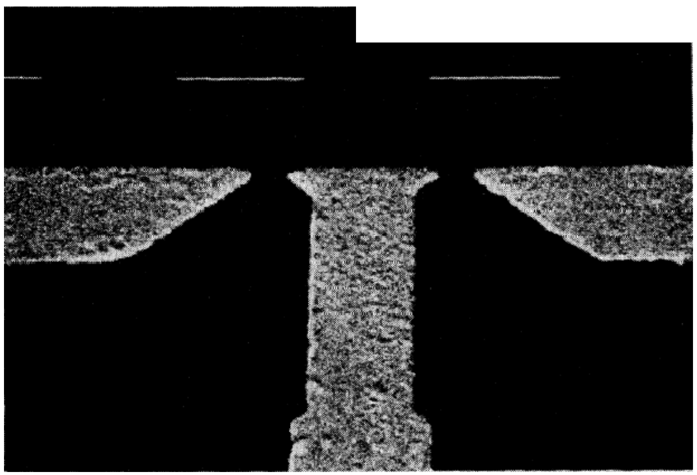
# lecture 5,6,7: ballistic motion

- classical electron focussing
- quantum point contacts
- shot noise
- integer quantum Hall effect

# classical electron focussing

top-gate structure
2DEG (GaAs-$Al_xGa_{1-x}As$)

$n = 3.5\ 10^{15}\ m^{-2}$
$\mu = 90\ m^2/Vs$
$L = 1.5$ or $3\ \mu m$
$\ell_e = 9\ \mu m$

Why does the signal becomes larger as B increases?

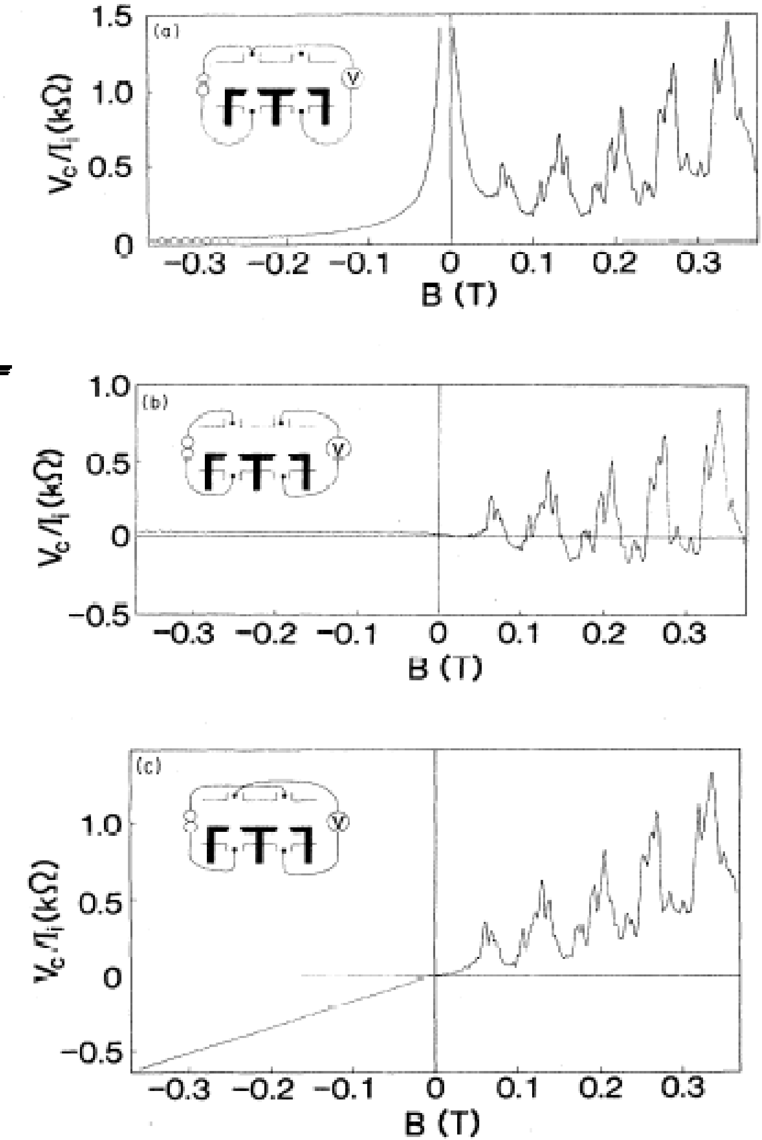



FIG. 8. Electron focusing at 50 mK for three measurement configurations, depicted in the insets. (a) Three-terminal measurement; (b) four-terminal generalized longitudinal-resistance measurement; (c) four-terminal generalized Hall-resistance measurement.

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# Spin Separation in Cyclotron Motion

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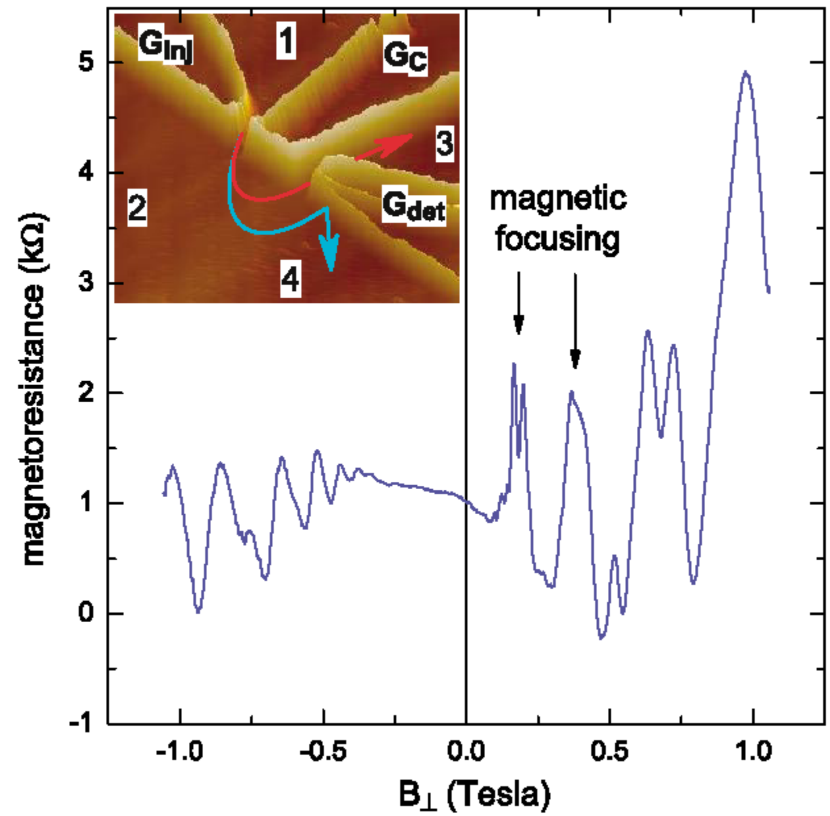
**Because of strong spin-orbit coupling, holes at the Fermi energy in GaAs have different momenta for two possible states traveling in the same direction; therefore in a weak magnetic field there are two cyclotron radii (i.e., two close peaks in the focussing experiment)**

