Positive cross-correlations induced by ferromagnetic contacts

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Due to the discrete nature of charge carriers, correlations between electric currents flowing through a conductor is subject to time-dependent fluctuations around its mean value. Correlations of such fluctuations are of great interest since they provide more information, with respect to average currents, on the physics of transport. Shot noise, defined as the mean-square fluctuations of the current flowing through a given terminal at zero temperature, has been extensively studied in a wide variety of systems (for a review on the subject see Ref. [1]). Here we are interested in the correlations of the current fluctuations between different contacts (cross-correlations). Büttiker [2] first pointed out that while cross-correlations can either be positive or negative for Bosons, for Fermions they are necessarily negative, both in the equilibrium situation and in the transport regime (see also Ref. [3]).

At this point a question arises naturally: what happens in the presence of superconductivity, where charge current is carried by the superconducting condensate instead of by Fermionic excitations. In the sub-gap regime the presence of the condensate manifests itself in the doubling of shot noise, as found for normal/superconductor (NS) interfaces theoretically in Refs. [1] and experimentally confirmed in Refs. [4,5]. Moreover, in Refs. [4,5] it has been shown that multi-terminal hybrid structures containing superconducting inclusions or leads can, in some cases, exhibit positive cross-correlations. In particular, in Ref. [4] current correlations have been studied as a function of the phase difference $\phi$ between the superconducting order parameter of two superconductors that are coupled to each other. We consider three-terminal hybrid structures and calculate the mean-square correlations of current fluctuations as a function of the bias voltage at finite temperature.

I. INTRODUCTION

Due to the discrete nature of charge carriers, the electronic current flowing through a conductor is subject to time-dependent fluctuations around its mean value. Correlations of such fluctuations are of great interest since they provide more information, with respect to average currents, on the physics of transport. Shot noise, defined as the mean-square fluctuations of the current flowing through a given terminal at zero temperature, has been extensively studied in a wide variety of systems (for a review on the subject see Ref. [1]). Here we are interested in the correlations of the current fluctuations between different contacts (cross-correlations). Büttiker [2] first pointed out that while cross-correlations can either be positive or negative for Bosons, for Fermions they are necessarily negative, both in the equilibrium situation and in the transport regime (see also Ref. [3]).

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It is worthwhile mentioning that all the above results are relative to a fully phase-coherent transport regime. A doubling of shot noise, however, has been also found within a semi-classical theory [8,9], therefore proving that phase-coherence is not required for such an effect to occur. More importantly, in hybrid systems in which a semi-classical treatment is valid, cross-correlations have been demonstrated to be always negative.

Recently, advances in nano-fabrication techniques of hybrid normal-metal/ferromagnet structures has led to the advent of spintronics [10]. In such a context the spin degree of freedom of electrons is exploited (instead of their charge) and spin-current correlations can be accessed. In this paper we introduce this new ingredient and we address the question whether ferromagnetism has an effect on the sign of the cross-correlations.

As far as transport is concerned, a ferromagnet can be thought as a conductor in which spin-up and spin-down electrons contribute by a different amount to the total current (the spin degeneracy is broken). For example, in the limit of a 100% polarized ferromagnet (the so called “half metal”), current is carried by a single spin species. Due to the fact that in a s-wave superconductor spin-up particles are coupled to spin-down holes, non-trivial effects are expected on the cross-correlations between two ferromagnetic contacts having magnetizations in opposite directions. We shall show that a positive value of cross-terminal correlations in such hybrid systems can be induced (as noticed in Ref. [11]) or, if already present, enhanced. Remarkably, positive cross-correlations are pre-

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dicted over a wide range of bias voltages, even above the energy gap, for structures which exhibit negative correlations when the ferromagnets are replaced with normal metals. As expected, such an effect gets stronger as the ferromagnetic exchange field is increased and reaches a maximum for exchange fields corresponding to the limiting case of half-metallic leads. The effect remains essentially unchanged even in the presence of disorder, due to impurities and lattice imperfections.

