Ballistic electron spectroscopy

Frank Hohls

I. Introduction – low dimensional electron systems and ballistic electrons
II. The idea – ballistic electron spectroscopy
III. Charge readout of detector
IV. Some data – proof of concept

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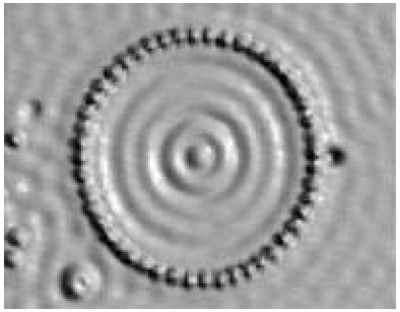
2d electrons – where do I find them?

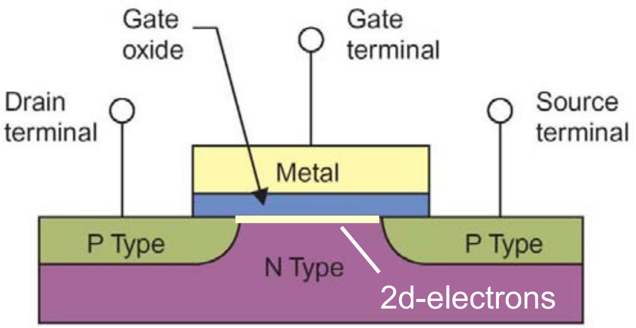
Confining electrons to an interface

- Electrons in metal: thin metal films or surface
  - high electron density, short length scales (Fermi length, mean free path)
  - ultra high vacuum

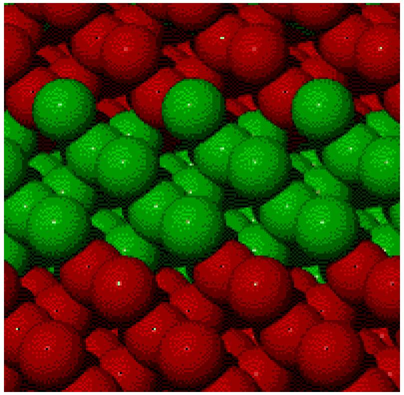


standing waves on metal surface

- Electrons in semiconductor:
  Field effect transistor (Silicon-MOSFET)
  + easy tunable electron density
  - Quantum Hall Effect (QHE)
    Nobel prize 1985

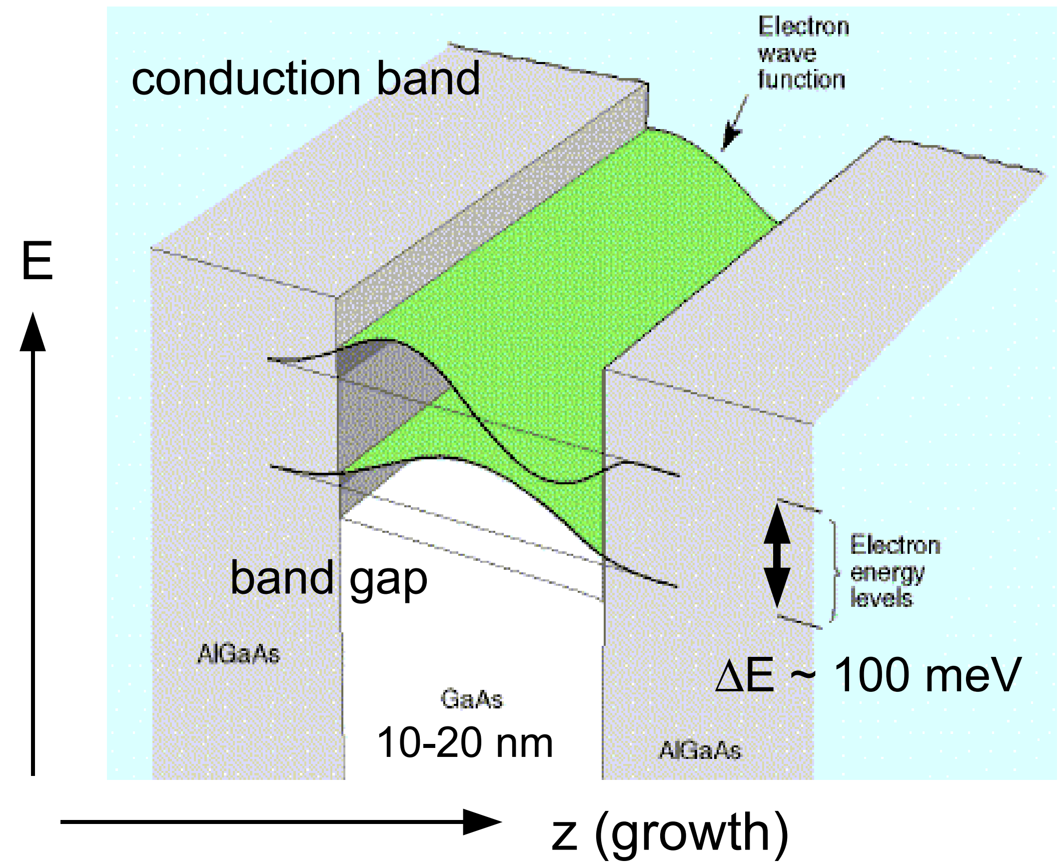


- Heterostructure grown atomic layer by layer (Nobel prize 2000)
  + Very clean system
  - Fractional QHE, Nobel prize 1998
  - ballistic electron effects



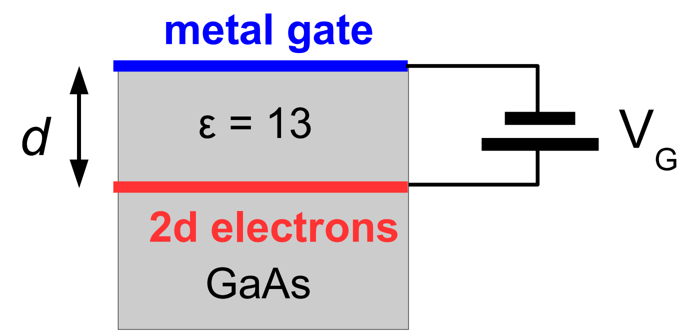
2d electrons in a heterostructure

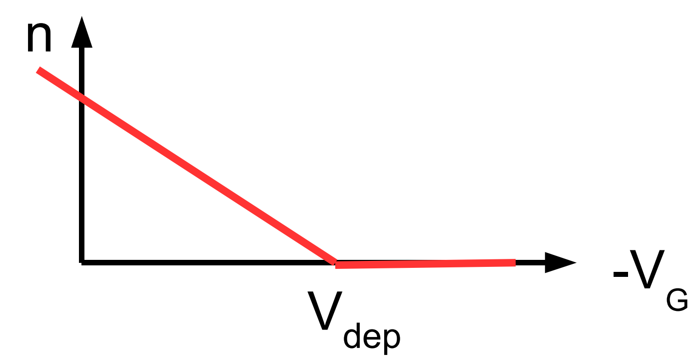
- Engineering of band edge to create a quantum well
  - Quantized energy in growth direction (z)
  - Free motion in x-y plane
- Electron density $n \sim 10^{15}\ m^{-2}$
  - Electron distance ~ 30 nm
  - Fermi wave length ~ 80 nm
- High interface quality and remote doping
  - Very high mobilty μ (measured from $\sigma = en\mu$)
  - Mean free path of up to 100 µm

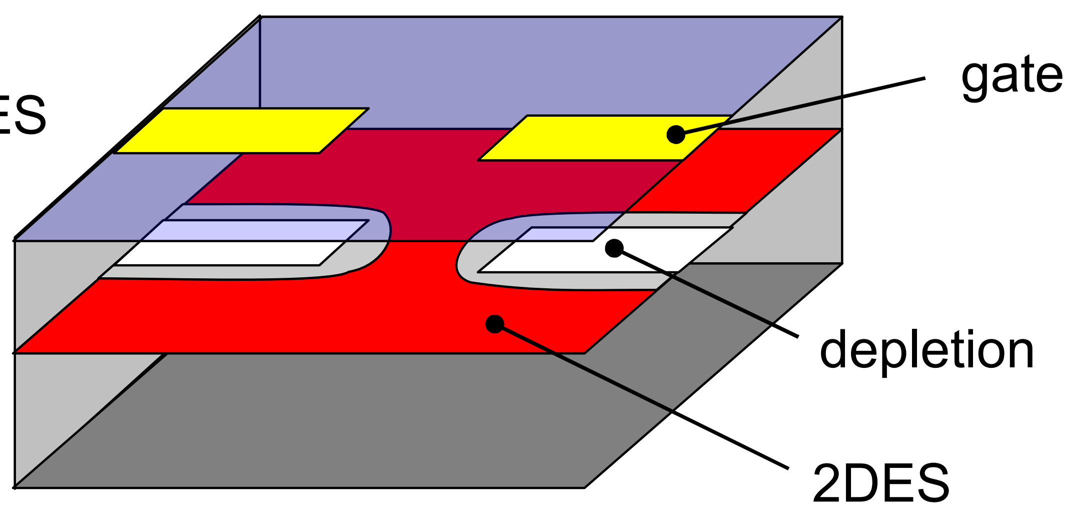


Getting smaller – gating the 2d electrons

- Metal on GaAs forms Shottky Diode
  - Current I ~ exp(eV_G/kT) negligible for $V_G<0$ and low T
- Gate and 2d electron sheet form plate capacitor
  - $C = \varepsilon\varepsilon_0 \cdot A/d$, $\Delta q = C \cdot V_G = A \cdot e \cdot \Delta n$
  - Change of electron density *n* by applied voltage
  - 1 gate + 2 contacts = MESFET
- Depletion of electrons beyond threshold voltage V_{dep}
  - Transfer gate pattern into 2DES

