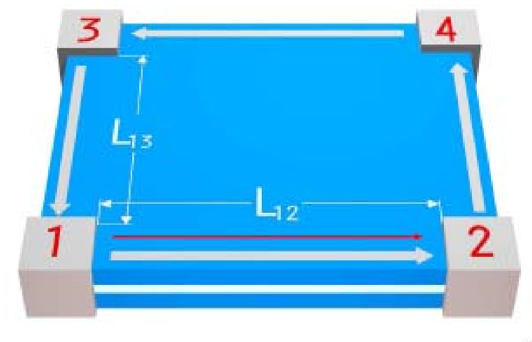
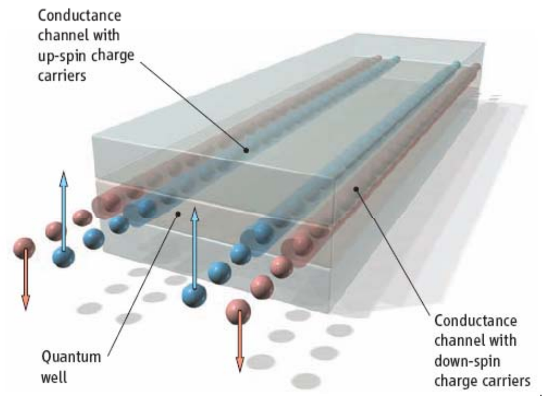
Optical manipulation of edge state transport in topological insulators



CARDEQ Meeting

Dresden, March 2009

Björn Trauzettel



Koenig et al. Science 2007

Collaborators:
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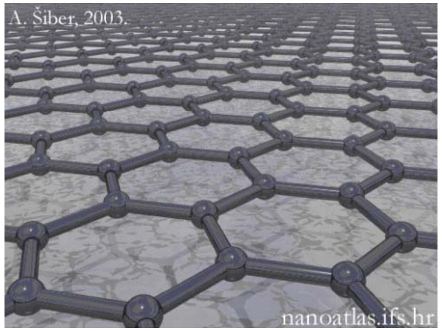
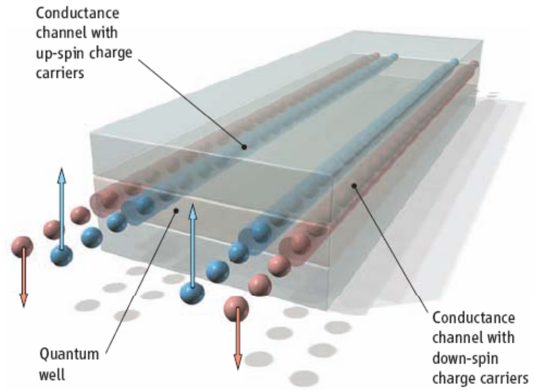
Manuel Schmidt (Basel)

Julius-Maximilians-UNIVERSITÄT WÜRZBURG

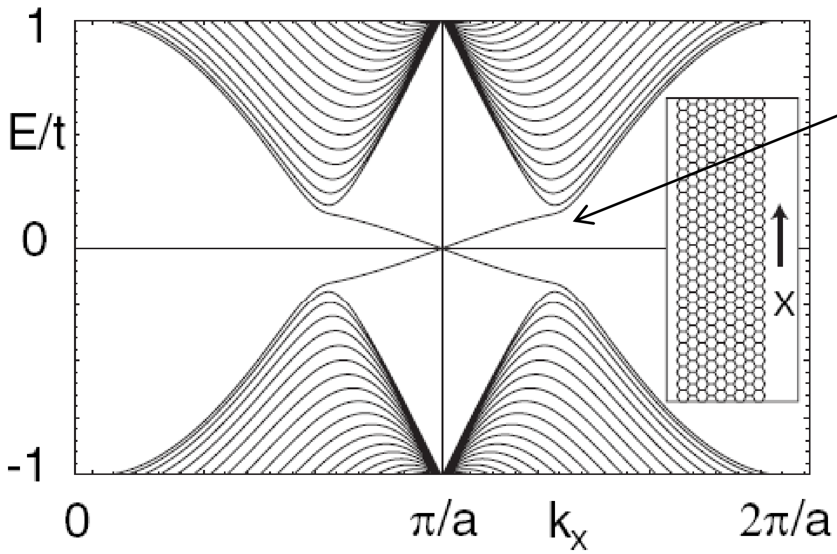
(my personal) motivation





Graphene	**Topological insulators**
valleys (K and K')	Kramers partners (+ and -)
sublattice (A and B)	CB and VB states (E and H)
spin (↑ and ↓)	---

