

Experimental Test of the High-Frequency Quantum Shot Noise Theory in a Quantum Point Contact

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We report on direct measurements of the electronic shot noise of a quantum point contact at frequencies ν in the range 4–8 GHz. The very small energy scale used ensures energy independent transmissions of the few transmitted electronic modes and their accurate knowledge. Both the thermal energy and the quantum point contact drain-source voltage V_{ds} are comparable to the photon energy $h\nu$ leading to observation of the shot noise suppression when $V_{ds} < h\nu/e$. Our measurements provide the first complete test of the finite frequency shot noise scattering theory without adjustable parameters.

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Pauli's exclusion principle has striking consequences on the properties of quantum electrical conductors. In an ideal quantum wire, it is responsible for the quantization of the conductance by requiring that at most one electron (or two for spin degeneracy) occupies the regularly time-spaced wave packets emitted by the contacts and propagating in the wire [1]. Concurrently, at zero temperature, the electron flow is noiseless [2,3] as can be observed in ballistic conductors [4–6]. In more general quantum conductors, static impurities diffract the noiseless electrons emitted by the contacts. This results in a partition of the electrons between transmitted or reflected states, generating quantum shot noise [1–3,7,8]. However, Pauli's principle possesses more twists to silence electrons. At finite frequency ν , detection of current fluctuations in an external circuit at zero temperature requires emission of photons corresponding to a finite energy cost $h\nu$ [9]. For drain-source contacts biased at voltage V_{ds} , a sharp suppression is expected to occur when the photon energy $h\nu$ is larger than eV_{ds} as an electron emitted by the source cannot find an empty state in the drain to emit such a photon [9–11]. Another striking consequence of Pauli's principle is the prediction of nonclassical photon emission for a conductor transmitting only one or few electronic modes. It has been shown that in the frequency range $eV_{ds}/2h < \nu < eV_{ds}/h$, the population of a photon mode obeys a sub-Poissonian statistics inherited from the electrons [12]. Investigating quantum shot noise in this high-frequency regime using a quantum point contact (QPC) to transmit few modes is thus highly desirable.

The first step is to check the validity of the above prediction based on a noninteracting picture of electrons. For 3D or 2D wide conductors with many quantum channels that are good Fermi liquids, one expects this noninteracting picture to work well. Indeed, the eV_{ds}/h singularity has been observed in a 3D diffusive wire in the shot noise derivative with respect to bias voltage [13]. However, for low dimensional systems like 1D wires or

conductors transmitting one channel or a few channels, electron interactions give nontrivial effects. Long 1D wires defined in 2D electron gas or single wall carbon nanotubes become Luttinger liquids. Long QPCs exhibit a 0.7 conductance anomaly [14] and a low frequency shot noise [15] compatible with Kondo physics [16]. Consequently, new characteristic frequencies may appear in shot noise reflecting electron correlations. Another possible failure of the noninteracting finite frequency shot noise model could be the backaction of the external circuit. For high impedance circuits, current fluctuations imply potential fluctuations at the contacts [17]. Also, the finite time required to eliminate the sudden drain-source charge buildup after an electron has passed through the conductor leads to a dynamical Coulomb blockade for the next electron to tunnel. A peak in the shot noise spectrum at the electron correlation frequency $1/e$ is predicted for a tunnel junction connected to a capacitive circuit [18]. Other time scales may also be expected which affect both conductance [19] and noise [20] due to long range Coulomb interaction or electron transit time. These effects have been recently observed for the conductance [21].

The present work aims at giving a clear-cut test of the noninteracting scattering theory of finite frequency shot noise using a quantum point contact transmitting only one or two modes in a weak interaction regime. It provides the missing reference mark to which further experiments in strong interaction regime can be compared in the future. We find the expected shot noise suppression for voltages $\leq h\nu/e$ in the whole 4–8 GHz frequency range. The data taken for various transmissions perfectly agree with the finite temperature, noninteracting model with no adjustable parameter. In addition, to provide a stringent test of the theory, the technique developed is the first step toward the generation of nonclassical photons with QPCs in the microwave range [12]. The detection technique uses cryogenic linear amplification followed by room temperature

detection. The electron temperature much lower than $h\nu/k_B$, the small energy scale used ($eV_{ds} \ll 0.02E_F$) ensuring energy independent transmissions, the high detection sensitivity, and the absolute calibration allow for direct comparison with theory without adjustable parameters. Our technique differs from the recent QPC high-frequency shot noise measurements using on-chip quantum dot detection in the 10–150 GHz frequency range [22]. Although most QPC shot noise features were qualitatively observed validating this promising method, the lack of independent determination of the QPC-quantum dot coupling, and the large voltage used from 0.05 to $0.5E_F$ making QPC transmissions energy dependent, prevents quantitative comparison with shot noise predictions. However, quantum dot detectors can probe the vacuum fluctuations via the stimulated noise, while the excess noise detected here only probes the emission noise [9,10].