**2DEG ($GaAs\text{-}Al_xGa_{1-x}As$)**

**$n = 1.4\ 10^{11}\ m^{-2}$**
**$\mu = 4\ 10^5\ cm^2/Vs$**
**$L = 0.8\ \mu m$**



# Quantized Conductance of Point Contacts in a Two-Dimensional Electron Gas

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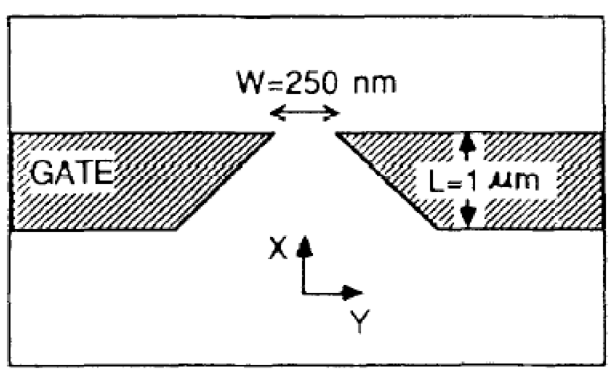
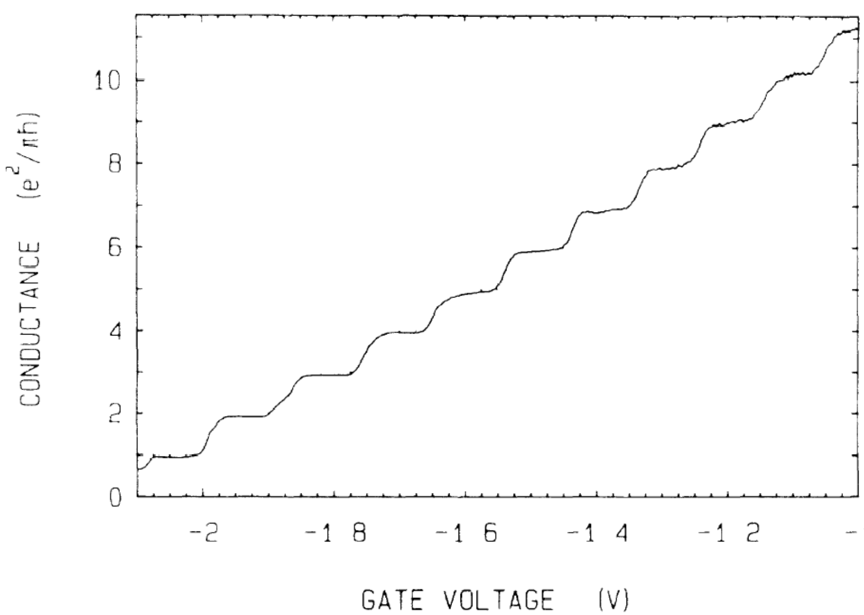
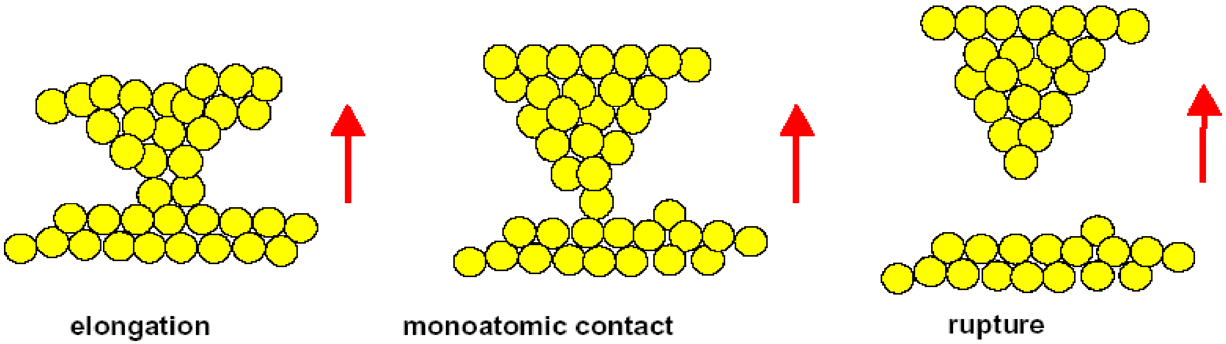
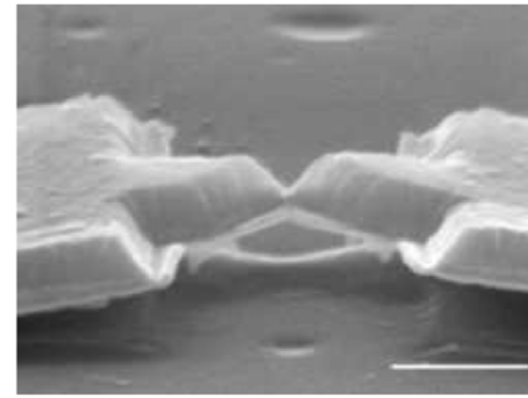
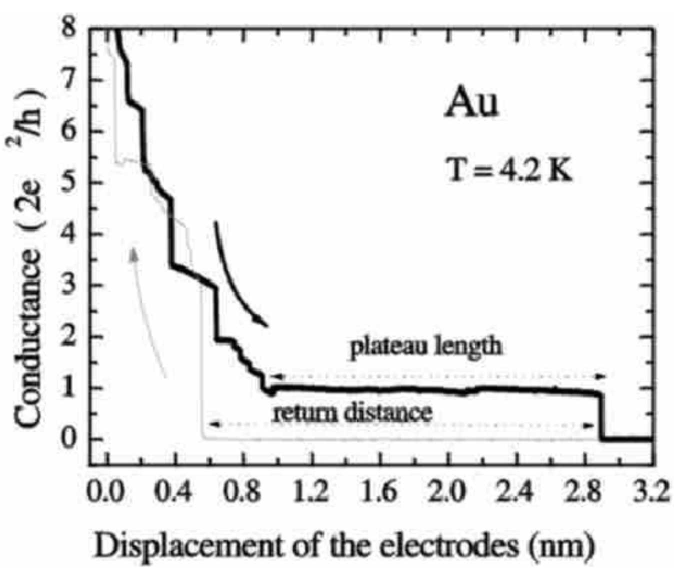


