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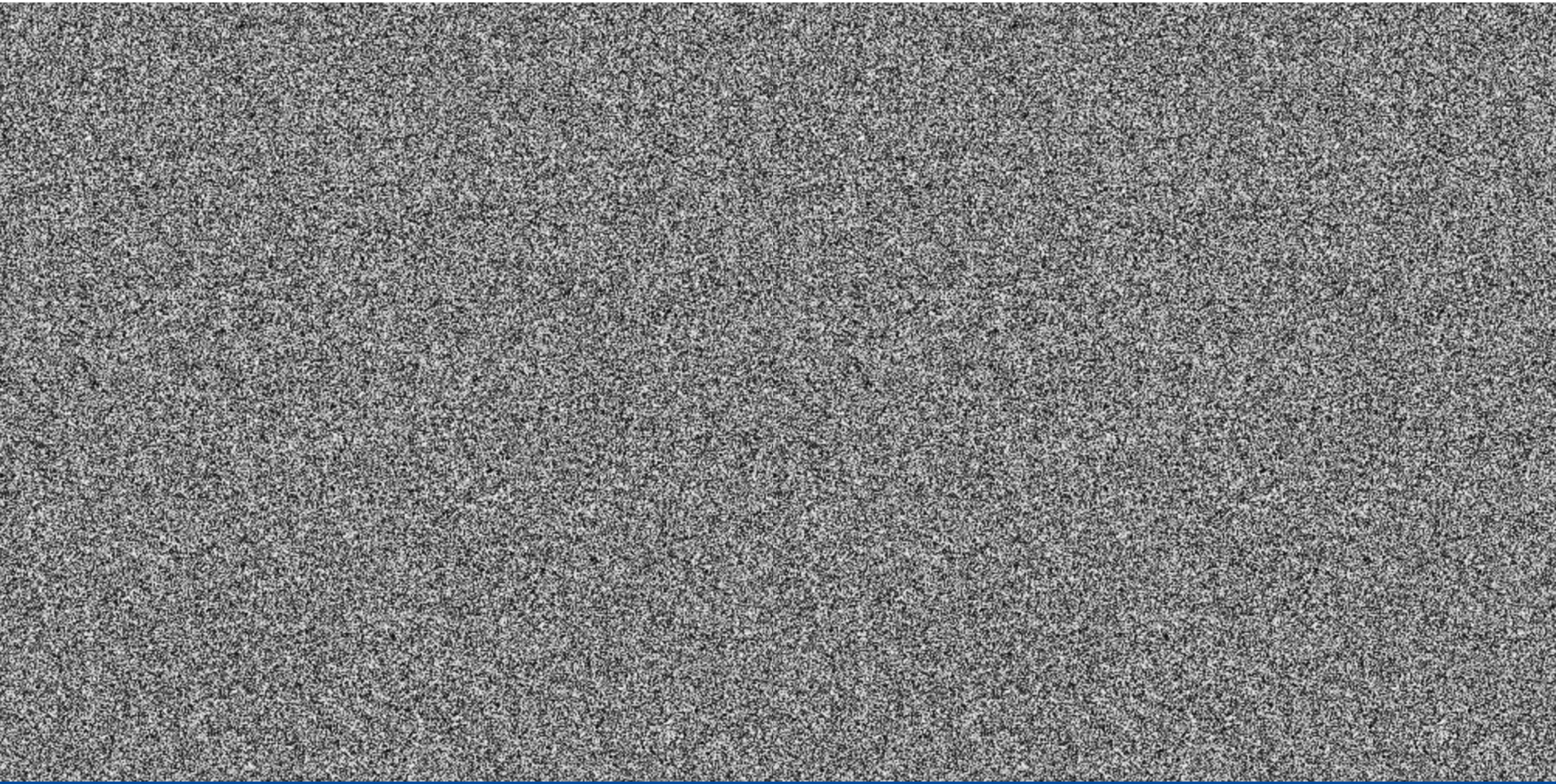
Noise

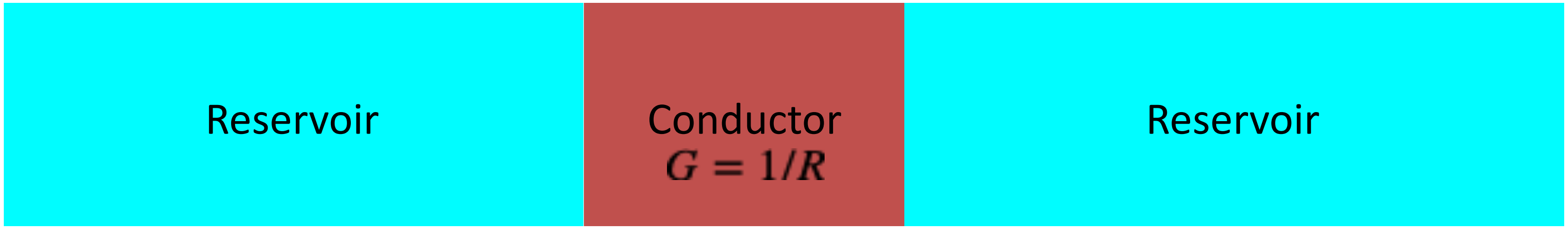


Noise

Current Fluctuations

$S_I(\omega \to 0) = \langle 2k_B T G \Delta I_c(t_2)\rangle$

Electrical conductor



Thermal fluctuations in reservoirs. Equilibrium fluctuations

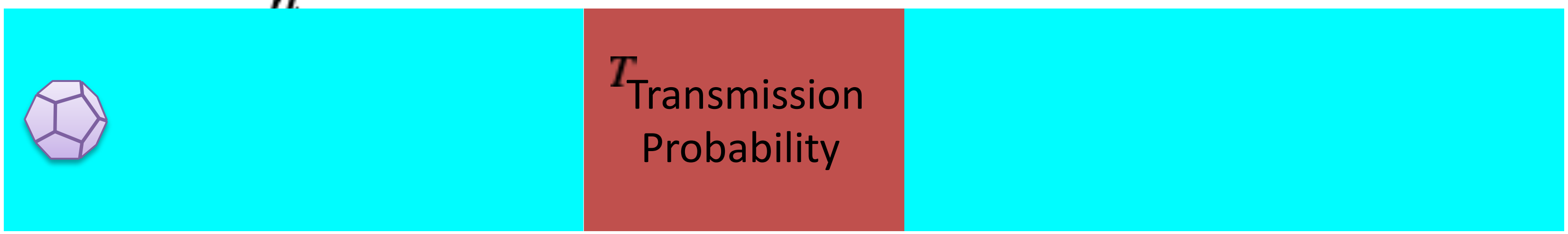
Johnson-Nyquist, fluctuation-dissipation theorem