The experimental setup is represented in Fig. 1. A two-terminal conductor made of a QPC realized in a two-dimensional electron gas (2DEG) in a GaAs/GaAlAs heterojunction is cooled at 65 mK by a dilution refrigerator and inserted between two transmission lines. The sample characteristics are a 35 nm deep 2DEG with $36.7 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ mobility and $4.4 \times 10^{15} \text{ m}^{-2}$ electron density. Interaction effects have been minimized by using a very short QPC showing no sign of 0.7 conductance anomaly. In order to increase the sensitivity, we use the microwave analog of an optical reflective coating. The contacts are separately connected to 50Ω coaxial transmission lines via two quarter wavelength impedance adapters, raising the effective input impedance of the detection lines to 200Ω over a one octave bandwidth centered on 6 GHz. The 200Ω electromagnetic impedance is low enough to prevent dynamical Coulomb blockade but large enough for good current noise sensitivity. The transmitted signals are then amplified by two cryogenic low noise amplifiers (LNA) with $T_{\text{noise}} \approx 5 \text{ K}$. Two rf circulators, thermalized at mixing chamber temperature, protect the sample from the current noise of the LNA and ensure a circuit environment at base temperature. After further amplification and eventually narrow bandpass filtering at

room temperature, current fluctuations are detected using two calibrated quadratic detectors whose output voltage is proportional to noise power. Up to a calculable gain factor, the detected noise power contains the weak sample noise on top of a large additional noise generated by the cryogenic amplifiers. In order to remove this background, we measure the excess noise $\Delta S_I(\nu, T, V_{ds}) = S_I(\nu, T, V_{ds}) - S_I(\nu, T, 0)$. Practically, this is done by applying a 93 Hz $0-V_{ds}$ square-wave bias voltage on the sample through the dc input of a bias- T and detecting the first harmonic of the square-wave noise response of the detectors using lock-in techniques. In terms of noise temperature referred to the 50Ω input impedance, an excess noise $\Delta S_I(\nu, T, V_{ds})$ gives rise to an excess noise temperature

$$\Delta T_n^{50\Omega}(\nu, T, V_{ds}) = \frac{Z_{\text{eff}} Z_{\text{sample}}^2 \Delta S_I(\nu, T, V_{ds})}{(2Z_{\text{eff}} + Z_{\text{sample}})^2}. \quad (1)$$

Equation (1) demonstrates the advantage of impedance matching: in the high source impedance limit $Z_{\text{sample}} \gg Z_{\text{eff}}$, the increase in noise temperature due to shot noise is proportional to Z_{eff} . Our setup ($Z_{\text{eff}} = 200\Omega$) is thus 4 times more efficient than a direct connection of the sample to standard 50Ω transmission lines. Finally, the QPC differential conductance G is simultaneously measured through the dc input of the bias- T using low frequency lock-in technique.

The very first step in the experiment is to characterize the QPC. The inset of Fig. 4 shows the differential conductance versus gate voltage when the first two modes are transmitted. As the experiment is performed at zero magnetic field, the conductance exhibits plateaus quantized in units of $G_0 = 2e^2/h$. The short QPC length (80 nm) leads to a conductance very linear with the low bias voltage used ($\delta G/G \leq 6\%$ for $V_{ds} \leq 80 \mu\text{V}$ for $G \approx 0.5G_0$). It is also responsible for a slight smoothing of the plateaus. Each mode transmission is extracted from the measured conductance (open circles) by fitting with the saddle point model (solid line) [23].

We then set the gate voltage to obtain a single mode at half transmission corresponding to maximum electron partition ($G \approx 0.5G_0$). Figure 2 shows typical excess noise measured at frequencies 4.22 and 7.63 GHz and bandwidths 90 and 180 MHz. We note a striking suppression of shot noise variation at low bias voltage, and that the onset of noise increases with the measurement frequency. This is in agreement with the photon suppression of shot noise in a noninteracting system. The expected excess noise reads

$$\Delta S_I(\nu, T, V_{ds}) = 2G_0 \sum_i D_i (1 - D_i) \left(\frac{h\nu - eV_{ds}}{e^{(h\nu - eV_{ds})/k_B T} - 1} + \frac{h\nu + eV_{ds}}{e^{(h\nu + eV_{ds})/k_B T} - 1} - \frac{2h\nu}{e^{h\nu/k_B T} - 1} \right). \quad (2)$$

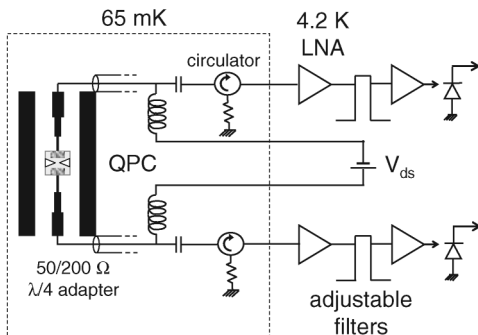


FIG. 1. Schematic diagram of the measurement setup. See text for details.

