

**Fano Factor Reduction on the 0.7 Conductance Structure of a Ballistic One-Dimensional Wire**

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We have measured the nonequilibrium current noise in a ballistic one-dimensional wire which exhibits an additional conductance plateau at  $0.7 \times 2e^2/h$ . The Fano factor shows a clear reduction on the 0.7 structure, and eventually vanishes upon applying a strong parallel magnetic field. These results provide experimental evidence that the 0.7 structure is associated with two conduction channels that have different transmission probabilities.

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Starting from a high mobility two-dimensional electron gas (2DEG) the fabrication of split-gate devices has allowed the study of one-dimensional (1D) ballistic transport. By applying a voltage  $V_g$  to the split gate it is possible to control the number of transverse modes transmitted through the 1D constriction created by the split gate, and in wires typically shorter than  $1 \mu\text{m}$  the differential conductance characteristics  $G(V_g) = dI/dV$  exhibit [1,2] plateaus quantized at integer multiples of  $2G_0$ , with  $G_0 = e^2/h$ . The factor of 2 arises from the spin degeneracy of the 1D subbands in the constriction.

In addition to the quantized conductance plateaus, an unexpected structure is observed near  $0.7 \times 2G_0$ . This feature, called the 0.7 structure, appeared but was not recognized in early work and subsequent investigations [3] of the effect revealed its fundamental connection with electron spin. Although extensively studied [3–8], one main question remains: Does the 0.7 structure correspond to a perfectly transmitted channel? Here, we give a clear experimental answer to this question by measuring the Fano factor  $F$  of the partition noise of the current.

For conductances  $G \leq 2G_0$  there are two conducting subbands, and to understand their role in the 0.7 structure it is easiest to consider them in a strong magnetic parallel field  $B$ , when they are spin split ( $\uparrow$  and  $\downarrow$ ) and separated by the Zeeman energy; the conductance characteristics  $G(V_g)$  show plateaus at  $G_0$  and  $2G_0$ . As  $B$  is reduced, measurements show [3] that the subband separation reduces linearly, and as  $B \rightarrow 0$  there remains a finite splitting. This finite splitting could be interpreted as a simple zero-field spin splitting, except that (a) the lowest plateau is at  $0.7 \times 2G_0 = 1.4G_0$  rather than at  $G_0$ , and (b) as the temperature is lowered the 0.7 structure weakens. Measurements of an enhanced  $g$  factor as the 1D subbands are depopulated suggests the importance of exchange interactions [3]. Early calculations [9] show that

spin splitting of the subbands is possible, and a later phenomenological model [10] based on the effects of a dynamical local polarization in the constriction has had some success in modeling the 0.7 structure, especially the unusual temperature dependence. More recent microscopic mechanisms [7,8,11] are also based on the spin degree of freedom. In many theoretical descriptions, the 0.7 structure is compatible with there being two conduction channels with different transmission probabilities. To date, there is no definitive proof that this is the case.

Previous noise measurements [12,13] in the vicinity of the 0.7 structure have included thermal noise contributions due to conductance nonlinearities, as well as  $1/f$  noise. Furthermore, the explored energy range (several meV) has exceeded the energy scale of the 0.7 structure [4]. Here, we present noise measurements at sub-Kelvin temperatures, with a wide frequency range that allows us to separate the white noise and  $1/f$  noise. Moreover, a careful analysis of the nonlinearities, which are intrinsic to the 0.7 anomaly [4,8], allows us to extract the thermal noise variations and to obtain the pure partition noise contribution. The deduced Fano factor shows a reduction on the 0.7 structure. In addition, we have measured the evolution of the Fano factor with a parallel magnetic field  $B$ ; at high  $B$  the 0.7 structure moves to  $G_0$  and the Fano factor goes to zero.