Shot Noise

$T = 0$

Electrical conductor

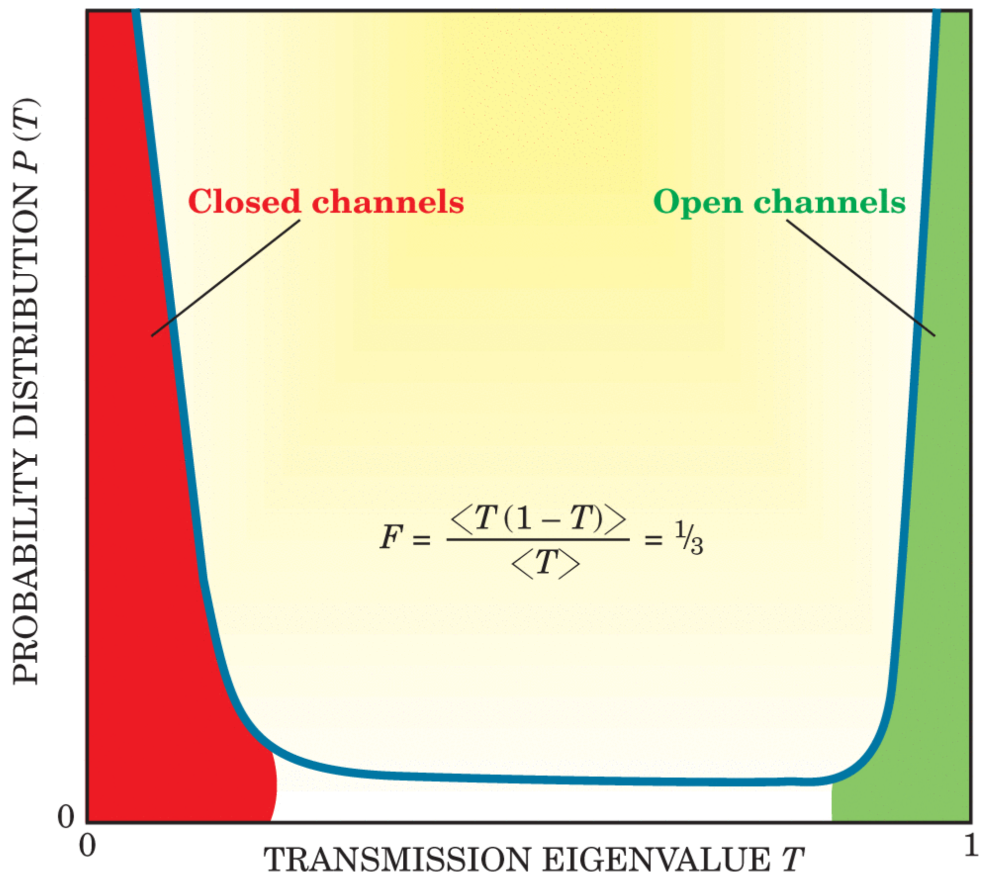
$$S_c(\omega \to 0) = \frac{2e^2}{h} eV \sum T_n(1 - T_n)$$



Determinism when and . No shot noise.

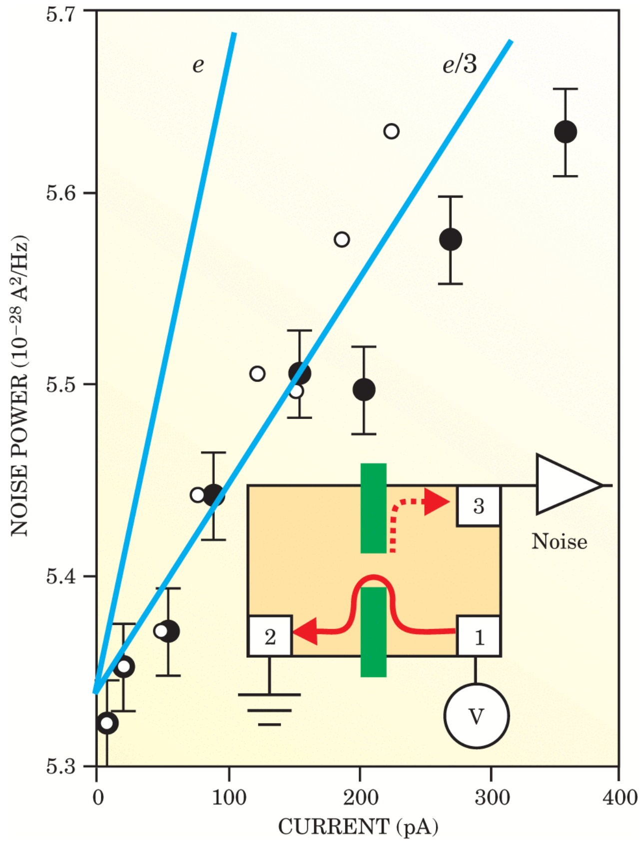
In general (Lesovik, Buttiker)