Topological insulator in graphene



spin filtered edge states:
topologically non-trivial
w/ respect to TRS

⇒no TRS-preserving (local) perturbation can open gap

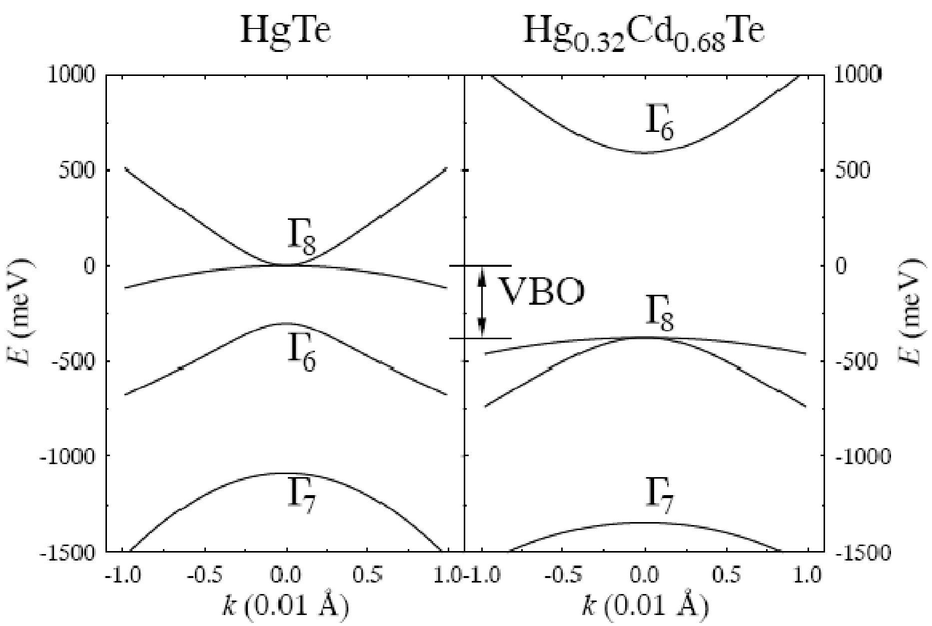
$$H = v\left(p_x\sigma_x\tau_x + p_y\sigma_y\right) + \Delta_{SO}\sigma_z\tau_z s_z$$

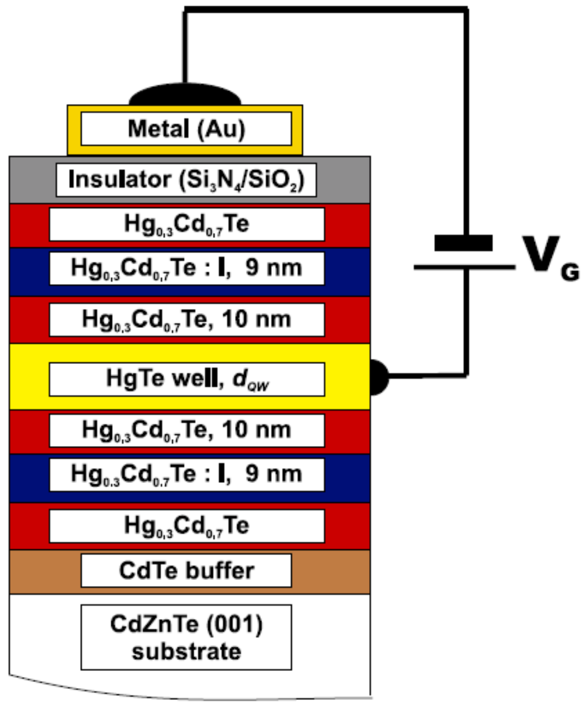
Kane & Mele PRL 2005

Outline

- Effective Hamiltonian of HgTe Quantum Wells
- Experimental consequences → QSHI
- Optical manipulation of edge state transport
- Summary and Outlook

Band structure of HgTe QW I





Koenig et al. JPSJ 2008

a little bit of group theory

T_d	E	$8C_3$	$3C_2$	$6S_4$	$6\sigma_d$	linear functions, rotations	quadratic functions
A_1	+1	+1	+1	+1	+1	-	$x^2+y^2+z^2$
A_2	+1	+1	+1	-1	-1	-	-
E	+2	-1	+2	0	0	-	$(2z^2-x^2-y^2, x^2-y^2)$
T_1	+3	0	-1	+1	-1	(R_x, R_y, R_z)	-
T_2	+3	0	-1	-1	+1	(x, y, z)	(xy, xz, yz)

including SOI:

A_1 → Γ_6

T_2 → $\Gamma_7 + \Gamma_8$

Γ_6: orbital part transforms s-like

Γ_7, Γ_8: orbital part transforms p-like

k.p theory

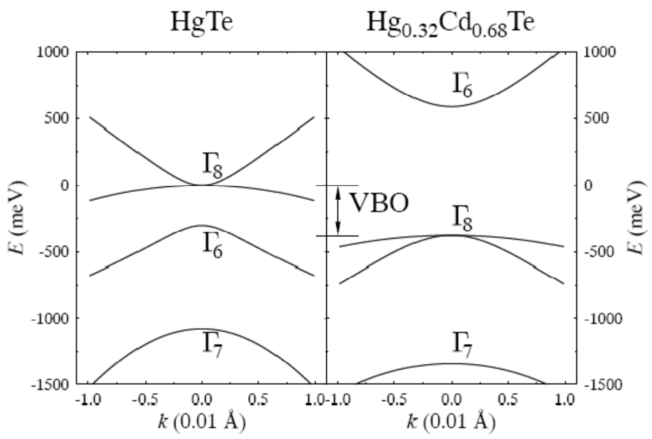
$$\left[\frac{p^2}{2m}+V(\vec{r})\right]\psi_{n,\vec{k}}(\vec{r})=E_n(\vec{k})\psi_{n,\vec{k}}(\vec{r})$$

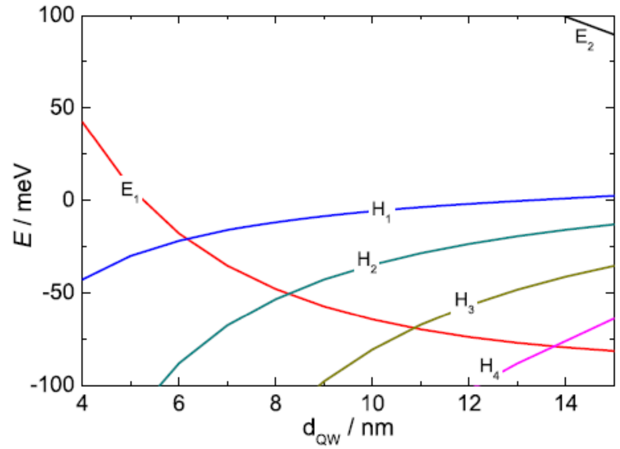
Bloch functions $\psi_{n,\vec{k}}(\vec{r})=e^{i\vec{k}\vec{r}}u_{n,\vec{k}}(\vec{r})$

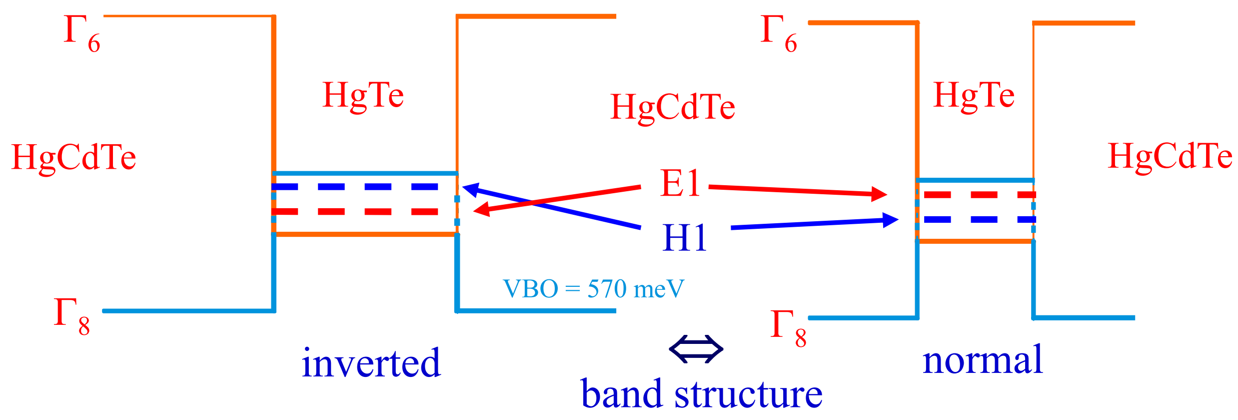
$$\left[\frac{p^2}{2m}+V(\vec{r})+\frac{\hbar\vec{k}\cdot\vec{p}}{m}+\frac{\hbar^2k^2}{2m}\right]u_{n,\vec{k}}(\vec{r})=E_n(\vec{k})u_{n,\vec{k}}(\vec{r})$$

