From Perfect Conductor to Perfect Insulator: the Zero-Plateau QH State in Graphene

Efrat Shimshoni (Bar Ilan U)

Collaborators:
Herb Fertig (Indiana)
Venkat Pai (Technion & U Haifa)

(arXiv:0807.2867)

Acknowledgements:
L. Brey, R. Berkovits, M. Goldstein, K. Novoselov, P. Ong

NSF, GIF

KITP Low Dimensions Conference, Feb 26, 2009
From Perfect Conductor to Perfect Insulator: the Zero-Plateau QH State in Graphene

“...Now, here, you see, it takes all the running you can do, to keep in the same place...” (L. Carroll, from “Alice’s Adventures through the Looking Glass”)
The Quantum Hall Effect in Graphene

Novoselov, Geim et al., Nature 438, 197 (05)
Stronger B: Dissipative QHE at the Dirac Point

- Plateau at $\nu=0$, but $\rho_{xx} \neq 0!$
- $\rho_{xx}$ increases with $T \Rightarrow$ Metal
- $\rho_{xx}$ increases with $B$

Abanin et al. (2007)
Checkelsky, Li and Ong (2007):
Checkelsky, Li and Ong (2008): more on the “Insulator” -

Divergence of $R_0$ at high $H$

$$R_0 \sim \exp \left\{ \frac{2C}{\sqrt{(H_c - H)}} \right\} \xi^2_{KT}$$
QH Edge-States in Graphene Ribbons

Brey and Fertig (2006):

Armchair Edge

Zigzag Edge

Zigzag Edge

Armchair Edge
QH Edge-States in Graphene Ribbons

\[ \sigma_{xy} \left( e^2/h \right) \]

\[ n \]

\[ 2 \]

\[ -2 \]
QH Edge-States in Graphene Ribbons

\[ \sigma_{xy} \left( \frac{e^2}{h} \right) \]

\[ n \]

\[ \mu_R \]

\[ \mu_L \]
Origin of $\nu=0$ plateau at high $H$: Zeeman splitting

Spin-flip impurities $\rightarrow$ Finite $\rho_{xx}$

(Abanin, Levitov & Lee)
Role of Coulomb interactions (Fertig & Brey, 2007):

Finite width Domain Wall
Our Theory: Effective 1D Model for the Domain Wall

\[ H_{DW} = \int \frac{dy}{2\pi} \left( uK (\partial_y \theta)^2 + \frac{u}{K} (\partial_y \phi)^2 - g \cos[4\phi] \right) \]

\[ K[H,U_c,\Delta'(X_0)], \quad u[H,U_c,\Delta'(X_0)], \quad g[H,U_c,\Delta'(X_0)] \]
Our Theory: Effective 1D Model for the Domain Wall

\[ H_{DW} = \int \frac{dy}{2\pi} \left( uK \left( \partial_y \theta \right)^2 + \frac{u}{K} \left( \partial_y \phi \right)^2 - g \cos[4\phi] \right) \]

- "charging energy"
- "SC stiffness"
- "Josephson Coupling"

\[ \begin{align*}
(j_e &\sim S_z) 
\end{align*} \]
Clean DW Phase Diagram

$\Delta_s$ vs $K$

Gapped "SC" Phase

$K_c$ vs $K$

LL
Theory for Transport: adding Spin-Flip Interaction

\[ H = H_{DW} + H_{\sigma} + H_{\text{int}} \]

\[ H_{\sigma} = \varepsilon_z \sigma_z \]

\[ H_{\text{int}} = J_k S \cdot \sigma \]

Back-scattering induced resistance for \( T > \Delta_s \):

\[ R_{xx} \approx g^2 T^{\nu(K)} F[\varepsilon_z / T] \quad (g \sim J_k) \]

\[ \nu(K_{MI}) = 0 \]
Full Phase Diagram

\[ \frac{\partial R_{xx}}{\partial T} > 0 \quad \text{(Metal)} \]

\[ \frac{\partial R_{xx}}{\partial T} < 0 \quad \text{(Insulator)} \]

\[ R_0 \sim \exp \left\{ \frac{2C}{\sqrt{(K_c - K)}} \right\} \]

Gapped Phase

LL
Full Phase Diagram

\[ \frac{\partial R_{xx}}{\partial T} > 0 \]
(Metal)

\[ \frac{\partial R_{xx}}{\partial T} < 0 \]

"Odd Metal"

\[ R_0 \sim \exp \left( \frac{2C}{\sqrt{(K_c - K)}} \right) \]

\[ \Delta_s \]

\[ T \]

\[ K_{MI} \]

Gapped Phase

\[ K_c \]

\[ K \]

LL

Insulator
Summary

♠ Finite $R_{xx}$ at the $\nu=0$ QH state induced by “chiral Kondo effect”: Spin-flip = Charge backscattering

♠ New type of edge state: spin Domain Wall = a non-chiral perfect conducting channel

♠ Diverse transport phenomena: $R_{xx}(T)$ is metallic, insulating or “odd metal” depending on $K$. Divergence of $R_0$ => quantum KT-transition (in 1+1d)