Shot noise of charge and spin in magnetic nanostructures

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Noise is a signal (Rolf Landauer)

FIG. 1: Whether noise is a nuisance or a signal may depend on whom you ask. (Cartoon by Rand Kruback. Used with permission of Agilent Technologies.)

Noise of electrical current

\[ I(t) \]

Noise power:

\[ \Delta I(t) = I(t) - \langle I(t) \rangle \]

\[ S(\omega) = 2 \int_{-\infty}^{\infty} dt e^{-i\omega t} \langle \Delta I(t) \Delta I(0) \rangle. \]

[Mesoscopic physics group, Basel]
Three different types of noise

• **Thermal noise** (Johnson-Nyquist noise, thermal agitations of electrons)

• **1/f noise** (random motion of impurities (time-dependent conductance fluctuations, dominates at low frequency)

• **Shot noise** (non-equilibrium noise, discreteness of electron Charge, independent of the frequency at low frequencies, $S$ varies linear with mean current)
Shot noise in a vacuum tube
(Schottky, 1918)

Electrons are emitted from cathode randomly and independently:
**Maximum** noise of carriers with charge $e$
(a Poissonian process)

\[ S_{\text{Poisson}} = 2eI \]

**Measuring the unit of charge in tunnel contacts**
Fano (1947) factor

\[ F = \frac{S}{2eI}, \]

$F=1$, for transfer of electrons (charge $e$) through a tunnel contact

$F$ can be different from 1 in presence of correlations and interactions, different charge carriers)
Shot noise suppression in diffusive conductors

Electrons transferring become quite due to the Fermi statistic

$F=0$, For ballistic contacts

Shot noise of fractional charge

Hall bar on the 1/3 plateau of the fractional quantum Hall effect: $p=1$ quasiparticle of charge $e/3$

$$q = e/(2p + 1)$$


Other example:

Doubled shot noise ($F=2$), in a tunnel contact between normal metal and superconductor (Cooper pair with $2e$ charge tunnelling)[ Lefloch et al., 2003]
Landauer-Buttiker formula

Correlations reduces the noise below the Poissonian value

transmission probability \( T_n \)

electrode

\[
\bar{I} = \frac{2e^2}{h} V \sum_{n=1}^{N} T_n.
\]

\[
S = 2e^2 \frac{2e^2}{h} V \sum_{n=1}^{N} T_n(1 - T_n).
\]

Pauli principal

\( T_n << 1 \) tunnel contact \( F=1 \)

\( T_n = 1 \) ballistic contact \( F=0 \)

\( Tn \) distribution \( p(T) \)
Classical to quantum transition in electron billiards

**Chaotic billiard**

Electron **dwell time** inside billiard

**Ehrenfest time**

$$\tau_E = \alpha^{-1} \ln(L/\lambda_F)$$

time to initially wave packet of Fermi wave length to spread over size of billiard $L$

Noise of massless Dirac Fermions in graphene

$F=1/3$, For **ballistic (!) graphene**

Electrical noise by **relativistic dynamics**

[Tworzydlo et al, cond-mat/0603315]
In mesoscopic and nanoscopic N metal, semiconducting, and superconducting Structures including tunnel, diffusive, ballistic contacts: Shot noise provide unique Information about the charge, the statistic and the scattering of the charge carriers.

What about spin?

Spintronic: Devices made up ferromagnetic and nonmagnetic materials to:
1-spin control of the currents and voltages
2-currents or voltages control of spin

Spin-polarization injection, relaxation, manipulation, detection: physics of spin and exciting applications

[I. Zutic et al, Rev. Mod. Phys. 76, 323 (2004); Y. Tserkovnyak et al, cond-mat/0409242]
Spin-valve

Spin injection experiment at room temperature

[Jedema et al., Nature (2001)]
Boltzmann-Langevin equations for spin-polarized currents

**Charge**

\[ f_c(r, E, t) = \tilde{f}_c(r, E) + \delta f_c(r, E, t) \]

\[ j_c(r, E, t) = \tilde{j}_c(r, E) + \delta j_c(r, E, t) \]

\[ \nabla \cdot j_c(r, E, t) = 0 \]

\[ j_c(r, E, t) = -\nabla f_c(r, E, t) + j^c_c(r, E, t) \]

**Spin**

\[ f_s(r, E, t) = \tilde{f}_s(r, E) + \delta f_s(r, E, t) \]

\[ j_s(r, E, t) = \tilde{j}_s(r, E) + \delta j_s(r, E, t) \]

\[ \nabla \cdot j_s(r, E, t) = -\frac{\sigma}{\ell_{sf}^2} f_s(r, E, t) + \overset{\text{sf}}{i}(r, E, t) \]

\[ j_s(r, E, t) = -\nabla f_s(r, E, t) + j^c_s(r, E, t) \]

