New Quantum Phenomena in Electrons on Helium under Microwave Excitation

Denis Konstantinov
Quantum Dynamics Unit
OIST Graduate University

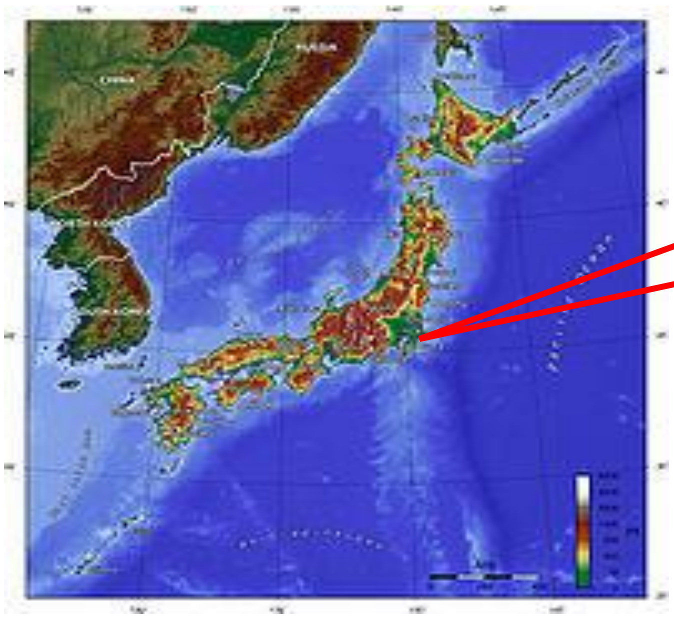
OIST

University Paris-Sud, March 18, 2015

My previous affiliation

RIKEN

理化学研究場　　RIKAGAKUKENKYUJYO - RIKEN



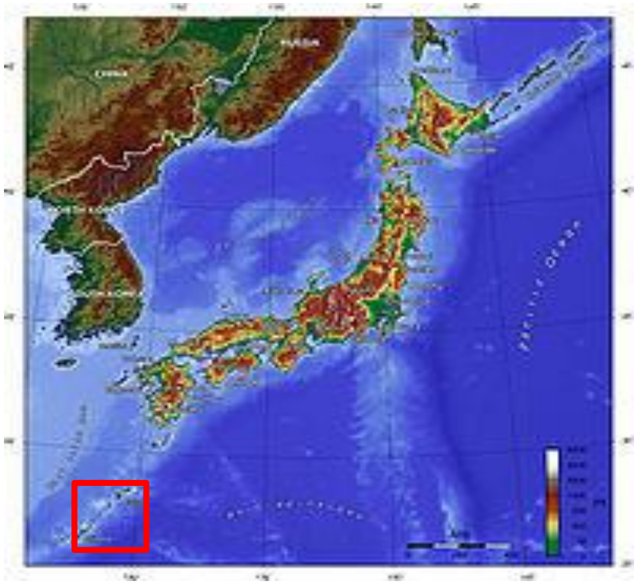
Wako campus

- Japan’s largest research institute
- Over 3,000 researches
- Largest campus - 15 min from downtown Tokyo

OIST

Present affiliation

Okinawa Institute of Science and Technology - OIST



- 45 Research Units in Neuroscience, Biology, Physics and Chemistry
- No divisions into departments
- 350 researches (approximately half are not Japanese)
- Graduate University since 2013

Collaborators

Experiment

Kimitoshi Kono, RIKEN

Hanako Isshiki, RIKEN

Hikota Akimoto, RIKEN

Alexei Chepelianskii, University Paris-Sud

Masa Watanabe, RIKEN

Theory

Yuriy Monarkha, ILTPE, Kharkov

Mark Dykman, Michigan State University

OIST

Talk Outline

- Electrons on helium versus 2DEG in semiconductors

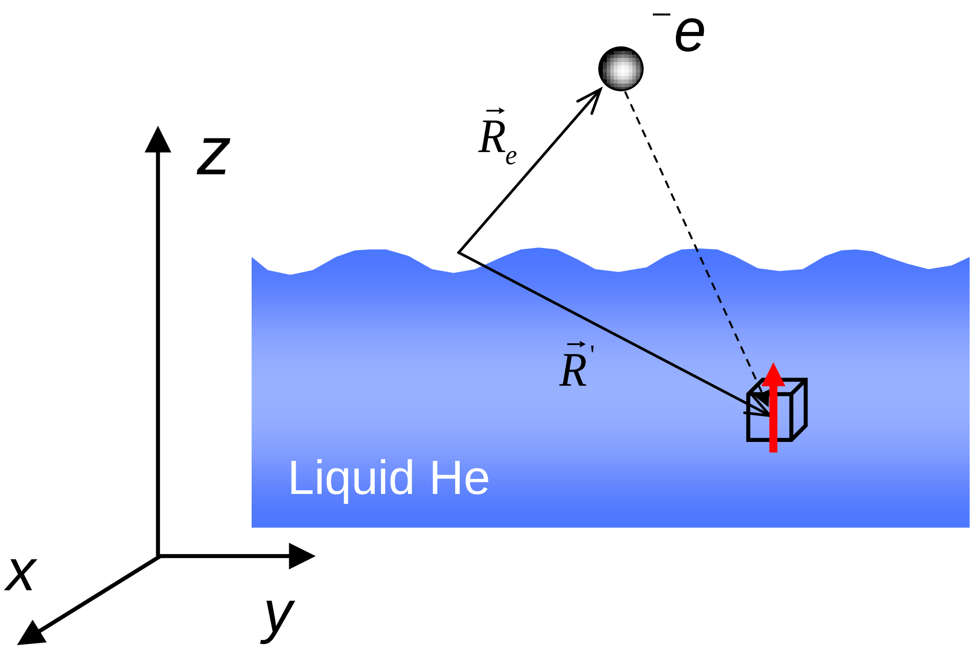
- Recent interests

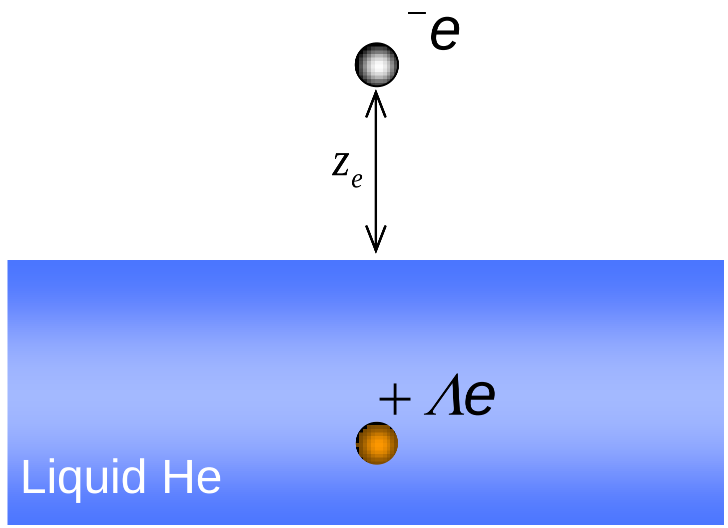
- Electrons under microwave excitation

- Microwave-induced Zero-Resistance States (ZRS)

- Future directions

Polarization attraction



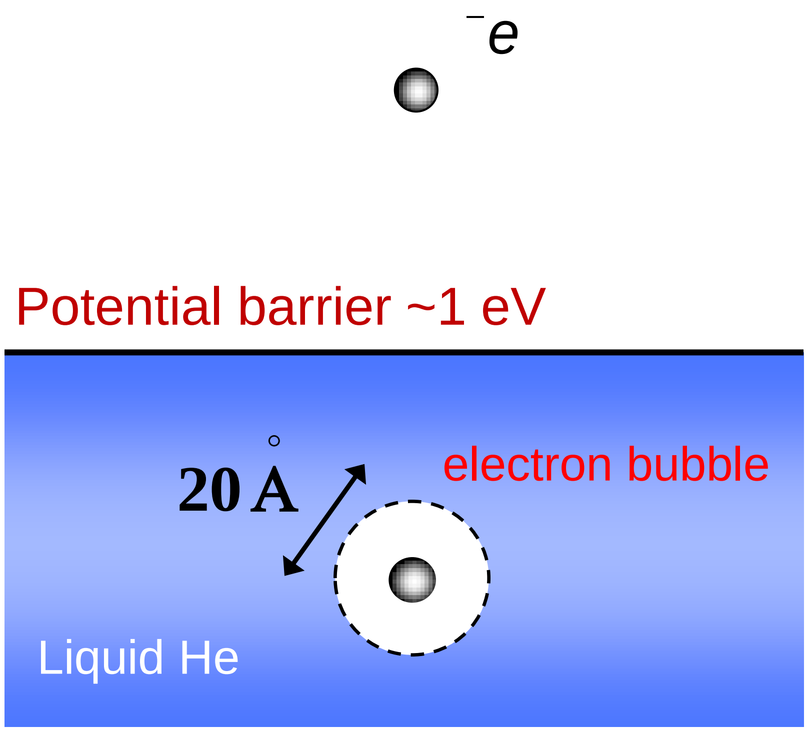


$$U_{pol}(\vec{R}_e) = -\frac{(\varepsilon-1)e^2}{4(\varepsilon+1)}\int d^3\vec{R}'\,\frac{1}{\left|\vec{R}'-\vec{R}_e\right|^4}$$

$$U_{pol}(z_e) = -\frac{\Lambda e^2}{z_e},$$

$$\Lambda = \frac{(\varepsilon-1)}{4(\varepsilon+1)} \approx 0.005$$

Surface barrier



The Pauli exclusion principle -

electron avoids He atoms

Sommer, 1964

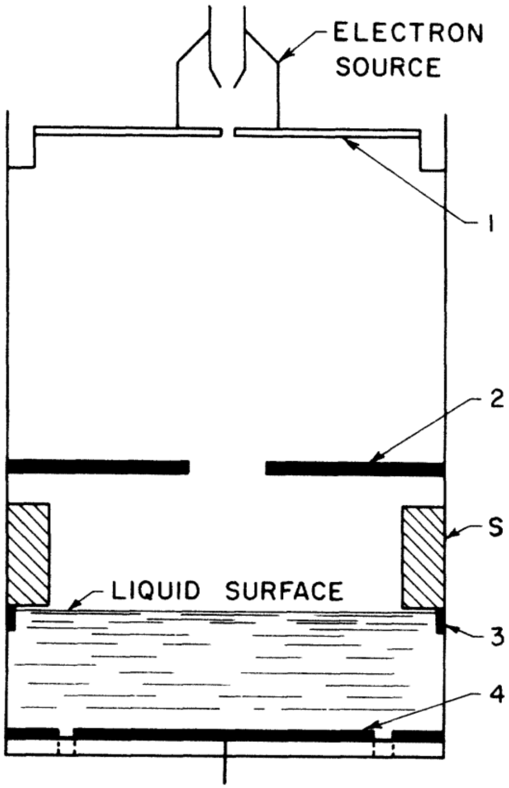
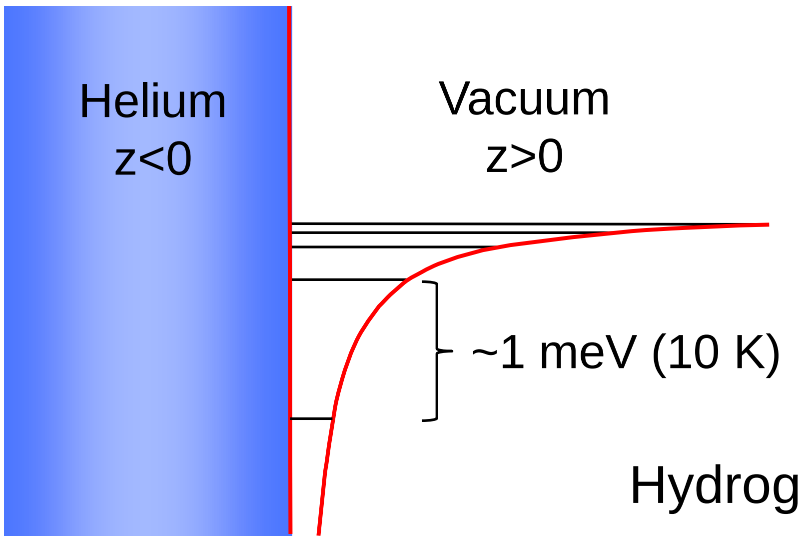


