Electrons on helium: towards quantum engeneering

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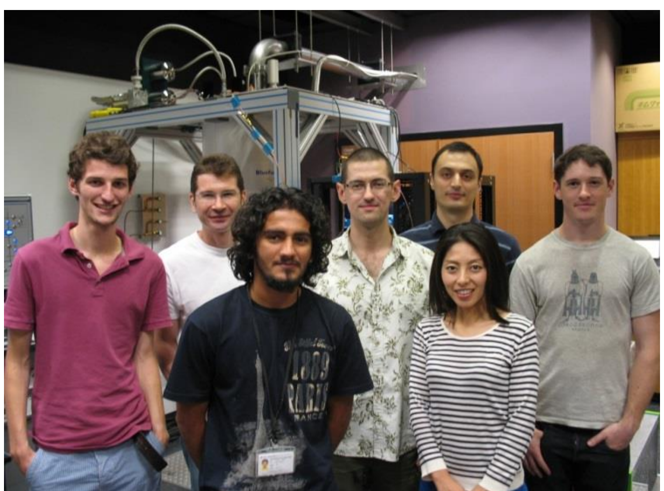
QSS-ASIA 2013, Tokyo, Nov. 25-26

OIST Graduate University

Okinawa Institute of Science and Technology - OIST

Cryogenic Lab.



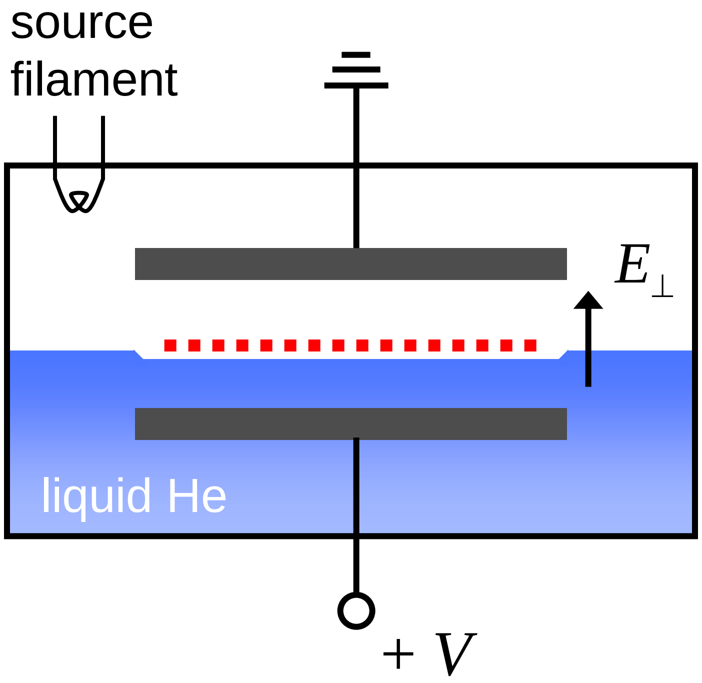
Quantum Dynamics Unit

- Magneto-transport in electrons on helium
- NMR in solid antiferromagnets
- Electron spin-resonance

Talk outline

- Electrons on helium: brief introduction
- Why electrons on helium?
- Quantum engineering: prospects and achievements

2D electrons on cryogenic substrates



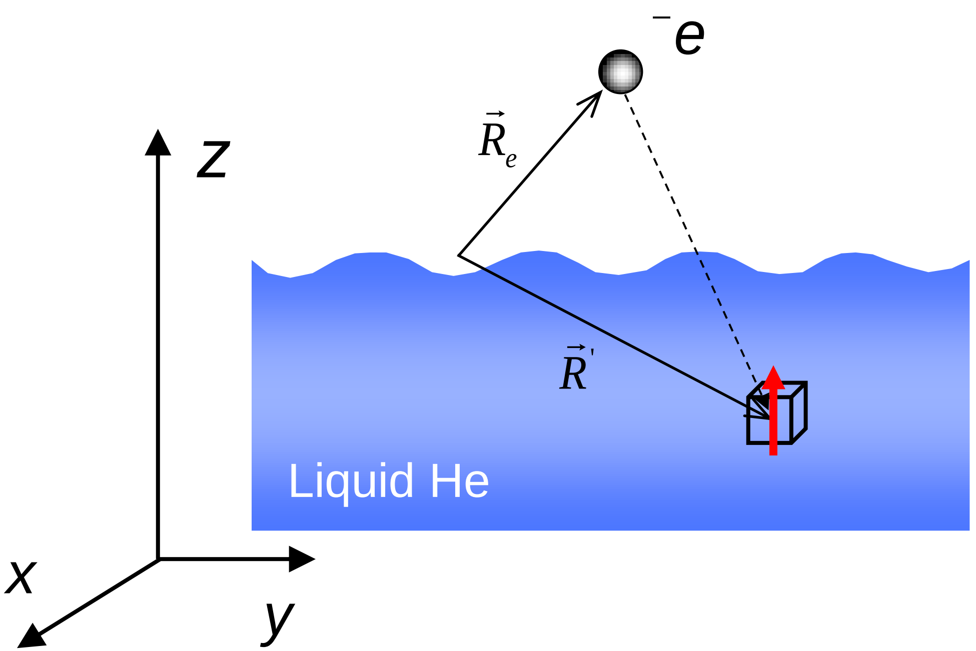
Cryogenic polar substrates:

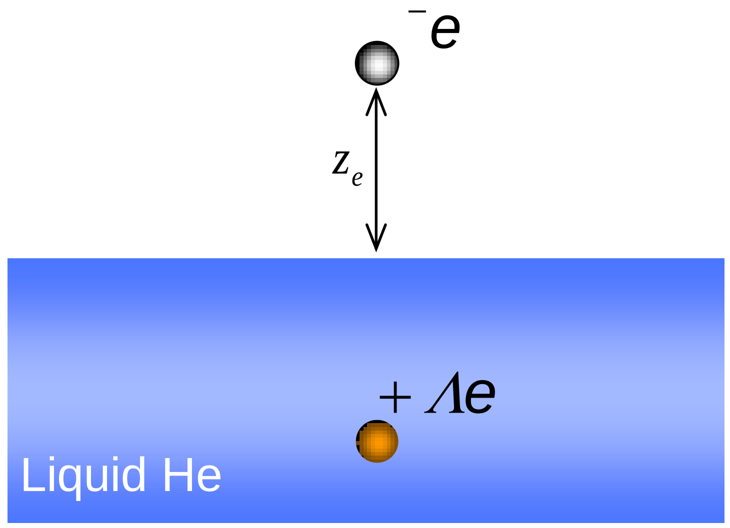
- solid hydrogen
- liquid neon
- liquid helium

Why liquid helium?