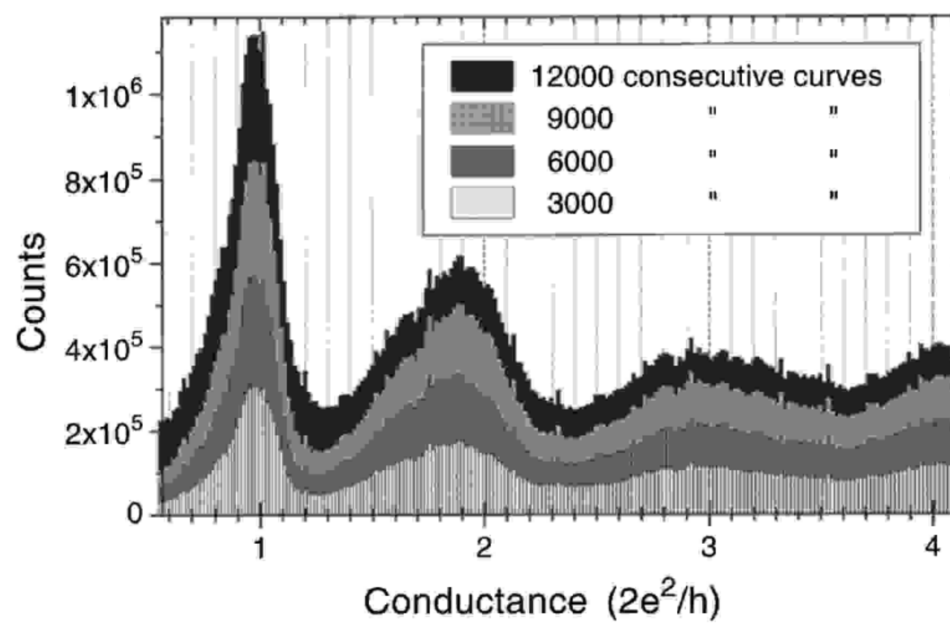



# quantized conductance: single-atom metallic point contacts





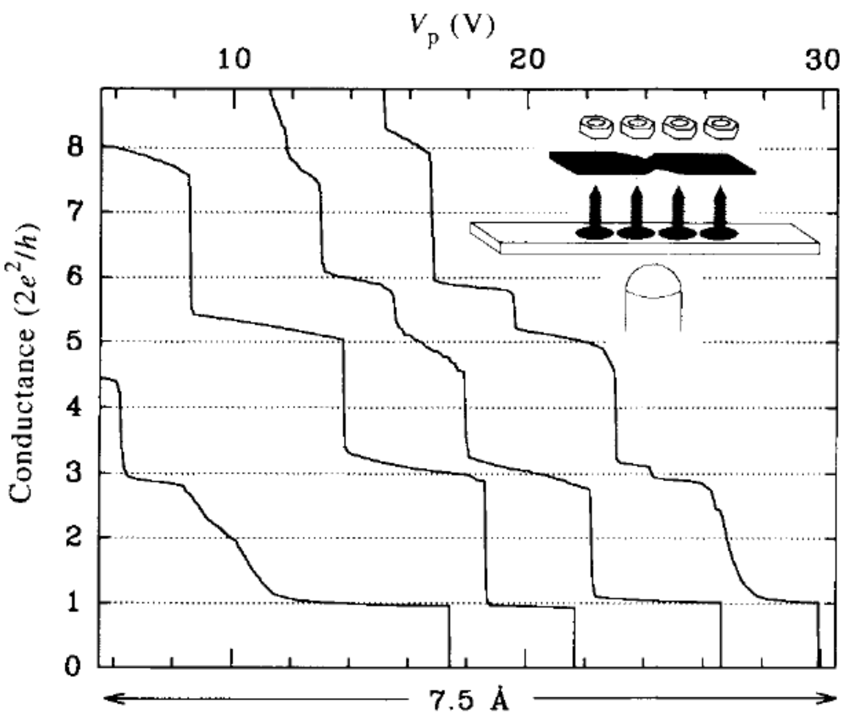



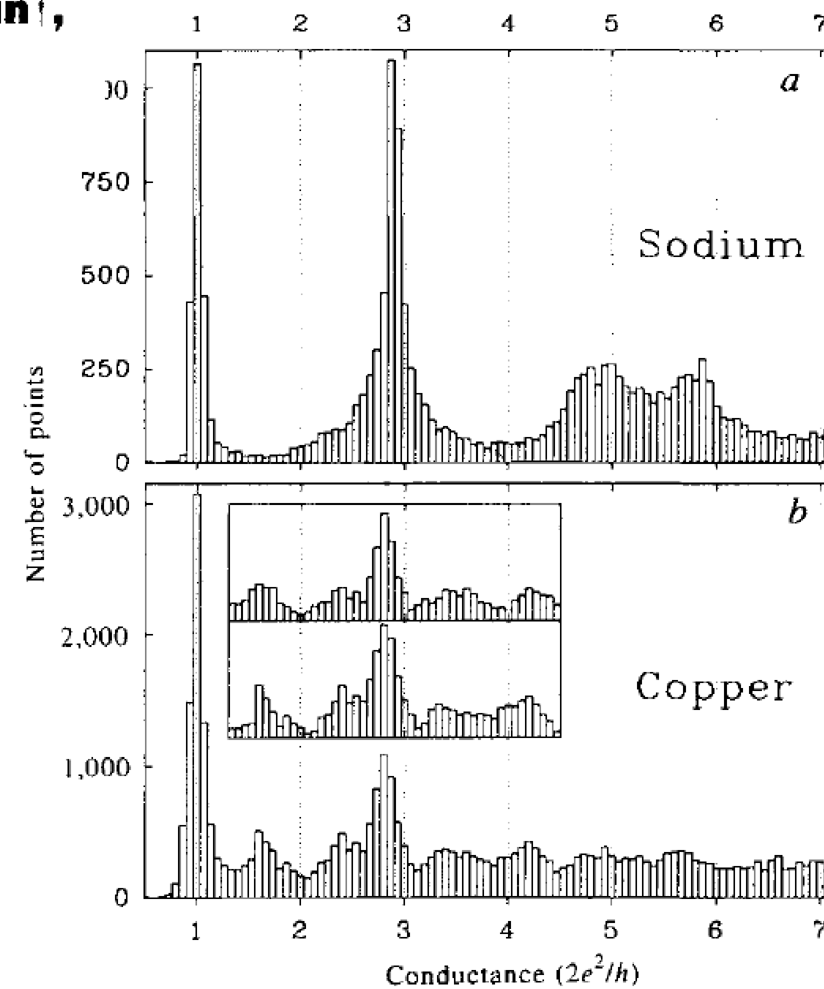

*Overview break junctions: N. Agrait, A.L. Yeyati, J.M. van Ruitenbeek, Physics Reports*

# The signature of conductance quantization in metallic point contacts

J. M. Krans*, J. M. van Ruitenbeek*, V. V. Fisun†, I. K. Yanson† & L. J. de Jongh*

NATURE · VOL 375 · 29 JUNE 1995 **767**



# Nanowire formation in macroscopic metallic contacts: quantum mechanical conductance tapping a table top

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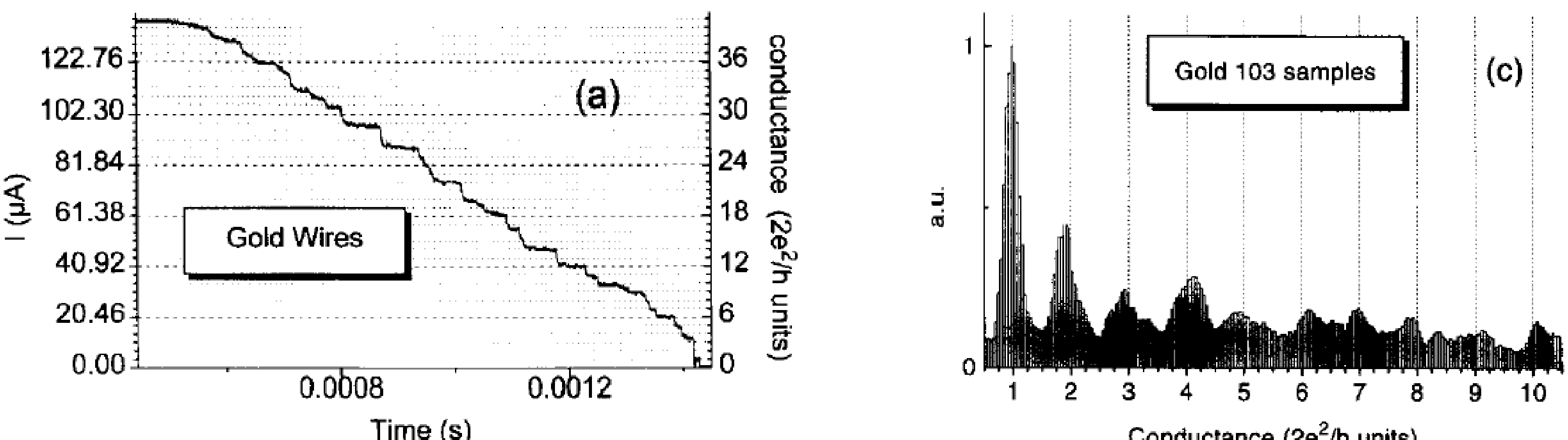
Surface Science 342 (1995) L1144–L1149

**Abstract**

In this letter we show that quantum mechanical conductance is observed in nanowires formed by placing two wires of macroscopic dimensions in contact, making them vibrate so they get in and out of contact, and measuring the conductance response of such a system with an oscilloscope. We do this by tapping the table top on which the loose contact formed by the macroscopic wires is placed. The formation of these nanowires and the associated quantized conductance is a universal phenomenon that occurs when any two metals get in and out of contact independently of the metal sizes. This should have strong technological implications in studying contact formation, friction, tribology, forming and breaking bonds, mechanics, etc., at the nanoscopic level. Results and simple specifications needed for the formation of nanowires are presented for Au, Cu, Pt and metallic glass wires.



