Fundamental and Environmental Contributions to the Cyclostationary Third Moment of Current Fluctuations in a Tunnel Junction

Pierre Février, Christian Lupien, and Bertrand Reulet
Institut Quantique and Département de Physique, Université de Sherbrooke, Sherbrooke, Québec J1K 2R1, Canada
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Current fluctuations generated by tunnel junctions are known to be non-Gaussian. However, this property is lost when fluctuations are measured at high frequency and limited bandwidth. We show that the quadratures of the electric field generated by a tunnel junction at frequency \( f \) displays third order correlations, i.e. skewness, when the junction is electrically driven at \( 3f \), revealing the Poissonian statistic of charge transfer by the barrier even at short time-scales. In addition to this intrinsic contribution from the junction, we observe extra correlations induced by the environmental noise at frequency \( f \) as well as a feedback effects coming from the environmental impedance not only at frequency \( f \) but also at some multiples of \( f \).

I. INTRODUCTION

Electronic noise in mesoscopic conductors has been the object of many investigations [1]. Indeed, quantum transport is determined by the statistics, dynamics and interactions of charge carriers. These are imprint in the statistics of current fluctuations, the study of which thus provides insights into the conduction mechanisms. Many experiments deal with the variance of voltage or current fluctuations, measured over long timescales i.e. at low frequency, which already provides interesting information beyond the measurement of the conductance. However, in order to access dynamical properties, it is usually necessary to perform detection at shorter timescales i.e. to work at finite frequency \( f \). Unfortunately, the variance of fluctuations, which is the simplest quantity to measure beyond average current, is usually frequency independent when charge is conserved [2]. Beyond the variance, the noise susceptibility, i.e. the dynamical response of noise to an ac excitation, has proven to be a probe of the energy relaxation time in wires [3, 4]. Photo-assisted noise can also be used to access the same quantity [5].

Beyond usual variance, higher order moments have been measured in various samples [11, 24]. For systems with slow dynamics like quantum dots, frequency-dependent statistics reveal the tunnel rates through the barriers [9, 10]. In samples with fast dynamics such as metallic wires [8, 12, 13], the frequencies involved are in the GHz range, and microwave techniques are mandatory. The third moment of current fluctuations in such a frequency domain has been performed in tunnel junctions [14] and short diffusive wires [15]. These experiments face, beside the very low signal, two difficulties: first, the need for a very wide bandwidth, which is difficult to achieve in microwave circuits. Second, it involves environmental contributions which arise as soon as the impedance of the detecting apparatus is non-zero [16]. In practice, this impedance is usually 50Ω and of the same order as that of the sample. As a consequence, there is no report of detection of third order fluctuations in mesoscopic devices beyond 1GHz, except by a mixed detection which involves both low and high frequencies [17, 18].

The constraint on the detection bandwidth is stringent: a signal in the range \([f_1, f_2]\) has no third moment if \( f_3 < 2f_1 \), so for example, experiments working with a 4-8 GHz bandwidth, common in the detection of cryogenic microwave signals, are useless for the detection of a third moment. This severe condition originates from stationary: the third moment in frequency domain \( \langle i(f_1)i(f_2)i(f_3) \rangle \) is zero unless \( f_1 + f_2 + f_3 = 0 \). This condition can be relaxed into \( f_1 + f_2 + f_3 = n f_0 \) with \( n \) any integer if the system is excited by a periodic signal at frequency \( f_0 \). This condition of cyclostationarity can be obeyed with a detector of narrow bandwidth for \( n = \pm 1 \), \( f_0 = f \), to give the cyclic moment \( K_1(f) = \langle i^2(f)(-f) \rangle \), or for \( f_0 = 3f \), to give the cyclic moment \( K_3(f) = \langle i^3(f) \rangle \). Under cyclostationary conditions, a third moment of current fluctuations can in principle be measured with a narrow bandwidth detection scheme. The purpose of this article is to implement such a measurement to address the second difficulty related to measurements of third moments in the microwave domain: what are the environmental effects in this measurement? This question has been partially addressed theoretically [19].

