Positive cross-correlations in a normal-conducting fermionic beam-splitter

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We investigate a beam splitter experiment implemented in a normal conducting fermionic electron gas in the quantum Hall regime. The cross-correlations between the current fluctuations in the two exit leads of the three terminal device are found to be negative, zero or even *positive* depending on the scattering mechanism within the device. Reversal of the cross-correlations sign occurs due to interaction between different edge-states and does not reflect the statistics of the fermionic particles which 'antibunch'.

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Measurements of time-dependent current fluctuations in mesoscopic devices serve as a great tool to investigate electronic correlations due to statistics and interactions [1]. It is well known that correlations caused by the fermionic statistics in a degenerated electron gas are responsible for the absence of any current fluctuations in mesoscopic devices with *open* channels and *normal* conducting contacts [2, 3, 4]. Consequently, the cross-correlations between different contacts in *multi-terminal* devices are always negative [5, 6]. Within the last years such negative cross-correlations have been observed in distinct experiments [7, 8, 9, 10]. It has also been shown that for a diluted stream of electrons obeying classical statistics the negative correlations vanish [9]. In the same period many theoretical papers report that the negative cross-correlations could be reversed into positive ones caused by 'non-normalconducting' contacts [11]. For example, this is the case if a current injecting normal contact is replaced by a superconducting one where positive cross-correlations occur due to the simultaneous emission of two electrons from the superconductor into different exit leads [12, 13, 14, 15, 16, 17, 18]. Alternatively, devices with ferromagnetic contacts can show positive cross-correlations due to 'opposite spin-bunching' [19] or dynamical spin-blockade [20].

In this article we are interested in a discussion by Texier and Büttiker [21] about another possibility for positive cross-correlations. These authors theoretically show how a device with only normal-conducting contacts could reveal positive cross-correlations due to current redistribution among different conducting states. We consider this idea here experimentally in a beam-splitter configuration (Fig. 1(a)) where a current I injected at contact 1 is split into two equal parts that exit into contacts 2 and 3. Our main result is the observation of positive cross-correlations between contact 2 and 3 for a particular implementation of the beam-splitter according to Ref. [21]. Positive cross-correlations have not been seen before in mesoscopic devices. Furthermore, we show that the interaction within the device can be turned on and off by an external 'knob' which allows to tune the cross-correlations between a positive value and zero.

Fig. 1(b) gives an 'inside view' of the physical implementation of the beam splitter configuration used to study the sign reversal of the cross-correlations: A two-dimensional electron gas (2DEG) is exposed to a perpendicular magnetic field so that the current flows in edge-states along the border of the device [22, 23]. Edge-states provide natural fermionic 'beams' which are, thanks to their chirality, easily split by a quantum point contact (QPC) into a transmitted and a reflected part [5]. The two (tunable) QPC's in series play different roles: the first one (A) introduces noise within the edge-state(s) while the second one (B) acts as a beam splitter that exits the edge-states or parts of them into different contacts.

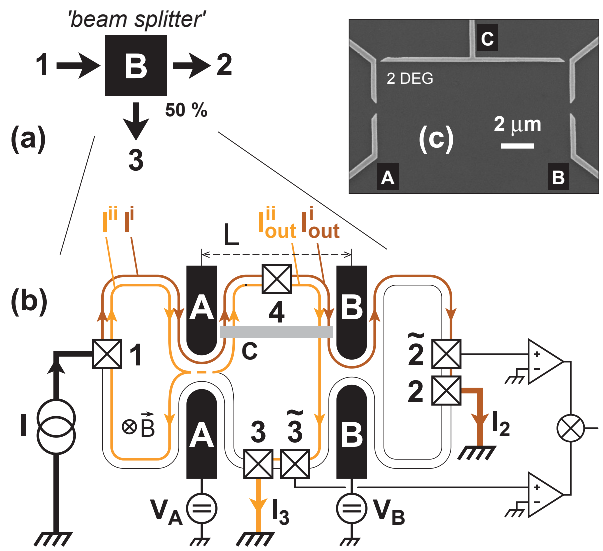

FIG. 1: (a) A current injected at 1 is split into partial currents flowing to 2 and 3. (b) Implementation of the beam splitter in the quantum Hall regime: The QPC A introduces partition noise in the current carried by the second edge-state (ii) (orange). The QPC B exits the two edge-states (i, ii) into different contacts. Equilibration between them occurs along the path from A to B when the current flows into an additional voltage probe 4. Gate C is used to disconnect probe 4 from the current path to switch the equilibration off. (c) Scanning electron microscope-image of the implementation in a two-dimensional electron gas with QPC's formed by metallic split gates.

