Aharonov-Bohm oscillation in nanomechanical resonance of topological insulator nanowire

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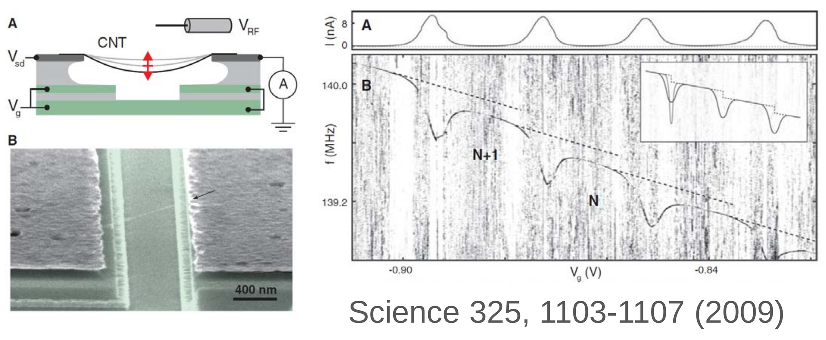
Abstract

In topological insulator (TI) nanowires, Aharonov–Bohm (AB) oscillations in conductance emerge as a result of gapless surface states. This quantum interference effect accompanies a change in the number of transverse one-dimensional (1D) modes in transport, and the density of states (DOS) of such nanowires is also expected to show AB oscillations. Here, we observe such quantum oscillation in DOS utilizing nanomechanical resonance measurements. The TI nanowire is configured as an electromechanical resonator, and quantum capacitance effects from DOS oscillation modulate the circuit capacitance to modify the spring constant and generate mechanical resonant frequency shifts. The small effective capacitances and high quality factors of nanomechanical resonators facilitate the detection of the quantum capacitance effects from surface-state DOS, and the technique could be extended to study diverse quantum materials at nanoscale [1].

[1] M. Kim et.al., Nanomechanical characterization of quantum interference in a topological insulator nanowire, arXiv:1902.02912

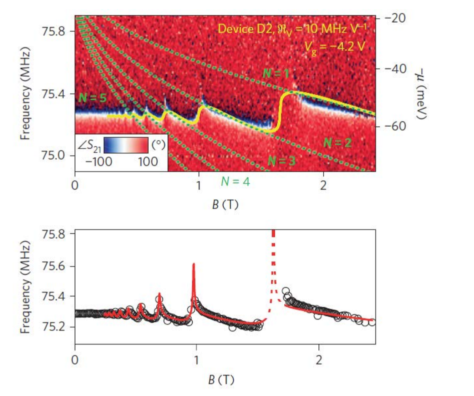
Motivation

▪ Mechanical motion coupled to quantum electronic systems



Science 325, 1103-1107 (2009)

Carbon nanotube mechanical resonator
→ Correlation between single electron transport and mechanical motion