FIG. 1. The experimental chamber.

OIST

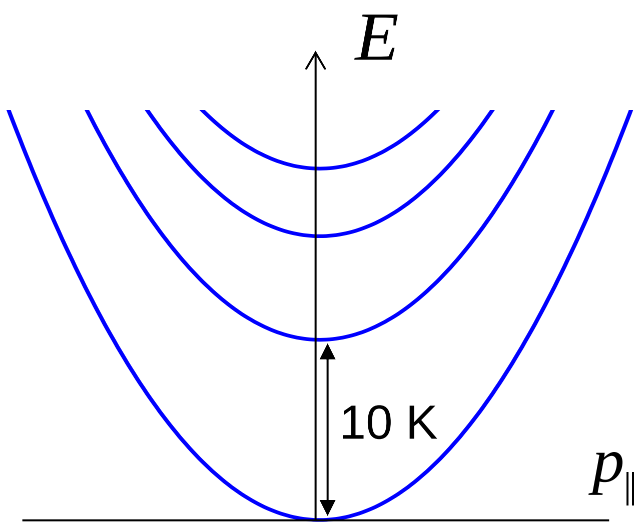
Surface-state electrons (SSE)



Equation of motion in *z*-direction:

$$\psi_n''(z) + \left(\frac{2mE_n}{\hbar^2} + \frac{\alpha}{z} \right) \psi_n(z) = 0$$

Hydrogen-like spectrum: $$E_n = -\frac{Ry}{n^2}$$

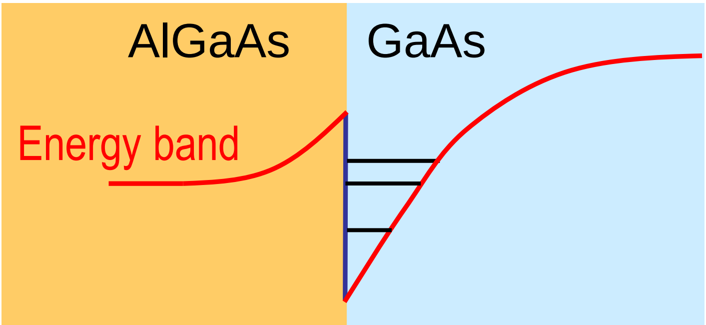


Total energy:

$$E = E_n + \underbrace{\frac{p_{\parallel}^2}{2m}}_{\text{2D motion}} \pm \overbrace{\mu_B B_{\parallel}}^{\text{due to spin}}$$

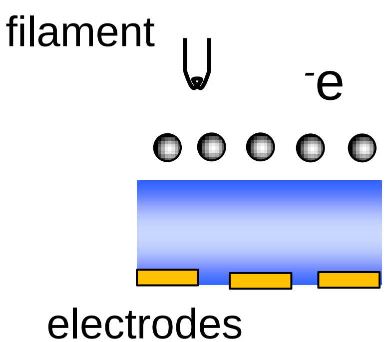
OIST

Comparison with traditional 2DES



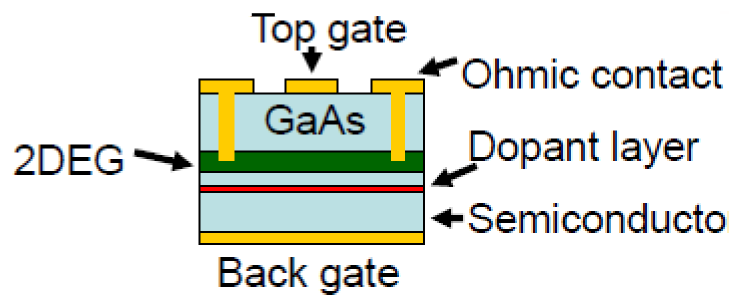
Complement to degenerate 2DEG in

Si MOSFETs and GaAs heterostructures



- Liquid/Superfluid interface
- Dielectric constant ε= 1
- Effective mass = 1.0 m_e
- g-factor = 2
- Electron density $n_s < 2x10^9$ cm^{-2}

Limited by surface instability!



- Crystalline interface
- Dielectric constant ε= 10
- Effective mass = 0.067 m_e
- g-factor = -0.44
- Electron density $n_s > 5x10^{10}$ cm^{-2}

Phase diagram

Relevant energies

$$r_p = \frac{V_C}{E_f} = \frac{e^2\sqrt{\pi n_s}}{4\pi\varepsilon\varepsilon_0}\frac{m^*}{\hbar^2\pi n_s}$$

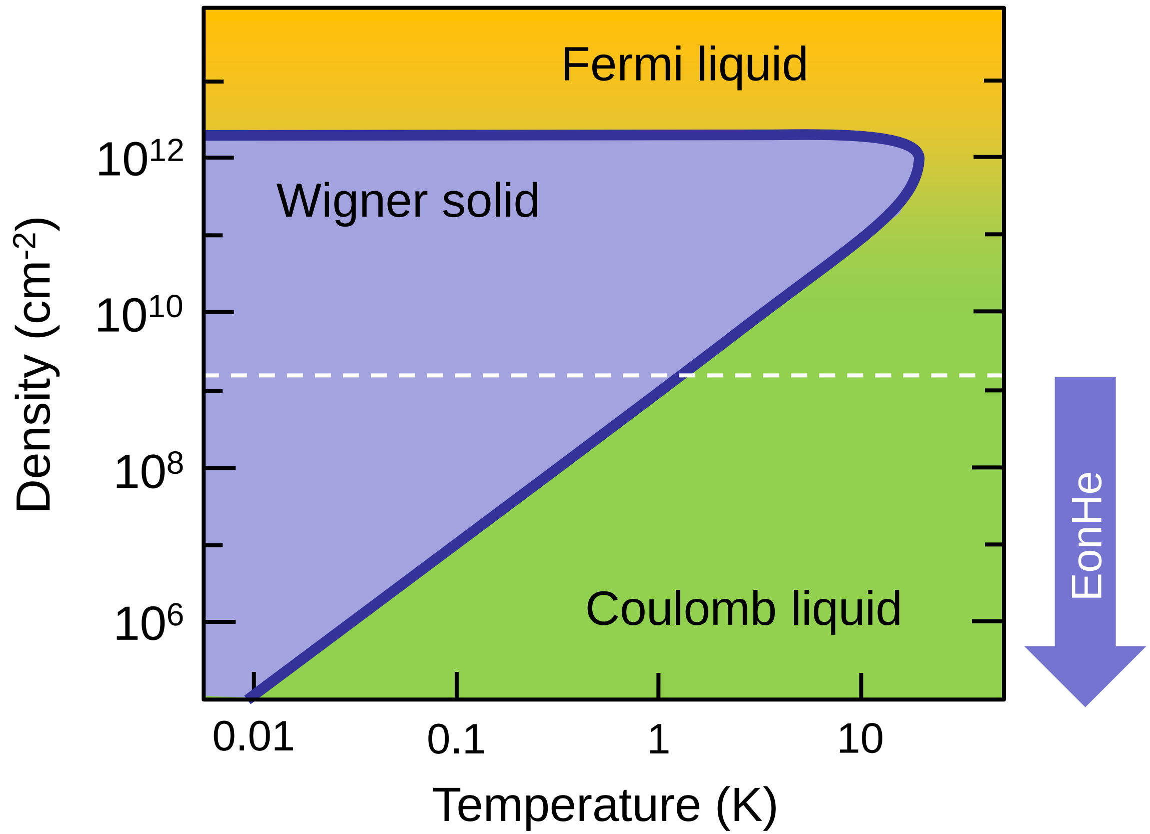
Quantum fluctuations

$$\Gamma_p = \frac{V_C}{E_{th}} = \frac{e^2\sqrt{\pi n_s}}{4\pi\varepsilon\varepsilon_0 k_B T}$$

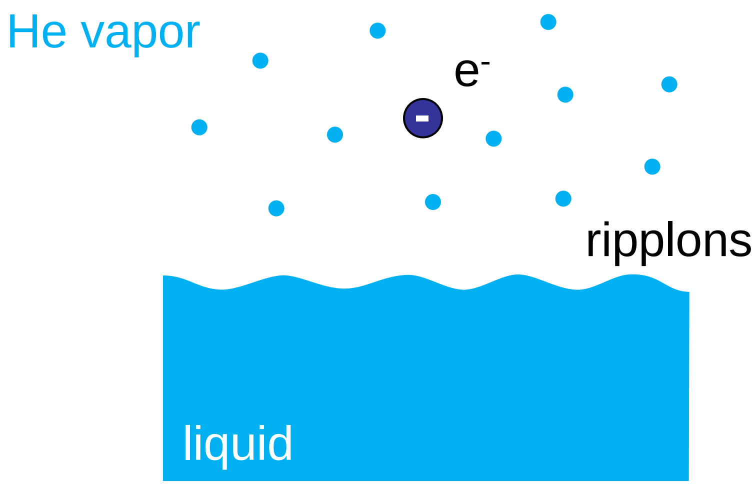
Thermal fluctuations

Typical electron densities

$n_s < 2\times10^9$ cm^{-2}



Scattering (elastic)



