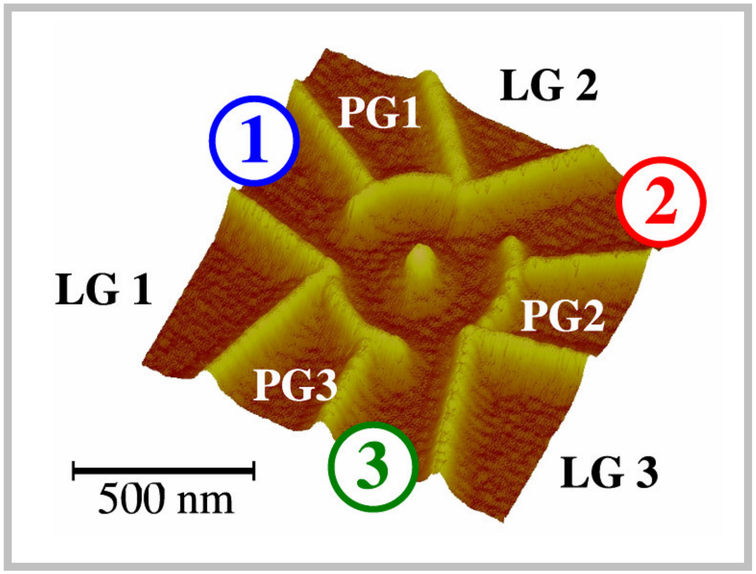
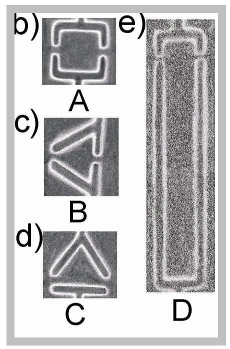
Mesoscopic fluctuations of nonlinear conductance.

Mikhail Polianski and Markus Büttiker, Université de Genève

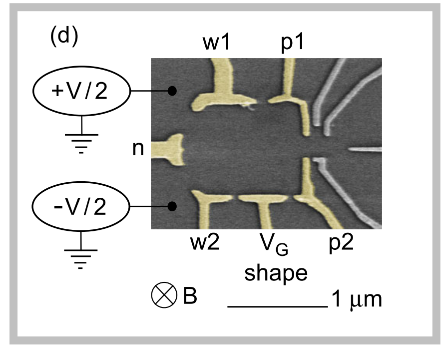
Magnetic field effect.



Leturcq et al



Marlow et al



Zumbühl et al

FORNEL

2nd FORNEL Workshop on Nanoelectronics, Würzburg, March 15th, 2006.

Outline of the talk

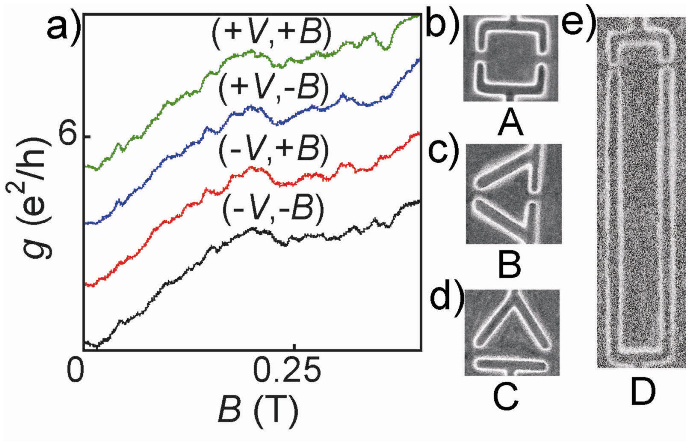
- Motivation: Nonlinearity +magnetic field
- Th./exp. background '04-05

What is important?

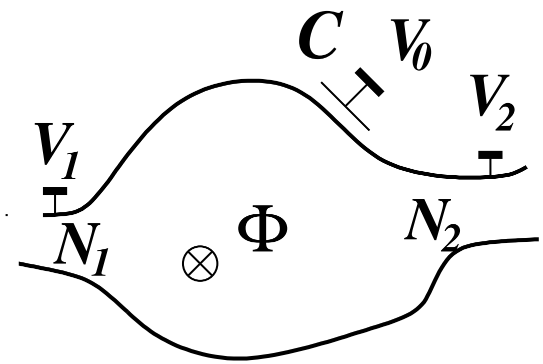
- Voltage *V* scale.
- Dependence on flux Φ.

  Relevant Φ scale.