In former experiments, only *one single* spin-degenerated edge-state was populated [9]. It was shown that the correlations are always negative as expected for a single stream of fermionic particles showing 'antibunching' behavior. What happens before the eletrons arrive at the beam splitter B is of no importance for the sign of the cross-correlation [9, 21].

In the following part we consider the case that exactly the last two spin-degenerated Landau levels are fully occupied. Partitioning at A with the transmission probability T_A^{ii} gives rise to current fluctuations in the second edge-state (ii). The power spectral density of these fluctuations is $\langle(\Delta I^{ii})^2\rangle_\omega = 2\,G_0\,T_A^{ii}(1-T_A^{ii})\,\mu_1$ with μ_1 the electrochemical potential of contact 1 and $G_0 = 2e^2/h$ [2, 3, 4]. The first edge-state remains noiseless because it is transmitted at A with unit probability ($T_A^i \equiv 1$). Inter-edge-state equilibration introduced via an extra voltage probe 4 redistributes the current fluctuations ΔI_{in}^{ii} in the current I_{in}^{ii} incident to the mixing contact 4 between the two outgoing edge-states I_{out}^i and I_{out}^{ii}: $\Delta I_{out}^i = \Delta I_{out}^{ii} = \Delta I^{ii}/2$. Finally, the 'beam splitter' B separates the two edge-states into two different contacts 2 and 3. Since the current fluctuations in both edge-states originate from the same scattering process at A the cross-correlations are expected to be *positive*. Their spectral density $\langle\Delta I_2\Delta I_3\rangle_\omega = \langle\Delta I_{out}^i\Delta I_{out}^{ii}\rangle_\omega$ divided by the Poissonian value $2e|I|$ equals [21]:

$$\frac{\langle\Delta I_2\Delta I_3\rangle_\omega}{2e|I|} = \frac{\langle(\Delta I^{ii})^2\rangle_\omega}{8e|I|} = +\frac{1}{4}\,\frac{T_A^{ii}(1-T_A^{ii})}{1+T_A^{ii}}. \quad (1)$$

Here, $I = G_0\,(1+T_A^{ii})\,\mu_1/e$ describes the total current injected at contact 1.

Experimentally, the device illustrated in Fig. 1(b) is implemented in a standard GaAs/$Al_{0.3}Ga_{0.7}$As-heterostructure. The QPC's A and B are defined by metallic split-gates on top of the 2DEG, which forms 60 nm below the surface with a carrier density of $1.5\cdot10^{15}\,\mathrm{m}^{-2}$ (Fig. 1(c)). A vertical magnetic field of 1.55 Tesla is applied to populate the last two spin-degenerated Landau levels. Two samples with different path lengths L (200 and 14 μm) between the two QPC's have been measured. The solid curve in Fig. 2(a) shows the reflected current I_3 (normalized to the total current I) as function of the voltage applied to gate B with gate A open. It is given by $I_3/I = 1 - (T_B^i + T_B^{ii})/2$. For $I_3/I < 0.5$ we obtain the transmission T_B^{ii} by measuring I_3 ($T_B^i \equiv 1$). The transmission T_A^{ii} is determined similarly.

In order to detect the current-current cross-correlations between contact 2 and 3 the time dependent currents $I_\alpha(t)$ ($\alpha = 2, 3$) are converted to voltage signals $V_{\tilde{\alpha}}(t)$ by two series resistors $R_{\tilde{\alpha}\alpha} = h/4e^2 + R_{0,\alpha}$ which are implemented in the device by means of additional ohmic contacts $\tilde{2}$ and $\tilde{3}$. $R_{0,\alpha}$ denotes the contact resistance of the ohmic contacts. The voltage fluctuations $\Delta V_{\tilde{\alpha}}(t) = \Delta I_\alpha(t) R_{\tilde{\alpha}\alpha}$ are measured by two low-noise amplifiers and fed into a spectrum analyzer which calculates the power spectral density. The RC-damping of the voltage noise due to the finite capacitance of the measurement lines (Fig. 2(b)) as well as the offset-noise S_0, which is related to the amplifiers, are obtained from a calibration measurement

