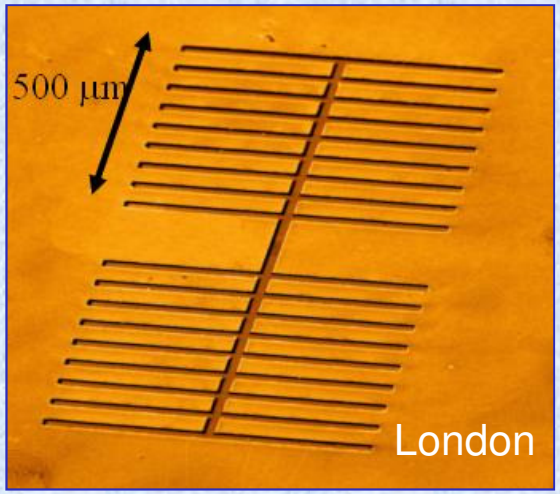
Many research groups

Mike Lea

Electrons on Helium?

(A *very* Brief History)



Surface-state electrons

Rydberg states

Electron mobility

Many electron effects

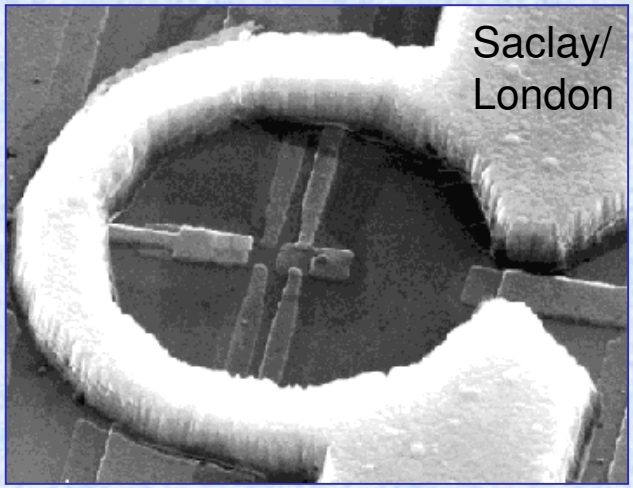
Wigner crystal

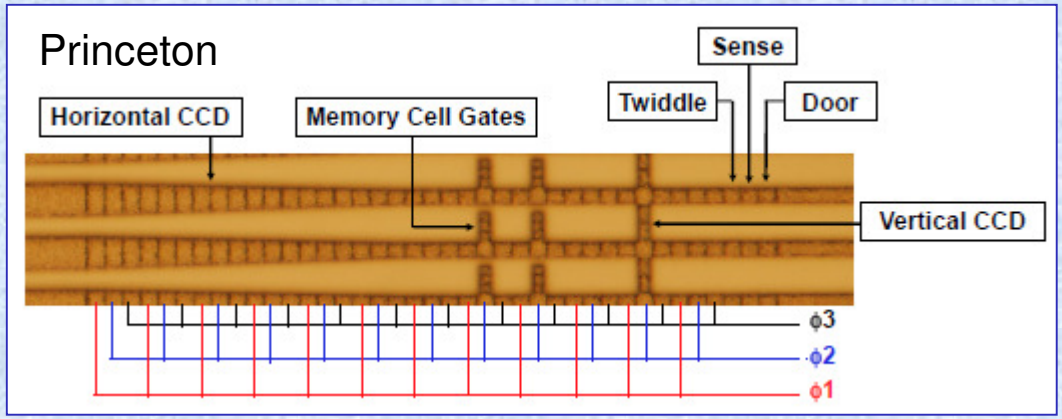
Restricted geometries

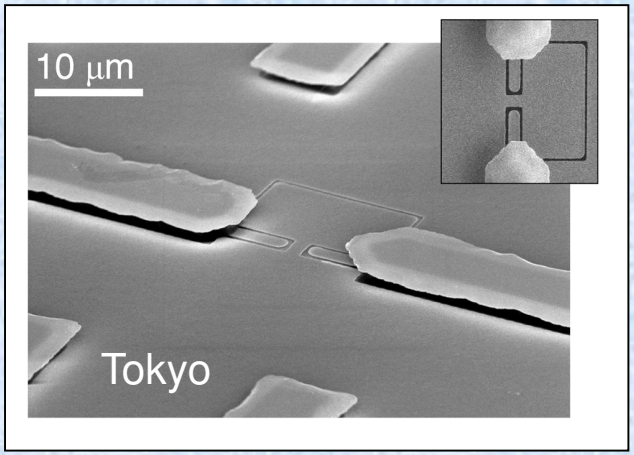
Single electronics

Electron manipulation

Qubits?







Two-dimensional electrons on helium

Generation:
Thermionic emission
Glow discharge
Photoemission

Liquid ^{4}He or ^{3}He

Magnetic field B

Holding field E_z

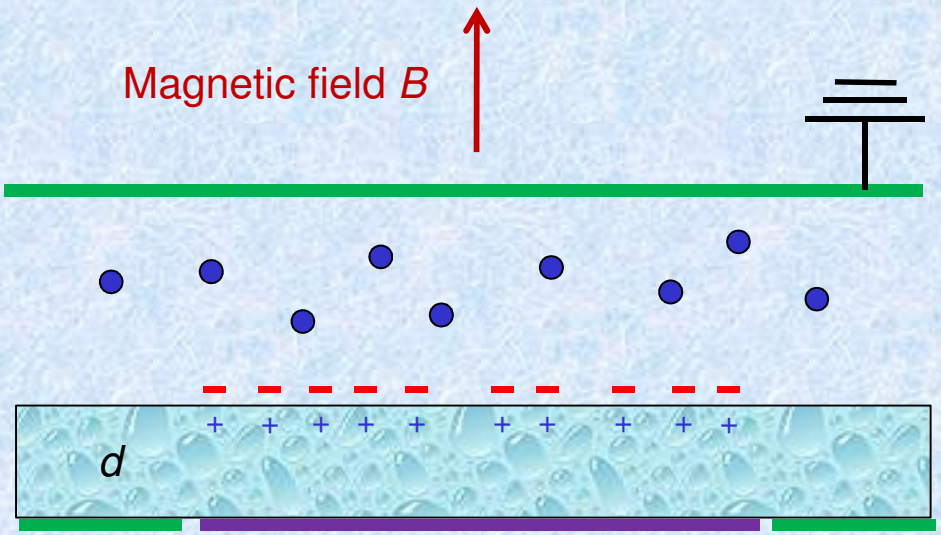
Electrons

Gas atoms

Ripplons
Qusiparticles in ^{3}He

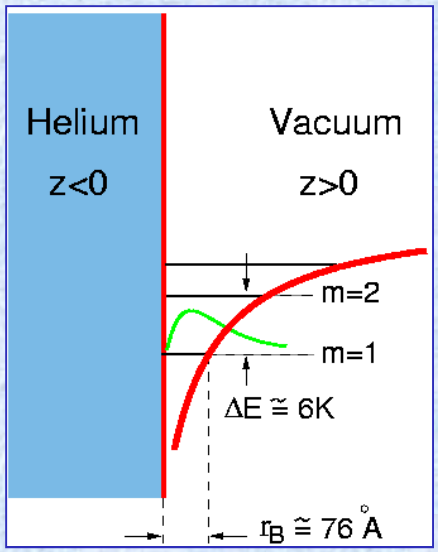
Weak Image Charge

$$Q = \frac{(\varepsilon - 1)e}{(\varepsilon + 1)} = 0.028e\ (^4\mathrm{He})$$



Saturation $n_s = \dfrac{\varepsilon\varepsilon_0 V}{ed}$

$10^5 < n < 10^9$ cm^{-2}



In-plane: Interelectron distance is ~ 1 μm

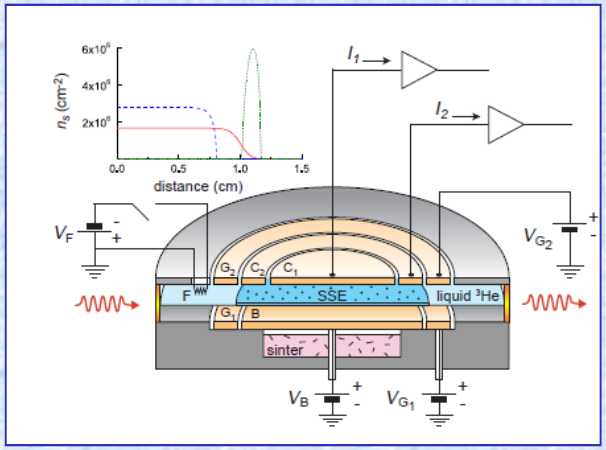
Vertical motion quantised: **Rydberg states**

Bohr radius 7.6 nm (^{4}He)

History
Theory: Cole and Cohen (1969), Shikin (1970)
Experiment: Crandall and Williams (1971)

Two-dimensional electrons on helium

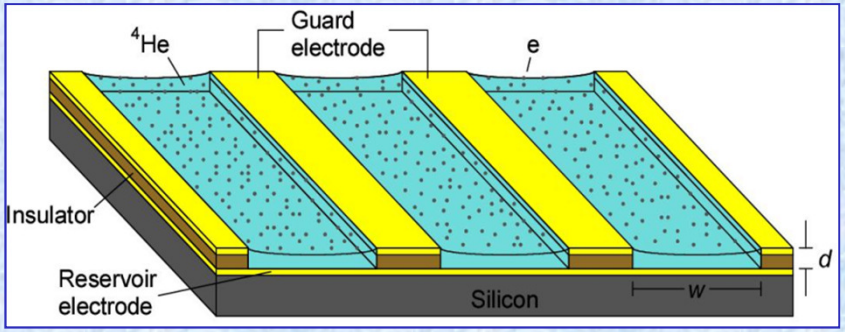
Bulk Helium
^{3}He, ^{4}He



diameter = 26 mm, d = 2.6 mm

Kimitoshi Kono (^{3}He),
Denis Konstantinov,
Valeriy Shikin + others

Channels

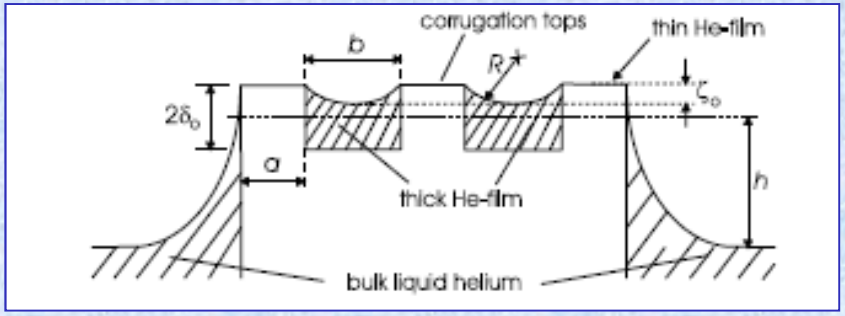


w = 20 μm, d = 1.5 μm

"Bulk helium"
Control electrodes
Microfabrication

Dave Rees, Hiroki Ikegami, Steve Lyon + many others

Films



van der Waals helium films
d ~ 20 – 100 nm
High electron density $n < 10^{15}$ m^{-2}
Roughness
Structured corrugations

Paul Leiderer, Hideki Yayama,
Alexandr Smorodin

Vast parameter range: n, T, B, E_z

Rydberg states

Image charge $U_0(z) = \dfrac{-0.007e^2}{4\pi\varepsilon_0 z}$ for $z > 0$

$$E_m = \frac{-R_e}{m^2}$$

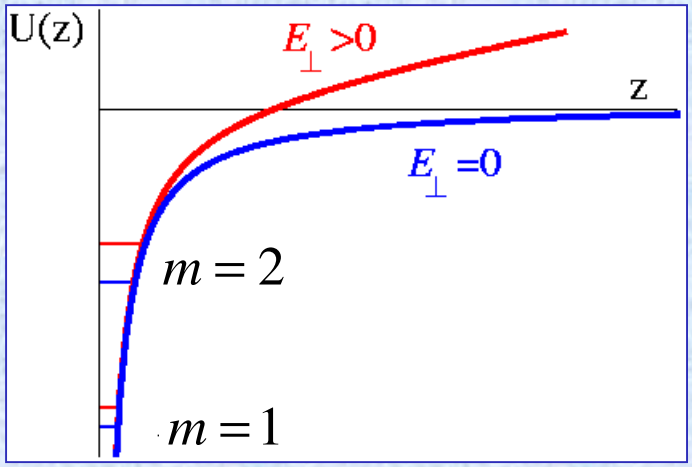
f_{12} = 119.3 GHz (^{4}He)

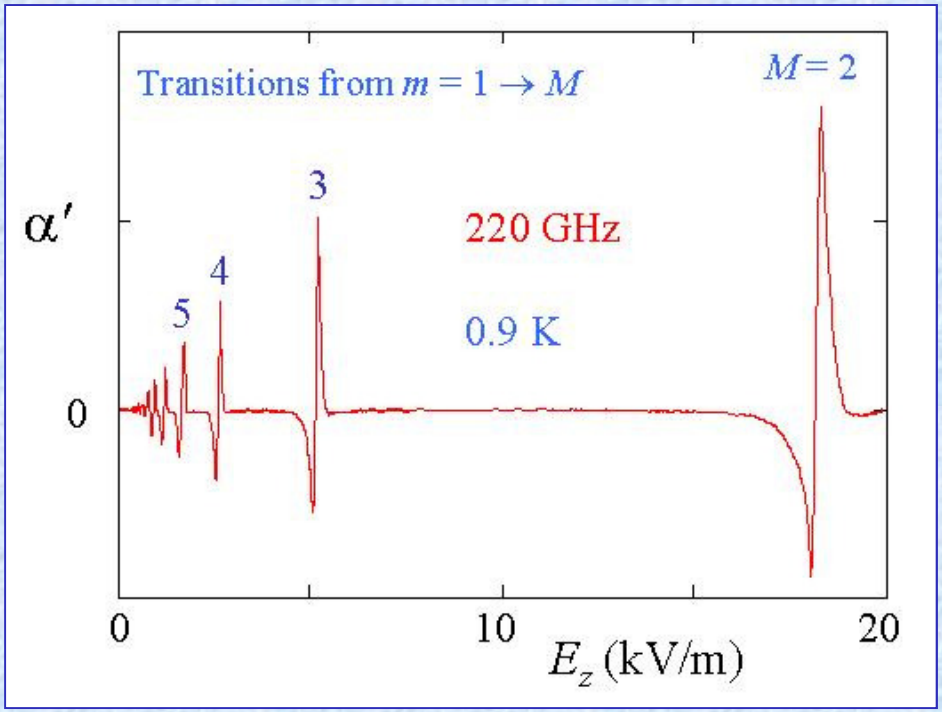
Grimes: $U_0(z) = \dfrac{-0.007e^2}{4\pi\varepsilon_0 (z+b)}$ for $z > 0$