- $E_n(\mathbf{k})$ known at $\mathbf{k}=\mathbf{k_0}$ (n: band index)
- band n has Γ_i symmetry $\Rightarrow$ $u_{n,\mathbf{k}}(\mathbf{r})$ transforms as Γ_i
- *in HgTe/CdTe:* $\Gamma_i = \{\Gamma_6, \Gamma_7, \Gamma_8\}$

Band structure of HgTe QW II







Effective model near Γ point

$$H=\begin{pmatrix} h(\vec{k}) & 0 \\ 0 & h^*(\vec{k}) \end{pmatrix} \quad \text{with} \quad h(\vec{k})=\varepsilon(\vec{k})+d_a(\vec{k})\sigma^a$$

Bernevig, Hughes, Zhang Science 2006

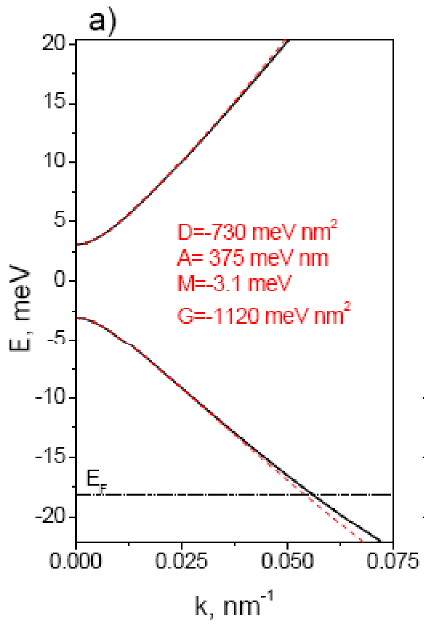
$$\varepsilon(\vec{k})=C-Dk^2$$

$$\vec{d}(\vec{k})=\left(Ak_x,-Ak_y,M-Gk^2\right)$$

with basis states:

$$\{|E+\rangle,|H+\rangle,|E-\rangle,|H-\rangle\}$$

±: degenerate Kramers partners



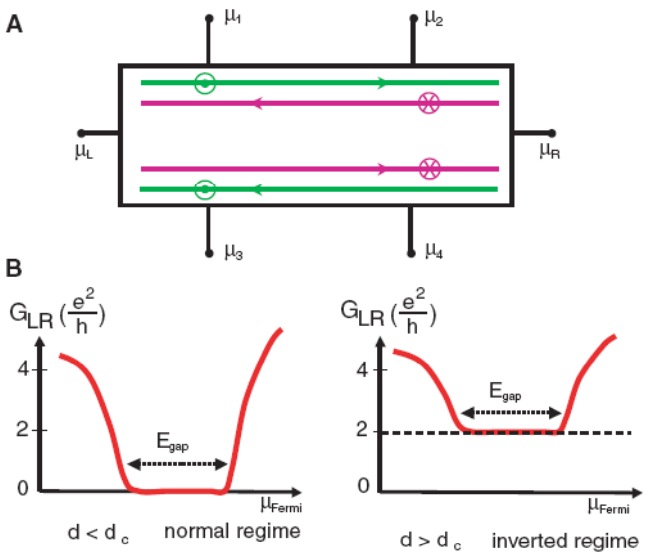
comparison to 8-band Kane model

Novik et al. PRB 2005

Schmidt, Novik, Kindermann & BT arXiv 2009

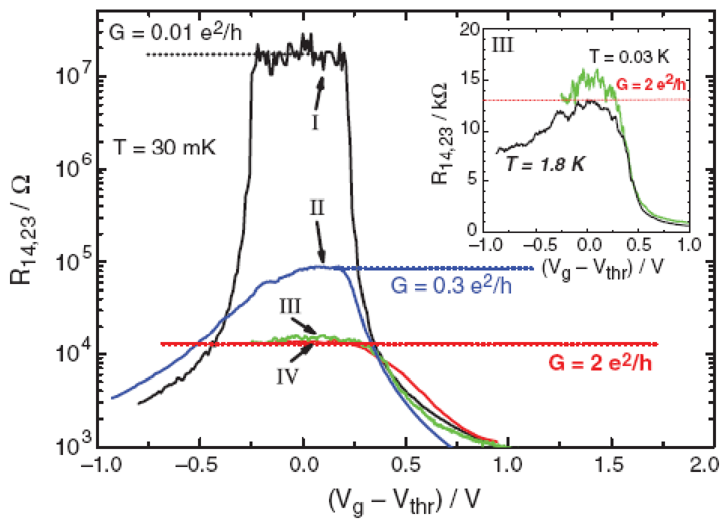
Experimental consequence: edge states at B=0

