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Current noise generated by spin imbalance in presence of spin relaxation

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The ability to detect nonequilibrium spin accumulation (imbalance) by all-electrical means is one of the key ingredients in spintronics [1]. Transport detection typically relies on a nonlocal measurement of a contact potential difference induced by the spin imbalance by means of ferromagnetic contacts [2–6] or spin resolving detectors [7]. A drawback of these approaches lies in a difficulty to extract the absolute value of the spin imbalance without an independent calibration.

An alternative concept of a spin-to-charge conversion via nonequilibrium shot noise was introduced in Ref. [8] and recently investigated experimentally [9]. Here, the basic idea is that a nonequilibrium spin imbalance generates spontaneous current fluctuations, even in the absence of a net electric current. Being a primary approach [10], the shot noise based detection is potentially suitable for the absolute measurement of the spin imbalance. In addition, the noise measurement can be used for a local non-invasive sensing, as recently demonstrated with a semiconductor nanowire probe [11].

It is well known, how a relaxation of the electronic energy distribution via inelastic electron-phonon [12] and electron- electron [13, 14] scattering influences the shot noise in diffusive conductors and nonequilibrium spin valves [15]. In this letter, we calculate the impact of a spin relaxation on the spin imbalance generated shot noise in the absence of inelastic processes. We find that the spin relaxation increases the noise up to a factor of two, depending on the ratio of the conductor length and the spin relaxation length.

Consider the system shown in Fig. 1. It consists of a diffusive wire, one end of which is grounded and the other is attached to a conducting island much larger than the transverse dimensions of the contact. The spin imbalance in the island is produced by electron tunneling through two junctions connecting it to ferromagnetic leads with antiparallel magnetizations. The junctions

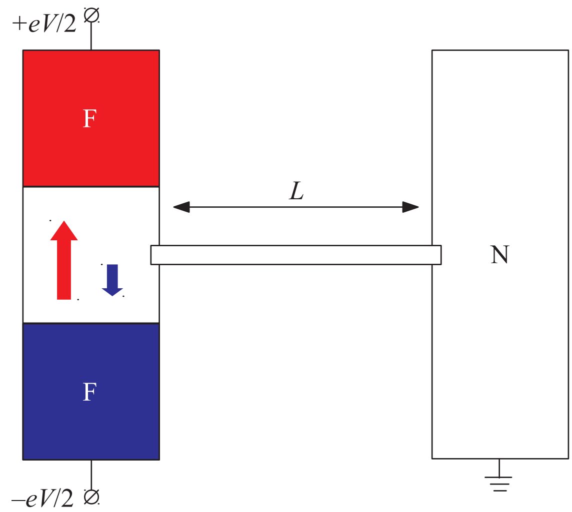

Fig. 1. (Color online) The design of the system. A diffusive normal wire of the length L is attached to normal islands on both ends. Nonequilibrium energy distribution on the left hand side of the wire generates the shot noise at a zero net current. The spin imbalance on the left-hand side of the wire is due to the electric current flowing from one ferromagnetic lead (red) to another one with opposite magnetization (blue)

are assumed to have equal conductances much smaller than that of the island, and the ferromagnetic leads are antisymmetrically biased by voltages $V/2$ and $-V/2$, so the island has zero electrical potential and the net electrical current through the wire is zero. However the tunneling results in a nonequilibrium spin-dependent distribution of electrons in the island. If the conductance of the diffusive wire is small as compared with the conductances of tunnel junctions, the equation for the distribution functions of spin-up and spin-down electrons, f_σ ($\sigma = \pm$) in the island may be written in the form

$$\frac{\partial f_\sigma}{\partial t} = \Gamma_{L\sigma}\left[f_0(\varepsilon - eV/2) - f_\sigma\right] + \\ + \Gamma_{R\sigma}\left[f_0(\varepsilon + eV/2) - f_\sigma\right] - \frac{1}{\tau_s}(f_\sigma - f_{-\sigma}), \qquad (1)$$

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where Γ's are the tunneling rates through the left and right barriers for spin-up and spin-down electrons, $f_0(\varepsilon)$ is the equilibrium distribution function of electrons, and τ_s is the spin-flip scattering time.