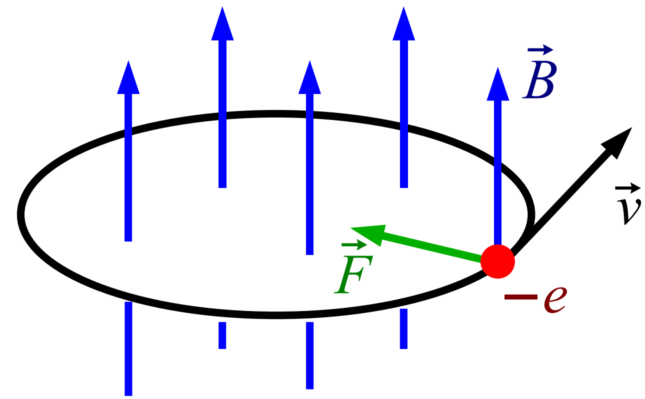


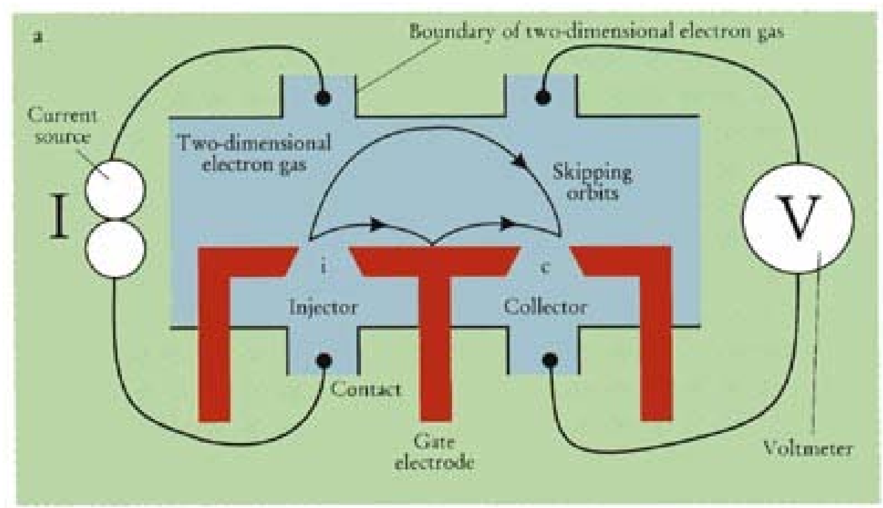


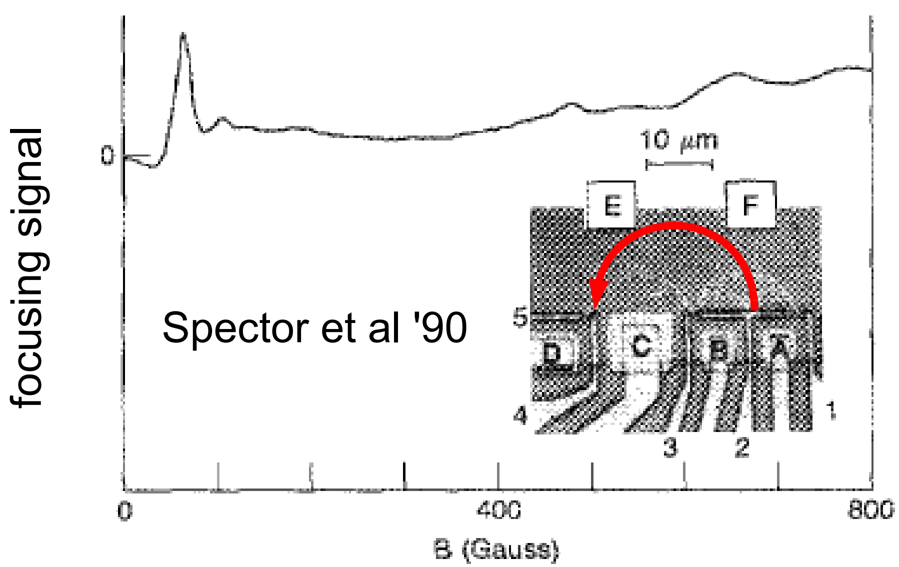


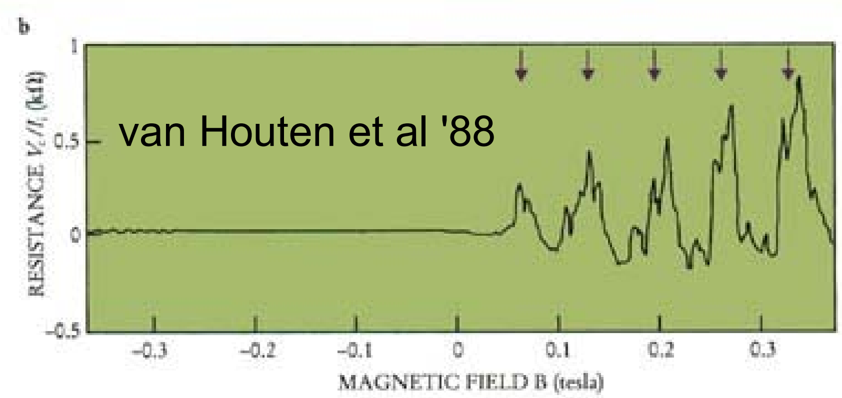
Ballistic electrons in 2d – focusing

- Electrons travel large distance without scattering
  - ballistic transport
- Revealed in magnetic focusing experiments
  - Lorentz force ~ $B \cdot v_F$ in perpendicular magnetic field B
  - Electrons forced on cyclotron orbits in with r_C ~ $1/B$

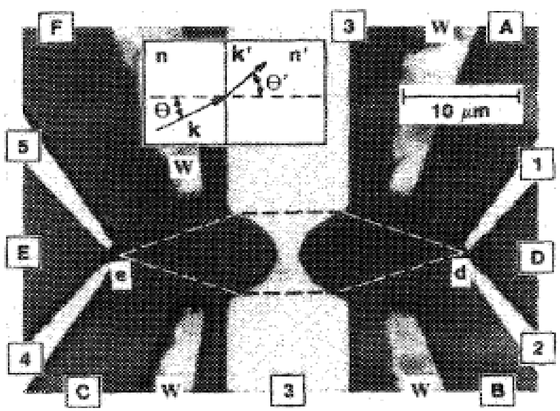






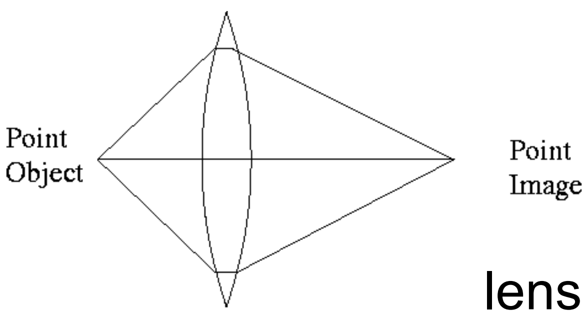


Ballistic electrons – optics and interference



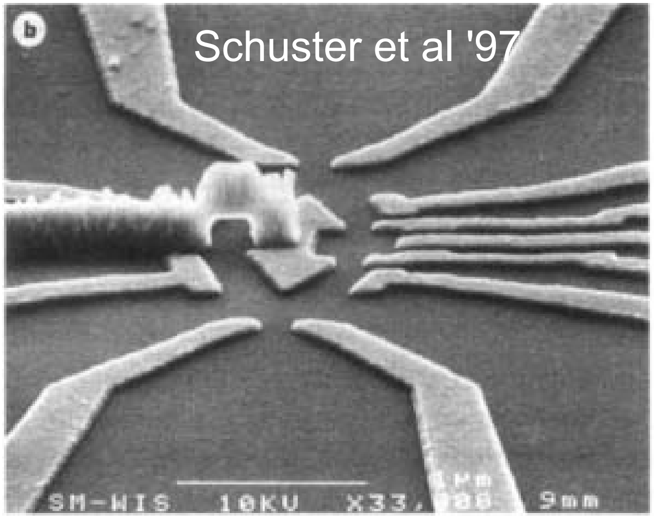
Spector et al '90

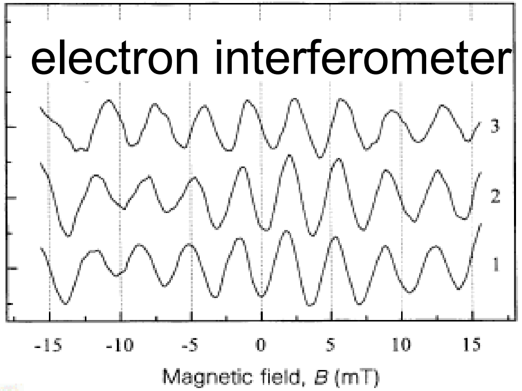
Electron lens



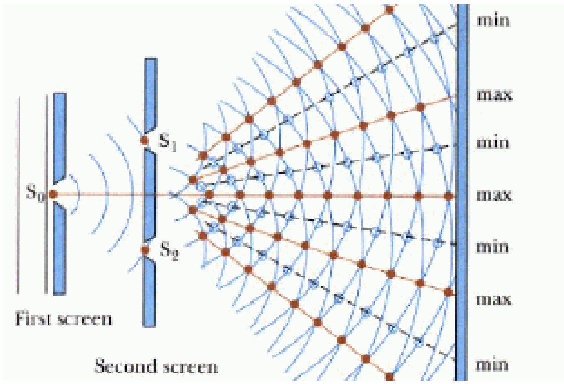
lens

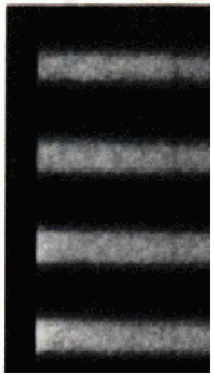
- Fermi wave vector $k_F \sim \sqrt{n}$ can be changed by gate
  - Electron optics
- Wave nature of electrons
  - interference effects
  - Double slit interferometer with magnetic field
  - Aharonov-Bohm effect $\Delta\varphi \sim \Phi/\Phi_0$ (Φ flux)
- Analogues to light optics





