Dynamic Mesoscopic Transport

Markus Büttiker
University of Geneva

Dynamic transport: Motivation

« Electronics » is not static, is not dc-transport, but a dynamic process!

To be useful we must be able to manipulate structures and to do that fast.

For most mesoscopic and more so for the nanoscopic structures the electron transit time is a very short time.

Of interest is therefore the low frequency range, or dynamic transport on time scales long compared to a transit time (or long compared to an RC-time).

Dynamic potentials

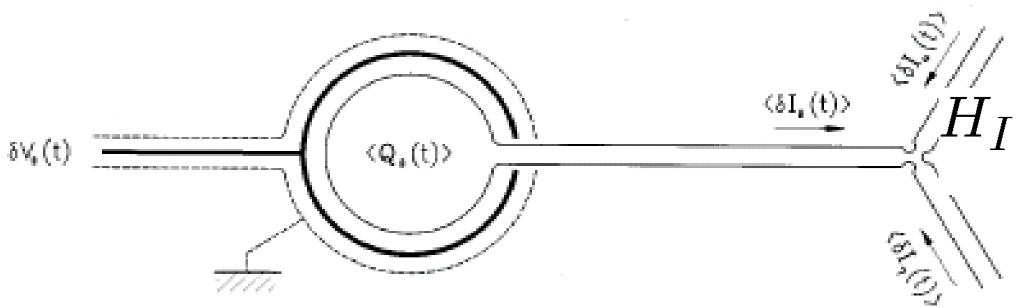
Buttiker, Pretre, Thomas, Phys. Rev. Lett. 70, 4114 (1993)

Linear response to oscillating voltages

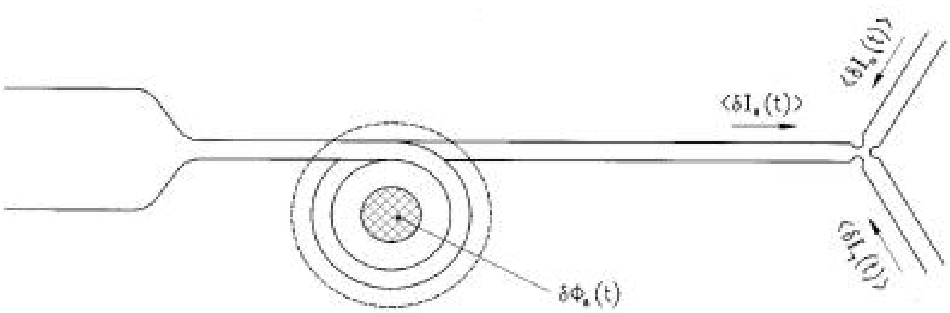
Distinguish:

potentials applied to terminals $dV_\alpha(t) = dV_\alpha(\omega)e^{-i\omega t}$

self-consistent electrostatic potential $dU(\omega, \mathbf{r})e^{-i\omega t}$



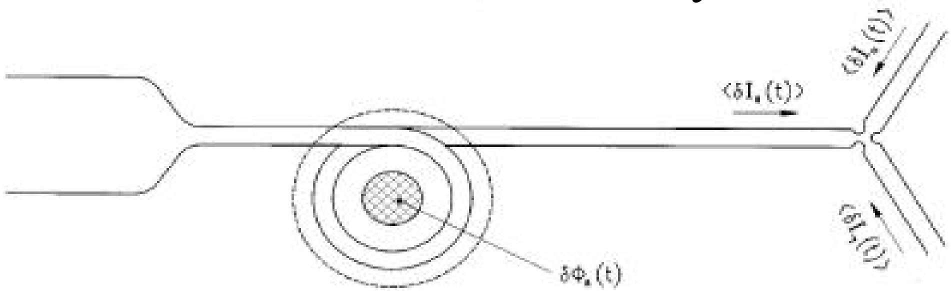
$$H_I = \sum_\alpha Q_\alpha dV_\alpha$$



$$H_I = \sum_\alpha I_\alpha d\Phi_\alpha$$

Response to external potentials

Buttiker, Pretre, Thomas, Phys. Rev. Lett. 70, 4144 (1993)



$$\phi_\alpha(E,t) = \phi_\alpha^+(E)e^{-iEt/\hbar} + c_\alpha\phi_\alpha^+ e^{-iE_+t/\hbar} - c_\alpha\phi_\alpha^+ e^{-iE_-t/\hbar}$$

$$E_\pm = E \pm \hbar\omega \ , \quad c_\alpha = eV_\alpha/\hbar\omega$$

$\hat{a}_\alpha(E)$; incident state $\qquad$ $\hat{a}'_\alpha(E)$; reservoir

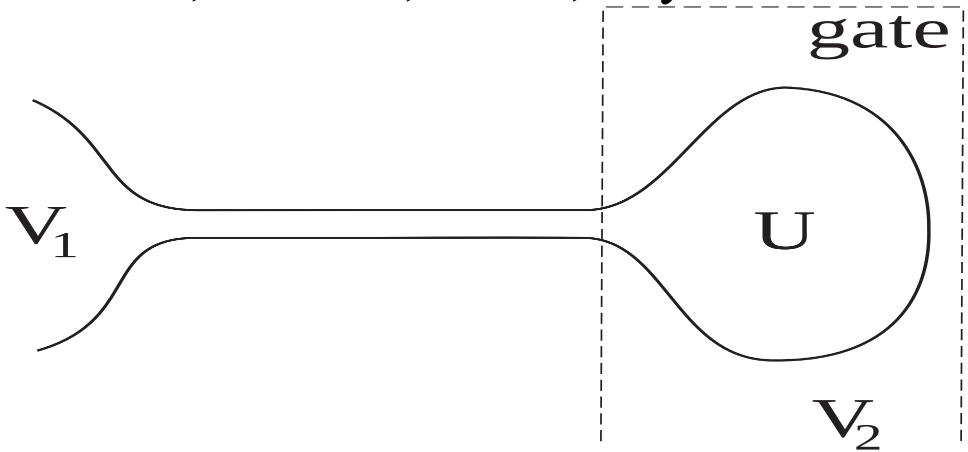
$$\hat{a}_\alpha(E) = \hat{a}'_\alpha(E) - c_\alpha\hat{a}'_\alpha(E_+) + c_\alpha\hat{a}'_\alpha(E_-)$$

$$\Longrightarrow$$

$$G^{ext}_{\alpha\beta}(\omega) = \frac{e^2}{h}\int dE\,Tr[A_{\beta\beta}(\alpha,E,E+\hbar\omega)]\frac{f_\beta(E) - f_\beta(E+\hbar\omega)}{\hbar\omega}$$