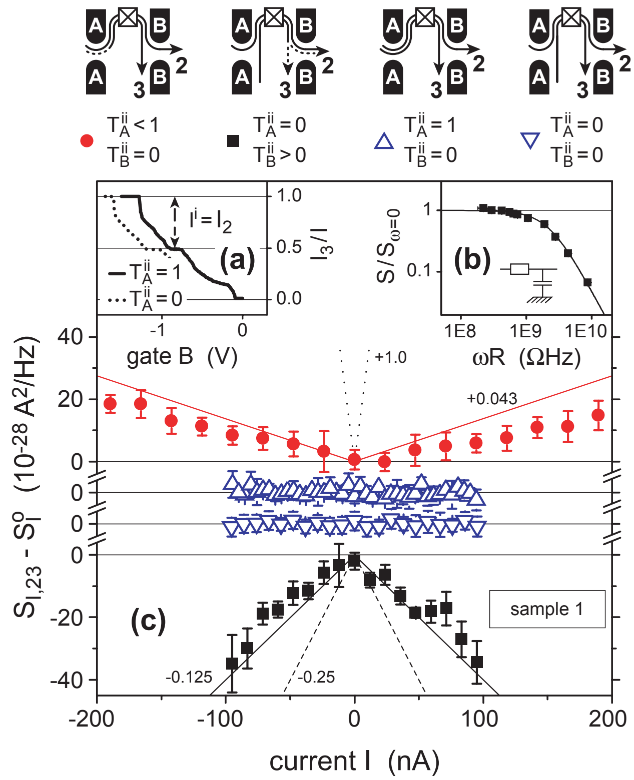

FIG. 2: Cross-correlations measurements for different transmissions of the QPC's A and B. The first edge-state (i) is always perfectly transmitted. Current fluctuations due to scattering at A are redistributed among the two edge-states so that positive cross-correlations are observed (red full circles). Partial scattering at the second point contact B reveals the fermionic nature of the edge-states and yields a negative correlation (black squares). The correlations are zero (blue triangles) in case that no partial scattering occurs at the QPC's. The data (▽) are measured on sample 2.

of the Nyquist noise $4k_B\theta R$ as function of the bath temperature θ for a given resistance R. The noise measurements are performed in a frequency range of 20 to 70 kHz with typical bandwiths of 5 kHz. The measurement frequencies as well as the current bias are chosen such that contributions from $1/f$-noise are negligible. All measurements were performed in a ^{3}He-cryostat with a base temperature of 290 mK.

Fig. 2(c) gives the cross-correlations $S_{I,23} = \langle\Delta I_2\Delta I_3\rangle_\omega$ between contact 2 and 3 measured on sample 1 for different configurations of gate A and B. Thereby, gate C is open and the outer edge-state (i) is always perfectly transmitted: $T_A^i = T_B^i \equiv 1$. In a first measurement T_A^{ii} equals $\simeq 0.5$ and the beam splitter B is adjusted such that the second edge-state is totally reflected ($T_B^{ii} = 0$), which corresponds to the configuration shown in Fig. 1(b). For these parameters we indeed observe a *positive* cross-correlation (red full-circles). The solid line is the maximal positive cross-correlation given by Eq. (1). For comparison the Poissonian-noise $S_0 = 2e|I|$ is given as dotted line. The total offset S_I^0 equals $3.13\cdot10^{-27}$ A^2/Hz. The current-noise of the amplifiers gives an offset $S_{I,\theta=0}^0$ of $3.91\cdot10^{-27}$ A^2/Hz, which we obtain from several temperature calibrations. From these two values