$= V_0$ for $z \le 0$

Experiment for $E_z = 0$:
125.9 GHz at 1.2 K

Stark tuning $U(z) = U_0(z) + eE_z z$

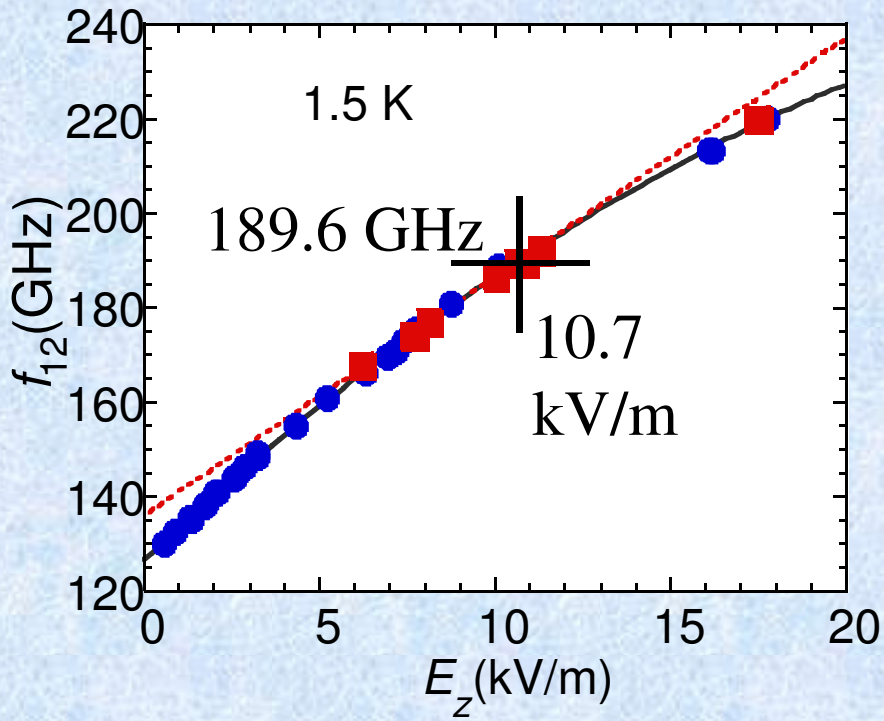




Resonant microwave absorption

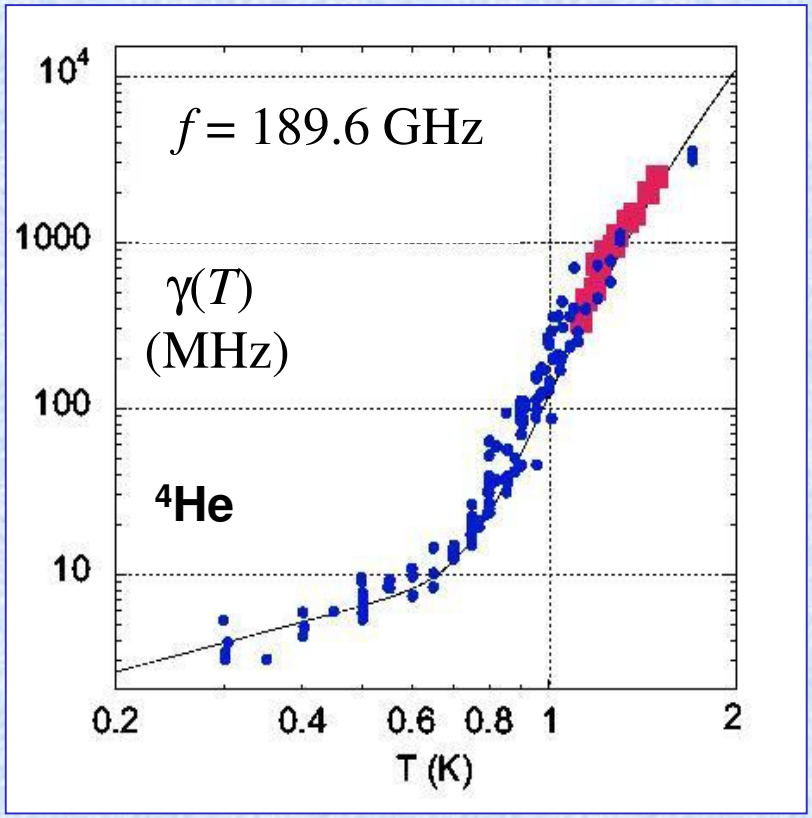
Ground state to first excited Rydberg state on ^{4}He – linewidth γ

Stark shift



Brown, Grimes, Zipfel, 1976

E. Collin *et al*, PRL **89**, 245301 (2002)



$$\gamma = AT + BN_{\text{gas}}$$

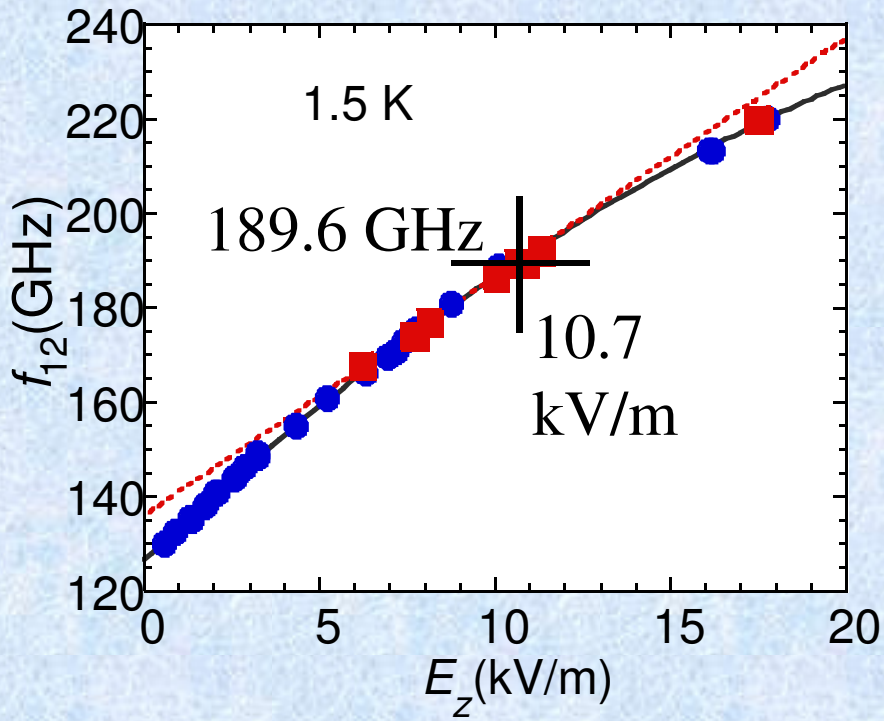
Ripplon Gas atom Scattering

Theory: Ando (1976)

Resonant microwave absorption

Ground state to first excited Rydberg state on ^{4}He – linewidth γ

Stark shift



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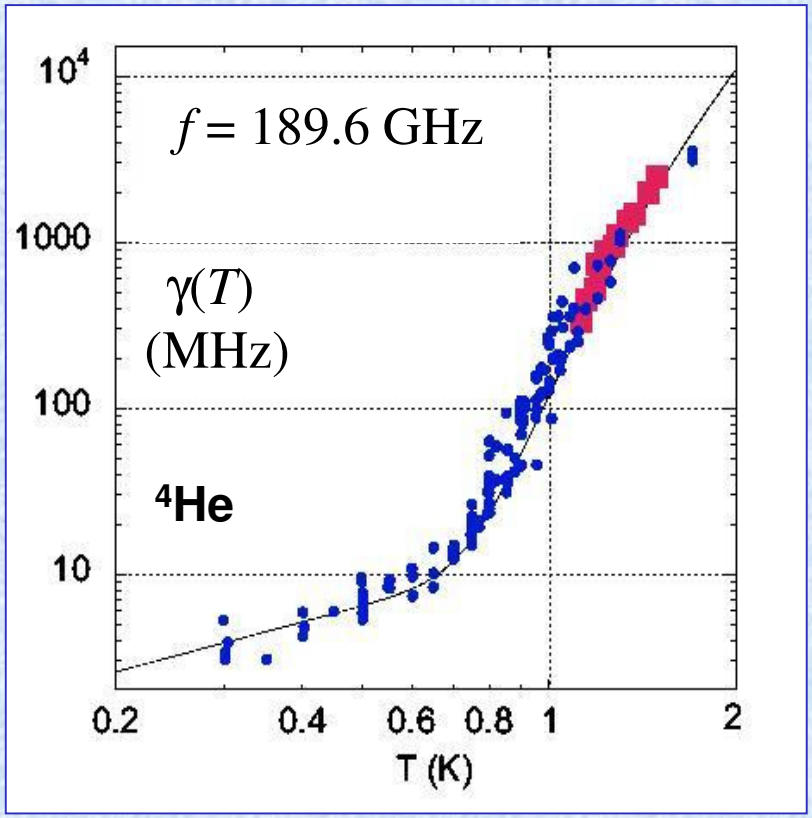


$$\gamma = AT + BN_{\text{gas}}$$

Ripplon Gas atom Scattering

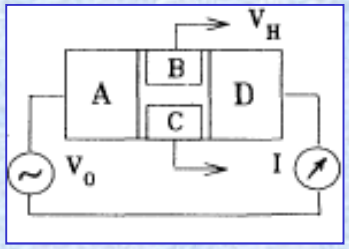
Theory: Ando (1976)

High Powers: "Non-linear Optics"
Electron heating - Power broadening -
Absorption bleaching – Coulomb shift - Bistability
(Denis Konstantinov)

The simplest conductor?

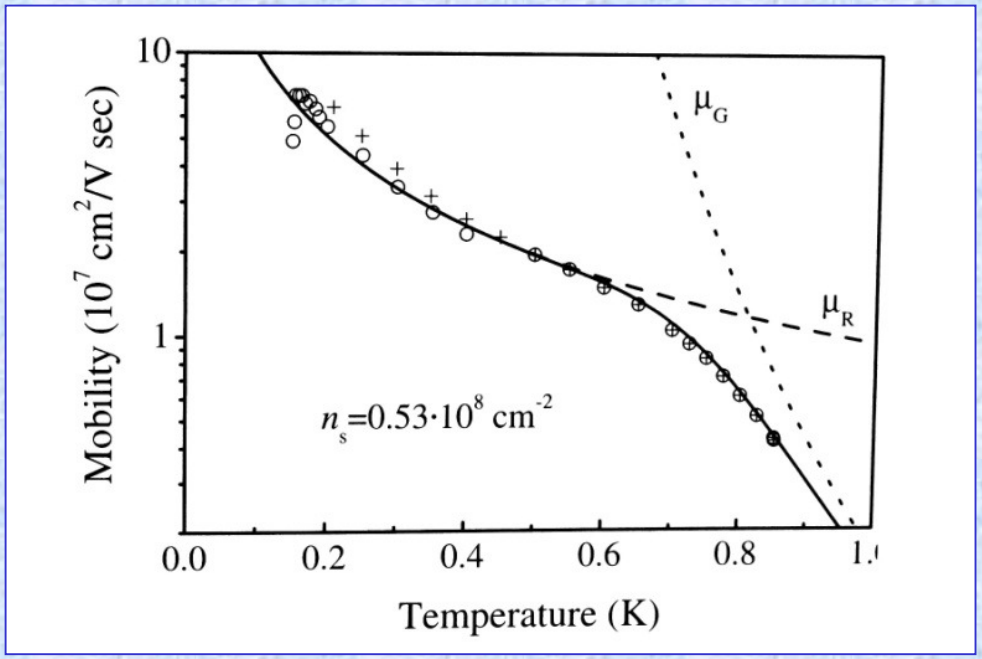
Non-degenerate conductor

AC measurements, phase shift φ



Sommer-Tanner

$\varphi \approx \rho_{xx}$



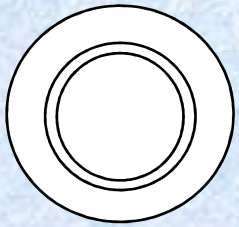
R.Mehrotra *et al.* Phys.Rev. B29, 5239 (1984)

Highest mobility μ

Conductivity $\sigma_0 = ne\mu = 1/\rho_0$

Corbino disk

$\varphi \approx 1/\sigma_{xx}$



Scattering from

Thermal ripplons

Gas-atoms

Depends on E_z, T

Agreement with theory

The in-plane mobility is record high, $\mu \leq 2\times10^8\ \mathrm{cm}^2/\mathrm{V}\cdot\mathrm{s}$

K. Shirahama *et al.*, JLTP (1995)

Electron Liquid

The 2D electron system on bulk helium is *nondegenerate* $\varepsilon_F[n_s = 10^{12}\,\mathrm{m}^{-2}] \approx 3\,\mathrm{mK}$

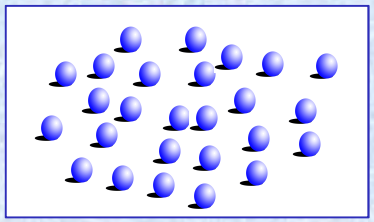
$$\text{Plasma parameter} \quad \Gamma = \frac{\text{Coulomb energy}}{\text{Kinetic energy}} = \frac{e^2(\pi n_s)^{1/2}}{4\pi\varepsilon_0 kT}$$