This communication is organized as follows: in section II we describe the experimental setup and results of the measurement of the cyclostationary third moment of voltage fluctuations generated by a tunnel junction placed at low temperature; in section III we analyze the results in terms of intrinsic contributions and environmental effects. Section IV contains a conclusion, remarks and perspectives.

II. EXPERIMENTAL SETUP

Sample and biasing. Tunnel junctions are known to produce non-Gaussian fluctuations due to the binomial statistics of the charge transfer through the tunneling barrier. We have used a junction similar to the ones used in shot-noise thermometry [20], with a planar geometry of area \( 5 \times 1 \mu m \). It has been made using usual lithography
techniques and evaporation of aluminum electrodes on a silicon substrate. The insulating tunnel barrier is obtained by controlled oxidation of the first electrode under oxygen atmosphere. The dc resistance of the junction is $R_J = 130\Omega$ at 3.7K (116Ω at 300K). The experiment has been performed in a helium-free cryostat with a base temperature of 3.7K so that aluminum is not superconducting. The junction is current biased through a bias-Tee (see Fig.1), allowing the separation of high frequency signals from the dc bias line. The junction is ac-biased by a single tone at frequency $f_0 = 3f = 14.55$GHz using a directional coupler.

**Homodyne measurement.** The spectral density of voltage fluctuations at the junction is of the order of $10^{-10}V/\sqrt{Hz}$ which is way too small for direct detection without amplification. The microwave signal generated by the junction propagates through an isolator before amplification by a low-noise 4-8GHz cryogenic amplifier with a noise temperature of 2.5K. The role of the isolator is to make the temperature and the impedance of the environment seen by the junction well defined: a 50Ω load at 3.7K instead of the input of the amplifier with an unknown, frequency-dependent impedance and noise temperature. After extra amplification at room temperature, the signal is down-converted from $f = 4.85$GHz to low frequency by an IQ mixer with high linearity.

The two resulting quadratures $X$ and $P$ are amplified and low-pass filtered, with a measurement bandwidth of $\Delta f = 225$MHz. The signal is then digitized with a fast acquisition card (14bits, 400MS/s). The joint probability density $P(X,P)$ is calculated on the fly from the acquired data. The skewness of the voltage fluctuations on each quadrature $\langle X^3 \rangle$ and $\langle P^3 \rangle$ is directly linked to the cyclic third moments $K_{v,3}(f) = \langle v_{meas}(f)^3 \rangle$ and $K_{v,1}(f) = \langle v_{meas}(f)^2 v_{meas}(-f) \rangle$ of voltage fluctuations $v_{meas}(f)$ measured at the input of the cryogenic amplifier:

$$\langle X^3 \rangle + i\langle P^3 \rangle = \frac{3}{4}G^3 \left[ K_{v,3}(f)e^{i3\phi_0} + 3K_{v,1}(f)e^{i\phi_0} \right] \Delta f^2$$

where $G$ is the total voltage gain of the amplification chain and $\phi_0$ a global phase due to the delay between excitation and detection. The amplitude of the ac excitation $I_{ac}$, the gain $G$ and the noise added by the amplification chain, are calibrated by measuring the variance of the photo-assisted noise $\langle X^2 \rangle$ and $\langle P^2 \rangle$ vs. $I_{dc}$, the theory of which is well established [21, 22]. The power gain $G^2$ is estimated around 78dB and the effective noise temperature of the measurement is 3K, as expected for a 130Ω load with this specific cryogenic amplifier. The signal-to-noise ratio at high bias is limited by the noise of the junction itself.