  Is it flux quantum Φ_0?
- Open questions
- Conclusions



Marlow et al



Motivation: Theory

Equilibrium: linear conductance

$$G_{\alpha\beta} \equiv dI_\alpha / dV_\beta$$

⇨ Onsager relations

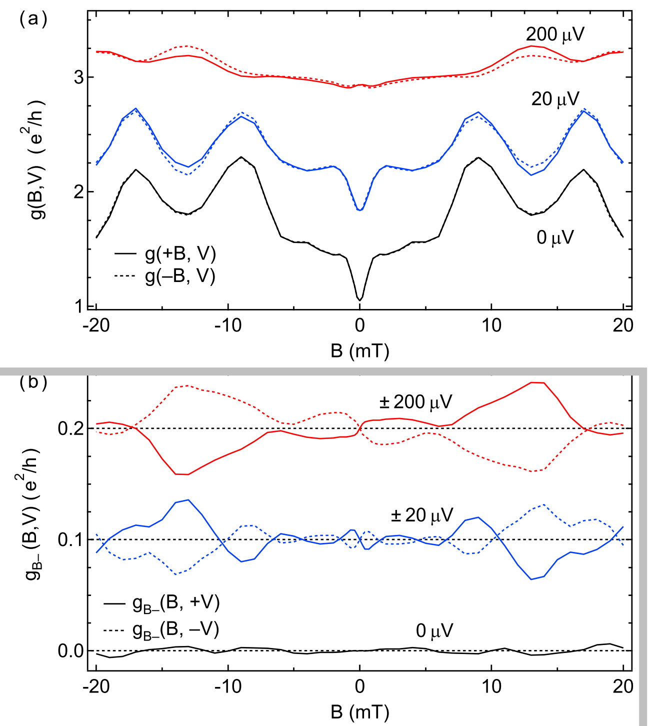
$$G_{\alpha\beta}(\Phi) = G_{\beta\alpha}(-\Phi)$$

Non-equilibrium: $I/V \neq dI/dV$

Onsager relations violated

but not too much if : Small V and Φ

and interaction strength



Asymmetry with field inversion

$\Phi \rightarrow -\Phi$ probes interactions

(Sanchez and Büttiker'04, Spivak and Zyuzin'04)

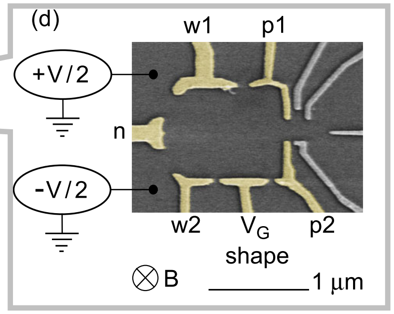
Want to find interaction strength

Zumbühl et al

Motivation: Experiment.

Experiments('05) in mesoscopic nonlinearity

- Wei et al (nanotube)
- Marlow et al (ballistic billiard)
- Leturcq et al (Aharonov-Bohm ring)
  Bouchiat et al (**cond-mat/0603303)**
- Zumbühl et al (quantum dot)



Strong nonlinearity in ***I-V*** and strong effect of Φ are observed

What is "small voltage ***V*** or flux Φ"?
What are relevant scales?

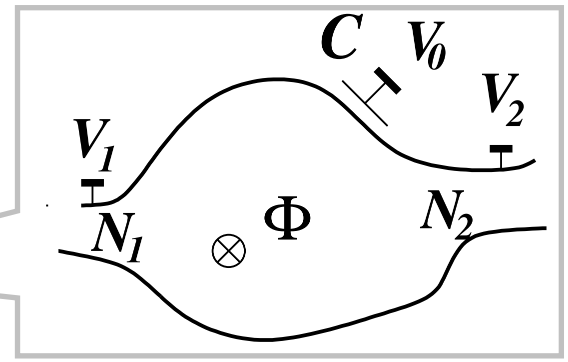
Theory at low *eV* : What was known?

