Spectroscopy in 1D GaAs CEO Quantum Wires

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Motivation

1D interacting electron can be describe by the Luttinger liquid theory

- Spin-charge separation
- Finite size effect
- Charge fractionalization
Cleaved Edge Over growth GaAs

GaAs/AlGaAs double quantum well heterostructure

Upper QW is 20 nm wide
Distance is 6nm
Lower QW is 30 nm wide

Electron propagation :
2DEG $\rightarrow$ UW $\rightarrow$ 2DEG
When the last mode in the upper wire is depleted
2DEG $\rightarrow$ UW $\rightarrow$ LW $\rightarrow$ UW $\rightarrow$ 2DEG
Or
2DEG $\rightarrow$ LW $\rightarrow$ 2DEG
Dispersion relation

The junction is long enough for tunneling to be space invariant

\[ L \gg \lambda_F \]

\[ n = 20 - 100 \, \mu m^{-1} \]

\[ \lambda_F \sim 60 \, \text{nm} \]

\[ L = 2 \mu m \]

Momentum conservation

\[ \lambda_F = \frac{2\pi}{k_F} \]

\[ k_F = \frac{\pi n_s}{2} \]

\[ F = e\mathbf{v} \times \mathbf{B} = evB = \frac{e\Delta s}{\Delta t} B \]

\[ F\Delta t = ev\Delta sB = mv = \hbar k \]

\[ k_B = \frac{evdB}{\hbar} \]

\[ E_{U1}(B, k - k_B) = E_L(B, k) - eV_{sd} \]
\[ B^\pm = \frac{\hbar}{e d} \left| k^U_F \pm k^L_F \right| \]

\[ n_U + n_L = \frac{4B^+ e d}{\hbar} \]

\[ n_U - n_L = \frac{4B^- e d}{\hbar} \]

We can use the fermi points of UW(LW) to map the dispersion of the LW(UW)

\[ -k_{FU} - k_{FL} \]

\[ +k_i \]

\[ \left( \begin{array}{c}
    k \\
    
    \frac{h^2k^2}{2m} - E_{F_L}
\end{array} \right) \]

Right Fermi point LW to map UW:
Deviation from noninteracting behavior

Dashed lines are the dispersions for noninteractive particles

\( m^* = 0.75m \)
The fits working

They observe an enhancement of the velocity of the collective excitations, relative to the velocity in a noninteractive wire.

\[
\frac{v_p}{v_F} = \frac{m}{m^*} \\
v_p = \frac{v_F}{g}
\]

Mass renormalization

Non interacting

\[ m^* = 0.7m_{GaAs} \]

Different velocity for charge and spin

Non interactive behavior

Finite interaction
1) Spin-charge separation
2) Interwire interaction

In a one-dimensional (1D) system of interacting electrons, excitations of spin and charge travel at different speeds, according to the theory of a Tomonaga-Luttinger liquid (TLL) at low energies

\[ \nu_v = \frac{\nu_F}{K_v} \]

\( K_p \) charge interaction parameter \[ 0.5 < K_p < 1 \]

\( K_\sigma \) spin interaction parameter \[ K_\sigma = 1 \]

Experimental results

\[ u = d^{-1} \left( \frac{\partial B}{\partial V_{SD}} \right)^{-1} \]

6 different slopes are in contrast with the theory

Spin-charge separation

Assume that there is a band-filling by a finite $V_{SD}$ between the wires.

Fast charge modes

Both wires have the same densities.

Spin mode lower that the Fermi velocity is due to the back scattering.

Fast mode which are connect with the charge a that is coherent with LL theory.

Densities differ

$n^*1$ mode per each wire

Array of 1D wires
They measured the tunneling between the 1D wire and the lower 2DEG

Finite size effect

I) Checker board pattern
II) Hatched pattern
III) No regular pattern

\[ \Delta V L/v_F = \Delta B L d = \phi_0 \]

The pattern can be explained within a noninteracting electron picture and assuming a soft confining potential for the upper wire.

\[ H_{\text{tun}} = \lambda \sum_s \int dx \Psi_{su}^\dagger \Psi_{sl} e^{-iq_Bx} + \text{H.c.} \]

Wave function for upper wire

\[ M(n, q_B, V) = \int dx \psi_n^*(x) e^{-iq_Bx} \varphi_{k_l}(x) \]

Wave function for the lower wire

Experimental data vs simulation

Noninteracting model they assume that $v_F = v_{FL} = v_{FL}$

They can due numerical simulation in the interacting case

Moire’ pattern which is the finger print for spin-charge separation

Fractional effect

In 1D system with momenta conservation, it is predicted that the charge of a unidirectional electron that is injected into the wire decomposes in right and left-moving charge excitations carrying fractional charge.

Asymmetry parameter

\[ AS = \frac{(I_R - I_L)}{(I_R + I_L)} \]

Fractional conductance

Two terminal conductance no current enter in the lower wire

\[ G_{2T} = \frac{I}{(V_3 - V_1)} \]

Three terminal conductance, they set
\[ V_1 = V_3 = 0 \] and they impose that
\[ I_S = I_R + I_L \]

@ \( B = -B^+ \)

\[ AS = \frac{\beta}{2 - \beta} (2f - 1), \]
\[ \frac{G_{2T}[G_0]}{AS} = \frac{g_c}{2f - 1}, \]

\[ G_{2T} [B^+] = AS[B^+] \]

\[ f_0 = (1 + g_c)/2, \]

Theoretical prediction

• Luttinger Liquid

• It’s possible observe interesting effect such as:
  ▪ Spin-Charge separation
  ▪ Breaking of translation symmetry (Finite size effect)
  ▪ Charge fractionalization
    ▪ Spectroscopy is a powerful tool to study 1D wires
  ▪ Density
  ▪ Luttinger Liquid parameter $v_c$, $g$. 
• Study finite size effect & spin-charge Separation with a better resolution
• Improve the gating with narrow gates
  ▪ Quantum dot
\[ E_{\text{tot}} = E_{\text{int}} + E_{\text{Coul}} \]

\[ E_{\text{Coul}} = (e\Delta n)^2 / 2\tilde{C} \]

\[ |eV| \ll \mu_0 \]

\[ \mu_0 + eV = \frac{e^2}{\tilde{C}} \Delta n + \left. \frac{\partial E_{\text{int}}}{\partial n} \right|_{n=n_0+\Delta n}. \]

\[ \left. \frac{\partial E_{\text{int}}}{\partial n} \right|_{n=n_0+\Delta n} = -\mu_0 \approx \frac{\Delta n}{D_0}. \]

\[ \Delta n = eV \frac{D_0}{1 + \zeta}. \]

\[ \zeta = \frac{e^2}{\tilde{C}} D_0. \]

\[ \zeta \ll 1 \text{ (absence of e-e interaction) a voltage will simply fill quasi-particle bands without shifting the bands} \]

\[ \zeta \gg 1 \text{ an applied voltage shift the bands} \]

Capacitance gate wire

\[ \tilde{C}^{-1} = (2\pi\epsilon)^{-1} \ln \left( \frac{D_g}{r} \right) \]

Capacitance inter wire

\[ \tilde{C}^{-1} = (4\pi\epsilon)^{-1} \ln \left( 1 + \left( \frac{D_g}{d} \right)^2 \right) \]

Tunneling conditions

- $B = 0$
- No Tunneling between UW and LW

Four Fermi points with momentums $\pm k_{FU}$ and $\pm k_{FL}$

(i) $E_F$

(ii) $k_{FU} - k_{FL}$

(iv) $k_{FU} + k_{FL}$

(v) \(-k_{FU} - k_{FL}\)