- remains liquid down to T=0
- no impurities
- the smoothed surface

Polarization attraction



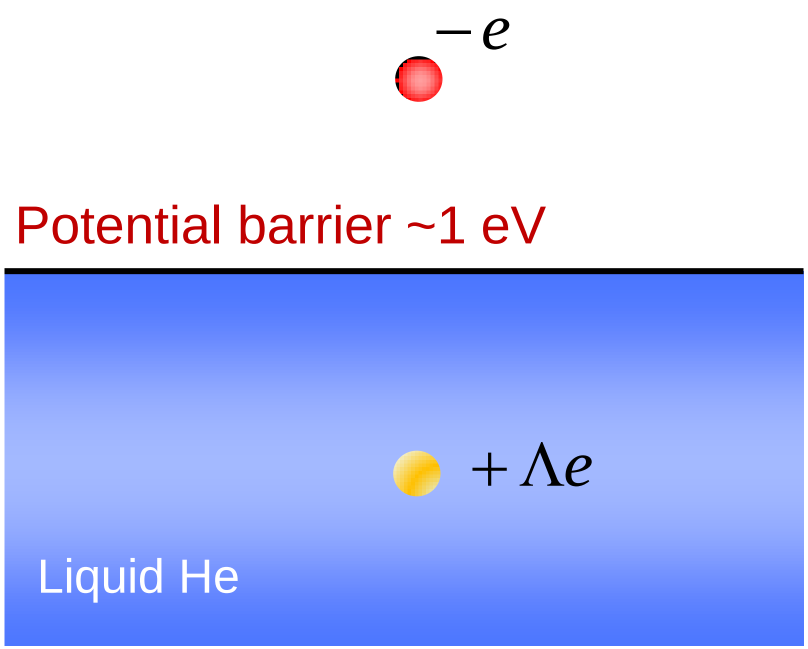


$$U_{pol}(\vec{R}_e) = -\frac{(\varepsilon-1)e^2}{4(\varepsilon+1)}\int d^3\vec{R}' \frac{1}{\left|\vec{R}' - \vec{R}_e\right|^4}$$

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

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

Repulsive barrier



The Pauli exclusion principle -
electron avoids He atoms

Sommer, 1964

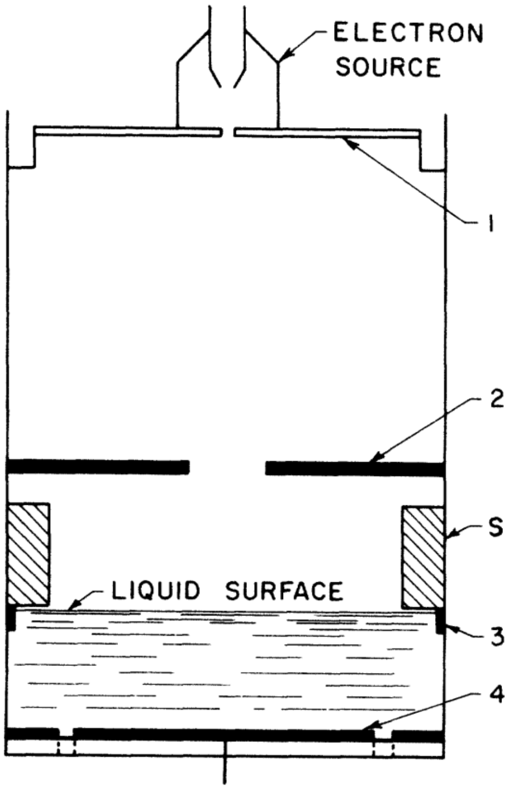
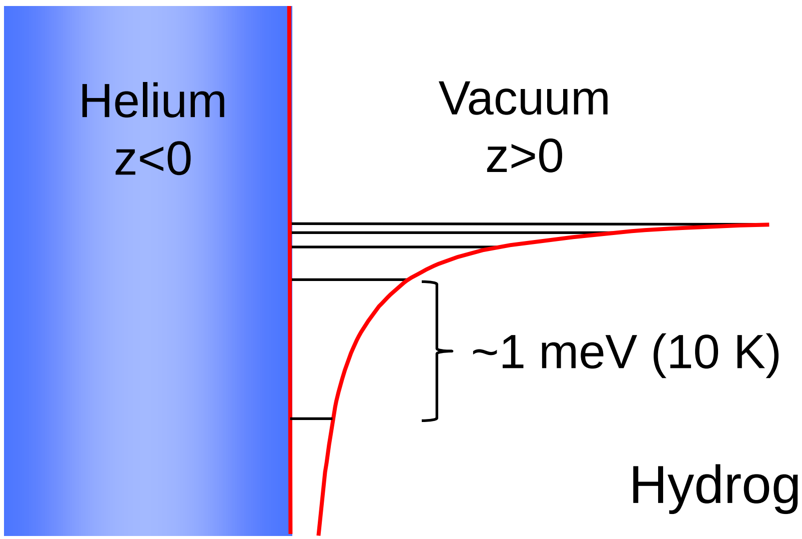


FIG. 1. The experimental chamber.

