$$

Brillouin zone





- **1 electron per π orbital: half-filled**
- **Kinetic energy: n.n. $t \sim 3$ eV**

  n.n.n. $t' \sim 0.1$ eV

Single layer graphene

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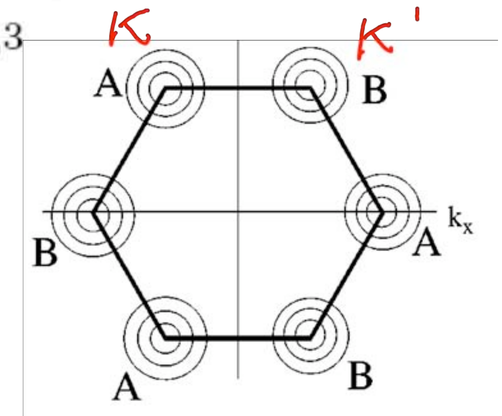
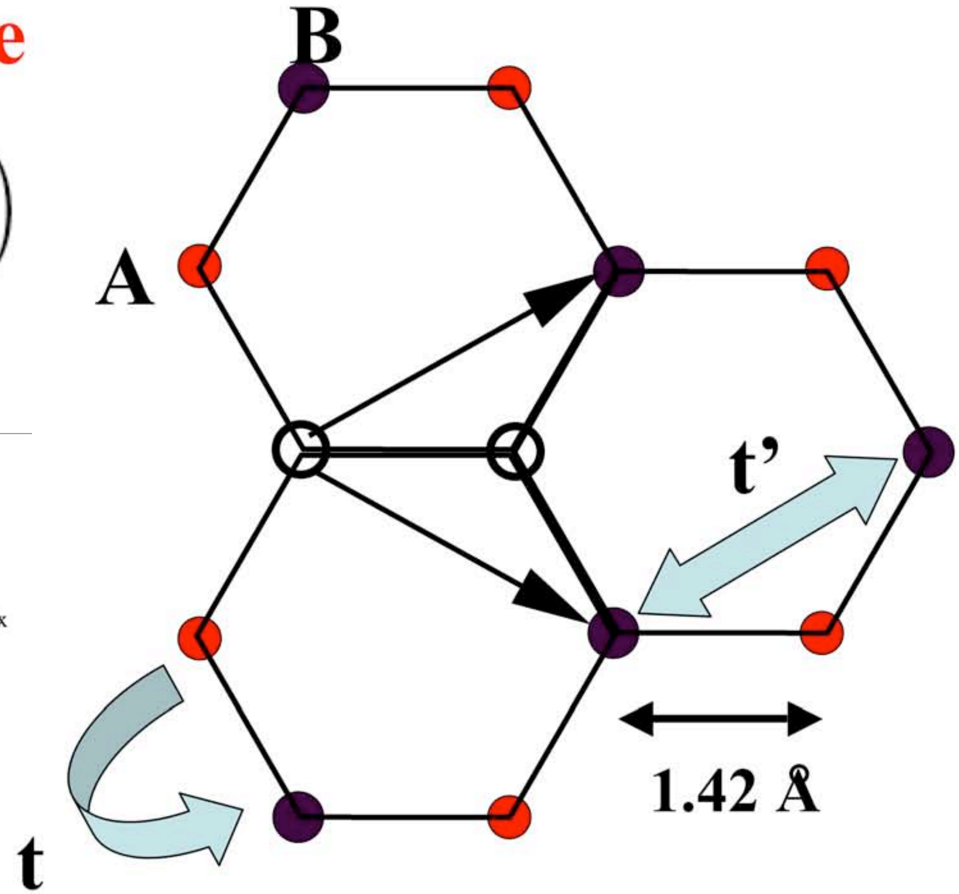




$$H_K = v_0 \begin{bmatrix} 0 & \tilde{p}_+ \\ \tilde{p}_- & 0 \end{bmatrix}$$

$$H_{K'} = v_0 \begin{bmatrix} 0 & \tilde{p}_- \\ \tilde{p}_+ & 0 \end{bmatrix}$$

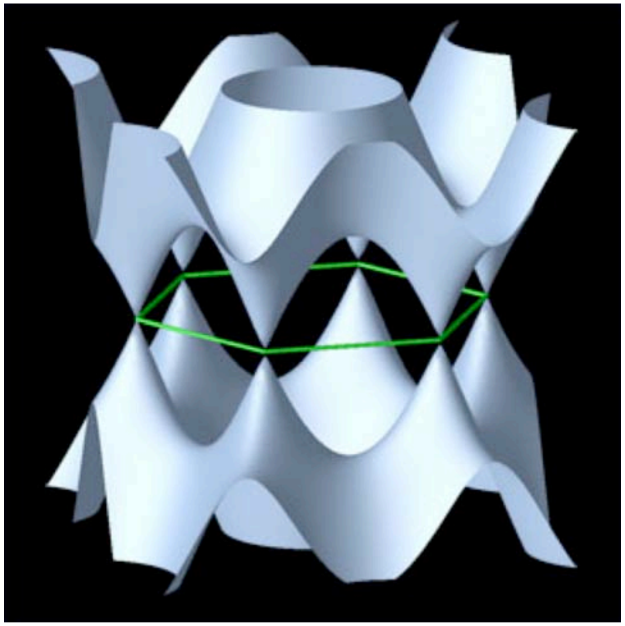
$$\tilde{p}_\pm = \tilde{p}_x \pm i\tilde{p}_y, \quad \tilde{p}_\mu = p_\mu - \frac{e}{c}A_\mu$$

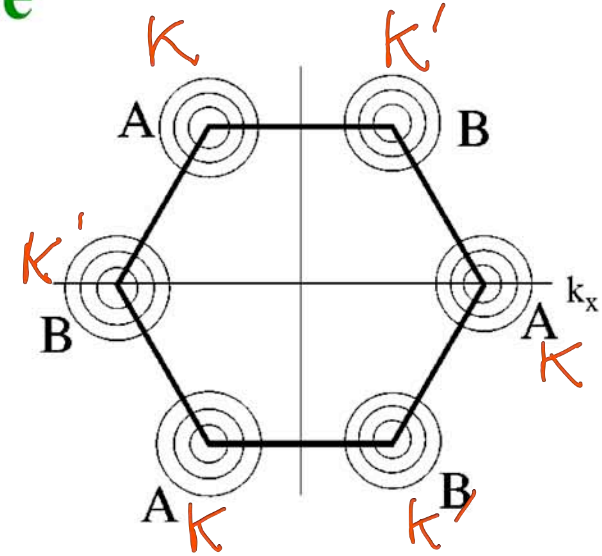
- 1 electron per π orbital: half-filled
- Kinetic energy: n.n. $t \sim 3$ eV