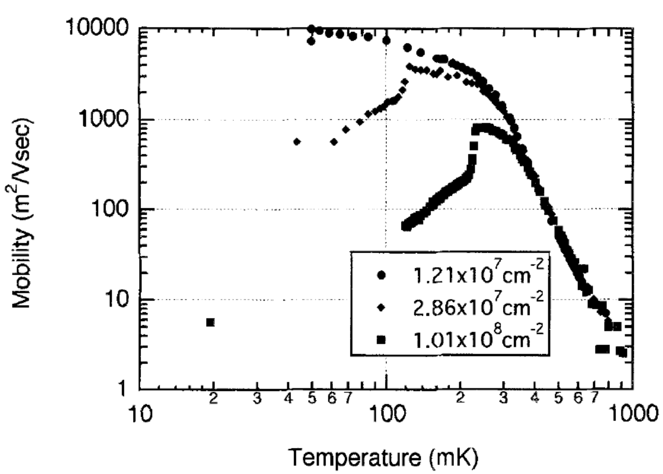
- Scattering at helium vapor atoms

$$N_{vapor} \propto T^{3/2} \exp\left(-\frac{Q}{T}\right)$$

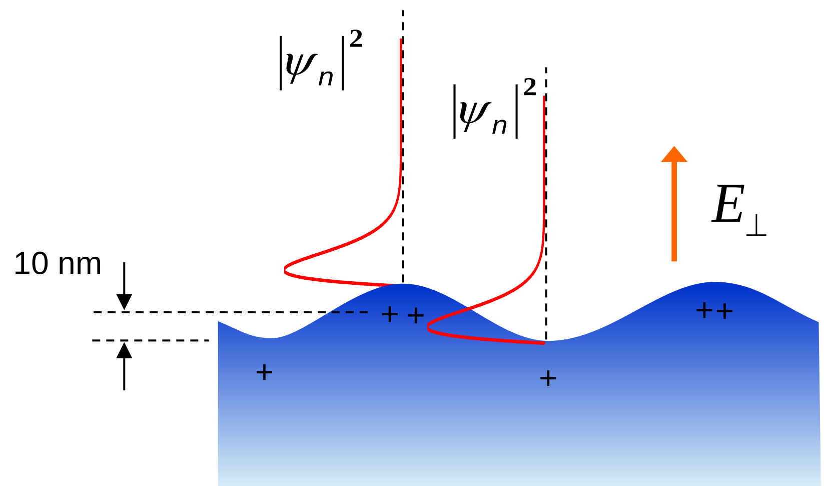
- Scattering at surface waves (ripplons)

$$N_q = \frac{1}{\exp\left(\frac{\hbar\omega_q}{k_B T}\right) - 1} \propto T$$

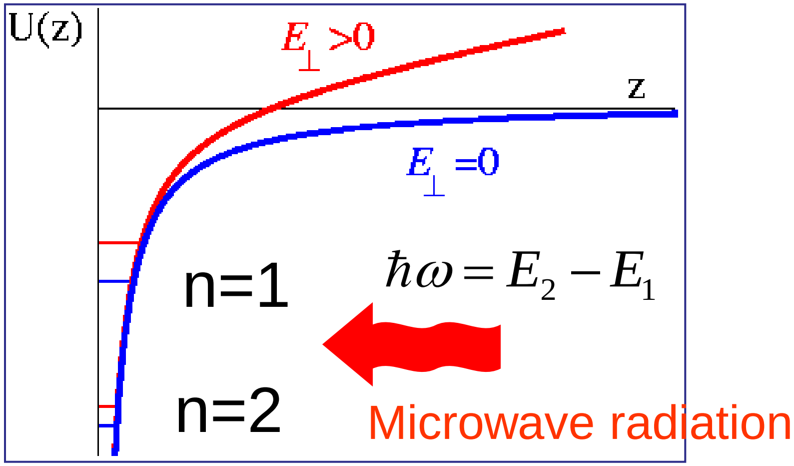
Highest mobility known!

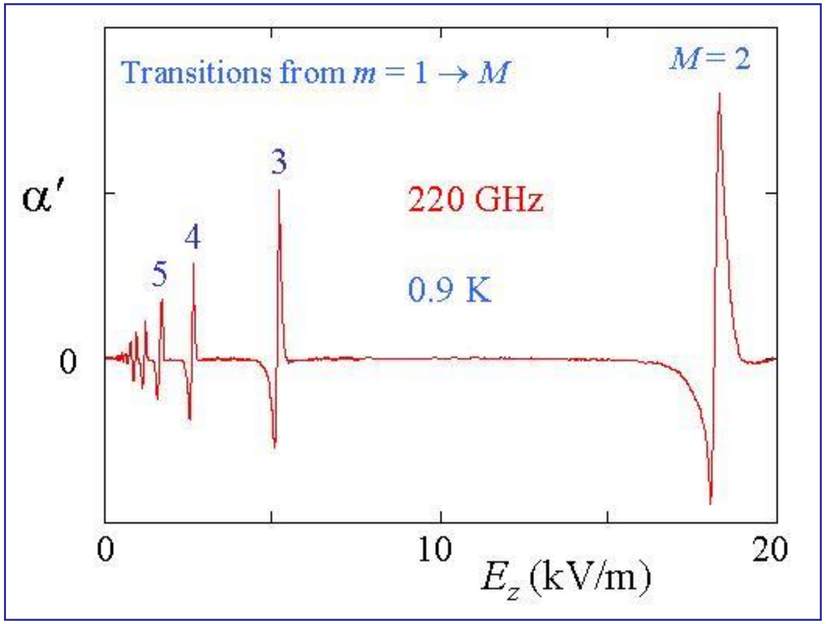


Shirahama et al. 1995



Past work





C.C.Grimes & Brown
PRL 32, 280 (1974)

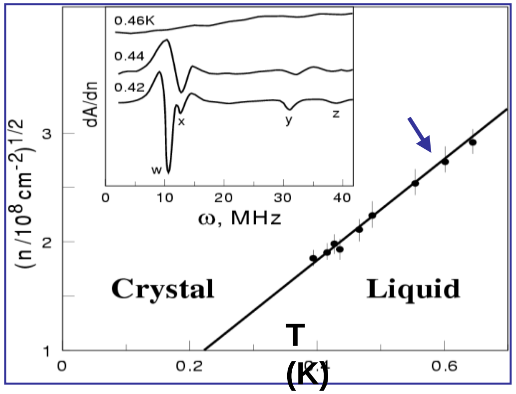
Interesting many-body physics

- Coupled plasmon-ripplon modes

  Grimes and Brown, Platzman

- Edge magneto-plasons

  Dahm, Williams, Glattli, Lea



Grimes & Adams,
PRL 42, 795 (1979)

Recent interest: proposal for qubits

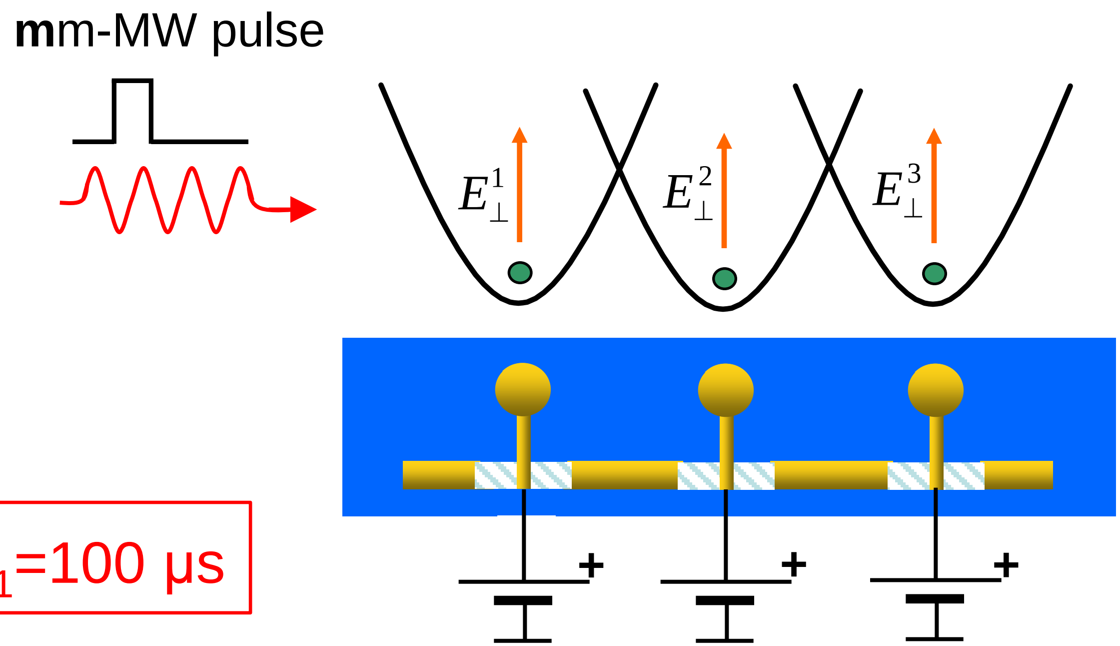
SCIENCE VOL 284 18 JUNE 1999

Quantum Computing with Electrons Floating on Liquid Helium

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

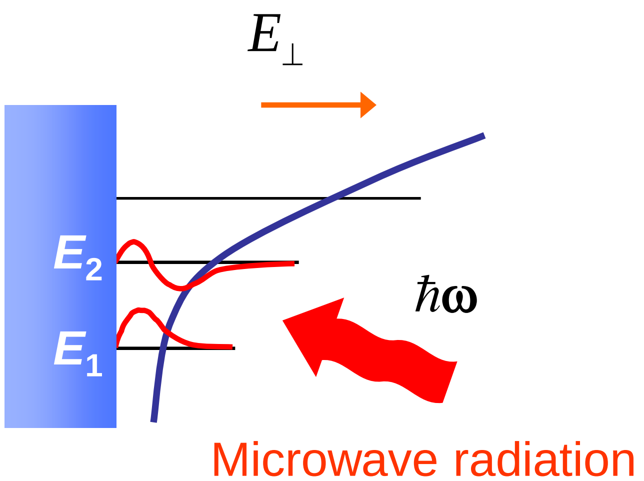
A quasi–two-dimensional set of electrons ($1 < N < 10^9$) in vacuum, trapped in one-dimensional hydrogenic levels above a micrometer-thick film of liquid helium, is proposed as an easily manipulated strongly interacting set of quantum bits. Individual electrons are laterally confined by micrometer-sized 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.