Strong electron correlations

Nondegenerate liquid

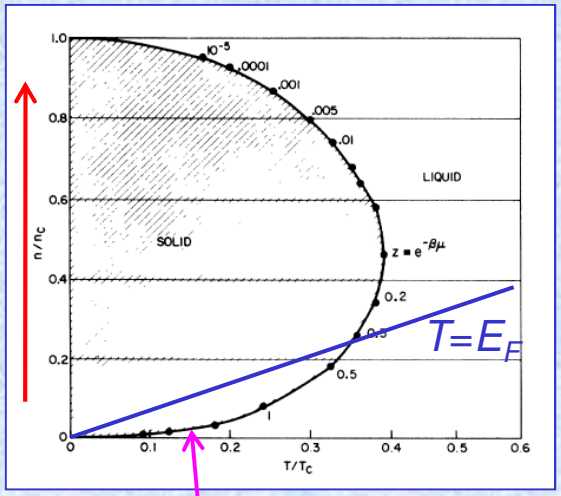
$$T_m = 2.25\times10^{-7} n^{1/2}\ \mathrm{K}$$

$$\Gamma < \Gamma_m \cong 130$$

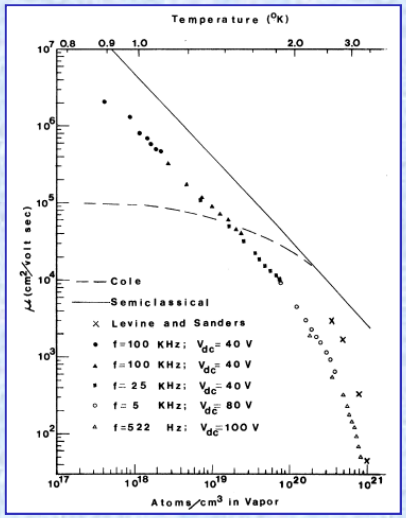


Phase diagram

Quantum melting



Classical 2D crystal
Electrons on helium



W.T.Sommer & D.G. Tanner, PRL **27**, 1345 (1971)

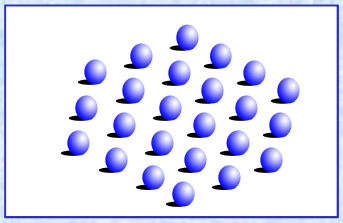
Wigner Crystal

The 2D electron system on bulk helium is *nondegenerate* $\varepsilon_F[n_s = 10^{12}\,\mathrm{m}^{-2}] \approx 3\,\mathrm{mK}$

$$\text{Plasma parameter} \quad \Gamma = \frac{\text{Coulomb energy}}{\text{Kinetic energy}} = \frac{e^2(\pi n_s)^{1/2}}{4\pi\varepsilon_0 kT}$$

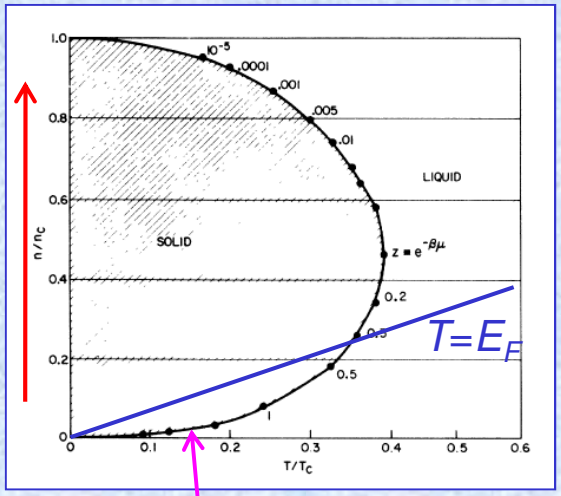
Wigner crystal | Strong electron correlations | **Nondegenerate liquid**

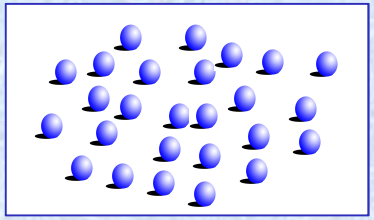
$\Gamma > \Gamma_m \cong 130$ | $T_m = 2.25\times10^{-7} n^{1/2}\ \mathrm{K}$ | $\Gamma < \Gamma_m \cong 130$

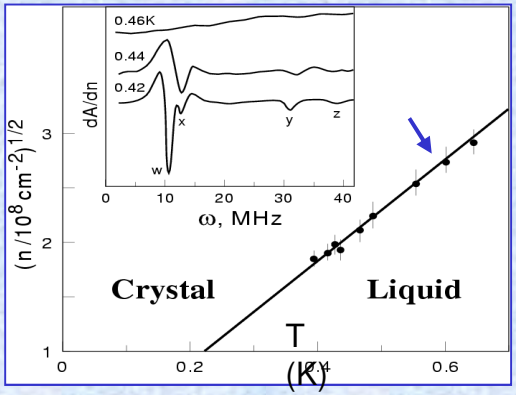


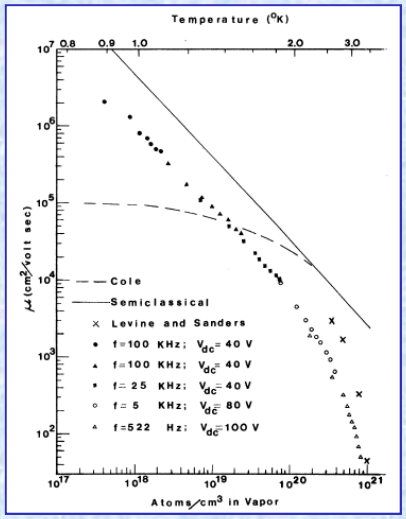
Phase diagram

Quantum melting









C.C.Grimes & G.Adams, PRL **42**, 795 (1979)

"A Repulsive Crystal"

Classical 2D crystal
Electrons on helium

W.T.Sommer & D.G. Tanner, PRL **27**, 1345 (1971)

Magnetoconductivity - Drude model

Drude model

$$\frac{\sigma_0}{\sigma_{xx}} = 1 + \mu^2 B^2$$

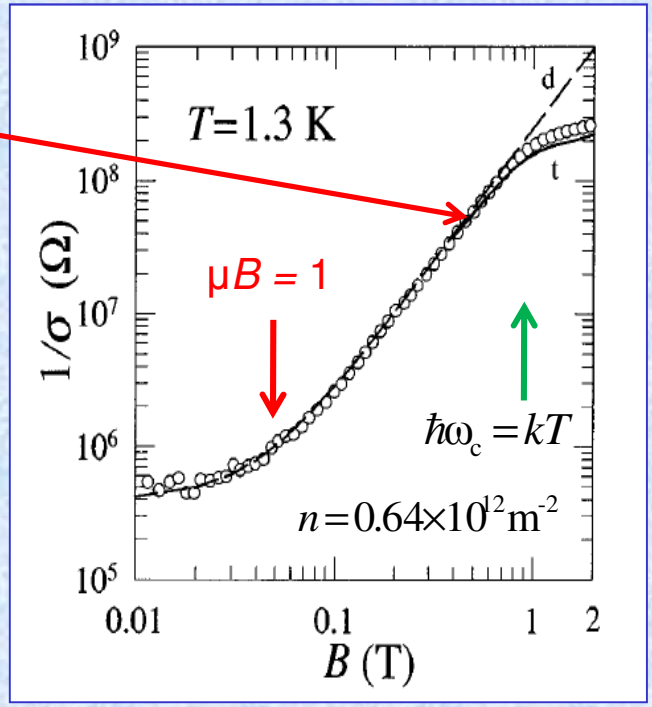
$$\sigma_0 = ne\mu = \frac{ne^2\tau_0}{m}$$

Einstein relation
Diffusion

$$\sigma_{xx} = \frac{ne^2}{kT}\frac{L^2}{\tau_B} \cong \frac{\sigma_0}{\mu^2 B^2}\frac{\tau_0}{\tau_B}$$

$$R_c = \frac{(2mkT)^{1/2}}{eB} \qquad \frac{\tau_0}{\tau_B} = 1$$

Classical cyclotron orbit



$$\mu B = \omega_c \tau_0$$

Dykman *et al.* PRB **55**, 16249 (1997); **55**, 16272 (1997); **55**, 16280 (1997)

Magnetoconductivity - Drude model

Drude model

$$\frac{\sigma_0}{\sigma_{xx}} = 1 + \mu^2 B^2$$

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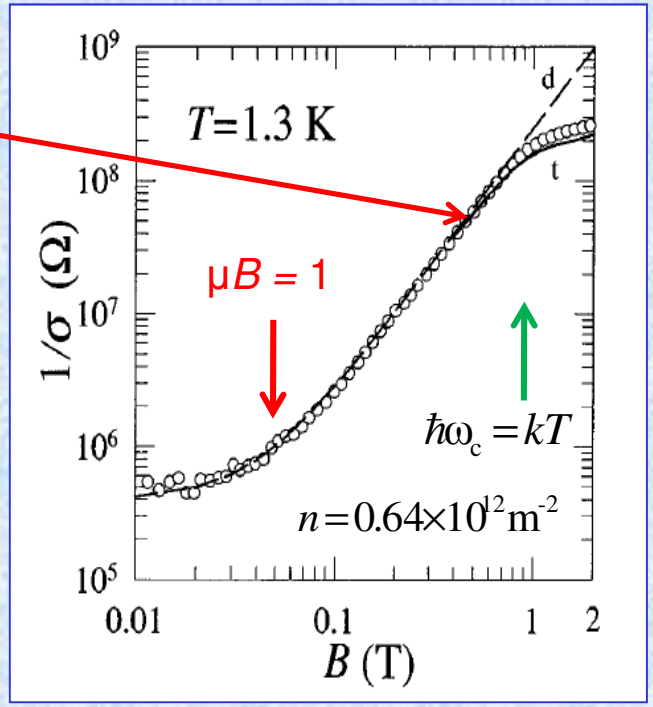


$$\mu B = \omega_c \tau_0$$

$$\omega_c = \frac{eB}{m}$$

Non-degenerate

$$R_c = \frac{(2mkT)^{1/2}}{eB} \qquad \frac{\tau_0}{\tau_B} = 1$$

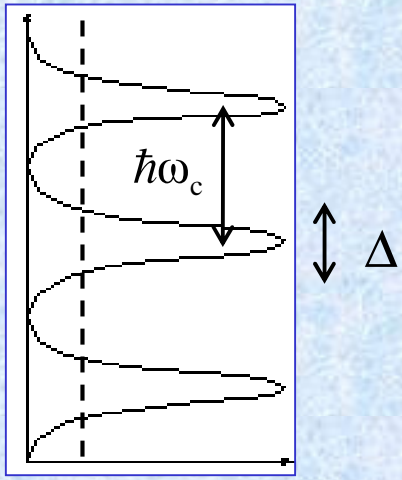
Classical cyclotron orbit

BUT $\omega_c \tau_0 = \mu B >> 1$

Landau levels $E_N = (N + 0.5)\hbar\omega_c$

$$\frac{\tau_0}{\tau_B} \approx \frac{\hbar\omega_c}{\Delta}$$

$$\frac{\tau_0}{\tau_B} \approx \frac{\hbar\omega_c}{\hbar/\tau_B} = (\omega_c\tau_0)^{1/2} = (\mu B)^{1/2}$$



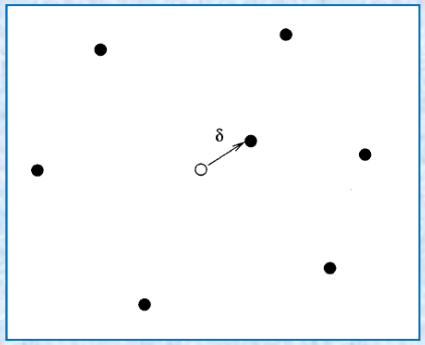
Single particles
Collision broadened (SCBA):
Enhanced scattering?

Fluctuational Many-electron Field

Electrons in a potential well, plasma frequency

$$\omega_p = (e^2 n^{3/2}/2\varepsilon_0 m)^{1/2}$$

KE = kT

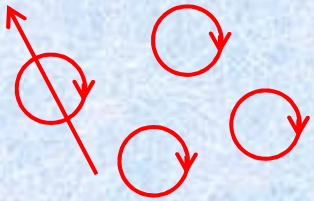


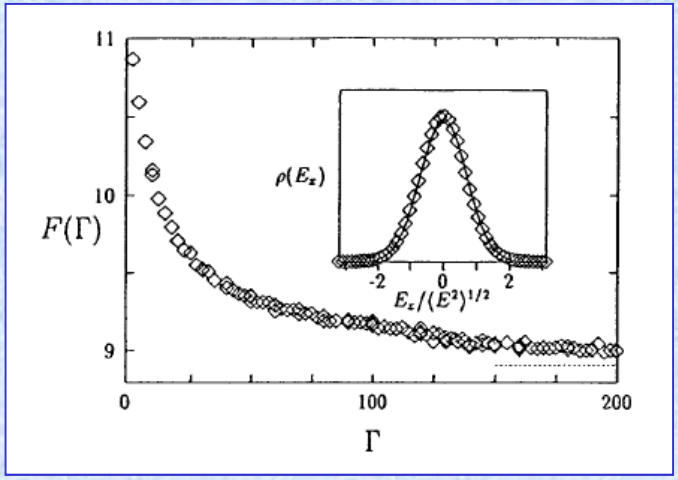
$$\langle E_f^2 \rangle = F(\Gamma)\left(\frac{2mkT\omega_p^2}{e^2}\right) = F(\Gamma)\left(\frac{kTn^{3/2}}{4\pi\varepsilon\varepsilon_0}\right) = F(\Gamma)E_0^2,$$

Fluctuating electric field $E_f \approx n^{3/4} T^{1/2}$

Energy fluctuation across a cyclotron orbit

$$\Delta_c = eE_f R_c$$





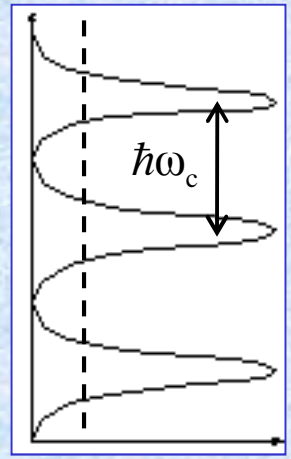
Wigner solid F =8.91

Dykman and Khazan, JETP (1979) – prehistory?