The conductance and noise properties of a 1D conductor are well understood using the Landauer-Büttiker (LB) formalism, where a scattering matrix describes a non-interacting system connected to reservoirs. LB theory predicts shot noise suppression for perfectly transmitted or reflected channels [14–16], which has been observed experimentally [17,18]. When conduction is linear (energy independent transmission probabilities), the Fano factor is easy to extract as the ratio of the excess noise  $\Delta S_I(I)$  to the current  $I$ . Unfortunately, this is not the case

for the 0.7 structure which exhibits intrinsic nonlinearities when the 1D wire is biased at energy scale  $eV$  larger than the temperature. Before analyzing our results, we outline how nonlinearities and finite temperature are incorporated into the LB formalism.

One considers two reservoirs (left and right) connected by  $n$  channels with energy-dependent transmission probabilities  $\tau_n(\epsilon)$ . The left and right reservoirs emit electrons at energy  $\epsilon$  with probabilities  $f_l(\epsilon) = f(\epsilon + eV/2)$  and  $f_r(\epsilon) = f(\epsilon - eV/2)$ , where  $f(\epsilon)$  is the Fermi-Dirac distribution. The current through the sample is  $I = \frac{e}{h} \times \int \sum_n \tau_n(\epsilon) [f_l(\epsilon) - f_r(\epsilon)] d\epsilon$ , and the differential conductance  $G$  is an average over  $k_B T$  of the transmission probabilities at normalized energy  $\pm v$ ,

$$G = \frac{dI}{dV} = G_0 \sum_n \frac{1}{2} [\tau_n(v) + \tau_n(-v)], \quad (1)$$

where  $v = eV/2k_B T$ . For energy independent transmission probabilities, we recover the well known expression for the conductance,  $G = G_0 \sum_n \tau_n$ .

The current noise  $S_I$  consists of two terms,  $S_I = S_{I \text{ Part}} + S_{I \text{ Therm}}$ : the first term  $S_{I \text{ Part}}$  is due to partitioning, and the second term  $S_{I \text{ Therm}}$  results from the thermal noise of the current emitted by reservoirs. The two noise contributions are [16,19]

$$S_{I \text{ Part}} = 2G_0 \coth(v) \int \sum_n \tau_n (1 - \tau_n) [f_l - f_r] d\epsilon,$$

$$S_{I \text{ Therm}} = 2G_0 \int \sum_n \tau_n^2 [f_l(1 - f_l) + f_r(1 - f_r)] d\epsilon.$$

For energy independent  $\tau_n$ , the two expressions become

$$S_{I \text{ Part}} = 2G_0 \coth(v) \sum_n \tau_n (1 - \tau_n) \times eV,$$

$$S_{I \text{ Therm}} = 2G_0 \sum_n \tau_n^2 \times [k_B T + k_B T].$$

The excess noise,  $\Delta S_I(I) = S_I(I) - S_I(0)$ , identifies with  $S_{I \text{ Part}} - 4k_B T G(0)$ , which is proportional to the Poissonian noise  $\Delta S_I = F \times S_{I \text{ Poiss}}$  with

$$S_{I \text{ Poiss}} = 2eI \coth(v) - 4k_B T G(0), \quad (2)$$

$$F = \frac{\sum_n \tau_n (1 - \tau_n)}{\sum_n \tau_n}.$$

This peculiar dependence of the Fano factor  $F$  with transmission has been demonstrated [17,18] in shot noise experiments in the linear regime.