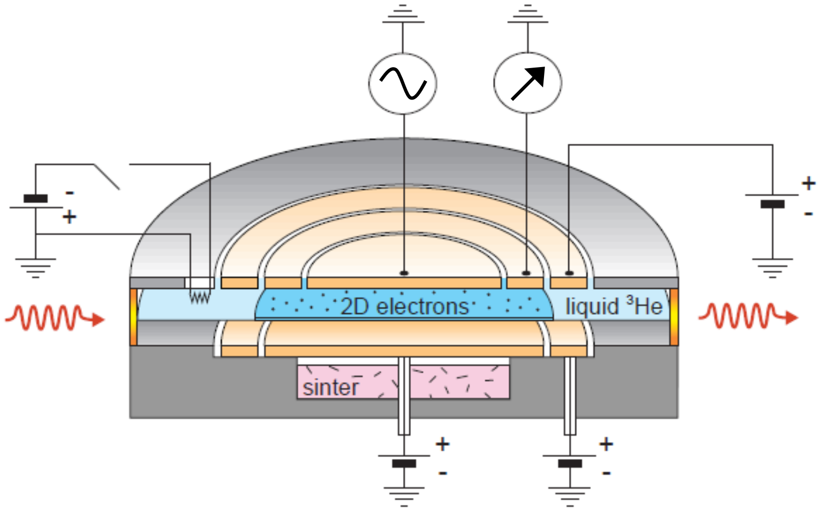
T_1=100 μs

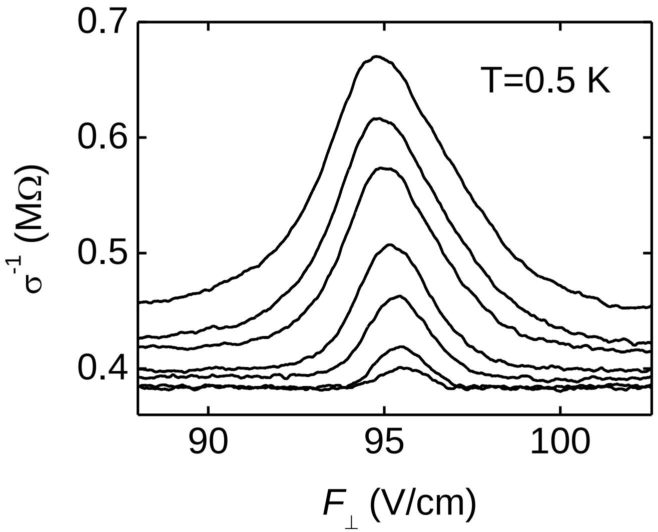


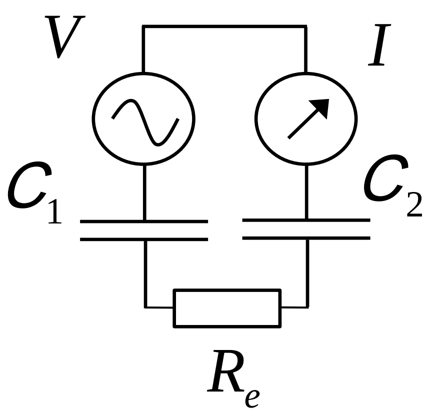
- Identification of well-defined qubits:
  I0> and I1> states of individual surface electrons
- Reliable state preparation:
  Below 1 K almost all qubits will be in the quantum ground state I0>
- Low decoherence
- Scalability!

Resistive Detection of resonance





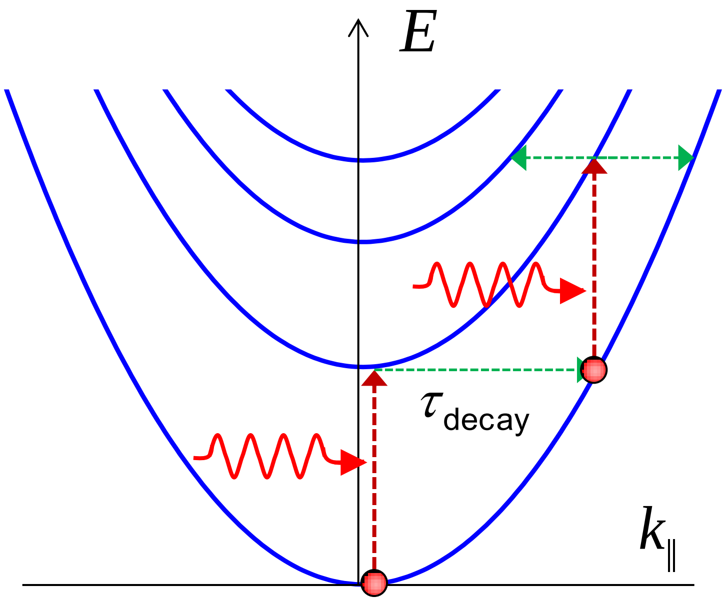


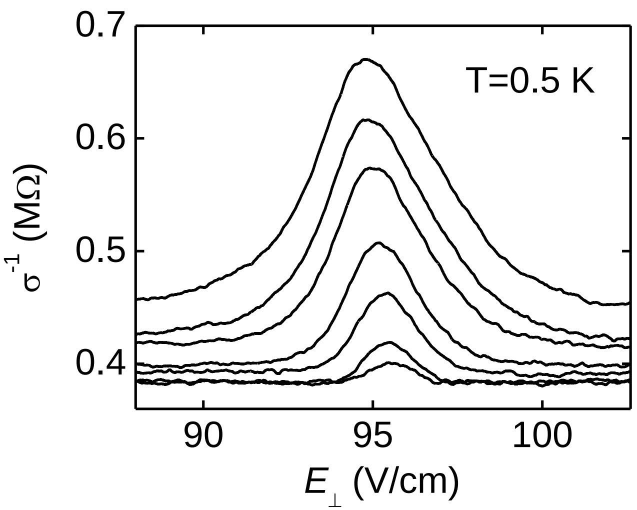


Sommer-Tanner method

DK et al. PRL 2007

Electron Heating





2D energy subbands

$$E = E_n + \frac{\hbar^2 k_\parallel^2}{2m}$$

Decay due to elastic scattering

$$\tau_{\text{decay}} \approx 10^{-9} - 10^{-8}\,\text{s}$$

Very fast thermalization $T_e >> T$

$$\tau_{\text{ee}} \sim \omega_p \approx 10^{-11}\,\text{s}$$

Cooling due to inelastic scattering

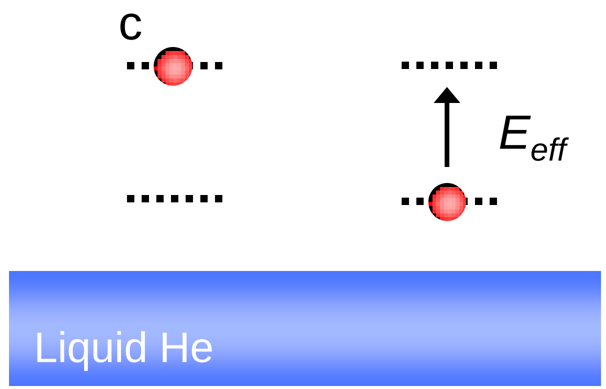
$$\tau_{\mathbf{E}} \approx 10^{-4} - 10^{-6}\,\mathbf{s}$$

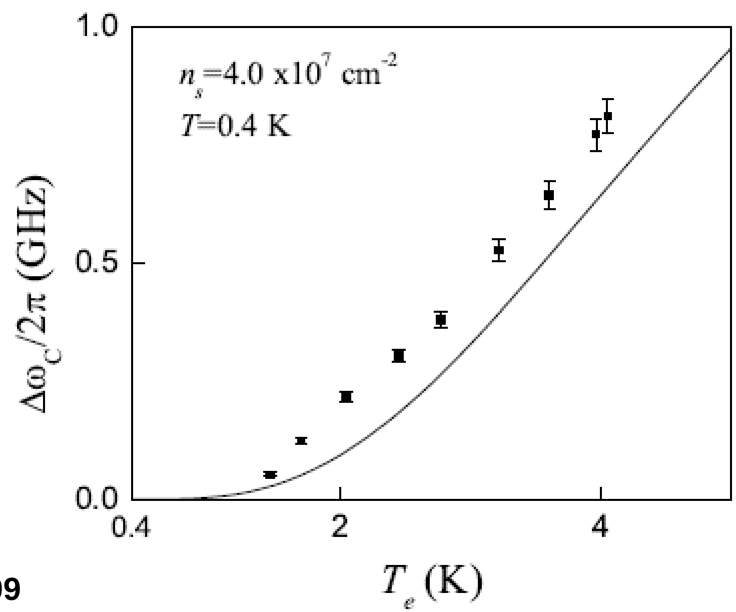
Optical bistability

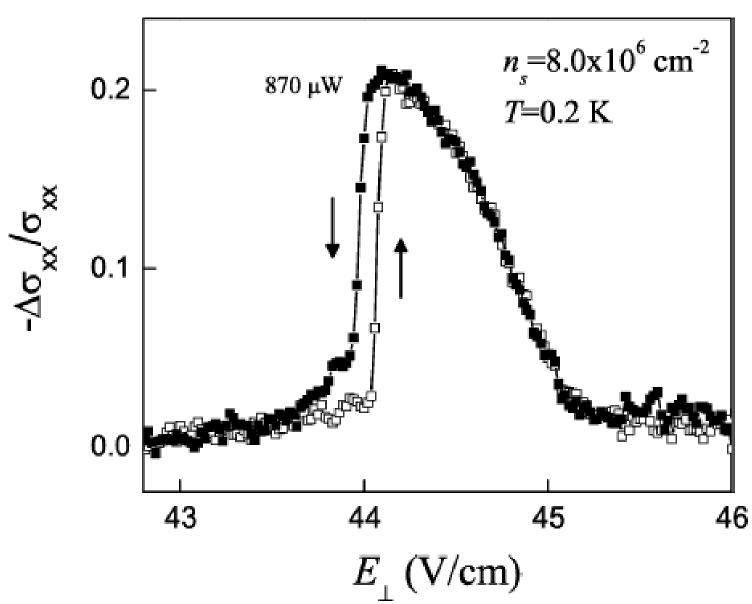
Estimate using mean-field approximation:

$$\Delta\omega_C = \frac{1}{\hbar}(z_{22}-z_{11})\times$$

$$\times\left[\sum_n \rho_n z_{nn} - z_{11}\right]\sum_{c\neq t}\frac{e^2}{\left|\vec{r}_t - \vec{r}_c\right|^3}$$

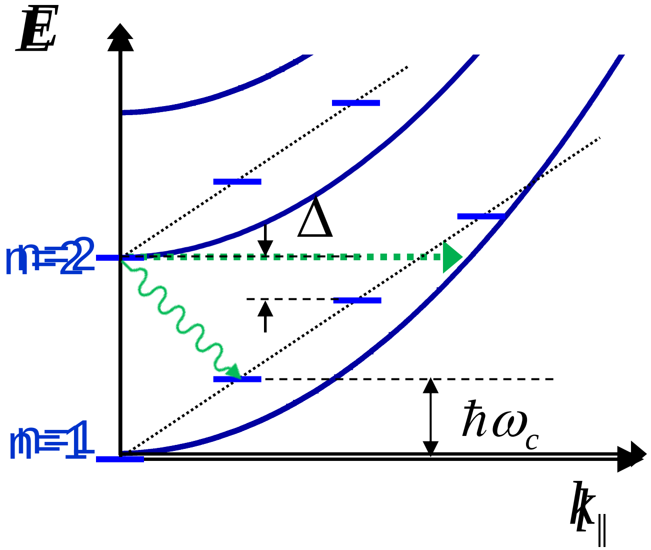






DK et al. PRL 2009

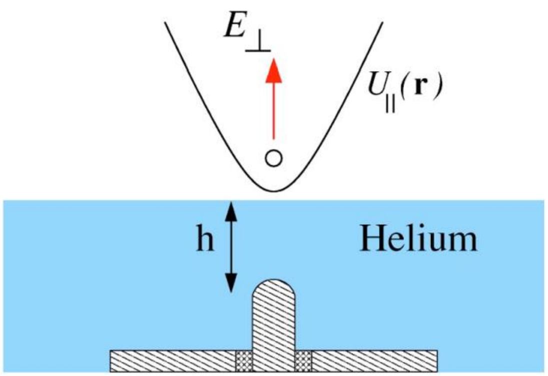
How to suppress heating?