Shot Noise and Probability Distribution



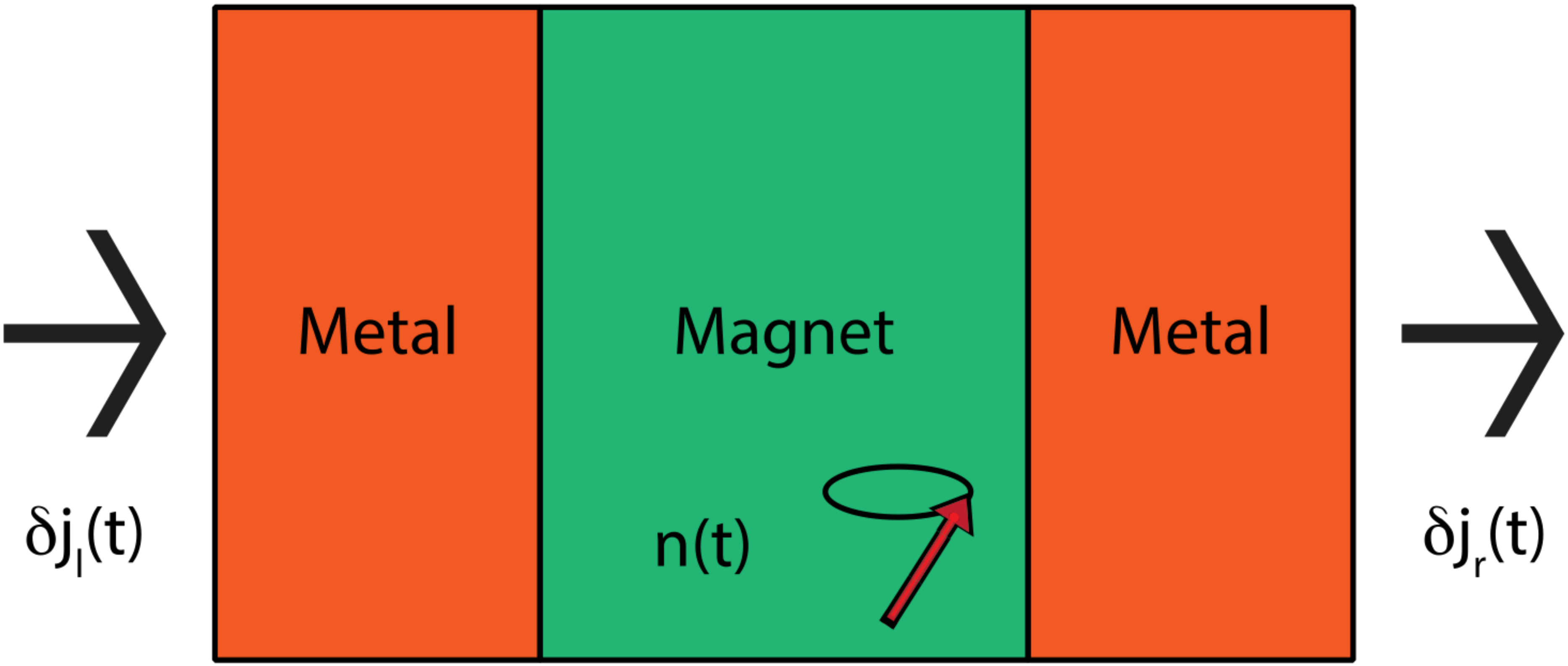
Beenakker & Schonenberger, Physics Today (2003)

Shot Noise and Fractional Charge



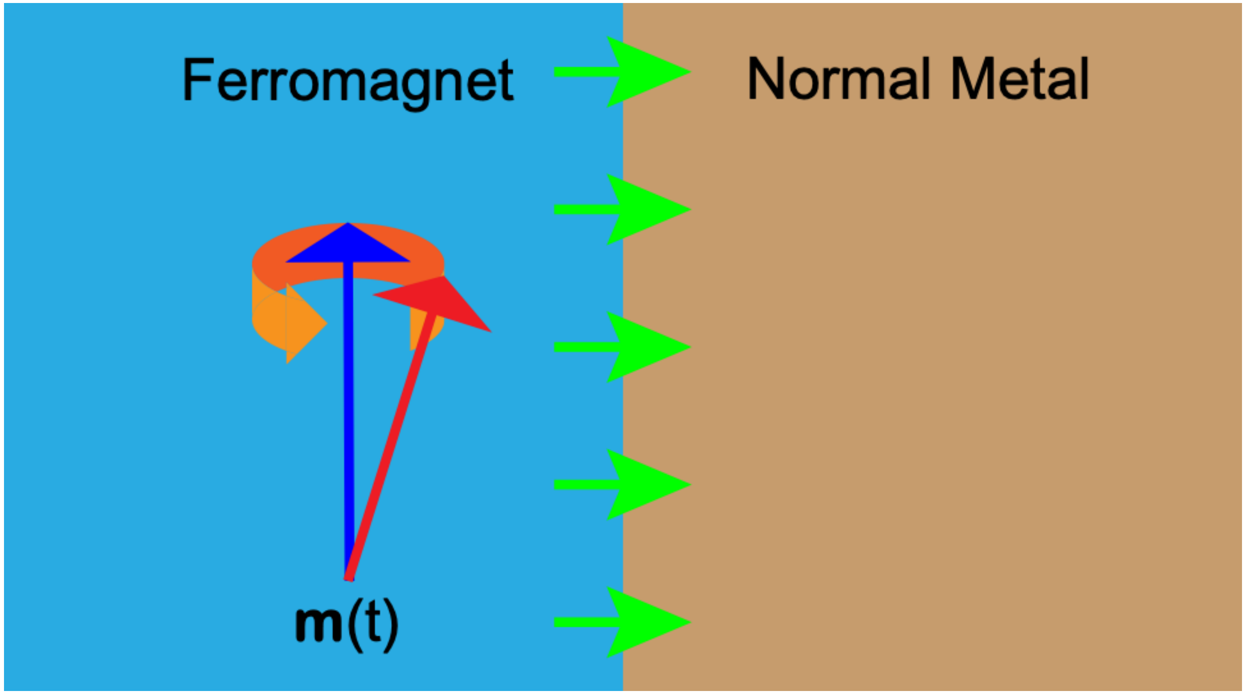
Beenakker & Schonenberger, Physics Today (2003)

Noise Driven by Magnetic Resonance



Ferromagnetic Resonance

- Spin-pumping



Silsbee, Janossy, Monod, Hurdequint, Berger

Spin-pumping

$$\mathbf{I}_s = \frac{\hbar}{4\pi} g_{\uparrow\downarrow} \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t}$$