In the present case, the  $\tau_n(\epsilon)$  are energy dependent. If  $F$  does not vary too strongly with energy, the following approximate expressions can be derived:

$$S_{I \text{ Part}} = 2eI \coth(v) F(0), \quad (3)$$

$$S_{I \text{ Therm}} = 2G_0 k_B T \sum_n [\tau_n(v)^2 + \tau_n(-v)^2], \quad (4)$$

where  $F(0)$  is the Fano factor averaged over  $k_B T$  around zero energy. This holds if the explored energy scale does not exceed a few  $k_B T$ . The excess noise  $\Delta S_I$  is not proportional to  $S_{I \text{ Poiss}}$ , but  $\Delta S_I = F(0) S_{I \text{ Poiss}} + \Delta S_{I \text{ Therm}}$ , where  $\Delta S_{I \text{ Therm}} = S_{I \text{ Therm}}(I) - S_{I \text{ Therm}}(0)$ . Therefore excess noise measurements are not a direct measure of the Fano factor  $F$ , but also contain thermal noise variations. As  $G$  measures the mean transmission over  $+v$  and  $-v$ , it is not possible to know  $\Delta S_{I \text{ Therm}}$ ; however, we can estimate a lower bound assuming that the  $n$  different modes all have the same transmission probability at zero bias

$$\Delta S_{I \text{ Therm}} \geq 4G_0 k_B T [\tilde{G}(I)^2 - \tilde{G}(0)^2]/n, \quad (5)$$

with  $\tilde{G} = G/G_0$ . We analyze the 0.7 structure assuming that there are two modes ( $n = 2$ ,  $G \leq 2G_0$ ), with equal transmission probabilities at zero bias. Therefore, the corrected noise variations  $\Delta S_{I \text{ Corr}} = \Delta S_I - 2G_0 k_B T [\tilde{G}(I)^2 - \tilde{G}(0)^2]$  can be fitted with

$$\Delta S_{I \text{ Corr}} = F^+ \times S_{I \text{ Poiss}}, \quad (6)$$

where  $F^+$  is a fitting parameter. Later in this Letter (see Fig. 3 below) the measured linear dependence of  $\Delta S_{I \text{ Corr}}$  with  $S_{I \text{ Poiss}}$  validates the above assumptions and allows us to measure  $F^+$  which, because thermal contributions have not been fully taken into account, is an *upper* bound of the real Fano factor  $F$ .

The split-gate device of length  $0.4 \mu\text{m}$  and width  $0.5 \mu\text{m}$  was fabricated over a GaAs/GaAlAs heterostructure where the 2DEG is  $3400 \text{ \AA}$  below the surface, and has a density of  $1.1 \times 10^{11} \text{ cm}^{-2}$  and a mobility of  $2.7 \times 10^6 \text{ cm}^2/\text{Vs}$ . The 1D constriction is biased with a current  $I$  with a  $10 \text{ M}\Omega$  resistance in series, the other side of the sample being grounded. Four-terminal measurements are performed, and the voltage across the sample is amplified through two independent lines using two low-noise pre-amplifiers (NF Electronics LI75A) with a total gain of  $1.042 \times 10^4$ . The cross-correlated voltage noise [18]  $S_V(I, \nu)$  is measured with  $\nu$  in the  $9.1\text{--}15.5 \text{ kHz}$  range. By measuring the Johnson-Nyquist noise for temperatures in the range  $T = 200\text{--}700 \text{ mK}$ , the noise accuracy has been checked to within 1%. We define  $V$  as the voltage across the constriction due to current biasing, taking into account the series resistance.

Simultaneous with the noise measurements, we measure the differential resistance  $R(V_g) = dV/dI$  at  $108 \text{ Hz}$  with a  $0.1 \text{ nA}$  rms excitation current. Figure 1(a) shows the conductance,  $G(V_g) = 1/[R(V_g) - R_S(B)]$ , of the sample for different temperatures; the 0.7 structure is more pronounced at higher temperatures, a hallmark of this anomaly. A series resistance  $R_S = 1730 \Omega$  was used to align the first quantized plateau at  $2G_0$ . Figure 1(b) shows the  $G(V_g)$  characteristics at  $T = 550 \text{ mK}$  in different parallel magnetic fields  $B$ ; as  $B$  approaches  $8 \text{ T}$  the 0.7 structure evolves into the spin-split plateau at  $G_0$ . The series resistance  $R_S(B)$  increases with  $B$  field, and from