double slit

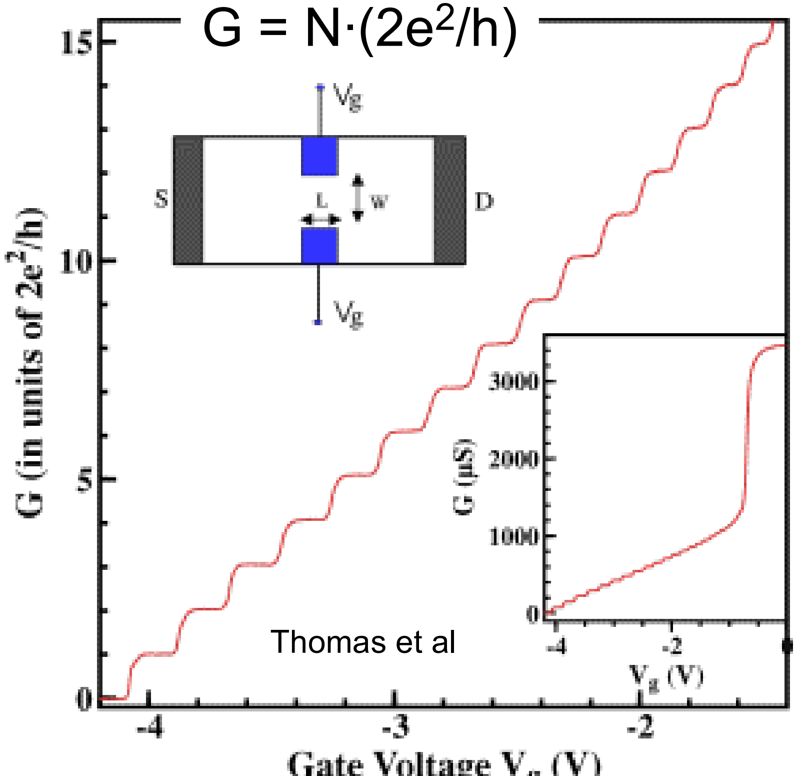


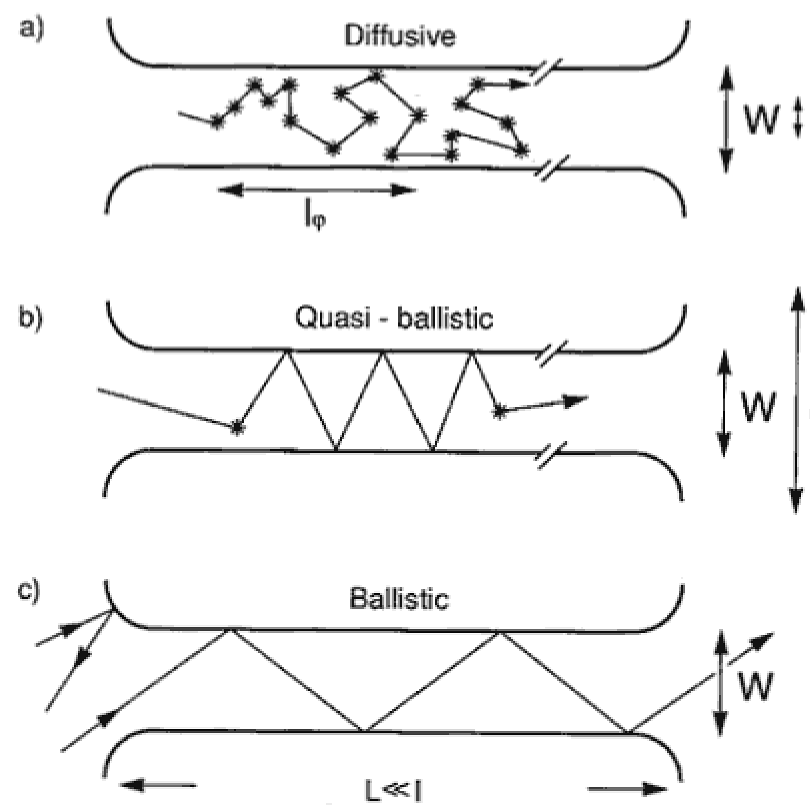


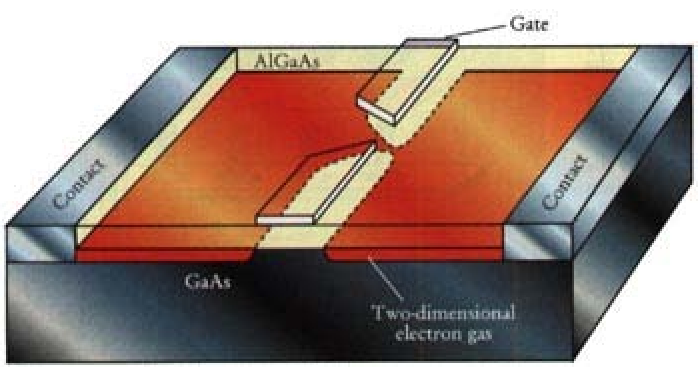
Ballistic 1d wire – quantized conductance

- Ballistic wire: width w and length L much smaller than scattering length l
  - no backscattering within channel
  - quantized conductance (Wharam et al '88, van Wees et al '88)

$G = N \cdot (2e^2/h)$







1d wire – why quantized in $2e^2/h$?

- Quantized energy perpendicular to wire (y)
- Free motion in 1d along wire (x)
- For one 1d sub-band:
  - Density of states 1d (no spin):

$$D(E)=\sqrt{\frac{m}{2h^2E}}=\frac{1}{hv}$$

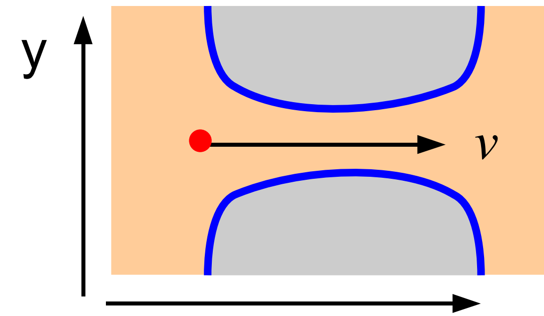
  - Current

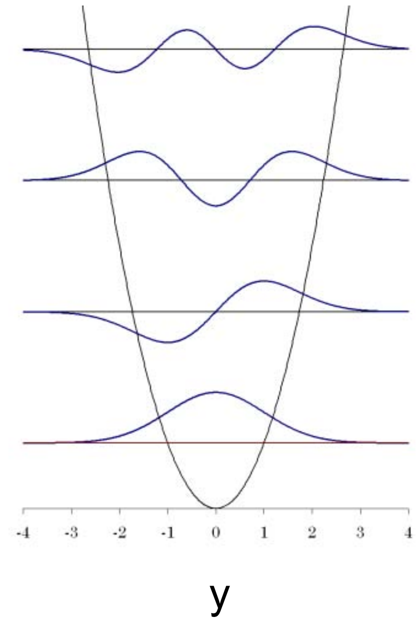
$$I=e\cdot v\cdot\left[D(E)\cdot\Delta E\right]=\frac{e^2}{h}V$$

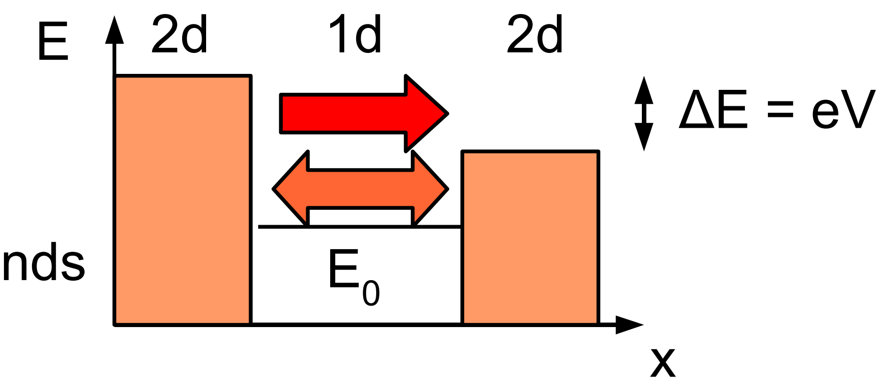
  - Add spin degeneracy g = 2

$$G=\frac{I}{V}=\frac{2e^2}{h}$$

- Add contributions of N occupied 1d sub-bands
  - $G = N(2e^2/h)$
- Conductance steps smoothed for short wire
  - Quantum point contact (QPC)