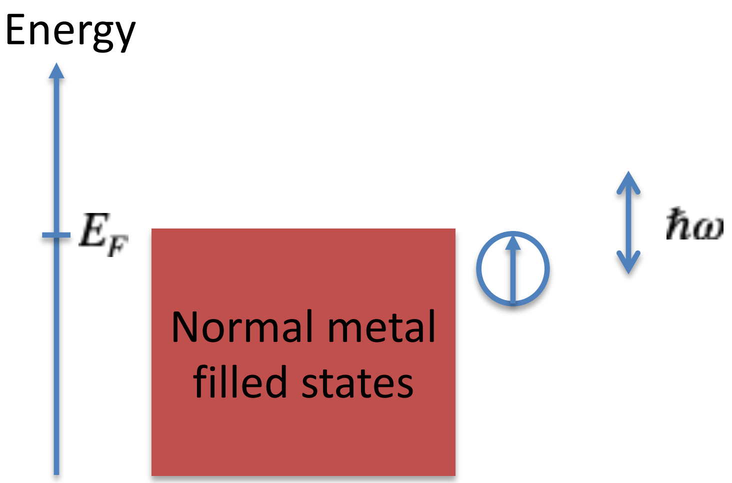
Tserkovnyak, Brataas, Bauer PRL (2002)

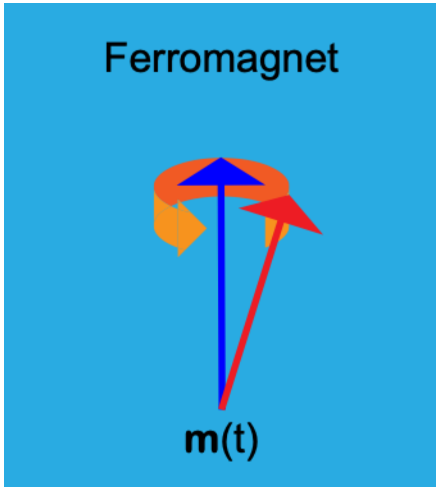
Extreme precession limit

$$\mathbf{m}(t) = \mathbf{x} \cos \omega t + \mathbf{y} \sin \omega t$$

$$e\mathbf{I}_s = \mathbf{z} \left(\frac{\hbar}{2}\right) N_\perp \left(\frac{\hbar\omega}{e}\right)$$

Number of transverse waveguide modes





Spin Current Noise

- Isolated ferromagnet

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times [\mathbf{H}_{\text{eff}} + \mathbf{h}_0(t)] + \alpha_0 \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t}$$

- Ferromagnet in contact with normal metal
  - Spin-pumping enhanced Gilbert damping

$$\alpha_0 \to \alpha_0 + \alpha_{\text{sp}}$$

  - Spin currents fluctuates
  - Spin-transfer torque fluctuates

$$h_0(t) \to h_0(t) + h_{\text{sp}}(t)$$

$$h_{\text{sp}}(t) = ?$$

Thermal Noise

- Described by a new random field

$$\langle h_{\text{sp},i}(t_1) h_{\text{sp},j}(t_2) \rangle = 2k_B T \frac{\alpha_{\text{sp}}}{\gamma M} \delta_{ij} \delta(t_1 - t_2)$$

- Total effective fluctuating field

$$\mathbf{h}(t) = \mathbf{h}_0(t) + \mathbf{h}_{\text{sp}}(t)$$

- Enhanced Gilbert damping

$$\alpha = \alpha_0 + \alpha_{\text{sp}}$$

- Fluctuation-dissipation theorem is satisfied [PRL (2005)]

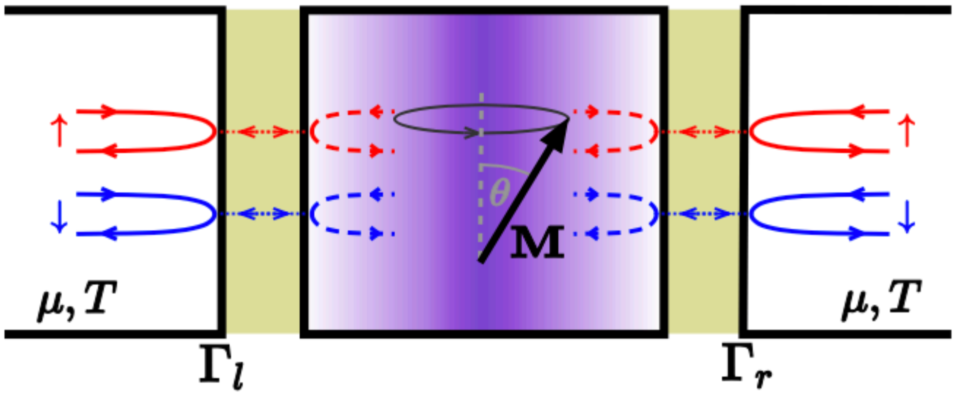
PHYSICAL REVIEW RESEARCH 2, 023221 (2020)

Qu Spin

Current noise geometrically generated by a driven magnet

Tim Ludwig,[1,2,3] Igor S. Burmistrov,[3,4] Yuval Gefen,[5] and Alexander Shnirman[2,6]

A small metallic ferromagnet tunnel coupled to two normal metal leads



(Charge) Current noise

$$S = 4g_t T + g_t \sin^2\theta(\dot{\phi}\coth\frac{\dot{\phi}}{2T} - 2T)$$

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Spin Pumping and Torque Statistics in the Quantum Noise Limit

