# Characterisation of spin-incoherent transport in one dimension

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**Abstract.** Spin-incoherent transport in quantum wires, whereby exchange coupling between neighbouring electrons is overcome by thermal energy, leading to the suppression of spin modes of transport expected in a Luttinger liquid, has been observed in the form of a conductance plateau at $e^2/h$ in the absence of a magnetic field. We present here further characterisation of this spin-incoherent plateau in a source-drain bias, which causes it to evolves to $0.85 \times 2e^2/h$. Laterally shifting the channel and illuminating the sample allows us to verify its origin.

## 1. Introduction

In the decade since the discovery of the 0.7 structure[1], it has become increasingly evident one-electron theory is insufficient to describe all of the phenomena that have been observed in one-dimensional (1D) transport, and electron-electron interactions must therefore be invoked.

The general model describing the low-energy states of an interacting one-dimensional system of electrons is the Luttinger liquid, wherein the elementary excitations are spin and charge density waves which propagate independently of one another. By exploiting this spin-charge separation, it is possible for the characteristic energy of the spin excitations $E_{\mathrm{spin}}$ to be exponentially suppressed with respect to that of the charge excitations $E_{\mathrm{charge}}$, which generally occurs when interactions are strong. If the thermal energy $k_{\mathrm{B}}T$ should then lie between these two characteristic energies, i.e., $E_{\mathrm{spin}} \ll k_{\mathrm{B}}T \ll E_{\mathrm{charge}}$, only charge modes are transmitted. This is the spin-incoherent Luttinger liquid, which exhibits characteristics qualitatively distinct from a normal Luttinger liquid.[2, 3, 4]

Can such a transport régime be observed experimentally? It has been shown that the reflection of the spin modes gives rise to an additional resistance contribution which suppresses the conductance of the 1D channel by a factor of 2 to $e^2/h$.[5, 6] Since $E_{\mathrm{spin}} \sim J$, the nearest-neighbour exchange interaction, and $E_{\mathrm{charge}} \sim E_{\mathrm{F}}$, the Fermi energy, the inequality can equivalently be expressed $J \ll k_{\mathrm{B}}T \ll E_{\mathrm{F}}$. This suggests that we may observe this suppression of the conductance in a quantum wire with a low electron density, as $J$ drops off exponentially with increasing electron separation.

