One-Dimensional Coulomb Drag: Probing the Luttinger Liquid State - I

The electron-electron (e-e) interaction in one-dimensional (1D) systems is one of the most important topics in modern condensed matter physics and has attracted considerable attention in recent years. 1D systems offer the opportunity to study a plethora of exceptionally rich physics not readily found in higher dimensions. In the presence of e-e interaction, even if very weak, a 1D system can not be described by the non-interacting quasi-particles of Landau’s Fermi liquid (FL) theory [1]. It is now theoretically established that in an interacting 1D electron gas the e-e interaction completely modifies the ground state of the system and at low temperatures the system forms a Luttinger liquid (LL) [2-5]. The low-energy excitations of the LL state are characterized by separate collective spin and charge excitation modes or charge- and spin-density waves propagating with different velocities. The spin and charge separation is a unique feature of the LL state. The spectral density of a LL has two singular peaks corresponding to the charge- and spin-density excitation modes, whereas a FL has only one quasi-particle peak.

Although the LL description of 1D interacting electron systems is now well established theoretically, experimental effort to study the LL state has been fairly limited. Part of the problem is that since the current is proportional to the total electron quasi-momentum, which is conserved in e-e collisions, the e-e interaction has little influence on the conductance of a single wire. To look for the experimental evidence of the LL state, one needs devices and physics beyond simple conductance measurements. Since 1D Coulomb drag (CD) depends on the e-e interaction, this phenomenon is an excellent tool to study the Luttinger liquid state.
We have reported [6, 7] the first experimental observation of Coulomb drag (CD) between two parallel quantum wires. The drag resistance followed a power-law temperature dependence with a negative exponent as expected from LL theory of 1D Coulomb drag [8]. However, this power-law temperature dependence can conceivably be explained as well by the newly proposed Fermi-Luttinger liquid (FLL) theory [9, 10]. More work is needed to put the existence of the LL state on a firm footing.

The LL picture describes only the low-energy properties of the system. This picture is valid at energy scales, such as the temperature $T$, low compared to bandwidths of both the charge ($D_{\rho}$) and the spin ($D_{\sigma}$) excitations. $D_{\rho} \sim E_F$, the Fermi energy, while $D_{\sigma} \sim J$, the exchange coupling of spins. Both bandwidths are of the same order when the e-e interactions are not very strong, as is typical when the electron density $n$ is high. The LL picture of completely separated charge and spin excitations is thus valid at $T \ll J, E_F$. At sufficiently low values of $n$, when $na_B \ll 1$, where $a_B$ is the Bohr radius, the interaction between electrons are strong and the electrons must tunnel through one another to exchange positions. This leads to an exponentially low $J$ with $J \ll T \ll E_F$. At sufficiently low values of $n$, when $na_B \ll 1$, where $a_B$ is the Bohr radius, the interaction between electrons are strong and the electrons must tunnel through one another to exchange positions. This leads to an exponentially low $J$ with $J \ll T \ll E_F$. 
There appears an interesting new regime in which the temperature does not strongly affect the charge excitations in the system, but completely destroys the ordering of the electron spins. This new state of a strongly interacting, highly correlated 1D electron system is called the spin-incoherent Luttinger liquid (SILL) [11, 12]. The physical picture of this state is the following. The condition $T >> J$ means that within the thermal coherence time the spin quantum numbers of individual electrons remain unchanged since the spin-flip time is much larger than the thermal coherence time. On the other hand, since $T >> J$, all spin states are excited with equal probability. The spin degrees of freedom are static and random and the electron gas behaves as spin-less. The propagating spin modes of the conventional LL state are lost. On the other hand, the charge excitation modes are maintained since $T << E_F$. The low-energy charge excitations of SILL are treated as a conventional spin-less (spin-polarized) LL with an interaction parameter $g = 2g_C$, where $g_C$ is the interaction parameter of the charge sector of a conventional LL. The SILL state is thus different from the conventional, spin-coherent LL state (SCLL).

1D Coulomb drag opens up a new opportunity and avenue for experimentally probing e-e interaction and the LL state in 1D interacting systems. This is especially true for the dual-wire device geometry [6, 7] we have used earlier that allows us to work in the fundamental mode of transport and independently vary in situ system parameters such as $k_F$, $w$, and $d$. Such a geometry also allows us to spin polarize the wire electrons by an applied magnetic field.
One-Dimensional Coulomb Drag: Probing the Luttinger Liquid State - IV

Our Project: Probing the Luttinger Liquid State

Using the dual-wire device geometry we are carrying out a comprehensive experimental investigation of Coulomb drag between 1D semiconductor quantum wires made on AlGaAs/GaAs hetero-structures. We are using the phenomenon of Coulomb drag as a tool to probe the conventional spin-coherent LL (SCLL), the Fermi-Luttinger liquid (FLL), and the spin-incoherent LL (SILL) state. We have a NSF grant to support this work.
What is 1D Coulomb Drag?

Current $I$ flows in wire 1 and induces, by momentum swapping via Coulomb interaction, a current $I_D$ in wire 2. When the drag wire is an open circuit, a drag voltage $V_D$ develops across it.

Drag resistivity

$$ r_D = - \frac{e^2}{h} \frac{1}{L} \frac{dV_D}{dI} $$

“$L$” is length of wire

Electrically isolated, no tunneling, no overlap of wave functions of the two wires.
Coulomb Drag Device

Samples made on AlGaAs/GaAs heterostructure with high-mobility 2DEG

Middle gate width = 56 nm

Channel: lithographic length \( L \approx 1 \mu m \) and width \( W \approx 350 \) nm
1D Coulomb Drag via Large and Small Momentum Transfer

Drag Wire

Energy Dispersion:

\[ dE_F = v_F q \]
\[ dE_F = v_F q + \frac{q^2}{2m} \]
\[ q = \left| k \right| - k_F \]


Fermi-Luttinger liquid (FLL) model: nonlinear dispersion and small momentum transfer (forward scattering). Non-monotonous temperature dependence.
Coulomb Drag due to Small Momentum Transfer

Presented at APS March 2008 Meeting

Positive curvature - positive drag

Negative curvature - negative drag

FLL theory Temp Dependence

Observed Temp Dependence