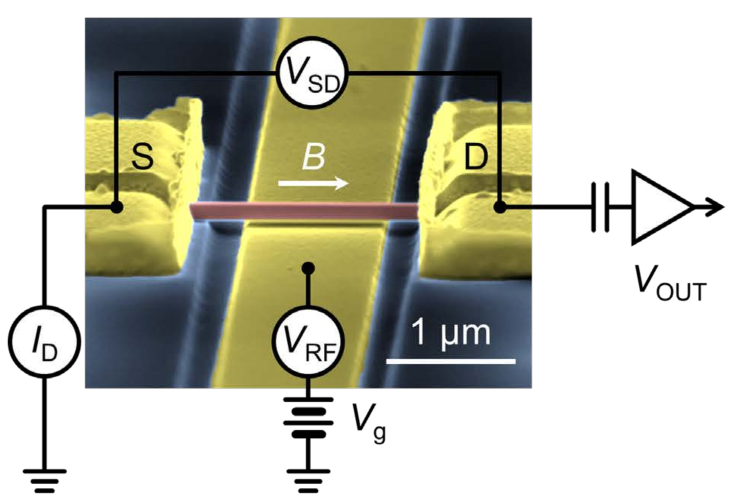


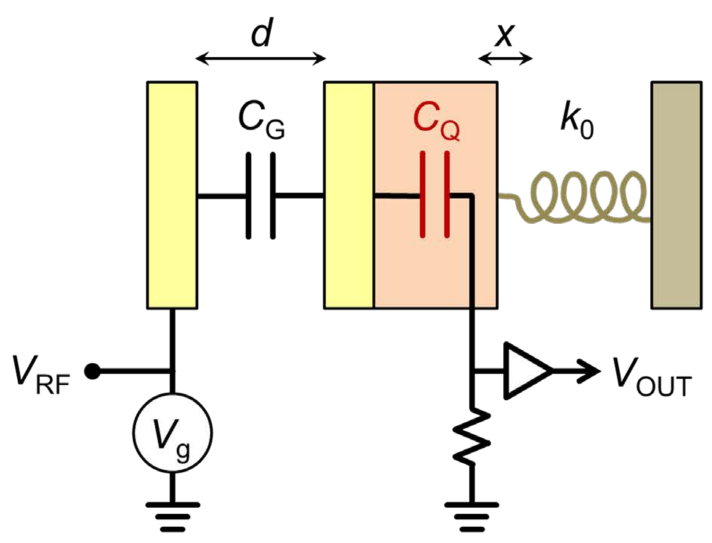
Nature Physics 12, 240–244 (2016)

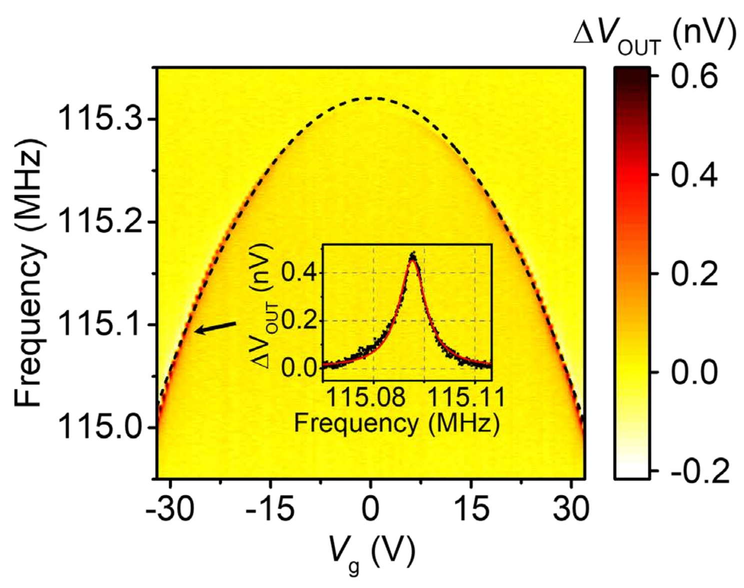
Graphene nanomechanical resonator
→ Correlation between quantum hall effect and mechanical motion

Nanomechanical resonator with a Bi_2Se_3 nanowire

▪ Device configuration and mechanical characterization







- Nanowire dimension (L × w × h)
  : 1.5 μm × 105 nm × 116 nm
- V_{RF}: Inducing nanowire vibration
- V_g: Inducing charge Q & Changing nanowire chemical potential μ

$$V_g = \frac{Q}{C_G} + \frac{\mu-\mu_0}{e} = Q\left(\frac{1}{C_G}+\frac{1}{e^2 D}\right) = Q\left(\frac{1}{C_G}+\frac{1}{C_Q}\right)$$