PHYSICAL REVIEW B **67**, 155402 (2003)

Qubits with electrons on liquid helium

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

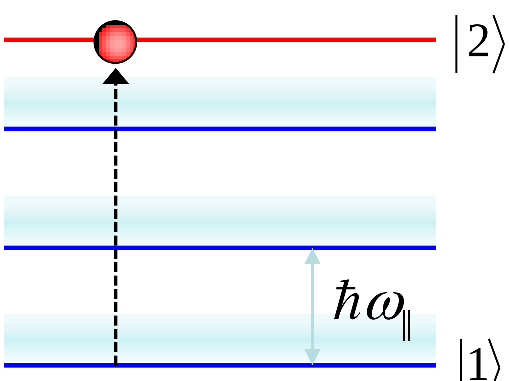


2D energy subbands

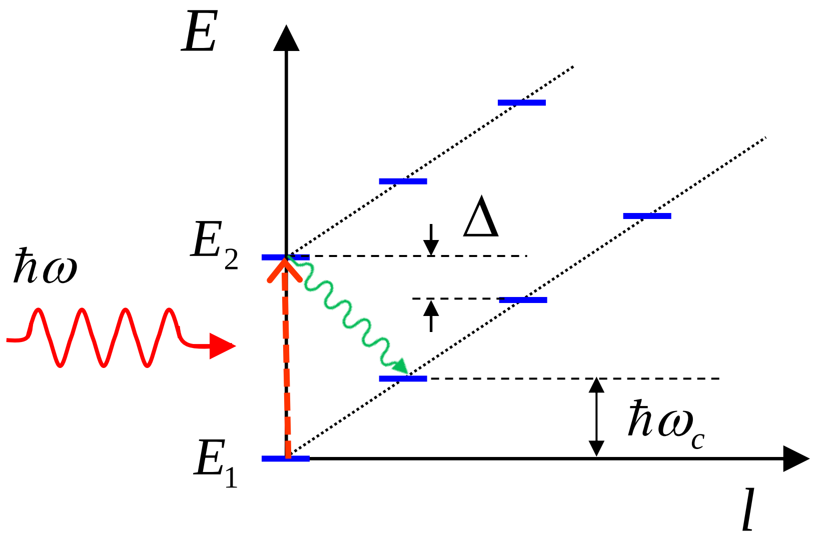
$$E = E_n + \frac{\hbar^2 k_\parallel^2}{2m}$$

What is we apply magnetic field?

$$E = E_n + \hbar\omega_c(l + 1/2)$$



Probe by transport measurements



How do we probe it?

- apply resonant microwaves

$$\hbar\omega = E_2 - E_1$$

- measure DC conductivity

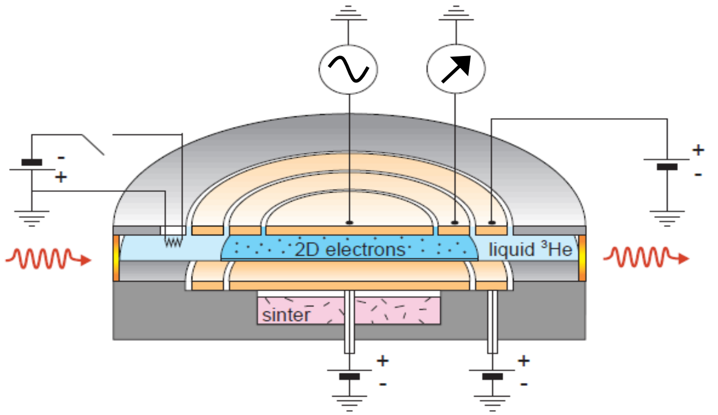
$$\sigma_{xx} = \frac{e^2 n_s \nu_{eff}}{m_e(\omega_c^2 + \nu_{eff}^2)}$$

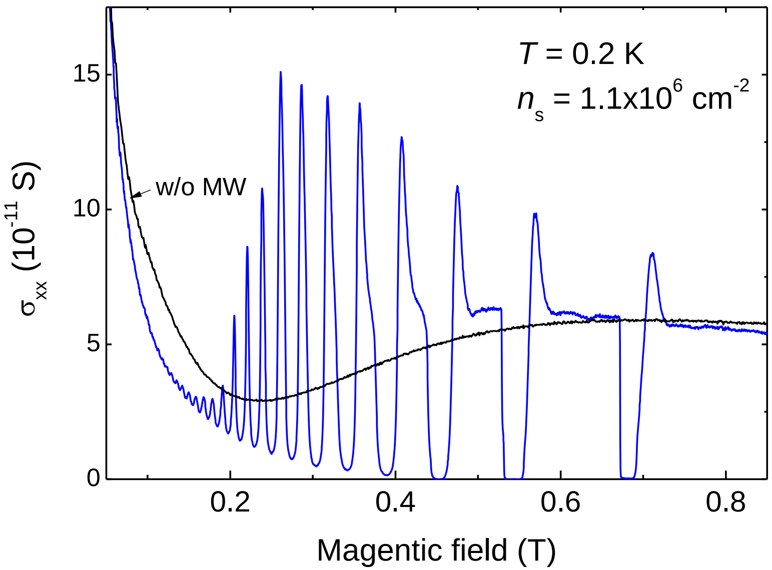
Relaxation dynamics must depend on ratio: $\frac{E_2 - E_1}{\hbar\omega_c} = \frac{\omega}{\omega_c}$

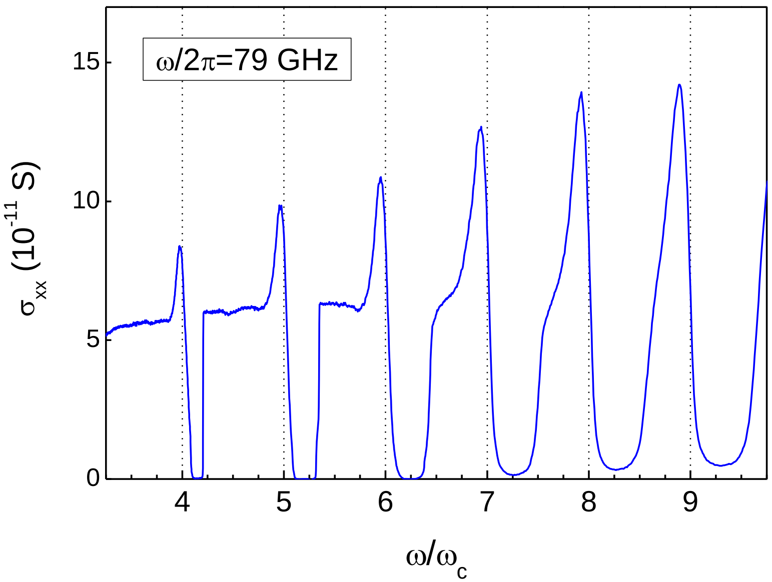
Experiment

Experimental setup

- Leak-tight copper cell
- Liquid height 1.3 mm
- Kapton windows for MW
- Tuning by Stark shift in perp. electric field



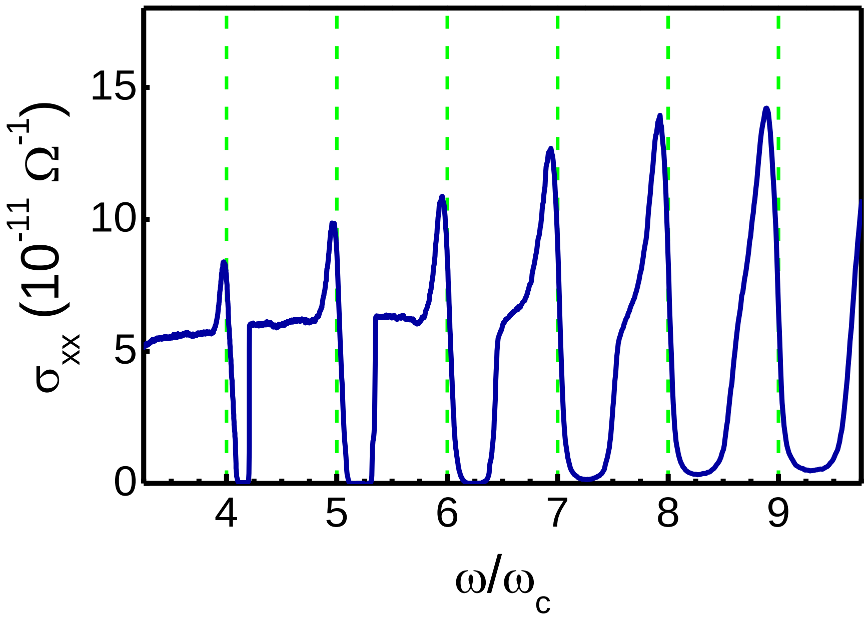




DK and Kono, PRL 2010

ZRS - Zero Resistance States

Vanishing conductivity: $\sigma_{xx} \to \mathbf{0}$



Tensor relation:

$$\rho_{xx} = \frac{\sigma_{xx}}{\sigma_{xx}^2 + \sigma_{xy}^2} \approx \frac{\sigma_{xx}}{\sigma_{xy}^2} \quad \Rightarrow \quad \rho_{xx} \to \mathbf{0}$$

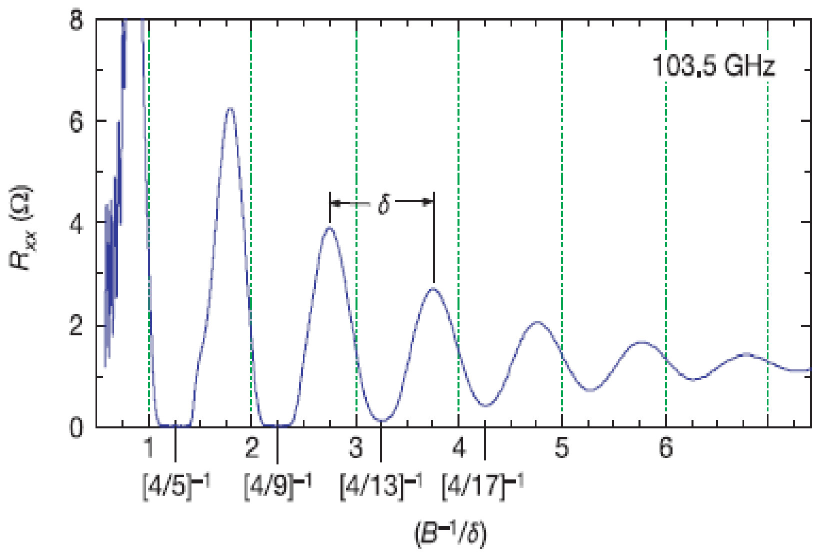
Vanishing resistance!

