Transport through a state with negative binding energy in a two-dimensional quantum wire

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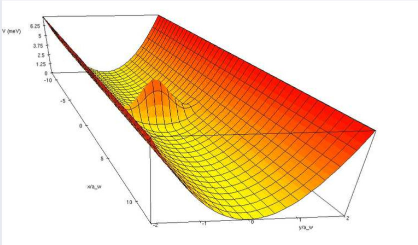
Outline

Model

Quantum wire

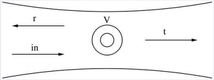


Scattering potential

- Narrow Gaussian shape
- Broad wire
  - Attractive
  - Repulsive

Model ↔ Transport

Quantum wire



- Single electron
- Multiple scattering
- General potential
- Analytic - numerical

T-matrix ← Lippmann-Schwinger

$$\tilde{T}_{nn'}(q,p) = \tilde{V}_{nn'}(q,p) + \sum_{m'} \int \frac{dka_w}{2\pi} \tilde{V}_{nm'}(q,k) G_E^{m'}(k) \tilde{T}_{nm'}(k,p).$$

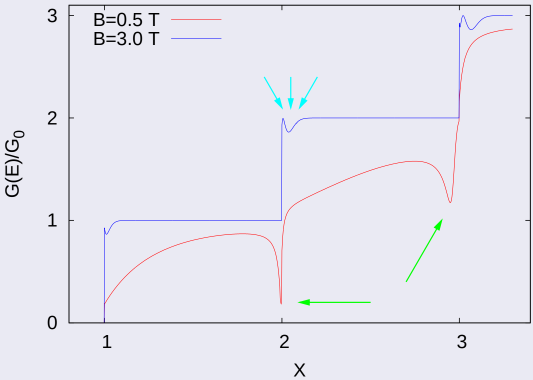
$$t_{nm}(E) = \delta_{nm} - \frac{i\sqrt{(k_m/k_n)}}{2(k_m a_w)} \left(\frac{\hbar\Omega_0}{\hbar\Omega_w} \right)^2 \tilde{T}_{nm}(k_n,k_m).$$

$$G(E) = \frac{2e^2}{h} \mathrm{Tr}[\mathbf{t}^\dagger(E)\mathbf{t}(E)],$$

- Phys. Rev. B71, 235302 (2005)

Results

Conductance, attractive potential



$$G_0 = \frac{2e^2}{h}$$

$$X = \frac{E}{\hbar\Omega_w} + \frac{1}{2}$$

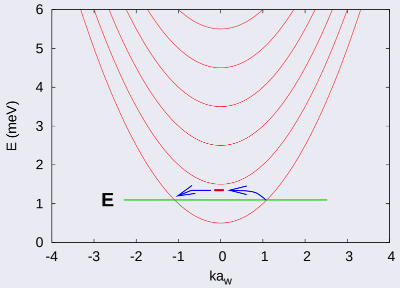
$$\Omega_w = \sqrt{\omega_c^2 + \Omega_0^2}$$