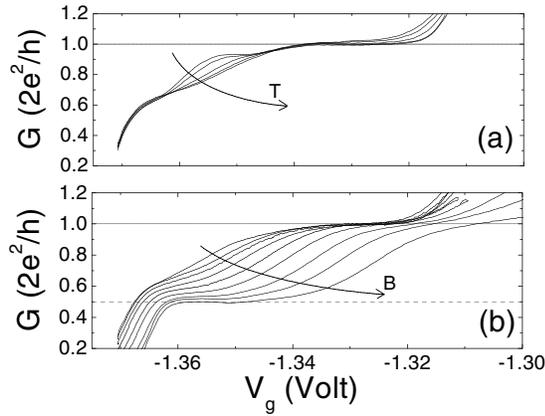


FIG. 1. (a) Conductance characteristics  $G(V_g)$  at  $T = 273, 360, 515, 666,$  and  $779$  mK. With increasing temperature the resonance at  $0.9 \times 2G_0$  disappears, whereas the  $0.7$  structure (in this case close to  $0.65 \times 2G_0$ ) becomes more pronounced. (b)  $G(V_g)$  at  $T = 560$  mK in parallel fields  $B = 0$  to  $8$  T, in steps of  $1$  T. With increasing  $B$ , the  $0.7$  structure evolves into the spin-split plateau at  $G_0$ .

the Shubnikov–de Haas oscillations of the 2DEG (at  $V_g = 0$ ) we estimate a misalignment of  $4.15^\circ$  between the  $B$  field and the plane of the 2DEG. The measured perpendicular component of  $B$  is consistent with the  $R_S(B)$  used to align the plateaus. At the maximum field ( $8$  T), the Landau level filling factor is  $7.85$ , and we believe that this does not affect our findings.

Having identified the  $0.7$  structure, we now focus on the noise properties. From the measured  $S_V(I, \nu)$ , we deduce the current noise power spectrum  $S_I(I, \nu) = [1 + (2\pi RC_S \nu)^2] S_V(I, \nu) / R^2$  where the shunt capacitance  $C_S = 444$  pF is measured independently.  $S_I(I, \nu)$  contains three distinct parts:  $S_I(I, \nu) = S_{I0}(\nu) + S_{1/f}(I) / \nu + S_I(I)$ .  $S_{I0}(\nu)$  is the current noise applied to the sample due to the polarization resistance and current noise of the amplifiers, and does not depend on  $R(V_g)$  or the current  $I$ . The  $1/f$  noise  $S_{1/f}(I) / \nu$  is zero when the sample is not current biased.  $S_I(I)$  is the physical noise of the 1D constriction we wish to obtain, and contains both partition noise and thermal noise.

Figure 2 shows  $\Delta S_I(I, \nu) = S_I(I, \nu) - S_I(0, \nu)$  as a function of the frequency  $\nu$ , at low frequency to reveal  $1/f$  noise. The frequency dependence is fitted with  $\Delta S_I(I, \nu) = S_{1/f}(I) \times \nu^\alpha + \Delta S_I(I)$ , where  $\alpha$ ,  $S_{1/f}(I)$ , and  $\Delta S_I(I)$  are free parameters. In the low frequency range, the fit is most sensitive to  $\alpha$  which is found to be  $\alpha = -1.007 \pm 0.005$ ; this value does not change with current, temperature, or the frequency range. We fix  $\alpha = -1$ ; in the measured frequency range,  $9.1$ – $15.5$  kHz, an error of  $0.005$  in this exponent leads to an error of less than  $0.5\%$  in  $\Delta S_I(I)$ .  $S_{1/f}(I)$  is found to be roughly proportional to  $S_{I\text{Poiss}}$  rather than to  $I^2$ . The inset of Fig. 2 shows the ratio  $S_{1/f}(I) / S_{I\text{Poiss}}$  as a function of the zero bias differential conductance  $G(V = 0)$ . The amplitude of