Mesoscopic capacitor

Buttiker, Thomas, Pretre, Phys. Lett. A 180, 364 (1993)



single potential U

geometrical capacitance C

$$G^{ext}_{\alpha\beta}(\omega) = \frac{e^2}{h}\int dE Tr[A_{\beta\beta}(\alpha, E, E+\hbar\omega)]\frac{f_\beta(E) - f_\beta(E+\hbar\omega)}{\hbar\omega}$$

$$A_{\beta\beta}(\alpha, E', E) = 1_\alpha\delta_{\alpha\beta} - s^\dagger_{\alpha\beta}(E')s_{\alpha\beta}(E)$$

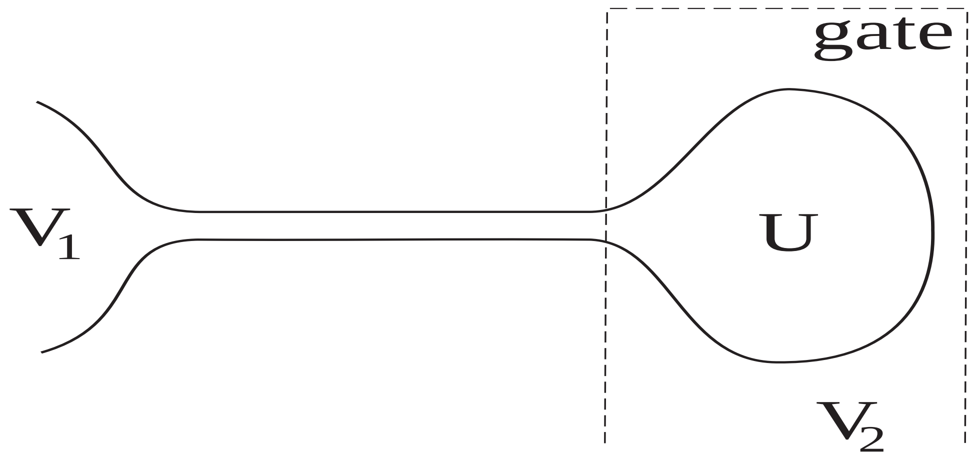
Internal response

$$G^{ext}dV_1 + i\omega\Pi dU = -i\omega C(dU - dV_2)$$

Invariance under arbitrary potential shift $\Longrightarrow$ $i\omega\Pi = G^{ext}$

$$G^{-1}(\omega) = (-i\omega C)^{-1} + (G^{ext}(\omega))^{-1}$$

Mesoscopic Capacitor



$$\frac{1}{G(\omega)} = \frac{1}{-i\omega C} + \frac{1}{G^{ext}(\omega)}$$

expansion in $\omega; kT = 0$

$$\Rightarrow$$

$$G^{ext}(\omega) = -i\omega e^2 Tr(N) + (1/2) h\omega^2 e^2 Tr(N^\dagger N) + ..$$

$$N = \frac{1}{2\pi i} s^\dagger \frac{ds(E)}{dE}$$

Wigner-Smith (delay)-time matrix

$$G(\omega) = -i\omega C_\mu + \omega^2 C_\mu^2 R_q + ..$$

electrochemical capacitance

$$C_\mu^{-1} = C^{-1} + (e^2 Tr[N])^{-1}$$

charge relaxation resistance

$$R_q = \frac{h}{2e^2} \frac{Tr[N^\dagger N]}{(Tr[N])^2}$$

Mesoscopic Capacitor

Buttiker, Thomas, Pretre, Phys. Lett. A180, 364 (1993)

$$G(\omega) = -i\omega C_\mu + \omega^2 C_\mu^2 R_q + ..$$

charge relaxation resistance

electrochemical capacitance

$$C_\mu^{-1} = C^{-1} + (e^2 Tr[N])^{-1} \qquad R_q = \frac{h}{2e^2}\frac{Tr[N^\dagger N]}{(Tr[N])^2}$$

Eigen channels of s; $\exp(i\phi_n)$; $n = 1, 2, ,$ $\Longrightarrow$

$$Tr[N] = \frac{1}{2\pi i} Tr[s^\dagger \frac{ds}{dE}] = \frac{1}{2\pi}\sum_n \frac{d\phi_n}{dE}$$

$$Tr[N^\dagger N] = (\frac{1}{2\pi})^2 Tr[\frac{ds^\dagger}{dE}\frac{ds}{dE}] = (\frac{1}{2\pi})^2 \sum_n (\frac{d\phi_n}{dE})^2$$

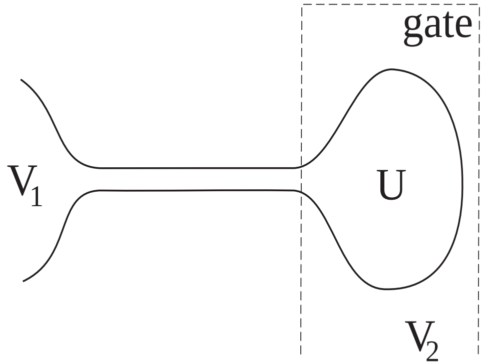
$\Longrightarrow$ Quantum corrections to capacitance