  n.n.n. $t' \sim 0.1$ eV

$E = v_0 | p |$ massless Dirac spectrum

Momentum Space

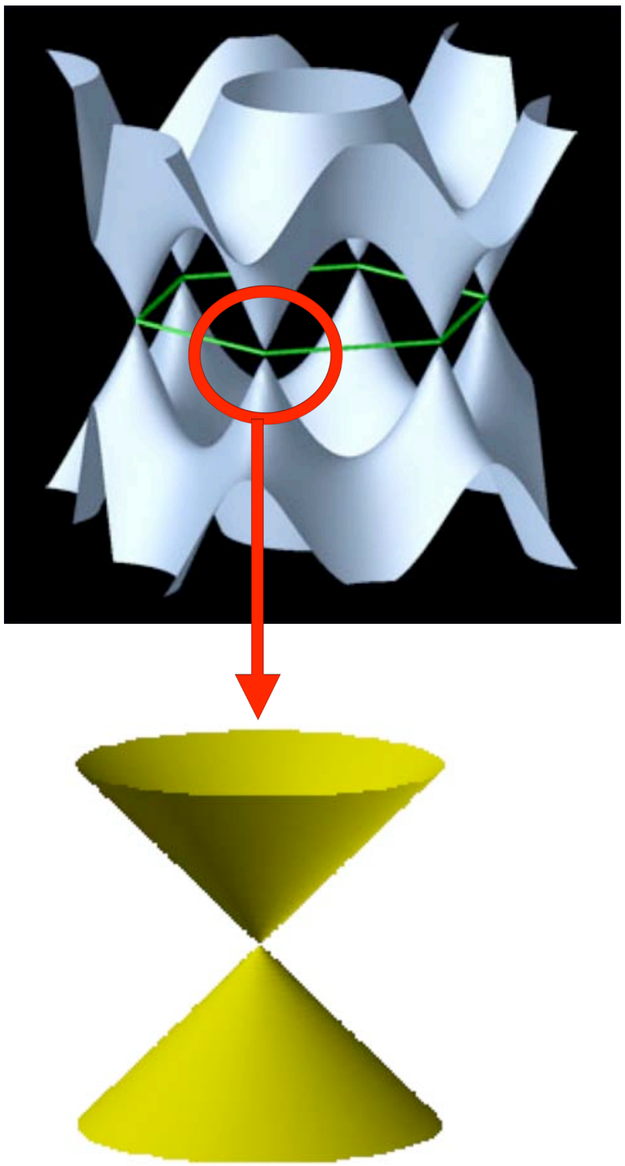


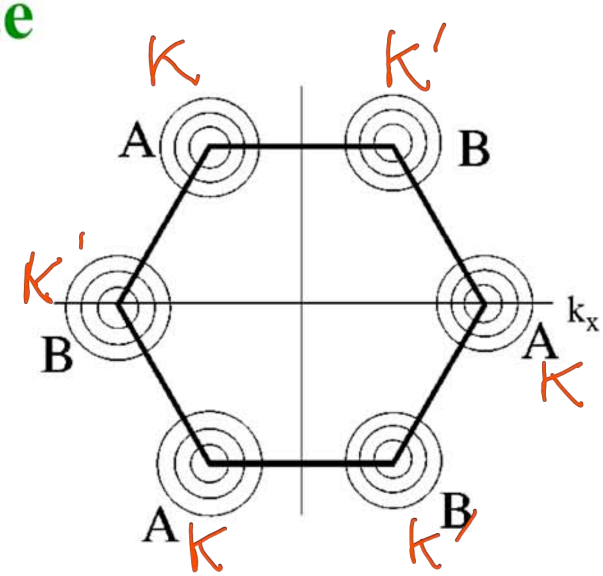


$E=v_0|\,p\,|$ massless Dirac spectrum

$v_0= 8x10^7$ cm/sec $=c/400$

Momentum Space



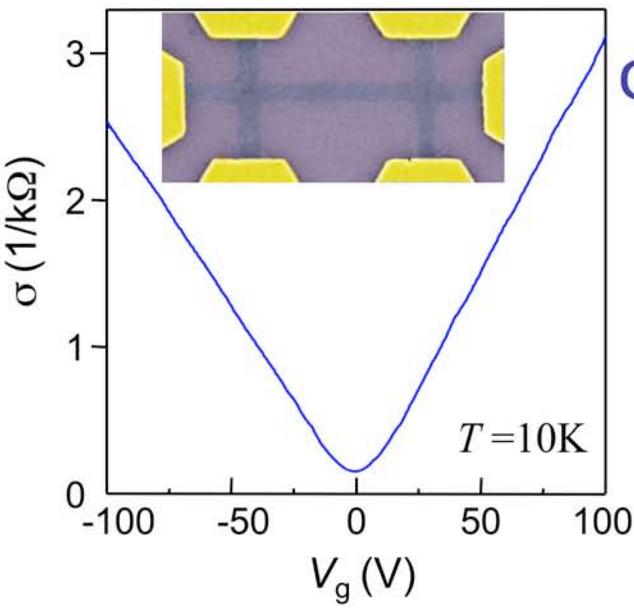


$E=v_0|\,p\,|$ massless Dirac spectrum

$v_0 = 8\times10^7$ cm/sec $= c/400$

Electric Field Effect in Graphene

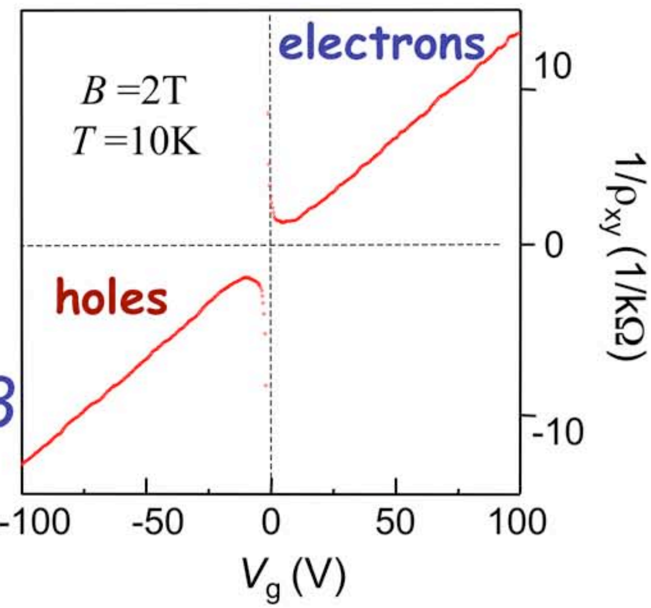
conductivity

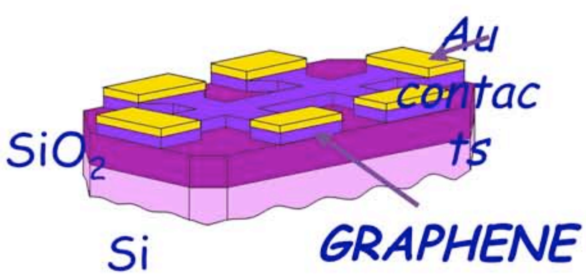


$\sigma = n(V_g)e\mu$

Hall effect

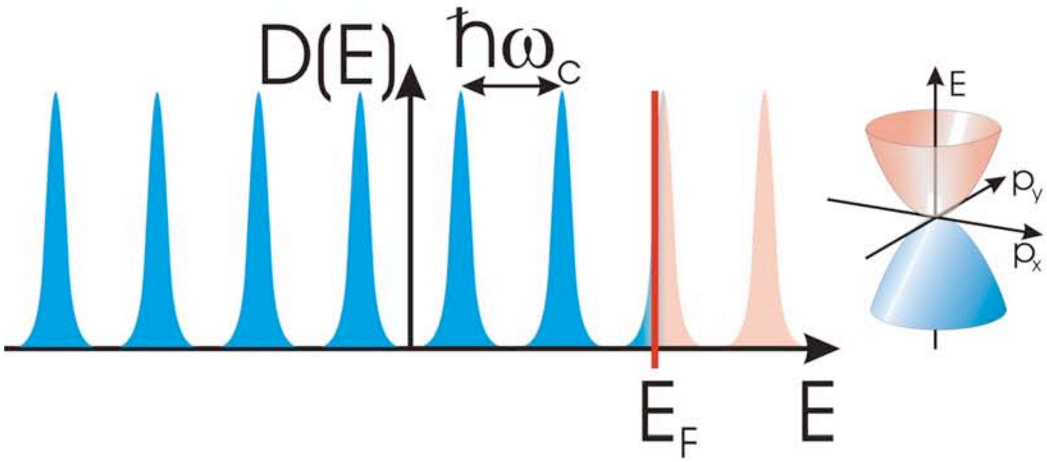
$1/\rho_{xy} = ne/B$





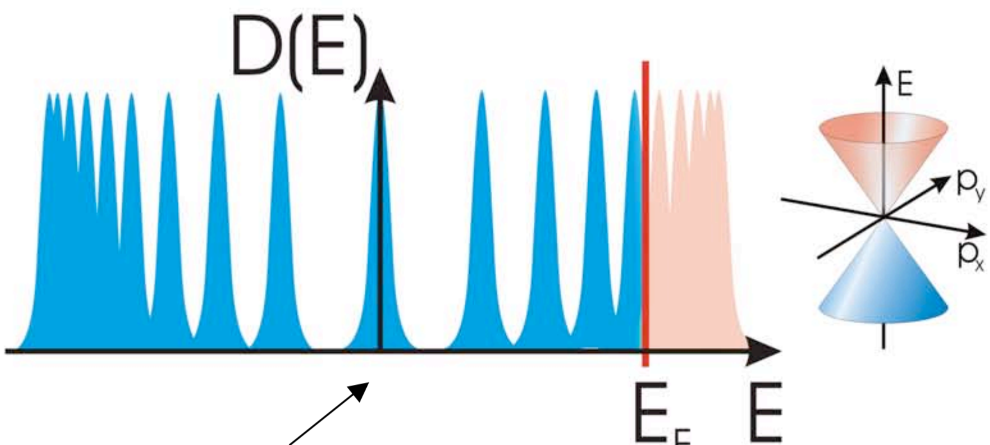
simple behaviour;
practically constant mobility;
no trapped carriers

In the presence of a magnetic field B: Landau levels



$$\ell_B = (\hbar c/eB)^{1/2}$$

$$\omega_c = eB/(mc) = \hbar/(ml_B^2)$$
$$l_B = \sqrt{\hbar c/(eB)}$$
$$B = 10T \qquad \hbar\omega_c \approx 1K$$

