Coulomb Drag Between Quasiballistic Quantum Wires: an Indication of Non-Fermi-Liquid Behavior.

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The Coulomb drag between two spatially separated, 2 µm long lithographically defined quantum wires has been studied experimentally in the absence of interwire tunneling. The drag resistance \( R_D \) shows peaks when the 1D subband bottoms of the wires are aligned and the Fermi wave vector \( k_F \) is small. \( R_D \) decreases exponentially with the interwire separation \( d \). In the temperature range \( 0.2K \leq T \leq 1K \), the drag signal shows the power-law dependence \( R_D \propto T^x \) with \( x \) ranging from -0.61 to -0.77 depending on the magnitude of \( k_F \). We interpret our experimental results in the framework of the Tomonaga-Luttinger liquid theory.

One-dimensional (1D) electron systems have recently been the focus of considerable attention since they are expected to show unique transport properties associated with the Coulomb interaction between carriers. In 1D systems this interaction modifies the ground state and the elementary excitations considerably and the systems are theoretically described in terms of a Tomonaga-Luttinger (TL) liquid rather than a Fermi-liquid (FL) model [1]. Recently attempts have been made to test some of the predictions of the TL theory in 1D systems, such as lithographically defined quantum wires, which proved to be convenient for transport measurements and allow the variation of the relevant parameters in a wide range. Though it has been argued [2] that according to the TL theory the single-mode conductance of a ballistic quantum wire should deviate from its fundamental value of \( G_0 = 2e^2/h \), the majority of the wires investigated do not show such a deviation, and where it is present [3], it still lacks a consistent explanation in terms of a TL liquid. The reasons that make the measured conductance independent of the interaction have been discussed by many authors [4], who emphasized the role of the FL reservoirs to which the wires are connected and of the screening effects. Therefore, one should search for other, more ingenious ways to obtain experimental evidence of a TL liquid behavior. One such way would be to use the Coulomb drag (CD) between parallel quantum wires in line with its recent TL liquid descriptions [5-7] which strongly suggest that it can be used to probe this TL liquid behavior experimentally.

Experimental and theoretical studies of the CD between two-dimensional (2D) electron layers, recently reviewed [8], established that the drag resistance \( R_D = -V_D/I \), where \( V_D \) is the voltage developed in the drag layer as a response to the current \( I \) flowing through only the drive layer, decreases with the decreasing temperature \( T \). This behavior is consistent with a FL description of the electron system, since the restrictions imposed by the momentum and energy conservation laws suppress the probability of electron-electron scattering at smaller \( T \). Similarly, within a FL description of the drag between 1D systems \([9] \), such restrictions have even stronger consequences: the low-temperature drag response is maximal when the energy levels of the wires are aligned so that the Fermi velocities are nearly equal. If the alignment is perfect, the drag linearly decreases with temperature, otherwise the decrease is exponential.

In contrast with this behavior of the CD in 2D or 1D systems, its temperature dependence changes completely when the electron subsystems in the two wires behave like TL liquids and the interwire momentum transfer is strongly modified by electron-electron interactions. Roughly speaking, the drag results from backscattering of density excitations in one wire from density fluctuations in the other one. Therefore, the present situation bears some similarity [7] to a TL liquid with backscattering by an impurity. Since for a repulsive interaction the effective backscattering strength of the impurity increases with decreasing temperature and eventually diverges at \( T = 0 \) [12], one should expect that similarly the drag becomes enhanced at low temperatures until, at \( T = 0 \), interlocked charge density waves form and the drag-resistance diverges too. (This divergence or absolute drag [6] applies only to wires that are infinitely long. For finite wires, at sufficient low temperatures the drag becomes suppressed due to the influence of the contact reservoirs [13].) Though this strong-coupling regime may remain elusive experimentally, the increase of the drag with decreasing \( T \) in a characteristic power-law fashion [7] may serve as a signature of the TL behavior.