$$R_q = \frac{h}{2e^2}\frac{\sum_n (d\phi_n/dE)^2}{(\sum_n d\phi_n/dE)^2}$$

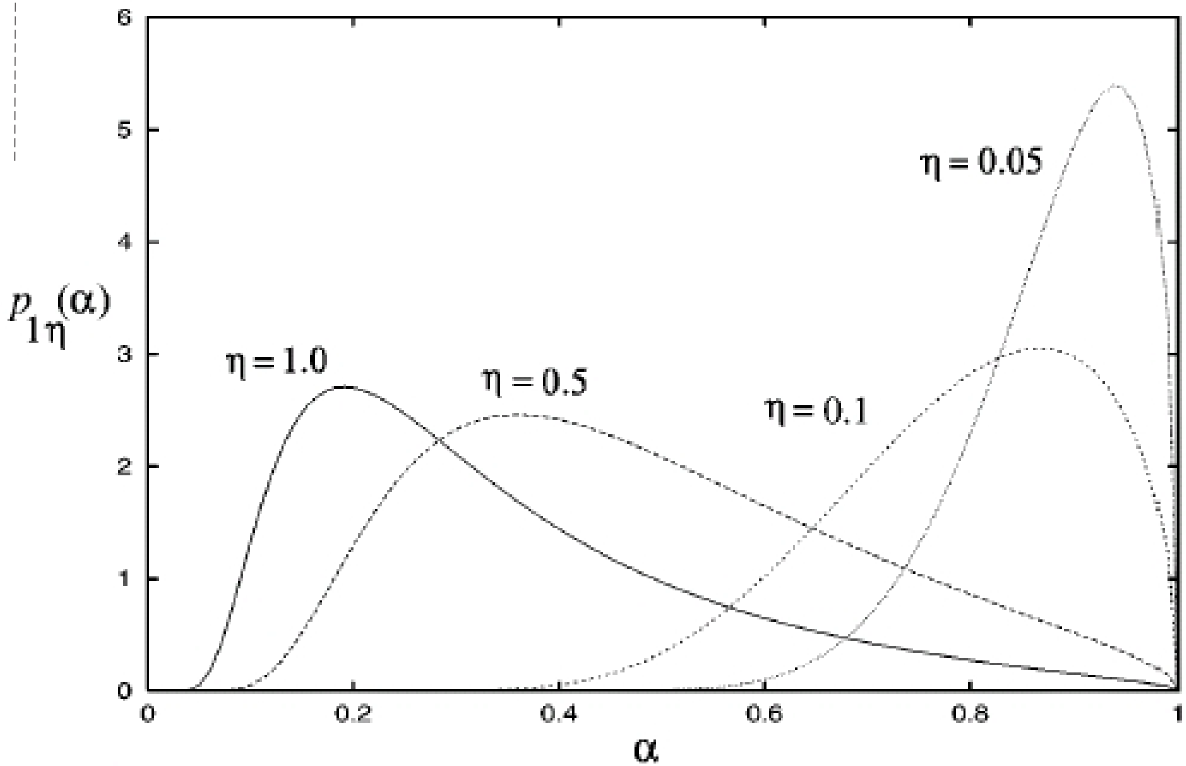
$\Longrightarrow$ Universal for n =1; $R_q = \frac{h}{2e^2}$

Capacitance Fluctuations

Gopar, Mello, Buttiker, PRL 77, 3005 (1996)



$$\alpha = C_\mu / C = \frac{e^2 Tr[N]}{C + e^2 Tr[N]}$$



$$\eta = C/(e^2/\Delta) = C/(e^2 < Tr[N] >)$$

Charge relaxation resistances

$$R_q = \frac{h}{2e^2} \frac{\sum_n (d\phi_n/dE)^2}{(\sum_n d\phi_n/dE)^2}$$ Universal for n =1; $$R_q = \frac{h}{2e^2}$$

For k degenerate channels

$$R_q = \frac{h}{2e^2} \frac{\sum_n (d\phi_n/dE)^2}{(\sum_n d\phi_n/dE)^2} = \frac{h}{2e^2} \frac{k}{k^2} = \frac{h}{2ke^2}$$

Spin less electrons $R_q = h/2e^2$

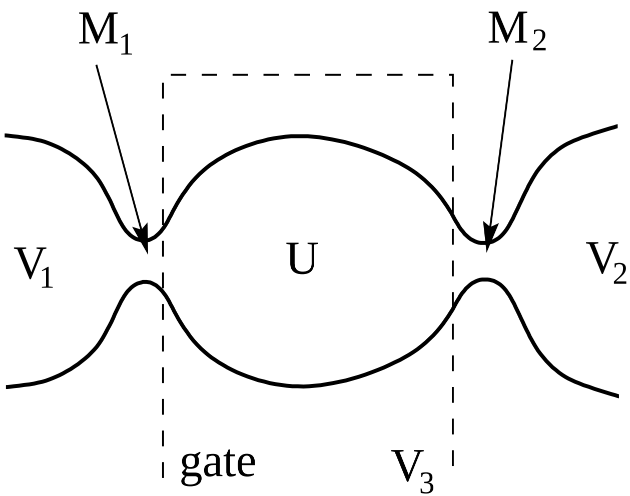
Spin degenerate channel $R_q = h/4e^2$

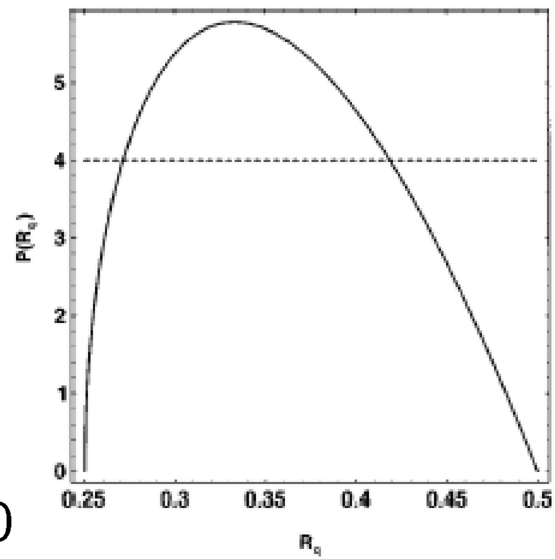
Ideally coupled Carbon Nanotube $R_q = h/16e^2$

Chaotic cavity coupled to two QPC (single channel limit) $P(R_q)$

Charge relaxation resistance fluctuations

Pedersen, van Langen, Buttiker, PRB57, 1838 (1998)





$$M_1 = M_2 = 1; V_1 = V_2 = V_3 = 0$$

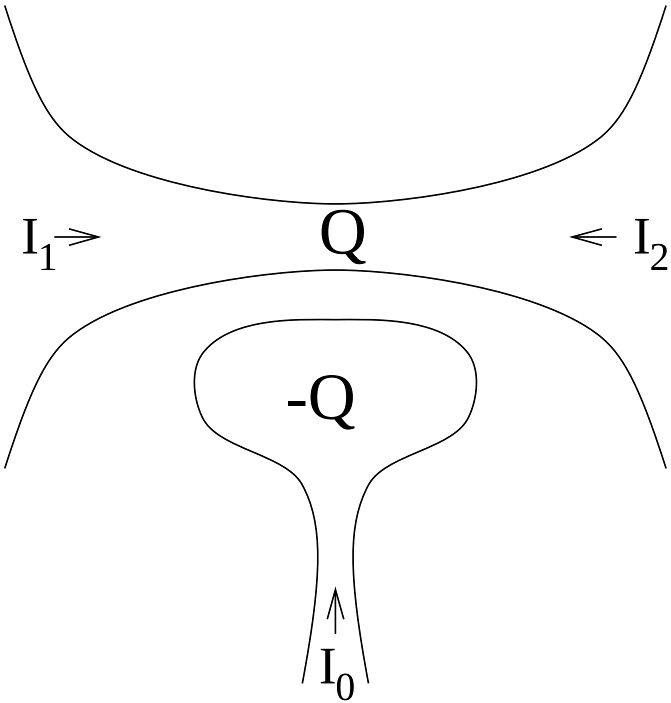
______ orthogonal --------- unitary

Large channel limit:

$$R_q = \frac{h}{2e^2} \frac{1}{M_1 + M_2} \qquad R = \frac{h}{e^2}\left(\frac{1}{M_1} + \frac{1}{M_2}\right)$$

parallel series

Dynamics: Multi-terminal



Dynamic transport:

Contacts which permit particle exchange and capacitively coupled « gates » need to be treated on equal footing:

current conservation

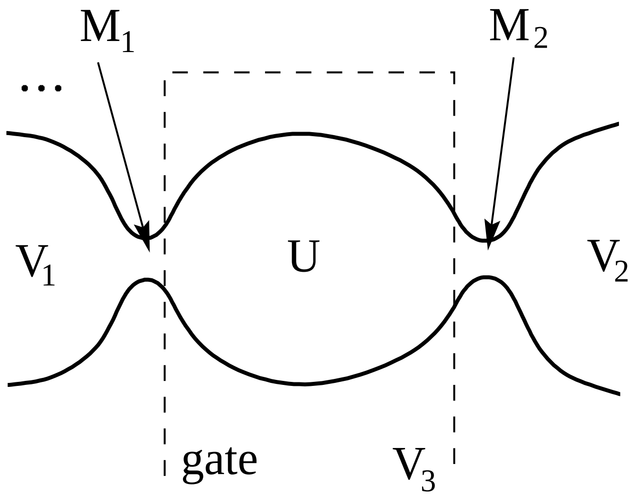
$$\sum_{\alpha=1}^{3} I_\alpha = 0$$

Long range Coulomb interaction Ensures that sum of all excess charges add up to zero in a sufficiently large Gauss volume:

(electrostatic-) gauge invariance

Dynamics: Multi-terminal

$$G_{\alpha\beta}(\omega) = G_{\alpha\beta} - i\omega E_{\alpha\beta} + \omega^2 K_{\alpha\beta} + \dots$$



current conservation gauge

$$\sum_\alpha G_{\alpha\beta}(\omega) = 0 \qquad \sum_\beta G_{\alpha\beta}(\omega) = 0$$

Emittance matrix $E_{\alpha\beta}\,;\,(kT = 0)$

$$G^{ext}_{\alpha\beta}(\omega) = G_{\alpha\beta} - i\omega e^2 N_{\alpha\beta} + \dots$$

$$N_{\alpha\beta} = \frac{1}{4\pi i}[s^\dagger_{\alpha\beta}\frac{ds_{\alpha\beta}}{dE} - \frac{ds^\dagger_{\alpha\beta}}{dE}s_{\alpha\beta}]$$

Partial (global) density of states

$\alpha = 1,2\ ,\beta = 1,2$

Bare emittance

Bare injectance

$$E_{\alpha\beta} = e^2[N_{\alpha\beta} - (\sum_\gamma N_{\alpha\gamma})\frac{e^2}{C + e^2 N}(\sum_\delta N_{\delta\beta})]$$

$\alpha = 1,2\ ,\beta = 3$

$$E_{\alpha 3} = -e^2(\sum_\gamma N_{\alpha\gamma})\frac{C}{C + e^2 N}$$

$E_{\alpha\alpha} > 0\,,\, E_{\alpha\beta} < 0$ capacitive

$E_{\alpha\alpha} < 0\,,\, E_{\alpha\beta} > 0$ inductive

Global density of states hierarchy

Partial (global) density of states

(pre- and post-selection)

$$N_{\alpha\beta} = \frac{1}{4\pi i}[s^{\dagger}_{\alpha\beta}\frac{ds_{\alpha\beta}}{dE} - \frac{ds^{\dagger}_{\alpha\beta}}{dE}s_{\alpha\beta}]$$

$N_{\alpha\alpha}$

not positive definite!

Injectance

(pre-selection)

$$\sum_{\delta} N_{\delta\beta}$$

Emittance

(post-selection)

$$\sum_{\gamma} N_{\alpha\gamma}$$

(Global) density of states

$$N = \sum_{\delta\beta} N_{\delta\beta}$$

Internal response

Buttiker, Thomas, Pretre, Z. Phys. B94, 133 (1994)

$$U(r,t) = U_{eq}(r) + dU(r,t)$$

$$dU(r,t) = dU_\omega(r)\exp(-i\omega t)$$

scattering matrix of Floquet type $s_{\alpha\beta}(E + n\hbar\omega, E)$

low-frequency limit

$$dI_\alpha(\omega) = ie\omega \int d^3r \sum_\beta \frac{1}{4\pi i}[s^\dagger_{\alpha\beta}\frac{\partial s_{\alpha\beta}}{\partial U(r)} - \frac{\partial s^\dagger_{\alpha\beta}}{\partial U(r)} s_{\alpha\beta}]U_\omega(r)$$

$$dI_\alpha(t) = -ie \int d^3r \sum_\beta \frac{1}{4\pi i}[s^\dagger_{\alpha\beta}\frac{\partial s_{\alpha\beta}}{\partial U(r)} - \frac{\partial s'_{\alpha\beta}}{\partial U(r)} s_{\alpha\beta}]\frac{dU(r,t)}{dt}$$

local partial density of states

$$\nu(\alpha, r, \beta) = -\frac{1}{4\pi i}[s^\dagger_{\alpha\beta}\frac{\partial s_{\alpha\beta}}{\partial eU(r)} - \frac{\partial s^\dagger_{\alpha\beta}}{\partial eU(r)} s_{\alpha\beta}]$$

Local density of states hierarchy

local partial density of states

$$\nu(\alpha, r, \beta) = -\frac{1}{4\pi i}[s^{\dagger}_{\alpha\beta}\frac{\delta s_{\alpha\beta}}{\delta eU(r)} - \frac{\delta s^{\dagger}_{\alpha\beta}}{\delta eU(r)}s_{\alpha\beta}]$$

injectivity

$$\nu(r, \beta) = \sum_{\alpha} \nu(\alpha, r, \beta)$$

emissivity

$$\nu(\alpha, r) = \sum_{\beta} \nu(\alpha, r, \beta)$$

local density of states

$$\nu(r) = \sum_{\alpha\beta} \nu(\alpha, r, \beta)$$

current generate by internal response

$$dI_{\alpha}(\omega) = ie\omega \int d^3r\, \nu(\alpha, r)\, U_{\omega}(r)$$

BTP

Buttiker, Thomas, Pretre, Z. Phys. B94, 133 (1994)

