Shot Noise in Fabry-Perot Interferometers Based on Carbon Nanotubes

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We report on shot noise measurements in carbon nanotube based Fabry-Perot electronic interferometers. As a consequence of quantum interference, the noise power spectral density oscillates as a function of the voltage applied to the gate electrode. The quantum shot noise theory accounts for the data quantitatively and allows us to determine directly the transmissions of the two channels characterizing the nanotube. In the weak backscattering regime, the dependence of the noise on the backscattering current is found weaker than expected, pointing either to electron-electron interactions or to weak decoherence.

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The quantum character of transport in mesoscopic conductors qualitatively modifies the behavior of both the average and the fluctuations of the current that flows through them [1]. If interactions between charge carriers can be neglected, an accurate description of such conductors is given by a set of transmission probabilities $\{D_n\}$ which characterize the scattering of carriers. This description has been tested successfully for current noise in various conductors, ranging from quantum point contacts (QPCs) [2], in which one can isolate one spin degenerate channel with a single tunable barrier, to superconducting/normal/superconducting (S/N/S) structures [3–5]. In coherent few channel double barrier systems, quantum interferences have also been shown to modulate the transmissions [6]. However, shot noise in such Fabry-Perot electronic interferometers has not been investigated experimentally so far.

Single wall carbon nanotubes (SWNTs) can display a Fabry-Perot behavior [7,8] when their coupling to metallic reservoirs is high enough. The K-K' orbital modes (natural basis) can be coupled and have in general two different reflection phase shifts [7]. They reduce to two transmissions $\{D_1, D_2\}$ in the eigenbasis. In SWNT based Fabry-Perot interferometers, the combined measurement of noise and conductance should allow a full characterization of any nanotube, D_1 and D_2 being related to the coupling and the reflection phase shifts of the K-K' modes. Early measurements of current noise in carbon nanotubes have shown that it was dominated by extrinsic $1/f$ noise below 100 kHz [9]. For this reason, few shot noise measurements are available. In Ref. [10], the Coulomb blockade regime was investigated and significant departures from the predictions of the noninteracting theory were found. In Ref. [11], very low shot noise was found in a bundle of SWNTs highly coupled to normal reservoirs, pointing to ballistic transport. Very recently, the high bias shot noise has been investigated in gated carbon nanotube based Fabry-Perot interferometers [12] and signatures of electron-electron interactions have been found.

In this Letter, we report on shot noise measurements in gated SWNTs in the low energy Fabry-Perot regime [13]. This allows a reliable quantitative comparison with the quantum shot noise theory. The measurement frequency, ranging from 400 kHz to 5 MHz, and the small current (<1.5 nA) make the intrinsic (shot) noise dominate [14]. We find that the nanotube is to a large extent well described by a noninteracting scattering theory accounting for the so-called K-K' orbital degeneracy commonly found in NTs [15]. We present two samples. For sample A, assuming full orbital degeneracy allows to account for the noise data. Near Fabry-Perot resonances, for which the transmission is close to 1, shot noise is strongly suppressed, as expected. However, its dependence with the backscattering current is found weaker than expected. For sample B, we find no orbital degeneracy from the combined shot noise and conductance measurements and we can extract the gate dependence of the two transmissions.

The SWNTs are grown by chemical vapor deposition with a standard recipe [8]. They are localized with respect to alignment markers with an atomic force microscope (AFM). The contacts are made by e-beam lithography followed by evaporation of a 70 nm-thick Pd layer at a pressure of 10^{-8} mbar. The highly doped Si substrate covered with 500 nm SiO_2 is used as a backgate at low temperatures. The typical spacing between the Pd electrodes is 500 nm as shown in Fig. 1. The two probe resistance of the obtained devices ranges from 10 to 200 kΩ at room temperature. For some samples, a third probe made of a multiwall carbon nanotube (MWNT) is placed with the help of the AFM tip on the top of the SWNT. Although the samples presented in this paper are of this kind, as shown in Fig. 1, the coupling of the SWNT with the MWNT is very weak and can be omitted in the diagram. The basic diagram of the circuit used to measure noise is displayed in Fig. 1. The biasing is done by means of two 20 kΩ/200Ω divider bridges mounted on a printed circuit board (PCB) supporting the sample and placed at the lowest temperature (1.5 K unless specified). One of