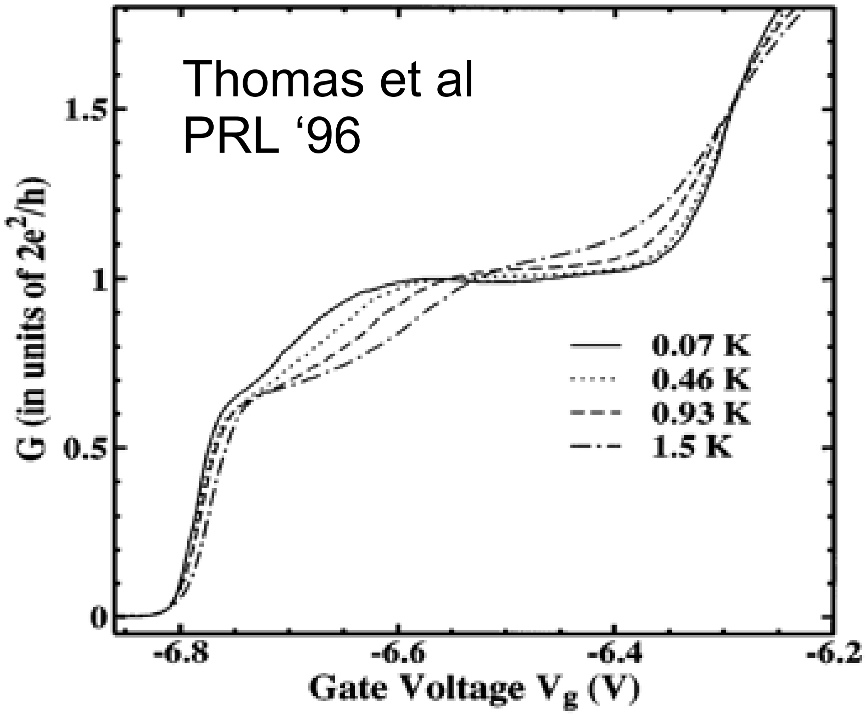




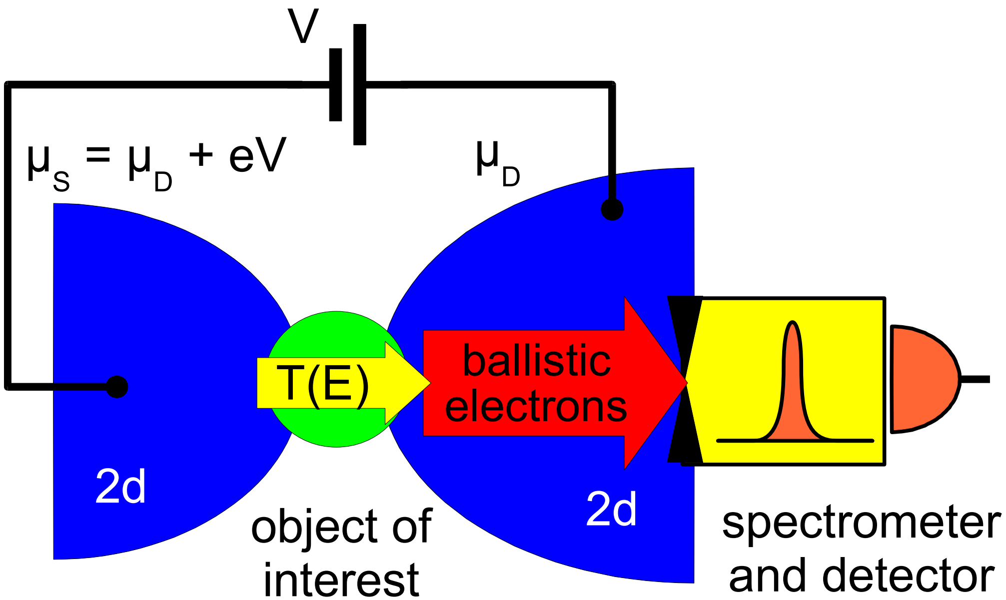


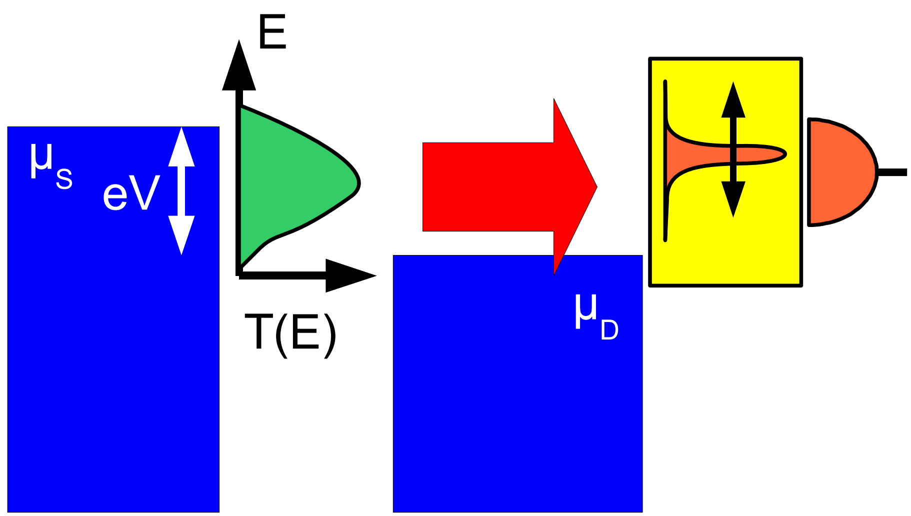
Open questions: Electron interaction in 1d

- Additional conductance plateau at $G = 0.7\cdot(2e^2/h)$
- Effect of electron-electron interaction
- Different models proposed
  - Kondo model
  - Spontaneous spin polarization
  - Jumping of subbands
- For all models we expect change of density of states $D(E)$
- How to measure without changing the system (no back-action) ?



Proposal: ballistic electron spectroscopy

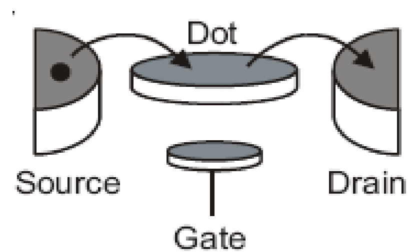


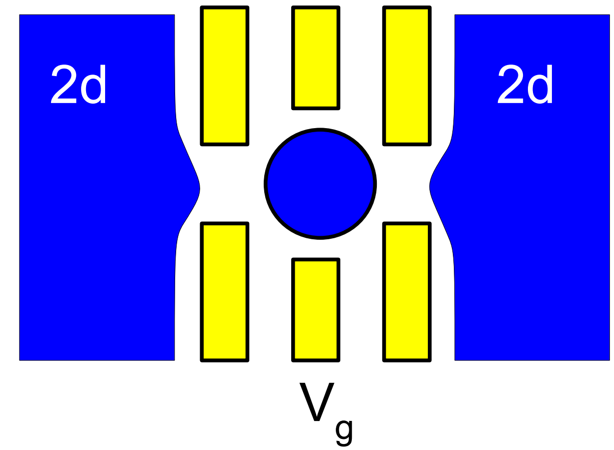


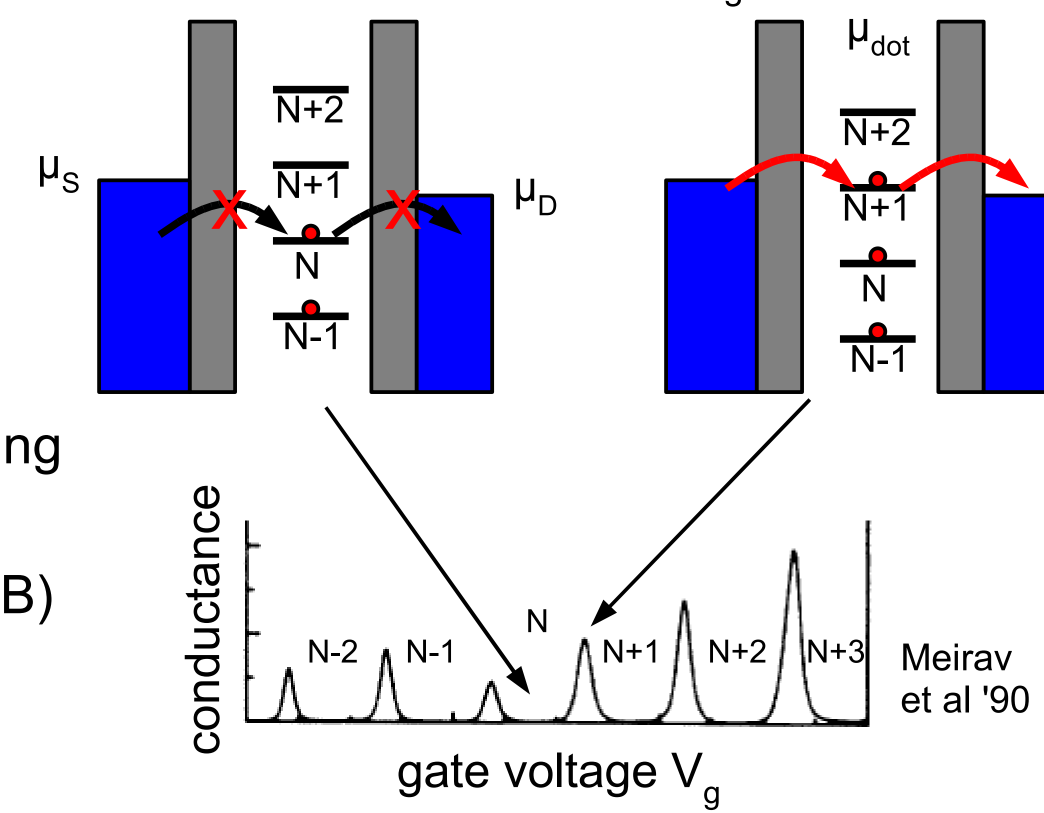
- Source non-equilibrium ballistic electrons by an object of interest
  - Energy distribution maps Transmission T(E)
  - Inner structure mirrored by transmission
- Energy resolved detection of ballistic electrons
- No back-action of measurement on object of interest
- Use quantum dot as spectrometer
  APL 89, 212103 (06)

Quantum dot – electrons in 0d

- Confinement in all dimensions
  - Quantum dot (QD)
  - N electrons in QD
- 1st approximation: disk with capacitance C
  - Coulomb blockade energy: $E_C = q^2/C = e^2/C$
  - Spacing of dot chemical potential: $\mu_{N+1} - \mu_N = E_C$
- Shift potential of quantum dot with gate V_g
  - Resonant single electron tunneling only for $\mu_S > \mu_{N+1} > \mu_D$
  - otherwise Coulomb blockade (CB)
- Conductance G displays peak for each change in electron number