It shows a zero temperature singularity at $eV_{ds} = h\nu$: $\Delta S_I(\nu, T, V_{ds}) = 2G_0 \sum_i D_i(1 - D_i)(eV_{ds} - h\nu)$ if $eV_{ds} > h\nu$ and 0 otherwise. At finite temperature, the singularity is thermally rounded. At high bias ($eV_{ds} \gg h\nu, k_B T$), Eq. (2) gives an excess noise

$$\Delta S_I(\nu, T, V_{ds}) = 2G_0 \sum_i D_i(1 - D_i)(eV_{ds} - eV_0), \quad (3)$$

with

$$eV_0 = h\nu \coth(h\nu/2k_B T). \quad (4)$$

In the low frequency limit, the threshold V_0 characterizes the transition between thermal noise and shot noise ($eV_0 = 2k_B T$), whereas in the low temperature limit, it marks the onset of photon suppressed shot noise ($eV_0 = h\nu$). As shown in Fig. 2, V_0 is determined by the intersection of the high bias linear regression of the measured excess noise and the zero excess noise axis. Figure 3 shows V_0 for eight frequencies spanning in the 4–8 GHz range for $G \approx 0.5G_0$. Equation (4) gives a very good fit to the experimental data. The only fitting parameter is the electronic temperature $T_e = 72$ mK, very close to the fridge temperature $T_{\text{fridge}} = 65$ mK. We will show that electron heating can account for this small discrepancy.

To get a full comparison with theory, we now investigate the influence of the transmissions of the first two electronic modes of the QPC. To do so, we repeat the same experiment at fixed frequency (here we used a 5.4–5.9 GHz filter) for different sample conductances. The noise suppression at $V_{ds} \leq h\nu/e$ is the only singularity we observe, independently of the QPC conductance G . Figure 4 shows the derivative with respect to eV_{ds} of the excess noise $d\Delta S_I/d(eV_{ds})$ deduced from the excess noise temperature

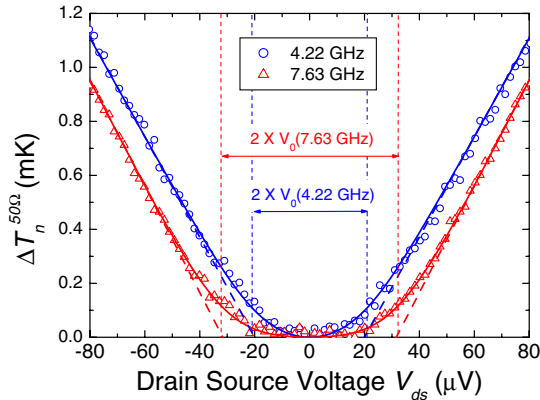


FIG. 2 (color online). Excess noise temperature as a function of bias voltage, measured at 4.22 GHz (open circles) and 7.63 GHz (open triangles). The dashed lines represent the linear fits to the data, from which the threshold V_0 is deduced. The solid lines represent the expected excess noise $S_I(\nu, T_e(V_{ds}), V_{ds}) - S_I(\nu, T_e(0), 0)$, using $T_e(V_{ds})$ obtained from Eq. (3). The frequency dependent coupling is the only fitting parameter.

measured between 50 and 80 μV . This energy range is chosen so that eV_{ds} is greater than $h\nu$ by at least $5k_B T_{\text{fridge}}$ over the entire frequency range. The data agree qualitatively with the expected $D(1 - D)$ dependence of pure shot noise, showing maxima at conductances $G = 0.5G_0$ and $G = 1.5G_0$, and minima at conductances $G = G_0$ and $G = 2G_0$. The short QPC is responsible for the nonzero minima as, when the second mode starts to transmit electrons, the first one has not reached unit transmission (inset of Fig. 4). However, Eq. (2) is not compatible with a second maximum higher than the first one, which is due to electron heating. The dimensions of the 2DEG being much larger than the electron-electron energy relaxation length, but much smaller than electron-phonon energy relaxation length, there is a gradient of electronic temperature from the QPC to the Ohmic metallic contacts assumed at the fridge temperature. Combining the dissipated power IV_{ds} with the Wiedemann-Franz law, one gets [5,24]