## 2. Experiment

We have investigated ballistic split-gate devices (width 0.7 $\mu$m, length 0.4 $\mu$m) defined in a two-dimensional electron gas (mobility $1.85 \times 10^6$ cm$^2$/Vs and density $1.53 \times 10^{11}$/cm$^2$) formed in a GaAs/AlGaAs heterostructure. The addition of a top gate (width 1 $\mu$m) above and parallel
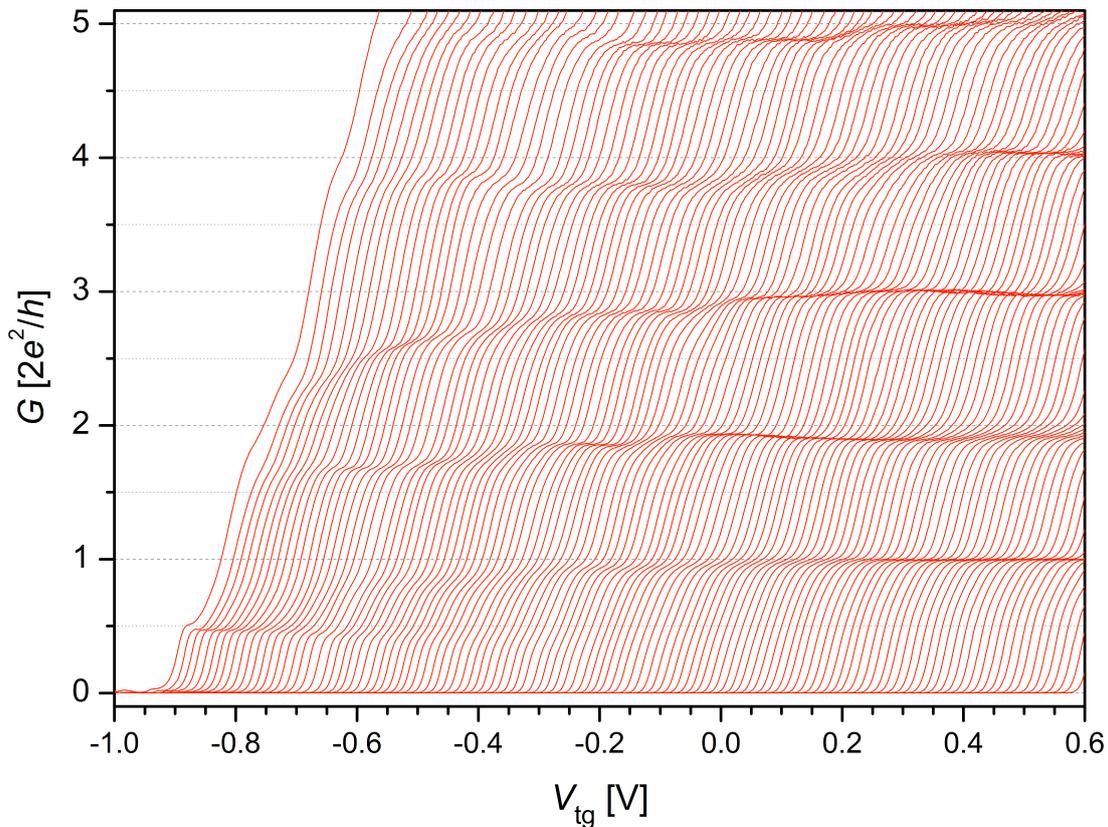
**Figure 1.** Differential conductance traces $G(V_{tg})$ measured by sweeping $V_{tg}$ at various fixed $V_{sg}$. Moving left-to-right, each successive trace corresponds to a slightly more negative $V_{sg}$, i.e., increasing 1D confinement. The régime of strong confinement is therefore to be found on the right, and that of weak confinement on the left.

to the split gates permits good control of the electron density relatively independently of the steepness of the 1D confinement potential.[7]

We operate our device by first defining a 1D channel, determining its width by tuning the voltage on the split gates $V_{sg}$. The more negative $V_{sg}$ is, the narrower the quantum wire. The top-gate voltage $V_{tg}$ is then used to deplete the carriers. The two-terminal differential conductance $G = dI/dV_{sd}$ is measured as a function of $V_{tg}$ using a 33 Hz excitation voltage of 5 $\mu$V at a base (electron) temperature of some 100 mK.

## 3. Results

Figure 1 shows the conductance characteristics of our device. On the right-hand side, where the wire is strongly confined, the plateaux are well-quantised in units of $2e^2/h$ as expected for non-interacting ballistic 1D transport. As the confinement weakens (moving to the left), a kink becomes apparent at $e^2/h$, developing into a plateau with further weakening of the confinement. At the same time, the plateau at $2e^2/h$ is suppressed in conductance, gradually fading away until it has disappeared altogether on the far left, leaving only the structure at $e^2/h$. This is a clear signature of the onset of spin-incoherent transport in our quantum wire. Measurements of the device in a magnetic field is supports this conclusion, for the structure at $e^2/h$ initially weakens when an in-plane magnetic field is applied until $B_\parallel \approx 9$ T, whereupon it begins to strengthen once again.[8]