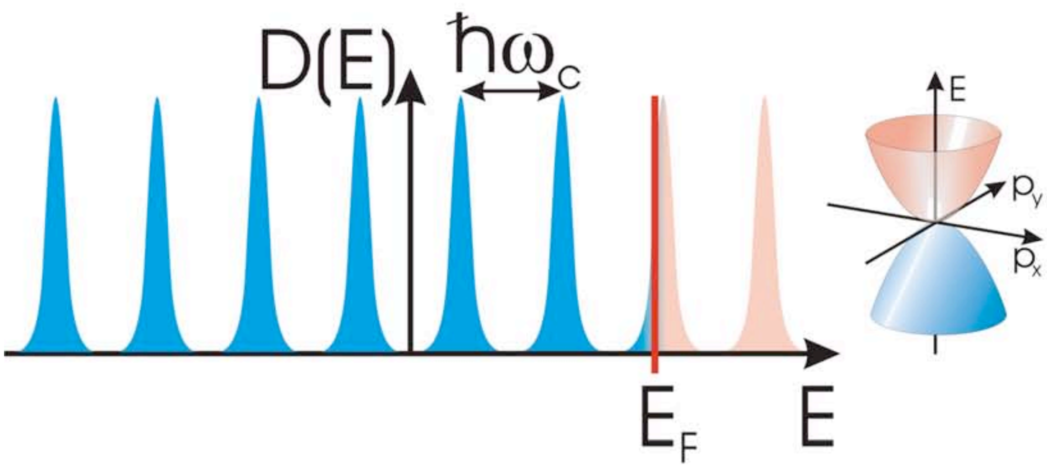


Zero mode

$$E_n = \mathrm{sgn}(n)|2n|^{1/2}\frac{\hbar v}{\ell_B}$$

B=10T, E_1-E_0=1500K

In the presence of a magnetic field B: Landau levels



$$\ell_B = (\hbar c / eB)^{1/2}$$

$$\omega_c = eB/(mc) = \hbar/(m l_B^2)$$

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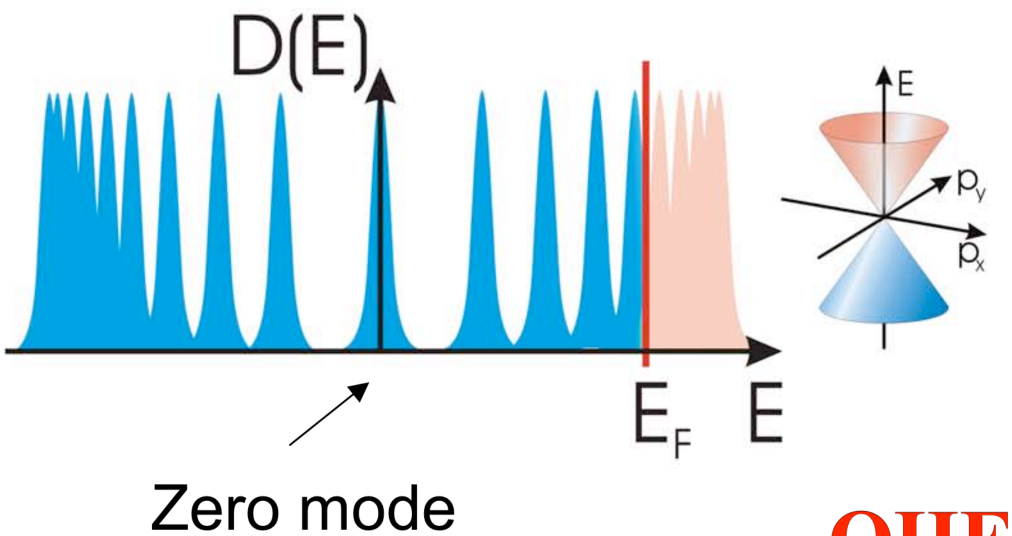
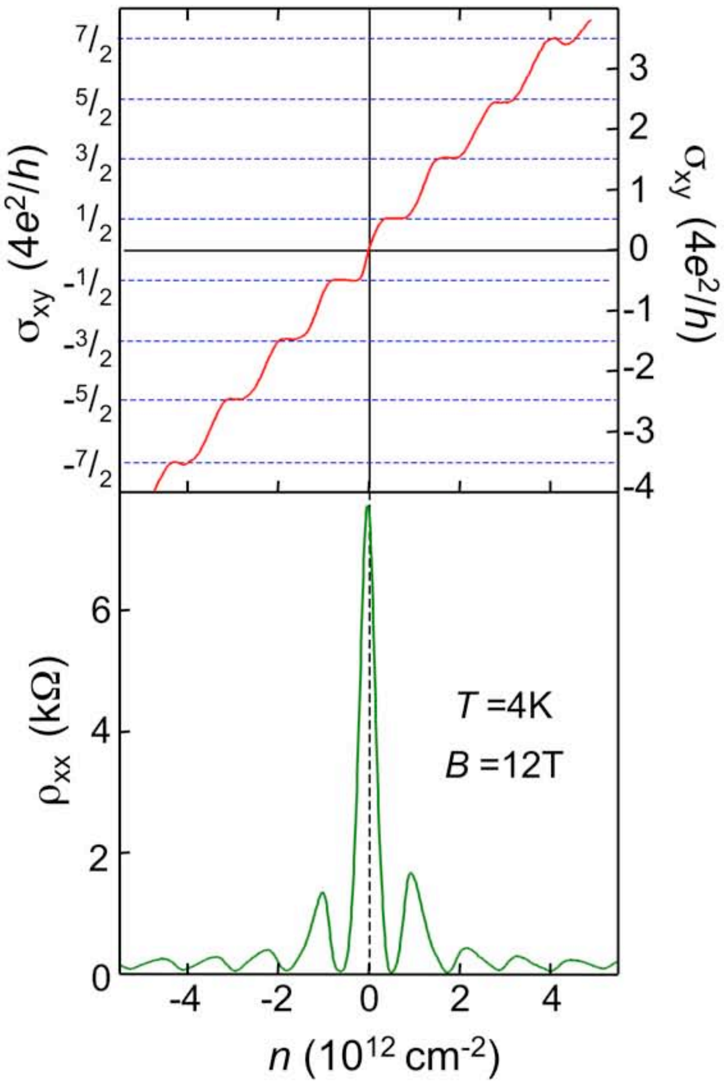


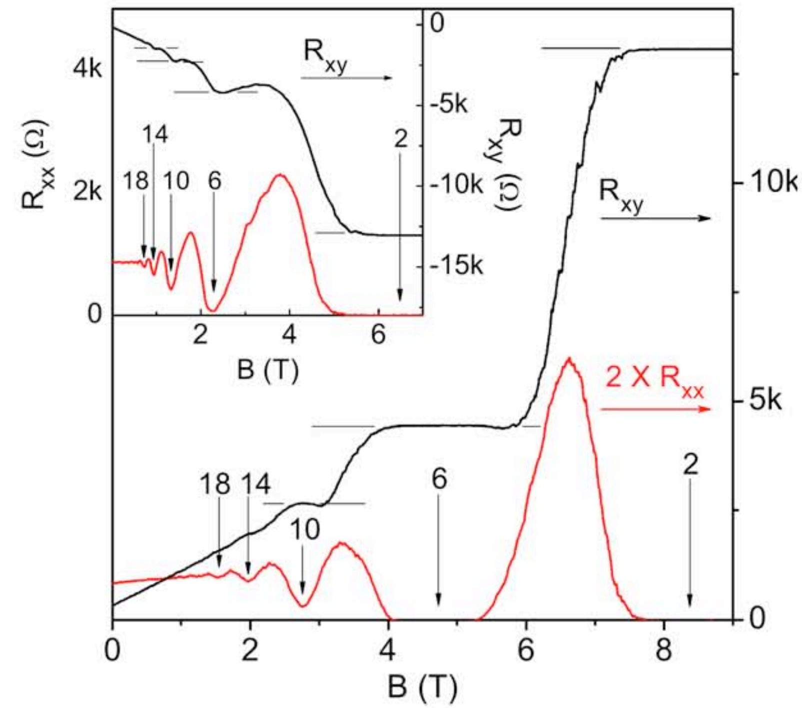
$$E_n = \mathrm{sgn}(n)|2n|^{1/2}\frac{\hbar v}{\ell_B}$$

B=10T, E_1-E_0=1500K

QHE at room temperature!

graphene





Y.Zhang et al., Nature 438, 201 (05)

Novoselov et al., Nature 438, 197 (05)