**Third moment from the symmetries of the histograms.** The phase coherence between the detection at frequency $f$ and the excitation at frequency $3f$ can be switched on or off. When off, a slight detuning of one of the microwave sources averages to zero the contributions that depend on $\phi_0$ and thus should lead to $\langle X^3 \rangle = 0$ and $\langle P^3 \rangle = 0$. All remaining contributions are due to the non-linearity of the amplification chain, and of the acquisition card. To remove these unwanted contributions in $P(X,P)$, we measure the difference in histograms obtained with and without phase coherence. The resulting differential probability $\Delta P(X,P)$, showed Fig.2, has a finite order rotational symmetry. This is the direct consequence of the homodyne demodulation of the noise at a fraction of the modulation frequency. It is then natural to write $P(X,P)$ in polar coordinates: $X = r \cos \theta$ and $P = r \sin \theta$ and express $P(r,\theta)$ as the Fourier series:

$$P(r,\theta) = \sum_{n \in \mathbb{Z}} P_n(r)e^{-in\theta}$$

We define:

$$W_{\alpha,n} = \frac{\pi}{2} \int_0^{\infty} P_n(r)r^{\alpha+1}dr$$

Moments of the probability distribution $P(X,P)$ are related to the $W_{\alpha,n}$, which can be interpreted as the contribution of the rotational symmetry of order $n$ to the
moment of order $\alpha$. For the third moment we find:

$$
\langle X^3 \rangle = \text{Re}(W_{3,3} + 3W_{3,1}) \\
\langle XP^2 \rangle = \text{Re}(W_{3,1} - W_{3,3}) \\
\langle P^3 \rangle = \text{Im}(W_{3,3} - 3W_{3,1}) \\
\langle PX^2 \rangle = \text{Im}(W_{3,1} + W_{3,3})
$$

(4)

The skewness of the marginal probability distributions $\mathcal{P}(X)$ and $\mathcal{P}(P)$ is finite when $\mathcal{P}(X, P)$ shows either a one-fold or three-fold symmetry characterized respectively by $W_{3,1}$ and $W_{3,3}$. The measurement of the joint probability is necessary to separate these two contributions. In our experiment, it appears that $W_{3,1} \approx 0$ (see Fig.3). This corresponds to $K_{x,1} = 0$ as expected for a modulation at frequency $3f$. We consider in the following $\langle X^3 \rangle = \text{Re}(W_{3,3})$ and $\langle P^3 \rangle = \text{Im}(W_{3,3})$, in order to improve signal to noise ratio, and an arbitrary phase $\phi_0$ that maximizes $\langle X^3 \rangle$ and makes $\langle P^3 \rangle$ vanish at high bias.

From Fig.3 we see that the measured third moment at high bias ($I_{dc} > 40\mu A$) shows a plateau with an amplitude proportional to $I_{ac}$. This is qualitatively close from what is expected for a tunnel junction, i.e. a third moment proportional to the average current $\langle I \rangle$: $\langle (I - \langle I \rangle)^3 \rangle = e^2 I_{ac}$. In the limit where the noise is adiabatically modulated, all the moments of the current distribution follow the bias modulation, and we should have $K_{v,3} \propto e^2 I_{ac}$. The third moment at low bias shows however a clear deviation from this behavior. In the following we show that there are extra contributions that comes from the measurement setup and demonstrate how to separate them.

III. EFFECT OF THE ENVIRONMENT

Ideally, current fluctuations in a conductor should be measured using a ammeter with both a fast response and a zero input impedance. However, microwave equipment has a 50Ω input impedance. Furthermore, the tunnel junction is embedded in an electromagnetic environment consisting of its own capacitance, connecting leads, wire bonds and a transmission line (TL). This can be modeled by the effective reciprocal circuit showed in Fig.1. The input impedance $Z_{in}$ represents the impedance seen by the junction, the output impedance $Z_{out}$, the effective load on the TL. The voltage transmission coefficients $t$ (resp. $t'$), from the junction to the TL (resp. the TL to the junction), include the finite propagation time in the circuit.

This environment induces voltage fluctuations across the junction given by:

$$
\delta V(f) = -i(f)Z_{eff}(f) + t'(f)v_{env}(f)
$$

(5)

with $Z_{eff} = R_{t}Z_{in}(f)/(R_{t} + Z_{in}(f))$. $v_{env}$ is the noise coming from the measurement setup (here dominated by the thermal noise of the 50Ω load of the isolator) and $i(f)$ the current fluctuations generated by the junction. Voltage fluctuations across the junction lead to environmental corrections to the cyclostationary third moment, in a similar way they do in the stationary regime [16,25,26]. Using circuit theory, we find the different contributions to the cyclostationary third moment of voltage fluctuations detected by the amplifier connected to the transmission line [19]:

$$
K_{v,3}(f) = t(f)^3R_{t}^3[K_{int}(f) + K_{env}(f) + K_{fb}(f)]
$$

(6)

with $K_{int}$ the intrinsic contribution of the sample, $K_{env}$ the contribution due to the term $t'(f)v_{env}(f)$ in Eq.(5) and $K_{fb}$ the contribution due to the term $i(f)Z_{eff}(f)$. In [19], these quantities have been calculated at zero bias and zero frequency, i.e. neglecting the signal propagation in the circuit, which does not correspond to our experiment. In the following we derive the last two terms in Eq.(6) at any bias $I_{dc}$, and in the case of realistic microwave setup. We have computed the contributions to the third moment due to thermal fluctuations of the environment $K_{env}$ and the feedback effect $K_{fb}$ using the so-called cascaded Langevin approach [19], where we use the separability of timescales between the fluctuations $\delta V(t)$ and $i(t)$.

Considering that the noise generated by the junction responds adiabatically to the applied voltage, we have:

$$
\langle i(t)^2 \rangle = S(V(t)) + \frac{\delta V(t) dS}{dV}\bigg|_{V(t)}
$$

(7)
where brackets $\langle \rangle$ designate an ensemble average and $V(t) = R_j [I_{dc} + I_{ac} \cos(2\pi f_0 t)]$ is the periodically modulated bias voltage. In the following, we choose a more general approach. Because of cyclostationarity, Fourier components $i(f')$ separated by a frequency $\alpha f_0$ where $f_0$ is the driving frequency (here $f_0 = 3f$ with $f$ the detection frequency) and $\alpha$ an integer, can be correlated:

$$S_\alpha(f') = \langle i(f')i(\alpha f_0 - f') \rangle$$

(8)

$S_\alpha(f')$ is the dynamical response of order $\alpha > 0$ of the noise at frequency $f'$ to an excitation at $f_0$. $S_0$ is the static response, i.e. the photo-excited noise. On the top of the excitation at $f_0$, the voltage fluctuations $\delta V(f + \varepsilon)$ around frequency $f$ introduce additional correlations:

$$\langle i(f')i(\alpha f_0 + f + \varepsilon - f') \rangle = D_\alpha(f')\delta V(f + \varepsilon)$$

(9)

where $D_\alpha(f')$ is the noise susceptibility of order $\alpha$. The most general correlator thus reads:

$$\langle i(f')i(f'') \rangle = \sum_{\alpha \in \mathbb{Z}} S_\alpha(f') \delta(f'' + f' - \alpha f_0)$$

$$+ D_\alpha(f')\delta V(f'' + f' - \alpha f_0)$$

(10)

Because of the adiabaticity, the quantities $S_\alpha$ and $D_\alpha$ are frequency independent, given by the coefficients of the Fourier series:

$$S(t) = \sum_{\alpha \in \mathbb{Z}} S_\alpha e^{i2\pi \alpha f_0 t}, \quad \frac{dS}{dt}(t) = \sum_{\alpha \in \mathbb{Z}} D_\alpha e^{i2\pi \alpha f_0 t}$$

(11)

Environmental thermal noise.

We now evaluate the term $K_{env}$ of Eq. (9), the contribution to the third moment of the noise generated by the external circuit. Due to the impedance mismatch between the junction and the measuring circuit, the voltage fluctuations propagating from the environment towards the junction are partially reflected back to the amplification chain, and the measured voltage is $\nu_{mes}(f) = -i(f)\frac{2}{t(i)}(f)R_j + r(f)\nu_{env}(f)$ with $r(f) = (Z_{out}(f) - Z_0)/(Z_{out}(f) + Z_0)$. The modulation by $\nu_{env}$ of the variance of the noise generated by the junction leads to a third order correlation:

$$K_{env}(f) = 3\frac{2r(f)}{t(i)R_j}(\nu_{env}(f)i^2(f))$$

(12)