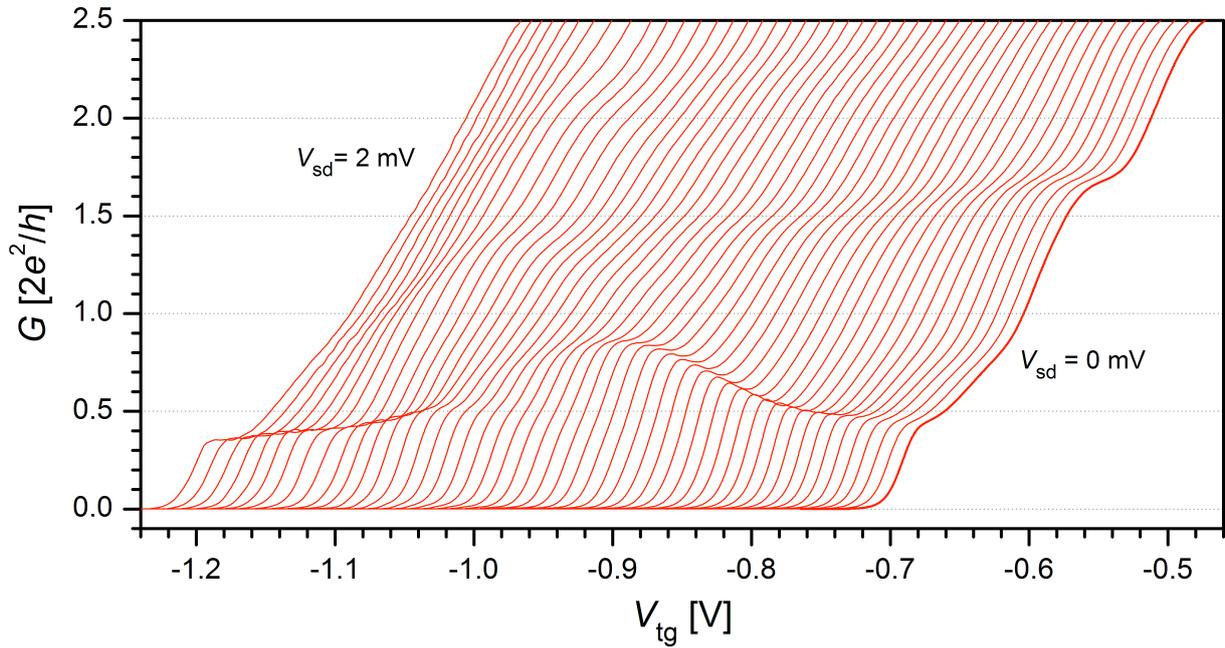**Figure 2.** Differential conductance traces $G(V_{\mathrm{tg}})$ in the régime of weak confinement showing the evolution of the $e^2/h$ plateau when a d.c. bias is applied between the source and drain ohmic contacts. The rightmost (bold) trace was taken with no bias applied, with increasing bias up to $V_{\mathrm{sd}} = 2\mathrm{mV}$ on the far left. (Successive traces have been offset from the $V_{\mathrm{sd}} = 0$ mV trace for clarity.)

Figure 2 shows the $e^2/h$ plateau evolving to $0.85 \times 2e^2/h$ as a small source-drain bias $V_{\mathrm{sd}}$ is applied. This behaviour bears a striking resemblance to that of the 0.7 structure, which likewise evolves to $0.85 \times 2e^2/h$ in the presence of a source-drain bias.[9] The plateau then gives way to another plateau at $0.5 \times 2e^2/h$, which falls with further increase in $V_{\mathrm{sd}}$, eventually reaching $0.25 \times 2e^2/h$ at high biases ($V_{\mathrm{sd}} > 3$ mV).

In order to rule out impurity scattering as the origin of the $e^2/h$ plateau, a differential bias $\Delta V_{\mathrm{sg}}$ was applied between the two split gates to shift the quantum wire laterally. It can be seen in Fig. 3a that the $e^2/h$ plateau persists as the channel is shifted across the 2DEG. The weakening of all the plateaux, especially the higher ones at the extremes may be attributed to a distortion in the shape of the confinement potential when $\Delta V_{\mathrm{sg}}$ is large. The remarkable symmetry of the conductance characteristics with respect to the central channel position confirms that the effects we see are not due merely to a random impurity in the channel.