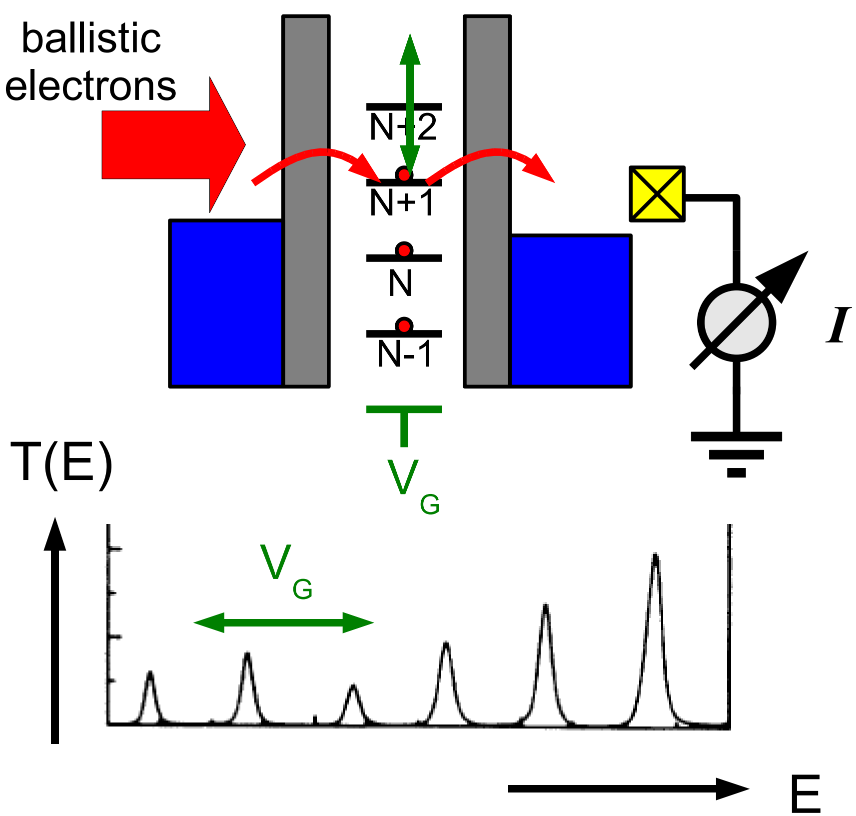
Analogue: Fabry-Perot spectrometer

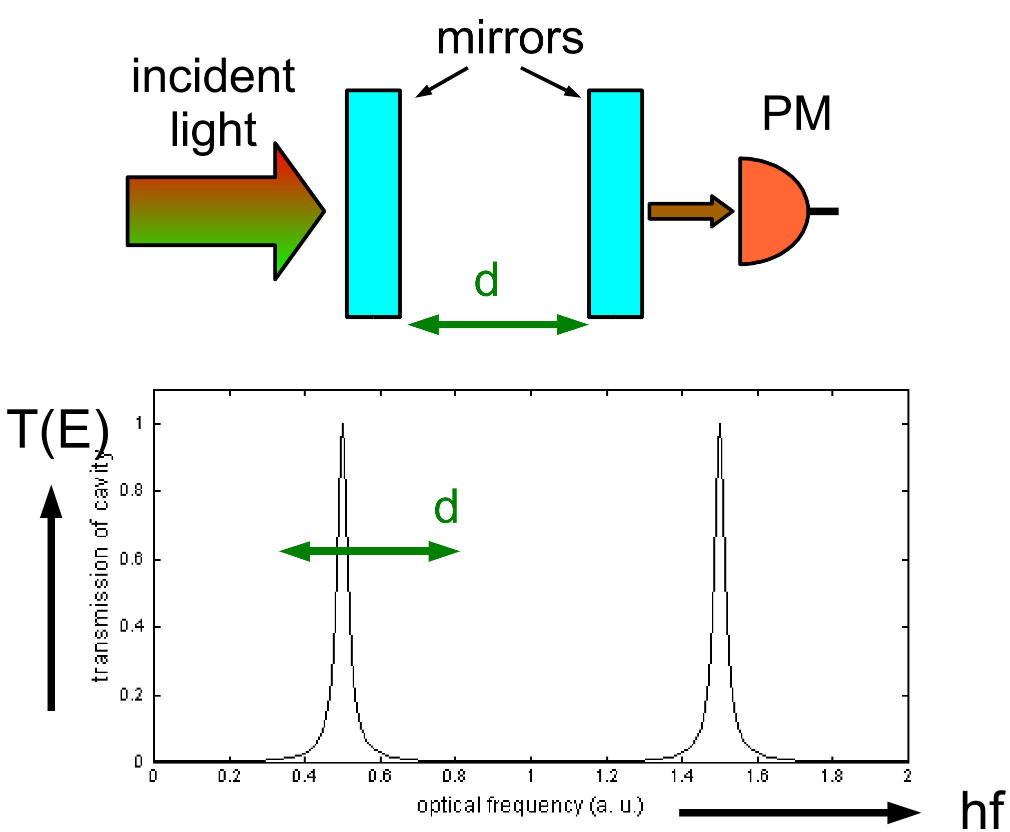
Quantum dot spectrometer

Fabry Perot spectrometer

- Transmission for selected energies (frequencies)
- Periodic transmission

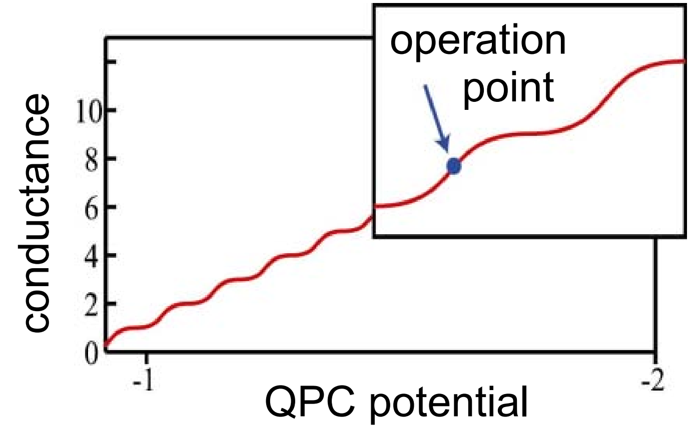
- Energy comb shifted by applied gate voltage
- Frequency comb tuned by distance d

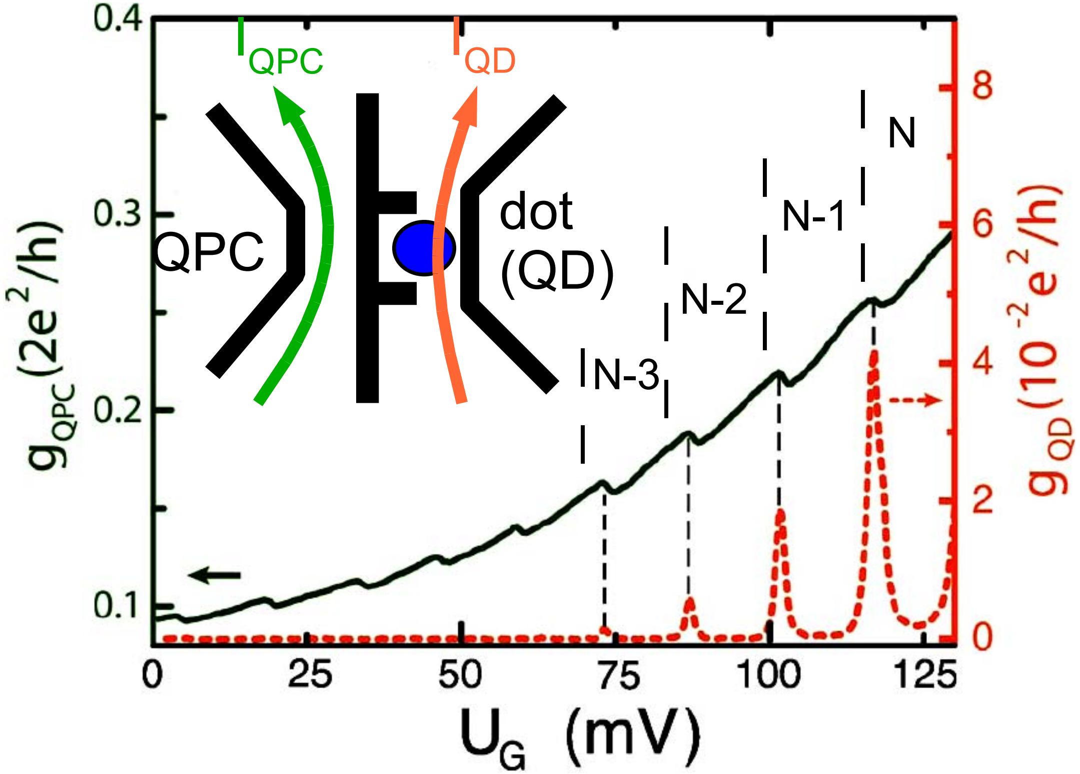




Quantum dot charge detection

- Detect charge state of quantum dot
- Use 1d wire near dot (Field et al '93)
  - Potential in wire changes due to charge on quantum dot
  - At step edge conductance very sensitive to local potential
- Step in wire conductance for each change of quantum dot charge





C. Fricke *et al.*, PRB '05

M. Rogge *et al.*, PRB '05

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Spectrometer with charge readout

- Occupation of the dot depends on occupation of impinging electrons $\Omega_\rightarrow(E)$ and accessible empty outgoing states $1 - \Omega_\leftarrow(E)$ $(0 \le \Omega \le 1)$

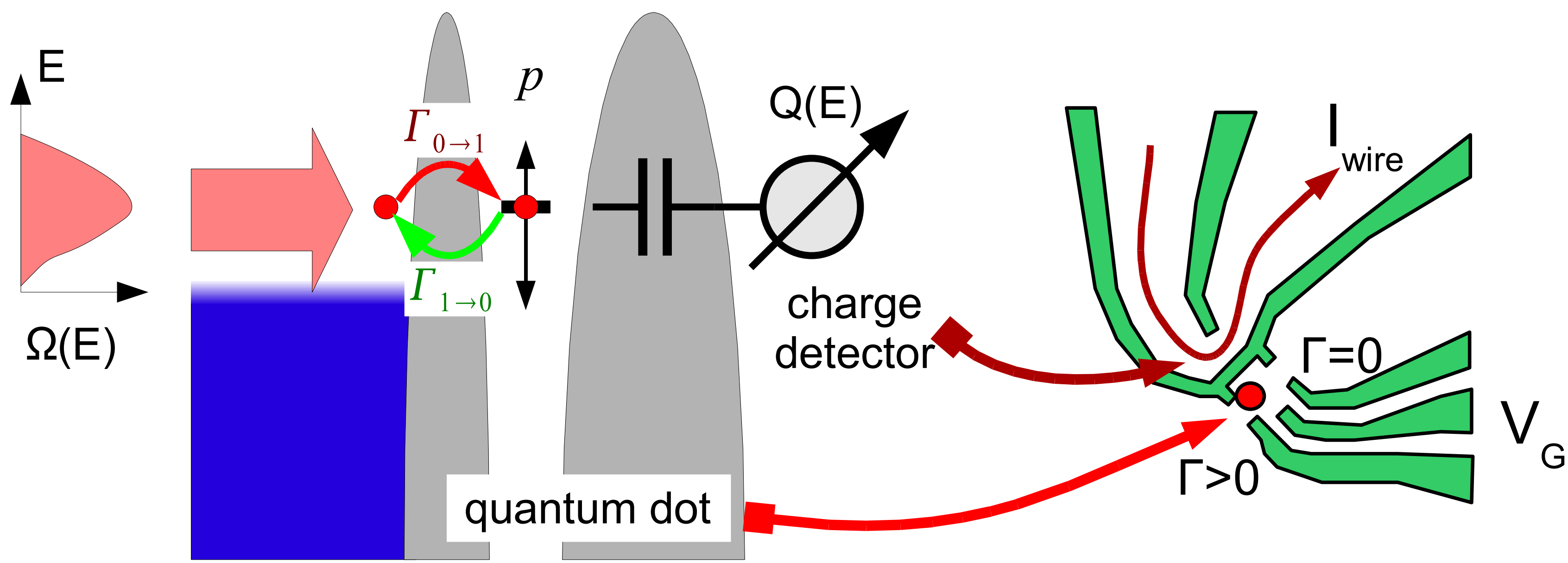
$$\Gamma_{0\rightarrow1} = 2\gamma\,\Omega_{\Rightarrow}(E) \qquad \Gamma_{1\rightarrow0} = \gamma\left(1-\Omega_{\Leftarrow}(E)\right)$$