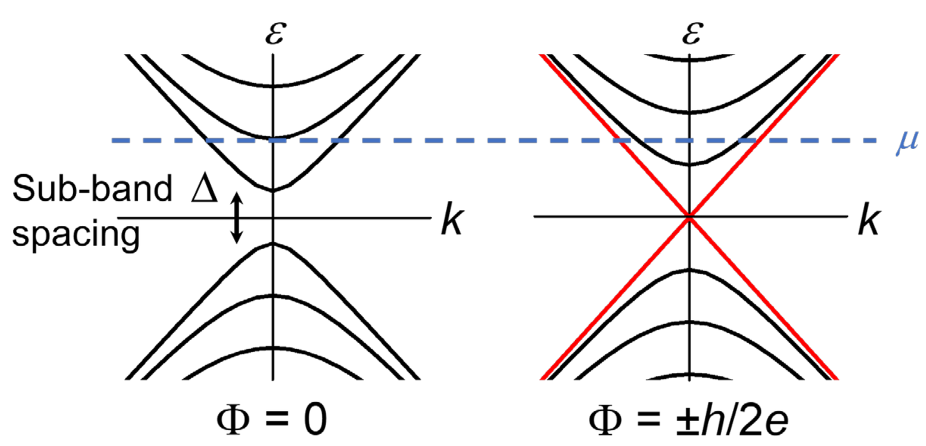
Q: total charge
e: electron charge
μ: chemical potential
C_G: geometric capacitance
C_Q: quantum capacitance
D: density of states

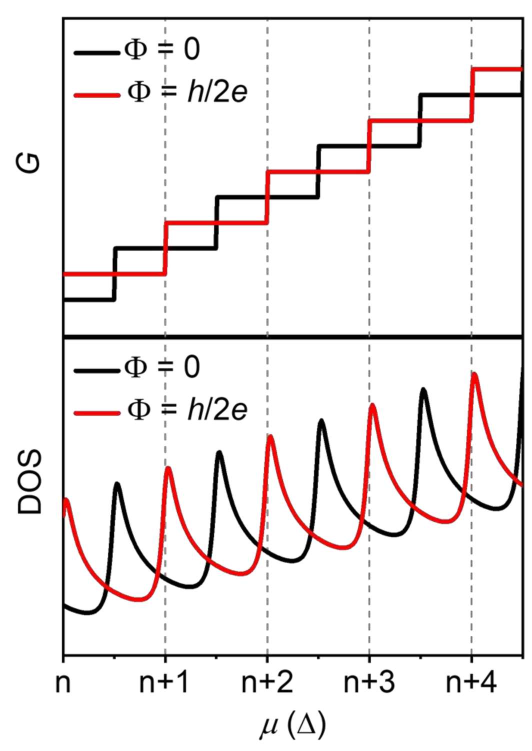
$$\delta U_{ec} = \delta\left(\frac{Q^2}{2C_G}\right) - V_g\,\delta Q + \delta\left(Q\frac{\mu-\mu_0}{e}\right)$$

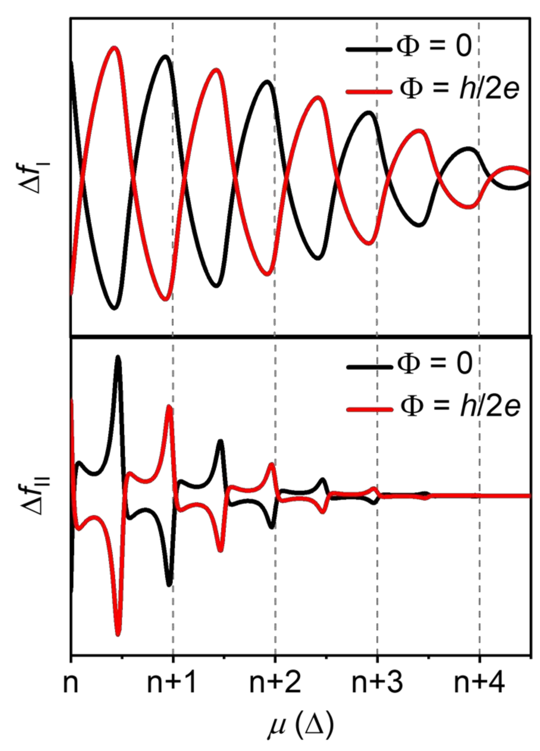
Electrostatic energy (U_{ec}) = Charging energy of the geometrical capacitor
+ Work done by the gate battery
+ Charging energy of nanowire

$$k - k_0 = \frac{d^2U_{ec}}{dx^2} \approx -\frac{1}{2}\left(\frac{\ddot{C}_G}{C_G^2}\right)Q^2 + \frac{e}{2}\left(\frac{\dot{C}_G}{C_G}\right)^2\frac{\partial}{\partial\mu}\left(\frac{1}{C_Q^2}\right)Q^3 = k_I + k_{II}$$