Prediction:



Bernevig, Hughes & Zhang Science 2006

Observation:



Koenig et al. Science 2007

see also: HL34 Spin controlled transport II, Wed 14:00-17:00, BEY 118

Effective model at finite B-field

$$H = \begin{pmatrix} h_+ & 0 \\ 0 & h_- \end{pmatrix} \quad \text{with} \quad h_\pm = h_{HO} + h_{JC}^\pm$$

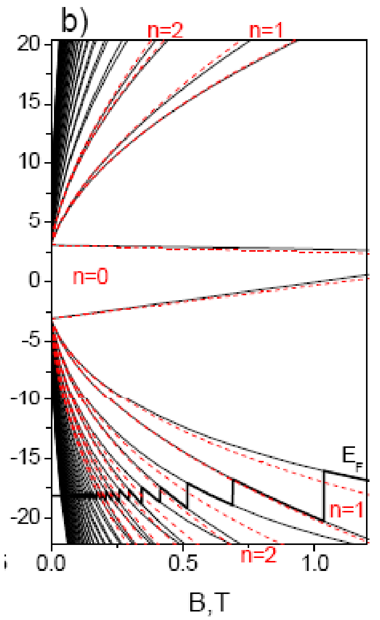
$$\vec{A}_0 = (-By, 0, 0)$$

$$h_{HO} = C - 2DB\left(a^\dagger a + \frac{1}{2}\right) + \left[M - 2BG\left(a^\dagger a + \frac{1}{2}\right)\right]\sigma^3$$

diagonal in E,H space and Kramers space

$$h_{JC}^+ = -\sqrt{2B}A\left(a^\dagger \sigma^+ + a\sigma^-\right)$$
$$h_{JC}^- = +\sqrt{2B}A\left(a\sigma^+ + a^\dagger \sigma^-\right)$$

couples HO levels, lifts ± degeneracy



comparison to 8-band Kane model

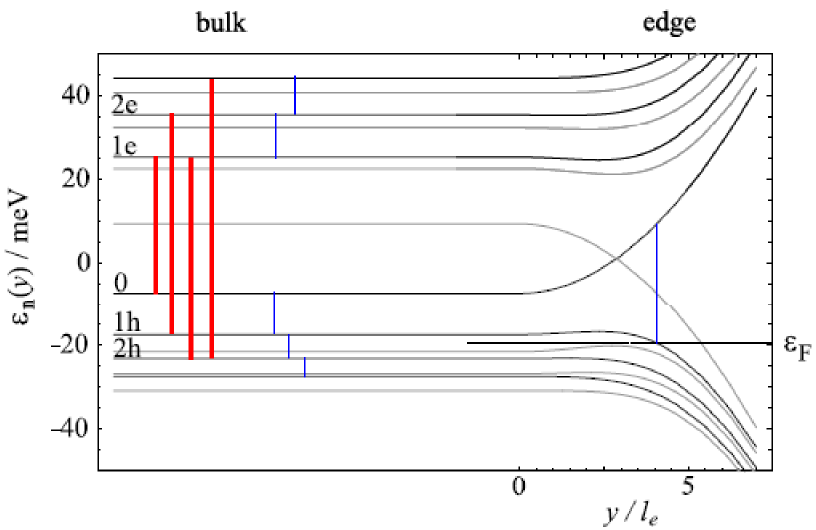
Schmidt, Novik, Kindermann & BT arXiv 2009

Edge states at finite B-field

$$M \rightarrow M + V_{edge}(y)$$

varies slowly on the scale of the typical extent of Landau level wave function in y-direction

$$V_{edge}(y) \rightarrow V_{edge}\left(\frac{k}{B}\right)$$



Optical transitions

$$\vec{A}_0 \to \vec{A}_0 + \vec{A}_1(\vec{r},t) \quad \text{with} \quad \vec{A}_1(\vec{r},t) = 2|A_1|\hat{\varepsilon}\cos\left(\frac{\omega}{c}\hat{n}\cdot\vec{r} - \omega t\right)$$