Many-electron Magnetoconductivity

Landau levels

$$\Delta_c = eE_f R_c > \hbar\omega_c$$



$$\hbar\omega_c < kT$$

$$\frac{\sigma_0}{\sigma_{xx}} \propto \frac{\mu^2 B^2}{\tau_0/\tau_B}$$

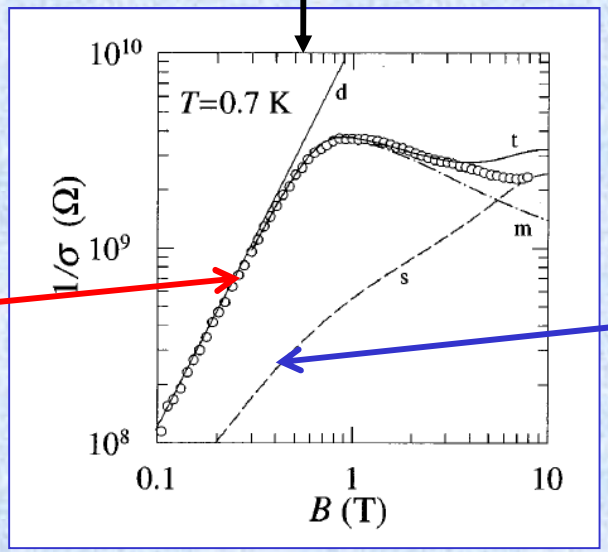
Many electron effects:
Electron liquid
Restores Drude model

$$\frac{\tau_0}{\tau_B} = 1$$

Single particles
(SCBA)

$$\frac{\tau_0}{\tau_B} \propto (\mu B)^{1/2}$$

$$\hbar\omega_c = kT$$



$$\sigma_{xx}^{-1} \propto B^2$$

$$\sigma_{xx}^{-1} \propto B^{3/2}$$

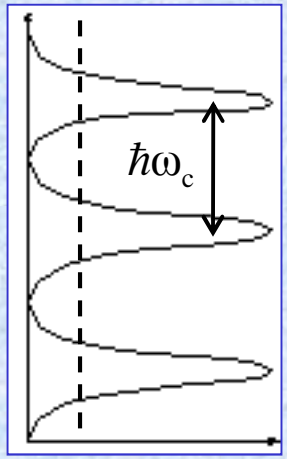
$$n = 0.55\times10^{12}\,\mathrm{m}^{-2}$$

Many-electron Magnetoconductivity

Landau levels

$$\Delta_c = eE_f R_c < \hbar\omega_c$$

$$B > B_0 = A\, n^{3/8} T^{1/2} \approx 0.1 \text{ to } 1\,\text{T}$$



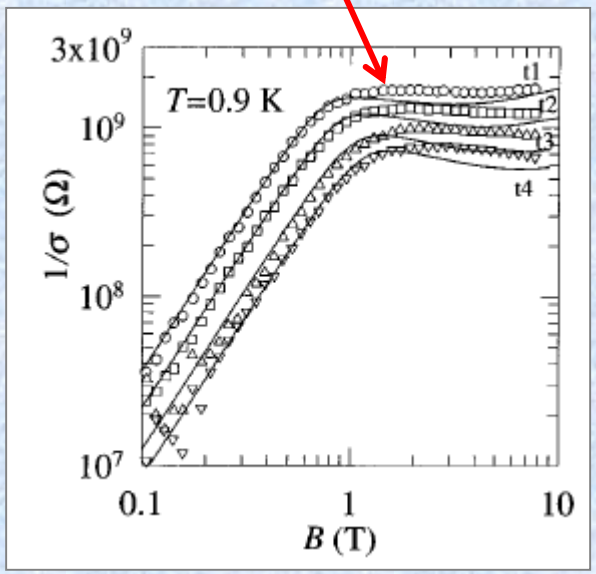
$$\hbar\omega_c < kT$$

$$\frac{\sigma_0}{\sigma_{xx}} \propto \frac{\mu^2 B^2}{\tau_0/\tau_B}$$

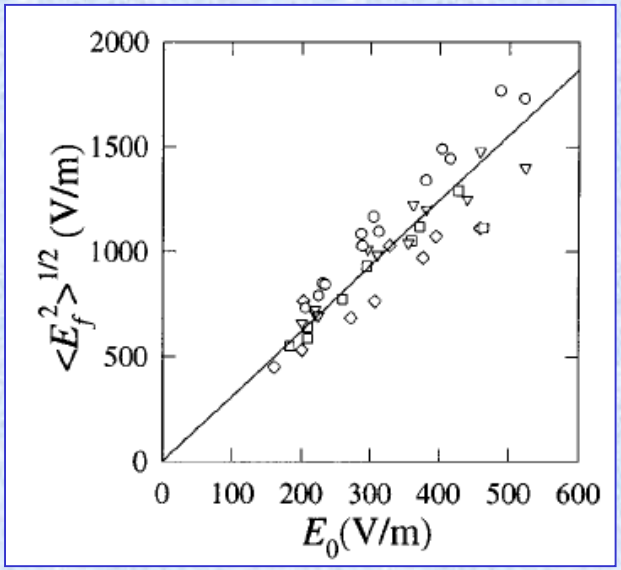
Many electron effects:
Electron liquid

$$\sigma_{xx}^{-1} \propto \mu B_0^2$$

$$\frac{\tau_0}{\tau_B} \propto \frac{\hbar\omega_c}{eE_f R_c} \propto \frac{B^2}{B_0^2}$$



Measure E_f



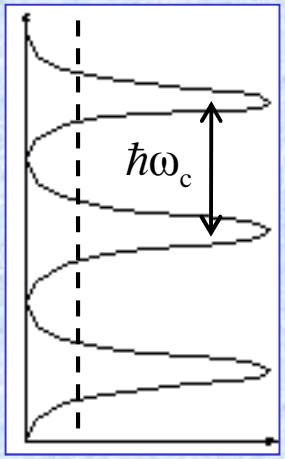
$n = 0.54, 0.85, 1.39, 1.88 \times 10^{12}\,\text{m}^{-2}$

Quantum Magnetoconductivity

Landau levels

$$l_B = \left(\frac{\hbar}{eB}\right)^{1/2}$$

$$\Delta_q = eE_f l_B < \hbar\omega_c$$



$$\hbar\omega_c > kT$$

$$\frac{\sigma_0}{\sigma_{xx}} \propto \frac{\mu^2 B^2}{\tau_0/\tau_B} \frac{1}{(2\hbar\omega_c/kT)}$$

Many electron effects:
Electron liquid
Density dependent

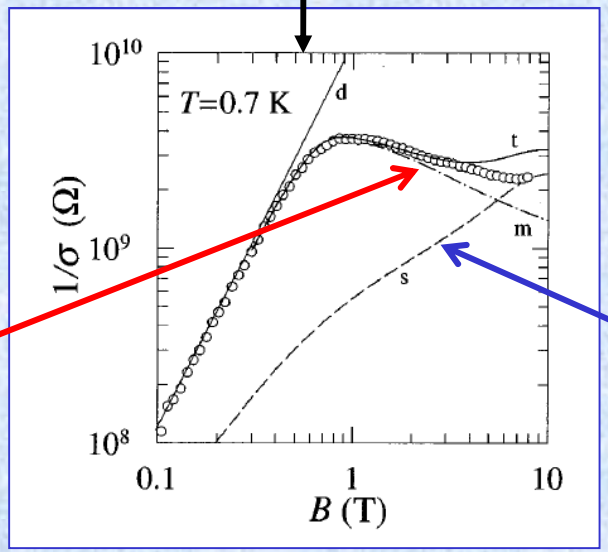
$$\frac{\tau_0}{\tau_B} \propto \frac{\hbar\omega_c}{eE_f l_B} \propto B^{3/2}$$

$$\hbar\omega_c = kT$$

Highest fields:
Single particles

$$\frac{\tau_0}{\tau_B} \propto (\mu B)^{1/2}$$

$$\sigma_{xx}^{-1} \propto B^{-1/2}$$



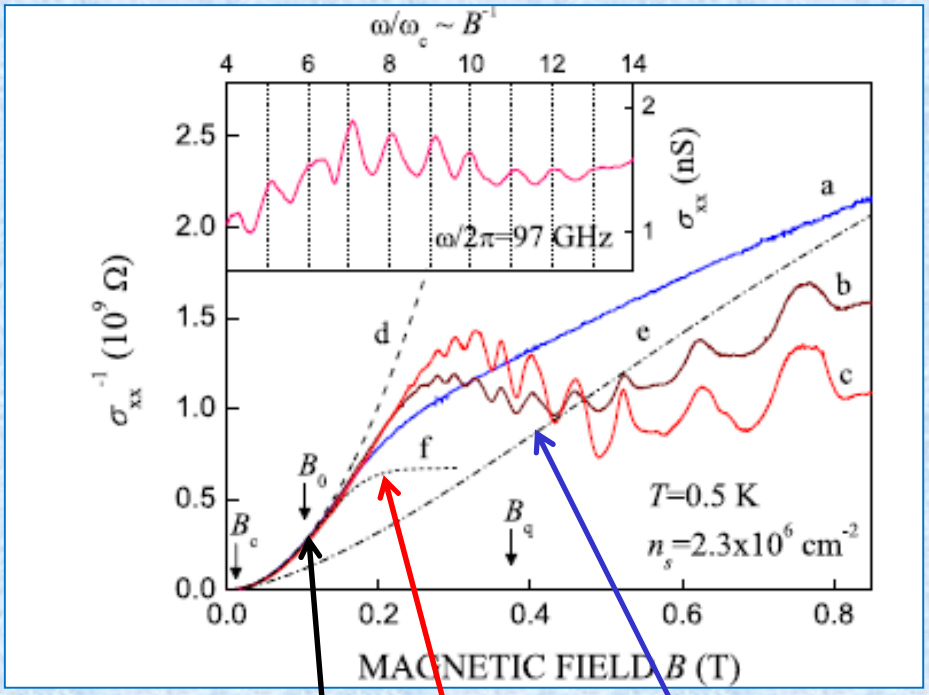
$$\sigma_{xx}^{-1} \propto B^{1/2}$$

$n = 0.55\times10^{12}\,\mathrm{m}^{-2}$

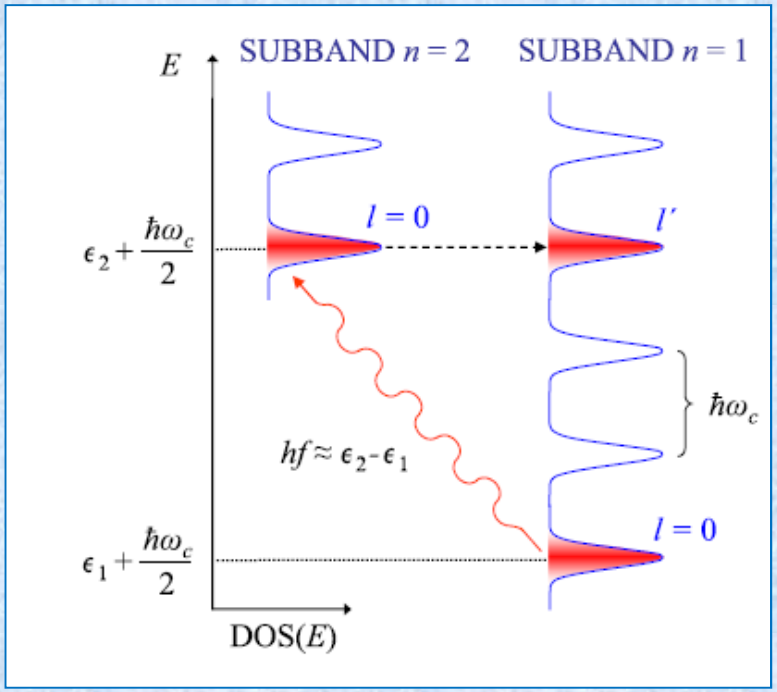
Microwave-induced Magnetoresistance Oscillations

Denis Konstaninov and Kimitoshi Kono, PRL **103**, 266808 (2009); PRL **105**, 226801 (2010)

Novel Radiation-Induced Magnetoresistance Oscillations



Photon-Induced Vanishing of Magnetoconductance



Many electron

Single particle

Drude model
no oscillations

Low density
SCBA at high fields
Higher densities
Oscillations smeared

Wigner crystal

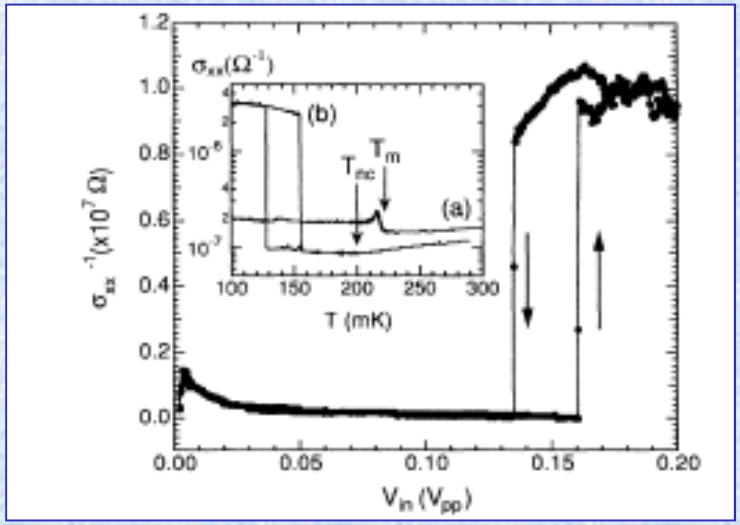
Non-linear magnetoconductivity

K. Shirahama and K. Kono,
PRL **74**, 782 (1995)

σ_{xx}^{-1} depends on V_0

Jumps, hysteresis

Collective sliding from dimples



$n = 1.08 \times 10^{12}\ \mathrm{m}^{-2}$

$T_m = 220\ \mathrm{mK}$

$B = 0.0289\ \mathrm{T}$

$T = 80\ \mathrm{mK}$

Non-linear transport:

a) Resonant Bragg-Cherenkov scattering

b) Decoupling of the Wigner solid from the helium surface

M.I.Dykman and Y.G.Rubo PRL **78**, 4813 (1997)
W.F.Vinen, J.Phys.CM, **11**, 9709 (1999)