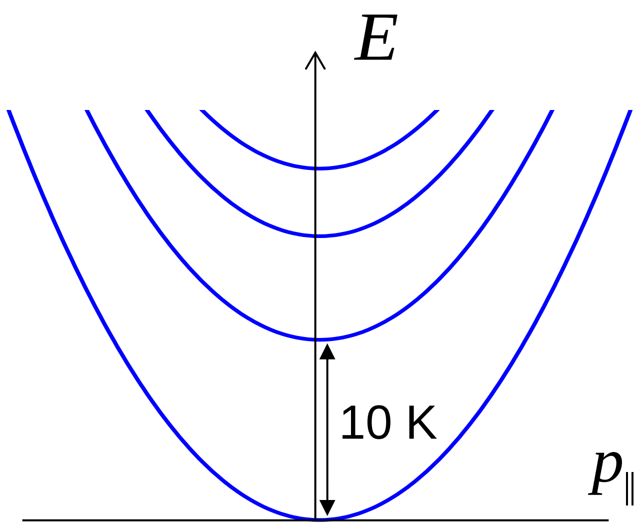
Surface-state electrons (SSE)



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



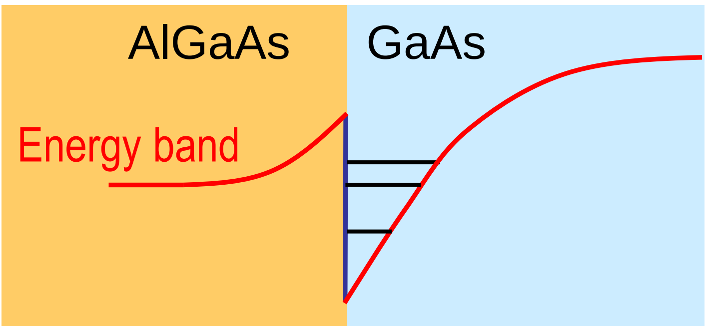
Total energy:

due to spin

$$E = E_n + \frac{p_\parallel^2}{2m} \pm \mu_B B_\parallel$$

2D motion

Classical 2D electron system

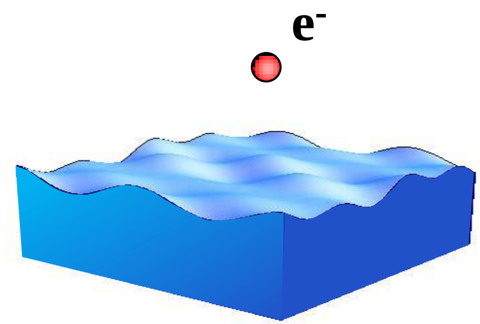


Complement to degenerate 2DEG in

Si MOSFETs and

GaAs/AlGaAs heterostructures

BUT…



- Classical non-degenerate electron system
- No impurities, scattering from ripplons
- Electron mobility exceeding 10^8 $cm^2/V \cdot s$ - highest known in nature!
- Unscreened Coulomb interaction – correlated liquid, Wigner solid
- Magneto-transport under excitation – zero-resistance states etc.

DK and Kono, PRL (2010)

DK, Monarkha and Kono, PRL – in press

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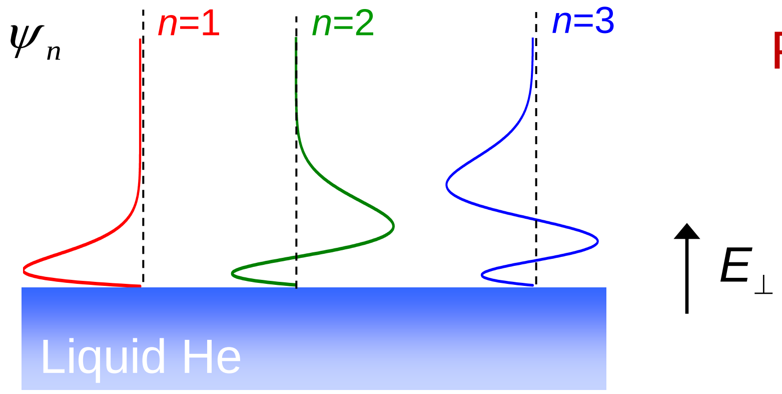
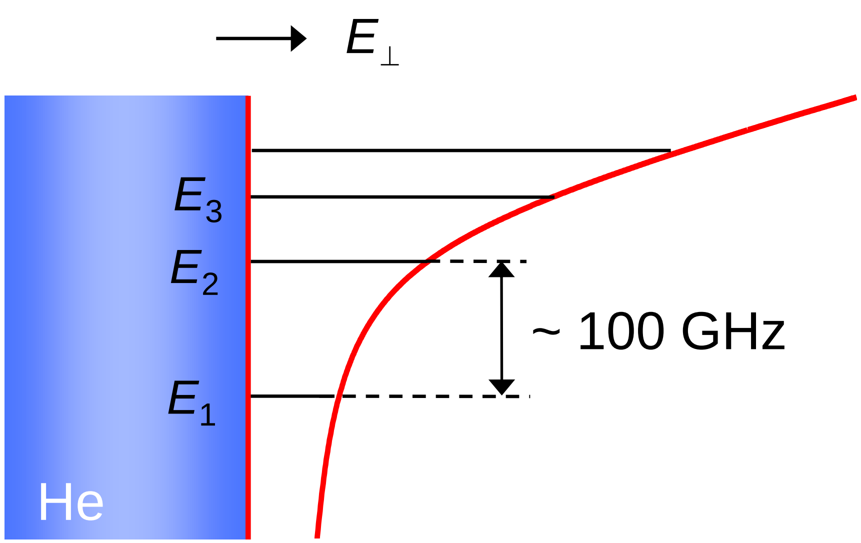
Rydberg resonance



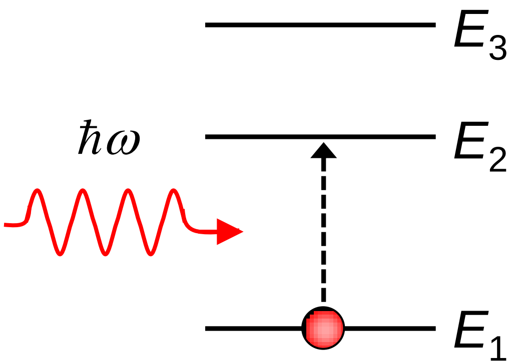
Parity symmetry-breaking of states ψ_n :

