Measurement of Spin-Charge Separation and Spontaneous Localization in One-Dimensional Wires

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Interactions have a profound effect on electrons confined to one-dimension, giving rise to long range correlations in the elementary excitations, which are best described in the framework of Luttinger-liquid theory. Unfortunately, the transport properties of clean wires do not reflect the unique properties of Luttinger-liquids. We have overcome this difficulty by measuring momentum resolved tunneling between two clean, parallel wires. This facilitates a direct measurement of the collective excitation spectrum of electrons in a wire, a direct observation of spin-charge separation from finite size interference and allows to determine the wavefunctions of electrons along a wire and their dependence on density.

The experiment consists of measuring tunneling between the wires at temperatures down to 0.25K. The wires are fabricated by cleaved edge overgrowth (CEO) from a GaAs/AlGaAs double quantum well heterostructure. The CEO creates two quantum wires, a few dozens of nanometers in diameter, separated by an AlGaAs barrier a few nanometers wide, that are parallel to within atomic precision. The high degree of invariance to translations along the wires ensures that tunneling is suppressed unless there exist elementary excitations that match both the energy and the momentum that are supplied by applying a voltage bias between the wires (V_{sd}) and a magnetic field perpendicular to their plane (B). Control of the density in the wires is achieved with voltage applied to a 2μm-long top gate (V_g).

A map of the non-linear tunneling conductance as a function of V_{sd} and B (see Fig. 1) constitutes a measurement of the dispersions of the elementary excitations in the wires. We find that the wires have two branches of excitation, corresponding to a spin mode and to a charge mode. As predicted by theory, the velocity of the former is very similar to the Fermi velocity while the velocity of the latter is enhanced by 30%, attesting to the importance of Coulomb interactions in the wires. Interference due to finite size is an even more sensitive tool for detecting excitation branches and provides us with direct evidence for the existence of spin-charge separation in the wires.

The momentum-space structure of the wavefunctions along the wires can be determined from the tunneling conductance. This novel approach is used to measure the density dependence of the wavefunctions (see Fig. 2). We find a dramatic difference between the nature of states in highly populated subbands and their nature when the density is low, and that the transition between the two regimes is abrupt. In the high-density regime the states are extended and have well defined momenta. This is manifested in the data by pairs of narrow peaks (see e.g. the pair marked (I) in Fig. 2). In the low density regime the states are localized, as can be seen from the feature marked (II) in Fig. 2. This feature is wide in B and is roughly bound by the extrapolation of the curves traced by the high-density regime peaks. In high resolution scans the dependence on V_g is found to be a set of Coulomb blockade oscillations. The transition is shown by conventional transport to coincides with the position of the conductance step related to the depleting subband. The fact that the behavior we observe is the same for all subbands and under all gates upon different cooldowns, together with the abruptness of the transition and the high quality of the wires, leads to the conclusion that the transition is spontaneous and is driven by electron-electron interactions.