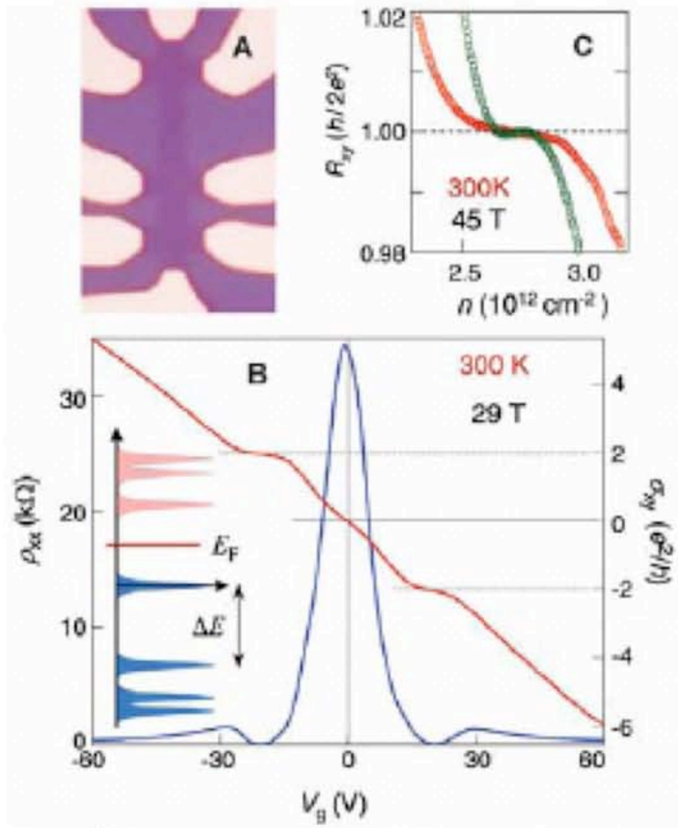


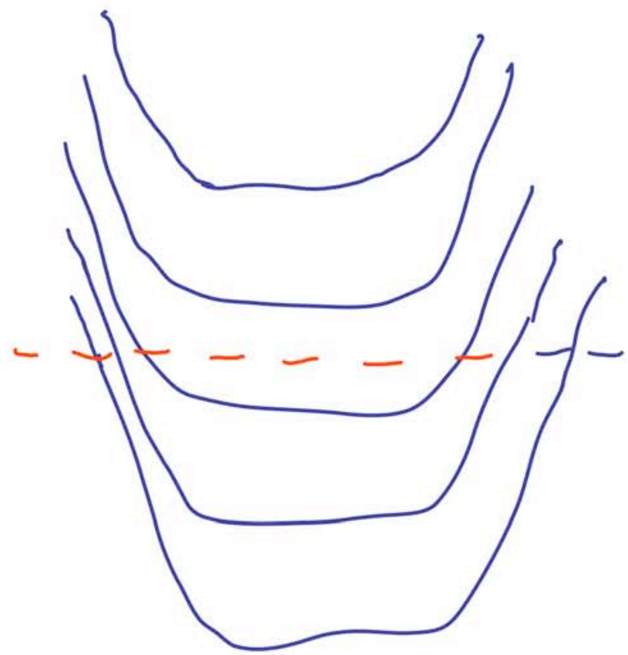
Figure 1. **Room-temperature QHE in graphene.** (**A**) – Optical micrograph of one of the devices used in the measurements. The scale is given by the Hall bar's width of 2 µm. Device fabrication procedures were described in (*5*). (**B**) - σ_{xy} (red) and ρ_{xx} (blue) as a function of gate voltages V_g in a magnetic field of 29 T. Positive (negative) gate voltages V_g induce electrons (holes) in concentrations $n = (7.2{\cdot}10^{10}\ \mathrm{cm^{-2}/V}){\cdot}V_g$ (*5*). The inset illustrates the Landau level quantization for Dirac fermions. (**C**) - Hall resistance R_{xy} for electrons (red) and holes (green) shows the accuracy of the observed quantization at 45 T.

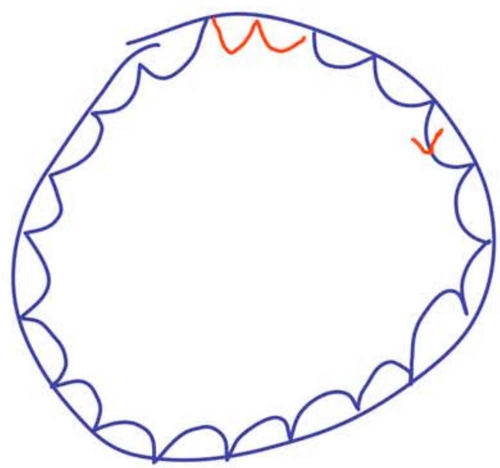
Novoselov et al
Science 07

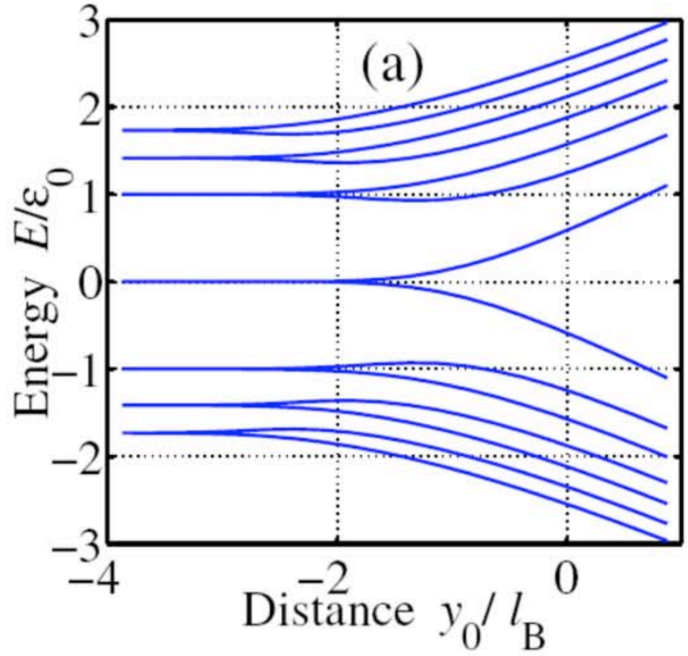
Edge state picture of QHE.

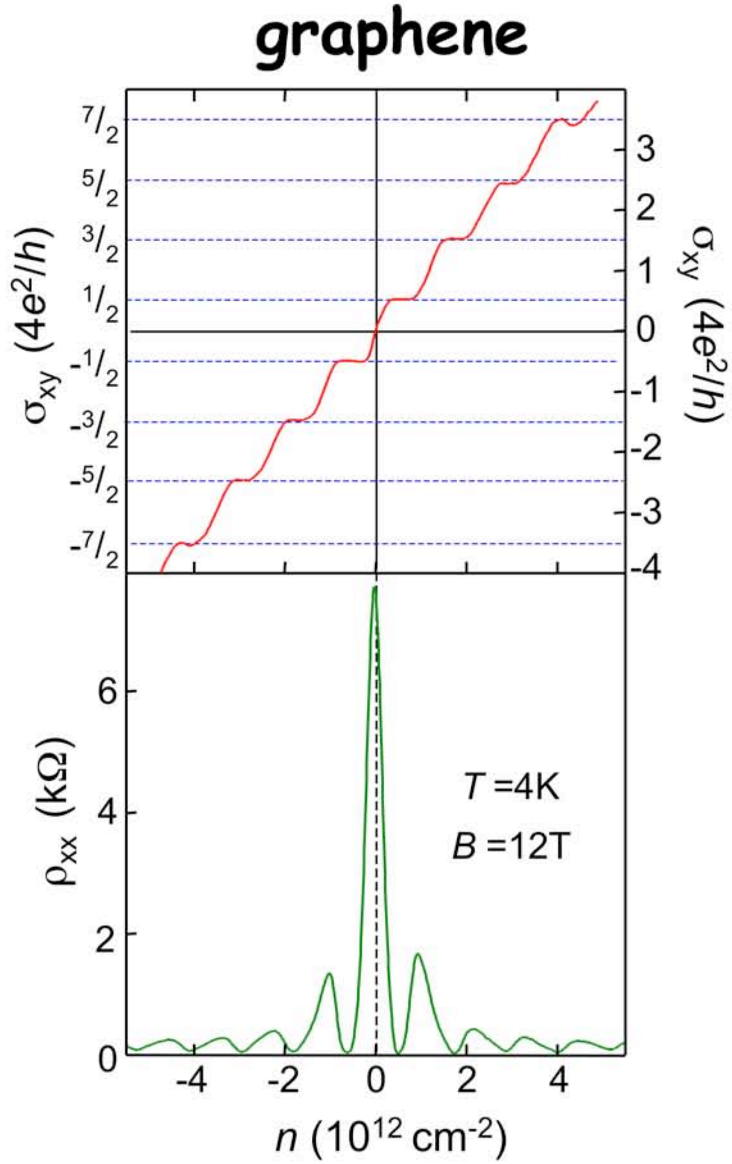
$R_{xy}=1/(N(e^2/h))$

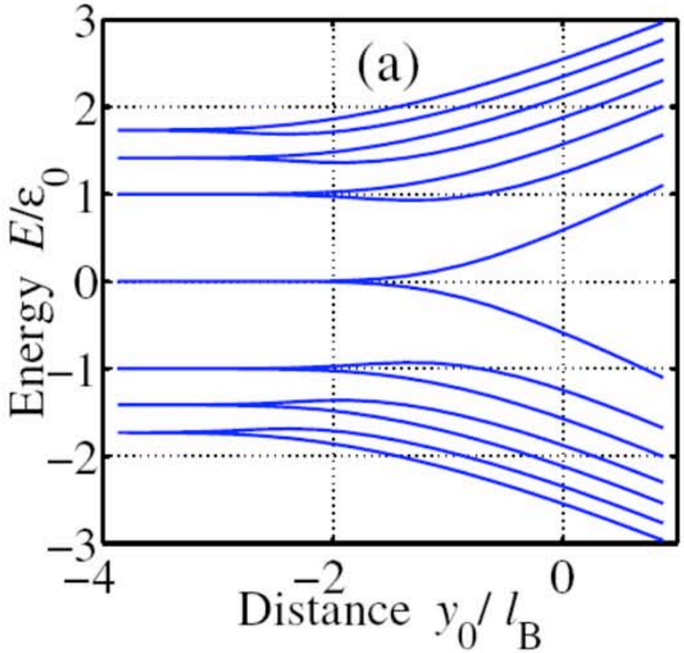
N=number of edge states that crosses the Fermi level.
Edge states propagate in one direction and are not back-scattered.