$$\langle n|z|n\rangle \neq 0$$

linear Stark effect

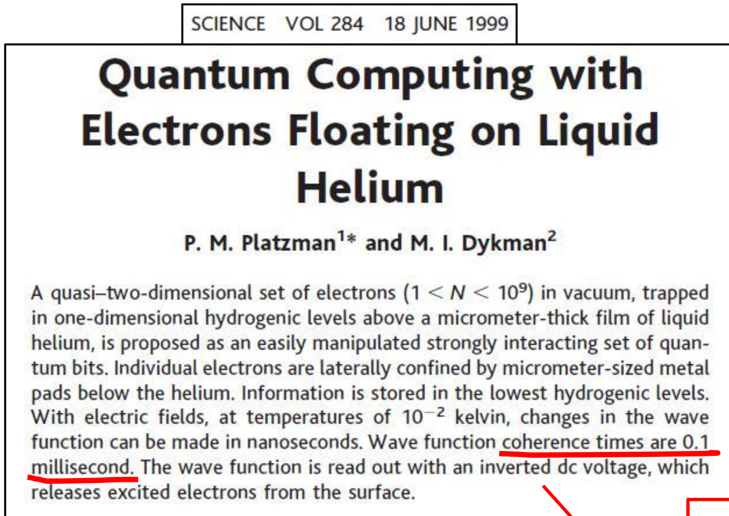


MW resonance: $\hbar\omega = E_2 - E_1$



2-level system

Surface state qubits



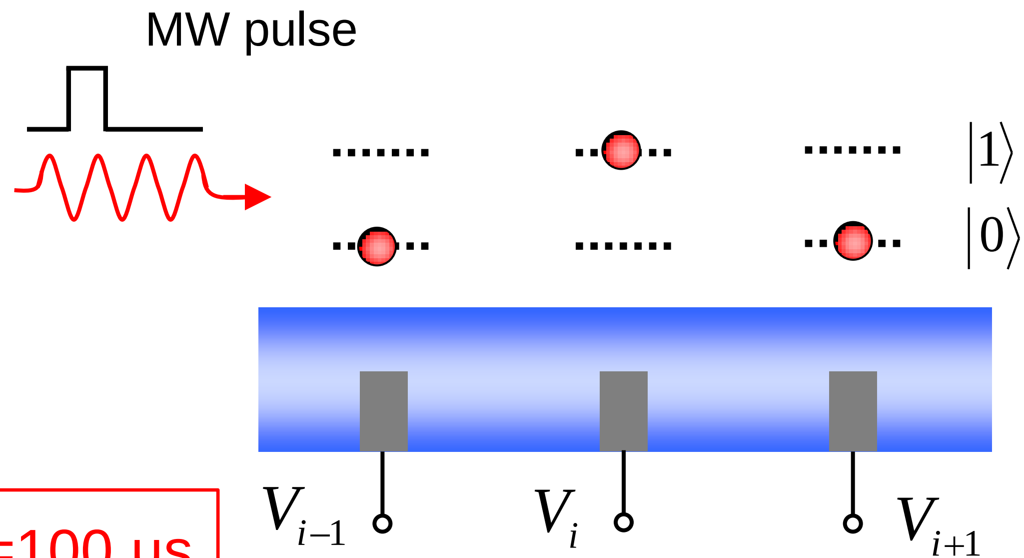
SCIENCE VOL 284 18 JUNE 1999

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.

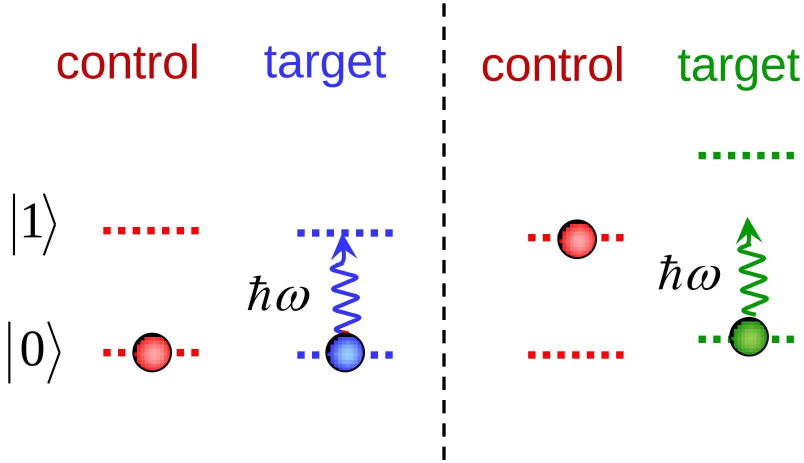
T_1=100 μs

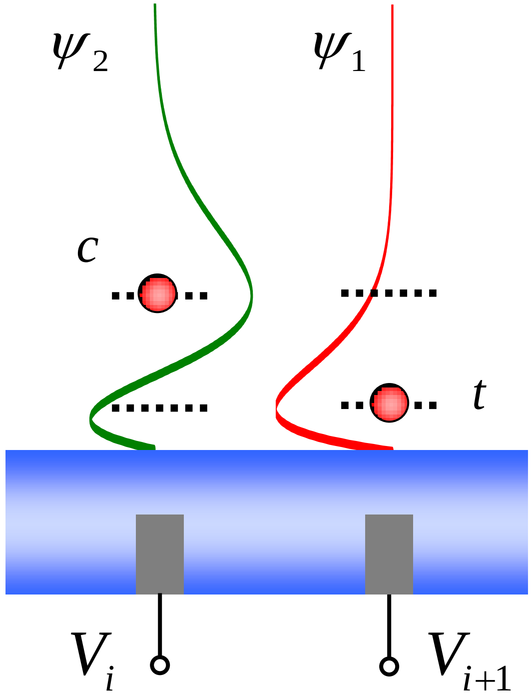


- Identification of well-defined qubits:
  I0> and I1> states of individual surface electrons
- Reliable state preparation:
  Below 1 K almost all qubits will be in the quantum ground state I0>
- Low decoherence (?):
  Suspended in vacuum
  Scattering from ripplons (ultra-high mobility)

Qubit coupling

- Two-qubit logic gate: depending on the state of control, target will be either excited or not (CNOT-gate)





Coulomb interaction between qubits:

$$V_{e-e} \approx \frac{e^2}{r_{ct}}\left(1 - \frac{(z_c - z_t)^2}{2r_{ct}^2}\right),$$