# Quantum Suppression of Shot Noise in Atom-Size Metallic Contacts

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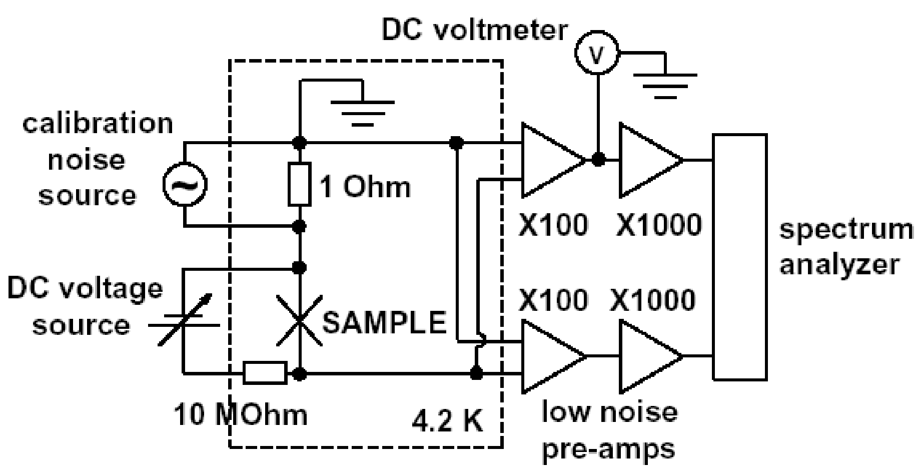
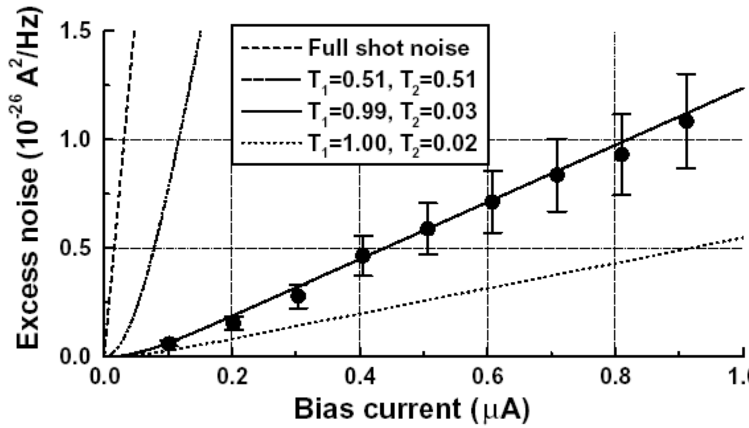
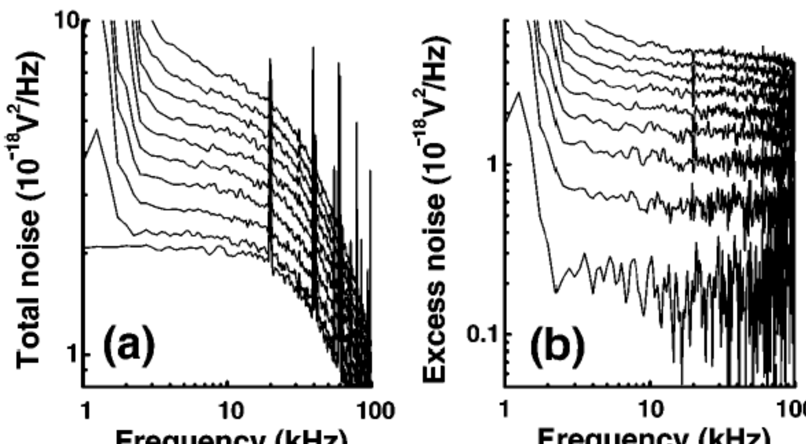
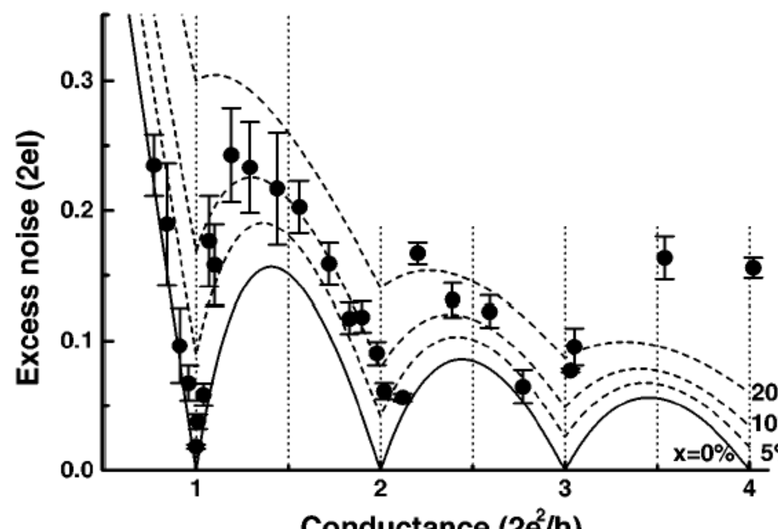
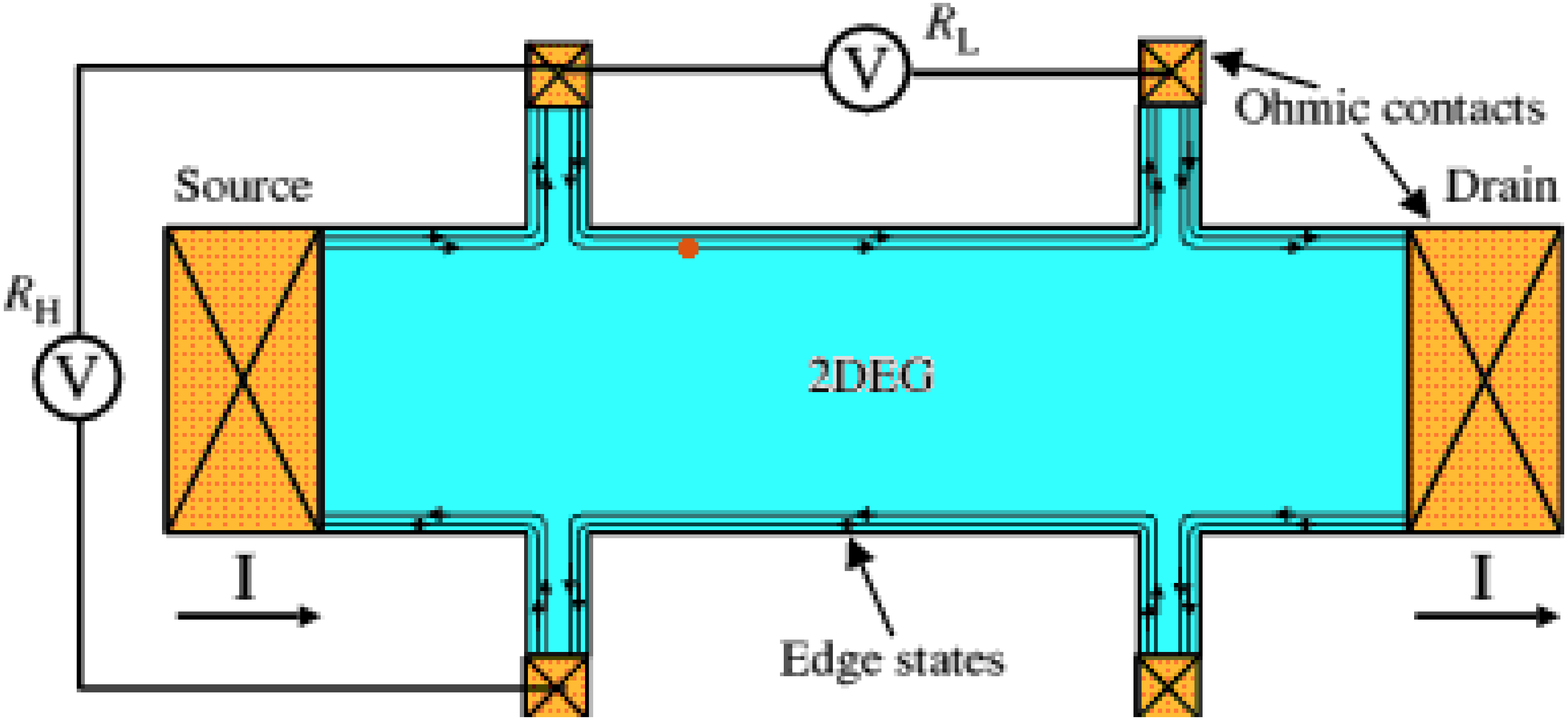