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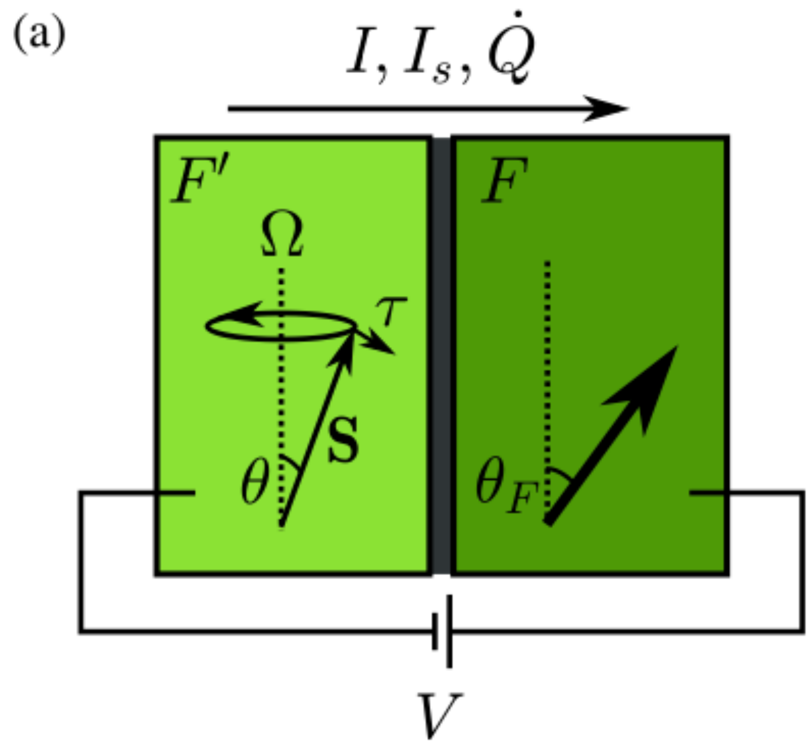
(Received 29 September 2016; revised manuscript received 21 March 2017; published 8 June 2017)



Electric Current Noise

- Novel aspect of Ludwig et al.
  - Detects and characterises
    - Ferromagnetic resonance
    - Electron transport in magnetic nanostructure
  - Does not require spin-to-charge conversion such as
    - Spin Hall effect
    - Inverse spin Hall effect