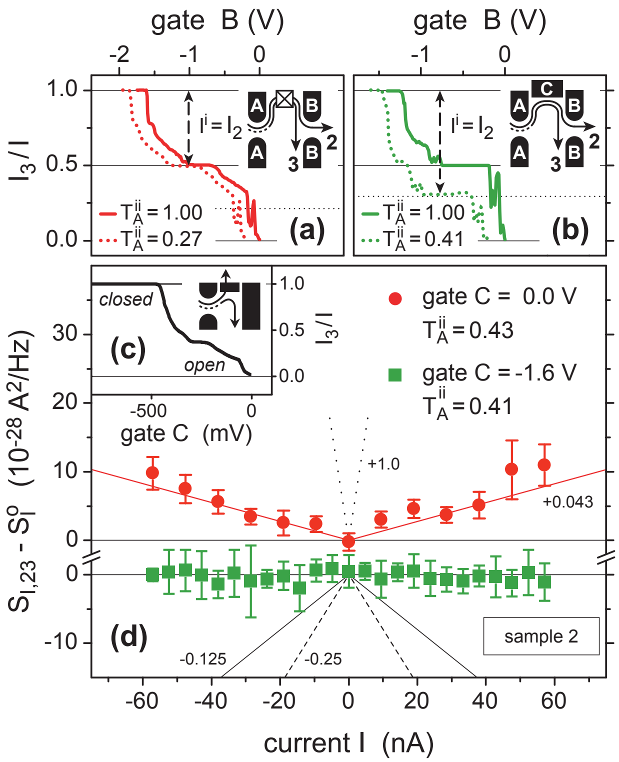

FIG. 3: (a, b) Normalized current at contact 3 for different transmissions T_A^{ii}. The curves are shifted for clarity. In (a) the edge-states equilibrate between A and B within a floating voltage probe so that they carry the same current. Thus, the height of the plateau in I_3/I does not change for different transmissions T_A^{ii}. (b) For gate C closed no equilibration occurs and thus, the current amounts carried by the two edge-states are unequal if the second edge-state is only partially transmitted at A ($T_A^{ii} = 0.41$). (c) I_3/I vs. gate C with gate B closed and $T_A^{ii} \simeq 0.4$. Contact 4 is put on ground. (d) A positive cross-correlation is observed with gate C open (equilibration) which disappears in the case of gate C closed (no equilibration).

the thermal correlations between contact 2 and 3 can be calculated $S_{I,23}(I{=}0) = S_I^0 - S_{I,\theta=0}^0 = -7.9 \cdot 10^{-28}$ A^{2}s, which turn out to be negative. Thermal correlations are always negative [5, 7]. They are not related to the statistics of the charge carriers but occur due to charge conservation. The measured value is in reasonable agreement with the theoretical prediction of $-k_B\theta\, G_0(3 - T^2) = -8.8 \cdot 10^{-28}$ A^{2}s for $T_B^{ii} = 0$, $T_A^{ii} = T = 0.5$ and $\theta = 290$ mK [21].

For transparencies $T_B^{ii} > 0$ the second edge-state is only partially reflected at the 'beam splitter'. Consequently, the statistical properties of the electrons in the fermionic 'beam' become apparent and the cross-correlations change sign from positive to negative. The solid line indicates the 'full anti-bunching' of $-2e|I|/8$ for $T_B^{ii} = 0.5$ and $T_A^{ii} = 1$ or 0. Naturally, for $T_A^{ii}, T_B^{ii} \in \{0, 1\}$ the cross-correlations are zero indicating that inelastic scattering between two edge-states alone does not introduce any noise in the system.

Next we will discuss what happens if there is no equilibration present. Fig. 2(a) gives the reflected current at contact 3 with gate C *closed* for $T_A^{ii} = 0$ and 1. The two curves are shifted in V for clarity. At the observed plateau, the second edge-state is totally reflected. Thus, it's height yields a direct measure for the amount of current carried by the edge-states [24]. Although for $T_A^{ii} = 0$, no current is carried by the second edge-state the plateau at $I_3/I = 0.5$ indicates current redistribution along the path $L = \overline{AB}$ from A to B of length $\simeq 200\,\mu$m. This is in agreement with detailed studies on equilibration lengths in the quantum Hall regime [24, 25]. In order to avoid equilibration, we have to consider another device where the path length L (=14 μm) of the two QPC's is much shorter.

Fig. 3(a, b) show the reflected current at contact 3 measured on this second device (sample 2). In (a) the edge-states equilibrate in contact 4, like in the first experiment, and the current is redistributed among the two edge-states so that the plateau does not change in height. In Fig. 3(b) however, gate C is closed and the current I^{ii} carried by the second edge-state now depends on the transmission T_A^{ii}. The dotted lines correspond to $I^{ii}/I = I_3/I = T_A^{ii}/(1 + T_A^{ii})$. The plateau which appears at the height of the dotted line in Fig. 3(b) thus proves that the two edge-states do not equilibrate. This should be noticed in the noise, too. Fig. 3(d) presents cross-correlation measurements with $T_B^{ii} = 0$ and $T_A^{ii} \simeq 0.42$. With equilibration in contact 4 (gate $C = 0.0$ V) the correlations are positive (red full circles) and in good agreement with the maximal positive correlation. If gate C is closed the first edge-state remains noiseless ($\Delta I^i = \Delta I_2 = 0$) and the correlator $\langle \Delta I^i \Delta I^{ii} \rangle_\omega = \langle \Delta I_2 \Delta I_3 \rangle_\omega$ vanishes (green squares). We thus have a 'knob' which allows us to turn the positive correlations on and off.