$$\hbar\omega_0 = 1.0 \text{ meV}$$

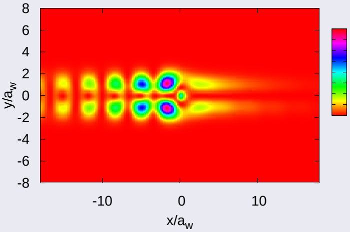
$$V_0 = -8.0 \text{ meV}$$

Evanescent States, $B = 0.5$ T, $V_0 = -8$ meV

Energy spectrum

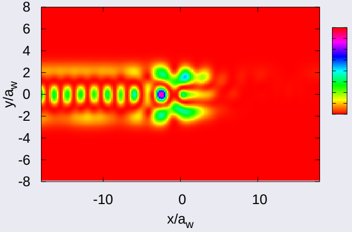


Instate: $n = 1$, $X = 1.9962$

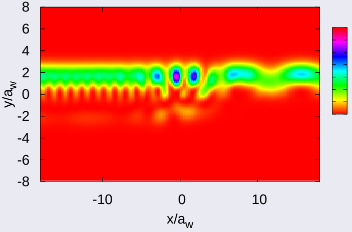


Evanescent States, $B = 0.5$ T, $V_0 = -8$ meV

Instate: $n = 2$, $X = 2.9482$

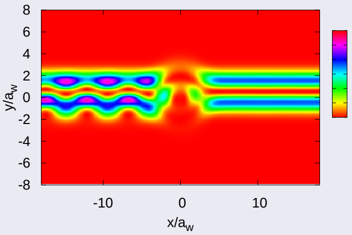


Instate: $n = 1$, $X = 2.9482$

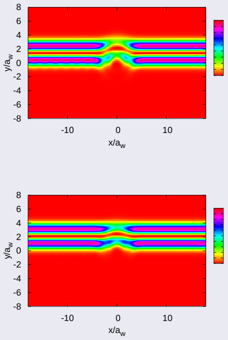


$B = 3.0$ T, $V_0 = -8$ meV

Instate: $n = 2$, $X = 2.0062$



Instate: $n = 2$, $X = 2.0382$, and $X = 2.0841$



“Quantized motion of three two-dimensional electrons in a Strong magnetic Field”,

R. B. Laughlin, Phys. Rev. B27, 3383 (1983)

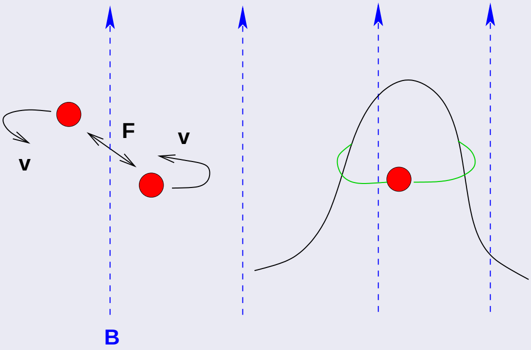
True in 2D:

“The physical origin of the quantization of electron separation in our picture is that particles of like sign in a strong magnetic field do not repel one another, but orbit about their center of mass with a speed proportional to the Coulombic force between them.”

“Thus we have a physical picture in which the particles orbit one another at distance r, as they would in the absence of a Coulomb interaction, but with a negative binding energy e^2/r.”

Idea

If true for two e^- $\longrightarrow$ also true for one e^- + hill

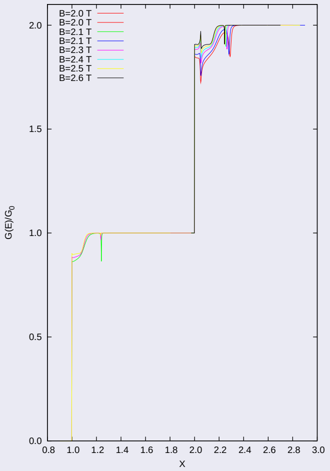


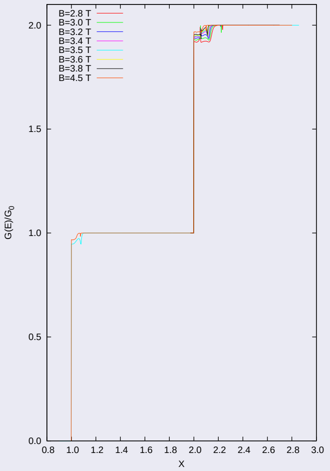
Can such a bound state be seen in transport?
$\leftrightarrow$ Quasi-bound state in the *wire*

Conditions for a state with simple structure

- Magnetic length $\sim$ potential size $<<$ wire width
- Smooth (Gaussian) potential
- $V_0 \geq$ subband separation
- High E-resolution in calculation