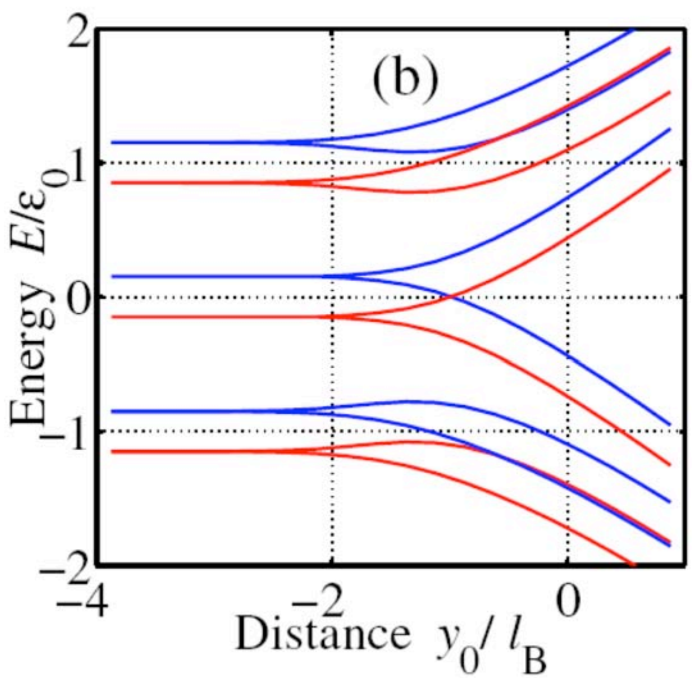



(a)
Energy E/ε_0
Distance y_0/l_B

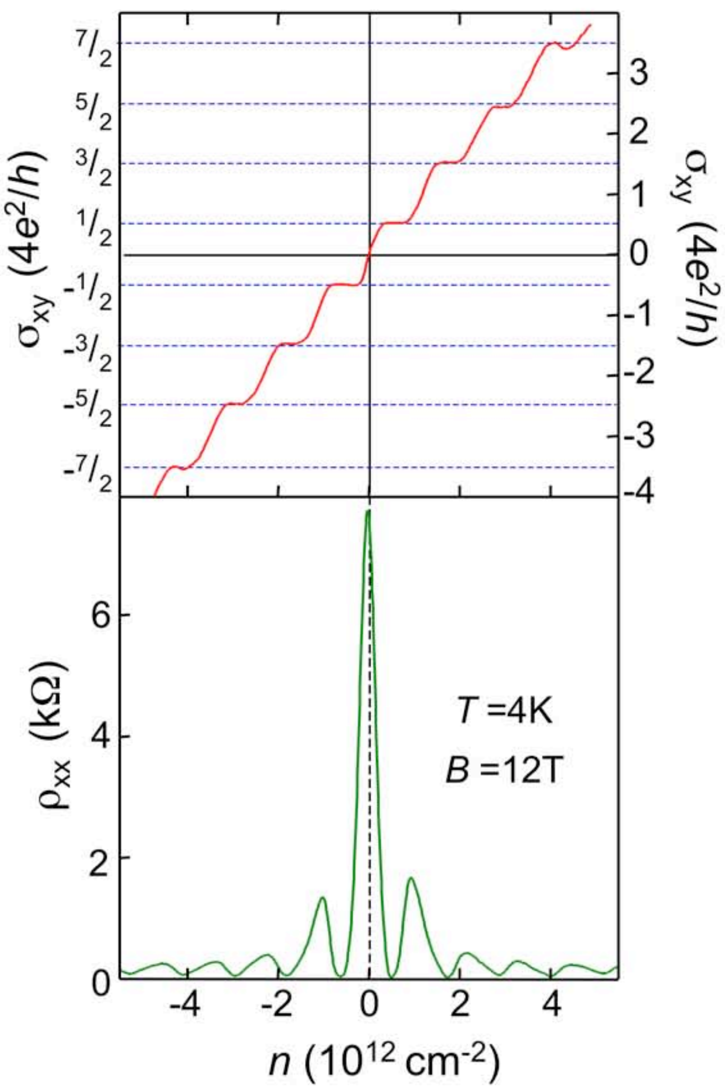

graphene
σ_{xy} ($4e^2/h$)
T =4K
B =12T
ρ_{xx} (kΩ)
n (10^{12} cm^{-2})

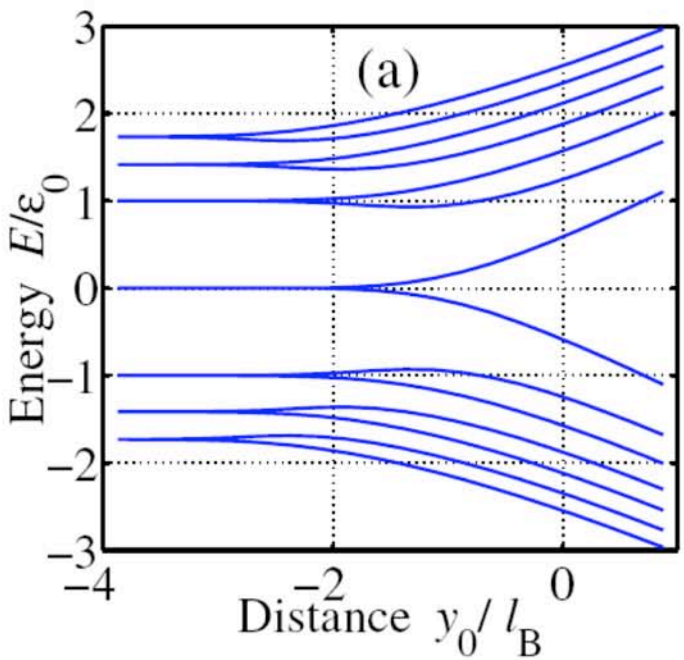


Spin splitting

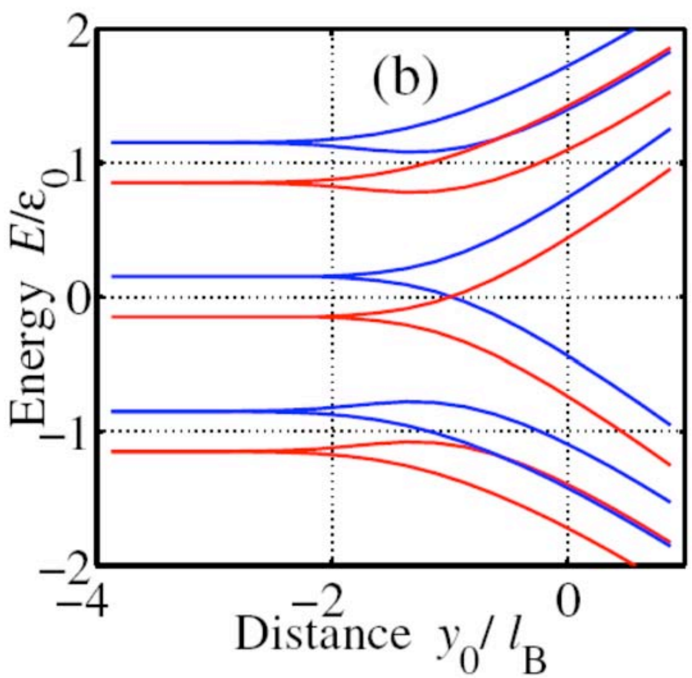


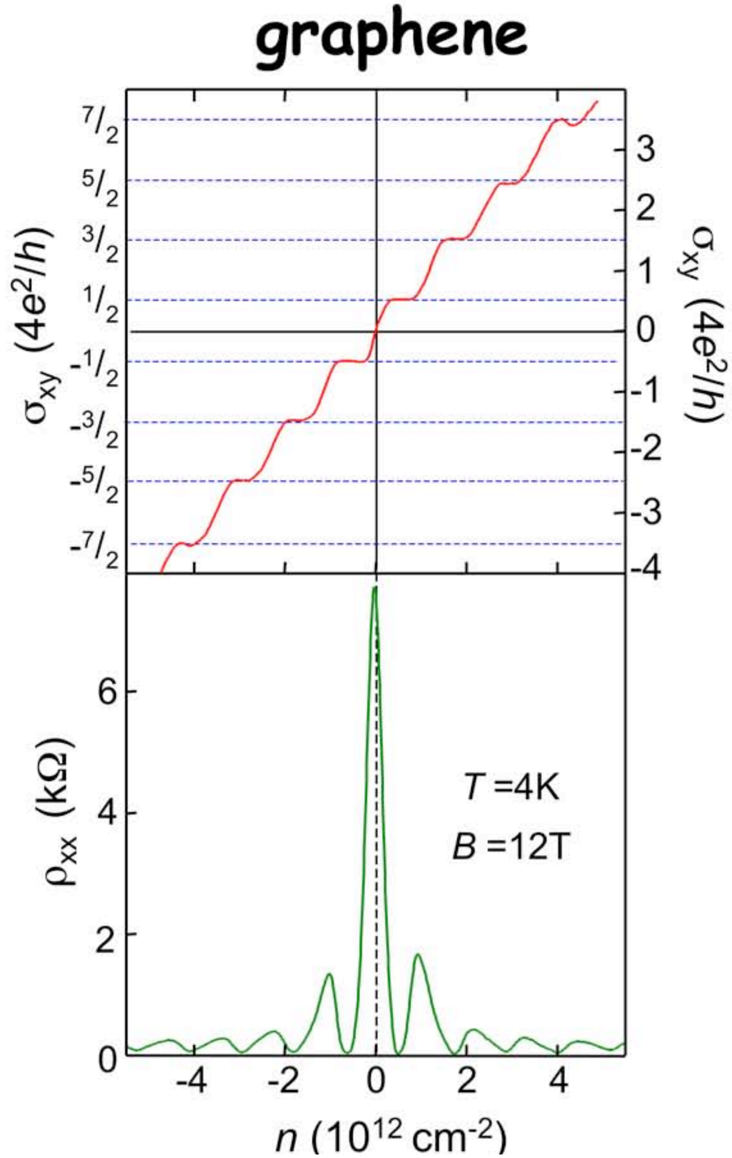
graphene





Spin splitting





$$\Delta = \frac{\pi^{1/2}e^2}{2\kappa\hbar v_0}(1-\alpha)\varepsilon_0 \approx 0.456\cdot(1-\alpha)\varepsilon_0,$$