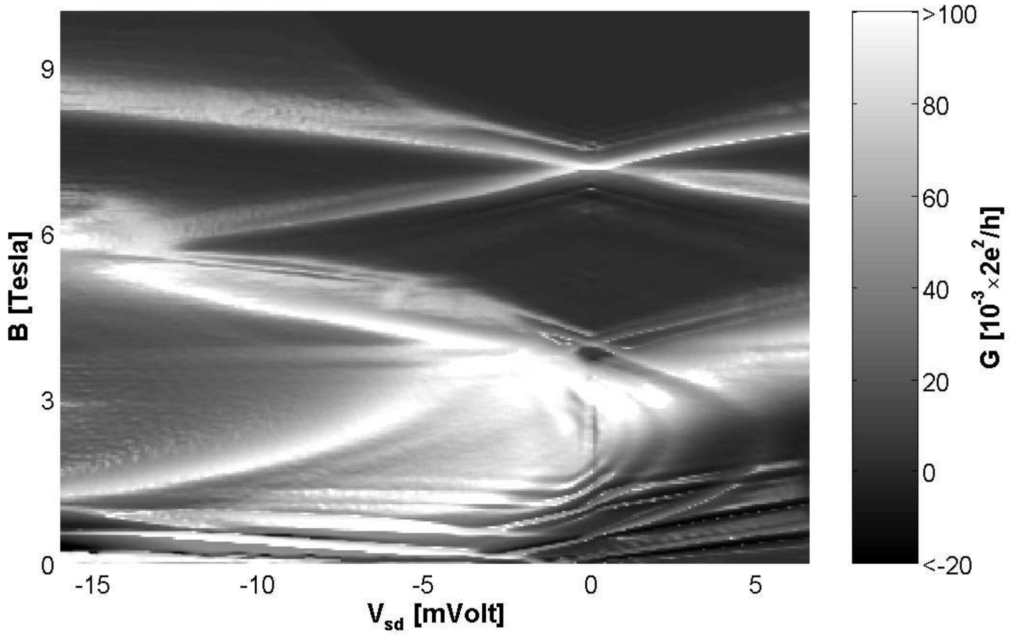

Figure 1: Scan of the non-linear tunneling conductance for a 10μm junction as a function of V_{sd} and B. The side-bar gives the scale. The curves traced out by the conductance peaks are dispersions of charge modes in the wires. At the crossing point near 7T the dispersion of an additional branch, a spin mode, can be faintly discerned splitting off from the charge-mode dispersion towards higher B on the negative V_{sd} side.

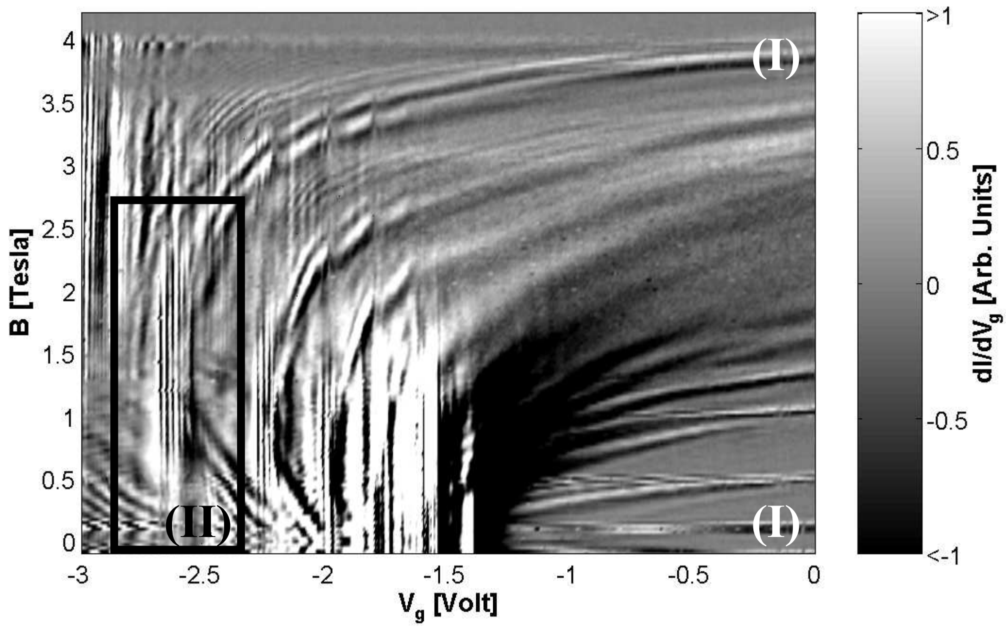

Figure 2: Derivative of the tunneling current with respect to V_g versus V_g and B for a 10μm wire. The side-bar gives the scale. V_g controls the density in the wires, predominantly affecting the wire closer to the gate. A scan along B determines the state of the electrons in each subband along the wire. At high density the state is given by a pair narrow peaks in B, marked by (I), showing that it is extended. Such pairs evolve along parabola-like curves. The critical density where a state localizes is given by the onset of Coulomb blockade oscillations, marked by (II), indicating that beyond the critical density the state is confined.