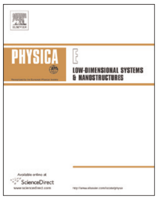
Physica E 75 (2016) 358–369

Contents lists available at ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe



Single-electron coherence: Finite temperature versus pure dephasing

Michael Moskalets [a,*], Géraldine Haack [b,c]

[a] Department of Metal and Semiconductor Physics, NTU “Kharkiv Polytechnic Institute”, 61002 Kharkiv, Ukraine
[b] University of Grenoble Alpes, INAC-SPSMS, F-38000 Grenoble, France
[c] CEA, INAC-SPSMS, F-38000 Grenoble, France

HIGHLIGHTS

- We investigate the coherence properties of mixed single-electron states.
- We clarify the difference between different types of mixedness.
- Temperature-induced mixedness suppresses a single-particle shot noise.
- Dephasing-induced mixedness hinders antibunching of two electrons.

ARTICLE INFO

Article history:
Received 30 June 2015
Received in revised form
17 August 2015
Accepted 3 September 2015
Available online 5 September 2015

Keywords:
Floquet scattering matrix
Quantum transport
Single-electron source
Mixed state
Shot noise measurements

PACS:
73.23.-b
72.10.-d
73.63.-b

ABSTRACT

We analyze a coherent injection of single electrons on top of the Fermi sea in two situations, at finite-temperature and in the presence of pure dephasing. Both finite-temperature and pure dephasing change the property of the injected quantum states from pure to mixed. However, we show that the temperature-induced mixedness does not alter the coherence properties of these single-electron states. In particular two such mixed states exhibit perfect antibunching while colliding at an electronic wave splitter. This is in striking difference with the dephasing-induced mixedness which suppresses antibunching. On the contrary, a single-particle shot noise is suppressed at finite temperatures but is not affected by pure dephasing. This work therefore extends the investigation of the coherence properties of single-electron states to the case of mixed states and clarifies the difference between different types of mixedness.

1. Introduction

Markus Büttiker was a person who pioneered the branch of Physics presently known as Mesoscopics. Many of his predictions were successfully confirmed experimentally and gave birth to new exciting directions in Mesoscopics. One of such predictions directly relates to the topic of the present work.

In 1993 Markus Büttiker, Harry Thomas, and Anna Prêtre predicted that the low-frequency dissipative response of a single-channel mesoscopic capacitor is governed by the universal quantity, $R_q = h/(2e^2)$, the charge relaxation resistance [1]. This value is for a single spin channel corresponding to half the value of the von Klitzing resistance quantum, $R_K = h/e^2$ [2]. The charge relaxation resistance was suggested to be renamed *the Büttiker resistance* [3], see also the comment in the work by P.P. Hofer, D. Dasenbrook, and C. Flindt in this special issue.

Besides being robust against interactions, see for instance Refs. [4,5], one of the key characteristics of this charge relaxation resistance is that it shows up if and only if the electrons conserve their quantum phase coherence while propagating through the sample [6]. When the Büttiker resistance was confirmed experimentally in 2006 using a single-channel mesoscopic capacitor [7], it then became clear that this setup could also serve as a coherent source of electrons. The year after, experimentalists made use of the relatively large energy level spacing in the capacitor to address a single quantum level. This ability allowed them to operate the

---

[*] Corresponding author.
E-mail addresses: michael.moskalets@gmail.com (M. Moskalets), geraldine.haack@gmail.com (G. Haack).

http://dx.doi.org/10.1016/j.physe.2015.09.002

mesoscopic capacitor as a single-electron source, i.e. a source which emits one particle at a time. With this experiment realized in 2007, Ref. [8], experimentalists achieved the emission of a periodic stream of alternating single electrons and single holes.

This experiment has then triggered a prolific both experimental [9–22] and theoretical [23–64] activity, which constitutes now a fascinating and fast developing sub-field of Mesoscopics, which can be called *quantum coherent electronics*. Here quantum refers to the granular nature of charge and emphasizes the fact that the current through the conductor is generated by a flux of well separated wave-packets.

Another step was then made theoretically by characterizing the coherence properties of the emitted electrons with the help of the first- and second order correlation functions [34,41,45], first introduced by Glauber in quantum optics. These works put forward the similar role played by the single-electron source in electronics compared to the already existing single-photon sources in quantum optics. This analogy also gave rise to an alternative denomination for this sub-field of Mesoscopics, electron quantum optics.

The past years have seen the realization of emblematic quantum optic experiments with single-electron sources. Analogs of the Hanbury–Brown and Twiss (HBT) experiment [65] and of the Hong–Ou–Mandel (HOM) experiment [66] with single electrons were respectively reported in Refs. [13,17] and [15,17].

Another important issue concerning the characterization of these single-electron sources concerns the nature of the quantum state which is emitted. This step was tackled in an ingenious experiment reported in Ref. [19], where the wave function of a single electron emitted at low temperatures was measured. This result agrees well with the theoretical expectations from Refs. [67–69].