Recently, we have reported [14] experimental evidence of the CD between 1D electron systems. In the present work we report comprehensive studies of this effect, successfully explain the observed features in the temperature dependence of \( R_D \) in the framework of the TL theory, and show how these features can be used to probe a TL liquid.
The magnitude of the first peak in the conductance was measured of one wire at a time, and of both of them simultaneously, as a function of wire width to establish the ballistic nature of electronic transport and to check if both wires had identical transport behavior. The two wires were found to have nearly identical conductance staircases with a small difference in the pinch-off voltages which could be compensated for by introducing an appropriate voltage shift between the gates T and B. The observed conductance showed characteristic features of ballistic transport. However, the conductance staircases were not sufficiently well defined due, very likely, to deviations from adiabaticity at the constriction openings and scattering in the wires caused by gate edge roughnesses. The application of a magnetic field $B < 1$ T perpendicular to the plane of the device improved the adiabaticity and suppressed the scattering, producing fairly well-defined plateaus (Fig. 2). This, together with the fact that we did not observe any sharp peaks in the pinch-off regime and/or resonant oscillations on the plateaus, confirmed that we were dealing with ballistic transport in quantum wires free of embedded impurities or dots. The information obtained from the above characterization made it possible to choose, as required, the location of the Fermi level $E_F$ in a specific 1D subband as well as the relative alignment of the 1D subbands belonging to the two wires. For measurements of the CD effect, the upper wire was chosen as the drive wire and the lower one was the drag wire (Fig. 1). The gates M and B were appropriately biased with voltages $V_M$ and $V_B$, respectively, to have $E_F$ slightly above the bottom of the lowest 1D subband of the drag wire. The influence of the voltage $V_T$ applied to the upper gate on the width of the drag wire was found to be insignificant. A driving voltage $V_{DS}$, low enough to be within the linear regime of transport, was applied to the drive wire to send a current $I$ through it. No current was allowed to flow in the drag wire. $I$ and the drag voltage $V_D$, opposite in sign to $V_{DS}$, were measured simultaneously as $V_F$ was swept. To ensure the absence of tunneling during the measurements, the tunneling current across the middle gate, between the drain of the drive wire and the source of the drag wire, was applied to the drive wire to send a current $I$ through it. No current was allowed to flow in the drag wire. $I$ and the drag voltage $V_D$, opposite in sign to $V_{DS}$, were measured simultaneously as $V_F$ was swept. To ensure the absence of tunneling during the measurements, the tunneling current across the middle gate, between the drain of the drive wire and the source of the drag wire, was applied to the drive wire to send a current $I$ through it. 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Figure 4 shows $V_D$ vs $V_T$ for $V_{DS} = 300 \, \mu\text{V}$, $B = 0$, and different temperatures. We see again the general pattern of Fig. 2 and a decrease in the drag response with increasing temperature. The corresponding decrease of the peak value of $R_D$ with $T$ is shown in the inset. For $0.2 \leq T \leq 1 \, \text{K}$ the temperature dependence can be described well by the power law $R_D \propto T^x$ with $x = -0.77(2)$. This behavior is in sharp contrast with the linear behavior ($x = +1.0$) expected [9], [11] for Fermi liquids. As we move to the right shoulder of the peak at less negative $V_T$, the temperature dependence of the drag signal becomes progressively weaker and is again described well by a power law. For example, at $V_T = -1.17 \, \text{V}$ we have found $x = -0.61(2)$. The presence of the magnetic field up to 0.86 T does not change the observed behavior: at 0.86 T we obtained $x = -0.73(6)$ at the peak.

The unusual temperature dependence cannot be attributed to a temperature-induced modification of the wire conductance, since the latter is found to be almost unchanged in this range of temperatures. Possible reduction of the interwire Coulomb coupling due to enhanced screening by the reservoirs and gates seems to be unlikely at such small temperatures. On the other hand, one can argue that correlated liquid behavior is established in the wires. Indeed, it is hardly surprising that the temperature dependence of the observed CD does not fit into a FL scenario, because for the peak conditions the ratio of the mean distance between the electrons within one wire to the Bohr radius $r_s = \bar{r}/a_B \approx 26$ is large. Below we find that the temperature dependence of $R_D$ is in good agreement with a theory of CD between TL liquids.

The smallness of the drag resistance ($R_D < 100 \, \Omega$) indicates a weak interwire backscattering coupling. In this case $R_D$ should obey a power law as long as the thermal length $L_T$ is well in between the wire length $L = 2 \, \mu\text{m}$ and the mean electron distance $\bar{r} \approx 250 \, \text{nm}$. The exponent $x$ is determined by the TL parameter $K_{\perp}$ of the relative charge mode [7]. For spin-uncpolarized electrons, as in the present experiment, it is

$$x = 2K_{\perp} - 1. \tag{1}$$

As $L_T$ approaches $L$, the temperature dependence of $R_D$ is expected to weaken.

Let us first see whether the condition $\bar{r} < L_T < L$ is fulfilled in our experiment. If Eq. (1) holds, the parameter $K_{\perp}$ can be determined from the experimental data as $K_{\perp} = 0.12 - 0.2$ depending on $V_T$. Given a Fermi wavevector $k_F \simeq 6 \, \mu\text{m}^{-1}$, we find that $L_T = h v_F / k_{\perp} = 2 \mu\text{m}$ at a temperature of $\approx 250 \, \text{mK}$, and that $L_T$ approaches $\bar{r} \approx 250 \, \text{nm}$ for temperatures of order 2 K. This means that there is a narrow temperature window in which a power-law behavior of $R_D(T)$ might be expected. The data is indeed consistent with such a power-law dependence of $R_D(T)$ for temperatures in the range 0.2 - 1 K, while at lower temperatures a weakening of the drag is observable, see inset of Fig. 4. It is crucial, however, to check if the rather low values of $K_{\perp}$ obtained are consistent with the system parameters, which we do next.