DK and Kono, PRL 2010

ZRS in heterostructures

Mani et al. Nature 2002

*(highlights in Phys. Today 2003,
Science 2003, Nature 2004)*



Possible explanations:

- Electron pairing due to excitons *(Nature 2002)*
- Dynamical symmetry breaking *(PRL 2003, PRB 2009)*
- Disorder-assisted transitions *(PRL 2003, Nature 2003)*
- Nonequilibrium population of LL *(PRL 2003, PRB 2003-2010)*
- Microwave stabilization of edge states *(PRB 2010)*
- Ponderomotive force near contacts *(PRB 2011)*

Mechanism of oscillations in EonHe

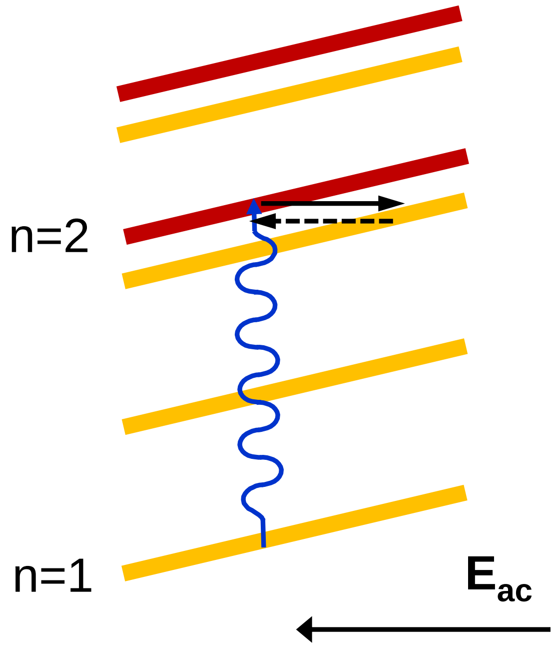
Linear transport theory

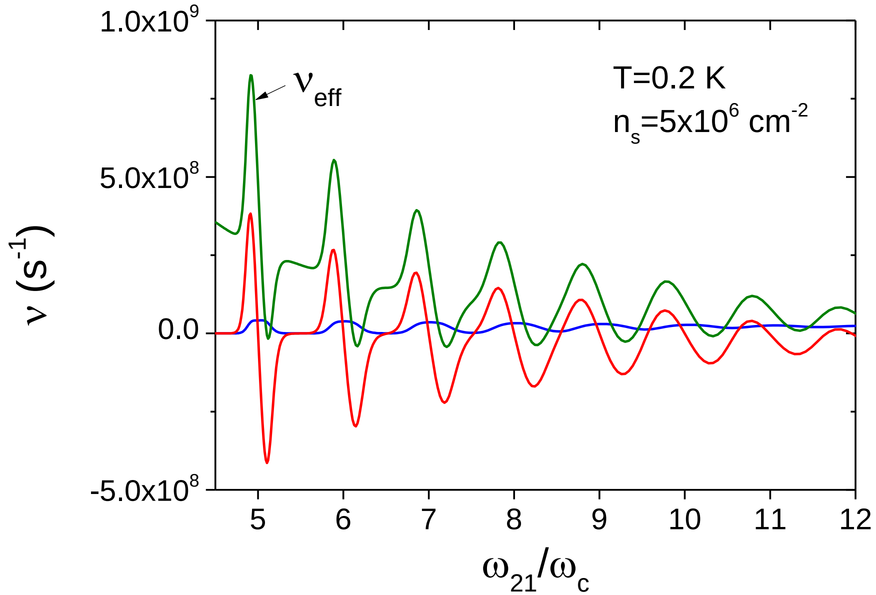
Yu. P. Monarkha

$$\nu_{\text{inter}} \sim \sum_{\mathbf{q}} \hbar \mathbf{q} \sum_{n>n'} \chi_{n,n'}(\mathbf{q}) \cdot \underbrace{S_{n,n'}(q,\omega_{n,n'})}_{\text{DSF}} \cdot \left(\rho_n + \rho_{n'} e^{-\frac{\hbar\omega_{n,n'}}{k_B T_e}}\right) +$$

$$+ \frac{\hbar}{k_B T} \sum_{\mathbf{q}} \hbar \mathbf{q} \sum_{n>n'} \chi_{n,n'}(\mathbf{q}) \cdot \overbrace{S'_{n,n'}(q,\omega_{n,n'})}^{\text{derivative of DSF}} \cdot \underbrace{\left(\rho_n - \rho_{n'} e^{-\frac{\hbar\omega_{n,n'}}{k_B T_e}}\right)}_{\text{non-zero for nonequilibrium population}}$$

Tilted LL in dc-field

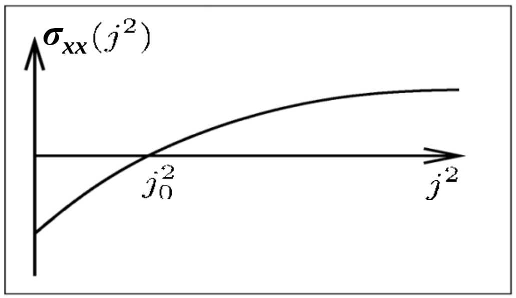




Zero-resistance states

There exists (some) mechanism

leading to absolute negative σ_{xx}

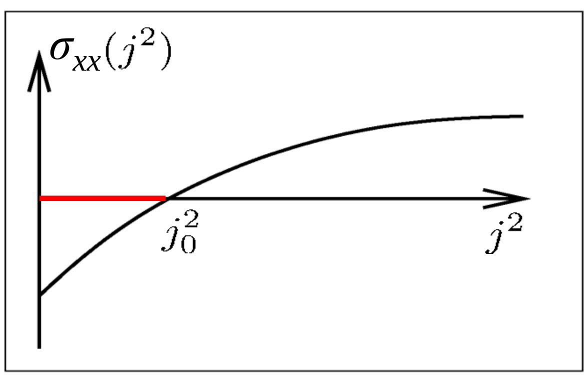


$$\frac{\partial \rho_s}{\partial t} = -\nabla \vec{j} = \sigma \nabla_r^2 V$$
$$\nabla^2 V = -\rho_s \delta(z)$$

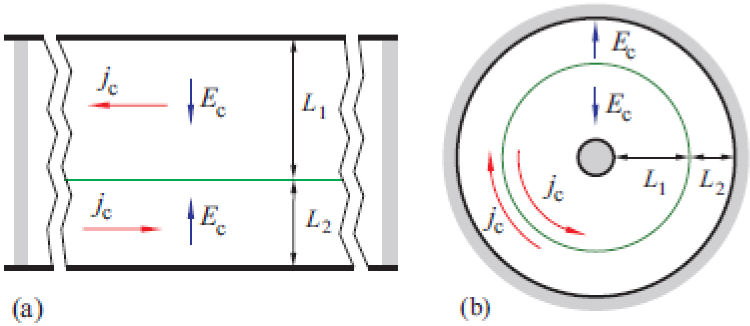
$$\rho_k \sim \exp\left(-\frac{\sigma k}{2} t\right) \to \infty$$