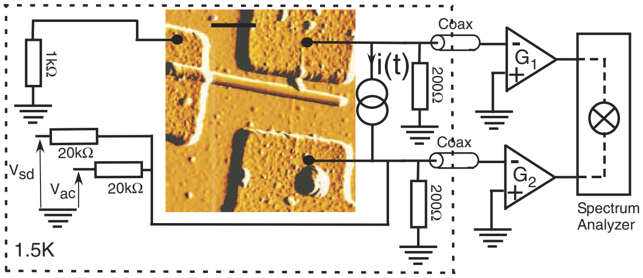

FIG. 1 (color online). Diagram of the circuit and AFM picture of one of the samples (sample A) presented in this Letter. The MWNT is shunted by a 1 kΩ resistor placed on the PCB. The bar is 500 nm.

them is used for dc biasing. The other one is used for ac measurement of the conductance at about 2 kHz. The current fluctuations in the NT result in voltage fluctuations along the two 200Ω. The two signals are fed into two coaxial lines and separately amplified at room temperature by two independent sets of low noise amplification stages (gains: $G_1 = 6182 \pm 50$, $G_2 = 4398 \pm 30$, amplifiers NF SA-220F5). The two signals are subsequently fed into the two inputs of a spectrum analyzer which calculates the cross correlation spectrum. This technique allows us to average out the voltage noise of the amplifiers and to reduce the contribution of their current noise [16]. Each noise point corresponds to 4 averaging runs of 60 000 spectra with a frequency span of 78.125 kHz (1601 frequency points) and a center frequency ranging from 1 to 10 MHz. This averaging allows to get the required sensitivity of about 5×10^{-23} V^2/Hz. The cutoff frequency is about 4 MHz. The calibration of each detection line is achieved by means of the temperature dependence of the Johnson-Nyquist noise of the 200Ω resistors in the range 1.5–15 K, through the autocorrelations of the current in each amplifier line. At the frequency of 2.221 MHz where most measurements have been done, the total power gain attenuation of the noise setup is 0.75, in very good agreement with the expected attenuation of 0.76 for a reasonable estimate of 200 pF for the total capacitance of the coaxial lines and the input capacitance of the amplifiers.

The circuit diagram (see Fig. 1) yields the relationship between the voltage correlations $S_{\rm cross} = \langle V_1 V_2^* \rangle$ and the different current noise sources which contribute to the voltage fluctuations along the 200Ω resistors R_1 and R_2. It turns out that the main contributions to these fluctuations arise from the current noise S_I in the SWNT, the current noise of the two low noise preamplifiers respectively S_{n1} and S_{n2} and the Johnson-Nyquist noise S_1 and S_2 of R_1 and R_2, respectively. The complex value of $S_{\rm cross}$ is

$$\begin{aligned} S_{\rm cross} &= |\alpha|^{-2} Z_1 Z_2^* [-S_I + S_{\rm off}], \\ S_{\rm off} &= \frac{Z_1}{R_{\rm NT}}(S_{n1} + S_1) + \frac{Z_2^*}{R_{\rm NT}}(S_{n2} + S_2), \end{aligned} \tag{1}$$

with $\alpha = 1 + (Z_1 + Z_2)/R_{\rm NT} + Z_1/R_{B1} + Z_1 Z_2/(R_{\rm NT} R_{B1})$, where $R_{\rm NT} = h/(4e^2 D)$ is the resistance of the SWNT, R_{B1} is the bias resistor of line 1, $Z_{1(2)} = R_{1(2)}/(1 + 2\pi j R_{1(2)} C_{1(2)} f)$, $C_{1(2)}$ the total capacitance in parallel with $R_{1(2)}$ and f the frequency. The linear behavior of the offset noise $S_{\rm off}$ as a function of D for sample A is shown in Fig. 2(a). A linear fit gives $S_{\rm off} = (0.05 \pm 1.01 + 10.44D \pm 1.27D) \times 10^{-27}$ A^2/Hz. Although the order of magnitude is correct, confirming that most of the signal comes from the noise of the NT, this is only in qualitative agreement with the expected offset of $21.1D \times 10^{-27}$ A^2/Hz. We think that this can be explained by residual correlations arising from partial shielding of the parasitic signals in the band 0–10 MHz.