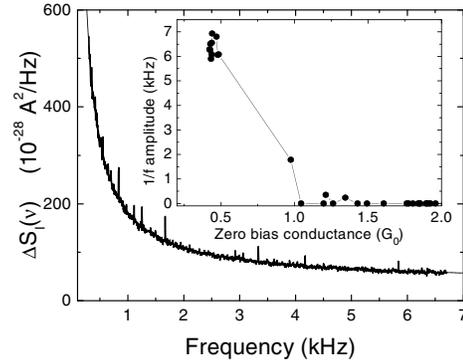


FIG. 2. Typical current noise power spectrum variation as a function of the frequency for  $I = 10$  nA. The solid line is a fit of white noise plus  $1/f$  noise. The inset shows the ratio  $S_{1/f}(I) / S_{I\text{Poiss}}$  as a function of the zero bias conductance.

$S_{1/f}(I)$  falls to zero near the  $0.7$  structure because the transconductance  $dG/dV_g$  does the same. The reduction of the  $1/f$  noise leads to an apparent noise reduction, which is not a suppression of the partition noise.

With the  $1/f$  noise characterized and subtracted, we determine the Fano factor using the corrected noise variation given in Eq. (6). For each determination, we measure the noise at  $\sim 500$  mK by varying the bias current  $I$  from  $-10$  to  $+10$  nA in steps of  $1$  nA. The uncertainty in  $\Delta S_I(I)$  is  $\sim 10^{-29}$  A<sup>2</sup>/Hz. Close to pinch off, there is a self-biasing effect due to the current, which leads to an asymmetry in the noise plot that disappears for smaller transconductances. The Fano factor is determined using both  $+I$  and  $-I$  to counter this effect.

Figure 3 shows both the raw excess noise  $\Delta S_I$  ( $\circ$ ) and the corrected excess noise  $\Delta S_{I\text{Corr}}$  ( $\bullet$ ) on the  $0.7$  structure at  $460$  mK with  $G(0) = 0.71 \times 2G_0$ . The uncorrected measurement  $\Delta S_I$  gives an overestimated  $F^+ = 0.28$ , in

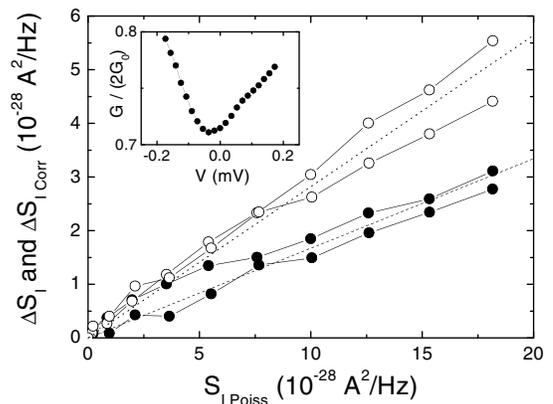


FIG. 3. Excess noise without ( $\circ$ ) and with ( $\bullet$ ) thermal corrections, as a function of the Poissonian noise at  $T = 460$  mK with  $G(0) = 0.71 \times 2G_0$ . The dotted line fit to the uncorrected data  $\Delta S_I$  gives an overestimated  $F^+ = 0.28$ . The dashed line fit to  $\Delta S_{I\text{Corr}}$  gives  $F^+ = 0.17$ , an upper bound closer to  $F$ . The inset shows  $G$  as a function of  $V$ .