In Fig. 4 we compare the cross-correlations $S_{23}/2e|I|$ measured on the two different samples for various parameters T_A^{ii} and T_B^{ii} with theoretical calculations from Ref. [21]. At zero temperature the correlations between contact 2 and 3 are described by:

$$\frac{S_{I,23}}{2e|I|} = -\frac{\sum T_B^n(1 - T_B^n)}{2} + \frac{(\sum T_B^n)(2 - \sum T_B^n)}{4} \frac{\sum T_A^n(1 - T_A^n)}{\sum T_A^n}, \quad (2)$$

where $n = i, ii$ denotes the index of the two edge-states. The first term in Eq. (2) describes the negative correlations due to partitioning of the edge-states at B whereas the second term gives a positive contribution due to inter-edge-state equilibration. With $T_A^i = T_B^i \equiv 1$, Eq. (2) yields a maximal possible positive cross-correlation of $(3/4 - 1/\sqrt{2}) \simeq 0.043 \cdot S_0$ that occurs for $T_A^{ii} = \sqrt{2} - 1$ with $T_B^{ii} = 0$. In Fig. 4(a) the measured positive correlations are somewhat smaller for sample 1 (black circles). For sample 2 with a smaller path length L between the QPC's the data points (open circles) are rather close to the expected value. Although the QPC B is adjusted to a plateau with high precision the second edge-state (ii) might not be reflected perfectly. Already a tiny transmission T_B^{ii} of 2 % reduces the maximal positive cross-correlation by 23 %, illustrated by one of the dashed curves in Fig. 4(a). The positive correlations completely disappear for $T_B^{ii} > 9\,\%$. The

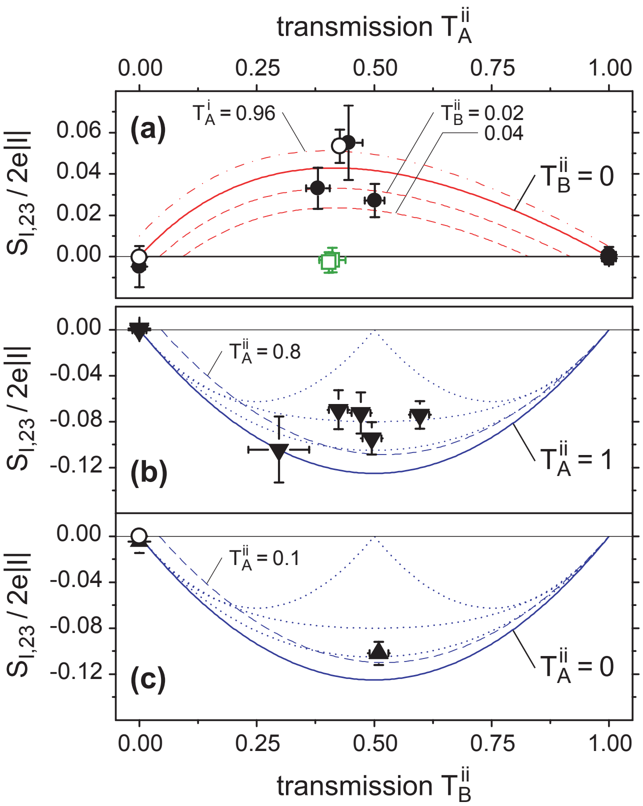

FIG. 4: Cross-correlation for various T_A^{ii}, T_B^{ii} extracted from noise measurements on two different samples (filled symbols: $\overline{AB} \simeq 200\,\mu$m, open symbols: $\overline{AB} \simeq 14\,\mu$m). (a) Positive cross-correlations occur for $T_B^{ii} = 0$. If the second edge-state is not totally reflected at the 'beam splitter' ($T_B^{ii} > 0$) the cross-correlations are less positive. (b, c) For $T_A^{ii} = 0$ or 1 the correlations are always negative. Deviations from Eq. (2) occur due to unequal transmission of the two spin-polarized parts of the second edge-state.

high sensitivity to any changes from $T_B^{ii} = 0$ thus might explain the deviations from the solid curve. The open (green) squares in Fig. 4(a) are the results from sample 2 where gate C is closed so that the state-mixing voltage probe 4 is disconnected. Cross-correlations larger than $0.043 \cdot S_0$ could theoretically occur due to additional scattering of the first edge-state at A. The dashed-dotted curve gives an example for $T_A^i = 0.96$ instead of 1 that would yield a maximal positive correlation of $0.051 \cdot S_0$.