$\vec{A}_0 = (-By, 0, 0)$

choice: $\hat{\varepsilon} = \hat{e}_y$ and $\hat{n} = -\hat{e}_z$

$$h_+ \to h_+ - 2i|A_1|\cos(\omega t)\sqrt{2B}\left(a^\dagger - a\right)\left(D\mathbf{1} + G\sigma^3\right) - 2|A_1|A\cos(\omega t)\sigma^2$$

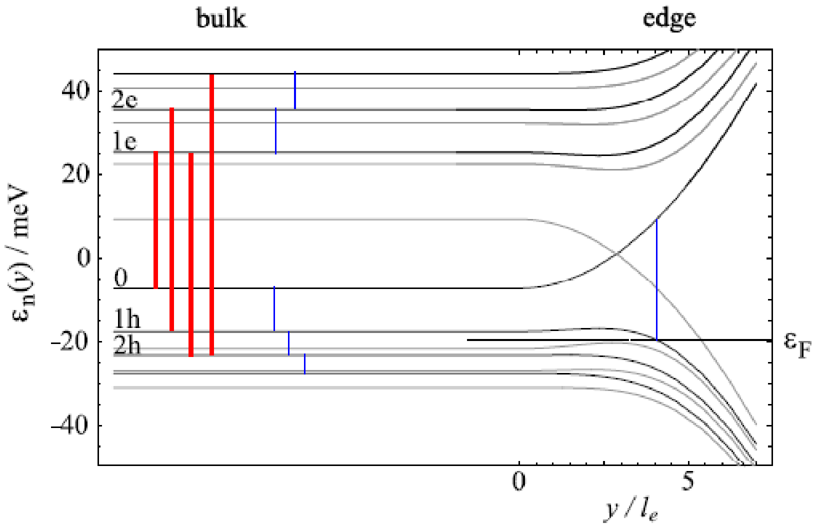
$$h_- \to h_- - 2i|A_1|\cos(\omega t)\sqrt{2B}\left(a^\dagger - a\right)\left(D\mathbf{1} + G\sigma^3\right) + 2|A_1|A\cos(\omega t)\sigma^2$$

Relative importance of terms:

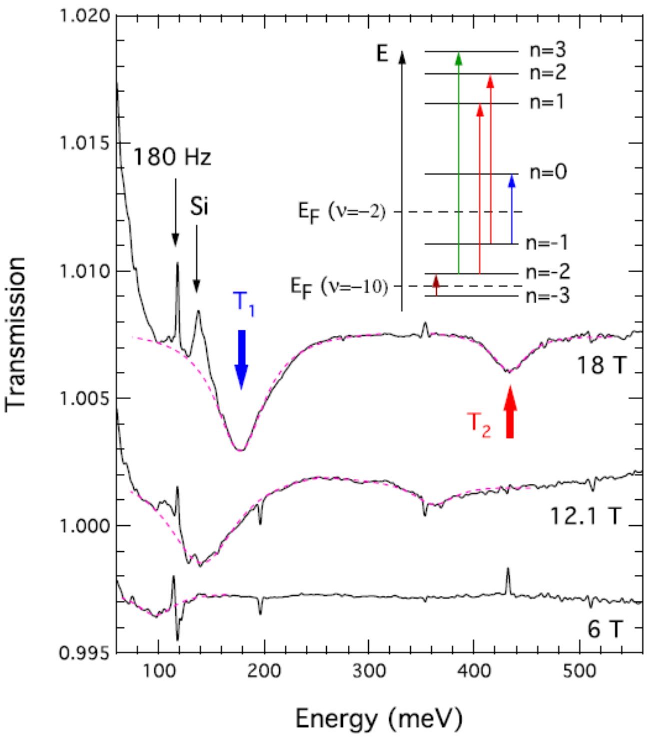
$$\sqrt{2B}D \simeq -28 \text{ meVnm}, \; \sqrt{2B}G \simeq -37 \text{ meVnm}, \; A \simeq 364 \text{ meVnm}, \; \text{for } B = 1\text{T}$$

Selection rules

$\Delta n = \pm 1$

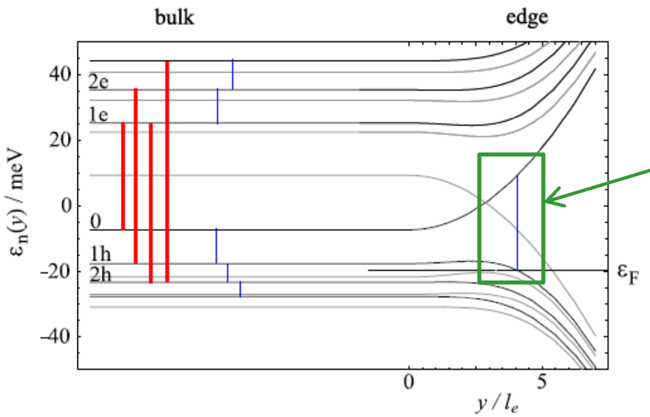


similar to graphene:



Jiang et al. PRL 2007

Optical manipulation of edge state transport



focus on two states that are resonantly connected

subspace: $\left\{|0\rangle, |\Psi_1^-(k)\rangle\right\}$

$$i\partial_t \tilde{\Psi}(x,t) = \left[E_0(k) + \frac{1}{2}\left(\Delta E(k) - \omega\right)\sigma^3 + Q\sigma^2 \right] \tilde{\Psi}(x,t)$$

with $E_0(k) + \frac{1}{2}\Delta E(k) = \varepsilon_0(k)$, $E_0(k) - \frac{1}{2}\Delta E(k) = \varepsilon_1^-(k)$, $Q = AA_1 \cos\left(\frac{\phi_1}{2}\right)$

depends on all system parameters

Transfer matrix approach

linearization of spectrum (at the edge) $\Rightarrow$

$$\left[E - \begin{pmatrix} v_1 & 0 \\ 0 & v_2 \end{pmatrix} p_x - Q\sigma^2 \right] \tilde{\Psi}_E(x) = 0$$

in transfer matrix notation:

$$\left[E + i\mathbf{v}\partial_x - Q\sigma^2 \right] T_E(x, x_0) = 0$$

with $\mathbf{v} = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 \end{pmatrix}$ and $\tilde{\Psi}_E(x) = T_E(x, x_0)\tilde{\Psi}_E(x_0)$

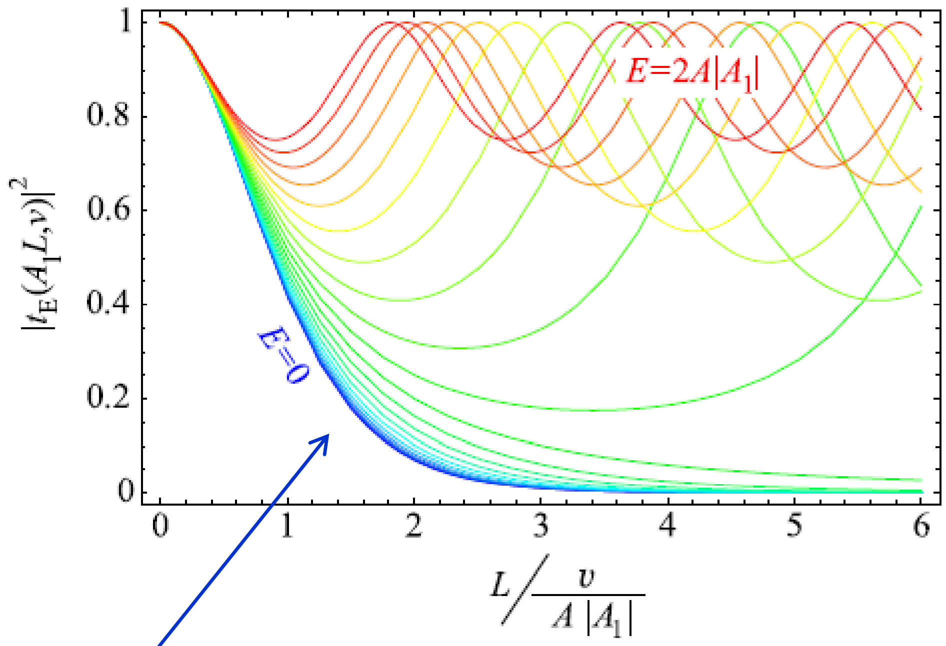
$$M_E \equiv T_E(0, L) = T_x \exp\left(-i\int_0^L dx\mathbf{v}^{-1}\left(E - Q(x)\sigma^2 \right) \right)$$