**Langevin source current fluctuations**

\[ \langle j^c_c(r, E, t) j^c_c(r', E', t') \rangle = \]

\[ \delta(r - r') \delta(E - E') \delta(t - t') \sigma \tilde{f}_c(r, E) [1 - \tilde{f}_c(r, E)] \]

[Nagaev (1992)]
Correlation of current fluctuations

\[ \langle j^c_c(\mathbf{r}, E, t) j^c_s(\mathbf{r}', E', t') \rangle = \langle j^c_s(\mathbf{r}, E, t) j^c_s(\mathbf{r}', E', t') \rangle = \Delta \sigma \sum_{\alpha = \pm} \bar{f}_\alpha(\mathbf{r}, E)[1 - \bar{f}_\alpha(\mathbf{r}, E)] \]

\[ \langle j^c_s(\mathbf{r}, E, t) j^c_s(\mathbf{r}', E', t') \rangle = \Delta \sigma \sum_{\alpha = \pm} \alpha \bar{f}_\alpha(\mathbf{r}, E)[1 - \bar{f}_\alpha(\mathbf{r}, E)] \]

\[ \langle i^{sf}(\mathbf{r}, E, t) i^{sf}(\mathbf{r}', E', t') \rangle = \Delta \frac{\sigma}{\ell^2} \sum_{\alpha = \pm} \bar{f}_\alpha(\mathbf{r}, E)[1 - \bar{f}_{-\alpha}(\mathbf{r}, E)] \]

\[ \langle j^c_c(\mathbf{r}, E, t) i^{sf}(\mathbf{r}', E', t') \rangle = 0 \]

Boundary condition:
Temporal current conservation in a tunnel contact

\[ I_{i\alpha}(E, t) = g_{i\alpha}[f_{FD}(E - eV_i) - f_\alpha(\mathbf{r}_i, E, t)] + \delta I_{i\alpha}(E, t) \]

\[ \langle \delta I_{i\alpha}(E, t) \delta I_{i\alpha}^*(E, t) \rangle = \delta_{\alpha \alpha} \delta(t - t') 2e \bar{I}_{i\alpha}(E) \]

[M. Z. and W. Belzig, PRB (2005)]
Three-terminal spin-valve

\[ F = \frac{S}{2eI} = \frac{\Delta I_{c1} \Delta I_{c1}}{2eI} \]

\[ F_{23} = \frac{S_{23}}{2eI} = \frac{\Delta I_{c2} \Delta I_{c3}}{2eI} \]

[Jedema et al., (2001)]
Shot noise

\[ g = \frac{g_i}{g_N}, \quad |p_i| = p, \quad \lambda = \frac{L}{\ell_{sf}} \]

\[ F(g, \lambda, \{p_i\}, p) \]

\[ F_N = \frac{15 + 6g + 4g^2 + 8/9g^3}{3 + 6g + 4g^2 + 8/9g^3} \]

\[ \lambda \to 0 \]
Shot noise: effect of spin-flip

\[ F(g = 1, |p| = 0.85, \{p_i\}, \lambda) \]
Cross correlations

$$F_{23} = \frac{S_{23}}{2eI} = \frac{\langle \Delta I_{c2} \Delta I_{c3} \rangle}{2eI}$$

$$F_{23}(g = 0.1, p2 = -p3, \lambda)$$
FFF structures: the model

\[ p_1 \quad p_N \quad p_2 \]

\[ j_\alpha \]

Extended BL theory:

Polarization of the conductivity

\[ p_\sigma = p_\sigma(p_N, p_W, \lambda) \]

\[ p_N = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \]

\[ p_W = \frac{W_\uparrow - W_\downarrow}{W_\uparrow + W_\downarrow} \]
**FFF structures: antiparallel**

Perfectly polarized terminals

![Diagram of FFF structures with terminals polarized](image)

[M. Hatami and M. Z. , PRB (2006)]
FFF structures: parallel
Summary


- Shot noise of N spin-valve: strong dependence on the spin-flip rate and the magnetizations configuration

- Shot noise of spin current: more sensitive [M. Z. and W. Belzig, (2005)]

- Shot noise of FFF structure probe the intrinsic DOS and the extrinsic impurity scattering rate polarizations

- Experiments?

Mesoscopic physics group at IASBS: http://www.iasbs.ac.ir/physics/condmat/research/condmatt/mesoscopic.htm