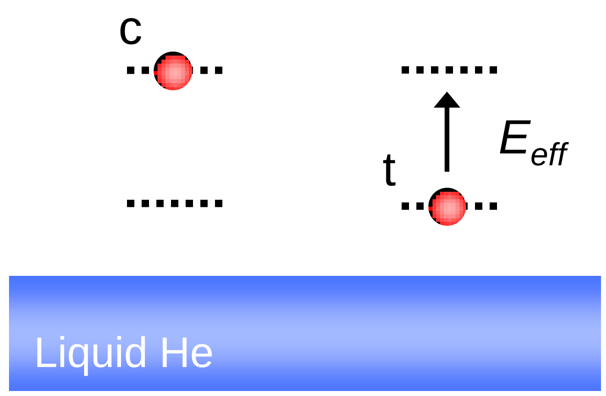
state-dependent part

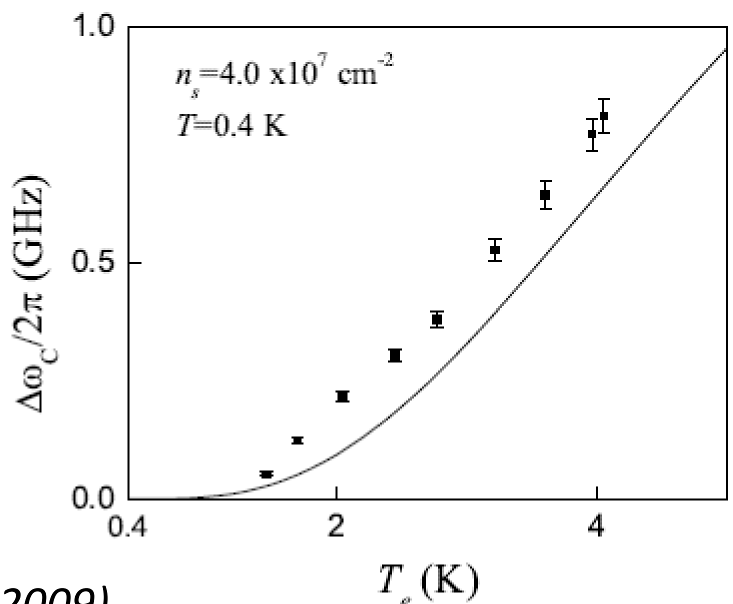
Coulomb shift of resonant transition

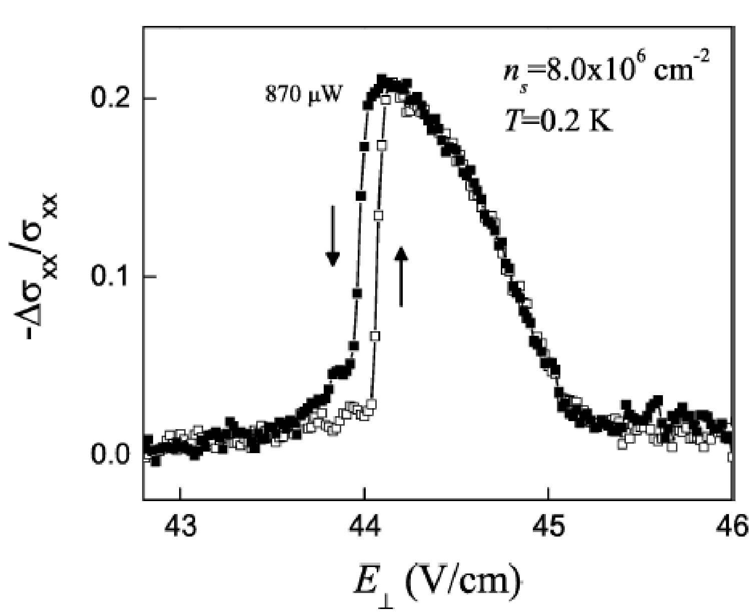
Estimate using mean-field approximation:

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

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

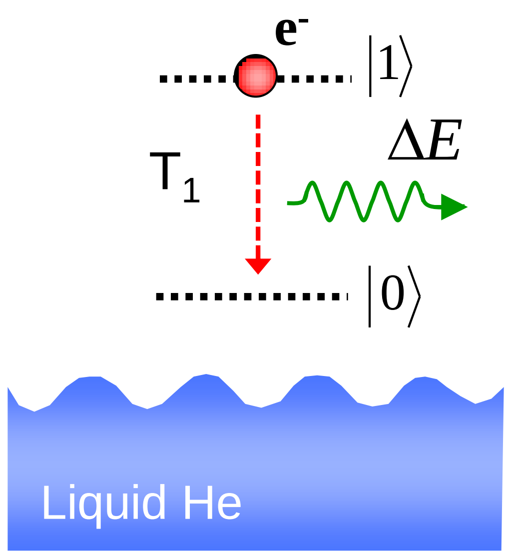






DK et al. PRL (2009)

Decay rate of |1> state



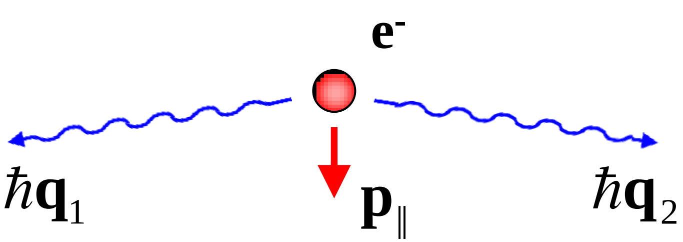
Need to match Energy and Momentum:

(1) One-ripplon scattering

$$\hbar q \approx p_{\parallel}$$
$$\hbar \omega_q << E_2 - E_1$$

essentially elastic process

(2) Two-ripplon scattering



$$2\hbar \omega_q = E_2 - E_1$$
$$\hbar |\mathbf{q}_1 + \mathbf{q}_2| = p_{\parallel}$$

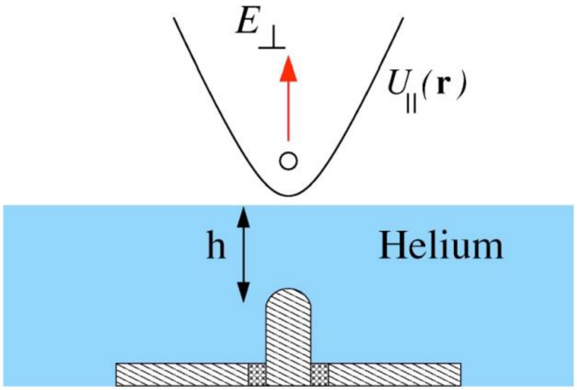
inelastic process

Energy relaxation

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

Qubits with electrons on liquid helium

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



Inelastic 2-ripplon decay

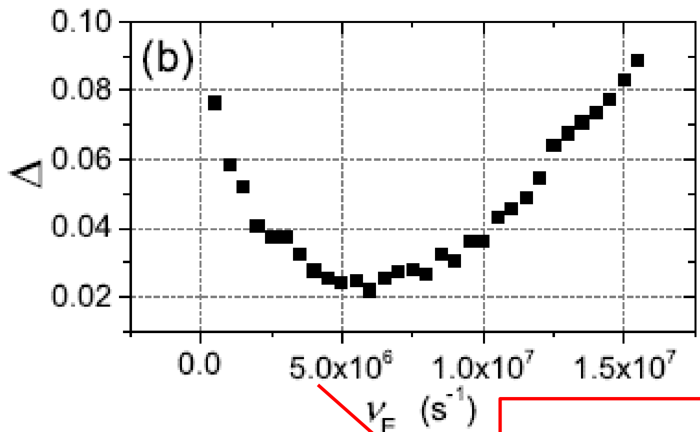
Adiabatic approximation

- electron follows surface deformation
- ripplon spectrum cut-off to avoid divergence