The gray scale plot of the nonlinear conductance dI/dV of sample A as a function of the gate voltage V_G and the source-drain bias $V_{\rm SD}$ is displayed on Fig. 2(c). It exhibits the characteristic "checkerboard" pattern of a Fabry-Perot interferometer [7,8]. As shown on the side scale of the gray scale plot, the conductance is modulated from $0.3 \times 4e^2/h$ to about $0.95 \times 4e^2/h$. One extracts a value of 3.4 meV for the level spacing. This value is in good agreement with the lithographically defined spacing between the Pd electrodes of 500 nm, which yields $h v_F / 2L = 3.34$ meV for a Fermi velocity of 8.10^5 m/s. This value corresponds to the full SWNT length between the Pd contacts. Therefore, the MWNT contact does not split the SWNT into two pieces, as previously reported [17]. The irregularity of the pattern is likely due to weak scattering.

The lower panel of Fig. 3 shows the bias dependence of the current cross-correlations of sample A, for gate volt-

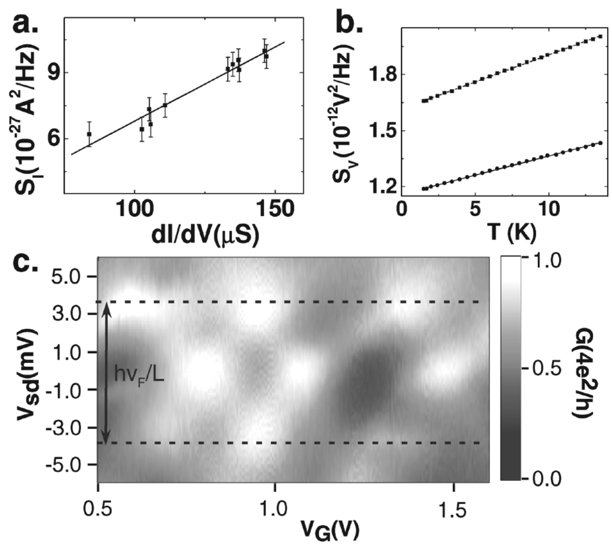

FIG. 2. (a) Calibration of the background noise at 1.5 K as a function of the differential conductance dI/dV of the nanotube for sample A. (b) Calibration of the autocorrelations of the current in each 200Ω resistor for each amplifier line. (c) Gray scale plot of the nonlinear conductance for sample A. The characteristic checkerboard pattern of a Fabry-Perot interferometer is observed. The level spacing (black double arrow) is of about 3.4 meV.

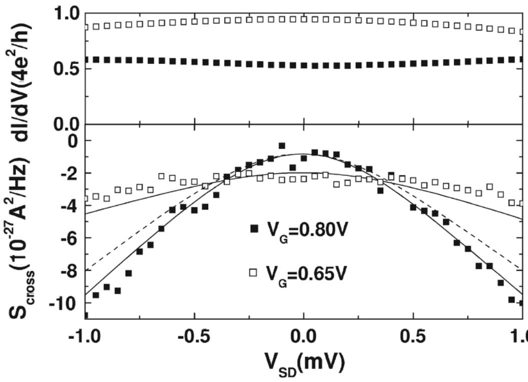

FIG. 3. Top: Nonlinear conductance as a function V_{SD} for gate voltages $V_G = 0.65$ V and $V_G = 0.80$ V for sample A. The closed squares correspond to $V_G = 0.65$ V and the open squares correspond to $V_G = 0.80$ V. Bottom: Corresponding noise power spectral density as a function V_{SD}. The lines correspond to formula (2) used for $D = 0.542$ and $D = 0.95$ which are the zero bias values of dI/dV for $V_G = 0.65$ V and $V_G = 0.80$ V in units of $4e^2/h$.