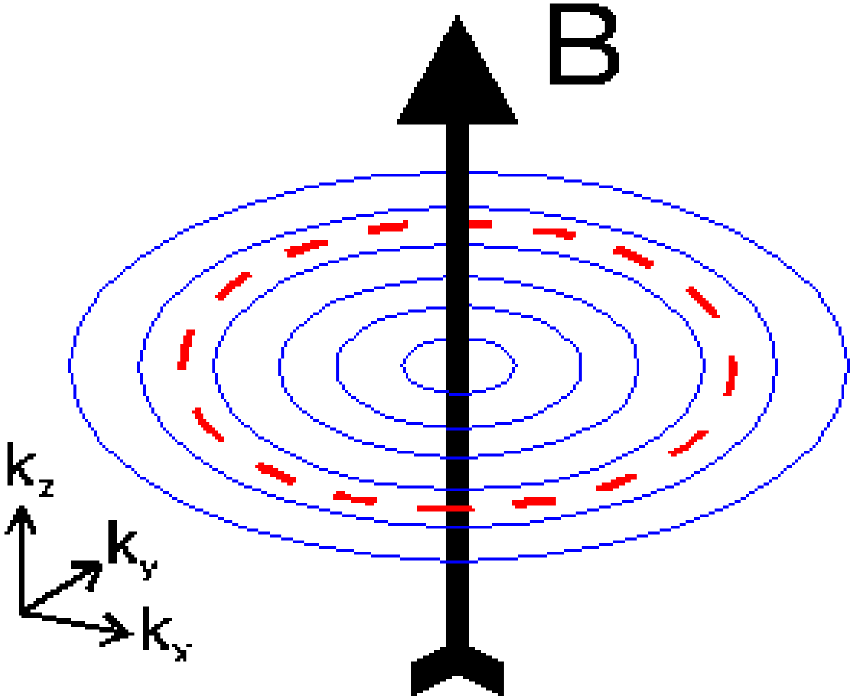



# A Hall Bar



# electrons in a high magnetic field: magnetic quantisation and Landau levels

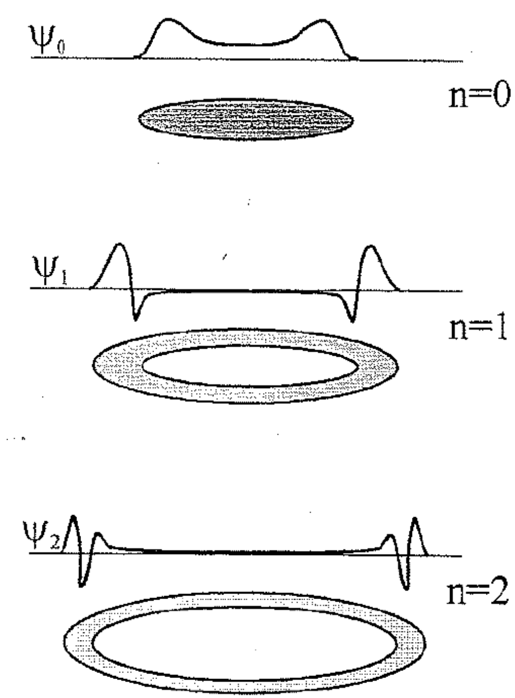



The kinetic energy in a magnetiuc field, B, is quantized in Landau levels due to quantized cyclotron motion.

A quantum mechanical calculations shows that the energy levels are given by:

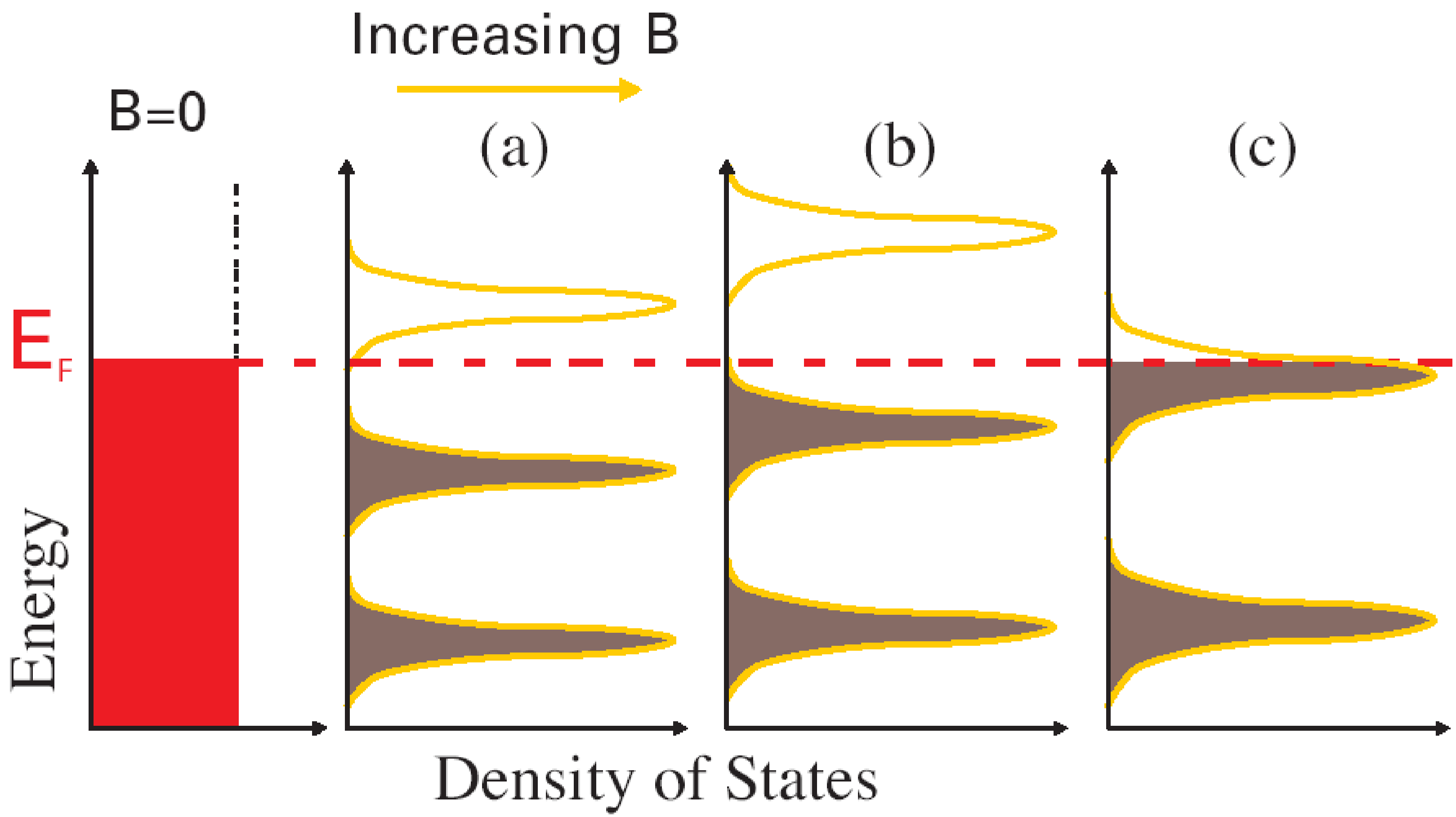
$$E_n = (n + 1/2)\,\hbar\omega_c$$

$$\omega_c = eB/m$$



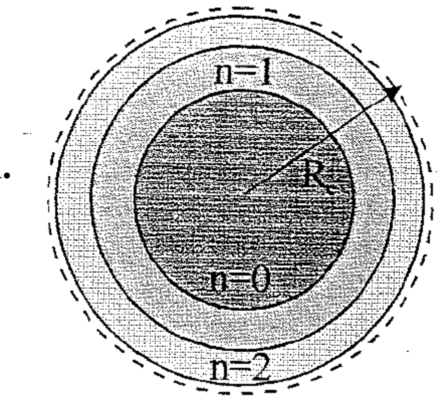

Recall classical argument to calculate $\hbar\omega_c$

# density of states in a magnetic field consists of a series of peaks




**Peak broadening is caused by disorder**

# filling factor ν and number of states per Landau level




**At B≠0, all zero-field states within a range $\hbar\omega_c$ are condensed into a single Landau level. The number of states per level, per unit area is therefore:**

$$N_L = D_{2D}(E)\,\hbar\omega_c = eB/h = \Phi/\Phi_0 S$$

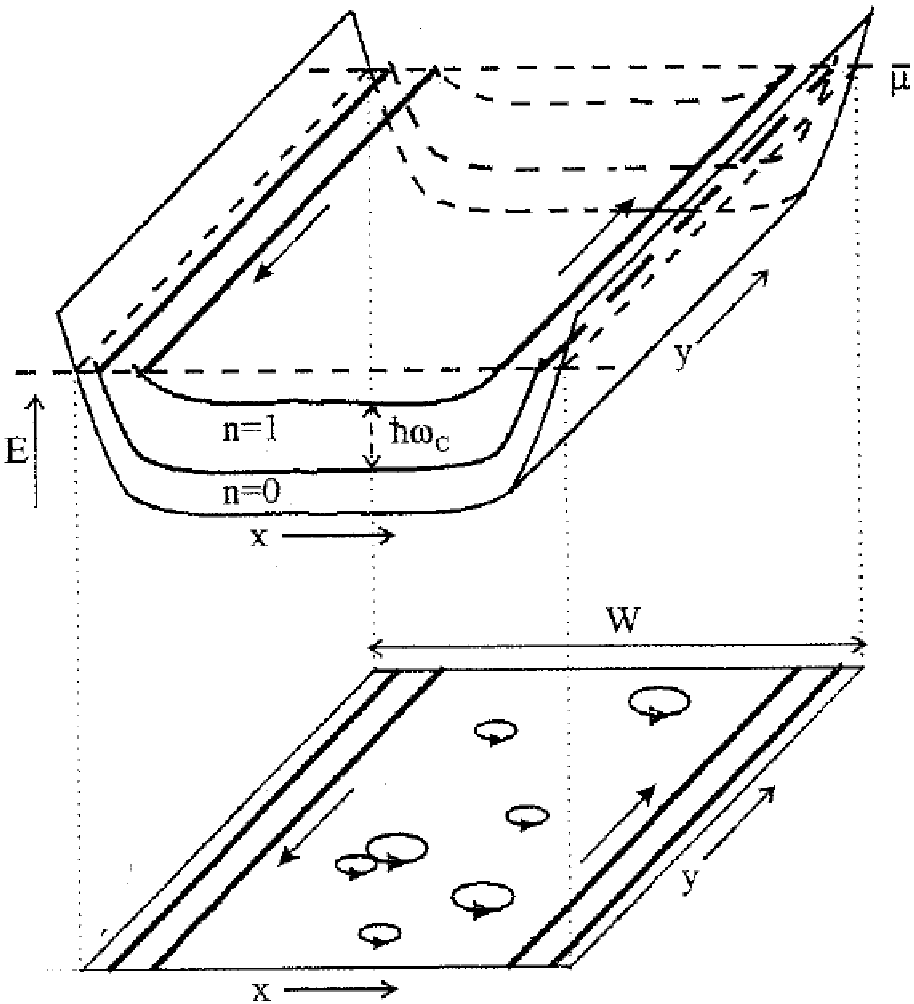
**(This is also the number of flux quanta threading unit area. This is not a coincidence; the number of different electron wave functions that can fits in each LL is equal to the number flux quanta. S = sample area )**

**Thus, the larger B the more states fit into a Landau level !!!!!**

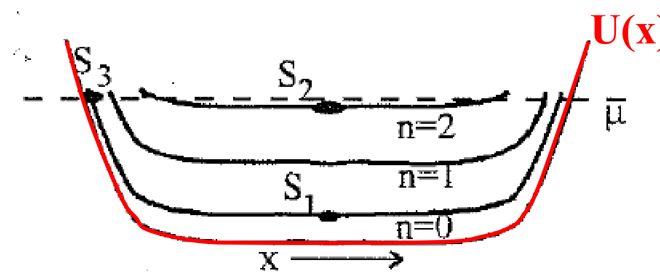
**When particles are put into these states, the *filling factor* ν is equal to the number of Landau levels filled. Clearly for partially filled LLs ν is a fraction. As the magnetic field is increased the filling factor decreases since more particles can be put in each LL; i.e., the number of filled Landau levels decreases and at some point even the last Landau level will be depopulated (what is a typical value of the magnetic field for that ??).**