Magnetic asymmetry+interaction $E_C \sim e^2/C$

$$I_1 = (e^2/h)\sum g^{(1)} V_1 + (e^3/h)\sum g^{(2)} V_1^2$$

$$\mathcal{G}_a = (g^{(2)}(\Phi) - g^{(2)}(-\Phi))/2$$

- Open dot: high flux, any E_C



Sanchez and Büttiker'04

$$\langle \mathcal{G}_a \rangle = 0, \mathcal{G}_a \propto C_\mu / C, \ \Phi \sim \Phi_0$$

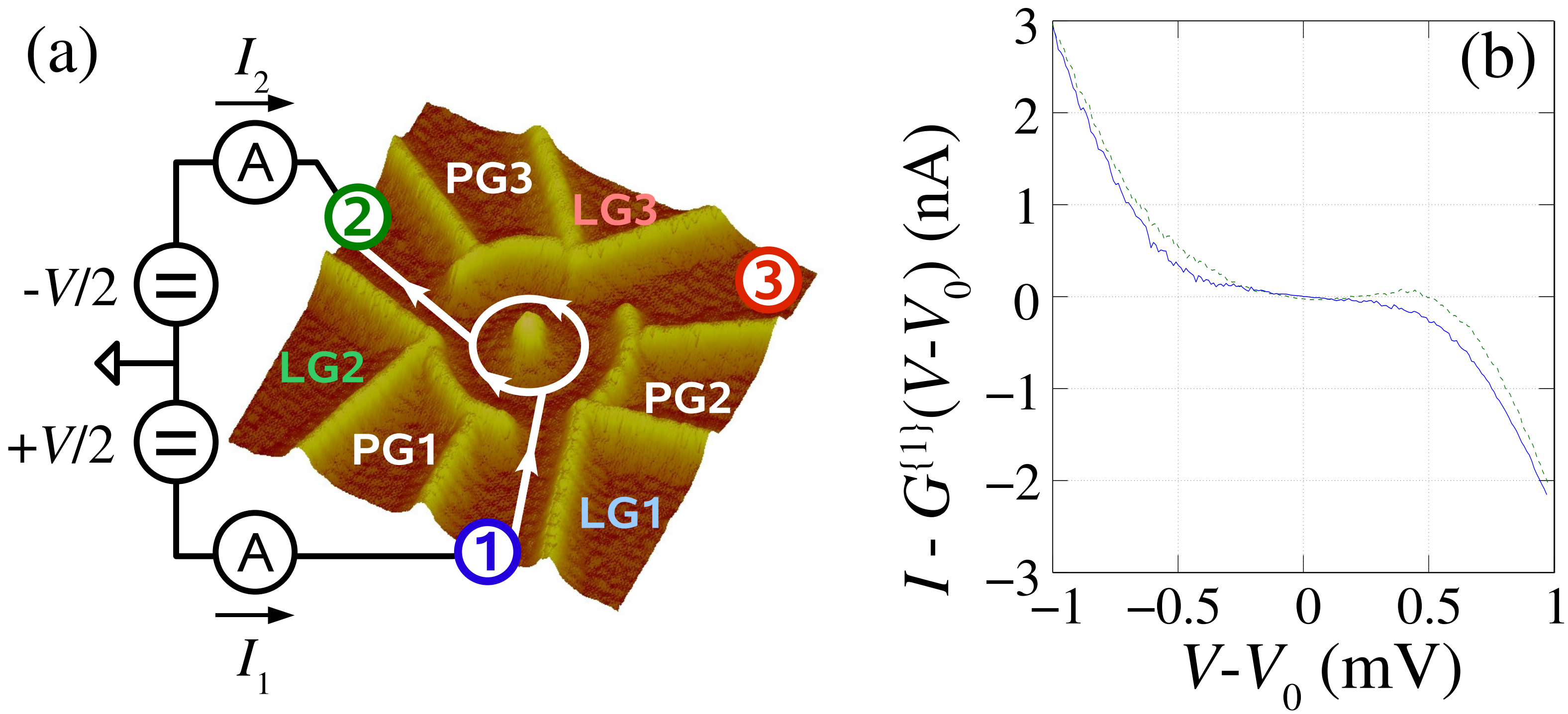
- Diffusive open sample: low flux, $E_C \ll \Delta$

Spivak and Zyuzin'04

?? ?

$$\langle \mathcal{G}_a \rangle = 0, \mathcal{G}_a \propto E_C (\Phi/\Phi_0), \ \Phi \ll \Phi_0$$

Leturcq *et al* (A.-B. ring) Measurements



Measures nonlinearities in transport (*y*-axis) *vs* applied voltage *V* up to V^5