ages of 0.65 and 0.80 V, for which the transmission is, respectively, of 0.542 and 0.95. The data are presented here without any background correction. For both gate voltages, the noise displays the expected linear behavior above 250 μeV ($\approx 2k_BT$ at 1.5 K). As shown on Fig. 3 top panel, the conductance is weakly nonlinear in the range of ± 1 mV where the shot noise is measured. The general formula for the shot noise in a quantum coherent conductor can cope with these nonlinearities [1]. Since the maximum variation of conductance is 10% in the bias range considered, we will assume a constant transmission as a function of energy for the excess noise. In this case, if $D_{1,2}$ are the transmissions for the two different orbitals, the noise reads

$$S_I = 4k_BT\frac{dI}{dV} + \frac{2e^2}{h}\sum_{1,2} D_n(1 - D_n)\chi(eV_{\mathrm{sd}}, k_BT), \quad (2)$$

with $\chi(eV_{\mathrm{sd}}, k_BT) = 2eV_{\mathrm{sd}}\coth(\frac{eV_{\mathrm{sd}}}{2k_BT}) - 4k_BT$. Figure 3 bottom panel displays in the solid curve the shot noise calculated using the *measured* zero bias total transmission (top panel), assuming full degeneracy is displayed. A quantitative agreement between the noninteracting theory and the data is found provided an offset of, respectively, 6.2×10^{-27} A^2/Hz and 10.0×10^{-27} A^2/Hz for $V_G = 0.80$ V and $V_G = 0.65$ V is incorporated in formula (2).

In order to test the transmission dependence of formula (2), we have measured the noise for a finite bias voltage $V_{\mathrm{sd}} = -0.7$ mV sweeping the gate voltage V_G from 0.65 to 1.25 V for sample A. In Fig. 4, the noise power spectral density normalized to the Schottky value is plotted as a function of the gate voltage which is swept through two resonant levels. Each point is represented with the statistical error bar associated to a single averaging run. Note that the shot noise contribution is obtained here by substraction of background noise, according to the fitted linear behavior of Fig. 2(a), and of the constant term $4e^2/h \times D^2 \times 4k_BT$ determined directly via the *measured* conductance. The noise displays modulations as a function of the gate voltage with extrema appearing exactly at the same gate voltages as for the conductance. Specifically, when the conductance reaches a maximum, the noise reaches a minimum. As the conductance maxima at $V_G = 0.80$ V and $V_G = 1.05$ V are close to 1 in units of $4e^2/h$ (respectively, 0.95 and 0.90), the noise almost vanishes, confirming the noiseless character of a fully transmitted fermionic beam *through a carbon nanotube*. After QPCs [2], carbon nanotubes provide a second example of *noiseless* conductors.

We now discuss measurements obtained in the weak backscattering limit for sample A. The inset of Fig. 4 displays the noise power spectral density for $V_G = 0.80$ V as a function of $2eI_{\mathrm{BS}}\coth(\frac{eV_{sd}}{2k_BT}) - \frac{4k_BT(1-D)h}{4e^2}$ where $I_{\mathrm{BS}} = \int_0^{V_{\mathrm{sd}}} dV(4e^2/h - dI/dV)$ is the backscattering current. A linear slope of $F = 0.59 \pm 0.15$ is observed (solid lines). However, the reflection coefficient being 0.05, the backscattered current fluctuations are expected Poissonian with $F \approx 1$. Interactions or decoherence could produce a reduction of the shot noise in the weak backscattering limit [18]. According to the existing theories, the first mechanism would imply that the leads are not fermionic [19,20]. However, it seems difficult to reduce F down to 0.59 for the parameters of our sample using the decoherence mechanism [21].

Combining conductance and shot noise has proved to be an efficient tool to probe the lifting of spin degeneracy in ballistic conductors transmitting a single orbital mode [22]. In the same spirit, we have investigated a possible lifting of