The problem we address in the present work is the effect of a finite temperature onto the state emitted by a single-electron source. This problem is important at least for two reasons. First, experimentally, the electronic temperature is finite and without a clear understanding of the temperature effect, it is difficult to judge whether a given temperature can be considered as low or high. Second, the experiment from Ref. [13] and the theory works [13,68] show that the shot noise caused by the scattering of single electrons at a quantum point contact gets suppressed with increasing electron temperature. This effect was explained as a result of antibunching of injected electrons with thermal excitations of the Fermi sea [13,68]. As we put forward in this work, there is an alternative interpretation of the shot noise reduction with a temperature increase.

Our interpretation exploits the fact that the type of emitted quantum state (pure or mixed) is essential for characterizing the suppression or not of the shot noise. Our reasoning is based on the following arguments: on one side, it is known that energy relaxation processes suppress shot noise [70]. On the other side, it is also known that when a pure state enters a region where it is subject to relaxation, then it becomes a mixed state. Therefore, a mixed state is expected to produce less shot noise compared to what is produced by a pure state. Previous works have demonstrated that, in general, a pure state at zero temperature becomes mixed at finite temperatures, see for instance Ref. [71].

In the present work, we show that this statement is also valid for a quantum state emitted by single-electron sources. We also demonstrate that temperature-induced mixedness is not equivalent to pure-dephasing induced mixedness with respect to the coherence properties of the emitted quantum state. To this end, we compare an emitted quantum state in the presence of finite-temperature and in the presence of pure dephasing and emphasize striking differences in the shot noise suppression in an HBT and HOM experiments. Indeed, in the latter experiment, the shot noise relies on the phase coherence property between two incident single electrons emitted by different sources when they antibunch. As soon as these quantum states lose their phase coherence, in the presence of pure dephasing, we observe a suppression of the antibunching. This has to be contrasted with the perfect antibunching at finite-temperature. On the other hand, the phase coherence is irrelevant for the shot noise in HBT experiment. This is why the pure dephasing does not affect it. In contrast, the energy averaging required at finite temperatures suppresses the shot noise. We formulate all our results in terms of the first-order correlation function of the emitted single electrons, which allows us to differentiate the effects caused by the suppression of phase coherence and averaging over energy.

The paper is organized as follows. In Section 2 we introduce the excess first-order correlation function $G^{(1)}$, the basic quantity we use to characterize the state emitted by a single-electron source into an electronic waveguide. In Section 3, we relate $G^{(1)}$ to measurable quantities such as the time-dependent current and the shot noise. The effect of a temperature of electrons in a waveguide onto $G^{(1)}$ is discussed in detail in Section 4 and we compare these results with the pure dephasing situation in Section 5. We conclude in Section 6.

2. Definition of $G^{(1)}$

The system we have in mind is a single-channel chiral waveguide of non-interacting and spinless electrons originating from a metallic contact. An electron system of a metallic contact is in equilibrium and is characterized by its Fermi distribution function f with temperature θ and chemical potential μ. As electronic waveguides one can use the edge states of conductors in the quantum Hall effect regime [2,72,73] or of topological insulators [74–76]. To inject electrons into a waveguide one can use a side-attached quantum dot, as experimentally realized in Refs. [7,8] in the quantum Hall effect regime and theoretically suggested in Refs. [77,78] for topological insulators. Another possibility is to use an in-line dynamic quantum dot [16,21,79]. A non-trivial way of generating single-electron excitations was demonstrated in Ref. [17], where, following a theoretical suggestion of Refs. [80,81], a periodic sequence of Lorentzian voltage pulses was applied directly to a metallic contact. A periodically working source emits a stream of particles. Here we assume that particles emitted during different periods do not overlap with each other.

The first-order electronic correlation function [34,41] in a waveguide after the source is defined in the full analogy with how it is done in optics [82],

$$\mathcal{G}^{(1)}(1;2) = \langle \hat{\Psi}^{\dagger}(1)\hat{\Psi}(2)\rangle, \tag{1}$$

where $\hat{\Psi}(j) \equiv \hat{\Psi}(x_j, t_j)$ is a single-particle electron field operator in second quantization evaluated at point x_j and time t_j (j=1,2). The quantum-statistical average $\langle ... \rangle$ is over the equilibrium state of electrons incoming from the metallic contact. The correlation function $\mathcal{G}^{(1)}$ contains information about electrons of the Fermi sea as well as about particles injected by the source.

To access information solely about the particles emitted by the source let us introduce *the excess correlation function* [34,35,41] evaluated as the difference of electronic correlation functions with the source on and off,

$$G^{(1)}(1;2) = \mathcal{G}^{(1)}_{on}(1;2) - \mathcal{G}^{(1)}_{off}(1;2). \tag{2}$$

The next step is to express $G^{(1)}$ in terms of some quantity characterizing an electronic source. To this end we first introduce the field operator in second quantization $\hat{\Psi}(x_j, t_j)$ for electrons in an electrical conductor [83]. For chiral electrons it reads