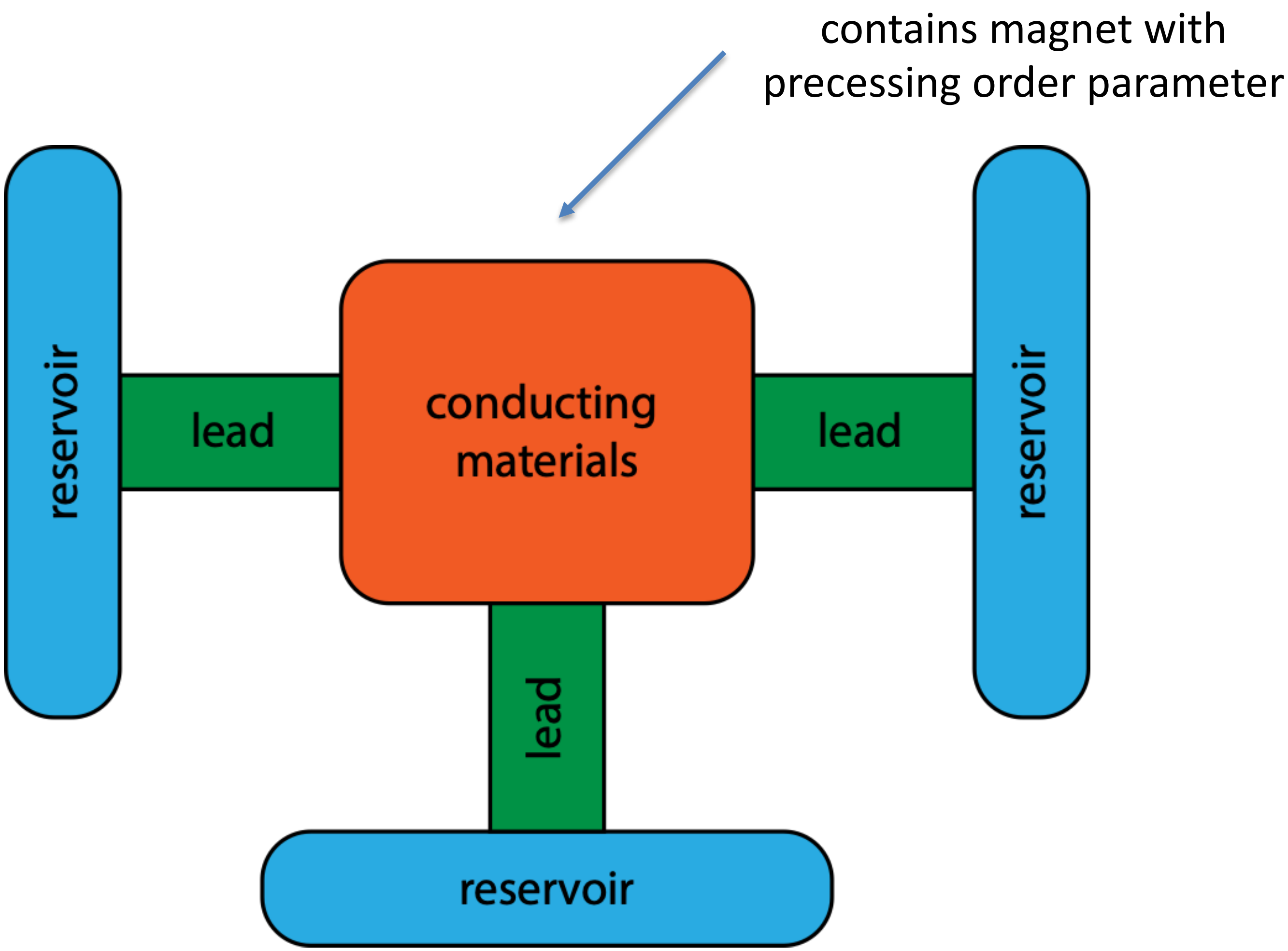
This Work - Generalization in 3 Ways

I. Arbitrary junctions
   - Ballistic
   - Diffusive
   - Tunnel

II. Ferromagnets and antiferromagnets

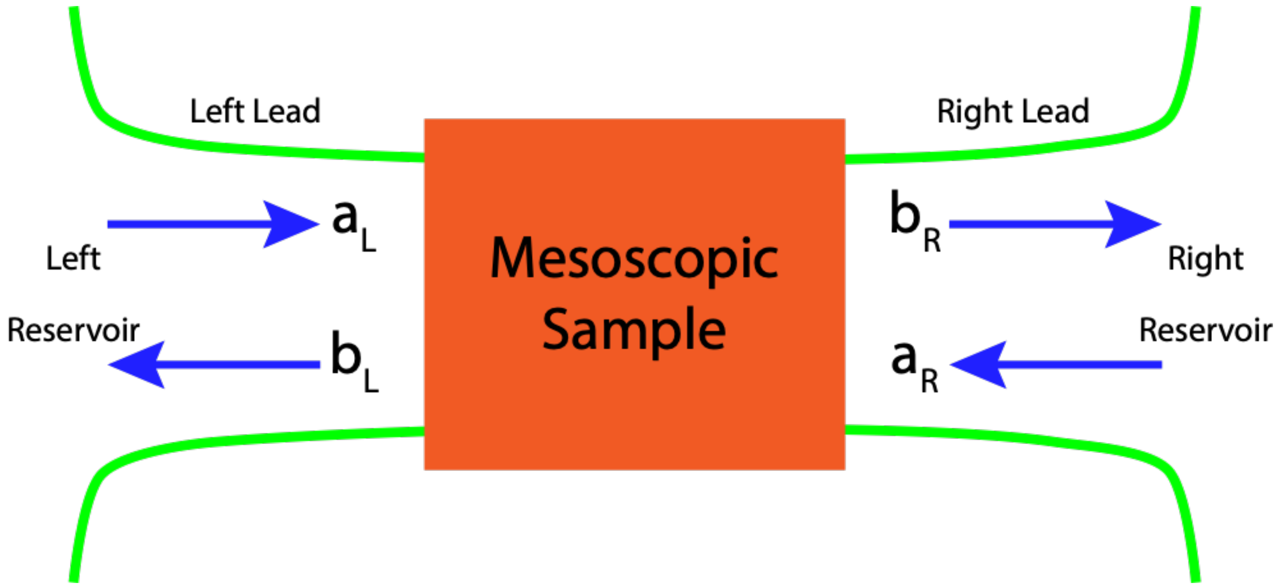
III. Multi-terminal devices

Noise Driven by Magnetic Resonance



Landauer formalism

$$G = \frac{2e^2}{h}|t_{LR}|^2 = \frac{2e^2}{h}|t_{RL}|^2$$



$$b_R = t_{RL}a_L + r_{RR}a_R$$

$$b_L = t_{LR}a_R + r_{LL}a_L$$

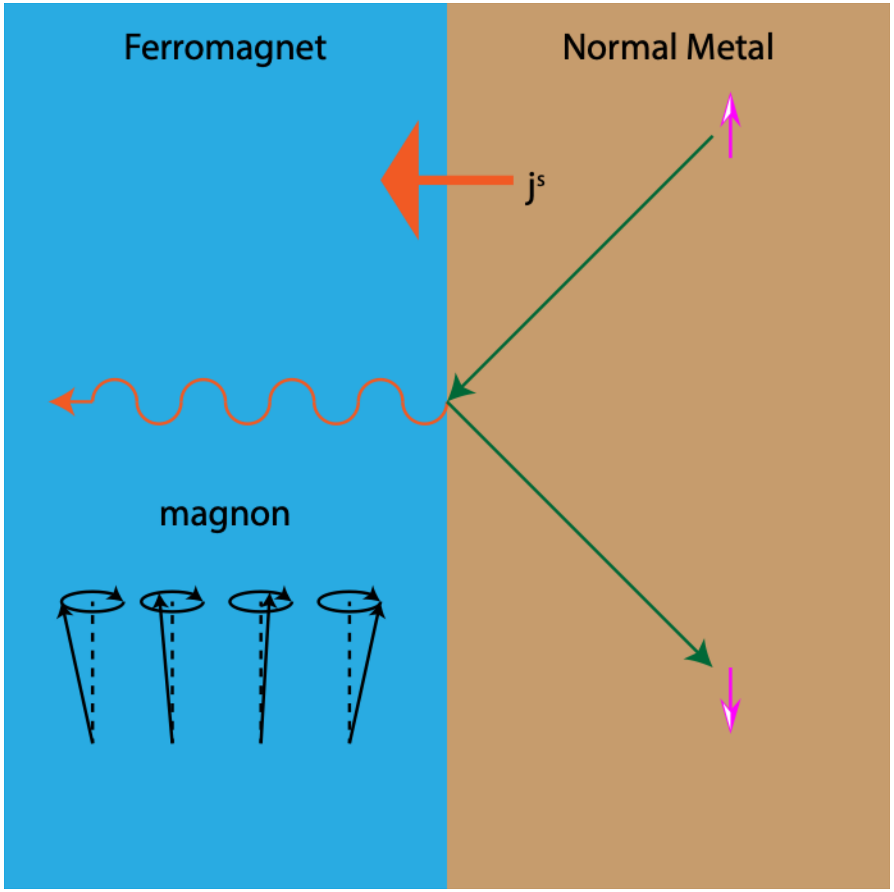
$$S = \begin{pmatrix} r_{rr} & t_{rl} \\ t_{lr} & r_{ll} \end{pmatrix}$$