Ripplon phase velocity
α - surface tension
ρ – helium density

Dynamical pinning for $\lambda = a$
Bragg-Çerenkov scattering

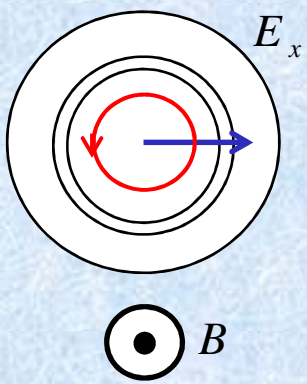
$$\omega_r^2 = \left(\frac{\alpha}{\rho}\right)^{1/2} q^3 \qquad v_r(\lambda) = \left(\frac{2\pi\alpha}{\lambda\rho}\right)^{1/2}$$

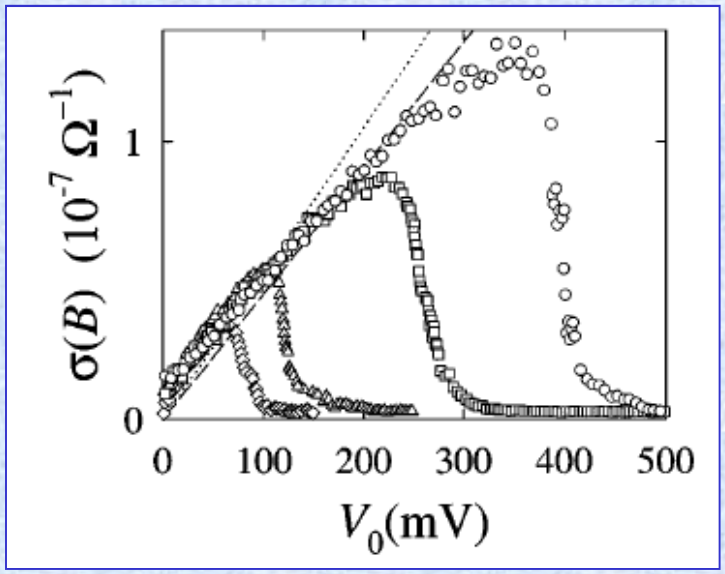
Ripplon barrier $\quad v_r(a) = \left(\frac{2\pi\alpha}{a\rho}\right)^{1/2} \propto n^{1/4}$

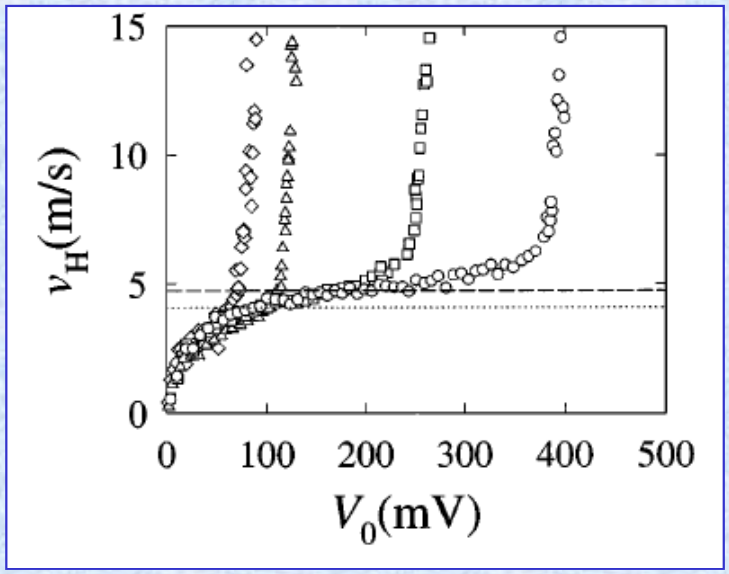
Non-linear magnetoconductivity – Ripplon Barrier

A. Kristensen et al, PRL **77**, 1350 (1996)

$v_H = \mu B v_x$







$n = 1.06,\ 1.20,\ 1.57,\ 1.90 \times 10^8\ \mathrm{cm}^{-2}; T = 60\ \mathrm{mK}$

$v_H = 4.09$ to 4.74 m/s

Corbino disk

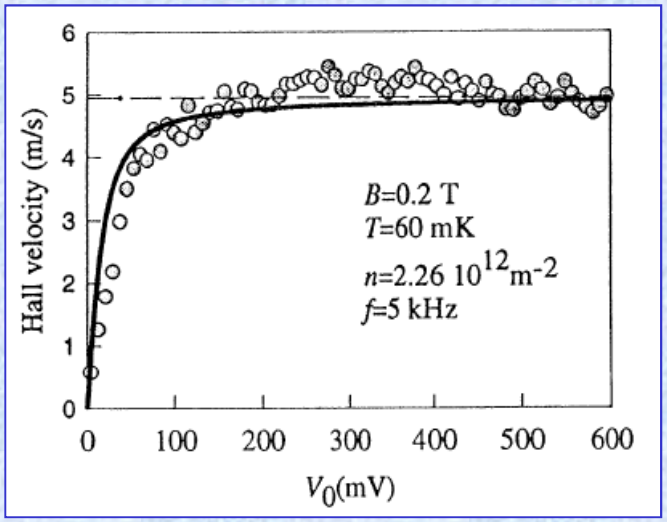
Capacitively coupled current

Radial electric field

Aximuthal Hall Velocity

$v_H = E_x/B$

$$\sigma_{xx}(B) = \frac{J_x}{E_x} = \frac{J_x}{v_H B} = \frac{KfV_0}{v_H B}$$



"Simple-minded model"

No fitting parameters

Polycrystalline domains?

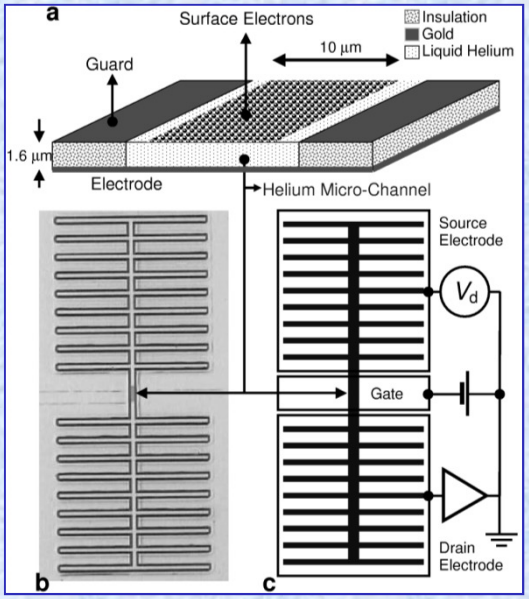
M.I.Dykman and Y.G.Rubo PRL **78**, 4813 (1997)

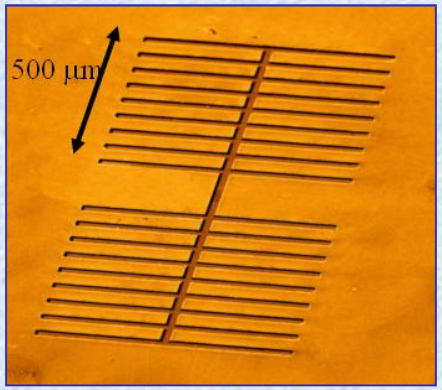
Restricted geometries

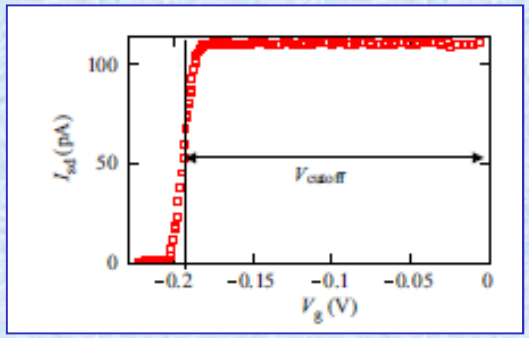
Helium microchannels

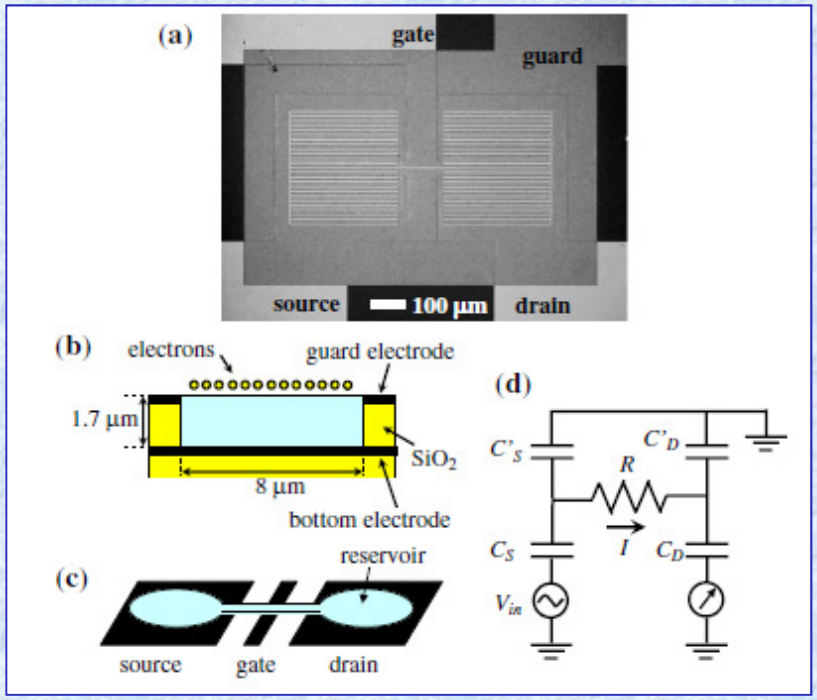
Microchannels filled by capillary action can be used for experiments on small numbers of surface-state electrons:

Ikegami et al, PRL 102, 046807 (2009); PR B 82, 201104 (2010)







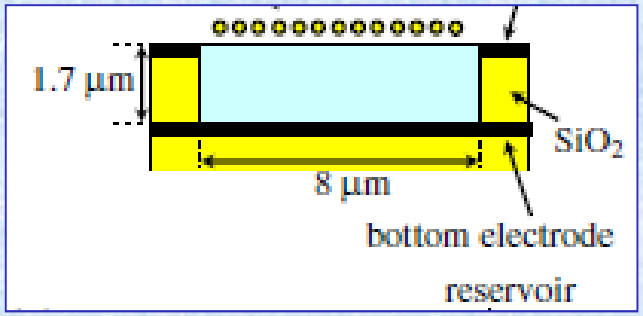


Glasson et al, PRL 87, 176802 (2001)

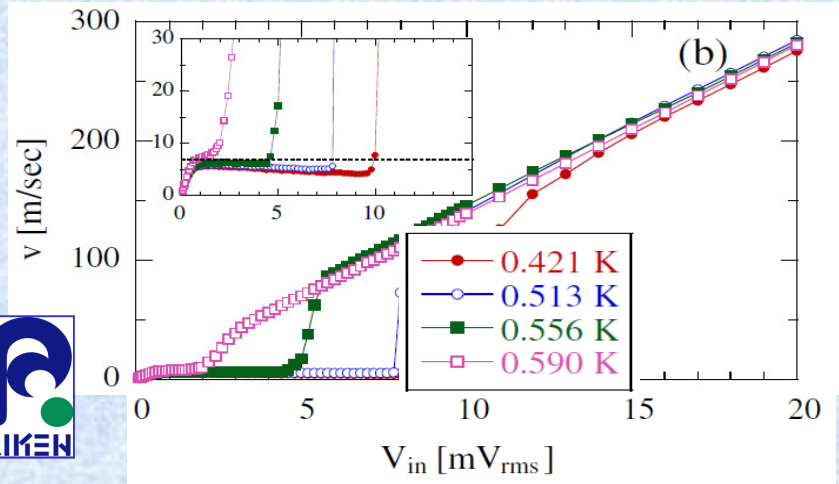
[History: D. Marty (1986)]

Wigner solid transport

A 'Wigner wire':
across the channel



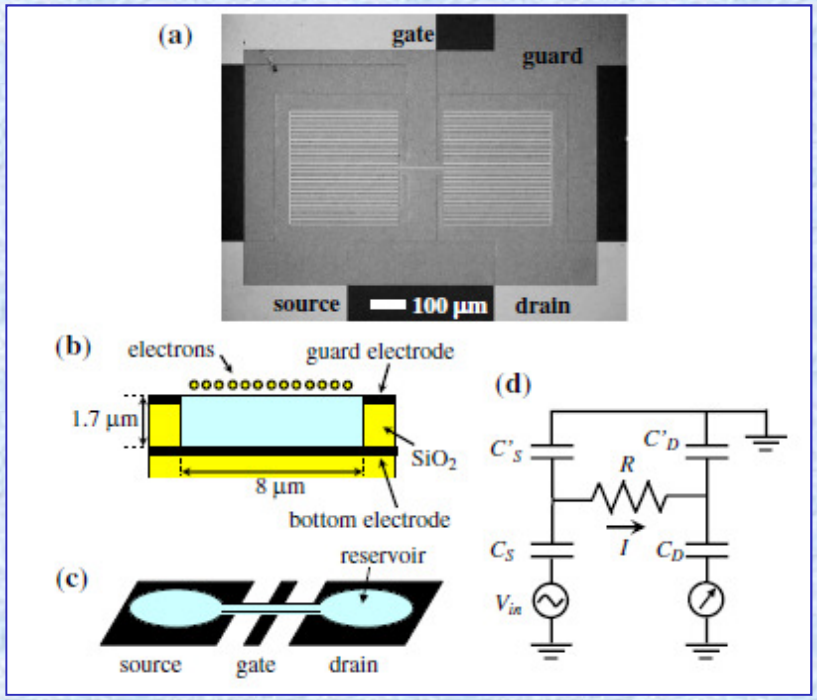
$v_r = 6.9\ \mathrm{m/s}$

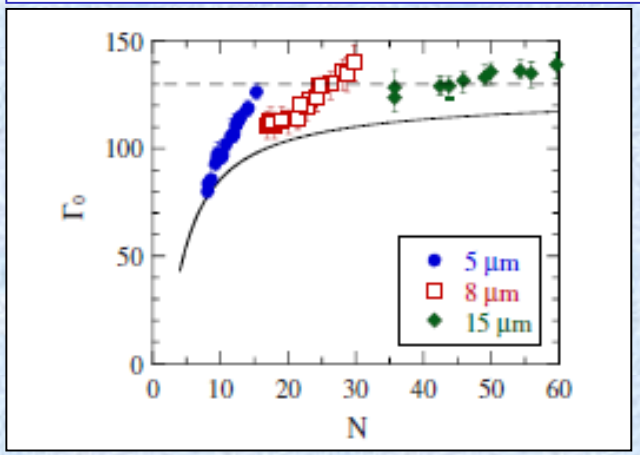


Quasi 1D: $\Gamma_0 < 130$
Dislocations?