Fig. 4(b, c) summerize the negative correlations obtained for $T_A^{ii} = 1$ and 0, respectively. The data points do not exactly agree with the expected values according Eq. (2) (solid curves). The dashed curves denote the changes that would occur due to additional scattering at the first QPC A, yielding a small positive contribution to the negative correlations [9]. However, the transmission at A equals 0 or 1 (open gate) with quite high precision ($|\Delta T_A^{ii}| \leq 0.03$) and we think that the deviations observed here are related to non-equal transmission probabilities of the two spin-polarized parts in the second edge-state. The dotted lines in Fig. 4(b) and (c) are the negative correlations for 20, 40 and 100 % unequal transmission (from bottom to top). For one spin-polarized edge-state totally transmitted and the other totally reflected the correlations would be zero for $\langle T_B^{ii} \rangle = 0.5$. From the data we estimate that the differences between the two transmissions are in the order of 20 - 40 % of T_B^{ii}.

In conclusion we have observed positive cross-correlations in a multi-terminal electronic device. This positive correlations occur due to interactions between different current carrying states inside the device and can be switched on and off by means of an external gate voltage, which controls the interaction inside the device.

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[1] For a review, see: Y. M. Blanter and M. Büttiker, Phys. Rep. **336**, 1 (2000); for a short introduction, see: C. W. J. Beenakker and C. Schönenberger, Phys. Today **56**, 37 (2003).
[2] V. A. Khlus, Sov. Phys. JETP **66**, 1243 (1987).
[3] G. B. Lesovik, JETP Lett. **49**, 592 (1989).
[4] M. Büttiker, Phys. Rev. Lett. **65**, 2901 (1990).
[5] M. Büttiker, Phys. Rev. B **46**, 12485 (1992).
[6] Th. Martin and R. Landauer, Phys. Rev. B **45**, 1742 (1992).
[7] M. Henny, S. Oberholzer, C. Strunk, T. Heinzel, K. Ensslin, M. Holland, and C. Schönenberger, Science **284**, 296 (1999).
[8] W. D. Oliver, J. Kim, R. C. Liu, Y. Yamamoto, Science **284**, 299 (1999).
[9] S. Oberholzer M. Henny, C. Strunk, C. Schönenberger, T. Heinzel, K. Ensslin, and M. Holland, Physica E **6**, 314 (2000).
[10] H. Kiesel, A. Renz, and F. Hasselbach, Nature **418**, 392 (2002).
[11] for a review, see: M. Büttiker, "Reversing the sign of current-current correlations" in "Quantum Noise", edited by Yu. V. Nazarov and Ya. M. Blanter, Kluwer, p. 3 - 31 (2003).
[12] M. P. Anantram and S. Datta, Phys. Rev. B **53**, 16390 (1996).
[13] Th. Martin, Phys. Lett. A **220**, (1996).
[14] J. Torres and Th. Martin, Eur. Phys. J. B **12**, 319 (1999).
[15] T. Gramespacher and M. Büttiker, Phys. Rev. B **61**, 8125 (2000).
[16] P. Recher, E. V. Sukhorukov, and D. Loss, Phys. Rev. B **63**, 165314 (2001).
[17] J. Börlin , W. Belzig, and C. Bruder, Phys. Rev. Lett. **88**, 197001 (2002).
[18] P. Samuelsson and M. Büttiker, Phys. Rev. Lett. **89**, 046601 (2002).
[19] O. Sauret and D. Feinberg, Phys. Rev. Lett. **92**, 106601 (2004).
[20] A. Cottet, W. Belzig, and C. Bruder, Phys. Rev. Lett. **92**, 206801 (2004).
[21] C. Texier and M. Büttiker, Phys. Rev. B **62**, 7454 (2000).
[22] B. I. Halperin, Phys. Rev. B **25**, 2185 (1982).
[23] M. Büttiker, Phys. Rev. B **38**, 9375 (1988).
[24] B. W. Alphenaar, P. L. McEuen, R. G. Wheeler, and R. N. Sacks, Phys. Rev. Lett. **64**, 677 (1990).
[25] B. J. van Wees *et al.*, Phys. Rev. Lett. **62**, 1181 (1989).