Effective Interaction

$$U(r) = U_{eq}(r) + dU(r)$$

$$dU(r) = \sum_{\alpha} (dU(r)/dV_{\alpha}) dV_{\alpha} + ..$$

characteristic potential

$$u_{\alpha}(r) = (dU(r)/dV_{\alpha}) \ ;$$

gauge

$$\sum_{\alpha} u_{\alpha}(r) = 1 \ ;$$

Poisson

$$-\Delta u_{\alpha}(r) + 4\pi e^2 \int d^3 r \Pi(r, r') du_{\alpha}(r') = 4\pi e^2 \nu(r, \alpha)$$

effective interaction

gauge

$$u_{\alpha}(r) = \int d^3 r g(r, r') \nu(r, \alpha) \ ; \ \ 1 = \int d^3 r g(r, r') \nu(r')$$

Emittance

$$E_{\alpha\beta} = e^2 \int d^3 r [\nu(\alpha, r, \beta) - \int d^3 r' \nu(\alpha, r) g(r, r') \nu(r', \beta)] \ ;$$

Buttiker, J. Phys:. Cond. Matt. 5, 9361 (1993)

Thermal charge fluctuations of a capacitor

$$(1/2)\langle I(\omega)I(\omega')+I(\omega')I(\omega)\rangle = 2\pi S_{II}(\omega)\delta(\omega+\omega')$$

Fluctuation-Dissipation Theorem

$$S_{II}(\omega) = \omega^2 S_{QQ}(\omega) = 2kTRe[G(\omega)]$$

with

$$G(\omega) = -i\omega C_\mu + \omega^2 C_\mu^2 R_q + .. \quad \Longrightarrow$$

Charge fluctuation spectrum

$$S_{QQ}(\omega) = 2kTC_\mu^2 R_q + ..$$

Thermal charge fluctations of a capacitor

$$\hat{I}_\alpha(t) = \frac{e}{h}\int dE' dE \hat{a}^\dagger_\alpha(E') A_{\alpha\alpha}(\alpha, E', E)\hat{a}_\alpha(E) e^{i(E'-E)t/\hbar}$$

$$\hat{I}_\alpha(\omega) = \frac{e}{h}\int dE \hat{a}^\dagger_\alpha(E) A_{\alpha\alpha}(\alpha, E, E+\hbar\omega)\hat{a}_\alpha(E+\hbar\omega)$$

$$A_{\alpha\alpha}(\alpha, E, E+\hbar\omega) = 1_\alpha - s^\dagger_{\alpha\alpha}(E) s_{\alpha\alpha}(E+\hbar\omega)$$

$$A_{\alpha\alpha}(\alpha, E, E+\hbar\omega) = 2\pi i N \hbar\omega + \ldots$$

$$N = \frac{1}{2\pi i} s^\dagger \frac{ds}{dE}$$

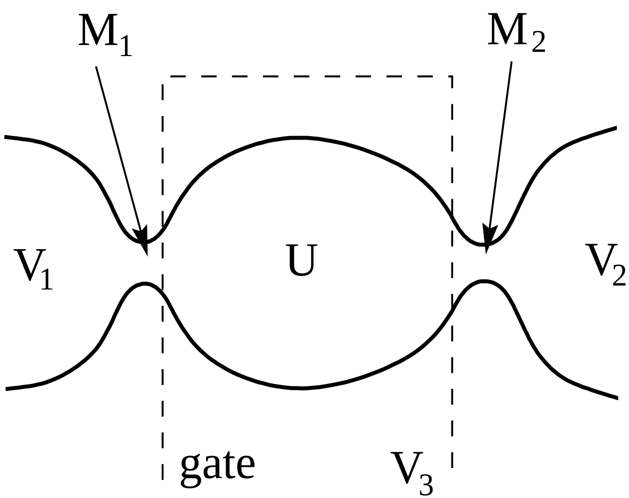
$$\hat{Q}^{ext}(\omega) = e\int dE\, \hat{a}^\dagger(E)\, N\, \hat{a}(E+\hbar\omega)$$

$$dI = G^{ext} dV_1 + i\omega \Pi dU = -i\omega C(dU - dV_2)$$

$$\hat{Q} = \hat{Q}^{ext} - \Pi d\hat{U} = C\, d\hat{U}$$ screened charge $\Longrightarrow$

$$S_{QQ}(\omega) = 2kTC_\mu^2 R_q + ..$$

Shot noise induced charge fluctuations on a gate



$$V \equiv V_1 - V_2 > 0; kT = 0$$

zero-frequency shot noise

$$S_{II} = 2\frac{e^2}{h}|eV| \sum T_n(1-T_n)$$

What will we see at the gate?

Charge fluctuation sensor

« Wigner-Smith matrix »

$$N_{\gamma\delta} = -\frac{1}{2\pi i} s^\dagger_{\alpha\gamma} \frac{ds_{\alpha\delta}}{deU} \qquad R_V = \frac{h}{2e^2} \frac{Tr[N_{12}N_{21}]}{(Tr[N])^2}$$

$$S_{I_3 I_3}(\omega) = \omega^2 S_{QQ}(\omega) = 2\omega^2 C_\mu R_V eV$$

Pedersen, van Langen, Buttiker, PRB 57, 1838 (1998)

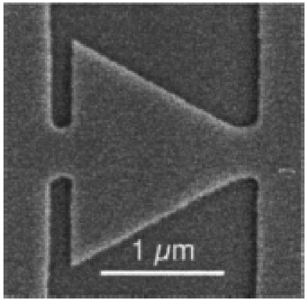
Non-linear transport

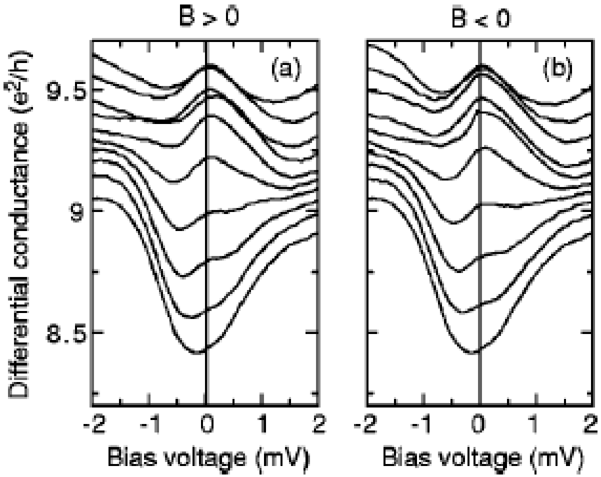
- Need of self-consistent model including screening potential

$$I = \frac{2e}{h}\int T(E,V)[f_L(E) - f_R(E)]dE$$

- Naive expectation: *since T is even in the two-probe case, nonlinear I-V is also even* $I(B) = I(-B)$