Helium microchannels

Ikegami et al, PRL 102, 046807 (2009);
PR B 82, 201104 (2010)





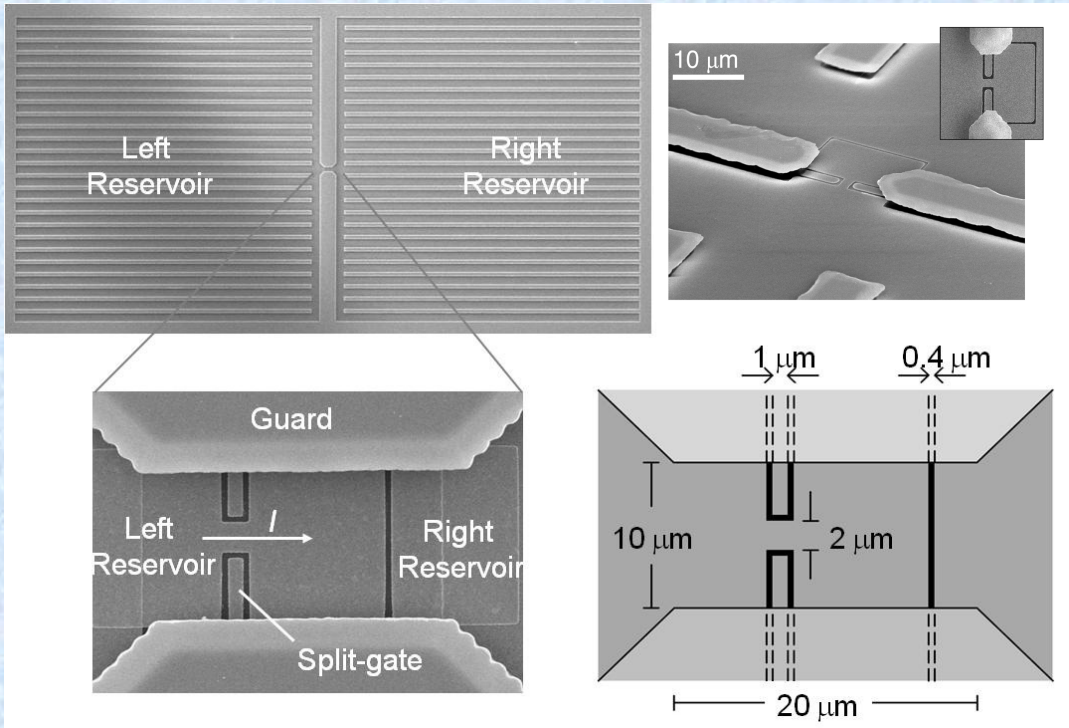
Current work at RIKEN - split-gate device

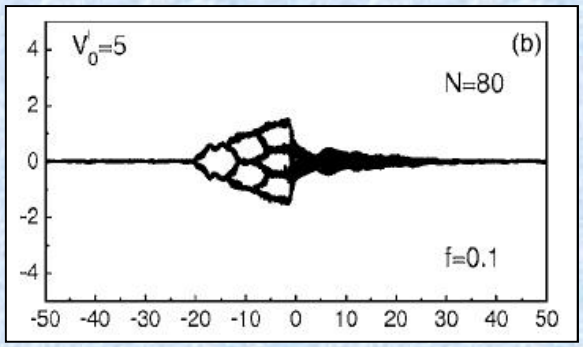
Point-Contact Transport Properties of Strongly Correlated Electrons on Liquid Helium

David Rees et al, PRL **106**, 026803 (2011)

A classical analogue to the quantum point contact . . .

Physics Focus: ***Electrons Take Turns Like Pedestrians***
Kimitoshi Kono





Piacente & Peeters PRB **72**, 205208 (2005)

QC "bombshell" in 1999

Experimental objective - qubits

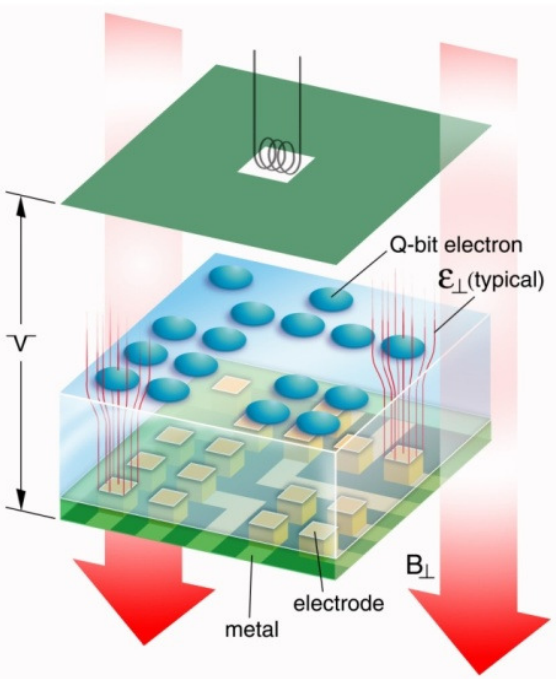
SCIENCE VOL 284 18 JUNE 1999

Quantum Computing with Electrons Floating on Liquid Helium

P. M. Platzman[1]* and M. I. Dykman[2]

A quasi–two-dimensional set of electrons ($1 < N < 10^9$) in vacuum, trapped in one-dimensional hydrogenic levels above a micrometer-thick film of liquid helium, is proposed as an easily manipulated strongly interacting set of quantum bits. Individual electrons are laterally confined by micrometer-sized metal pads below the helium. Information is stored in the lowest hydrogenic levels. With electric fields, at temperatures of 10^{-2} kelvin, changes in the wave function can be made in nanoseconds. Wave function coherence times are 0.1 millisecond. The wave function is read out with an inverted dc voltage, which releases excited electrons from the surface.

16 bit quantum computer based on electrons on liquid helium



Requires:
Quantum States
Quantum Dots
Electron Manipulation

(Lian-Fu Wei, Steve Lyon, David Schuster)

SCIENCE VOL 284 18 JUNE 1999

Quantum Computing with Electrons Floating on Liquid Helium

P. M. Platzman[1]* and M. I. Dykman[2]

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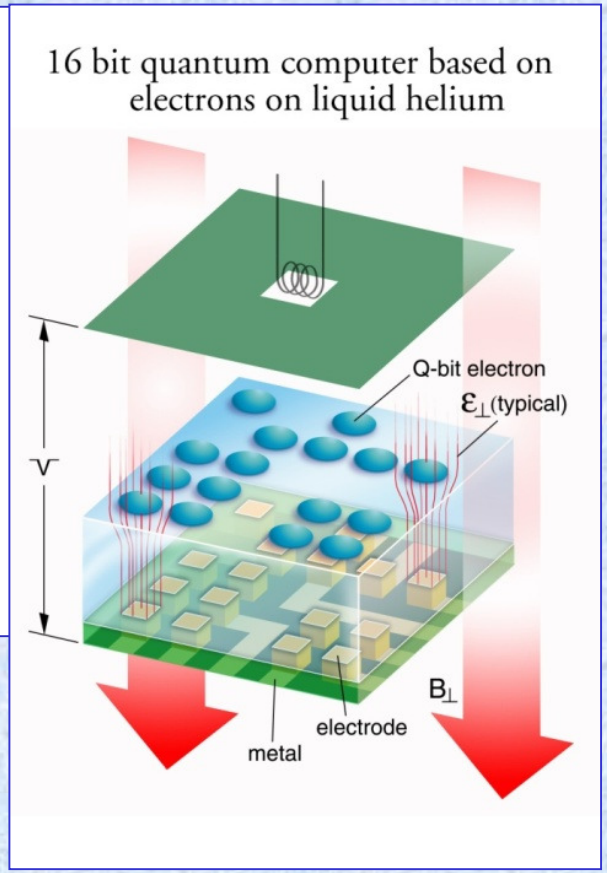
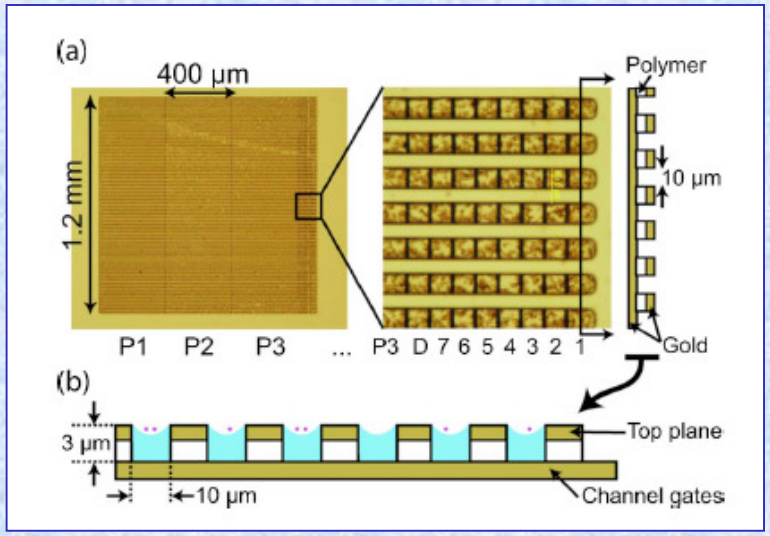
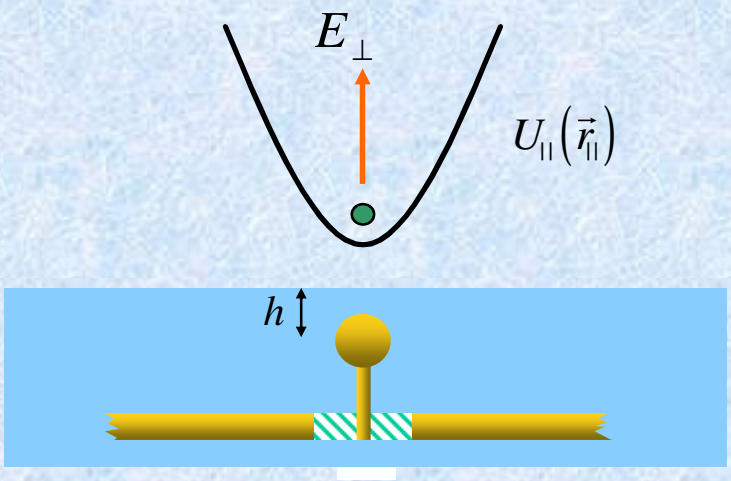


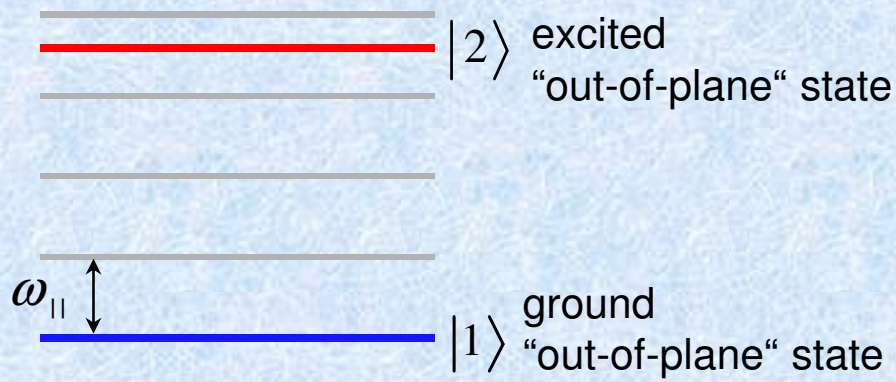


G. Sabouret *et al*, APL, (2008)

Qubits with electrons on helium?

Qubits are made by confining electrons with electrodes into quantum dots





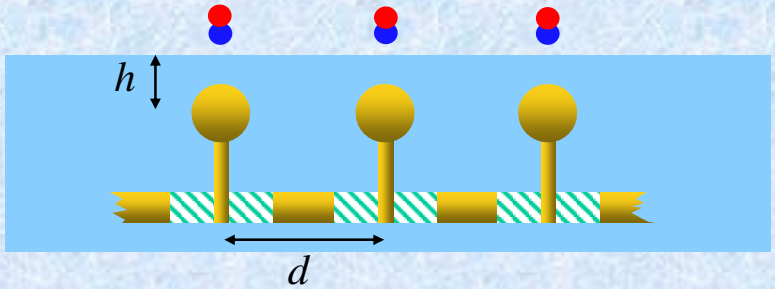
level spacing $E_2 - E_1$ is **tuned** by the electrode field via Stark effect

$$\delta(E_2 - E_1) \sim 1\,\text{GHz} \text{ for } \delta V_{el} \sim 0.3\,\text{mV}$$

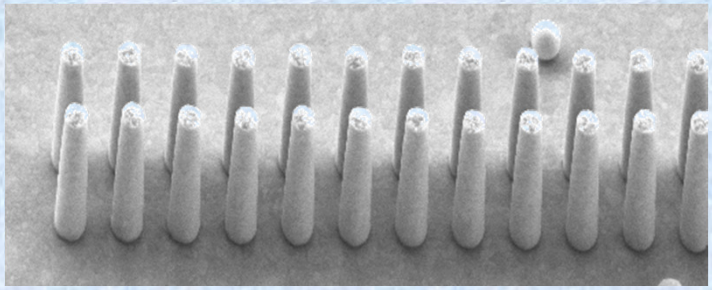
$$h \sim 0.5\,\mu\text{m}$$

$$\omega_{||} = 20\,\text{GHz} \text{ for } V_{el} \sim 10\,\text{meV}$$

Experimental objective - scalable many-qubit system?