$$\varepsilon_0 = \hbar v_0(2eB/\hbar c)^{1/2}$$

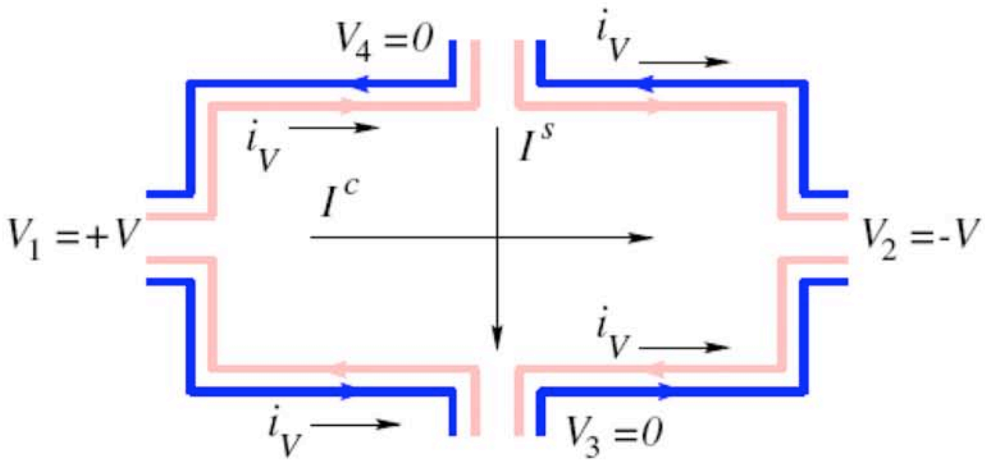
$\kappa = 1 + \pi e^2/2\hbar v_0 \approx 5.24$ is RPA screening

ν =0 state is qualitatively different.
It is a Spin quantum Hall state.

Abanin, Lee and Levitov, PRL96,176803(2006)

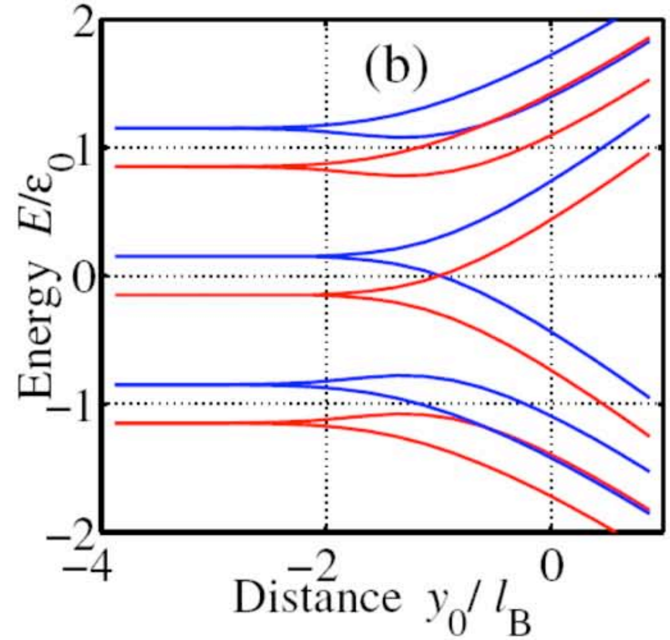
Landauer-Buttiker picture: $I_k^c = \sum_{k'} g_{kk'}(V_k - V_{k'}),$

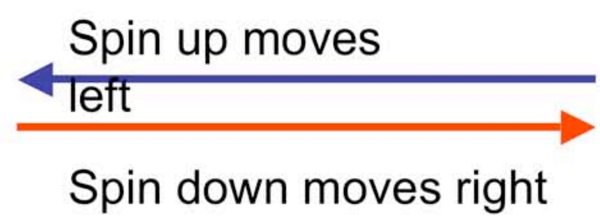
Each contact inject both spins with the same voltage: full spin mixing.



No Hall current R_{xy}=0 , but ideal spin current: I_s=2e^{2}V/h.
Also predicts longitudinal charge current, ie R_{xx}=h/2e^2. (13 kOhms)

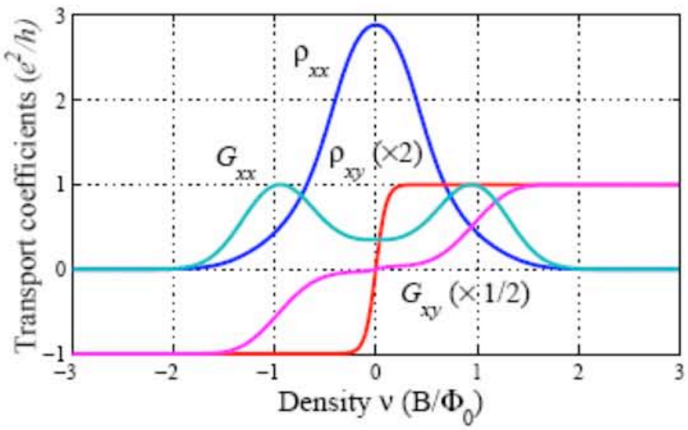
Dissipation from the voltage contacts





Simple example of a topological Hall insulator. (Kane and Mele,PRL2005, Bernevig and Zhang,2006) where gap is opened by spin-orbit effect.

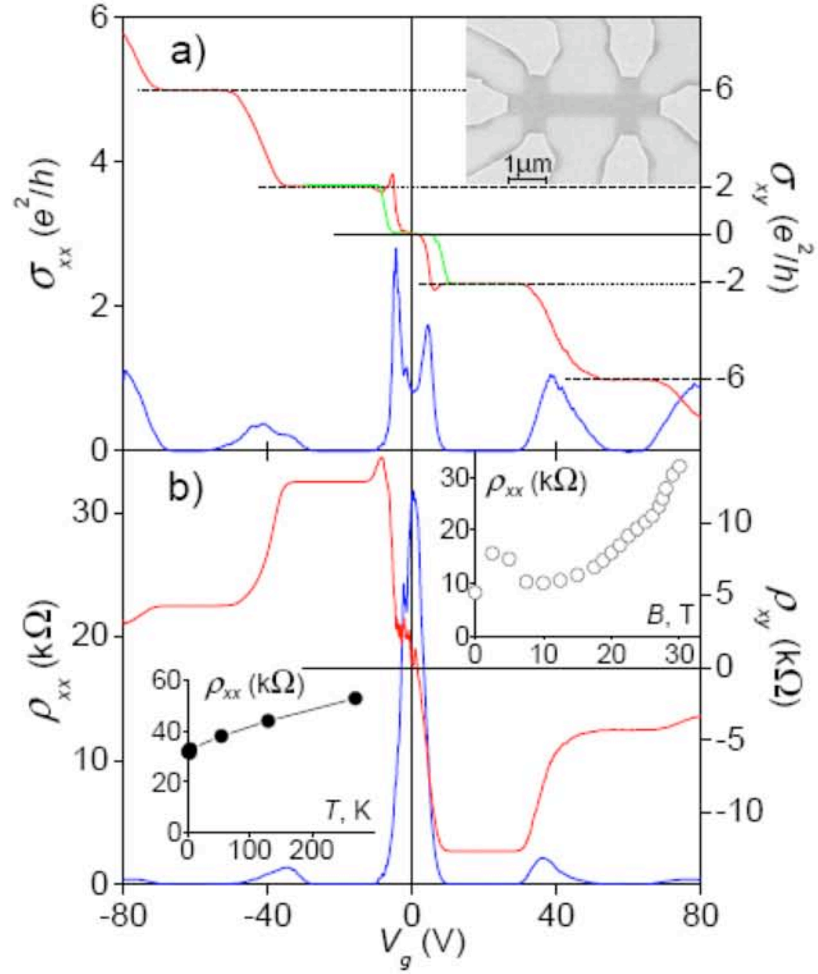
Include back-scattering.



$$R_{xx} = (\gamma L + 1)\,\frac{h}{2e^2}, \quad \rho_{xx} = (w/L)R_{xx}$$

we estimate $\gamma w \approx 2.5$

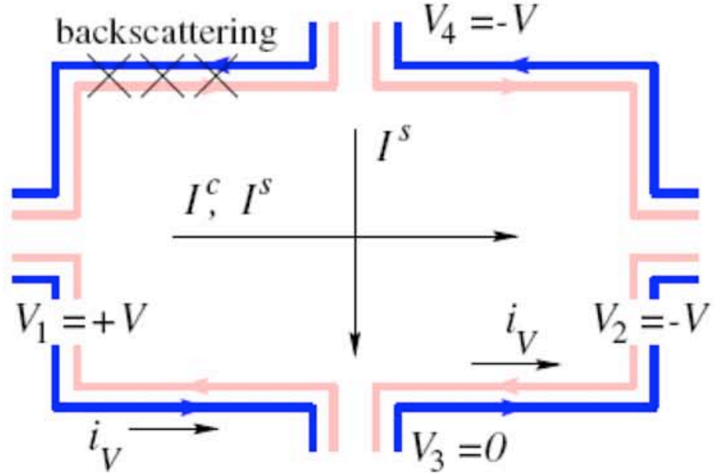
mean free path of $0.4\,\mu$m.



