The development of quantum electronics based on the coherent manipulation of single to few quasi-particles in a ballistic quantum conductor has raised a strong interest in the recent years [1–7]. On the theoretical side, many proposals have suggested to generate and manipulate single electronic excitations in optics like setups [2–4] and to use them in Fermion based quantum information processing [5]. On the experimental side, triggered electron sources that supply single electron states on-demand have been demonstrated [6, 7] but there has been no report so far of their implementation in an electron quantum optics experiment (i.e. electron optics at the single charge level).

Actually, the very principle of electron quantum optics is still under question as singling out a single elementary excitation remains a complex issue [8] in solid state where the Fermi sea builds up from many interacting electrons.

In this work, we have realized the partitioning of single electron/hole excitations emitted one by one by the on-demand emitter. We show that the measurement of the output currents correlations in the HBT geometry provides a direct counting, at the single charge level, of the elementary excitations (electron/hole pairs) generated by the emitter at each cycle. We observe the antibunching of low energy excitations emitted by the source with thermal excitations of the Fermi sea already present in the input leads of the splitter, which suppresses their contribution to the partition noise. This effect is used to probe the energy distribution of the emitted wave-packets.

AC sources differ from DC sources as their elementary emission processes consist in the generation of coherent electron/hole pairs [12, 13], so that the electron and hole populations deviate from equilibrium. As a first consequence, contrary to DC sources, no information can be gained from low frequency noise measurement of the current directly emitted by the source, as there is no charge transfer or charge fluctuations on long times, the electron and hole currents compensating each other. The statistics of charge transfer is then revealed in the high frequency noise [14]. However, the number of elementary excitations produced by the source is hardly extracted from such measurements since an electron/hole pair is detected only if the delay between the two particles is larger than the temporal resolution of the setup. It is known that low frequency noise can be recovered from the random and independent partitioning of electrons and holes on an electronic beam-splitter [15, 16]. The information one can extract from noise measurements in the HBT geometry then strongly depends on the nature

Electron quantum optics: partitioning electrons one by one

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of the source. While for a DC emitter, the low frequency correlations of the current can reveal the fluctuations of the number of particles (electrons) emitted by the source, when dealing with an AC emitter, the same measurement instead yields the average number of elementary excitations (electron/hole pairs) generated by the source at each of its cycles.

Considering a periodically driven emitter at frequency $f_d$ placed on input 1 of a splitter independently transmitting electrons and holes with probability $T$, the average number of electron/hole pairs emitted in one period can be directly extracted from the low frequency correlations between the currents at the output 3 and 4, $S_{3,4} = -2eT(1-T)\langle I_{\text{part}} \rangle$, where $\langle I_{\text{part}} \rangle = e f_d \langle N_e + N_h \rangle$ is the particle current, $\langle N_e \rangle$ and $\langle N_h \rangle$ being the average numbers of electrons and holes emitted per period (see supplementary material).

$$S_{3,4} = T(1-T) [S_{2,2} - 4e^2 f_d N_{\text{HBT}}]$$

$$N_{\text{HBT}} = \langle N_e \rangle + \langle N_h \rangle - \int_0^\infty d\epsilon (n_e(\epsilon) + n_h(\epsilon)) f_2(\epsilon)$$

$$\langle N_e \rangle = \int_0^\infty d\epsilon n_e(\epsilon)$$

$$\langle N_h \rangle = \int_0^\infty d\epsilon n_h(\epsilon)$$

where $S_{2,2}$ is the low frequency thermal noise on input 2 and $f_2(\epsilon)$ the equilibrium Fermi distribution at arm 2 temperature $T_{el,2}$. The energy reference is the Fermi energy of the electron gas, i.e. $\epsilon_F = 0$. $n_e(\epsilon)$ is the energy density of electronic (respectively hole) excitations added by the source during one period. The HBT contribution $N_{\text{HBT}}$ differs from the classical one $\langle N_e \rangle + \langle N_h \rangle$ by: $-\int_0^\infty d\epsilon (n_e(\epsilon) + n_h(\epsilon)) f_2(\epsilon)$. The minus sign reflects the antibunching of fermionic particles colliding on the splitter and replaces the plus sign observed for bosons, for example in the Hong Ou Mandel experiment [17]. The number of detected electron/hole pairs $N_{\text{HBT}}$ is thus reduced by the energy overlap between the source excitations and the thermal ones. For a vanishing overlap, classical partitioning is recovered. For a non vanishing overlap, some of the source excitations cannot be distinguished from thermal ones and do not contribute to the partition noise. This antibunching provides a powerful tool to probe the energy distributions of the excitations produced by the source. In a real system, one should also take care of thermal excitations in arm 1 emitted by the reservoir upstream of the source, which also interfere with the ones additionally produced by the source.