**filling factor = areal density of particles/areal density of flux quanta = $n/N_L = nh/(eB)$**

# edge state carry the current

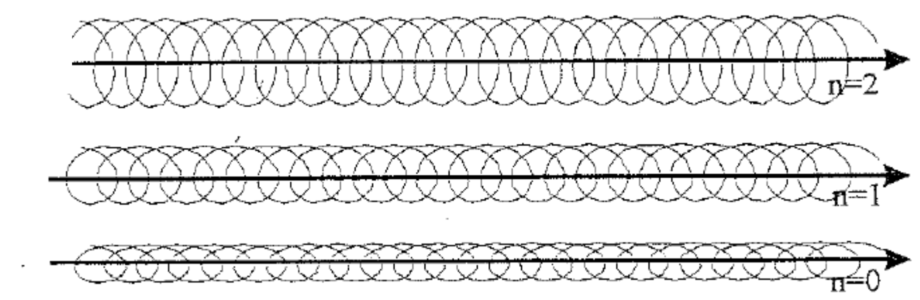



$$E_n(x,k_y) = (n+\frac{1}{2})\hbar\omega_c + U(x) + \frac{\hbar^2 k_y^2}{2m}$$



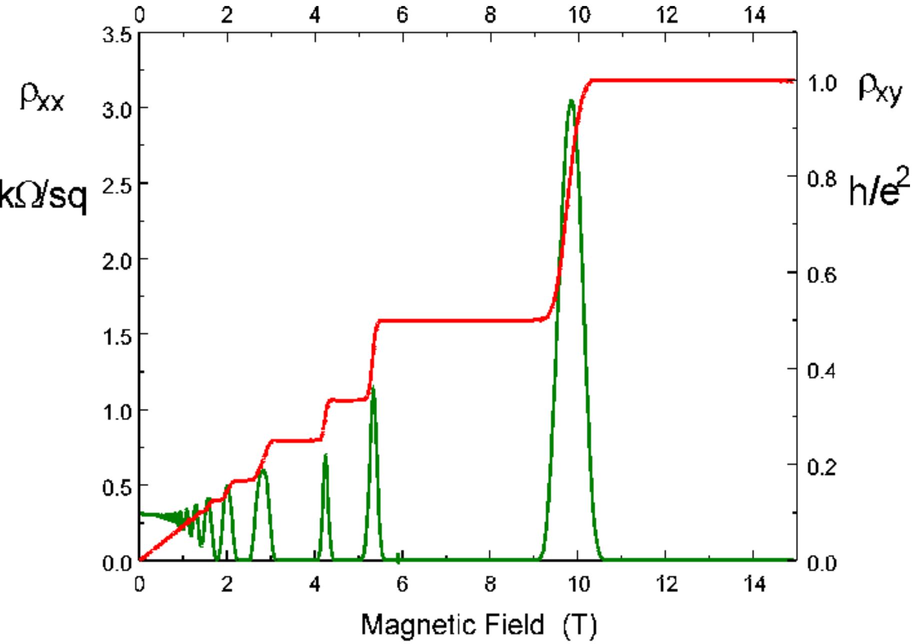

$$\vec{E}(x) = -\vec{\nabla}U(x)$$

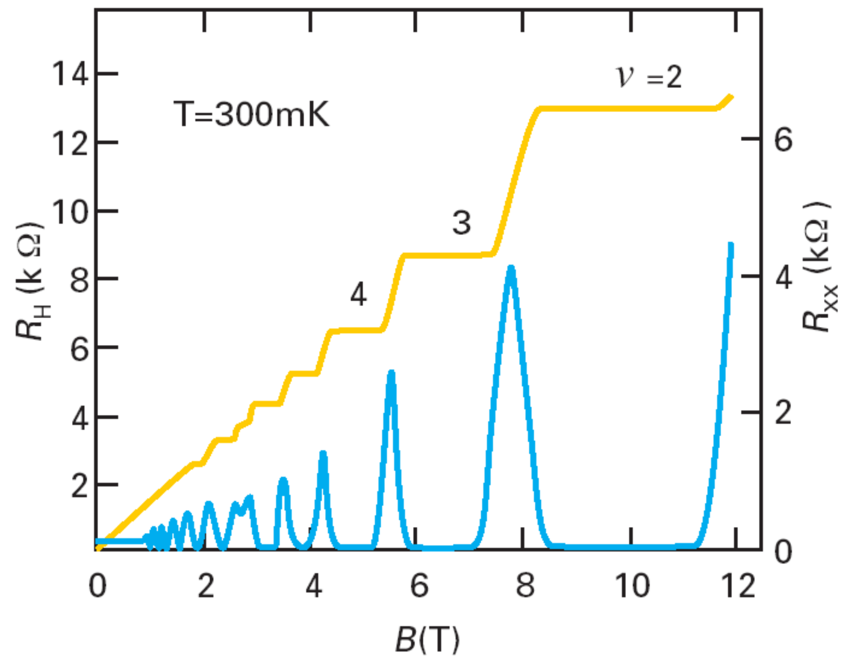
$$v_{d,n,y}(x) = -\frac{|\vec{E}|}{|\vec{B}|}$$

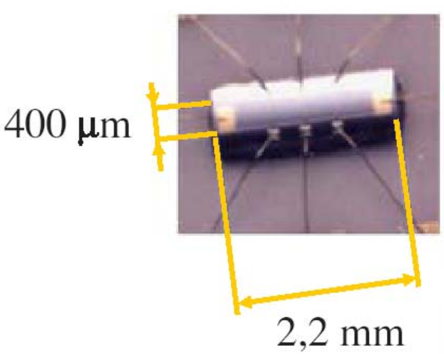


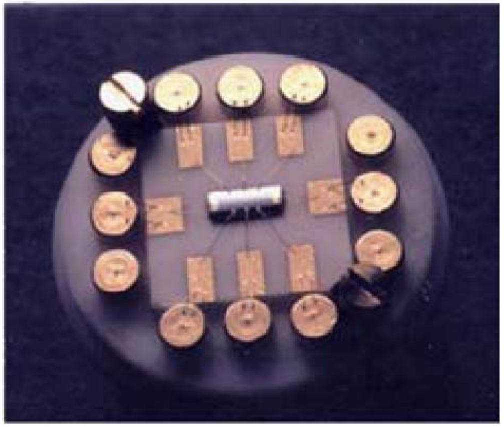

**When the Fermi energy lies in a gap between LLs electrons can not move to new states and so there is no scattering. Thus the transport is dissipationless and the 4-probe longitudinal resistance falls to zero ⇒ edge channels act as 1D ballistic channels.**