- Experimental "verification"





Linke *et al*., Phys. Rev. B **61**, 15914 (2000); Loefgren et al, PRL 92, 046803 (2004)

Non-linear transport

- Scattering matrix: $s_{\alpha\beta} = s_{\alpha\beta}[E; U(\vec{r})]$
- Weakly nonlinear transport:

$$I_\alpha = \sum_\beta G_{\alpha\beta} V_\beta + \sum_{\beta\gamma} G_{\alpha\beta\gamma} V_\beta V_\gamma$$

where

$$G_{\alpha\beta} = -\frac{e^2}{h}\int dE \frac{\partial f(E-\mu_0-V_\alpha)}{\partial E} A_{\alpha\beta}(E;\{V_\alpha\}=0)$$

$$A_{\alpha\beta}(E;\{V_\alpha\}) = \mathrm{Tr}[1_{\alpha\beta}\delta_{\alpha\beta} - s^\dagger_{\alpha\beta} s_{\alpha\beta}]$$

$$G_{\alpha\beta\gamma} = -\frac{e^2}{h}\int dE \frac{\partial f}{\partial E}\int d^3r \frac{\delta A_{\alpha\beta}}{\delta U(\vec{r})}[2u_\gamma(\vec{r}) - \delta_{\beta\gamma}]$$

M. Büttiker, J. Phys.: Condens. Matter **5**, 9361 (1993);
T. Christen and M. Büttiker, Europhys. Lett. **35**, 523 (1996)

Non-linear transport

Transmission probability is even in magnetic field only if

$$s_{\alpha\beta} = s_{\alpha\beta}[E; U_{eq}(\vec{r})]$$

Non-equilibrium potential is not even in B !

$$-\Delta u_\beta(\vec{r}) + 4\pi e^2 \int d\vec{r}' \Pi(\vec{r}, \vec{r}') u_\beta(\vec{r}') = 4\pi e^2 \nu(\vec{r}, \beta)$$

Reversing magnetic field turns injectivity into emissivity

$$\nu(\vec{r}, \alpha, B) = \nu(\alpha, \vec{r}, -B)$$

Second order conductances are not even

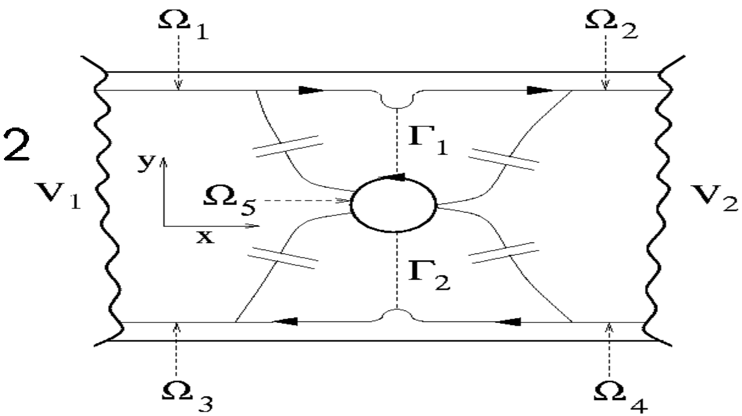
$$\Phi \equiv \frac{1}{2}[G_{111}(B) - G_{111}(-B)]$$

Non-linear transport: anti-dot

Sanchez and Buttiker, PRL (unpubl.)

$$\Phi \equiv \frac{1}{2}[G_{111}(B) - G_{111}(-B)]$$

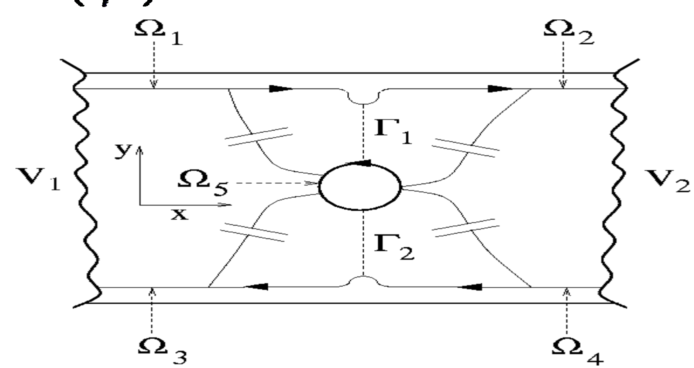
$$R = \frac{\Gamma_1 \Gamma_2}{|\Delta|^2} \qquad \Delta = \mu_0 - E_0 - eU_5 + i\Gamma/2$$



scattering asymmetry

$$\eta = (\Gamma_1 - \Gamma_2)/\Gamma$$

$$\Phi = -\frac{e^3}{h}\frac{\partial T}{\partial E}\bigg|_{\text{eq}} \frac{\eta R(C + e^2 D)}{2\pi C D \Gamma + R(C + e^2 D)} + \mathcal{O}(\eta^3)$$



electrical asymmetry

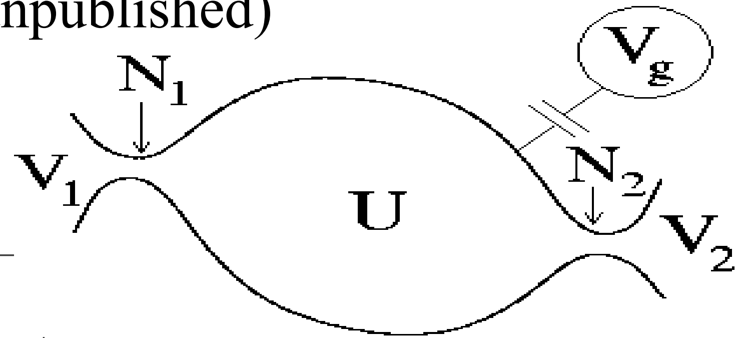
$$\xi = (C_1 - C_2)/2C$$

$$\Phi = -\frac{e^3}{h}\frac{\partial T}{\partial E}\bigg|_{\text{eq}} \frac{\pi \xi C e^2 D^2 \Gamma T}{(C + e^2 D)(2\pi C D \Gamma + R(C + e^2 D))} + \mathcal{O}(\xi^3)$$