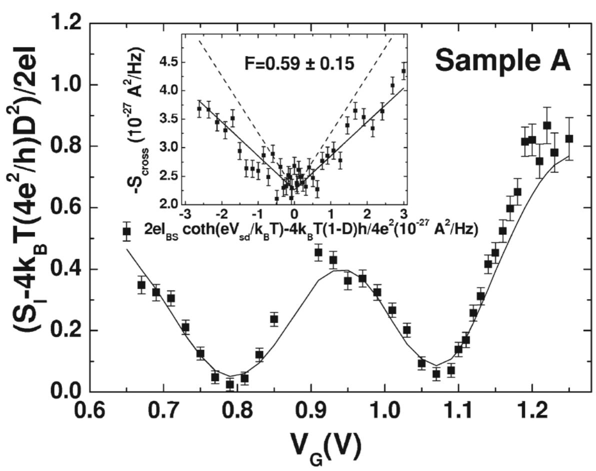

FIG. 4. Noise power spectral density measured (closed squares) at $V_{\mathrm{SD}} = -0.7$ mV normalized by the Schottky value $2eI_{\mathrm{SD}}$ as a function of V_G for sample A. The constant term $4e^2/h \times D^2 \times 4k_BT$ has been substracted to allow a direct comparison with theory. This term is determined directly via the *measured* conductance. The line is the theory with the assumption of full orbital degeneracy and constant transmission. Inset: Noise power spectral density as a function of the backscattering current. In the solid line, the linear fit gives $F = 0.59 \pm 0.15$. In dashed lines, the two-terminal noninteracting theory ($F = 1$).

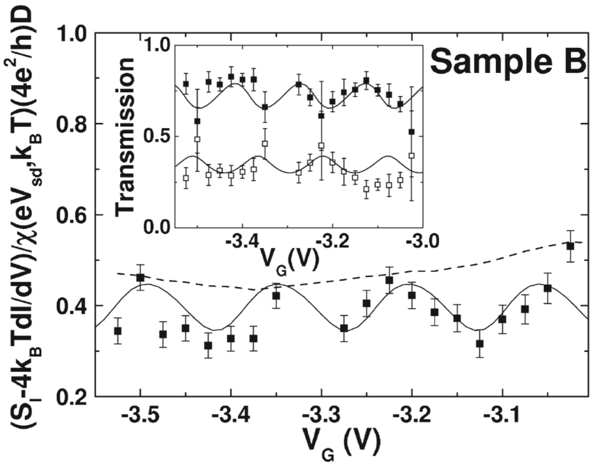

FIG. 5. Noise power spectral density measured (closed squares) at $V_{SD} = -0.7$ mV normalized by $\chi(eV_{sd}, k_BT) \times 4e^2/h \times D$ as a function of V_G for sample B. The Johnson-Nyquist noise $4k_BTdI/dV$ has been substracted to allow a direct determination of D_1 and D_2. The dashed lines correspond to the theory with the assumption of full orbital degeneracy, in clear disagreement with the noise data. Inset: Gate dependence of D_1 and D_2.

the orbital degeneracy in sample A. We illustrate this for $V_G = 0.65$ V. The dashed lines in Fig. 3 lower panel correspond to the case where $D_1 + D_2 = 2 \times 0.542$ but $D_1 - D_2 = 0.4$, in clear disagreement with the data. This suggests to use both noise and conductance to determine the gate dependance of D_1 and D_2, by combining Eq. (2) and the Landauer formula. Figure 5 shows such a determination for sample B. The noise oscillates also as a function of gate voltage, like for sample A, but the total transmission D (the conductance in units of $4e^2/h$) oscillates only weakly, as illustrated by the dashed lines which correspond to $1 - D$. Figure 5 shows also that the shot noise is qualitatively and quantitatively different from the single channel formula $(1 - D)$. The inset of Fig. 5 shows the gate dependence of D_1 and D_2, which oscillate with a phase shift of approximately π. These oscillations and their phase shift are characteristic of mode coupling and probe indirectly the exchange interference effects [1]. The extrinsic noise corresponding to the second part of Eq. (2) can be calculated using the model of Ref. [7]. The full lines correspond to a phase shift of $\pi/2$ between the reflection coefficients for the K and K' mode and an intermode reflection coefficients of 0.25 and 0.4, respectively, for the left and the right contact. The intramode reflection coefficient is 0.1 and 0.5, respectively, for the left and the right contact. Note that the agreement is only partially quantitative here since we have assumed no disorder to keep the model simple.

In summary, we have measured the zero frequency shot noise of carbon nanotube based Fabry-Perot interferometers. The noise is modulated as one sweeps the resonant levels through the Fermi energy of the reservoirs. The data are in quantitative agreement with the noninteracting theory. When orbital degeneracy is lifted, the combination of the noise and the conductance allows us to determine directly the gate dependence of the eigenchannels of the SWNT. In the weak backscattering limit, the noise is found slightly smaller than expected. This may indicate an effect of electron-electron interactions or weak decoherence.

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