$$T_e^2 = T_{\text{fridge}}^2 + \frac{24}{\pi^2} \frac{G}{G_m} \left(1 + \frac{2G}{G_m}\right) \left(\frac{eV_{ds}}{2k_B}\right)^2, \quad (5)$$

where G_m stands for the *total* conductance of the 2D leads, estimated from measurements to be $12 \text{ mS} \pm 20\%$. The increased noise temperature is then due to both shot noise and to the increased thermal noise. For a fridge temperature of 65 mK and $G = G_0/2$, the electronic temperature will increase from 69 to 77 mK as V_{ds} increases from 50 to 80 μV . This accounts for the small discrepancy between the fridge temperature and the electron temperature deduced from the variation of V_0 with frequency. As G increases, the effect is more important, as can be seen both in Fig. 4 and Eq. (3). The solid line in Fig. 4 gives the average derivative with respect to eV_{ds} of the total expected excess noise $S_I(\nu, T_e(V_{ds}), V_{ds}) - S_I(\nu, T_e(0), 0)$, using the attenuation of the signal as a free parameter.

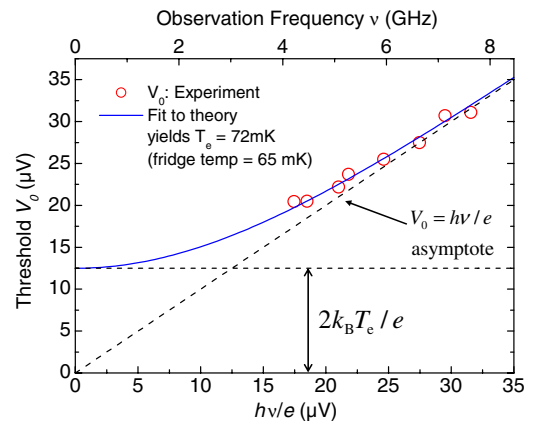


FIG. 3 (color online). Onset V_0 as a function of the observation frequency. The experimental uncertainty corresponds to the size of the symbols. The dashed lines correspond to the low ($eV_0 = 2k_B T$) and high ($eV_0 = h\nu$) frequency limits, and the solid line is a fit to theory, with the electronic temperature as the only fitting parameter.

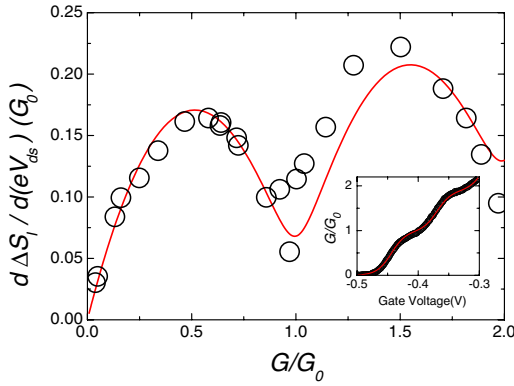


FIG. 4 (color online). Open circles: $d\Delta S_I/d(eV_{ds})$ deduced from $\Delta T_n^{50\Omega}$. Solid line: theoretical prediction. The only fitting parameter is the microwave attenuation. The experimental uncertainty corresponds to the size of the symbols. Inset: open circles are the conductance of the QPC as a function of gate voltage; the solid line is the fit to the saddle point model [23].

The agreement is quite satisfactory, given the accuracy of the saddle point model description of the QPC transmission. We find a 4.7 dB attenuation, which is in good agreement with the expected 4 ± 1 dB deduced from calibration of the various elements of the detection chain. Moreover, the voltage dependent electron temperature obtained from Eq. (3) can also be used to evaluate $S_I(\nu, T_e(V_{ds}), V_{ds}) - S_I(\nu, T_e(0), 0)$ as a function of V_{ds} at fixed sample conductance $G = 0.5G_0$. The result, as shown by the solid lines of Fig. 2, is in excellent agreement with experimental observations.

In conclusion, we performed the first direct measurement of the finite frequency shot noise of the simplest mesoscopic system, a QPC. An accurate comparison of the data with noninteracting shot noise predictions has been done showing perfect quantitative agreement. Even when a single mode is transmitted, no sign of deviation related to interaction was found, as expected for the experimental parameters chosen for this work. We have also shown that accurate and reliable high-frequency shot noise measurements are now possible for conductors with impedance comparable to the conductance quantum. This opens the way to high-frequency shot noise characterizations of carbon nanotubes, quantum dots, or quantum hall samples in a regime where microscopic frequencies are important and will encourage further theoretical work in this direction. Our setup will also allow one to probe the statistics of photons emitted by a phase coherent single mode conductor.

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