- Dot occupancy p $(0 \le p \le 1)$:

$$(1-p)\,\Gamma_{0\rightarrow1} = p\,\Gamma_{1\rightarrow0}$$

- Measure charge Q = -pe
- For dilute ballistic electrons:

$$\left.\begin{array}{c}\Omega_{\Rightarrow} \ll 1 \\ (1-\Omega_{\Leftarrow}) \approx 1\end{array}\right\} \Rightarrow p \approx 2\,\Omega_{\Rightarrow}$$

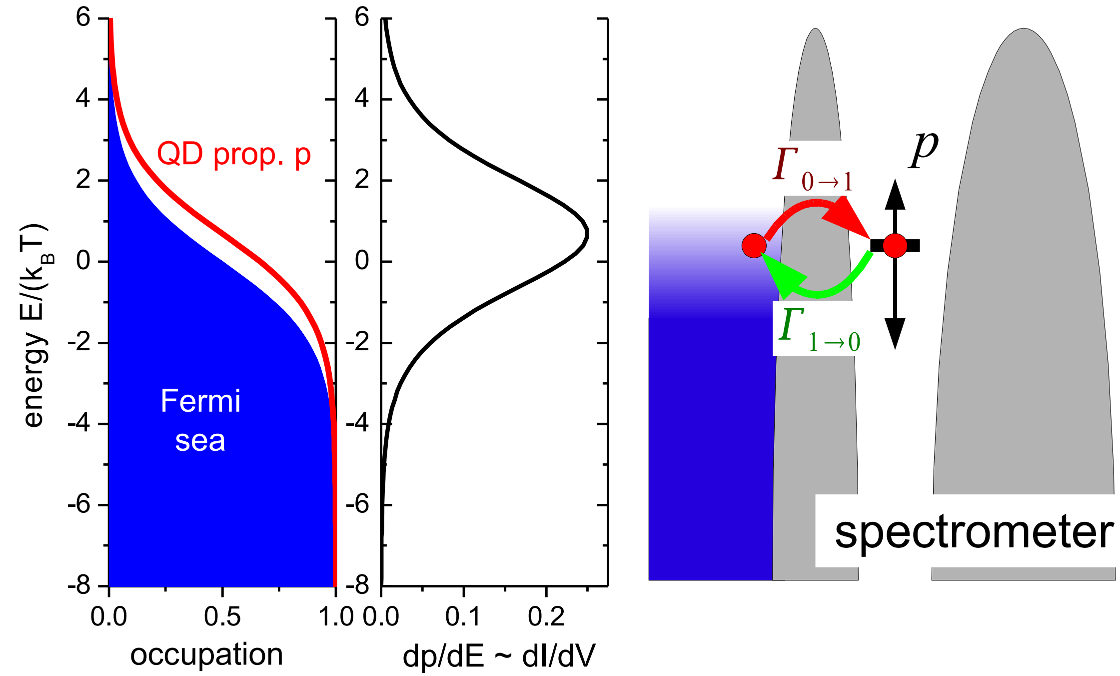


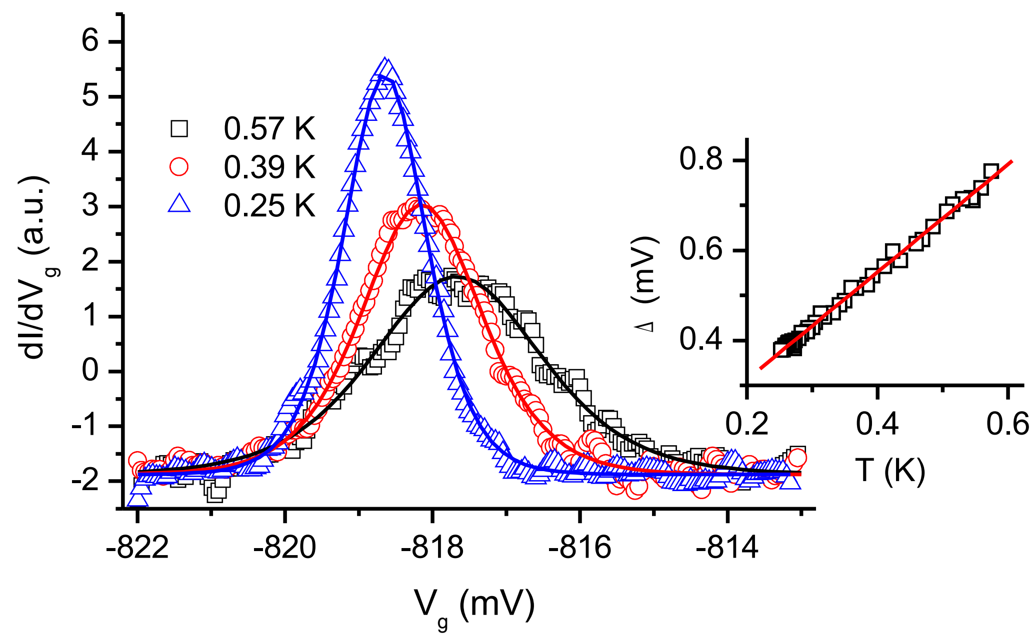
Spectrometer calibration

- Spectrometer signal near Fermi energy maps Fermi distribution f(E)

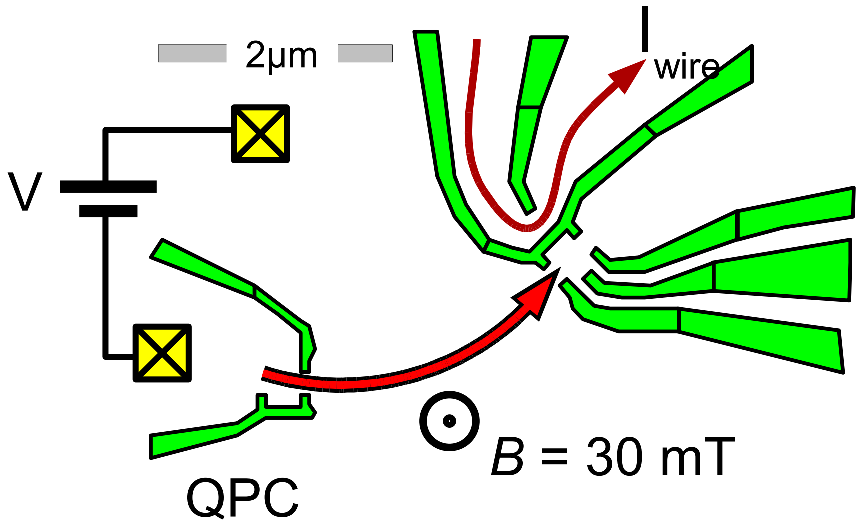
$$p = \frac{2}{1 + \frac{1}{f(E)}}$$

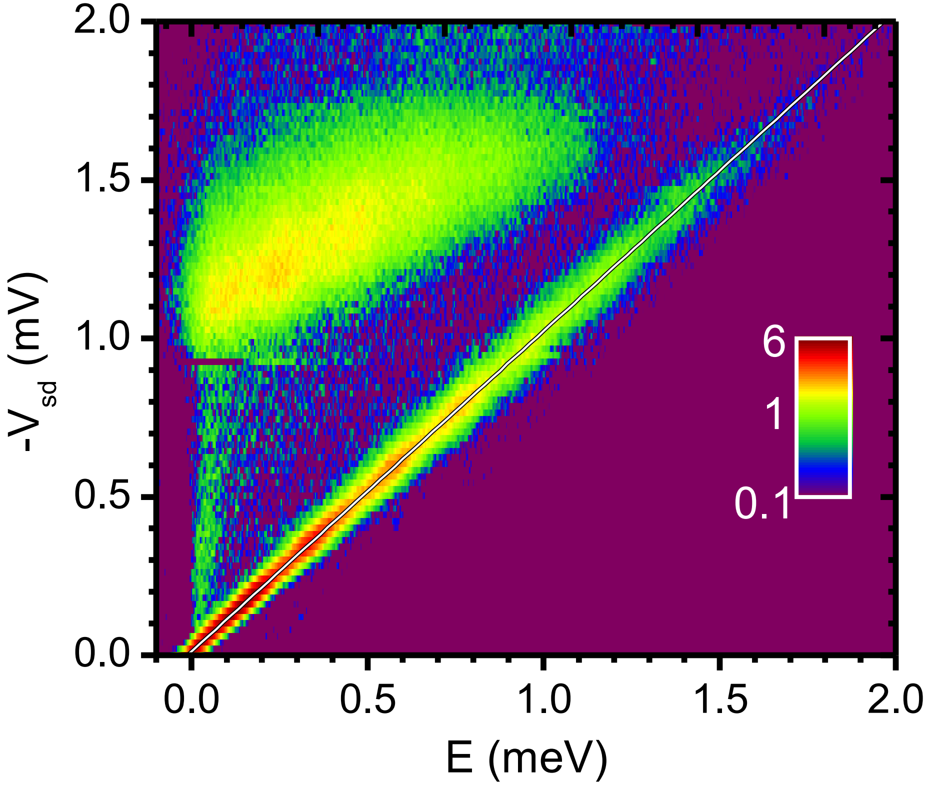
- Measure $dI/dV_g \sim dp/dE$
- Use temperature dependence of peak width Δ for spectrometer calibration
- $\Delta E/\Delta V_g = 0.0719 \pm 0.0007$