Explanation of Electric Current Noise

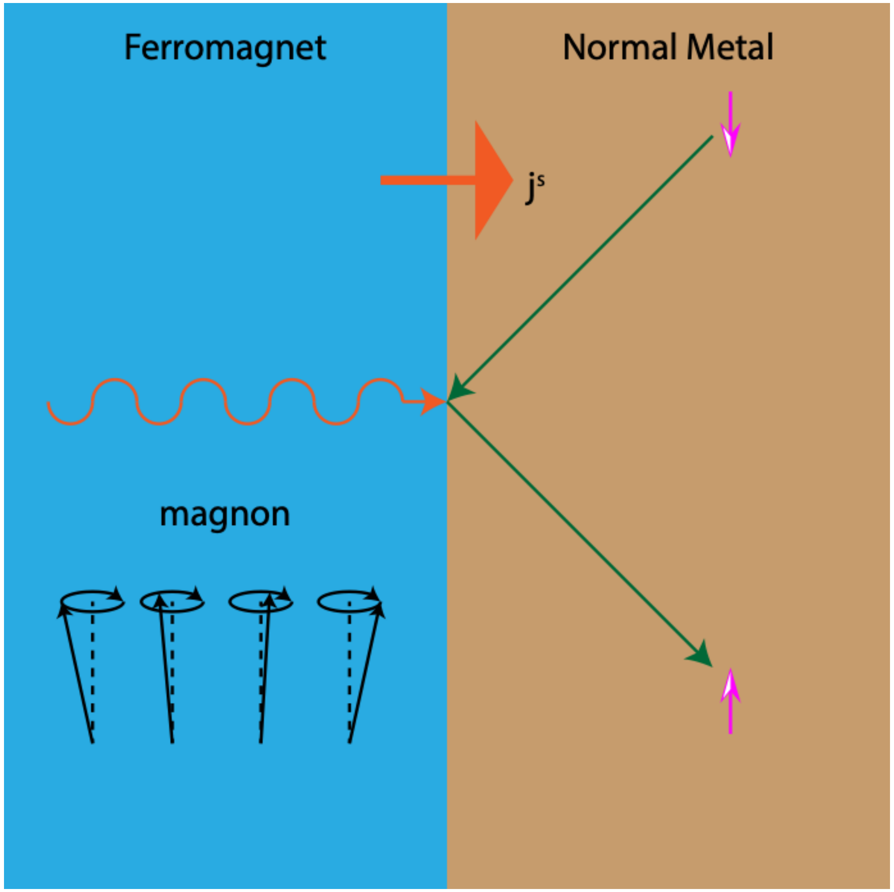
- Temporal variation in
  - Spin-pumping
  - Spin accumulation
  - Spin filtering

Spin-transfer and spin-pumping

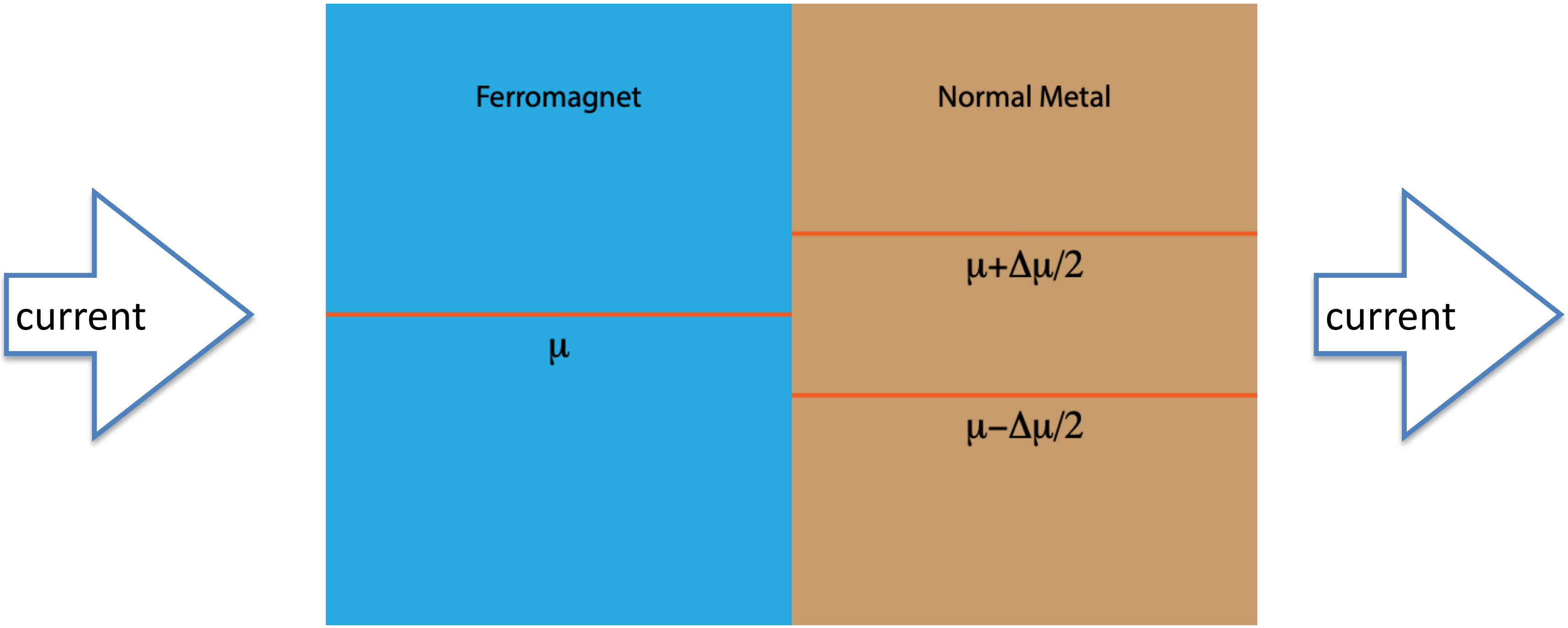
Spin-transfer



Spin-pumping



Spin to Charge Conversion



Spin accumulation in normal metal drives charge current via spin filtering

$$I_c = I_\uparrow + I_\downarrow$$
$$I_c = (G_\uparrow - G_\downarrow)\Delta\mu/2$$

Experimental Consequences

- Low-temperature shot noise when

$$\hbar\omega > k_B T$$

- Ferromagnets

$$\omega \sim 100\text{GHz} \sim 1K$$

- Antiferromagnets

$$\omega \sim 1\text{THz} \sim 10K$$

- Suppressed contributions also at higher temperatures

- Shot noise depends on drive, thermal noise does not

Current Noise

- Current fluctuations

$$P_{\zeta\eta}(t_1, t_2) = \frac{1}{2}\langle \Delta I_\zeta(t_1)\Delta I_\eta(t_2) + \Delta I_\eta(t_2)\Delta I_\zeta(t_1)\rangle$$

Labels lead

- Low-frequency noise

$$p_{\zeta\eta} = \int_0^T \frac{dt}{T} \int_{-\infty}^{\infty} d\tau P_{\zeta\eta}(t + \tau/2, t - \tau/2)$$

- Two contributions, thermal noise (th) and shot noise (sn)

$$p_{\zeta\eta} = p_{\zeta\eta}^{(\mathrm{th})} + p_{\zeta\eta}^{(\mathrm{sn})}$$

