

Current Noise Generated by Spin Imbalance in Presence of Spin Relaxation¹

V. S. Khrapai^{a, b*} and K. E. Nagaev^{a, c}

^a Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka, Moscow region, 142432 Russia

^b Moscow Institute of Physics and Technology (State University), Dolgoprudnyi, Moscow region, 141700 Russia

^c Kotel'nikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Moscow, 125009 Russia

* e-mail: dick@issp.ac.ru

Received November 2, 2016

We calculate current (shot) noise in a metallic diffusive conductor generated by spin imbalance in the absence of a net electric current. This situation is modeled in an idealized three-terminal setup with two biased ferromagnetic leads (F-leads) and one normal lead (N-lead). Parallel magnetization of the F-leads gives rise to spin-imbalance and finite shot noise at the N-lead. Finite spin relaxation results in an increase in the shot noise, which depends on the ratio of the length of the conductor (L) and the spin relaxation length (l_s). For $L \gg l_s$ the shot noise increases by a factor of two and coincides with the case of the antiparallel magnetization of the F-leads.

DOI: 10.1134/S0021364017010015

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 [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 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 (see Fig. 2).

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

$$\begin{aligned} \frac{\partial f_\sigma}{\partial t} = & \Gamma_{L\sigma}[f_0(\epsilon - eV/2) - f_\sigma] \\ & + \Gamma_{R\sigma}[f_0(\epsilon + eV/2) - f_\sigma] - \frac{1}{\tau_s}(f_\sigma - f_{-\sigma}), \end{aligned} \quad (1)$$

where Γ 's are the tunneling rates through the left and right barriers for spin-up and spin-down electrons,

¹The article is published in the original.

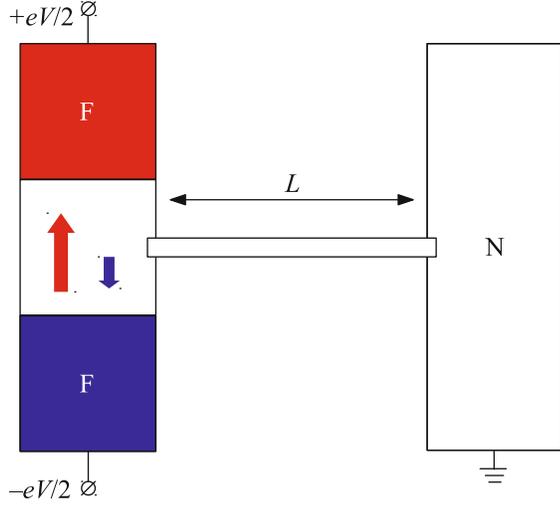


Fig. 1. (Color online) Design of the system. A diffusive normal wire of the length L is attached to normal islands on both ends. Nonequilibrium energy distribution on the left hand side of the wire generates the shot noise at a zero net current. The spin imbalance on the left-hand side of the wire is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

$f_0(\epsilon)$ 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

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

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

where

$$\alpha = \frac{\Gamma\tau_s}{1 + \Gamma\tau_s}. \quad (4)$$

For the parallel magnetization of the leads, $\Gamma_{L-} = \Gamma_{R-} = 0$ and $\Gamma_{L+} = \Gamma_{R+} = \Gamma$, so $f_+(\epsilon)$ and $f_-(\epsilon)$ are given by Eqs. (2) and (3) with $\alpha = 0$, respectively.

The distribution functions in the diffusive wire satisfy the diffusion equation

$$D \frac{\partial^2 f_\sigma}{\partial x^2} = \frac{f_\sigma - f_{-\sigma}}{2\tau_s} \quad (5)$$

with the boundary condition at the left end given by Eqs. (2) and (3) and the boundary condition at the

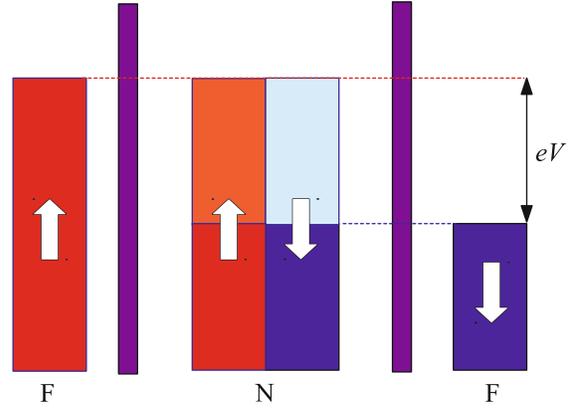


Fig. 2. (Color online) Energy diagram of (red) spin-up and (blue) spin-down electrons in the ferromagnetic electrodes and in the normal-metal island at the left end of the wire. Stronger and lighter colors show fully and partially occupied states, respectively. Narrower bars indicate tunnel barriers.

right end $f_\sigma(L, \epsilon) = f_0(\epsilon)$. The solution of this equation is of the form

$$f_\sigma(x, \epsilon) = \frac{x}{L} f_0(\epsilon) + \frac{1}{2} \left(1 - \frac{x}{L}\right) [f_0(\epsilon - eV/2) + f_0(\epsilon + eV/2)] + \sigma \alpha \frac{\sinh\left(\frac{L-x}{l_s}\right)}{2 \sinh(L/l_s)} [f_0(\epsilon - eV/2) - f_0(\epsilon + eV/2)], \quad (6)$$

where $l_s = \sqrt{D\tau_s}$.