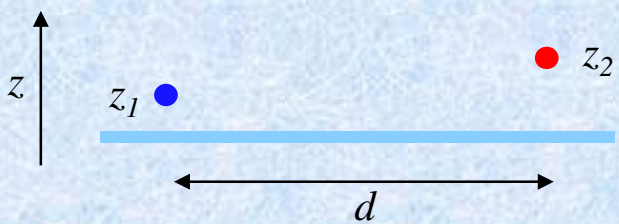
$$h \approx 0.5\,\mu\text{m},\ \ d \approx 1\,\mu\text{m}$$



Goodkind & Pilla, Quant. Inf. Comp. (2001)

Speed of a single-qubit gate: ~1 GHz for the microwave field *E* =1 V/cm

Dipolar near-neighbors interaction : V_{ee}



Typical qubit parameters

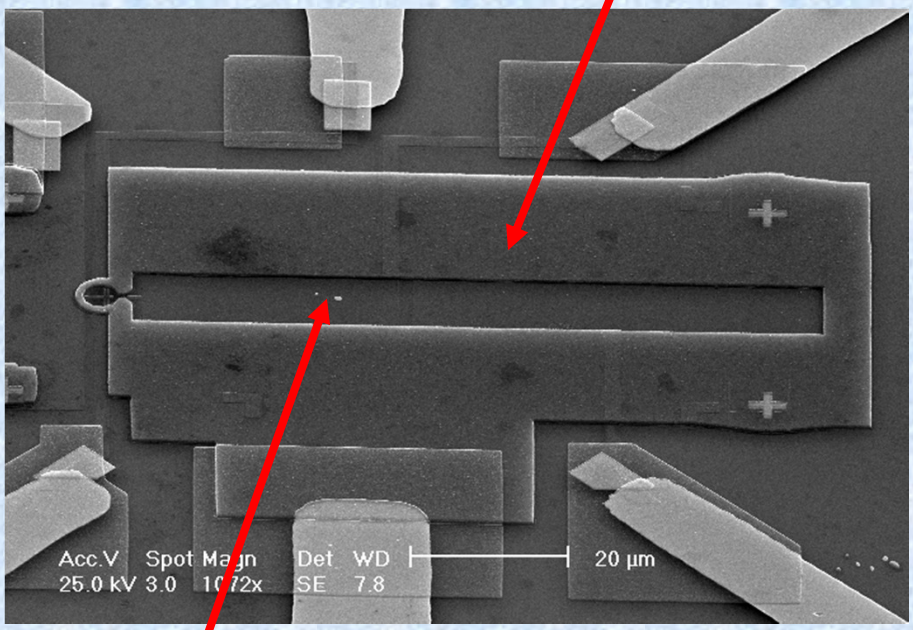
$$E_2 - E_1 \approx 1.6\times10^{11}\,\text{Hz},\ \ V_{ee} \geq 10^{8}\,\text{Hz}$$

speed of two-qubit gates

Classical dots

SET detector

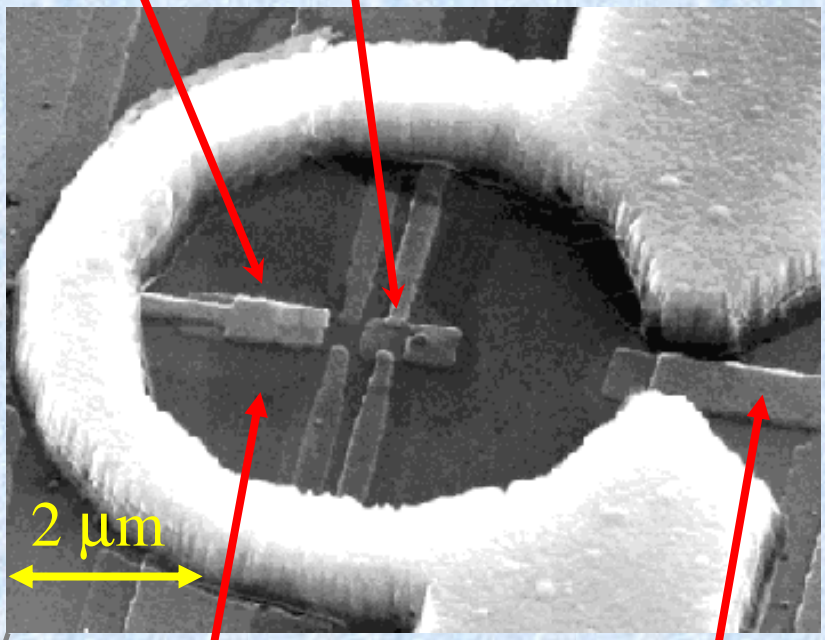
Guard



Reservoir

Gate

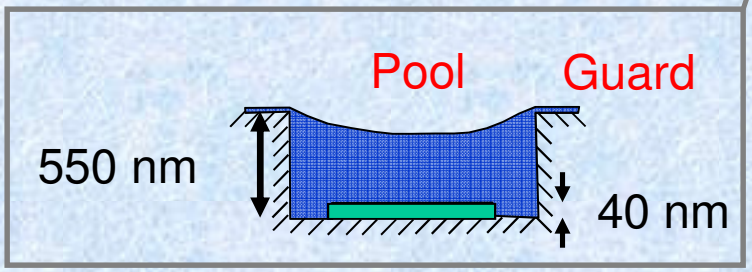
SET



Helium Pool

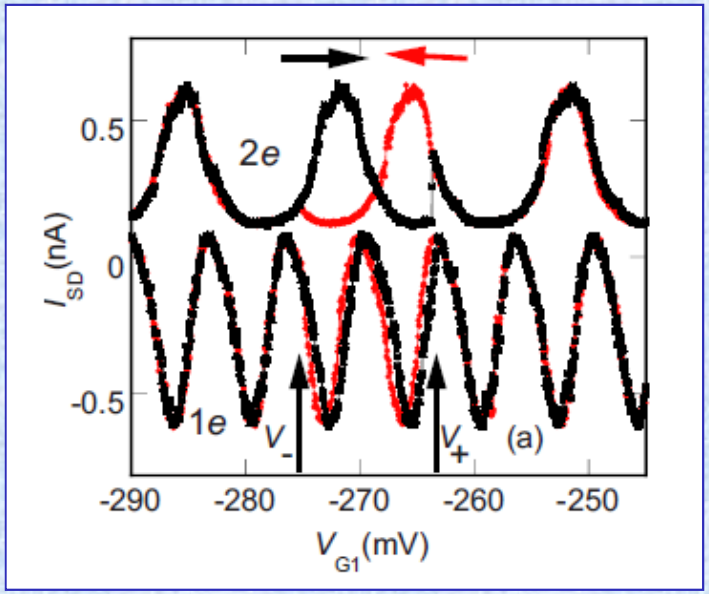
0.7 µm deep

Injector



Royal Holloway University of London

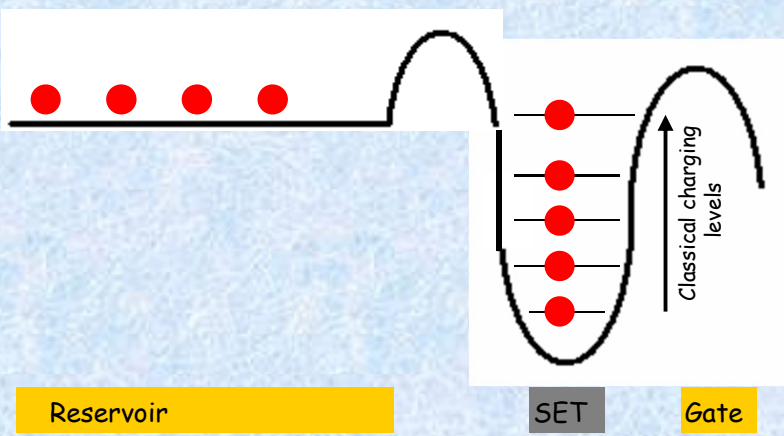
Single electronics on liquid helium

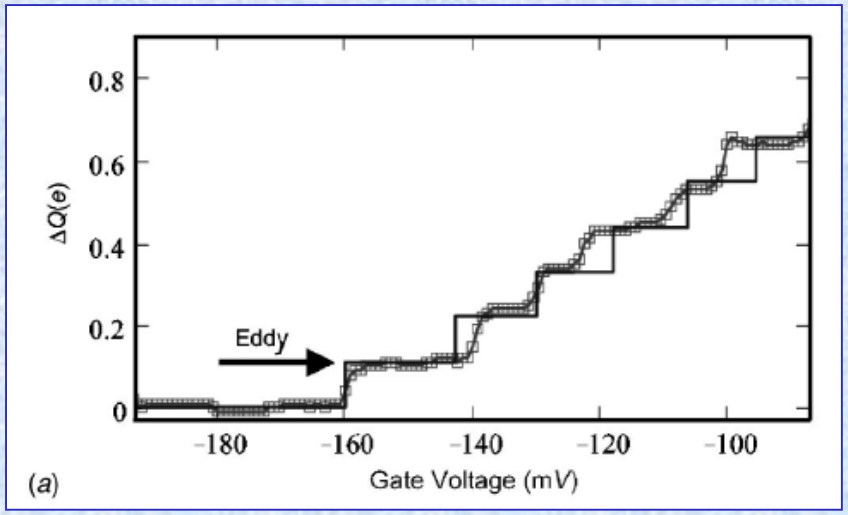


Coulomb Blockade Oscillations
Single Electron Transistor

SCPT – periodicity 2*e*

SET – periodicity 1*e*



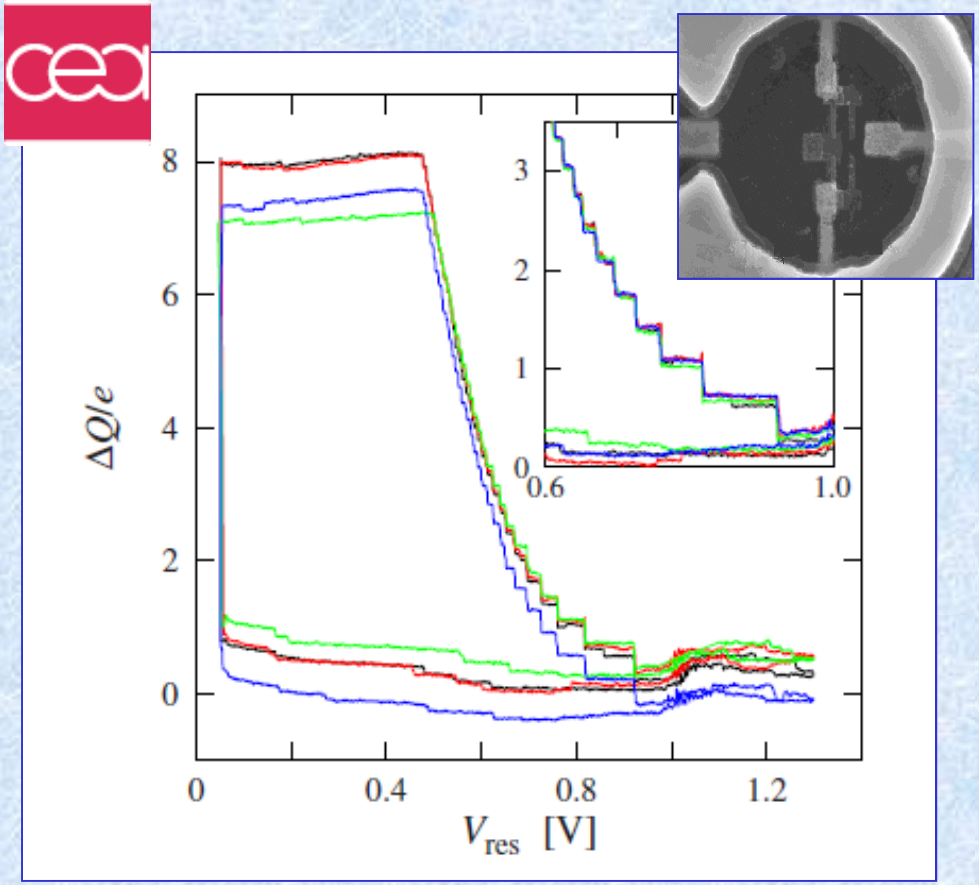


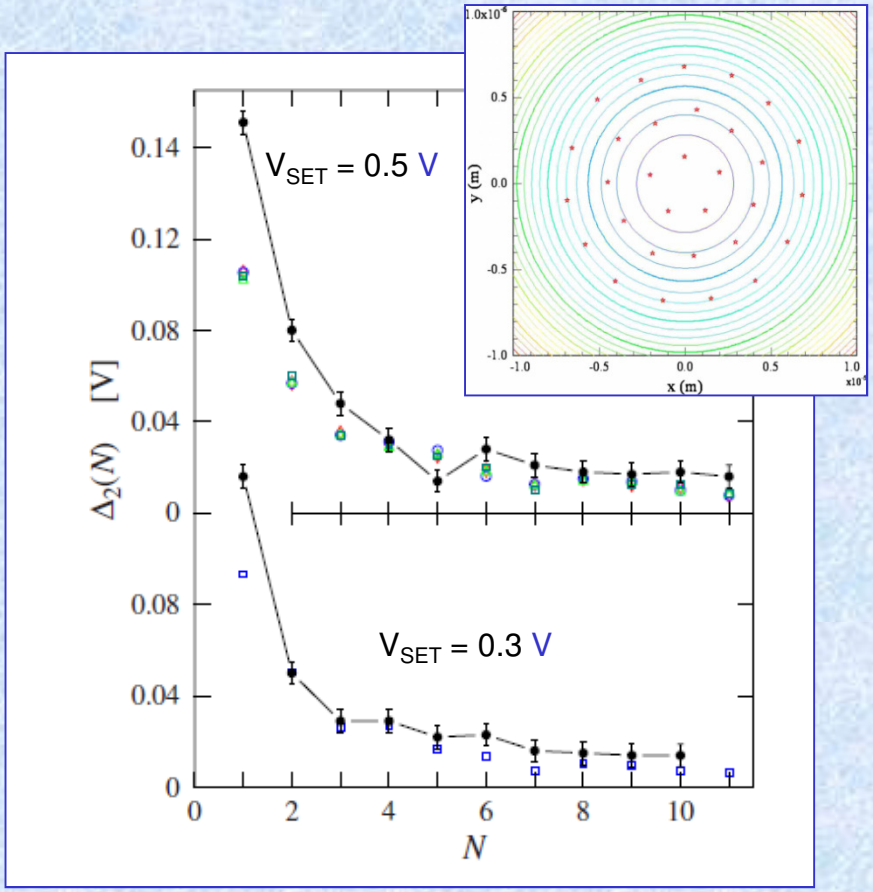
Papageorgiou et al, APL, **86**, 153106 (2005)
Simkins et al, J.Appl.Phys. **106**, 124502 (2009)