Control spin filter with local gate.

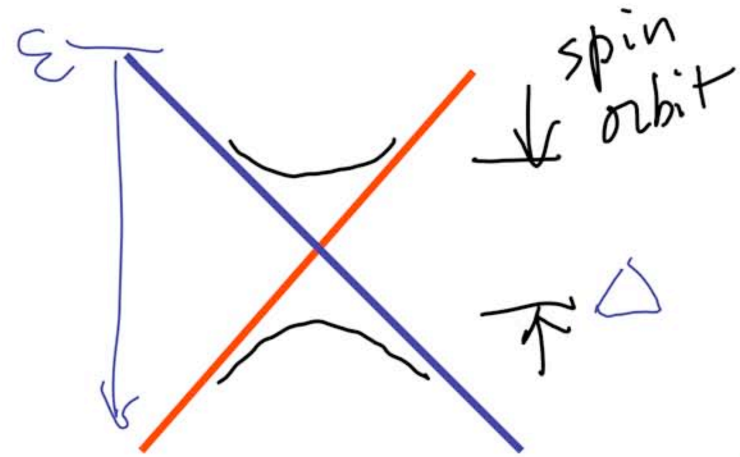
Spin up moves left

Spin down moves right



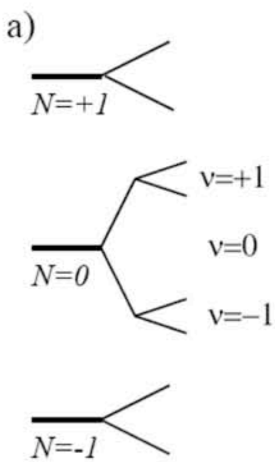
Backscattering require spin flip.
Spin orbit coupling is estimated to be very weak.
Rashba term 0.5mK

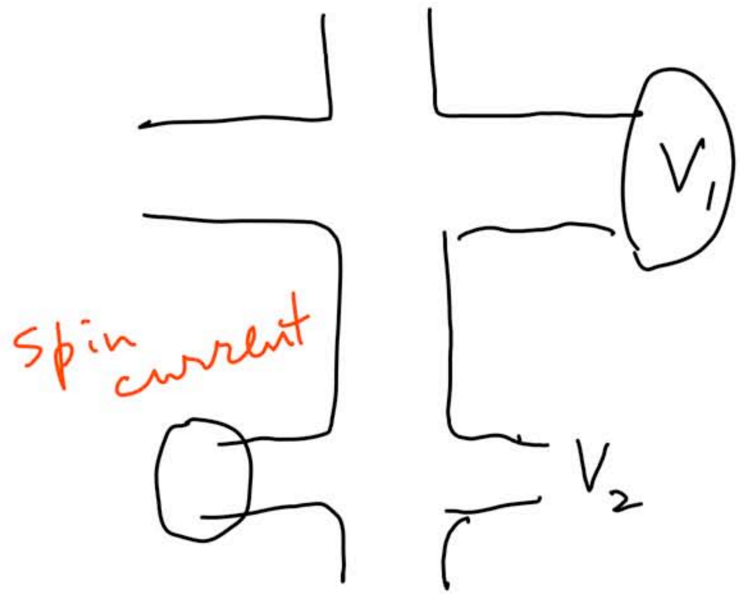
Strong scattering limit: only down spin is transmitted: spin filter.



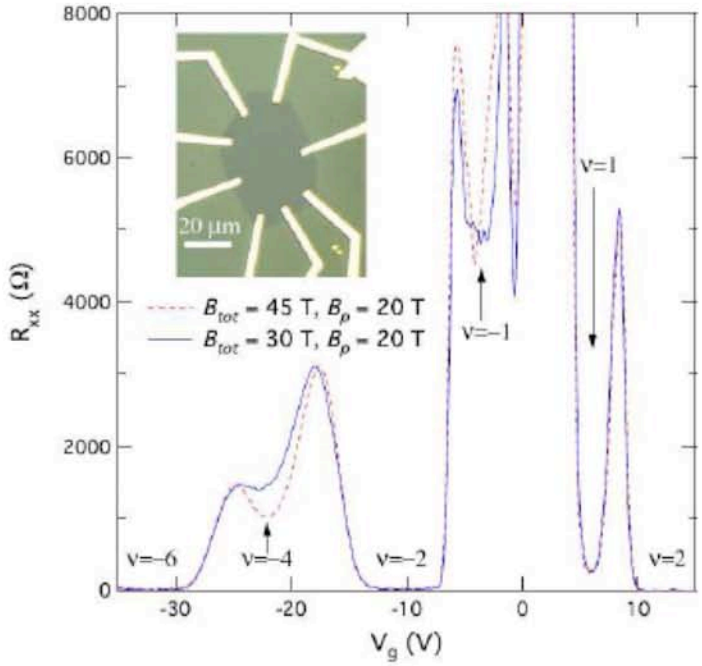
Control spin flip rate with a local gate. $\sim \left(\frac{\Delta}{\varepsilon}\right)$

Generation and detection of spin current:
Nonlocal transport is the key experimental test.





We estimate the energy difference of K ,K' for n=0 level to be very small. This raises the question which orbital state is preferred.



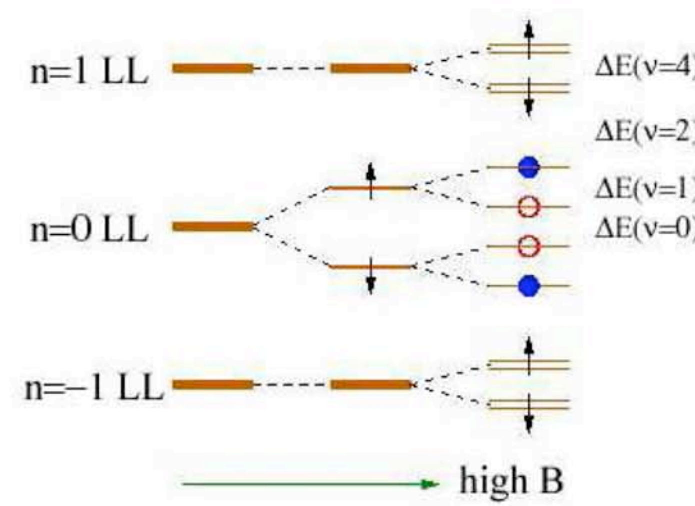


FIG. 3: (color online). Schematic of the LL hierarchy in graphene in magnetic fields. The up and down arrows represent the spin of the charge carries, and the solid (blue) and open (red) dots indicate different valleys in the graphene electronic band.

Jiang et al, cond. Mat 07

Summary:

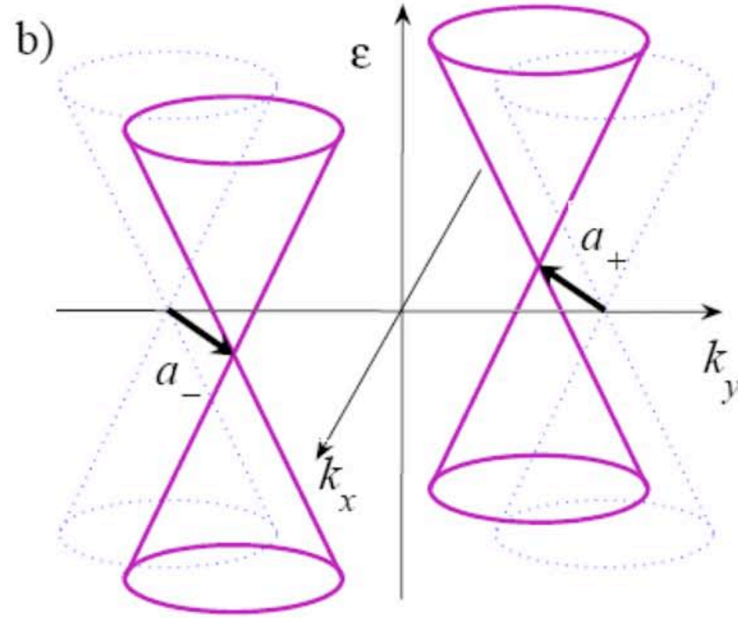
- The ν =0 Landau level is qualitatively different. It is a Spin Quantum Hall state. Transport is by counter propagating edge states carrying opposite spins.

  Circuit is described by Landauer-buttiker formalism. Non-local transport is the key signature.

  While the edge state transport is non-dissipative, any coupling to voltage probes leads to strong dissipation.