T_1=100 μs

Probe experimentally by studying the energy relaxation of hot electrons

$$\nu_E \times (T_e - T) = \hbar\omega \times \text{AbsorptionRate}$$



T_{relax}=0.2 μs

DK et al. PRL (2007)

A. Badrutdinov, DK et al. EPL (2013) – in press

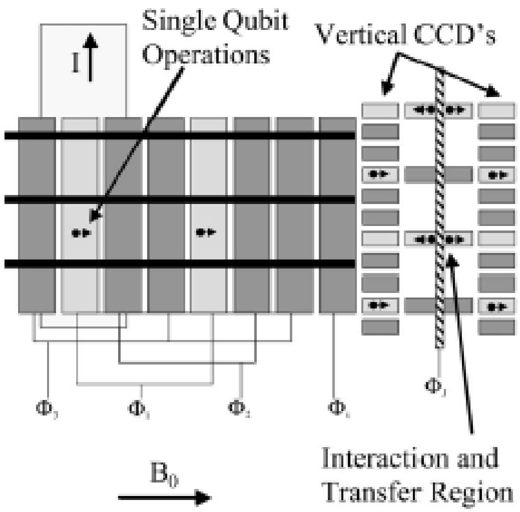
Qubits with long decoherence

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)

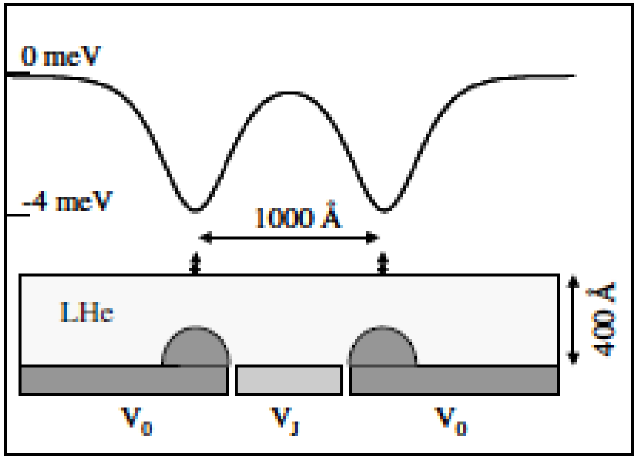
Numerous physical systems have been proposed for constructing quantum computers, but formidable obstacles stand in the way of making even modest systems with a few hundred quantum bits (qubits). Several approaches utilize the spin of an electron as the qubit. Here it is suggested that the spin of electrons 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):

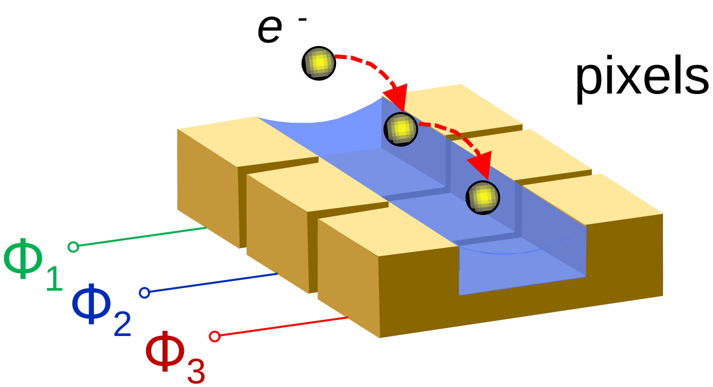
$$H_{s-o} = \alpha\left(\mathbf{p}_{\parallel} \times \mathbf{E}_{\perp}\right)\cdot \hat{S}$$

- T_2 exceeding 100 sec
- Qubit coupling by dipole interaction

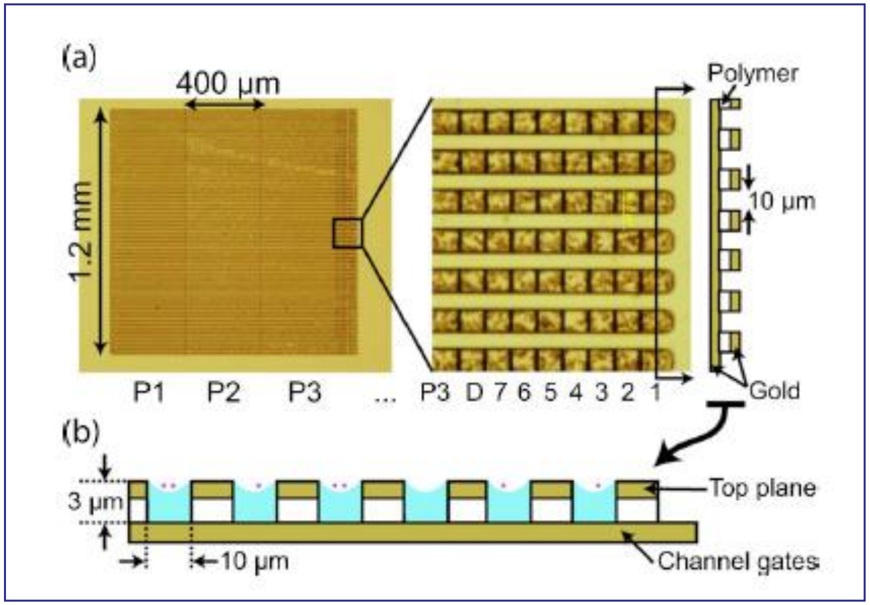


[S. A. Lyon, Phys. Rev. A, 74, 052338]