energy of scattering states relative to Fermi energy

x-dependent intensity of the FIR source

Transmission

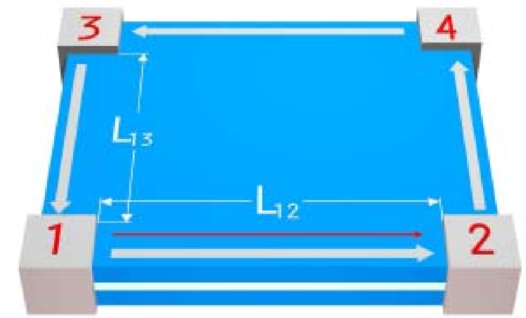
$$t_E = \frac{1}{(M_E)_{22}}$$

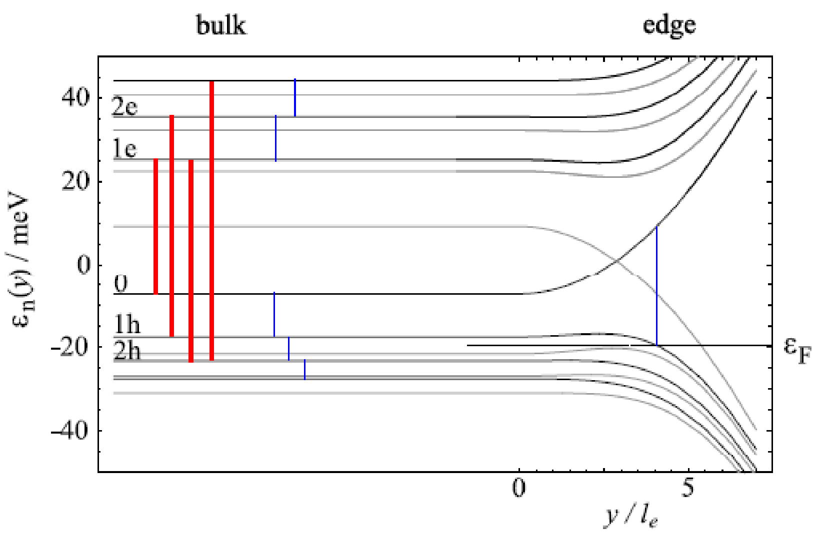


in the off-resonant case, current is barely blocked

$$t_0 = \frac{1}{\cosh\left(\frac{A}{\sqrt{v_1 v_2}} \int_0^L dx A_1(x)\right)}$$

How to detect it? → Setup1





Assumptions

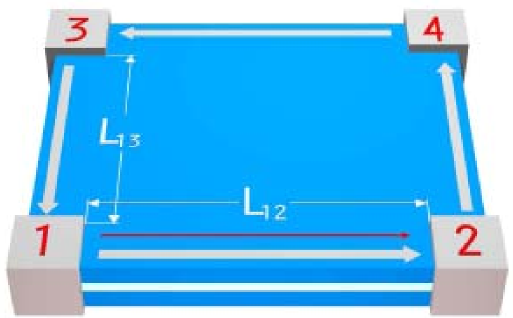
- all chemical potentials tuned between 1h and 2h
- $\mu_1 > \mu_2 = \mu_3 = \mu_4$
- $L_{12} = L_{13}$

$$I_{12} \propto \mu_1 - \mu_2$$

- FIR ⇒ counterclockwise movers scatter into clockwise movers
- at resonance: I_{12} exponentially suppressed

$$I_{12} \propto \frac{1}{\cosh^2\left(\frac{A|A_1|L_{12}}{v}\right)}$$

How to detect it? → Setup2



Assumptions

• all chemical potentials tuned between 1h and 2h

⇒• $\mu_1 = \mu_2 = \mu_3 = \mu_4$

• $L_{12} \gg L_{13}$

• without radiation ⇒ no net current

• FIR ⇒ parts of large counterclockwise background current is blocked

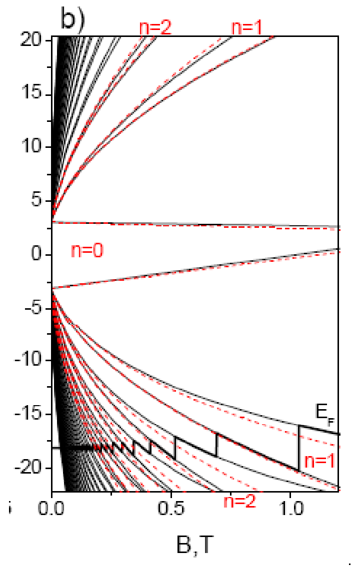
• more efficient on long edge

⇒ net current, e.g., from 3 to 1

Summary and Outlook

- Similarities and difference between TI's and graphene
- Low-energy theory of TI's
- Optical manipulation of edge state transport

Schmidt, Novik, Kindermann & BT arXiv:0901.0621



- Relaxation mechanism for excited edge states
- Role of Rashba SOI