▪ Band structure and density of states of topological insulator nanowire

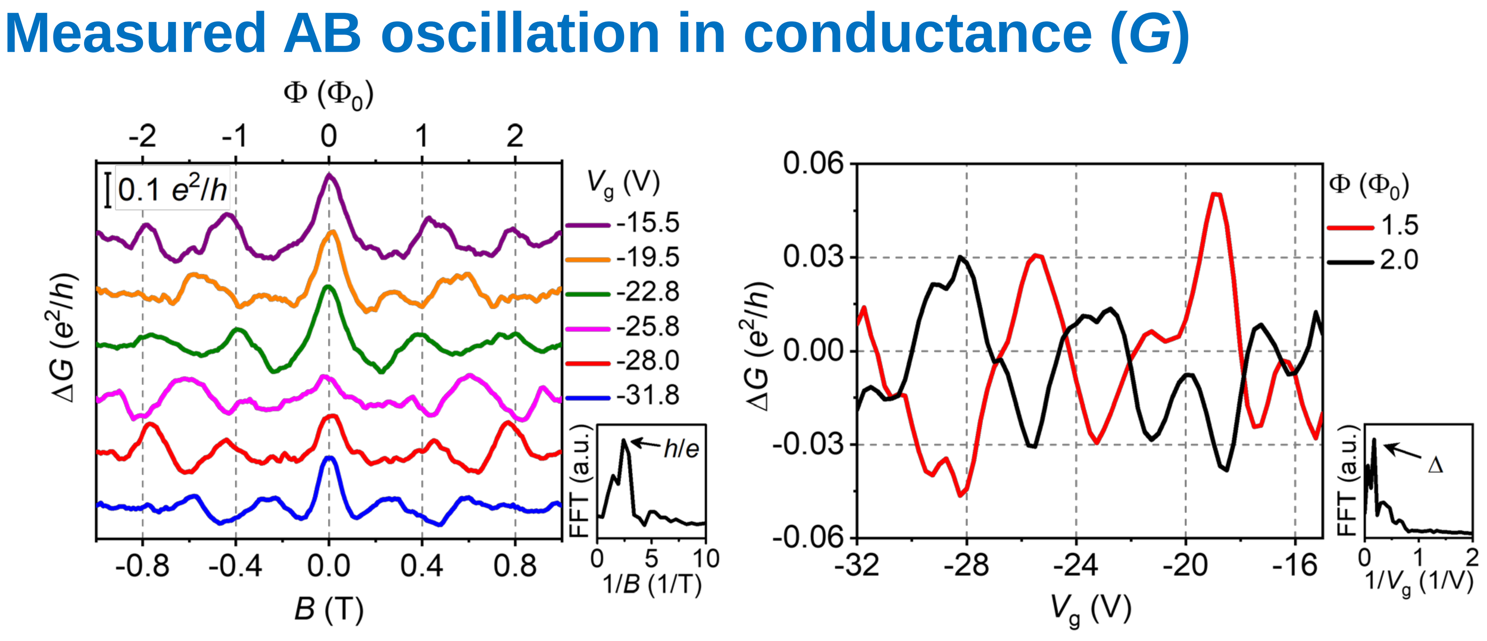




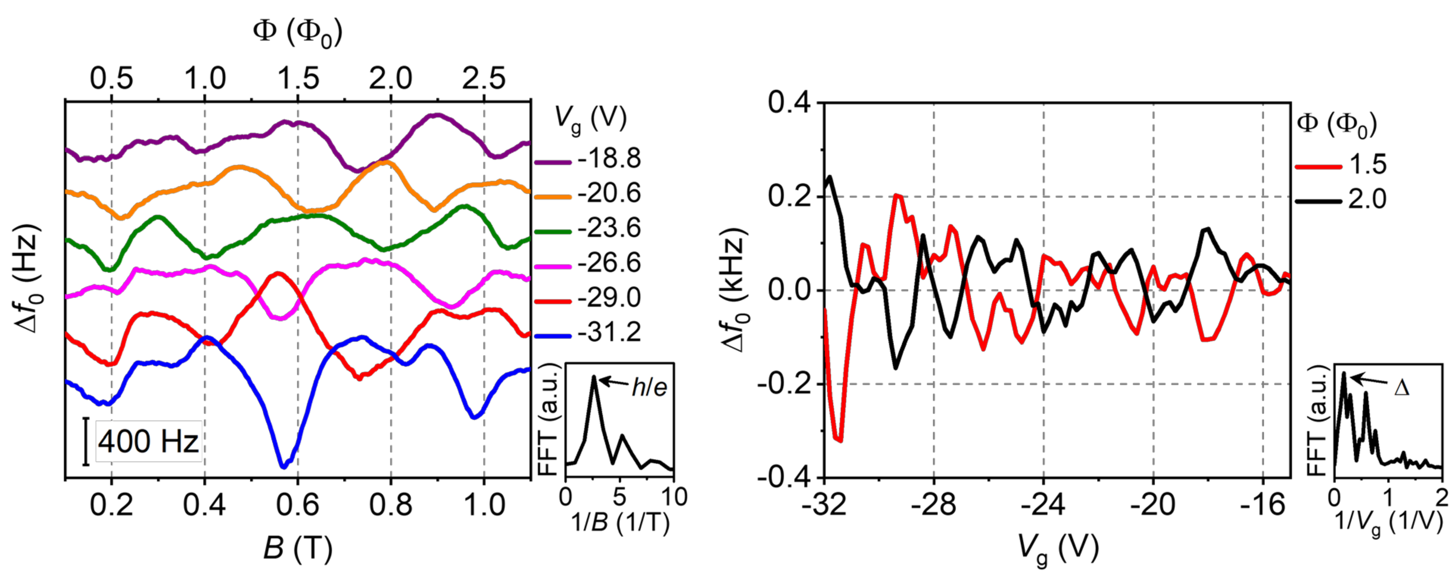


Mechanical resonant frequency and conductance oscillations

▪ Measured AB oscillation in conductance (G)