Mobile spin-state qubits



- Electrons confined in microchannels
- Capacitive coupling to metal electrode
- Possibility to build a CCD



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

Steve Lyon, Princeton University, USA

F. R. Bradbury et. al., Phys. Rev. Lett. 107, 266803 (2011)

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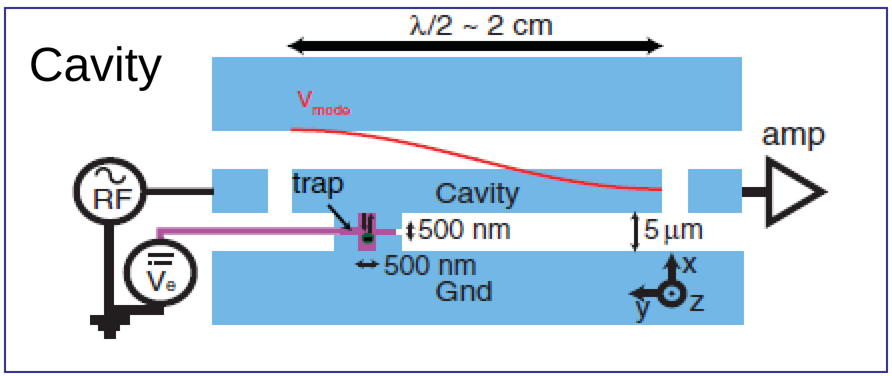
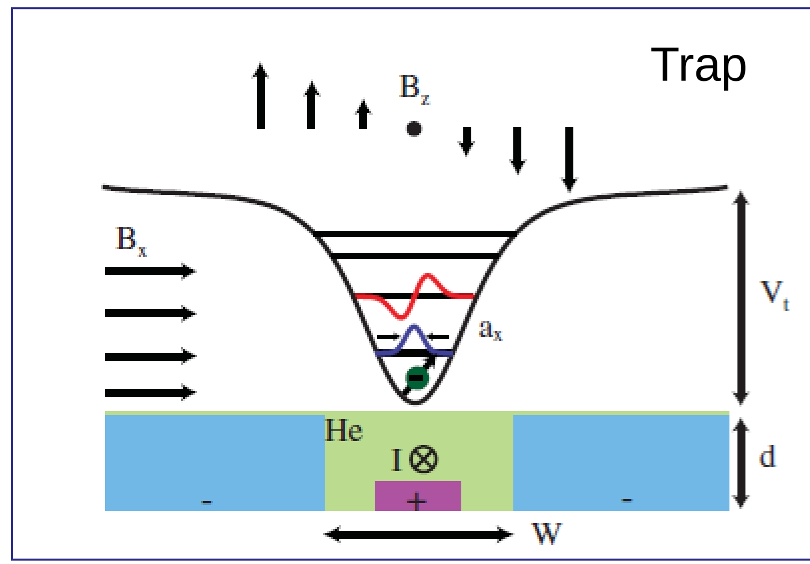
Towards a hybrid quantum computer

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*





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

Progress: APS March Meeting 2012

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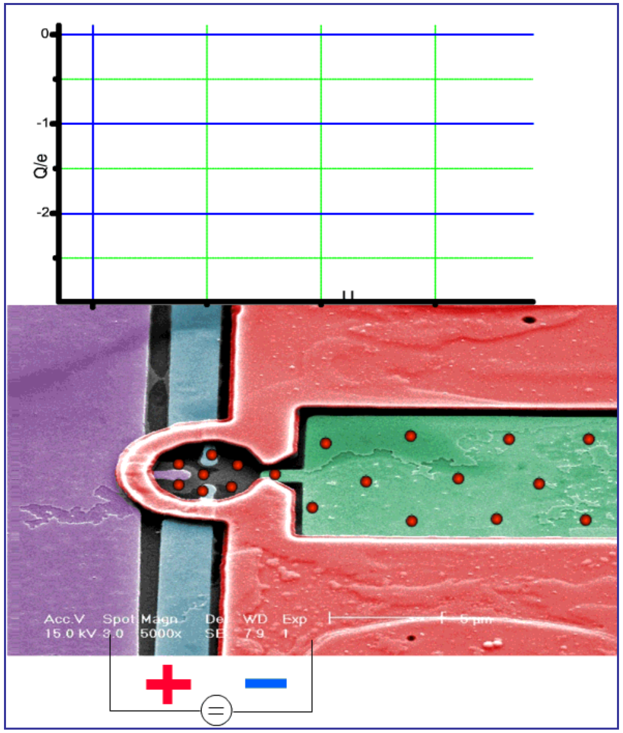
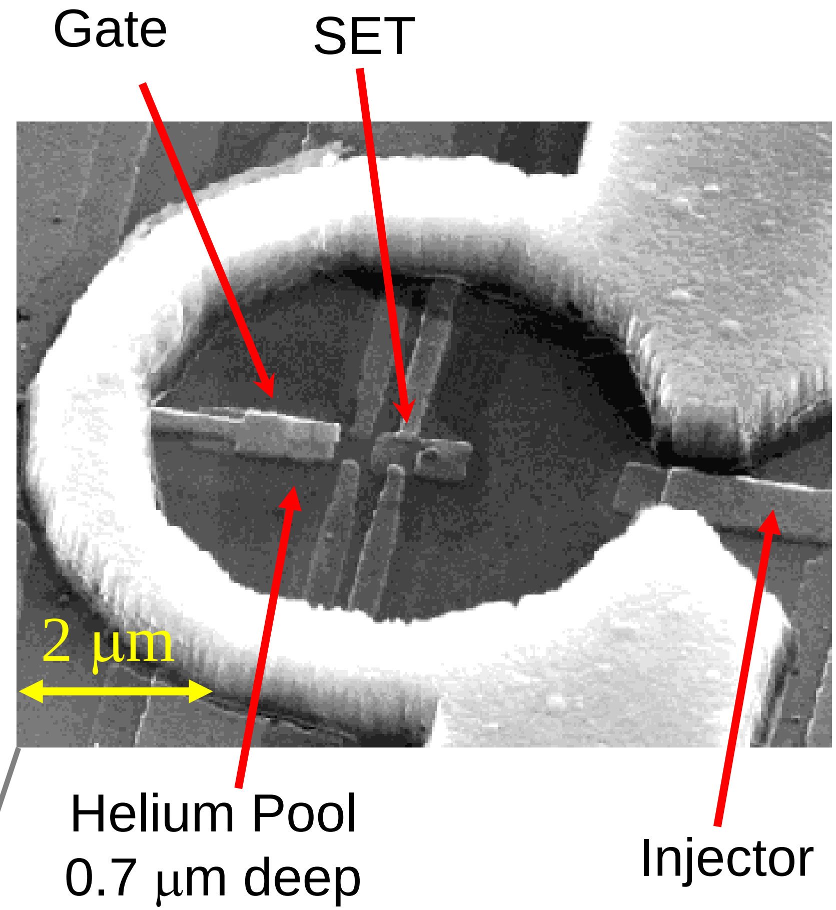
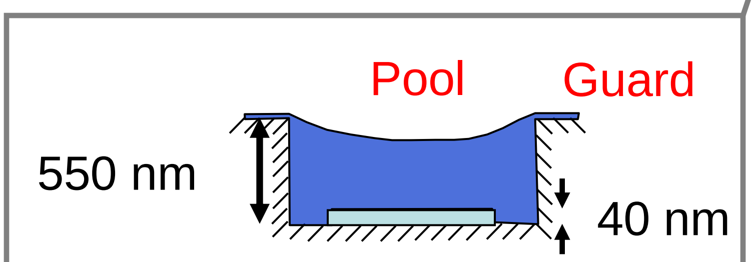
Single-electron detection