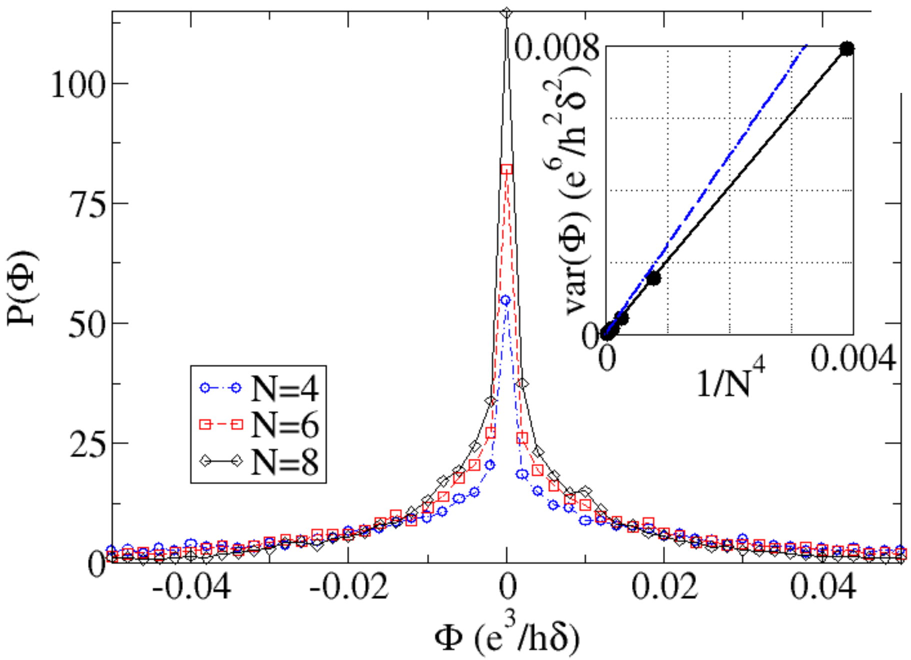
Non-linear transport: chaotic cavity

Sanchez and Buttiker, PRL (unpublished)

$$\mathrm{var}\,\Phi = \frac{e^6}{h^2\delta^2}\frac{16\pi^2 N_1^3 N_2^3}{N^{10}}\left(\frac{C_\mu}{C}\right)^2$$



$$N_1 = N_2 = N/2$$



$$\Phi \equiv \frac{1}{2}[G_{111}(B) - G_{111}(-B)]$$

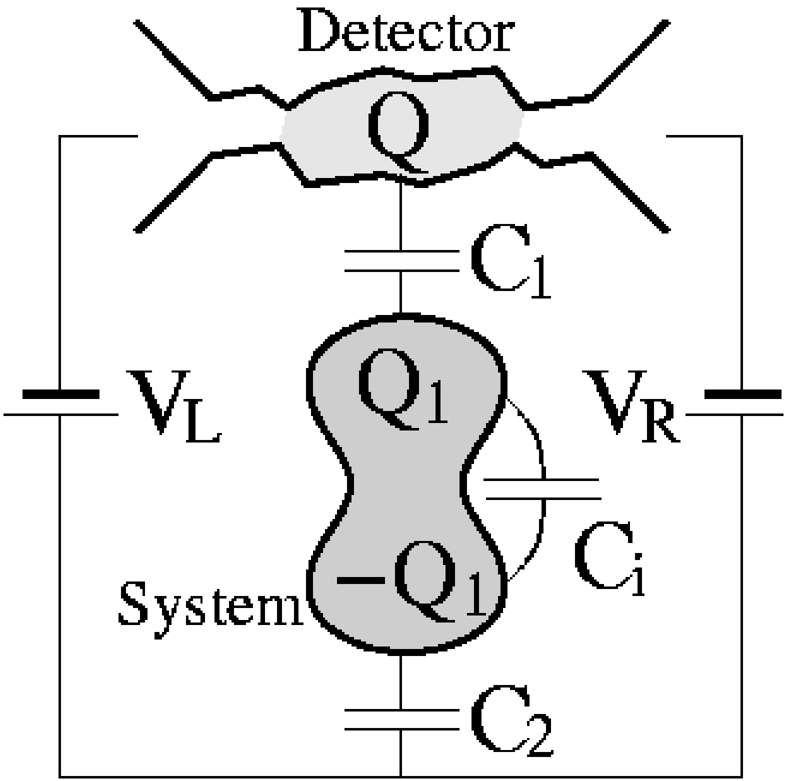
Experiments:

Zumbuhl, Marcus,..

Linke,..

Mesoscopic detectors

Pilgram and Buttiker, PRL 89, 200401 (2002)



$$\Gamma_{rel} = 2\pi \frac{\Delta^2}{\Omega^2} \left(\frac{C_\mu}{C_i}\right)^2 R_q \frac{\Omega}{2} \coth \frac{\Omega}{2kT};$$

$$\Gamma_{dec} = 2\pi \frac{e^2}{\Omega^2} \left(\frac{C_\mu}{C_i}\right)^2 (R_q kT + R_v e|V|) + \Gamma_{rel}/2,$$

$$\Gamma_m = 2\pi \left(\frac{C_\mu}{C_i}\right)^2 R_m e|V|.$$

$D = e^2 \mathrm{Tr} N,$ $\qquad C_\mu^{-1} = C^{-1} + D^{-1},$

$$R_q = \frac{1}{2} \frac{(\mathrm{Tr} N^2)}{(\mathrm{Tr} N)^2}; \quad R_v = \frac{(\mathrm{Tr} N_{12} N_{21})}{(\mathrm{Tr} N)^2}; \quad R_m = \frac{1}{4\pi^2} \frac{\left(\sum \frac{dT_n}{dU}\right)^2}{(\mathrm{Tr} N)^2 \left(\sum R_n T_n\right)}.$$

Mesoscopic detectors

Buttiker and Pilgram, Surface Science 532, 617 (2003)

