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Reprint of : Hanbury-Brown Twiss noise correlation with time controlled quasi-particles in ballistic quantum conductors

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HIGHLIGHTS

- The robust antibunching of indistinguishable leviton charge pulses is demonstrated.

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ABSTRACT

We study the Hanbury Brown and Twiss correlation of electronic quasi-particles injected in a quantum conductor using current noise correlations and we experimentally address the effect of finite temperature. By controlling the relative time of injection of two streams of electrons it is possible to probe the fermionic antibunching, performing the electron analog of the optical Hong Ou Mandel (HOM) experiment. The electrons are injected using voltage pulses with either sine-wave or Lorentzian shape. In the latter case, we propose a set of orthogonal wavefunctions, describing periodic trains of multiply charged electron pulses, which give a simple interpretation to the HOM shot noise. The effect of temperature is then discussed and experimentally investigated. We observe a perfect electron anti-bunching for a large range of temperature, showing that, as recently predicted, thermal mixing of the states does not affect anti-bunching properties, a feature qualitatively different from dephasing. For single charge Lorentzian pulses, we provide experimental evidence of the prediction that the HOM shot noise variation versus the emission time delay is remarkably independent of the temperature.

1. Introduction

Markus Büttiker has made important contributions regarding the predictions of Hanbury-Brown Twiss (HBT) electron interference in quantum conductors using current noise correlations. A prerequisite to address current noise problems was the modeling of dc currents in multi-terminal conductors [1,2]. Using a scattering approach he was able to relate the current I_α injected in a contact α to the voltages V_β applied to another contact β, i.e. $I_\alpha = G_{\alpha,\beta} V_\beta$. Büttiker's multiterminal conductance formula has given a useful frame to understand the meaning of voltage drops in quantum conductors or to implement decoherence modeling [3]. The formulation also had important impact on the practical description of edge states in the quantum Hall effect [4]. Soon after this work Markus Büttiker applied the multi-terminal approach to current fluctuations or shot noise [5]. In a long article [6], exploiting the multi-terminal approach he made very enlightening comparisons between experimental situations encountered in quantum optics with photons and the physics of current noise cross-correlations with electrons. In this analogy a voltage biased contact plays the role of the photon source while a contact absorbing electrons the role of the photon receiver. He proposed "electron quantum optics" experimental situations, like the generic Hanbury Brown Twiss optical experiment [7] where the mixing of two beams of indistinguishable particles emitted by two different voltage sources α and β gives non-trivial correlation in the statistics of joint particle detection at two separate contacts $\gamma$and δ, see also [8]. In quantum conductors, measuring the particle detection statistics is better realized by measuring current fluctuations. Ref. [6] showed that the current noise correlation $\langle I_\gamma(t) I_\delta(t') \rangle$ provides direct access to the electronic HBT exchange term which is made of the product of four scattering amplitude probabilities $s_{\gamma\alpha} s^*_{\delta\alpha} s_{\delta\beta} s^*_{\gamma\beta}$. This quantity is in general not separable as a product transmission probabilities. Here s_{ij} is the probability amplitude of a particle emitted from contact i to reach contact j.

The electron quantum optics approach of [6] has stimulated a large number of experimental and theoretical works, see [9] for a review. The noiseless electron injection due to Fermi statistics gave

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rise to observation of negative shot noise correlation as expected from the partitioning of electrons between different contacts [10,11]. The Fermi statistics also leads to electron anti-bunching, contrasting with photon bunching. This is observed as a suppression of the cross-correlation noise in quantum conductors in a HBT like set-up where two voltage sources emit electrons in the same quantum channel [12]. In order to compare with optical Hong Ou Mandel (HOM) experiments a time control is required [13]. Continuous voltage sources do not allow us to control the emission time of particles and so to introduce a time delay between them as in the original optical HOM experiment. Markus Büttiker addressed time control in an article where he considered two sine-wave voltage sources [15]. He found that the two-particle exchange term in the shot noise periodically depends on the delay between the sources. HBT and HOM experiments will be the focus of the present paper and particularly addressing on-demand quasi-particle sources.

The study of current fluctuations, i.e. time variation of the current, also pushed Markus Büttiker to be early interested in a finite frequency formulation of the multiterminal conductance formula $I_\alpha(\omega) = G_{\alpha,\beta}(\omega)V_\beta(\omega)$ [14]. By emphasizing the role of displacement currents associated to the internal potential in the conductor he provided a consistent gauge invariant formulation. He introduced the notion of emittance which allows us to take into account quantum inductance (i.e. kinetic inductance) and quantum capacitance effects. He particularly considered the situation where a quantum capacitor is weakly connected to a quantum lead via a single electronic channel of transmission D. While we would naively expect the RC-circuit resistance h/De^2 from the Landauer formula, he predicted a remarkable resistance quantization even for low transmission as long as the electrons keep full quantum coherence in the capacitor. This so-called charge relaxation resistance, that we will call Büttiker resistance, is half the resistance quantum $R_B = h/2e^2$ (spin degeneracy is here disregarded). This has been later verified in experiments lead by one of the author, see [16].