Johnson-Nyquist Noise

- Thermal noise contribution

$$p_{\zeta\eta}^{(\mathrm{th})} = (G_{\zeta\eta} + G_{\eta\zeta}) k_B T$$

- Conductance matrices

$$G_{\zeta\eta} = \frac{e^2}{h} \mathrm{Tr_o} \left[\delta_{\zeta\eta} - S_{\eta\zeta}^{\uparrow\dagger} S_{\zeta\eta}^{\uparrow} \right] + \frac{e^2}{h} \mathrm{Tr_o} \left[\delta_{\zeta\eta} - S_{\eta\zeta}^{\downarrow\dagger} S_{\zeta\eta}^{\downarrow} \right]$$

scattering matrices for spin-up and spin-down electrons

- Two-terminals, single mode

$$G = \frac{e^2}{h} \left(T^{\uparrow} + T^{\downarrow} \right)$$

Shot Noise

frequency of external drive

$$p^{(\mathrm{sn})}_{\zeta\eta} = \frac{A_{\zeta\eta} + A_{\eta\zeta}}{8} \left[\hbar\omega \coth \frac{\hbar\omega}{2k_B T} - 2k_B T \right] D(\omega)$$

electron transport coefficients

spin-dynamics factor

Shot Noise

- Main new result

$$p^{(\mathrm{sn})}_{\zeta\eta} = \frac{A_{\zeta\eta} + A_{\eta\zeta}}{8}\left[\hbar\omega \coth\frac{\hbar\omega}{2k_BT} - 2k_BT\right] D(\omega)$$

- Shot noise coefficients

$$A_{\zeta\eta} = \frac{e^2}{h}\mathrm{Tr}_\sigma\left[\delta_{\zeta\eta} - \sum_{\alpha\beta} S^{\uparrow}_{\zeta\alpha} S^{\downarrow\dagger}_{\alpha\eta} S^{\downarrow}_{\eta\beta} S^{\uparrow\dagger}_{\beta\zeta}\right] + \frac{e^2}{h}\mathrm{Tr}_\sigma\left[\delta_{\zeta\eta} - \sum_{\alpha\beta} S^{\downarrow}_{\zeta\alpha} S^{\uparrow\dagger}_{\alpha\eta} S^{\uparrow}_{\eta\beta} S^{\downarrow\dagger}_{\beta\zeta}\right]$$

- Spin-dynamics factor

$$D(\omega) = \sum_i n_{i+} n_{i-} = \sum_{ijk} \chi_{ij+}\chi_{ik-} H_{j+} H_{k-} \, .$$

out-of-equilibrium deviation of order parameter

Shot Noise

- Low-temperature

$$p_{\zeta\eta}^{(\mathrm{sn})} \approx \frac{A_{\zeta\eta} + A_{\eta\zeta}}{8} |\hbar\omega| D(\omega)$$

- High-temperature

$$p_{\zeta\eta}^{(\mathrm{sn})} \approx \frac{A_{\zeta\eta} + A_{\eta\zeta}}{8} \frac{(\hbar\omega)^2}{6k_B T} D(\omega)$$

Spin-dynamics Factor - Ferromagnet

transverse driving field

$$D_F(\omega) = \frac{\omega_{H_\perp}^2}{2\left[(\omega - \omega_A)^2 + \alpha^2\omega^2\right]}$$

frequency of drive

FMR frequency
(uniaxial anisotropy)

Gilbert damping

$$D_F(\omega = \omega_A) = \frac{\omega_{H_\perp}^2}{2\alpha^2\omega_A^2}$$

Spin-dynamics Factor - Antiferromagnet

transverse driving field

$$D_{AFM}(\omega) = \frac{\omega^2 \omega_{H_\perp}^2}{2(\omega^2 - \omega_r^2)^2 + 8\alpha^2\omega^2\omega_E^2}$$

frequency of drive

AFMR resonance frequency

Gilbert damping

$$D_{AFM}(\omega = \omega_r) = \frac{\omega_{H_\perp}^2}{8\alpha^2\omega_E^2}$$

Shot Noise Coefficients

- Many-terminal expression

$$A_{\zeta\eta} = \frac{e^2}{h}\mathrm{Tr_o}\left[\delta_{\zeta\eta} - \sum_{\alpha\beta} S^{\uparrow}_{\zeta\alpha} S^{\downarrow\dagger}_{\alpha\eta} S^{\downarrow}_{\eta\beta} S^{\uparrow\dagger}_{\beta\zeta}\right] + \frac{e^2}{h}\mathrm{Tr_o}\left[\delta_{\zeta\eta} - \sum_{\alpha\beta} S^{\downarrow}_{\zeta\alpha} S^{\uparrow\dagger}_{\alpha\eta} S^{\uparrow}_{\eta\beta} S^{\downarrow\dagger}_{\beta\zeta}\right]$$

- Two-terminal expression

$$A_{ll} = \frac{2e^2}{h}\mathrm{Tr_o}\left[1 - (r^{\uparrow}_{ll} r^{\downarrow\dagger}_{ll} + t^{\uparrow}_{lt} t^{\downarrow\dagger}_{rl})(r^{\downarrow}_{ll} r^{\uparrow\dagger}_{ll} + t^{\downarrow}_{lt} t^{\uparrow\dagger}_{rl})\right]$$

Shot Noise Coefficients

- Ballistic junctions

$$A_{ll}^{(F)} = \frac{2e^2}{h} PN \qquad P = \frac{G_\uparrow - G_\downarrow}{G_\uparrow + G_\downarrow} \qquad A_{ll}^{(AF)} = 0$$

- Disordered junctions

$$\langle A_{ll}^{(F)} \rangle = 2\left(G_\uparrow + G_\downarrow - 2\frac{G_\uparrow G_\downarrow}{G_{sh}} \right) \qquad \langle A_{ll}^{(AF)} \rangle = 2G\left(1 - \frac{G}{2G_{sh}} \right)$$

$$\langle A_{ll}^{(F)} \rangle \approx \langle A_{ll}^{(AF)} \rangle \approx 2G$$

Conclusion

- General expression - noise driven by magnetic resonance
- Characterizes and detects
  - Magnetic resonance
  - Electron transport
- Thermal and shot noise contributions
- Shot noise attains its maximum at magnetic resonance
- Shot noise coefficients differ for various junctions
- Brataas, PRB 102, 054440 (2020)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