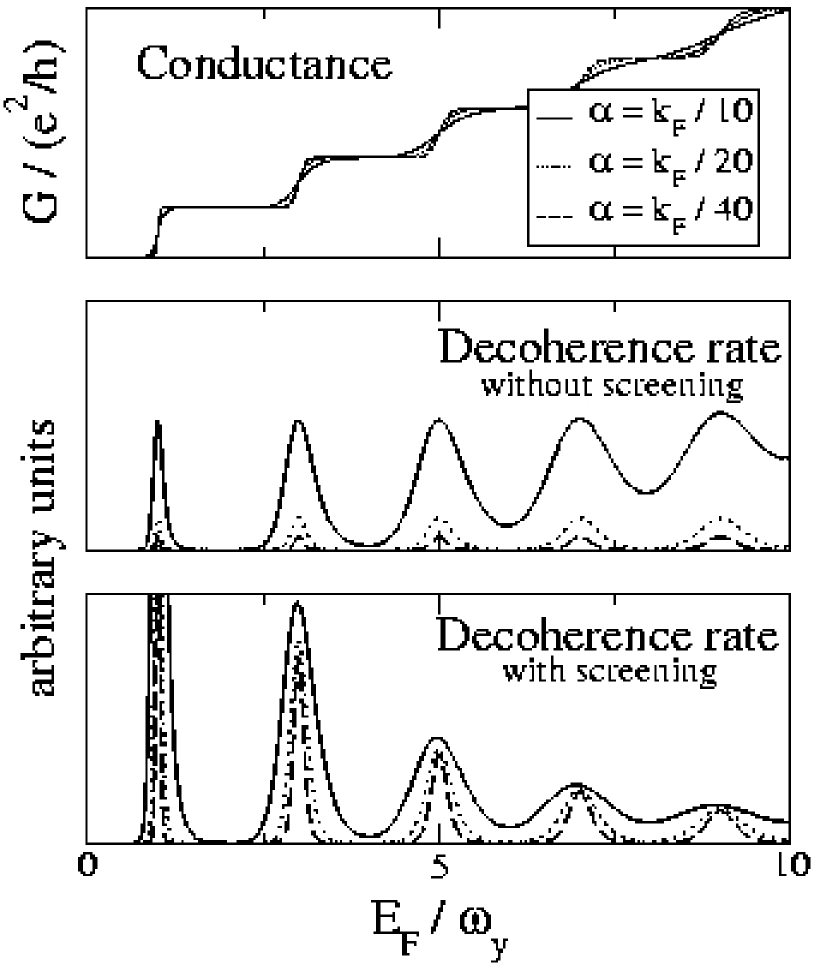
Quantum Point Contact

$$V(x,y) = X(x) + Y(y)$$

$$X(x) = \frac{V_0}{cosh^2(\alpha x)}$$

$$Y(y) = \frac{1}{2} m \omega_y y^2$$

$$\Gamma_{dec} \propto R_V |eV|$$



Adiabatic Quantum Pumping

Brouwer, Phys. Rev. B58, 10135 (1998)

$$s_{\alpha\beta}(E, U, X_1, X_2)\,;\, X_1 = x_1 cos(\omega t),\;\; X_2 = x_2 cos(\omega t + \phi)$$

Internal response

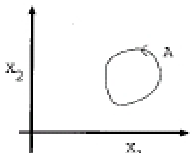
$$dI_\alpha(\omega) = ie\omega N_\alpha U_\omega$$

$$dI_\alpha(t) = -eN_\alpha\, dU/dt$$

$$N_\alpha(U) = -\frac{1}{2\pi i}\sum_\beta s^\dagger_{\alpha\beta}\frac{ds_{\alpha\beta}}{deU}$$

Modulated emittance

$$dQ_\alpha(t) = eN_\alpha(X_1)\, dX_1 + eN_\alpha(X_2) dX_2$$

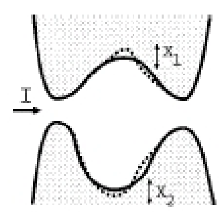


(b)

$$Q_\alpha = e\int_0^T dt[N_\alpha(X_1)\, dX_1/dt + N_\alpha(X_2)\, dX_2/dt]$$

$$Q_\alpha = e\int_A dX_1\, dX_2\, [dN_\alpha(X_2)/dX_1 - dN_\alpha(X_1)/dX_2]$$

$$I^p_\alpha = \frac{e\omega x_1 x_2 sin(\phi)}{2\pi}\sum_\beta \Im[\frac{ds^\star_{\alpha\beta}}{dX_1}\frac{ds_{\alpha\beta}}{dX_2}]$$



(a)

Conductance from the internal response

D. Cohen, PRB 68, 201303 (2003)

Internal response

$$dI_\alpha(\omega) = ie\omega N_\alpha U_\omega$$

$$dI_\alpha(t) = -eN_\alpha \, dU/dt$$

$$N_\alpha(U) = -\frac{1}{2\pi i}\sum_\beta Tr\left[s^\dagger_{\alpha\beta}\frac{ds_{\alpha\beta}}{deU}\right]$$

Response to flux generated by dc voltage

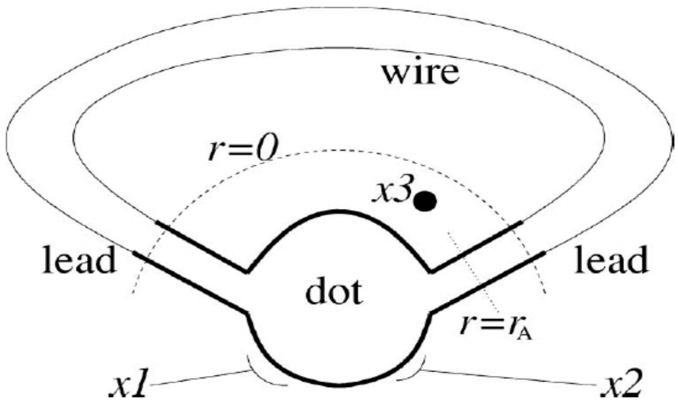
$$dI_\alpha = -eN_\alpha(\Phi)\, d\Phi/dt = ecN_\alpha V \; ; \qquad d\Phi(t)/dt = -cV$$

$$s = \begin{pmatrix} r_{11} & t_{12}e^{-i\phi} \\ t_{21}e^{i\phi} & r_{22} \end{pmatrix}$$

$$\phi = 2\pi\Phi/\Phi_0 \, ; \; \Phi_0 = hc/e$$

$$N_2(\Phi) = Tr\left[t^\dagger_{21}\, t_{21}\right]/\Phi_0$$

$$G = \frac{e^2}{h} Tr\left[t^\dagger_{21}\, t_{21}\right]$$



Summary

Scattering theory of dynamic transport

External and internal response

Partial density of states

Mesoscopic capacitance

Mesoscopic emittance (kinetic inductance)

Charge relaxation resitance

Charge fluctuations

Mesoscopic detectors

Adiabatic quantum pumping

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