The quantum capacitor has been the starting point towards new electron optics experiments. Beyond the ac linear capacitive response, by operating Büttiker's mesoscopic capacitor in a non-linear regime, an ac current can be generated made of an alternate stream of emitted single electrons and single holes [17]. This is achieved by pulsing the capacitive gate voltage to periodically push and pull the last occupied energy level above and below the Fermi energy. The single particle emission time can be viewed as the time of a RC circuit. In the coherent but the non-linear regime, the associated charge relaxation resistance is no longer quantized but equals that expected in an incoherent regime $(\frac{1-D}{D} + \frac{1}{2})h/e^2$, i.e. the Landauer resistance plus the access resistance of a single contact [18]. For unit transmission $D=1$, no level quantization in the capacitor, Büttiker's resistance $R_B = h/2e^2$ is recovered. Single electron sources provided by either a mesoscopic capacitor and by the recent voltage pulse source became one of the main focus in the contributions of Markus Büttiker and his team [19–23]. They particularly addressed HBT and HOM electron correlations, in close connection with experiments [24–29], extending very far the first electron optics shot noise predictions of Markus Büttiker.

In the present work, we would like to discuss new experimental results related to Markus Büttiker's early work where he considered HOM experiments with ac biased voltage contact [15]. We compare the sine-wave drive case to the recent Lorentzian voltage pulse case giving rise to minimal excitation states [31–35] called levitons [28]. Single and multiple charge pulses are considered both theoretically and experimentally. The paper is organized as follows. In Section 2 we discuss how to implement shot noise measurements of Hanbury Brown Twiss correlation in quantum conductors. In Section 3 we introduce basic results for the expected shot noise when the contacts are driven by ac voltage and specifically discuss the Hong Ou Mandel correlation of electron–hole pairs generated by sine-wave voltages. Section 4 discusses the case of voltage driven by periodic Lorentzian pulses giving rise to clean integer charge excitations called levitons. We propose a set of orthogonal wave-functions defined on the pulse period which allows us to give a simple interpretation of the HOM shot noise for single but also multiple electron Lorentzian pulses. Section 5 discusses the effect of temperature and presents experimental HOM measurements showing that, following the recent general prediction by Moskalets and Haack [36], this issue, the thermal mixing of the states cannot affect the HOM noise for zero emission time delay, a result contrasting with the effect of decoherence. We also show that for levitons carrying single charge the shape of HOM shot noise versus time is remarkably independent of the temperature. Section 6 is the conclusion.

2. Measuring Hanbury Brown Twiss correlations in ballistic conductors

In this section we discuss the conditions to realize a HOM experiment with electrons. A HOM experiment measures HBT correlations, but contrary to the original HBT measurements the thermodynamic sources randomly emitting particles are replaced by sources providing time-resolved particle emission. Examples of such sources are the optical parametric down conversion of light creating pairs of photons and the on-demand electron sources for electrons.

In the mid-1990s, following early shot noise experiments demonstrating noiseless electron flow due to Fermi statistics [37,38], several experimental groups [10–12] have addressed HBT shot noise correlations to test the electron anti-bunching predictions [5,6,8]. These experiments used continuous voltage sources which can be viewed as black-body sources of electrons. At zero temperature, a contact biased at a voltage V above the voltage of all other contacts can be thought as emitting electrons in each quantum channel at a rate eV/h. This corresponds to a current $ge(eV/h)$ per quantum where $g=2,1$ depends on spin degeneracy. The current coming from each channel is in general partitioned by the conductor towards different output contacts. The resulting quantum partition of emitted electrons gives negative cross-correlation between currents of the output contacts. When a second contact is biased with the same voltage, the newly emitted electrons mix in the conductor with those emitted from the first contact. As electrons obey Fermi statistics, a significant reduction of the cross-correlation current fluctuations occurs due to anti-bunching. This effect is the fermionic counterpart of the noise doubling observed in an optical HOM experiment (or equivalently a dip in the photon coincidence detection). Although there is no doubt that anti-bunching is what was measured in experiments, the lack of time control prevents a complete parallel with Hong Ou Mandel experiments with photons. A more appropriate evidence of anti-bunching requires sending particle one by one from each source and control their arrival time in the mixing region. When the relative delay between particle τ is zero, electrons (photons) are indistinguishable and antibunching (bunching) for electrons (photons) is expected. On the opposite, for τ larger than the extension of the particle wave-packets independent partition gives no anti-bunching (no bunching) as the particle are discernable by their different arrival time at the detectors. The comparison between these two limiting case provides a clean way to quantify bunching effects.

Not related to the present discussion, another advantage of controlling the particle emission time is the measurement of the overlap of the particle wave-functions by varying τ, see Sections 4 and 5. This provides a way to measure the wave-packet shape and its width (actually the initial motivation of Hong, Ou and Mandel) [28,27]. This provides also information on decoherence