Classical dot

Experiment at Saclay
Excellent reproducibility ("My Precious")

Allows the investigation of the *classical* addition spectrum…



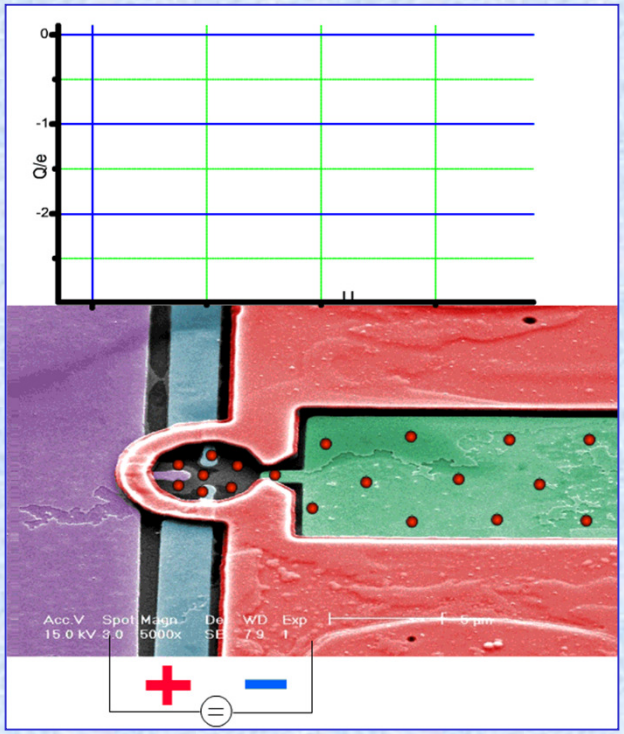


E. Rousseau *et al.* Phys.Rev.B **79**, 045406 (2009)

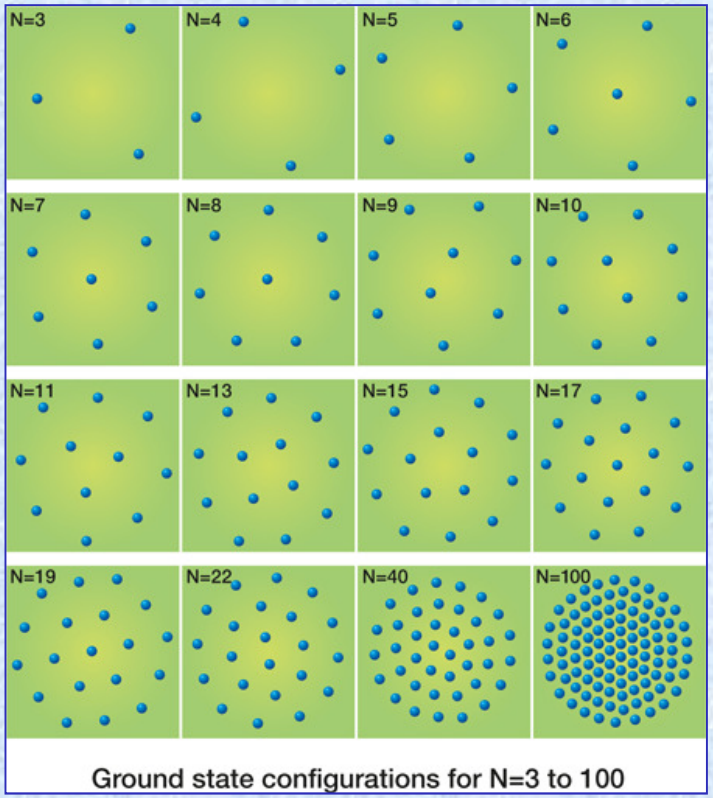
Monte Carlo Simulations

Single electronics

Electron dots



Yury Mukharsky, CEA, Saclay, France
E. Rousseau *et al.* PRB **79**, 045406 (2009)



Viewpoint: Electron crystallites floating on superfluid helium
François Peeters
V. M. Bedanov and F. M. Peeters, **PRB 49, 2667 (1994)**

Clocking Electrons on an array of pixels

Princeton

Electron transfer (clocking) along a charge-coupled-array (CCD)-like array of gates.

Previously . . .

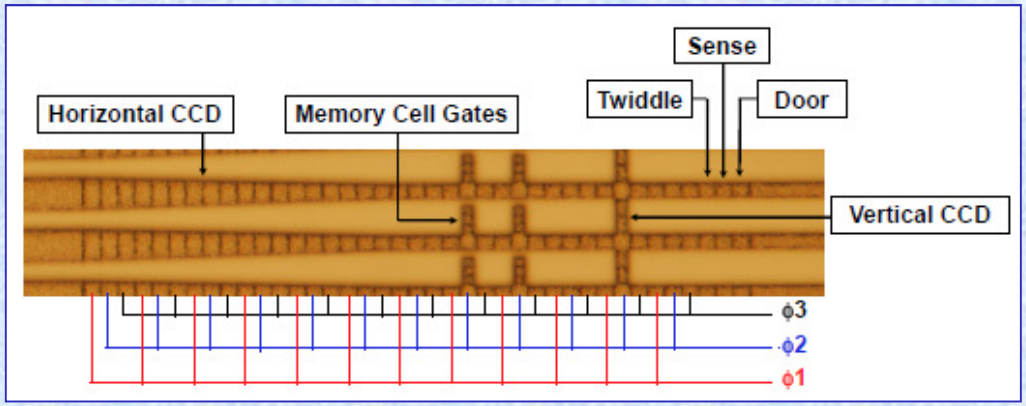
- 60 parallel channels
- CTE = 0.999 999 92

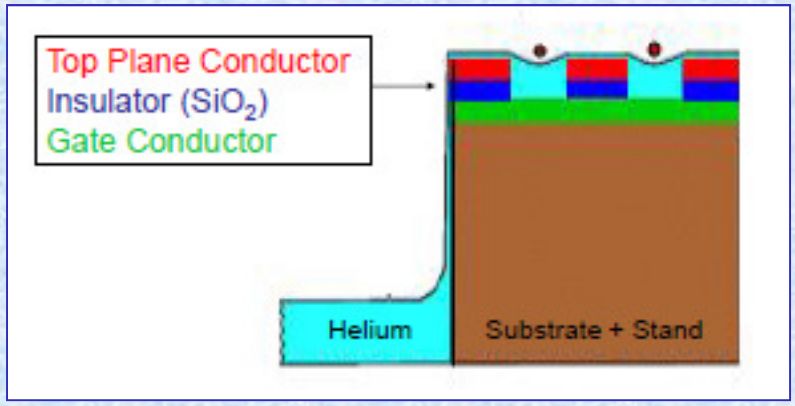
G. Sabouret *et al*, APL **92**, 082104 (2008)

(Extremely) Efficient Clocked Electron Transfer on Superfluid Helium

(It works perfectly!) F.R.Bradbury *et al.* PRL **107**, 266803 (2011)

- Clocking on a 2D array of pixels
- 120 channels
- Efficiency of **99.99999999%**
- Down to one electron per pixel





Physics Viewpoint by Kimitoshi Kono:

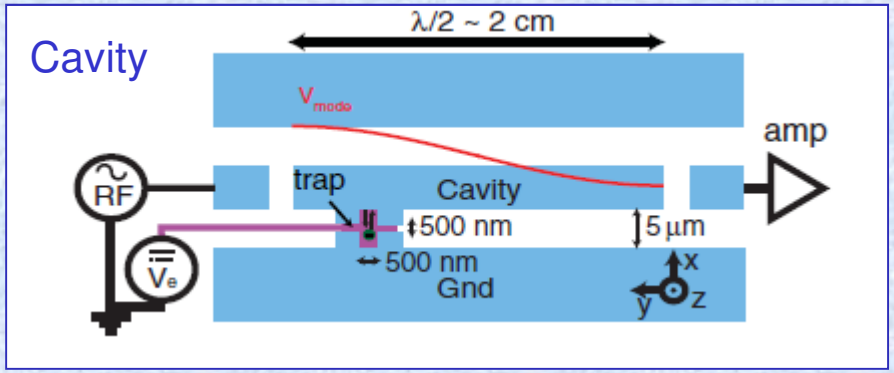
Electrons take their places on a liquid helium grid

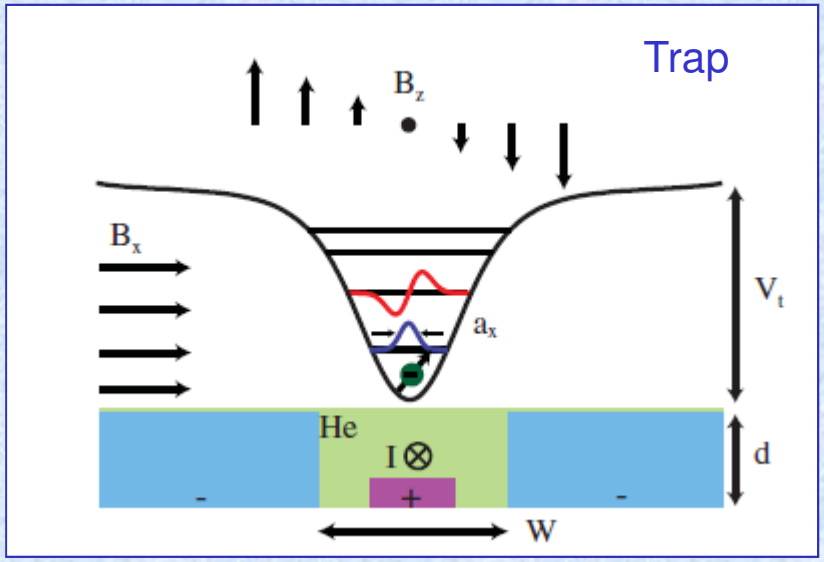
Hybrid Quantum Information Processing with Electrons on Helium

Proposal for Manipulating and Detecting Spin and Orbital States of Trapped Electrons on Helium Using Cavity Quantum Electrodynamics

D. I. Schuster,[1] A. Fragner,[1] M. I. Dykman,[2] S. A. Lyon,[3] and R. J. Schoelkopf[1]

PRL **105**, 040503 (2010)





Single electron trap – quantised lateral motion
Resonate with microwave cavity ≈ 5 GHz
Magnetic field B_x gives spin quantisation
Inhomogeneous B_z gives spin-orbit coupling
Manipulation and readout via RF input
Electron-electron coupling via single cavity photons

Cavity to charge coupling 10 ns; spin coupling 1 µs

David Schuster,
Andreas Fragner,
Ge Yang

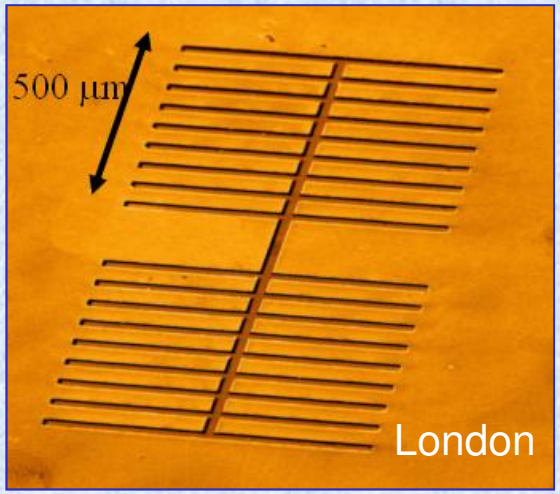
Progress: APS March Meeting 2012

Conclusions

- Electrons on helium - “ideal” 2D conductor
  Correlated Coulomb liquid - Magnetoconductivity
  Classical Wigner solid - Dynamic pinning
- Quantum states
  Rydberg states - Landau levels - non-linear optics - zero conductance states
- Microchannel devices offer precise control over small dimensions
  Used to study Novel mesoscopic phenomena
- Wigner wires
  Non-linear transport
  2D melting in confined geometries
  Transport through a constriction
- SET detectors - ultra-sensitive charge detectors
  Single electronics - ‘Classical dot’ addition spectra
- Electron Transport and Manipulation - clocking of electrons in arrays
- Cavity Quantum Electrodynamics
- Qubits may be possible…

Thank you

Electrons on Helium



Surface-state electrons

Rydberg states

Electron mobility

Many electron effects

Wigner crystal

Restricted geometries

Single electronics

Electron manipulation

Qubits?