II. THE MODEL

We consider a realistic hybrid 2D system attached to three multi-channel terminals. As sketched in Fig. 1, it consists of a superconducting island (which defines the scattering region) connected to one normal metallic lead (1) on the left-hand-side and two ferromagnetic leads (2 and 3) on the right-hand-side (similar structures have already been considered in Refs. [19–22]). The directions of magnetization of leads 2 and 3 are chosen to be anti-parallel to each other. The two ferromagnetic electrodes are kept at the same potential with respect to the normal lead (\( V_1 - V_2 = V_1 - V_3 = V \)). For definiteness we assume the magnetization of lead 2 directed upward while the magnetization of lead 3 directed downward.

Shot noise and cross-correlations are calculated within the multiple scattering approach. The scattering matrix \( S \) completely characterizes a given structure (scatterer) attached, through perfect conductors (leads), to \( N \) reservoirs of particles. \( S \) is defined via the asymptotic wave functions of the leads, known as scattering states. When the scatterer contains superconducting regions, the scattering states are solutions of the Bogoliubov-de Gennes equation [23]

\[
\begin{pmatrix} H_p & \Delta \\ \Delta^* & H_h \end{pmatrix} \begin{pmatrix} u(x) \\ v(x) \end{pmatrix} = E \begin{pmatrix} u(x) \\ v(x) \end{pmatrix}.
\]

In Eq. (1) \( H_p \) is the Hamiltonian relative to the particle degrees of freedom, \( H_h \) is the Hamiltonian relative to hole degrees of freedom and \( \Delta \) is the superconducting order parameter, non-zero only in the superconducting regions. Let us consider, for example, a unit flux of particles originating from the \( j \)-th reservoir. The scattering state for the \( j \)-th lead (assuming for simplicity a single open channel per lead) takes the form

\[
\psi_j(x) = \begin{pmatrix} u(x) \\ v(x) \end{pmatrix} = \begin{pmatrix} (r_0)_{j} e^{i k_x x} + (r_a)_{j} e^{-i k_x x} \\ \langle r_a \rangle_{j} e^{i k_x x} \end{pmatrix}, \tag{2}
\]

whereas for the \( i \)-th lead, with \( i \neq j \), it reads

\[
\psi_i(x) = \begin{pmatrix} u(x) \\ v(x) \end{pmatrix} = \begin{pmatrix} (t_0)_{ij} e^{i k_x x} + (t_a)_{ij} e^{-i k_x x} \\ \langle t_a \rangle_{ij} e^{i k_x x} \end{pmatrix}. \tag{3}
\]

Here \( (r_0)_{j} \) and \( (r_a)_{j} \) are, respectively, normal and Andreev reflection amplitudes, while \( (t_0)_{ij} \) and \( (t_a)_{ij} \) are, respectively, normal and Andreev transmission amplitudes. In Eqs. (2) and (3) \( \omega_j \) is the group velocity in lead \( j \) for particles (holes) and \( k_j \) (\( q_j \)) is the wave-vector for particles (holes). \( S \) is the matrix of scattering amplitudes of dimension \( (2N \times 2N) \) defined by

\[
| \text{out} \rangle = S | \text{in} \rangle
\]

which relates the amplitudes of an incoming wave function \( (| \text{in} \rangle) \) to the amplitudes of an outgoing wave function \( (| \text{out} \rangle) \). We assume the convention that the upper \( N \) elements of such vectors are relative to particles and the lower ones to holes.

Following Refs. [13–22] the noise power \( s_{ii} \) is defined as the Fourier transform of the mean correlations of the current fluctuations in leads \( i \) and \( l \):

\[
\frac{1}{2} \langle \Delta I_i(t) \Delta I_l(t') + \Delta I_l(t') \Delta I_i(t) \rangle \tag{5}
\]

where \( \Delta I_i(t) = \bar{I}_i(t) - \langle \bar{I}_i \rangle \) is the current fluctuation operator in lead \( i \) at time \( t \) and the angle brackets \( \langle \ldots \rangle \) denotes a statistical average. By defining the time-dependent current operator as

\[
\tilde{I}_i(t) = \frac{2 e}{h} \int_0^\infty dE \sum_a \sum_{j', \beta} \bar{\tilde{a}}_{j' \beta}^\dagger (E) \bar{A}^a_{j' \beta} (i, E, E') \tilde{a}_{j \beta} (E'), \tag{6}
\]

one obtains the following expression for the zero-frequency noise power [22]

\[
s_{ii}(V, T) = \frac{2 e^2}{h} \int_0^\infty dE \sum_{a_1 a_2} \sum_{j_1 j_2} \bar{A}^a_{j_1 \beta b_1} (i, E, E') A^a_{j_2 \beta b_2} (l, E, E') \langle f_{j_1 \beta} (E) [1 - f_{j_2 \beta} (E)] + f_{j_2 \beta} (E) [1 - f_{j_1 \beta} (E)] \rangle. \tag{7}
\]