It was shown recently [16] that the interaction parameter of a single quantum wire, calculated by standard perturbative methods, yields reliable values even for small values of $k_F w$ ($w$ is the width of the wire) down to 0.1, while in our experiment $w \simeq 23 \, \text{nm}$ (determined from experimental data) and $k_F w \simeq 0.14$. Encouraged by this result, we determine $K_{\perp}$ in a similar way via the compressibility of the relative charge mode obtained in the Hartree-Fock approximation; this leads to

$$K_{\perp}^{\text{HF}} = (1 + [2(V_0 - \bar{V}_0) - V_{2k_F}] / \pi v_F)^{-1/2}, \tag{2}$$

where $V$ and $\bar{V}$ denote intra- and inter-wire potentials, respectively. Modeling the potentials by $V = e^2 \epsilon^{-1} (x^2 + w^2)^{-1/2}$ and $\bar{V} = e^2 \epsilon^{-1} (x^2 + d^2)^{-1/2}$, we obtain an interaction parameter of $K_{\perp}^{\text{HF}} = 0.178$. To obtain this result we used the parameters $d = 200 \, \text{nm}$, determined experimentally as well as estimated from electrostatic calculations of the double-well potential profile created by the three parallel infinite gates for $V_M = -0.8 \, \text{V}$ and $V_T = V_B = -1.5 \, \text{V}$, $w = 23 \, \text{nm}$, $k_F = 6.1 \, \mu\text{m}^{-1}$, $\epsilon = 12.5$, and $m^* = 0.068 m_e$. If we take into account screening by a homogeneous gate, i.e., if we subtract the image-charge potentials $e^2 \epsilon^{-1} (x^2 + w^2 + 4l^2)^{-1/2}$ and $e^2 \epsilon^{-1} (x^2 + d^2 + 4l^2)^{-1/2}$ ($l = 80 \, \text{nm}$), from $V$ and $\bar{V}$, respectively, we obtain $K_{\perp}^{\text{HF(S)}} = 0.212$. Since in reality we have split gates, the true value of $K_{\perp}$ is expected to be somewhere between $K_{\perp}^{\text{HF}}$ and $K_{\perp}^{\text{HF(S)}}$ and is in reasonable agreement with the experimental value.

The drag resistance itself is proportional [7] to the square $|V_{2k_F}|^2$ of the $2k_F$-component of the interwire interaction, which leads to the exponential dependence $R_D \sim e^{-4k_F d}$ for $d > k_F^{-1}$, whether the screening is present or not. Thus, we stress that our previous analysis based on this dependence remains valid in the TL liquid approach.

The negative power-law temperature dependence is not the only signature against a FL drag theory we obtained in our experiment. The experimental peak value of $R_D$, at $T = 60 \, \text{mK}$, is more than one order of magnitude larger than the value obtained using equations of the FL theory for the ballistic transport regime [10], [11]. That the measured drag is larger could be explained by the interaction renormalized interwire backscattering probability, which should be larger than the bare one.
Considering the large interwire separation in our experiment, one cannot rule out a possibility of a phonon-mediated drag (PMD) contribution to \( R_D \). Existing results for 2D systems [17,8] show that the PMD rapidly decreases with \( T \) at \( T < 2 \) K and depends rather weakly on the interlayer separation. Since our data qualitatively contradict such a behavior, we conclude that the PMD, if any, does not play a major role in our measurements. Since little information is available on PMD in 1D systems, further discussion of this subject can only be of purely speculative nature and is not appropriate here.

In conclusion, we have investigated the Coulomb drag between 1D electron systems and observed a negative power-law temperature dependence of the drag resistance, which can be explained quantitatively in terms of the TL liquid concept. Clearly, further work is necessary to put the TL nature of the CD on a firm footing.

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FIG. 1. Schematics of the device. The letters T, M, and B denote upper, middle and lower gates.

FIG. 2. Drag voltage \( V_D \) and drive wire conductance \( G \) vs voltage of the upper gate \( V_T \) at \( T = 70 \) mK, \( V_M = -0.74 \) V, \( V_B = -1.525 \) V, and \( V_{DS} = 300 \mu V \). The dot-dashed and dashed lines show the staircases \( G(V_T) \) in magnetic fields of 0.35 T and 0.86 T, respectively. The inset shows the dependence of the first peak in \( V_D \) on \( V_{DS} \).

FIG. 3. (a) Drag voltage \( V_D \) vs voltage of the middle gate for \( T = 60 \) mK. (b) The logarithm of \( R_D \) vs \( V_M \). The dotted curve shows the exponential decay of \( R_D \) with \( V_M \).

FIG. 4. The same as in Fig. 2 for temperatures 70, 180, 300, and 600 mK, corresponding to the curves in a descending order. The inset shows the peak drag resistance \( R_D \) vs temperature \( T \) and the dotted curve is a power-law fit.
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Fig. 2. Debray et al, Coulomb drag…
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