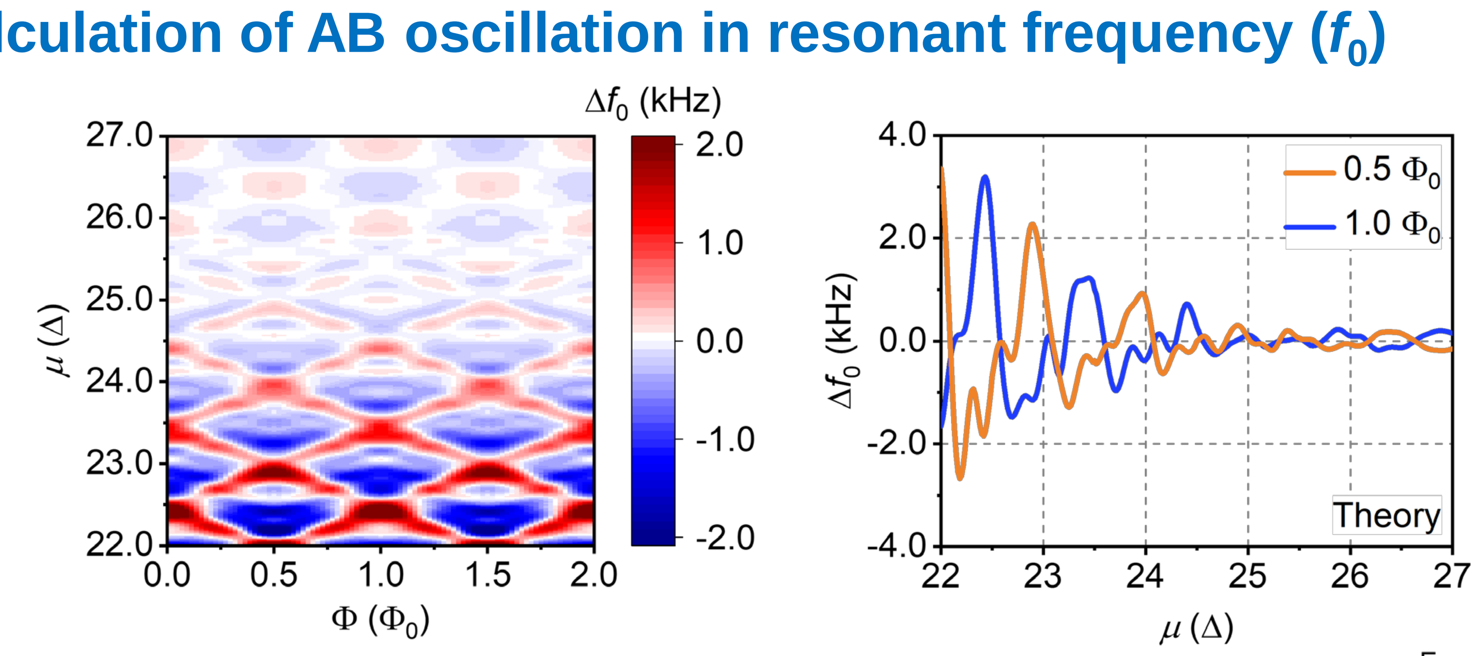


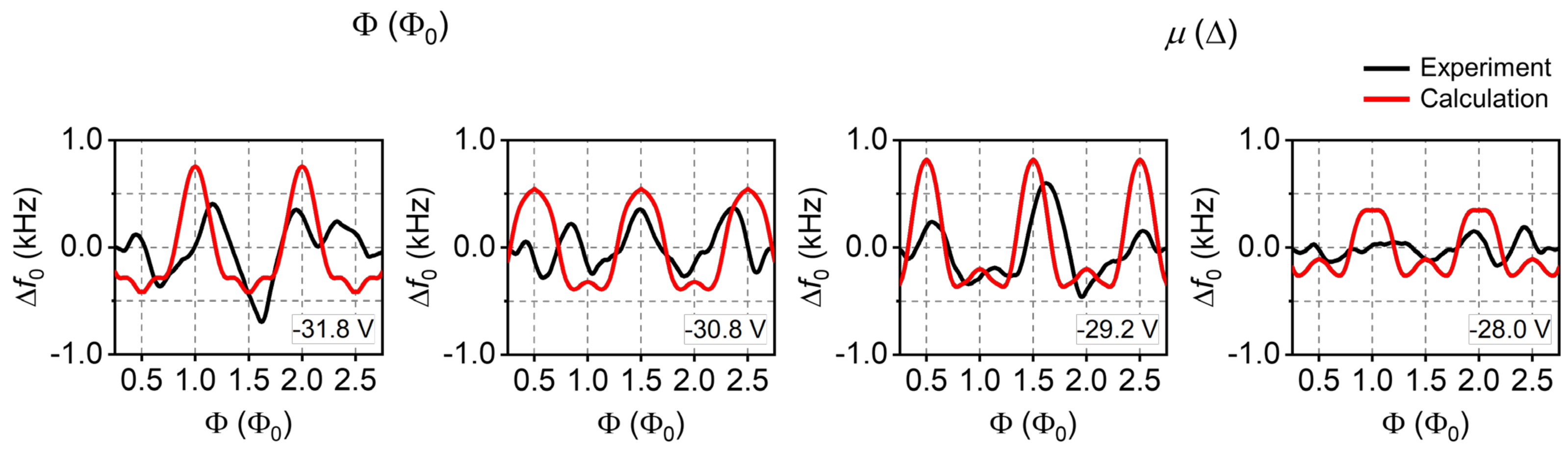
▪ Measured AB oscillation in resonant frequency (f_0)



- Oscillation with magnetic field B : ΔB = 0.4 T → h/e period
- Oscillation with gate voltage V_g : ΔV_g = 5.73 V → Δ period

▪ Calculation of AB oscillation in resonant frequency (f_0)





- Qualitative change in the oscillation pattern from a checkerboard-like shape for $\mu > 25\,\Delta$ where Δf_I is dominant, to a diamond-like shape for $\mu < 25\,\Delta$ where Δf_{II} begins to dominate.
- Aharonov–Bohm oscillation of the resonant frequency shift gets more pronounced as the chemical potential approaches the Dirac point.