In Eq. (6) \( \tilde{a}_{j \beta}^\dagger (E) \) is the creation operator for an incoming particle (\( \beta = +1 \)) or hole (\( \beta = -1 \)) with open channel index \( b \) at energy \( E \) originating from lead \( j \). The quantity \( \bar{A}^a_{j_1 \beta b_1} (i, E, E') \) is defined in terms of the scattering matrix as

\[
\bar{A}^a_{j_1 \beta b_1} (i, E, E') = \frac{1}{2} \sum_{j_2 \beta b_2} e^{\frac{i}{\hbar} k_{j_2} x} \bar{a}_{j_2 \beta} (E) A^a_{j_2 \beta} (i, E, E') \tilde{a}_{j_1 \beta} (E').
\]
where $A_{jβkj′β′}(i,E,E') = δ_{ij}δ_{j′i}δ_{βk}δ_{β′k'}δ_{ba}δ_{b′a'} - δ_{ij}δ_{j′i}δ_{βk}δ_{β′k'}δ_{ba}δ_{b′a'} - S^*_{(i+a),(jβb)}(E)S_{(i+a),(j′β′b')}(E') + S^*_{(i-a),(jβb)}(E)S_{(i-a),(j′β′b')}(E')$, relative to spin-down particles and spin-up holes. Since they are decoupled, no correlations are present between spin-up and spin-down particles (or holes). From this follows that, as long as the system is symmetrical under the exchange of leads 2 and 3, the results for spin-down polarized injected current are equal to the results for spin-up polarized injected current once indices 2 and 3 are exchanged. For simplicity, then, we assume the current injected from lead 1 to be 100% spin-up polarized and for this reason we can drop the spin index in the definition of the on-site energy. In the recursive Green’s function technique the scattering amplitudes are calculated numerically from the total Green’s function of the system, which in turn is evaluated through the effective Hamiltonian of the scattering region and the Green’s functions of the isolated leads.

### III. RESULTS

In our calculations the scatterer (shaded region in Fig. 1) is a superconductor 15 sites long (in unit of lattice spacings) and 15 sites wide. The leads are 3 sites wide: lead 1 is attached in the central position on the left-hand-side, whereas leads 2 and 3 are placed symmetrically with respect to the center of the right-hand-side at a distance of 5. In arbitrary units, the order parameter is set to $Δ = 0.1$ uniformly in the superconducting region, therefore neglecting the suppression of the superconducting order parameter in the regions adjacent to the ferromagnets. Such a suppression would lead to very small corrections, since it is expected to occur over very short lengths (units of nanometers for hard ferromagnets), orders of magnitude smaller than the superconducting coherence length. The temperature in the reservoirs is set to $T = 0.01$, while the Fermi energy is about 1.6. With these values we have three open channels in the normal lead for particles and holes at the Fermi energy and a superconducting coherence length of the order of 10 lattice constants. Note furthermore that the condensate electrochemical potential $µ$ is set to $µ = 0$.

As a reference situation we first consider the case where leads 2 and 3 are normal-metallic ($h = 0$). In Fig. 2 and Fig. 3 we plot the noise power relative to the different pairs of leads as a function of the bias voltage $V$. When the superconductor is in the normal state (Fig. 2) we find, as expected, that the shot noise in lead 1 is positive whereas the cross-correlations are negative. In the presence of superconductivity (Fig. 3), even though the magnitude of the cross-correlations changes, the sign remains negative. We now arrive at the main result of the paper, namely, that a positive sign can be induced by replacing leads 2 and 3 with ferromagnets characterized by
magnetizations in opposite directions. This is shown in Fig. 3 for the limiting case of half-metals, where cross-correlations exhibit a positive sign. While $s_{12}$ changes sign as $V$ is increased, the effect on $s_{23}$ is more dramatic as it maintains a positive sign over the whole voltage range, with a large magnitude. It is remarkable that $s_{23}$ remains positive over wide ranges of voltages, even exceeding the superconducting energy gap. Of course $s_{12}$ and $s_{13}$ are less affected by ferromagnetism than $s_{23}$, since lead 1 is normal-metallic. In the following we will concentrate on the behaviour of $s_{23}$.