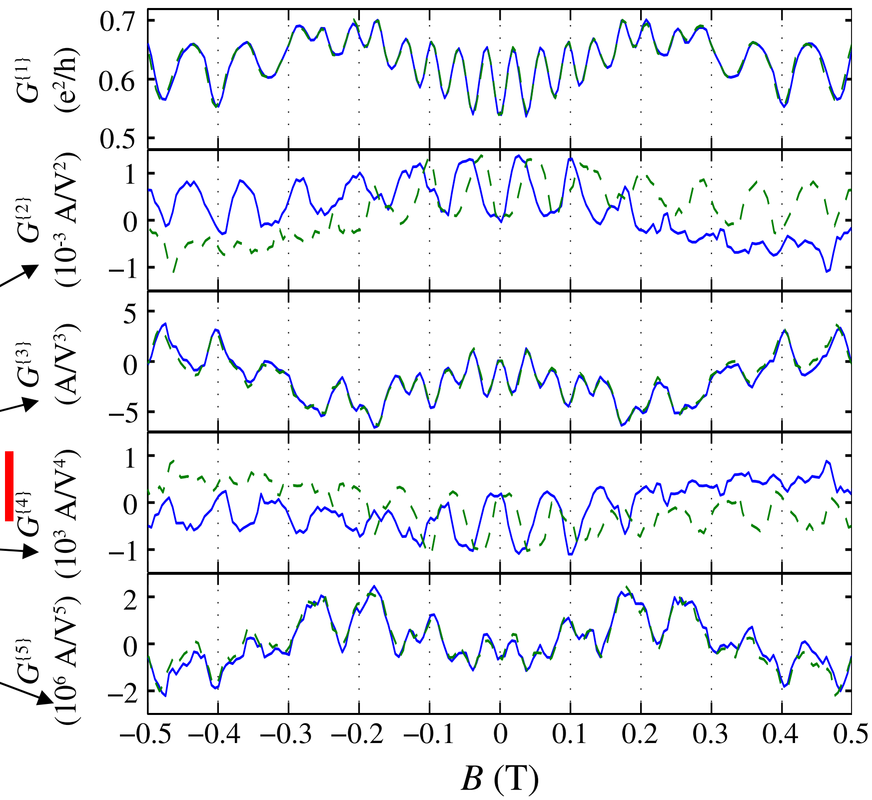
Q: How to estimate this voltage scale?

Leturcq *et al* (A.-B. ring) Results

Role of ***B*** field:

Asymmetric response to ***B***, ***–B***

Note: plots are scaled by 1*mV* in all plots!