Spin-incoherent transport is a low-density effect, and we test this by illuminating the sample, raising the carrier density of the 2DEG to some $n_{\mathrm{2D}} \approx 1.7 \times 10^{11}/\mathrm{cm}^2$. Figure 3b shows the conductance characteristics of the device after a brief illumination. It is immediately obvious that the plateau at $e^2/h$ is much weaker than before, and the $2e^2/h$ plateau moreover persists further to the left. The $e^2/h$ plateau penetrates all the way to $V_{\mathrm{tg}} \sim -0.3$ V on the horizontal axis before illumination (Fig. 1), whereas it has all but disappeared by $V_{\mathrm{tg}} \sim -0.7$ V afterwards (Fig. 3b). Further illumination (not shown) eliminates the spin-incoherent plateau entirely, and one is left with nothing but the standard quantised plateaux at integer multiples of $2e^2/h$. This behaviour is, of course, entirely consistent with a phenomenon that manifests at low carrier densities.
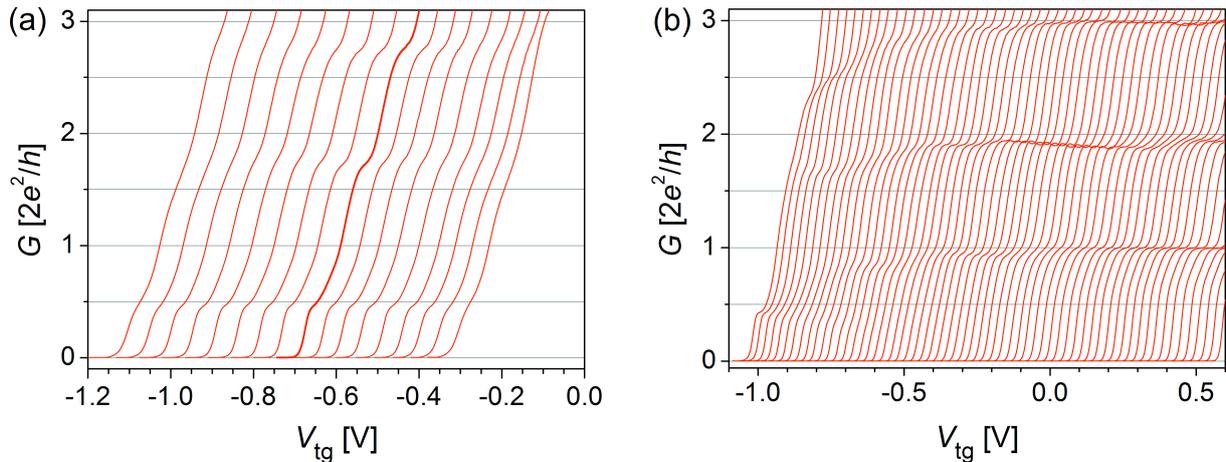
**Figure 3.** **(a)** Behaviour of the $e^2/h$ plateau when the channel is shifted laterally by differentially biasing the split gates. (Successive traces have been offset from the central bold trace, which corresponds to equal bias on the two split gates.) The left- and rightmost traces correspond to a differential bias of $\Delta V_{sg} = \pm 320$ mV. **(b)** Conductance traces of the same device after it has been briefly illuminated with an infrared LED to raise the carrier density.

## 4. Conclusion

A zero-field conductance plateau at $e^2/h$ emerges in a quantum wire of low carrier density when the potential confining the electrons to one dimension is made sufficiently weak. The emergence of this plateau accompanies the suppression of the quantised plateau at $2e^2/h$. Spin-incoherent Luttinger-liquid theory predicts the emergence of such a plateau under these conditions. It evolves to $0.85 \times 2e^2/h$ when a small source-drain bias is applied, like the 0.7 structure. By shifting the channel laterally, it has been shown that the structure is not due to a random scattering centre along the wire. As expected, it weakens and eventually disappears with increasing carrier density as the sample is illuminated. The further characterisation of the spin-incoherent plateau we have undertaken here corroborates our initial report of this phenomenon and is consistent with theoretical predictions thereof.

## References

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