According to Eq. (10), $\langle i^2(f) \rangle = D_1(f)\delta V(-f) = D_1(f)t'(-f)\nu_{env}(-f)$. Since the circuit is reciprocal, $t'(-f)/t(f) = (R_j/Z_0)e^{-2i\phi}$ with $\phi$ the phase of $t(f)$. Introducing the spectral density of the environmental noise $\langle \nu_{env}(f)\nu_{env}(-f) \rangle = \frac{1}{2}k_BT_{env}Z_0$ Eq. (12) becomes:

$$K_{env}(f) = 3D_1k_BT_{env}r(f)e^{-2i\phi}$$

(13)

To demonstrate this environmental effect experimentally, we increased the effective temperature $T_{env}$ so that $K_{env}$ becomes the main contribution to the measured third moment. To do so, we excited the sample with a sine wave $\nu_{env}(t) = A\sin 2\pi(f + \varepsilon)t$ with $\varepsilon = 83$ MHz in addition to the drive at frequency $3f$. This is equivalent to an increase in the noise temperature at frequency $f + \varepsilon$ in a very narrow band. The effective $T_{env}$ is estimated from the amplitude of the reflected sine wave superimposed to the measured noise. We measured the skewnesses ($X^3$) and $\langle P^3 \rangle$ for different $I_{ac}$ and $I_{dc}$ and are presented Fig. 5. One clearly observes a quantitative agreement between the measurements (symbols) and the theoretical prediction of Eq. (13), both for the dependence on $I_{dc}$ (main plot in Fig. 5) and $I_{ac}$ (right inset), up to an overall multiplicative factor.

Feedback effect.

The feedback term $K_{fb}$ in Eq. (10) represents the contribution of the junction modulating its own noise through
the impedance $Z_{in}$. Using Eq. (10) we calculate the feedback contribution to the three current correlation:

$$\langle (i f' i (f') (f'') \rangle_{fb} = \sum_{\text{perm}, \alpha} \langle i (f) i (f') i (f'') \rangle_{fb}$$

$$= \sum_{\text{perm}, \alpha \in \mathbb{Z}} D_\alpha (f') \langle i (f) i (f' + f'' - \alpha f_0) \rangle_{eff} (f' + f'' - \alpha f_0)$$

(14)

where the sum is over the cyclic permutation of frequencies $f$, $f'$ and $f''$ with $f + f' + f'' = 3f$ as imposed by the cyclostationarity. This gives for a narrow-bandwidth:

$$K_{fb}(f) = 3 \sum_{\alpha \in \mathbb{Z}} D_\alpha S_1 - \alpha Z_{eff}((2 - 3\alpha)f)$$

(15)

This is a quite unexpected result: the feedback effect on the cyclostationary third moment measured in a narrow band around frequency $f$ involves the environmental impedance not only at $f$ but also at higher frequencies $2f$, $4f$, $5f$, etc. This is a generalization of previous derivation [10], which treated only the case $I_{dc} = 0$.

At zero dc bias $I_{dc} = 0$, only the term $D_1 S_0 Z_{eff}(f)$ is non-zero. In contrast with the environmental contribution which is proportional to $D_1$ and saturates at high ac excitation, the $D_1 S_0$ term is almost linear in $I_{ac}$, see insets of Fig. 4. We use this property to separate the different contributions to the skewnesses, which can be reliably fitted by $aI_{ac} + bD_1(I_{ac})$, with $a$ and $b$ real numbers (which are different for the two quadratures), see Fig. 5. Besides the global gain of the measurement, $a = (K_{int} + K_{fb})/I_{ac}$, and $b = 3k_b T_{env} r(f)$, $b$ being known allows us to remove the $K_{env}$ contribution from previous measurements, by subtracting $b D_1(I_{ac}, I_{dc})$ from $\langle X^3 \rangle$ and $\langle P^3 \rangle$ for all values of $I_{dc}$ and $I_{ac}$.

We show in Fig. 7 the skewnesses of both quadratures after subtraction of environmental contributions $K_{env}$. Obviously, these differ from a constant, indicating the presence of extra terms in the feedback contributions, see Eq. (15). This equation contains an infinite sum involving the environmental impedance taken at very high frequency. We expect however these contributions to decay as frequency increases because of the capacitance of the junction ($C \approx 0.2\mu F$ based on geometry) shunting the environmental impedance at high frequency, the cutoff being approximately given by $\sim 20\text{GHz}$.