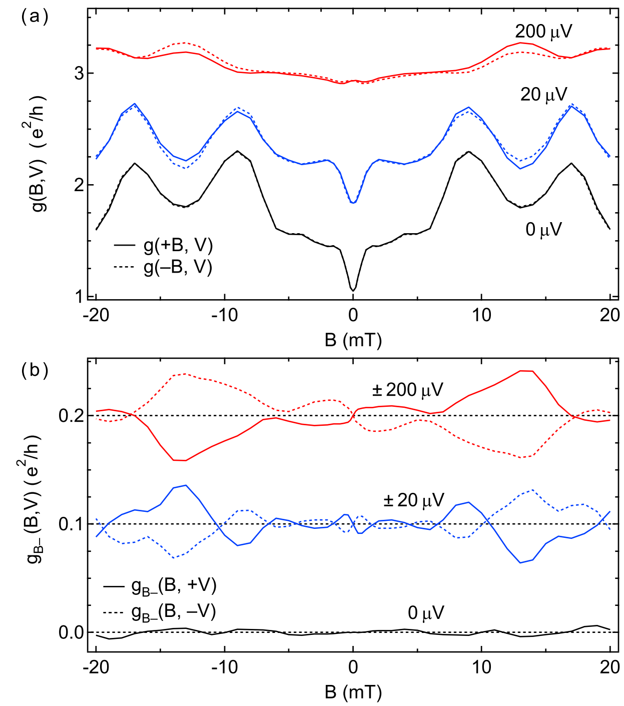


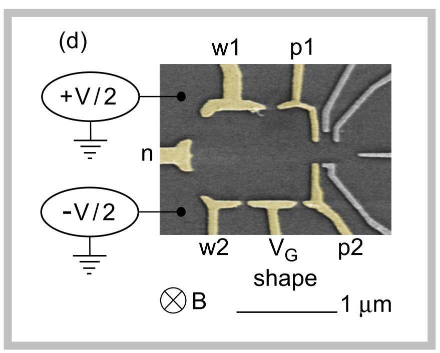
Zumbühl *et al* (q. dot) Measurements

Measure full conductance $g(B,V)$ and its (anti) symmetric component

$$g_{B-},\ g_{B+}$$

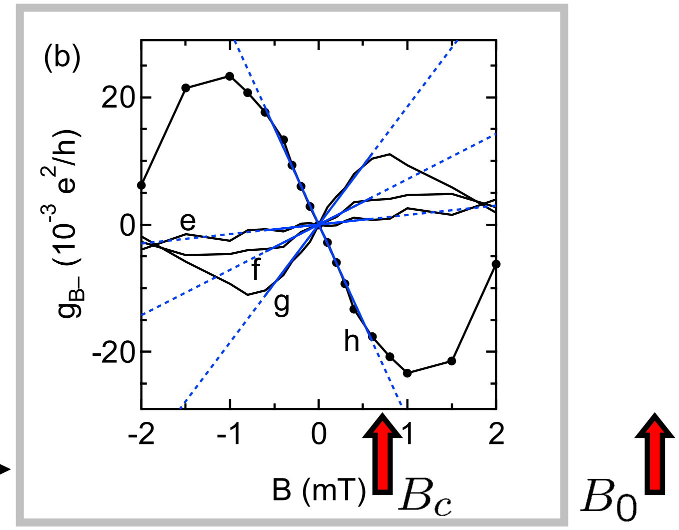
(stronger at higher V)

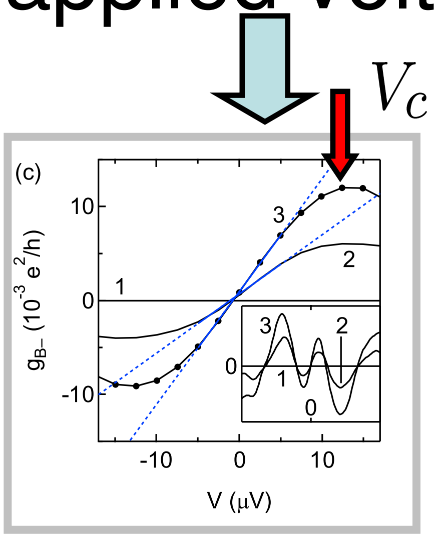




Zumbühl *et al* (q. dot) Results

- Random sign in B response
- Observe non-linearity in magnetic field *B*, in applied voltage *V*





Puzzle:

Crossover field is **much** smaller then

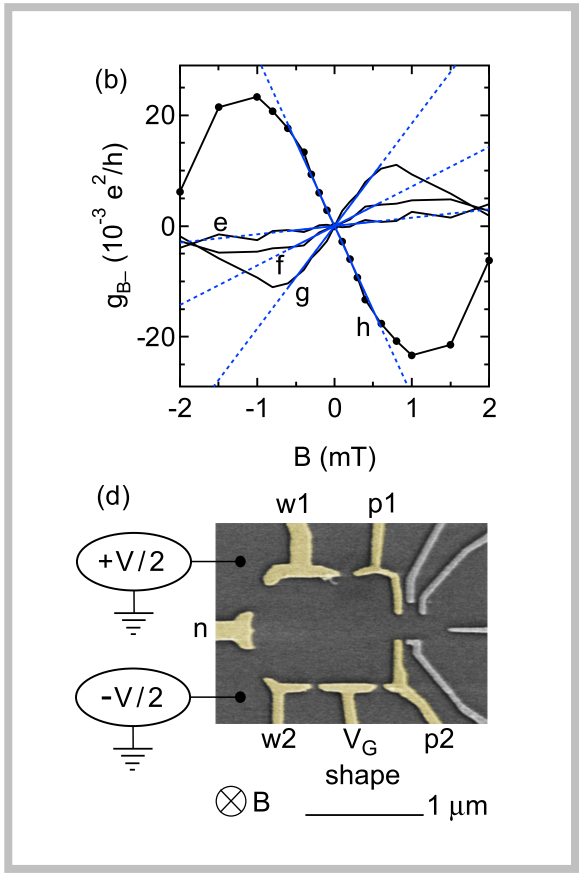
$$B_0 = 4mT$$

Questions addressed here

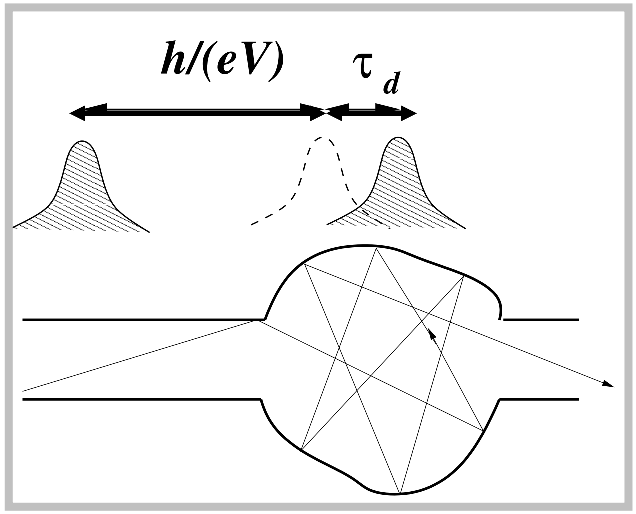
1. Relevant voltage scale

2. Magnetic flux Φ
a) What to expect?
b) The right scale.

3. Open questions



Wave-packets and voltage scale.



Waves arrive after $\sim h/(eV)$

and spend inside time $\sim \tau_{\mathrm{d}}$

At low ***eV*** wave-packets arrive rarely ⇨

no interaction ⇨

$$I_1 = \frac{e^2}{h}\sum g^{(1)} V_1 + \frac{e^3}{h}\sum g^{(2)} V_1^2 + \ldots$$

Usually $g^{(n)} \propto (\tau_{\mathrm{d}}/h)^{n-1}$ ⇒makes sense to look at $g^{(2)}$ if $eV \ll h/\tau_{\mathrm{d}}$

Experiment vs theory: *V*-scale

- **quantum dot:**

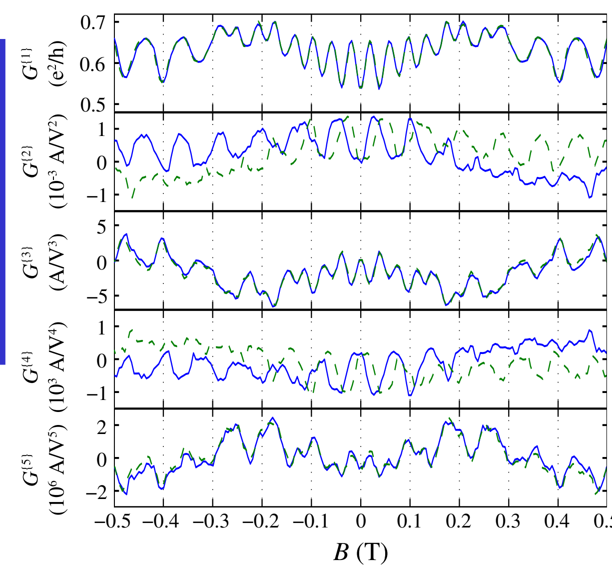
$$\Delta = 7\mu eV, N\Delta = 14\mu eV \approx V_c$$

- **Aharonov-Bohm ring**

$$\Delta \approx 200\mu eV, N\Delta \sim 800\mu eV = V_c \sim 1meV$$

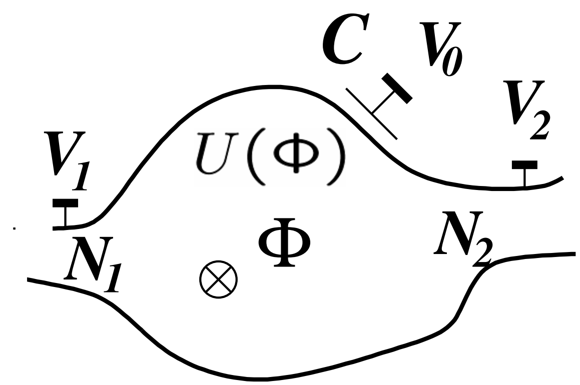
In open dot $h/\tau_\mathrm{d} = N\Delta$,
→ should compare eV
with $N\Delta$ not with Δ

No interactions → no field asymmetry



Coulomb interactions

- Coulomb interaction via capacitance *C*. Electron in a sample shifts potential ***U*** and affects next



- Flux Φ distorts trajectories

$$\Longrightarrow U(\Phi) \neq U(\Phi')$$

- ***U*** depends on interaction

$$\langle U \rangle \propto \langle C_\mu \rangle / C = 1/(1 + C\Delta/2e^2)$$

$$\langle U \rangle \propto 2e^2/(C\Delta), C \to \infty \text{ (weak interaction)}$$

$$\langle U \rangle \propto 1 - C\Delta/2e^2, C \to 0 \text{ (strong interaction)}$$

N-lin. conductance depend on ***U,*** measure screening strength

Magnetic flux. What to expect?