Instability and formation of current domains

Andreev, Aleiner, Millis, PRL 2003



Andreev et al. PRL 2003



Non-dissipative current domains

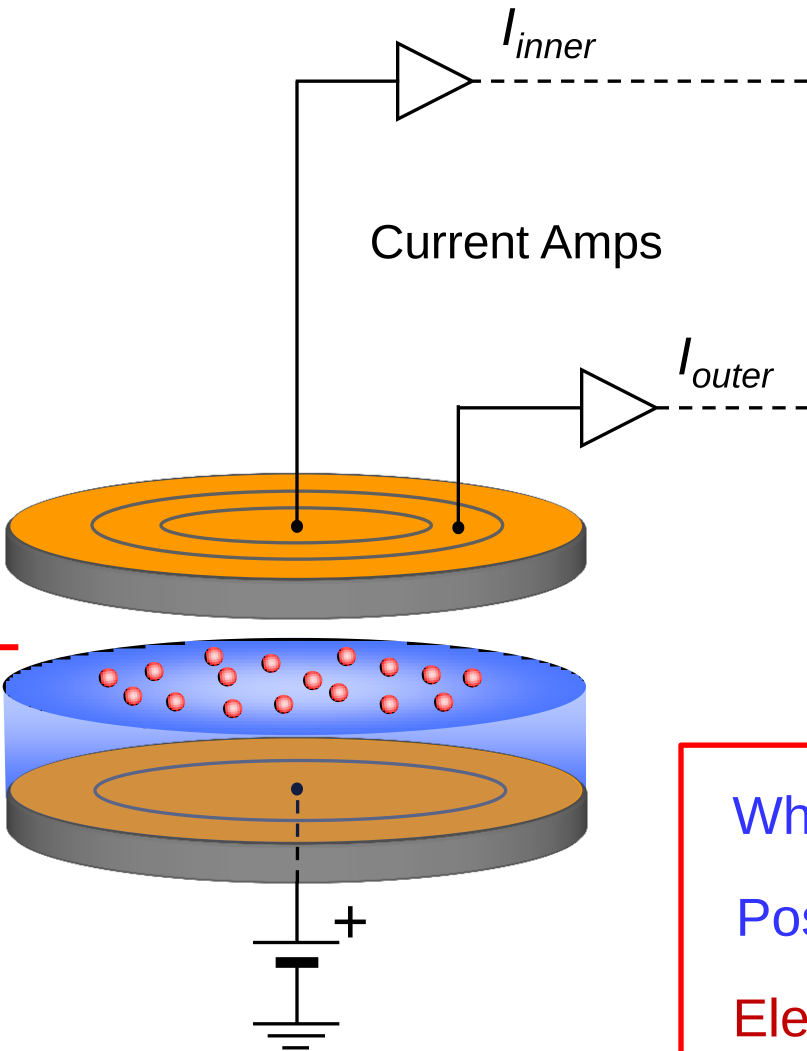
Photocurrent experiment

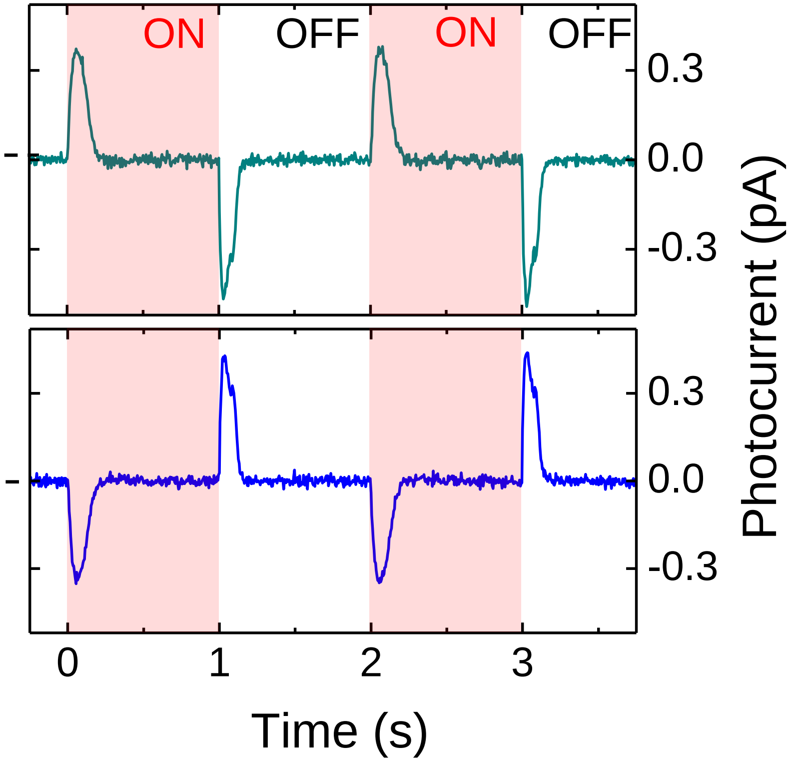
DK, Chepelianskii, Kono, J. Phys. Soc. Jpn. 2012

Fix B-field at minima of σ_{xx}

Microwave modulation ON/OFF

MW





When MW switched ON

Positive image charge released

Electrons moved away

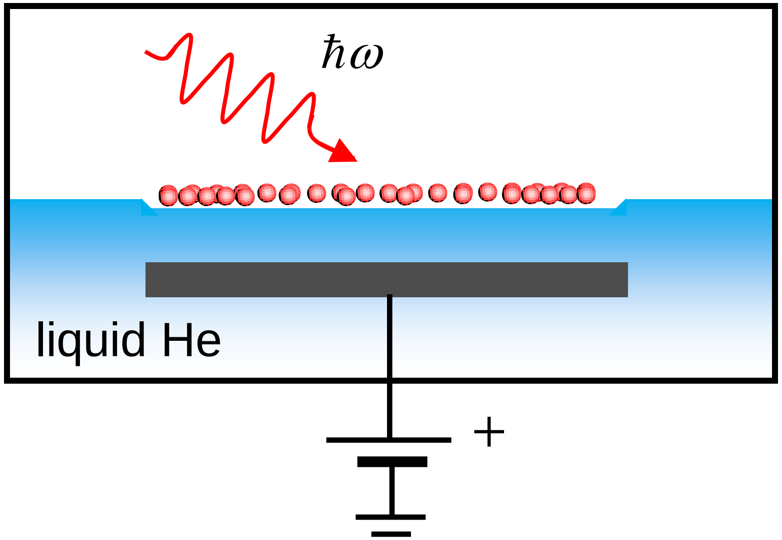
e⁻ redistribution and self-oscillations

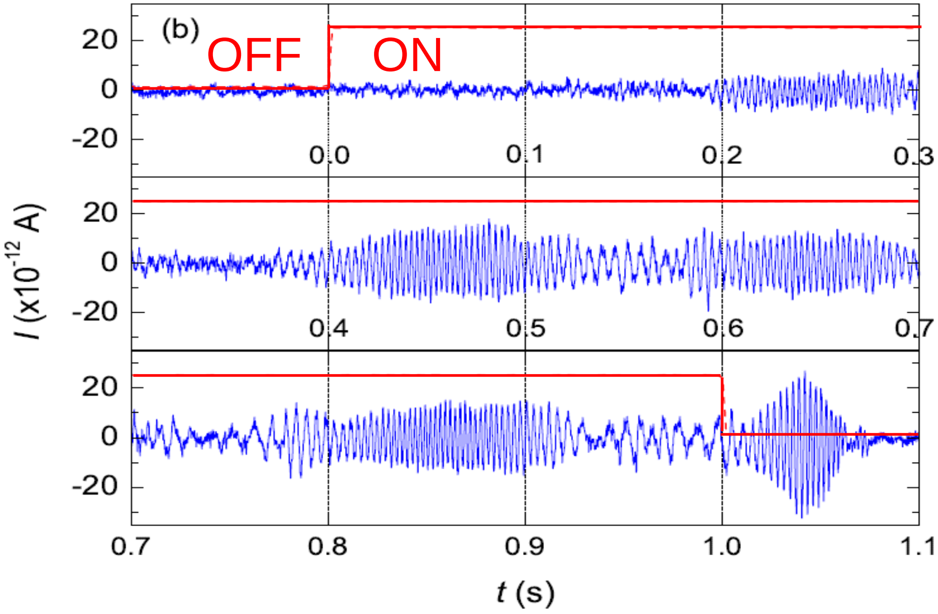
When MW switched ON

Electrons deplete from the center

AND accumulate at the edge

(large fraction up to 50%)





In certain range of e^- density appears self-organized (audio-frequency) oscillations

DK, M. Watanabe, K. Kono J. Phys. Soc. Jpn. (2013)

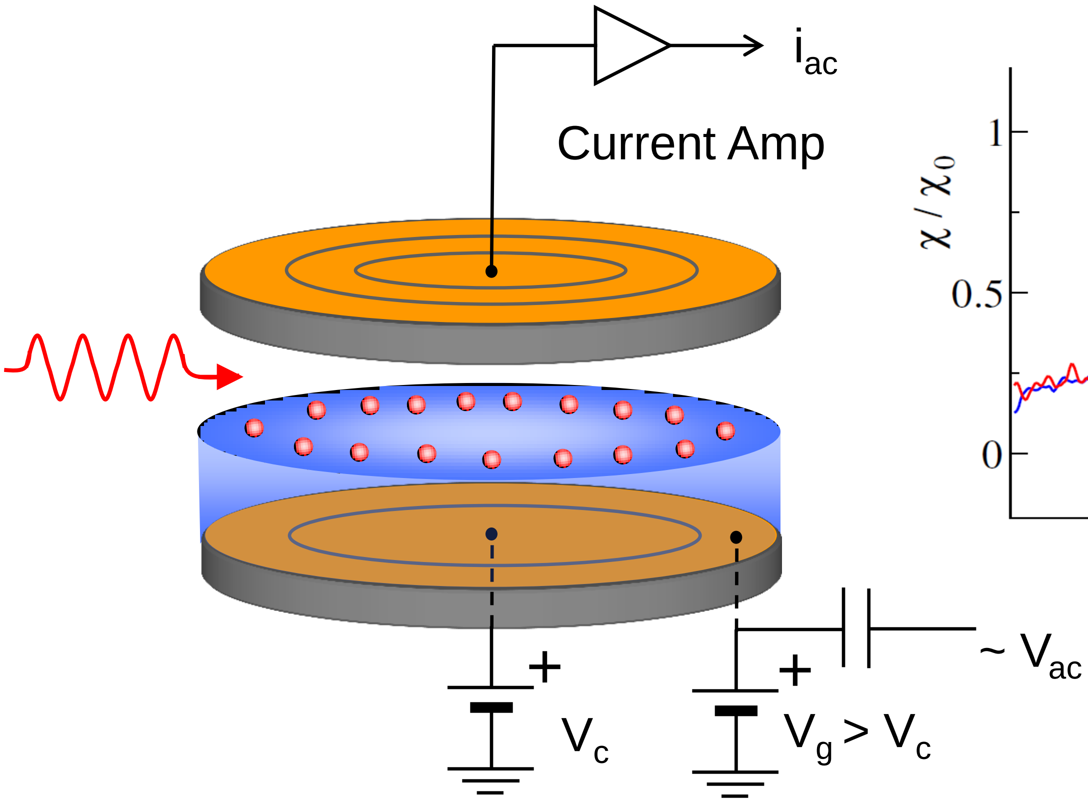
Compressibility experiment

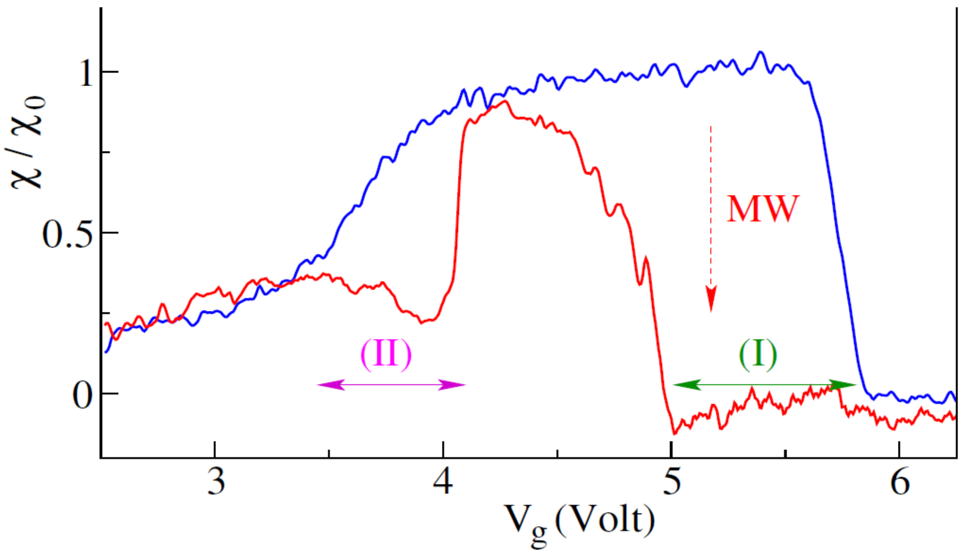
Recent experiment in RIKEN

A. Chepelianskii et al. Nature Communication, in press

Can directly measure compressibility

defined by $\chi = \frac{dn_e}{dV_g} \sim i_{ac}$

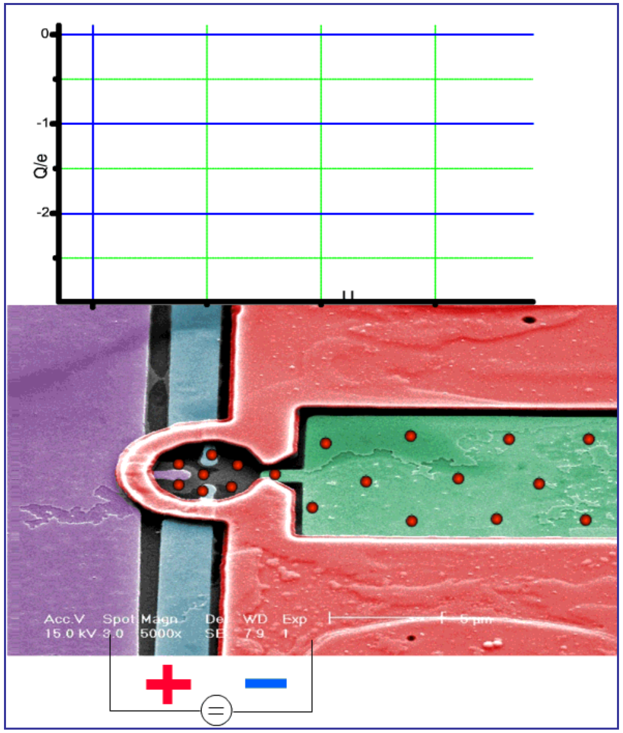




Vanishing compressibility!