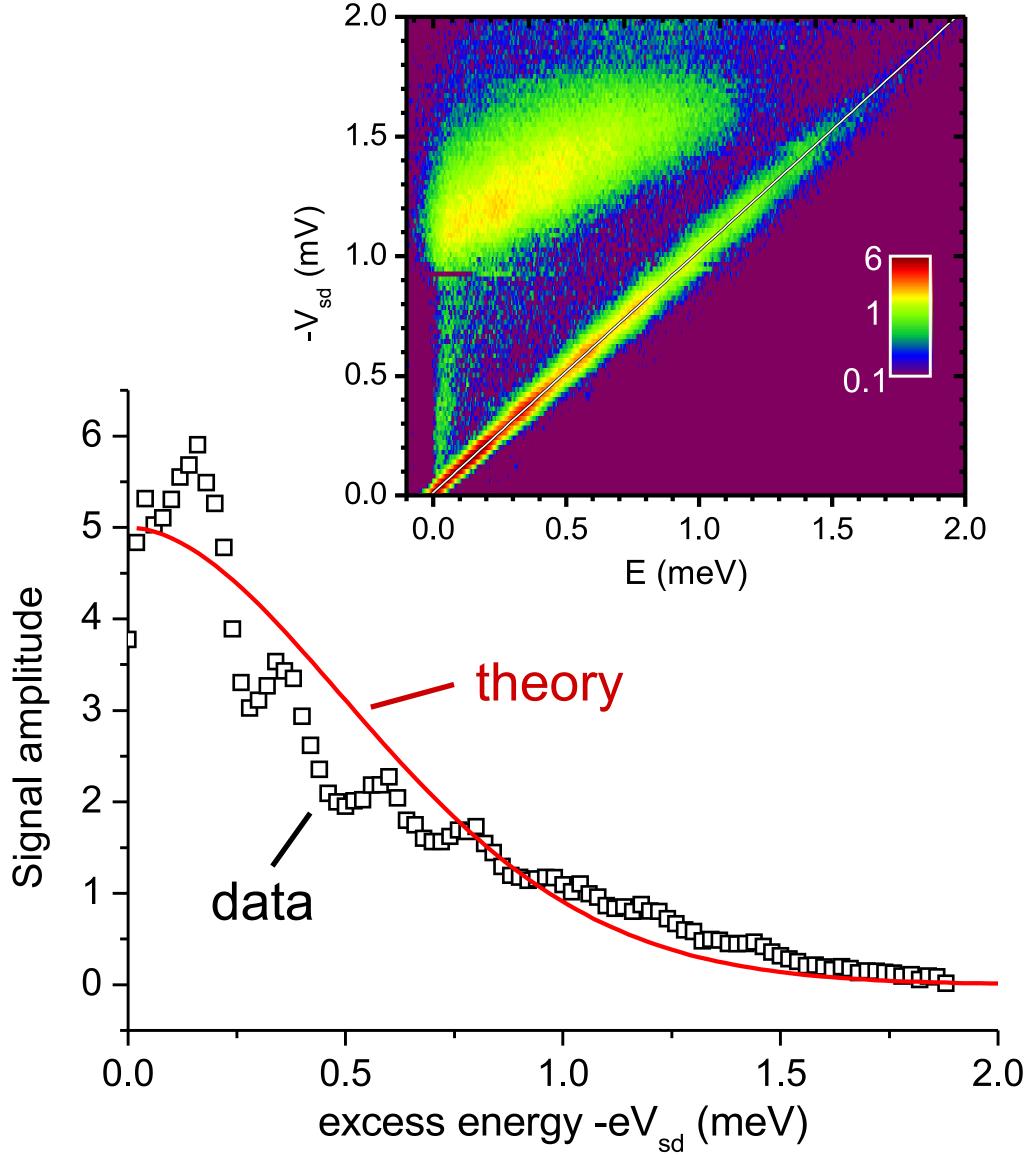
Ballistic signal



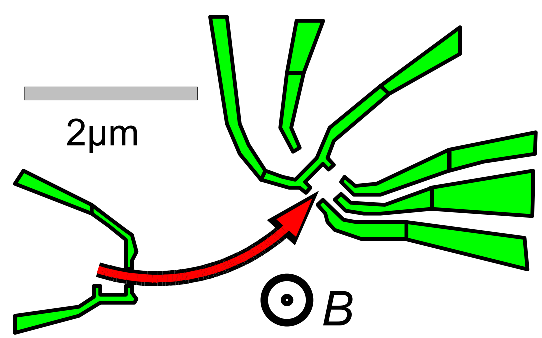


- Source ballistic electrons with QPC set to first plateau for well defined injection spectrum
  - Inject Ω(E) = const
- Magnetic field *B* bends ballistic electrons into the spectrometer
- Vary maximum energy $E_{max} = -eV_{sd}$ of ballistic electrons
- AC-modulation: Mark electrons injected at E_{max}
- Linear shift of ballistic peak position: $-eV_{sd} = 1.01 \cdot E$
  - No energy scaling factor $E = -\alpha \cdot eV_{sd}$ with $\alpha<1$ as claimed previously
- It works!

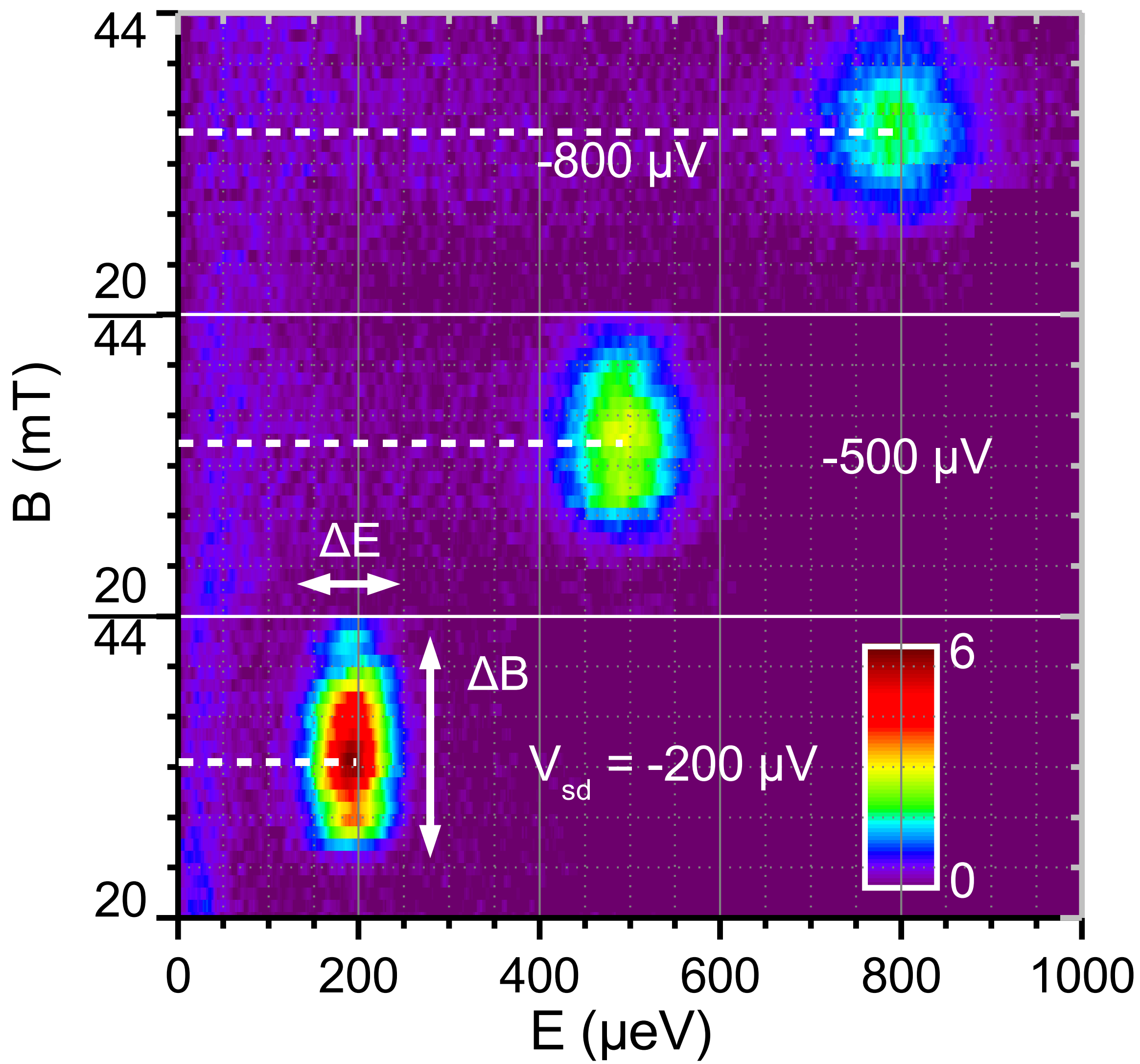
Ballistic peak – amplitude



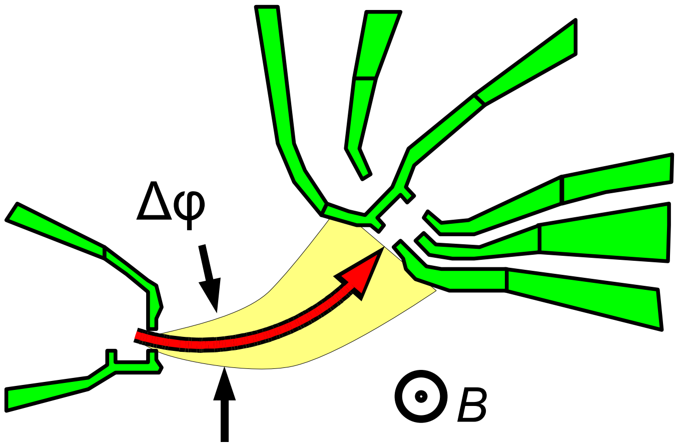
- Signal decays for rising energy
  - Scattering of ballistic electrons
- Compare to theory for e-e scattering with equilibrium electrons (Giuliani and Quinn, 1982)
  - Deviation due to large population of non-equilibrium electrons?
  - Agreement observed in interference experiment (Yacoby *et al* '91) – difference between phase and energy relaxation?
- Superimposed oscillations due to interference of different paths