To obtain quantitative results, we extracted the values of the environmental impedance using a fitting routine. First we determine the global gain $G(f)^3 \Delta f^2$, from the magnitude of $K_{env}$, assuming $T_{env} = 3.7\text{K}$ and $|r| = 0.44$. Then we used a three parameter fit on each quadrature of $K_{int} + K_{fb}$, corresponding to the environmental impedances appearing in $K_{fb}$ for $\alpha < 4$, plus one parameter for the dephasing $\phi$ between $K_{int}$ and $K_{env}$. The fitted data are represented on Fig. 4. The fitting routine has also been performed with less parameters, by omitting for example the $D_2 S_1$ contribution, however the obtained impedances were unrealistic.

**Characterization of the electromagnetic environment.** Our data on both quadratures ($X^3$) and ($P^3$) are very well accounted for by Eq. (10) for all dc and ac excitations. This involves, besides the total gain $G(f)^3 \Delta f^2$, environmental parameters: the electromagnetic response of the environment through the phase $\phi = -0.1\text{rad}$ (for $K_{env}$) and the impedances $Z_{in}(f)$, $Z_{in}(2f)$ and $Z_{in}(4f)$ (for $K_{fb}$), whose values are presented in Fig. 8.

We also show in Fig. 8 the magnitude of the reflection coefficient $|r|$ measured at room temperature with a vector network analyzer. The magnitude below 5GHz is close to what is expected for a transmission line terminated by a simple resistor, which coincides with $Z_{in}(f)$ being close to $50\Omega$. At 10GHz, a lower reflection can indicate a better matching which coincides with $Z_{in}(2f)$ being closer to the junction resistance. Our knowledge of the environment is however too crude to predict the value of $Z_{in}(4f)$ from $|r|$.

From this analysis, two conclusions can be drawn for future works. Because of the frequency dependence of reactive part of $Z_{eff}(f)$ and $r(f)$, all environmental contributions cannot be projected on a single quadrature. Therefore, in order to extract the intrinsic third moment of the sample, both noise quadratures must be measured. Second, a careful design of the electromagnetic environment is necessary to separate the intrinsic contribution from the environmental ones. For example, by providing a low impedance environment at frequency $2f$, $K_{int}$ becomes the dominant contribution at high dc bias.
FIG. 7. Third moment of both quadratures $X$ and $P$ after subtraction of the environmental contribution $K_{env}$. Graphs on the left: Dots represent data and black plain lines are the result from the fitting routine using Eq. (15) plus a constant which is attributed to the intrinsic contribution $K_{int}$. Graphs on the right: each contributions to $\langle X^3 \rangle$ and $\langle Y^3 \rangle$ for $I_{ac} = 20 \mu A$ plotted separately.

IV. CONCLUSION

We have measured the cyclostationary third moment of current fluctuations at finite frequency $f = 4.85$GHz in a tunnel junction photo-excited at frequency $3f$. We have observed third order correlations between the quadratures of the electric field at frequency $f$ which depends on both the dc and ac bias. Thanks to a theoretical analysis we can decompose these correlations into three contributions: the intrinsic shot noise of the junction, and its modulation by the external noise at frequency $f$ as well as through a feedback mechanism that involves the impedance of the detection circuitry even way outside the detection bandwidth.

Our analysis paves the way towards the design of new experiments probing the third moment of current fluctuations at high frequencies. This includes for example the case of systems with non-trivial dynamics, like diffusive wires [13] or systems in the regime where the quantum dynamics associated with the timescale $h/eV$ matters.

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FIG. 8. Top: Input impedance $Z_{in}$ seen by the junction, extracted from the fit of $K_{fb}$ (circles). Bottom: Magnitude of the reflection coefficient of the sample at 300K (solid line), measured using a vector network analyzer. The dashed line corresponds to the reflexion of a pure resistance of $116 \Omega$, i.e. the dc resistance of junction measured at 300K.
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