In Fig. 3 we plot $s_{23}$ as a function of the magnitude of the exchange field $h$ in the ferromagnetic leads 2 and 3 for four different values of bias voltages. First note that the four curves show the same behaviour, more pronounced in magnitude for larger $V$. For zero exchange field, i.e. with normal contacts, $s_{23}$ takes negative values despite the presence of superconductivity. For finite values of $h$, $s_{23}$ increases turning to positive values, and thereafter increasing further rapidly reaching a plateau. The plateau corresponds to values of exchange field relative to full polarization, therefore it is an artifact of the small number of open channels.

As already noted in Refs. [1,13], the reason for which positive cross-correlations arise in the presence of superconductivity can be understood by expressing the current operator of Eq. (6) as a sum of particle and hole contributions:

$$I_i(t) = \tilde{I}_i^+(t) + \tilde{I}_i^-(t).$$

By substituting Eq. (13) in Eq. (8), the noise power $\tilde{s}_{il}$ [Eq. (9)] can be written as the following sum:

$$\tilde{s}_{il} = \tilde{s}_{il}^{++} + \tilde{s}_{il}^{--} + \tilde{s}_{il}^{+-} + \tilde{s}_{il}^{-+}$$

where $\tilde{s}_{il}^{++}$ is the particle-particle (pp) cross-correlation, $\tilde{s}_{il}^{+-}$ is the particle-hole (ph) cross-correlation, and so on. Quite generally it was shown in Ref [1] that while $\tilde{s}_{il}^{++}$ and $\tilde{s}_{il}^{--}$ are negative, $\tilde{s}_{il}^{+-}$ and $\tilde{s}_{il}^{-+}$ take a positive sign. Intuitively, one can understand that pp (and hh) correlations are negative because of the anti-bunching behaviour due to the Fermionic nature of electrons. For the same reason, ph and hp correlations present a positive sign simply because particle and hole have opposite charge (note that when the superconductor is in the normal state ph and hp correlations are zero). The sign of the overall cross-correlation is therefore determined by the competition between the positive (ph and hp) and the negative (pp and hh) contributions. The important observation is that pp and hh cross-correlations can be drastically suppressed in the presence of spin-polarized transport, for example by allowing only spin-up polarized current in one lead and only spin-down polarized current in the other. As a result an overall positive sign will be induced.

In the system under investigation the different contributions to $\tilde{s}_{23}$, in the zero-temperature, small bias voltage limit and with $\mu$ set to zero, take the simple form

$$\tilde{s}_{23} = -\frac{4e^3V}{h} \left[T_{21}^{++}T_{31}^{++} + T_{21}^{--}T_{31}^{--}\right],$$

where $T_{i1}^{\alpha\beta}$ is the transmission probability, evaluated at $E = 0$, for a particle ($\beta = +1$) or a hole ($\beta = -1$) injected from lead 1 to be transmitted into lead $i$ as a particle ($\alpha = +1$) or a hole ($\alpha = -1$). In the limiting situation where leads 2 and 3 are half-metallic with magnetizations aligned anti-parallel to each other (for example upward for 2 and downward for 3), we have that positive correlations are non-zero. Particle-particle and hole-hole correlations, in fact, vanish ($\tilde{s}_{23}^{++} = \tilde{s}_{23}^{--} = 0$) because transmission of spin-up particles is forbidden in lead 3 and transmission of spin-down particles is forbidden in lead 2: $T_{31}^{++} = T_{21}^{--} = 0$. For weaker ferromagnets $s_{23}^{++}$ are finite, but nevertheless suppressed with respect to ph correlations so that $\tilde{s}_{23}$ remains positive. It is worthwhile noting that it is possible to switch the sign of $s_{23}$ from positive to negative by changing the relative alignment of the magnetizations in the two ferromagnetic leads from anti-parallel to parallel. In the latter case, in fact, $T_{31}^{++}$ and $T_{21}^{--}$ in Eq. (15) are both equal to zero in the limit of half-metallic leads, so that only $\tilde{s}_{23}^{++}$ is left finite, analogously to what happens when the superconductor is turned normal. For completeness, note that by summing over the indices $\alpha$ and $\gamma$ in Eq. (13) and employing the particle-hole symmetry one obtains the simple expression

$$\tilde{s}_{23} = -\frac{8e^3V}{h} \left(|(t_0)_{31}|^2 - |(t_a)_{31}|^2\right) \times \left(|(t_0)_{21}|^2 - |(t_a)_{21}|^2\right).$$