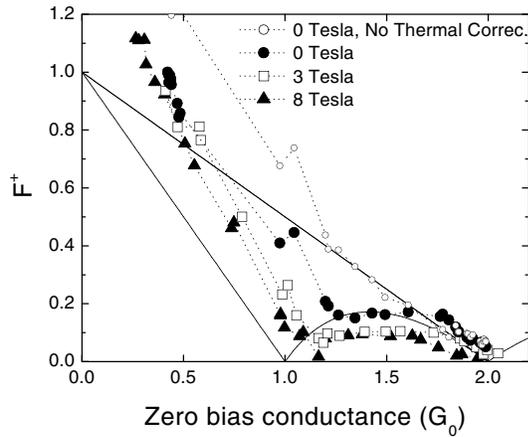


FIG. 4. Upper bound of the Fano factor at  $T = 460$  mK without thermal corrections ( $\circ$ ), plotted versus the zero bias conductance. The solid circles ( $\bullet$ ) show the same measurements as the open circles, but with thermal corrections applied. Squares ( $\square$ ) show the Fano factor with thermal corrections at  $T = 610$  mK and  $B = 3$  T, and the triangles ( $\blacktriangle$ ) are similarly corrected data at  $T = 580$  mK and  $B = 8$  T.

apparent agreement with the Fano factor expected for two channels with the same transmission probability ( $F \approx 1 - 0.71$ ). However, if thermal corrections are taken into account, the linear variation of  $\Delta S_{I \text{ Corr}}$  with  $S_{I \text{ Poiss}}$  gives  $F^+ = 0.17$ , much smaller than 0.29. There is a clear *reduction* of the Fano factor on the 0.7 structure [20]. The accuracy on  $F^+$  is  $\pm 0.025$ , determined by both the fit and by repetition of the measurement at fixed  $V_g$ . The inset of Fig. 3 shows the variation of the conductance with the bias on the 0.7 structure. The observed nonlinearities are similar to those observed previously [4,8].

Figure 4 presents the central result of our Letter, where the measured  $F^+$  are plotted as a function of the zero bias conductance. The two solid lines in Fig. 4 show the expected  $F$  when there is full spin splitting ( $F \rightarrow 0$  at  $G_0$  and  $2G_0$ ) or no spin splitting ( $F \rightarrow 0$  at  $2G_0$ ). The open circles ( $\circ$ ) are  $F^+$  obtained when thermal corrections are not taken into account; these data do not show a reduction at the 0.7 structure and follow the Fano factor for the case of no spin splitting (the upper straight line). As explained previously, because the system is nonlinear these points are overestimated upper bounds of  $F$ . The solid circles ( $\bullet$ ) in Fig. 4 are obtained from the same data as the open circles, but with the nonlinearities taken into account using Eq. (6); in contrast to the uncorrected data there is a reduction close to the 0.7 structure. Whereas one cannot calculate the transmission of the two modes from  $F^+$ , one can show that they are not identical: we use thermal corrections assuming identical zero bias transmissions of the two channels, thus  $F^+$  should be above the upper straight line of Fig. 4. As  $F^+$  is below this line, one can conclude that *the two channels do not have the same transmission on the 0.7 structure*. Such

information can be obtained only from simultaneous noise and conductance measurements. The upper bound Fano factors at  $B = 3$  and 8 T are plotted in Fig. 4 as squares ( $\square$ ) and triangles ( $\blacktriangle$ ), respectively. For both magnetic fields the suppression of the Fano factor is more developed than for  $B = 0$  and the conductance at which the reduction occurs shifts towards  $G_0$ . This high  $B$  field result is consistent with a Zeeman splitting of the  $\uparrow$  and  $\downarrow$  1D subbands. The evolution of the reduction with  $B$  indicates that the two channels having different transmissions at zero field may have different spin orientations.

In conclusion, we have performed careful measurements of the Fano factor which shows a clear reduction on the 0.7 structure. This reduction demonstrates for the first time that the 0.7 structure is accompanied with two conducting channels with different transmission probabilities. The evolution of the reduction with a parallel magnetic field  $B$  supports the picture of two channels with different spin orientations. In the future it would be interesting to measure the evolution of the Fano factor reduction with temperature, in order to understand the underlying mechanism that leads to these spin dependent transmissions.

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