Energy + angle distribution

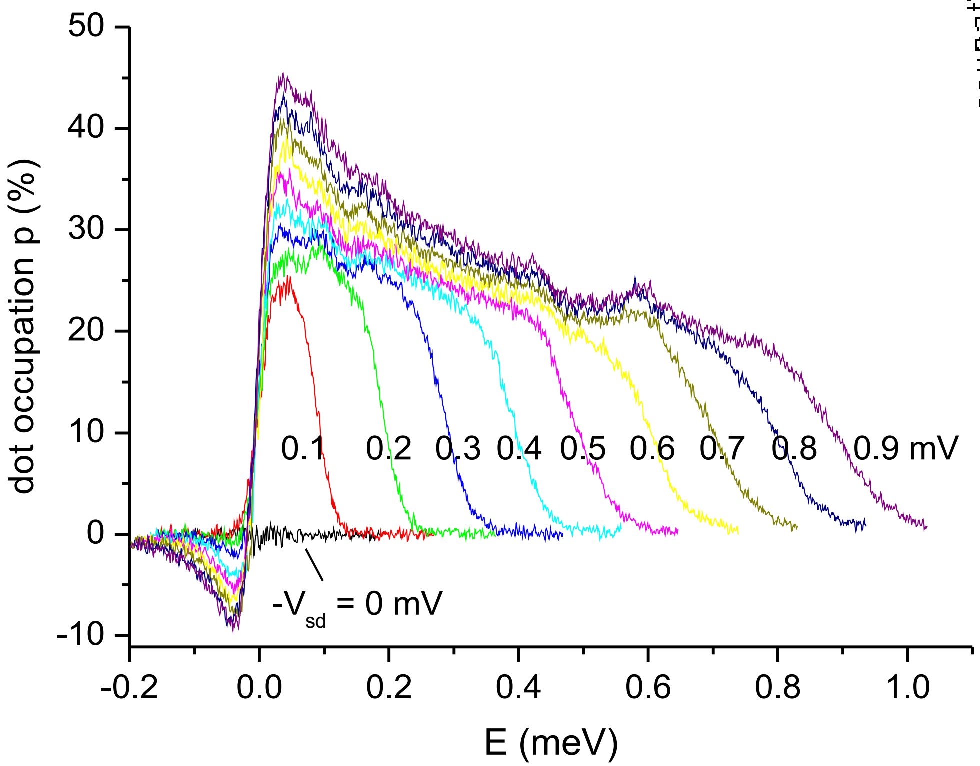


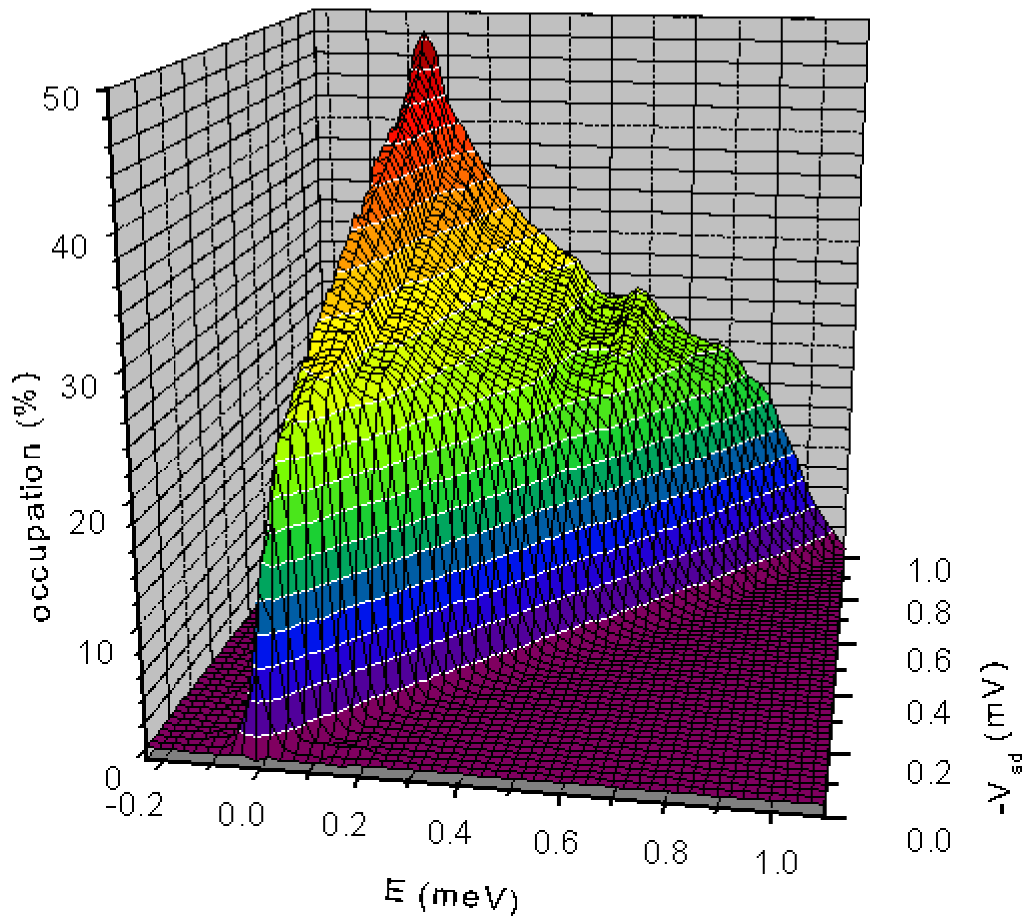
- Maximum signal shifts to larger field
  - Velocity increases with increasing energy
- Energy spread ΔE wider for larger excess energy -eV
  - Small energy scattering
- No noticeable change in angle spread ΔB ∝ Δφ
  - Small energy scattering results in little momentum change



Full DOS

- Again QPC on 1st plateau
- Measures full energy distribution Ω(E) of ballistic electrons

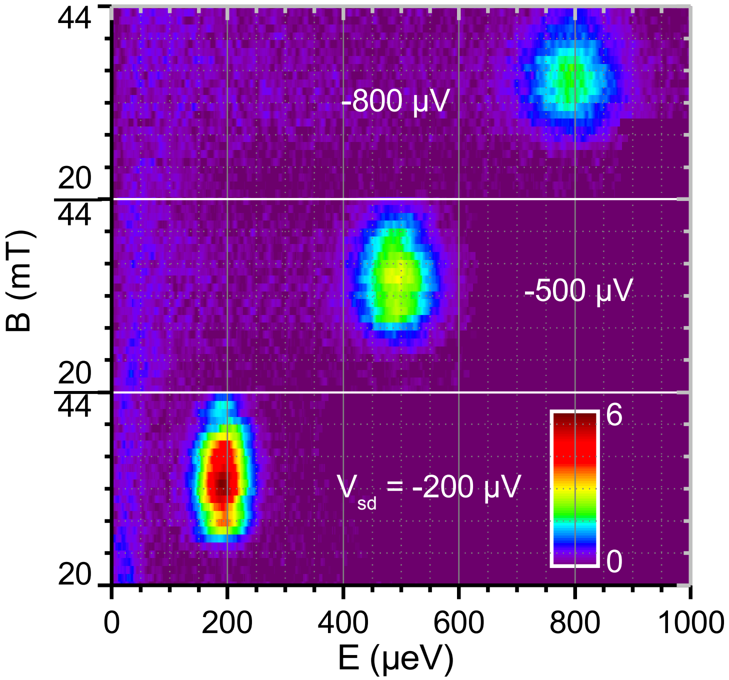


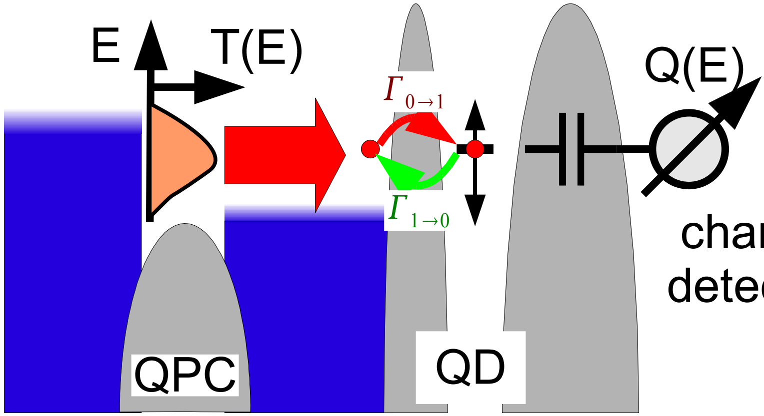


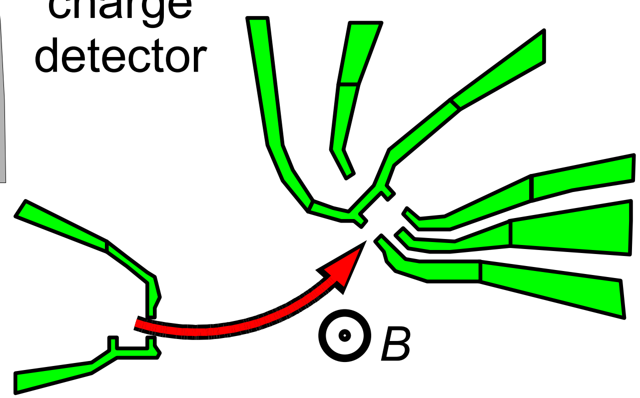
$$p = 2\,\Omega_{\Rightarrow}\left(1 - 2\,\Omega_{\Rightarrow} + \Omega_{\Leftarrow}\right) + O\left(\Omega^3\right)$$

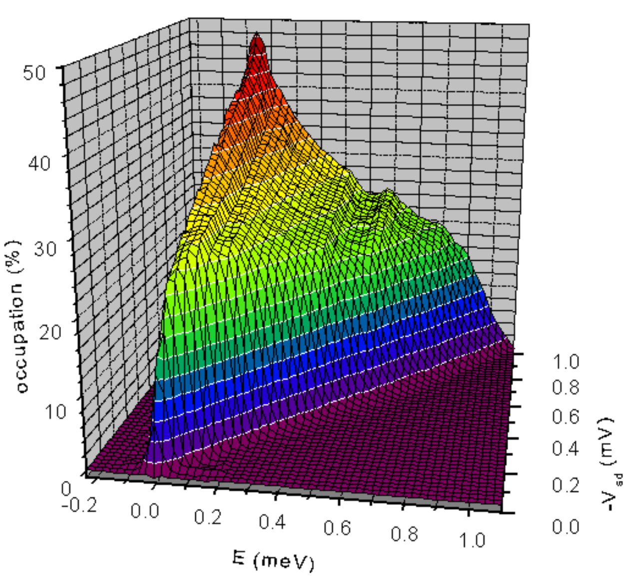
Summary

- Ballistic electron spectroscopy APL 89, 212103 (2006)
- QPC charge detector for measurement with empty dot
- Measurement of energy and angle distribution of non-equilibrium ballistic electrons
- Apply now: QPC (0.7 anomaly), QD (Kondo effect), energy relaxation, ...









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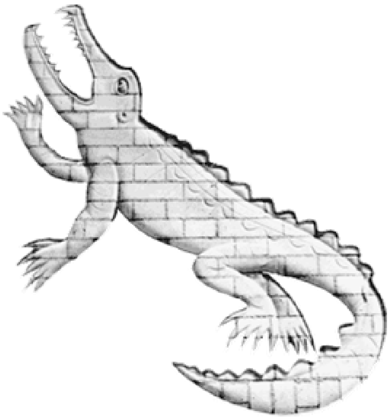

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