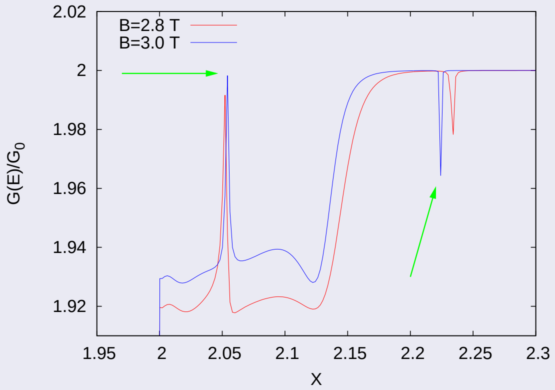
Conductance, $V_0 = 8$ meV





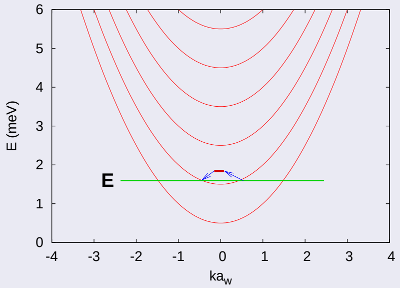
Conductance, $V_0 = 8$ meV

Magnification

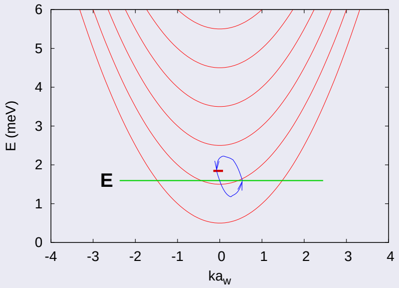


Energy spectrum, $V_0 = 8.0$ meV

Backscattering resonance



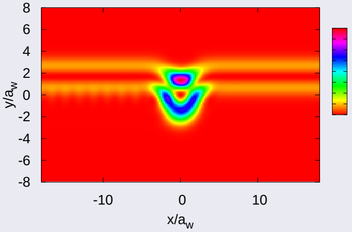
Forward scattering resonance



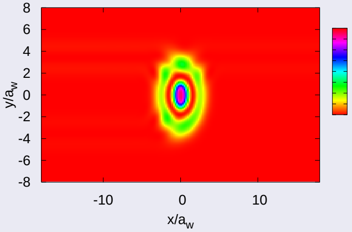
Probability density

Boundstate around a hill, narrow resonances

$n = 2, X = 2.0542, B = 3$ T



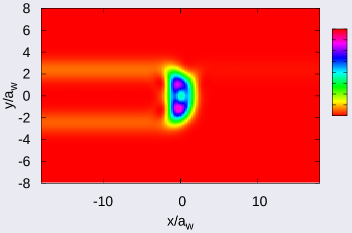
$n = 2, X = 2.242, B = 3$ T



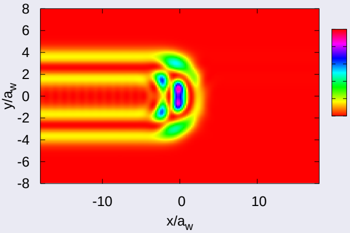
Probability density

Boundstate around a hill, $B = 2$ T

$n = 1, X = 1.2422$
lower energy

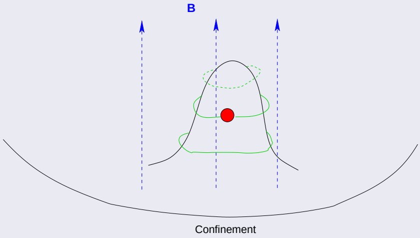


$n = 2, X = 2.29$
broad resonance



Structure of states

Quasi-bound states



Structure

- Upper states have simpler structure
- Edge influence on lower states
- Estimate by Bohr quantization
- Upper states difficult to see

Related results of others

- J. K. Jain and S. A. Kivelson, Phys. Rev. Lett. 60, 1542 (1988), Smooth scatterer, QHE - narrow constrictions, Extreme Q-limit, one subband
- Y. Takagaki and D. K. Ferry, Phys. Rev. B 48, 8152 (1993), Hard-wall large scatterer, tight-binding, AB-oscillations
- S. Chaudhuri, S. Bandyopadhyay and M. Cahay, Phys. Rev. B 47, 12649 (1993), δ-scatterer, QHE, magnetically bound state, vortex state

Conclusions

- Bound state with negative binding energy seen in transport calculation
  - Why difficult to notice in transport calculations
    - Smooth potential
    - Resolution
    - Overlap of wavefunctions, matrix elements
    - Several thousand CPU-hours
- Can it be seen in experiments?
- http://arxiv.org/abs/cond-mat/0506009
- See also:
  Phys. Rev. B71, 235302 (2005),
  Phys. Rev. B70 245308,(2004),
  cond-mat/0411378