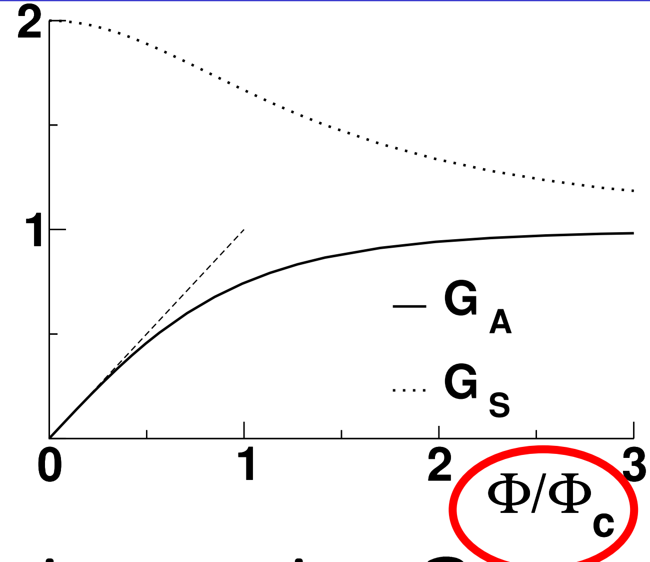
$$\binom{\mathcal{G}_s}{\mathcal{G}_a} = (g^{(2)}(\Phi) \pm g^{(2)}(-\Phi))/2$$

$$\mathcal{G}_a(\Phi) \propto U(\Phi) - U(-\Phi)$$

very sensitive to

small flux Φ and

interaction strength C_μ/C



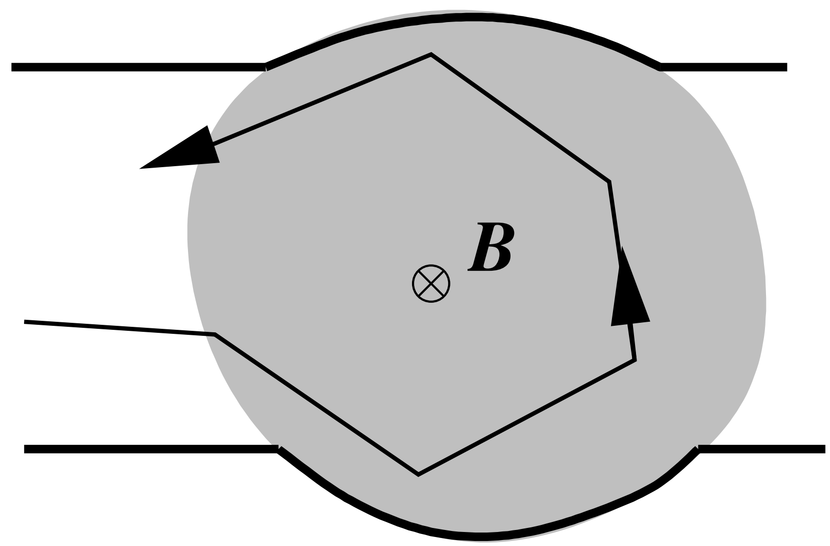
$\Phi_c = \Phi_0$?

Interactions+ Φ → strong $\mathcal{G}_a(\Phi)$ at low $\Phi \ll \Phi_c$

Φ-scale. Electronic trajectories

Important: flux through trajectory, NOT the area.
Find flux Φ_c through the sample such that flux through a trajectory becomes $\sim \Phi_0$

Time-scales: τ_d and ergodic $\tau_{erg} \sim \mathrm{Area}/D$



Diffusive: $\tau_d \sim \tau_{erg}$

Trajectory covers area once

$$\Phi_c = \Phi_0$$

Φ-scale. Electronic trajectories

Important: flux through trajectory, NOT the area.
Find flux Φ_c through the sample such that flux through a trajectory becomes $\sim \Phi_0$