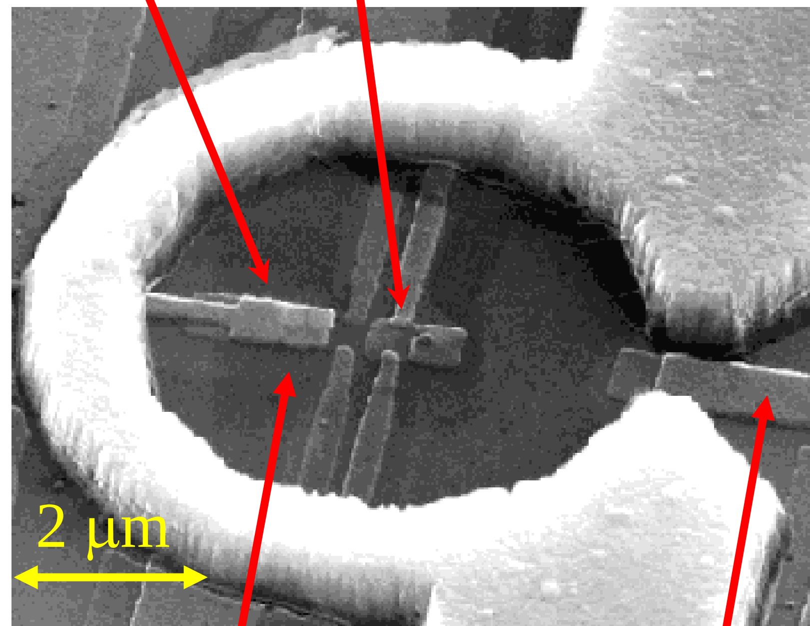
OIST

Single-electron detection



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

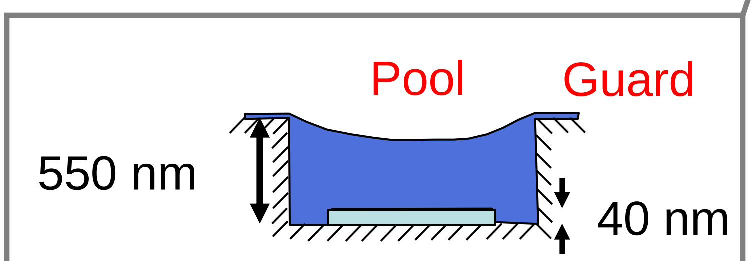
Gate
SET



Helium Pool
0.7 µm deep

Injector

Mike Lea, RHUL, London, UK
G. Papageorgiou *et al.* APL 86, 153106 (2005)



Royal Holloway University of London

cea

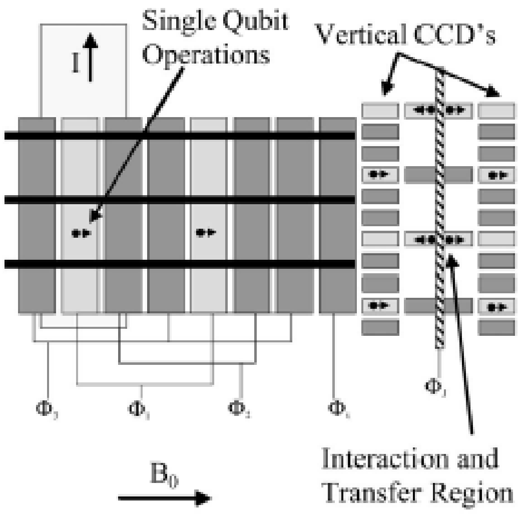
Qubits with long decoherence

PHYSICAL REVIEW A **74**, 052338 (2006)

Spin-based quantum computing using electrons on liquid helium

S. A. Lyon
Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA
(Received 17 September 2006; published 30 November 2006)

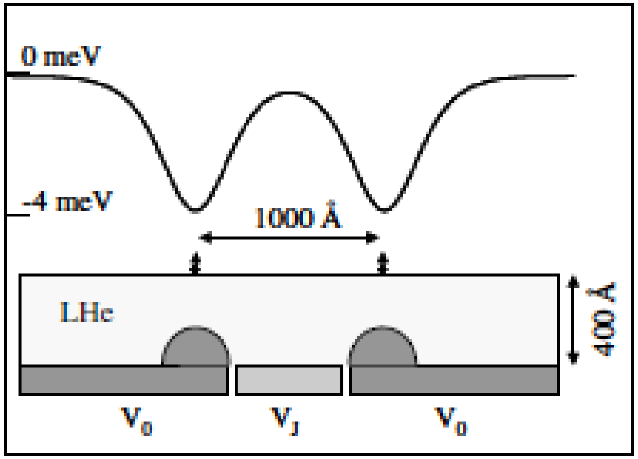
Numerous physical systems have been proposed for constructing quantum computers, but formidable obstacles stand in the way of making even modest systems with a few hundred quantum bits (qubits). Several approaches utilize the spin of an electron as the qubit. Here it is suggested that the spin of electrons floating on the surface of liquid helium will make excellent qubits. These electrons can be electrostatically held and manipulated much like electrons in semiconductor heterostructures, but being in a vacuum the spins on helium suffer much less decoherence. In particular, the spin-orbit interaction is reduced so that moving the qubits with voltages applied to gates has little effect on their coherence. Remaining sources of decoherence are considered, and it is found that coherence times for electron spins on helium can be expected to exceed 100 s. It is shown how to obtain a controlled-NOT operation between two qubits using the magnetic dipole-dipole interaction.



Fluctuating magnetic field due to Rashba effect (spin-orbit interaction):

$$H_{s-o} = \alpha\left(\mathbf{p}_{\parallel} \times \mathbf{E}_{\perp}\right)\cdot \hat{S}$$

- T_2 exceeding 100 sec
- Qubit coupling by dipole interaction



[S. A. Lyon, Phys. Rev. A, 74, 052338]

OIST

Towards a hybrid quantum computer

PRL 105, 040503 (2010) PHYSICAL REVIEW LETTERS week ending 23 JULY 2010

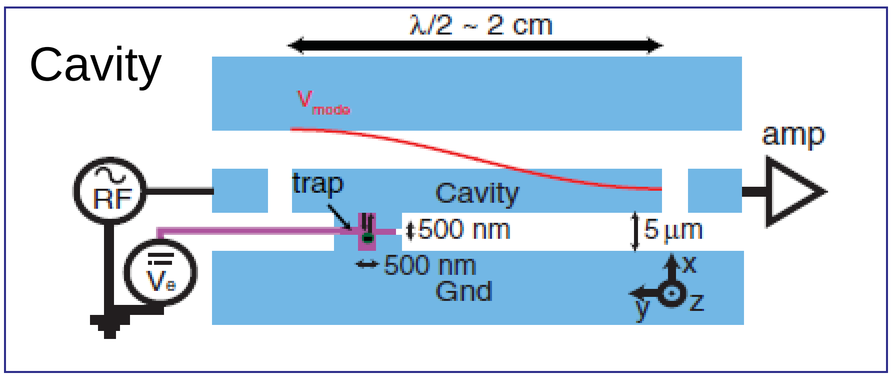
Proposal for Manipulating and Detecting Spin and Orbital States of Trapped Electrons on Helium Using Cavity Quantum Electrodynamics

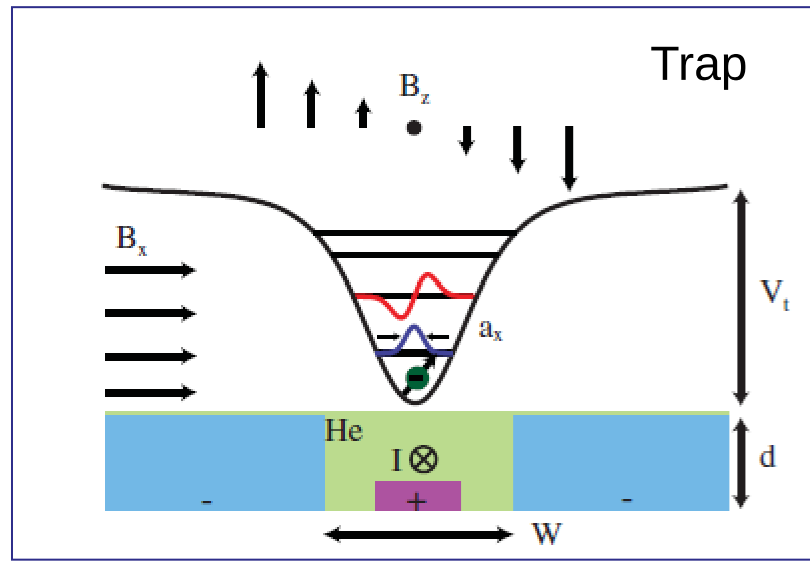
D. I. Schuster,[1] A. Fragner,[1] M. I. Dykman,[2] S. A. Lyon,[3] and R. J. Schoelkopf[1]

[1]*Department of Applied Physics and Physics, Yale University, New Haven, Connecticut 06511, USA*

[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824-2320, USA*

[3]*Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA*





Progress: APS March Meeting 2012

- Strong coupling to RF cavity
- Electron-electron coupling via a single photon
- Manipulation of spin states via spin-orbit coupling

Summary

- Electrons on helium: unique model system

- New quantum phenomena under MW excitation

- Some remarkable progress in quantum engineering

Steve Lyon, Princeton: CCD device
Mike Lee, University of London Royal Holloway and
Yuriy Moukharskii, Sacley: SET
David Rees, NCTU-RIKEN Joint Laboratory: Point Contact
David Shuster, University of Chicago and
Andreas Fragner,Yell University: Cavity QED

end more..

- Still exciting object of study!