The magnetization of the leads enters into Eq. (1) via the tunneling rates, which is nonzero for the majority-spin electrons and zero for the minority-spin electrons. For the antiparallel magnetization, we assume that $\Gamma_{L-} = \Gamma_{R+} = 0$ and $\Gamma_{L+} = \Gamma_{R-} = \Gamma$. The stationary solution of Eq. (1) is given by

$$f_+(\varepsilon) = \frac{1+\alpha}{2}\, f_0(\varepsilon - eV/2) + \frac{1-\alpha}{2}\, f_0(\varepsilon + eV/2), \tag{2}$$

$$f_-(\varepsilon) = \frac{1-\alpha}{2}\, f_0(\varepsilon - eV/2) + \frac{1+\alpha}{2}\, f_0(\varepsilon + eV/2), \tag{3}$$

where $\alpha = \Gamma\tau_s/(1+\Gamma\tau_s)$. For the parallel magnetization of the leads, $\Gamma_{L-} = \Gamma_{R-} = 0$ and $\Gamma_{L+} = \Gamma_{R+} = \Gamma$, so $f_+(\varepsilon)$ and $f_-(\varepsilon)$ are given by (2) and (3) with $\alpha = 0$. The distribution functions in the diffusive wire satisfy the diffusion equation

$$D\,\frac{\partial^2 f_\sigma}{\partial x^2} = \frac{f_\sigma - f_{-\sigma}}{2\,\tau_s}$$

with the boundary conditions (2) and (3) at the left end and $f_\sigma(L,\varepsilon) = f_0(\varepsilon)$ at the right end. Using a standard expression for the shot noise of a diffusive conductor [12], $S_I = \frac{2}{R}\int_0^L \frac{dx}{L}\int d\varepsilon \sum_\sigma f_\sigma\,(1-f_\sigma)$, we obtain the final result for the shot noise ($T \ll eV$)

$$S_I = \frac{eV}{R}\left[\frac{2}{3} - \frac{\alpha^2 l_s}{2L}\,\frac{e^{2L/l_s}+1}{e^{2L/l_s}-1} + \frac{2\alpha^2 e^{2L/l_s}}{(e^{2L/l_s}-1)^2}\right], \tag{4}$$

where $l_s = \sqrt{D\,\tau_s}$ is the spin relaxation length.

For $\alpha = 0$, i.e. the non-equilibrium double-step electronic energy distribution in the absence of spin imbalance, the spin relaxation has no effect and we recover a familiar result [11, 16] $S_I = 2eV/3R$. By contrast, the case of $\alpha = 1$, which corresponds to the injection of a pure spin current into the conductor, is strongly sensitive to the spin relaxation. In this case, the noise equals $S_I = eV/3R$ for a vanishing spin relaxation and increases with the ratio L/l_s. In the asymptotic limit $L \gg l_s$, the noise increases by a factor of 2, see Eq. (4), where the results for $\alpha = 0$ and $\alpha = 1$ coincide.

Our results lead to a more general conclusion. Elastic spin relaxation always tends to equalize the distributions of spin-up and spin-down electrons and bring them to $\overline{f}_\pm = (f_+ + f_-)/2$. Obviously, this results in the increase of the shot noise, since $2\overline{f}_\pm(1-\overline{f}_\pm) \geq \sum f_\sigma(1-f_\sigma)$. The magnitude of the increase is thus a measure of the spin imbalance.

In summary, in an idealized three-terminal setup with two tunnel-coupled ferromagnetic leads and one normal lead the shot noise is found to increase by a factor of two as the length of the conductor becomes larger than the spin relaxation length. The increase of the noise governed by the spin relaxation is a generic effect that may be useful for the measurements of the spin relaxation length and the degree of the spin imbalance.

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