However, there are deviations to this classical reason-
We now turn to the experimental realization of the HBT experiment using a single particle emitter. The quantum conductor is a two-dimensional electron gas in the quantum Hall regime. Using one-dimensional chiral propagation along a quantum Hall edge channel, and a quantum point contact taken as an electronic beamsplitter, the geometry used in the seminal HBT experiment can be mimicked, as depicted on Fig.1. The emitter placed on input 1 is a periodically driven mesoscopic capacitor [18] made of a quantum dot (with level spacing $\Delta = 2.1$ K) tunnel coupled to input lead 1 by a quantum point contact whose gate voltage $V_g$ tunes the dot/edge channel transmission $D$. A periodic RF drive, applied on a metallic top gate capacitively coupled to the dot, gives rise to the periodic emission of a single electron followed by a single hole. The top gate of the source is driven at frequency $f_d = 1.7$ GHz using either a square wave (containing approximately three odd harmonics) or a sine wave, so as to engineer different single particle wave-packets. As described in ref. [6], we adjust the emitter parameters so that the average charge $Q^d$, emitted from the dot in time $\frac{1}{f_d}$, equals the elementary charge $e$ for a large range of dot transmission $D$. For $D \approx 1$, $Q^d$ exceeds $e$ as the dot is fully open. $Q^d$ goes to zero for small $D$ as the average escape time $\tau$ increases as can be seen by comparing the red and black curves in Fig.2. The solid lines represent adjustments with the expected $T(1-T)$ dependence.

Fig.2 presents measurements of the low frequency correlations $\delta S_{4,4} = -S_{3,4}$ in units of $e^2 f_d$ (left axis) and $A^2 Hz^{-1}$ (right axis) as a function of the beam-splitter transmission $T$. Three types of RF drives are plotted, a sine wave at $D = 1$ (black triangles), a sine wave at $D = 0.3$ (red circles) and a square wave at $D = 0.4$ (green squares). The solid lines represent adjustments with the expected $T(1-T)$ dependence.

$\delta S_{4,4} = -S_{3,4}$ within 10 percent for $0.2 \leq D \leq 0.7$.

FIG. 2. Low frequency correlations $\delta S_{4,4} = -S_{3,4}$ in units of $e^2 f_d$ (left axis) and $A^2 Hz^{-1}$ (right axis) as a function of the beam-splitter transmission $T$. Three types of RF drives are plotted, a sine wave at $D = 1$ (black triangles), a sine wave at $D = 0.3$ (red circles) and a square wave at $D = 0.4$ (green squares). The solid lines represent adjustments with the expected $T(1-T)$ dependence.
1 or 2, are lost. When the actual temperature (extracted from equilibrium noise thermometry of the sample) is introduced on both arms \( (T_{el,1} = T_{el,2} = 150 \text{ mK}, \text{black dashed curves}) \), a good agreement is obtained with the experimental points (symbols) without any adjustable parameters.

As a conclusion, we have realized an HBT partitioning experiment with single electrons. We have used it to count the number of electron and hole excitations emitted per period. Antibunching of low energy excitations with thermal ones is observed which is used to probe the energy distribution of emitted particles. Since the demonstration of on demand generation of single electron states ⁶, many experiments relying on the coherent manipulation of single to few particles have been suggested ²⁴. This experiment is the first realization of an electron optics experiment at the single charge level which will kick-off the emerging field of electron quantum optics. Furthermore, the HBT geometry benefits from its high versatility. By applying a combination of \( AC + DC \) voltages on input 2, one can perform a complete tomography ⁴ of the electronic state in input 1.

In particular, one can obtain the detailed spectroscopy of single excitations which might be affected by interactions during propagation. The electronic variant of the Hong Ou Mandel experiment ² can also be realized by synchronizing the emission of one electron on each arm. This can be envisioned in the near future thanks to the present experimental realization.

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