We can also understand the reason why positive correlations in Fig. 3 survive over such a wide voltage range. While pp correlations are zero, ph correlations tend to vanish only for quasi-particles energy well above the superconducting gap (about one order of magnitude), i.e. when Andreev processes are negligible. Furthermore, the effect on the sign of $s_{12}$ and $s_{13}$ is less pronounced than on $s_{23}$, because in the former cases pp or hh correlations can still be large. It is worthwhile mentioning that the presence of barriers at the interfaces between electrodes and the superconductor is expected to affect the cross-correlations (analogously to the findings of Ref. [13]). Eq. (17) shows that the sign of $s_{23}$ can change with the barrier strength, since such a sign is determined by the interplay between normal and Andreev transmissions between leads 1 and 2, and 1 and 3. In the case of half-metallic contacts, it is clear that cross-correlations $s_{23}$ will still be positive regardless of the value of the barrier strength, because negative contributions (pp and hh correlations) are always zero. However, we expect that the magnitude of $s_{23}$ might depend on the barrier strength non-monotonically. In fact, while normal transmission coefficients decrease with increasing barrier strength, Andreev transmissions do not monotonically depend on the
IV. SUMMARY

The study of electronic current-current correlations in mesoscopic structures has been receiving interest since the last decade. On the one hand, it has been found that the correlations between different leads are always negative. On the other, in hybrid NS structures it has been proved that such correlations can, in some cases, be positive. Here we have considered the sign of cross-correlations in a hybrid NS three-terminal structure in which ferromagnetic leads are employed. We have found that a positive sign of the cross-correlations between two ferromagnetic leads is induced when their magnetizations are aligned anti-parallel to each other. It is remarkable that such a positive sign persists over a wide range of voltages exceeding the value corresponding to the superconducting energy gap. Furthermore positive cross-correlations have also been found between normal metallic and ferromagnetic leads. The origin of this effect has been attributed to the suppression of particle-particle and hole-hole cross-correlations (which contribute with a negative sign) in favour of particle-hole correlations (which contribute with a positive sign), due to the strong spin-asymmetry introduced by ferromagnetism. We have moreover realized that it is possible to switch the sign of $\bar{s}_{23}$ from positive to negative by changing the the relative alignment of the magnetizations in the two ferromagnetic leads from anti-parallel to parallel. Such effects are robust against the presence of weak disorder within the superconducting region. To conclude, we would like to emphasize that our approach can be applied to disordered diffusive samples as well as clean and ballistic ones and to any geometry. Furthermore, it can be easily extended to finite frequencies.

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Fig. 1. The system consists of a superconductor (S) connected to 3 contacts. Terminals 2 and 3 are made of ferromagnets, with anti-parallel magnetizations, while terminal 1 is normal-metallic. Lead 1 is kept at positive potential $V_1$ with respect to leads 2 and 3. The relevant geometric lengths are of the same order of the superconducting coherence length.

Fig. 2. Noise power as a function of bias voltage $V$ with S in the normal state and $h = 0$ in leads 2 and 3. Due to the geometrical symmetry $\bar{s}_{13}$ is exactly equal to $\bar{s}_{12}$.

Fig. 3. Noise power as a function of bias voltage $V$ with S in the superconducting state and $h = 0$ in leads 2 and 3. The vertical line denotes the voltage corresponding to the superconducting energy gap. Due to the geometrical symmetry $\bar{s}_{13}$ is exactly equal to $\bar{s}_{12}$.

Fig. 4. Noise power as a function of bias voltage $V$ with S in the superconducting state and half-metallic leads 2 and 3. Note that cross-correlations are plotted on a different scale with respect to $\bar{s}_{11}$. The vertical line denotes the voltage corresponding to the superconducting energy gap.

Fig. 5. Cross-correlation $\bar{s}_{23}$ as a function of the magnitude of the exchange field $h$ in leads 2 and 3 for four different bias voltages.