The electrical noise is calculated as [12]

$$S_I = \frac{2}{R} \int_0^L \frac{dx}{L} \int d\epsilon \sum_\sigma f_\sigma (1 - f_\sigma). \quad (7)$$

The substitution of Eq. (6) into Eq. (7) gives at low temperatures $T \ll eV$

$$S_I = \frac{eV}{R} \left[\frac{2}{3} - \frac{\alpha^2 l_s}{2L} \frac{e^{2L/l_s} + 1}{e^{2L/l_s} - 1} + \frac{2\alpha^2 e^{2L/l_s}}{(e^{2L/l_s} - 1)^2} \right]. \quad (8)$$

In Fig. 3, we plot the dependence of the dimensionless shot noise spectral density on the conductor length (in units of l_s). The upper curve corresponds to the case of $\alpha = 0$, i.e., the non-equilibrium double-step electronic energy distribution in the absence of spin imbalance, see Eqs. (2) and (3). As expected, the spin relaxation has no effect here 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. The lower curve in Fig. 3 demonstrates that in this case the noise equals $S_I = eV/3R$

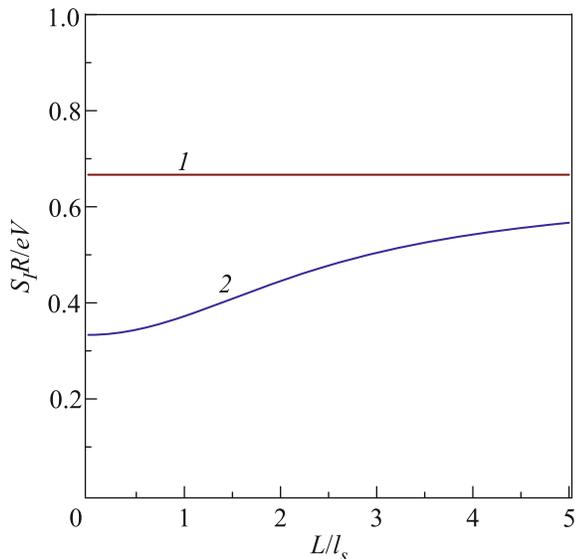


Fig. 3. (Color online) Dimensionless spectral density $S_I R / eV$ versus the ratio L/l_s for $\alpha = (1) 0$ and $(2) 1$.

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. (8), where the results for $\alpha = 0$ and 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 $\bar{f}_{\pm} = (f_+ + f_-)/2$. Obviously, this results in the increase in the shot noise, since $2\bar{f}_{\pm}(1 - \bar{f}_{\pm}) \geq \sum f_{\sigma}(1 - f_{\sigma})$, cf. Eq. (7). The magnitude of the increase is thus a measure of the spin imbalance.

In summary, we calculated the impact of the spin relaxation on the nonequilibrium shot noise generated by spin imbalance in a diffusive conductor. In an idealized three-terminal setup with two tunnel-coupled ferromagnetic leads and one normal lead the 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 in 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.

We acknowledge discussions with V.T. Dolgoplov, S.V. Piatrusha, and E.S. Tikhonov. This work was supported by the Russian Science Foundation (project no. 16-42-01050).

REFERENCES

1. I. Žutić, J. Fabian, and S. das Sarma, *Rev. Mod. Phys.* **76**, 323 (2004).
2. R. H. Silsbee, *Bull. Magn. Reson.* **2**, 284 (1980).
3. M. Johnson and R. H. Silsbee, *Phys. Rev. Lett.* **55**, 1790 (1985).
4. F. J. Jedema, A. T. Filip, and B. J. van Wees, *Nature* **410**, 345 (2001).
5. F. J. Jedema, H. B. Heersche, A. T. Filip, J. J. A. Baselmans, and B. J. van Wees, *Nature* **416**, 713 (2002).
6. X. Lou, Ch. Adelman, S. A. Crooker, E. S. Garlid, J. Zhang, K. S. Madhukar Reddy, S. D. Flexner, Ch. J. Palmström, and P. A. Crowell, *Nat. Phys.* **3**, 197 (2007).
7. P. Chuang, Sh.-Ch. Ho, L. W. Smith, F. Sfigakis, M. Pepper, Ch.-H. Chen, J.-Ch. Fan, J. P. Griffiths, I. Farrer, H. E. Beere, G. A. C. Jones, D. A. Ritchie, and T.-M. Chen, *Nat. Nanotechnol.* **10**, 35 (2015).
8. J. Meair, P. Stano, and P. Jacquod, *Phys. Rev. B* **84**, 073302 (2011).
9. T. Arakawa, J. Shiogai, M. Ciorga, M. Utz, D. Schuh, M. Kohda, J. Nitta, D. Bougeard, D. Weiss, T. Ono, and K. Kobayashi, *Phys. Rev. Lett.* **114**, 016601 (2015).
10. Ya. M. Blanter and M. Büttiker, *Phys. Rep.* **336**, 1 (2000).
11. E. S. Tikhonov, D. V. Shovkun, D. Ercolani, F. Rossella, M. Rocci, L. Sorba, S. Roddaro, and V. S. Khrapai, *Sci. Rep.* **6**, 30621 (2016).
12. K. E. Nagaev, *Phys. Lett. A* **169**, 103 (1992).
13. K. E. Nagaev, *Phys. Rev. B* **52**, 4740 (1995).
14. V. I. Kozub and A. M. Rudin, *Phys. Rev. B* **52**, 7853 (1995).
15. T. T. Heikkilä and K. E. Nagaev, *Phys. Rev. B* **87**, 235411 (2013).
16. E. V. Sukhorukov and D. Loss, *Phys. Rev. B* **59**, 13054 (1999).