Spin-resolved quantum interference in graphene

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device:
- mech. exfoliated graphene on SiO2
- 2-/4-wire conductance vs backgate/B-field
- typical $V_D<10V$

measurements:
- 4K/20mK base temp.
- 2axis magnet (12T / 120mT)
- LockIn exc. 1nA/78Hz

single layer: QHE signature
$(n + \frac{1}{2})G_0$
**UCF**: (universal) conductance fluctuations
- time reversal symmetry
- interference of coherent current paths
  \( l_\phi \gg L; \ l_{mf}\ll L \)

\[ \delta G \equiv [\text{Var}(G)]^{1/2} = \frac{g_s g_v}{2} \beta^{-1/2} C_0^2 \frac{e^2}{h} \]

**spin dependency**: (no SO-coupling/interactions)
- \( B=0 \): spin degenerate \( n_\uparrow = n_\downarrow \)
- \( B\neq0 \): Zeeman splitting
  different contributions for up/down spin

\[ n_\uparrow - n_\downarrow = \frac{1}{2}(dn/d\epsilon)g\mu_B B \]

\[ n_{\uparrow/\downarrow} = \frac{\alpha}{2} \left( V_G \pm \frac{V_{\text{offset}}}{2} \right), \quad V_{G_{\text{offset}}} = \frac{1}{\alpha} \frac{dn}{d\epsilon} g\mu_B B \]
CF in parallel magnetic field: splitting depends on Zeeman-energy ($B_\parallel$) and density ($V_G$)

experiment:

\[
V_G^{\text{offset}} = \frac{1}{\alpha} \frac{dn}{d\epsilon} g \mu_B B
\]

theory: no change of interference with splitting
prerequisite for spin-resolved CF’s visible:
- low DOS ($V_{\text{offset}}$ not too big)
- low SO-coupling (spin independent)
- no Aharonov-Bohm flux (induced by $B_\parallel$)

magnet orientation:
compensation with weak-localisation signal ($l_\phi \sim 3\mu m$)

time-reversal symmetry:
also broken with $B_\parallel$ (!) but on much larger field scale ($l_{\text{perp}} \sim 1\text{nm}$)
precise measurement of spin-splitting:

statistical evaluation with auto correlation

\[ C_{[\delta G]}(\Delta V_G) = \langle \delta G(V_G) \delta G(V_G + \Delta V_G) \rangle \]

\[ B_\parallel = 8 \text{T} \]

\[ \begin{align*}
3 \text{mT} < B_\perp &< 120 \text{mT} \\
\delta G &\equiv \frac{e^2}{h} \\
C_{\delta G G}(\Delta V_G) &\equiv \frac{e^4}{h^2}
\end{align*} \]
$V_{\text{offset}}$ vs density:
mapping the DOS of graphene 

$(dn/d\varepsilon)(V_G) = (2\sqrt{\alpha/\pi/hv_F})\sqrt{|V_G - V_0|}$

$V_{\text{Fermi}} = \text{density-dependent}(\!)$

capacitiv coupling
determined from SdH-oscillations
around the Dirac-point:

finite density on sample A ($V_0 = 1V$) no sidepeaks for $|V_G - V_0| < 3V$
on sample B ($V_0 = 9V$)

remanent density $\sim 3.5 \times 10^9$ cm$^{-2}$/meV

[A. Yacobi: inverse compressibility $\sim 3 \times 10^{-10}$ cm$^2$ meV]

strong disorder breaks the correlation here;
$v_{\text{Fermi}}$ increasing with density