Time-scales: τ_d and ergodic $\tau_{erg} \sim \mathrm{Area}/D$

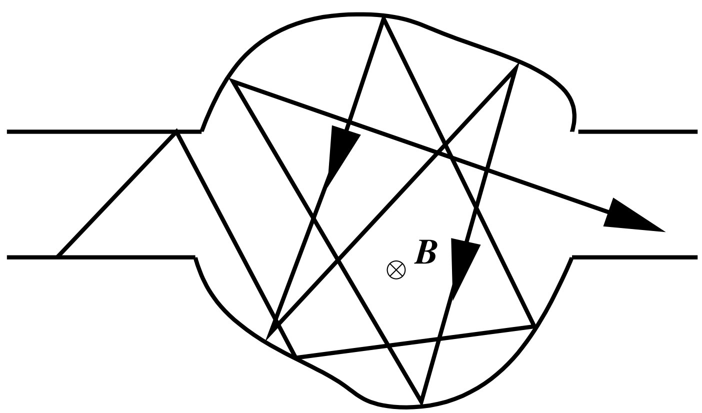
Dots: $\tau_d = \frac{h}{N\Delta} \gg \tau_{erg}$

$\tau_d/\tau_{erg} \gg 1$ "brownian"

random steps $\sim \pm\Phi_c$

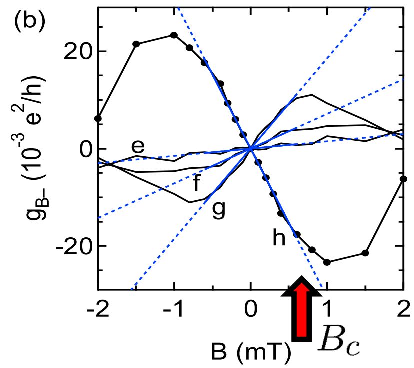
$\Rightarrow \quad \Phi_c\sqrt{\tau_d/\tau_{erg}} \approx \Phi_0$

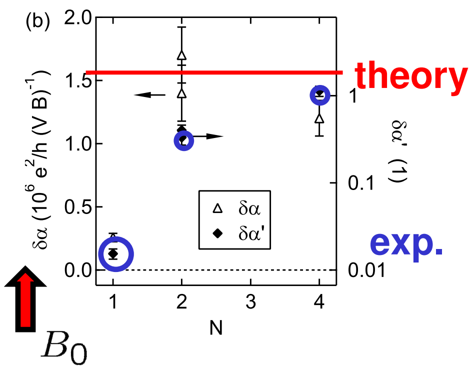
$\Rightarrow \quad \Phi_c \sim \sqrt{\tau_{erg}/\tau_d}\,\Phi_0 \ll \Phi_0$



Open questions and problems

- Comparison with experiment (dots)





rms $\mathcal{G}_a = \delta\alpha'/N^2,\ T = 0$

But in experiment $\delta\alpha'$ depends on *N* !

Temperature? We find $\delta\alpha' \propto \sqrt{N}$

Dephasing ? Most probably (affects small ***N***)

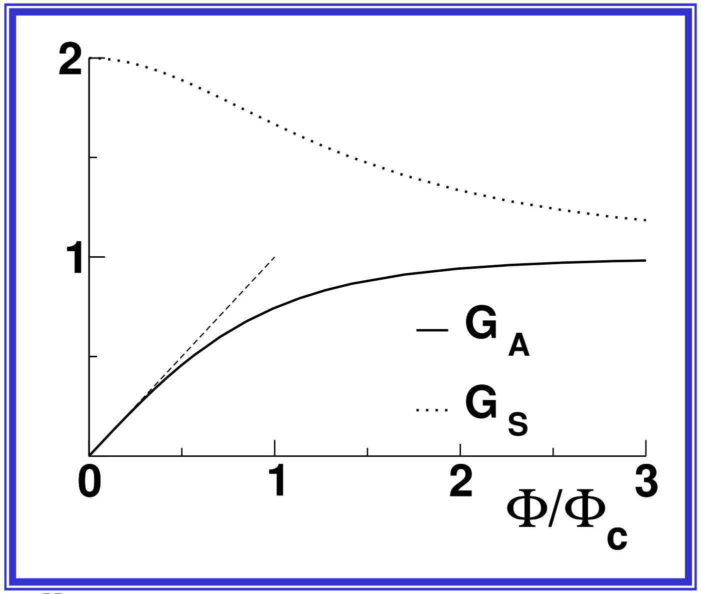
Conclusions.

Φ_0

$\Phi_c \ll \Phi_0$

- Magnetic field asymmetry $\mathcal{G}_a(\Phi)$ probes interactions
- Voltage scale $eV_c \sim N\Delta$
- Flux scale is <u>not</u> Φ_0
  Depends on dwell time and ergodic time

$$\Phi_c \sim \sqrt{\tau_{\rm erg}/\tau_{\rm d}}\,\Phi_0 \ll \Phi_0$$



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