# integer Quantum Hall effect (IQHE)



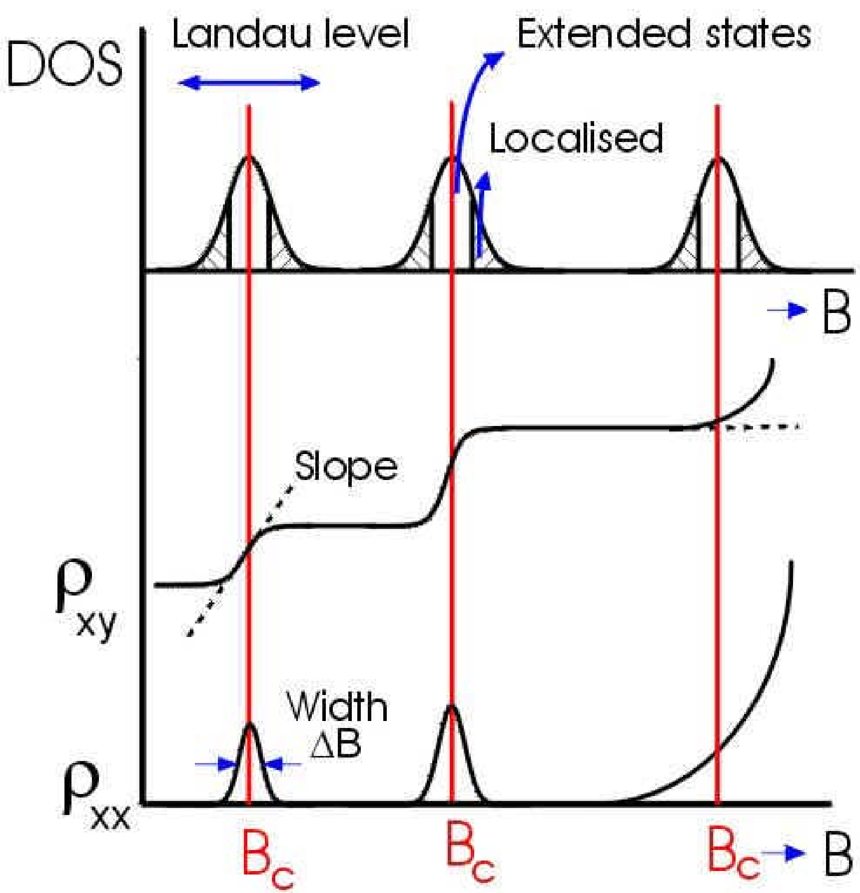



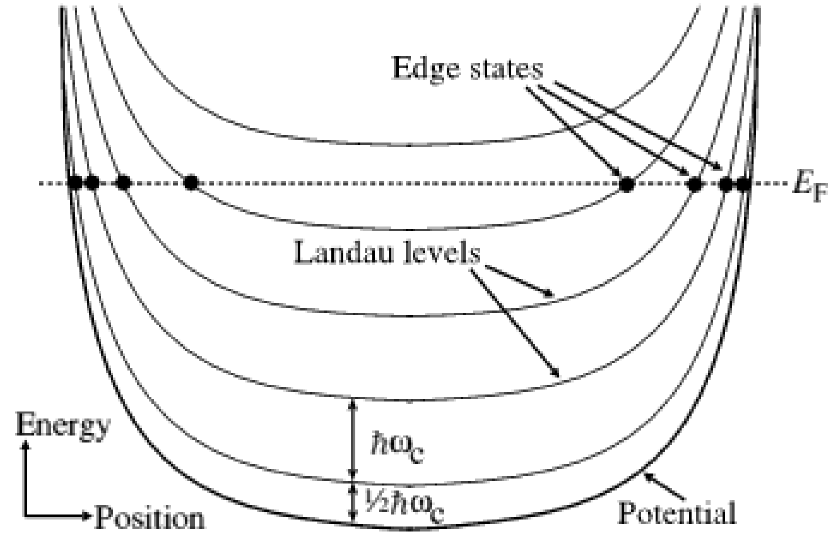



What is the difference between the two samples of which the measurement is shown in the two plots?

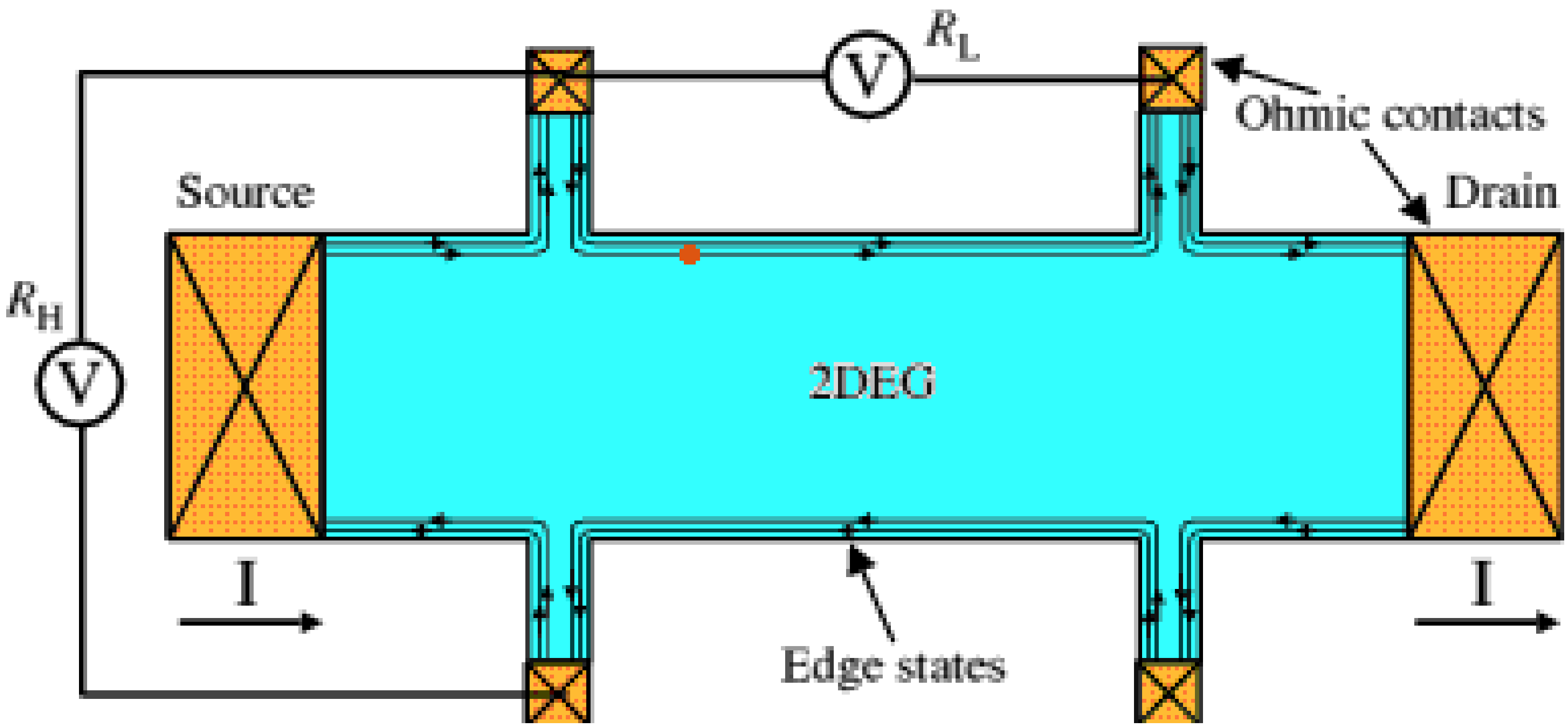
# integer Quantum Hall effect (IQHE): localized and delocalized states




**Schematic picture of density of states (DOS) of a 2DEG in field and the quantum Hall effect. The Landau quantization results in a sequence of impurity broadened Landau levels with extended states in the center and localized states in the tails. Upon increasing the magnetic field B, successive Landau levels are depopulated, as they move through the Fermi level. The lower traces show the corresponding Hall resistance $\rho_{xy}$ and longitudinal resistance $\rho_{xx}$. At the most right Landau level (the lowest Landau level) the $\nu$=1 plateau is depicted.**

# a few questions …




**How large is the 2-probe resistance between the source and drain?**

**In which contacts does dissipation take place?**

**At which temperature is the IQHE visible?**

**Why is quantized conductance observed whereas the sizes are much larger than the electron mean free path?**