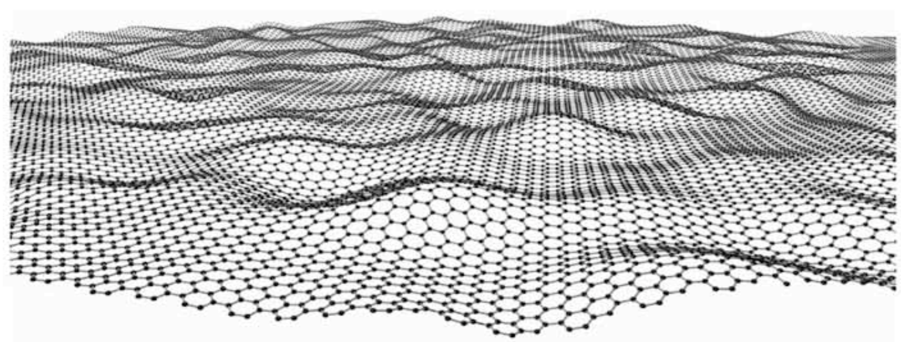
  The edge state structure is identical to the more exotic proposals of Kane and Mele and of Bernevig and Zhang, where the bulk gap is generated by spin-orbit coupling rather than an external field. The only difference is that the Rasba term gives back-scattering in our case not their cases. All the above comments apply.

$$H_\pm = v \begin{bmatrix} 0 & ip_x \mp p_y + \frac{e}{c} a_\pm \\ -ip_x \mp p_y + \frac{e}{c} a_\pm^* & 0 \end{bmatrix}$$



$$a_\pm \ = \ \frac{c}{e} \sum_{i=1,2,3} \delta t_i e^{\pm i \mathbf{q}_0 \cdot \mathbf{e}_i}$$

Distortion of the bonds due to strain or buckling is equivalent to a random gauge field a, which couples to K,K' nodes with opposite signs. (Iordanskii and Koshelev, 1985)

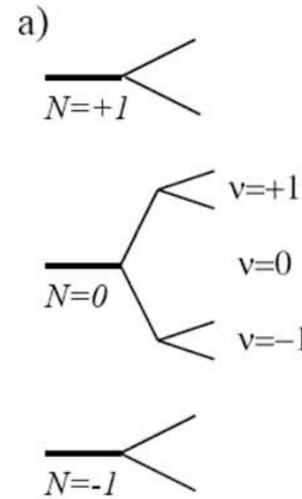


height ≈5Å; size ≈5nm;

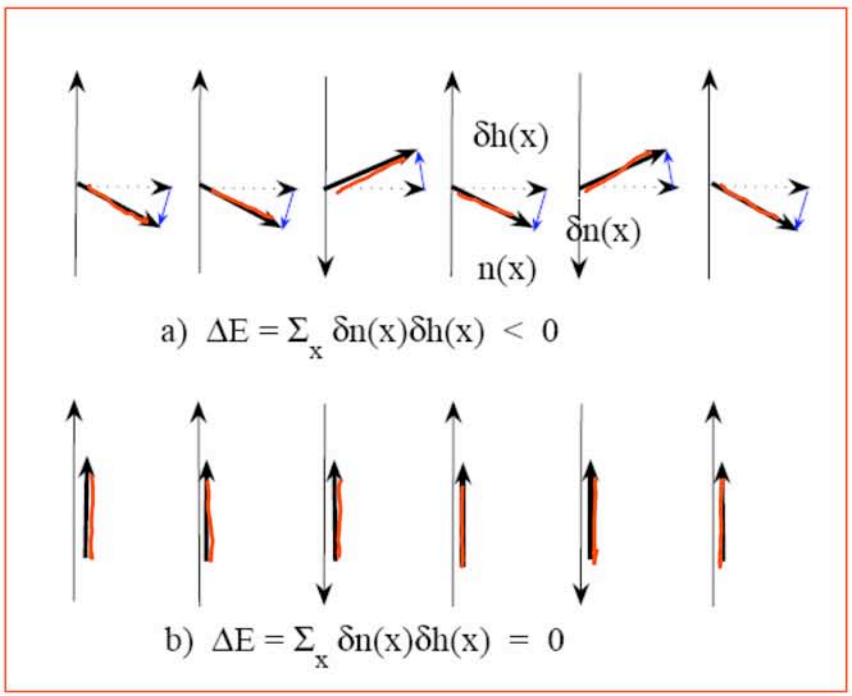
Consequences of random gauge fields:

1. Equivalent field is quite large (0.1T to 1T).
2. Explains why weak localization is not seen.(Morozov et al PRL 06)
3. Order out of disorder: select a linear combination of K, K' to be the occupied ν=-1 state. (Abanin, Lee and Levitov, cond-mat,06)

Pseudo-spin picture: K is spin up and K' spin down.
(like the bilayer quantum Hall problem).



Predict XY transition and meeron (1/2 integer excitation)

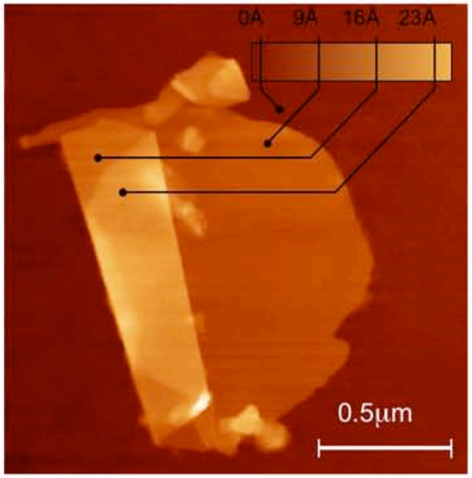


a) $\Delta E = \Sigma_x \delta n(x)\delta h(x) < 0$

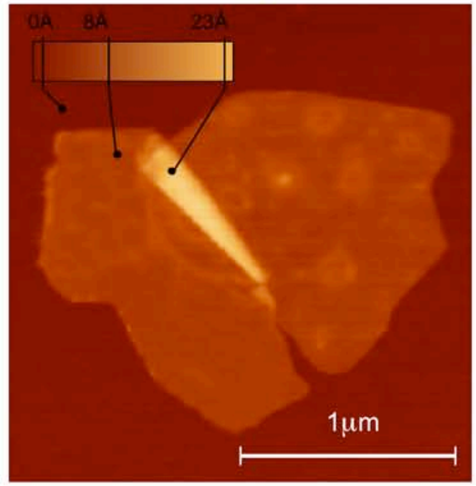
b) $\Delta E = \Sigma_x \delta n(x)\delta h(x) = 0$

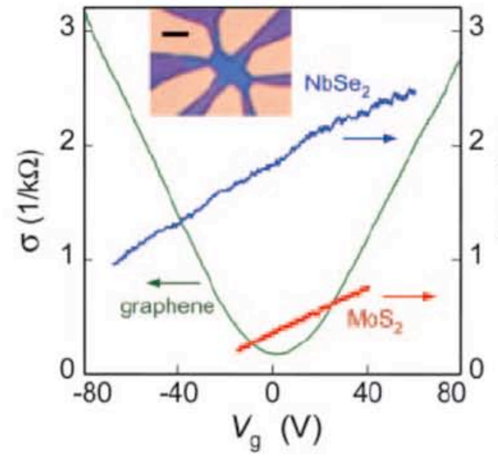
Other 2D Atomic Crystals

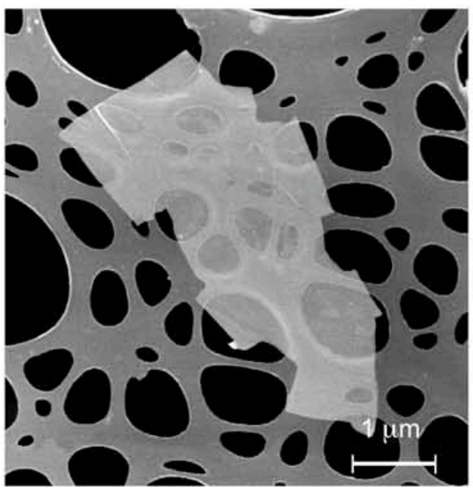
2D boron nitride in AFM



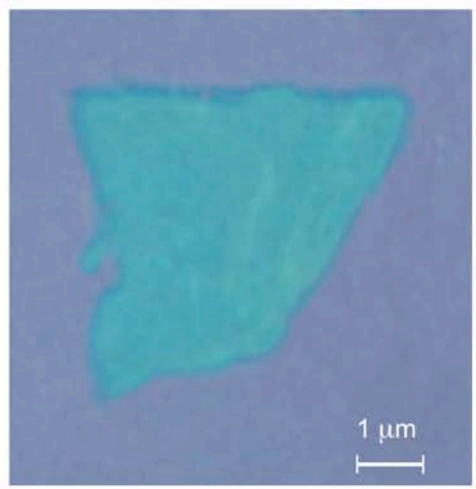
2D $NbSe_2$ in AFM







2D $Bi_2Sr_2CaCu_2O_x$ in SEM



2D MoS_2 in optics

Geim et al PNAS **102,** 10451 (2005)

Special features of graphene:

Strong bonding, robust layer structure: Large layer with high mobility.

Dirac spectrum: large gating effect and new physics.

Here we discussed interesting spin current effects.

Other applications:

Graphene based electronics and spintronics?

superconducting FET. (Delft group).

………