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



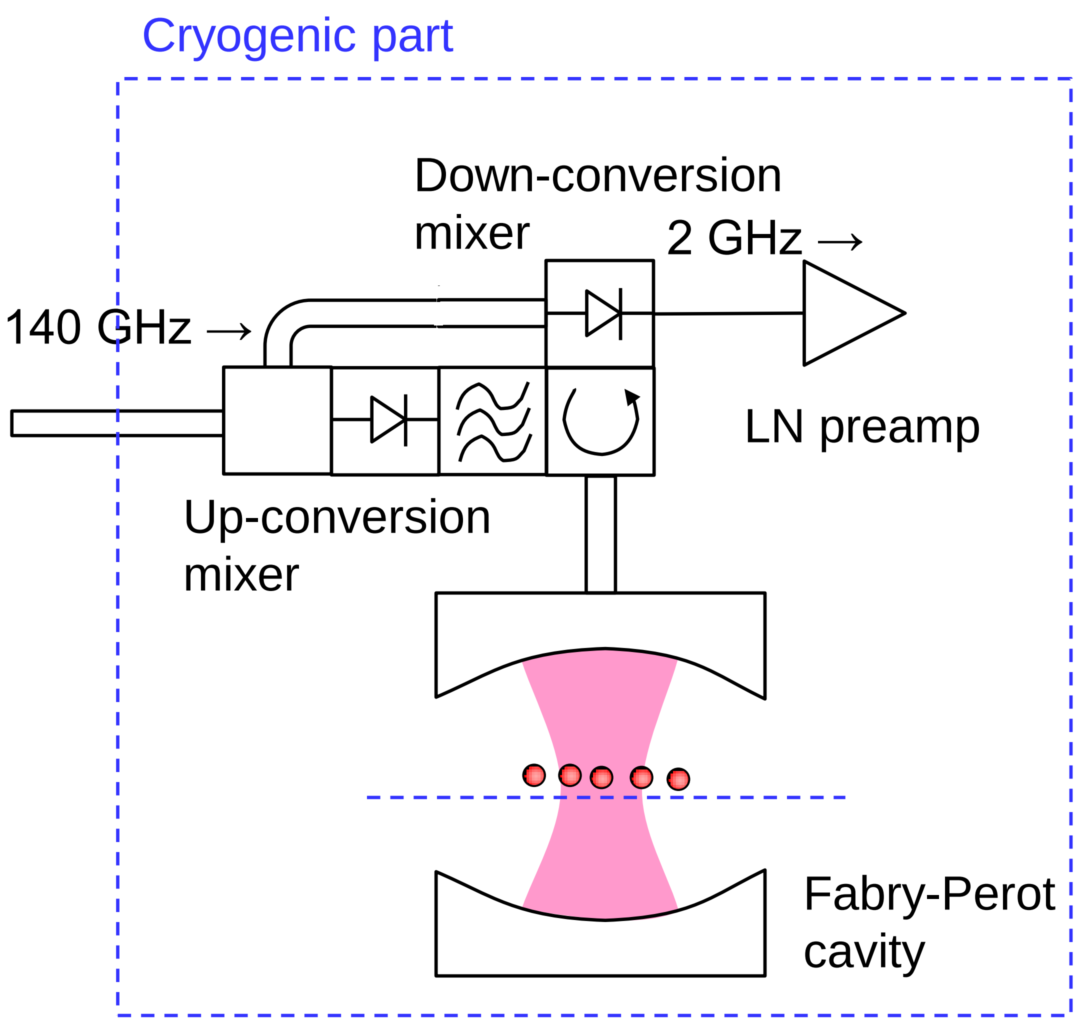
Mike Lea, RHUL, London, UK
G. Papageorgiou *et al.* APL 86, 153106 (2005)



Royal Holloway University of London

Towards spin-resonance detection

Heterodyne spectrometer with double frequency conversion:



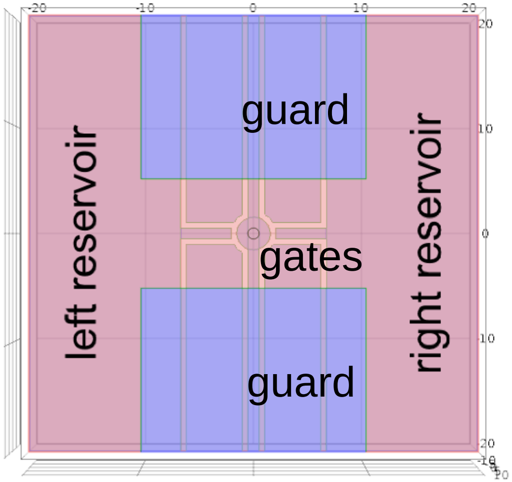
- Cryogenic mixers (8dB conversion losses)
- Down-conversion to 100 MHz (lock-in detection)
- High-Q Fabry-Perot (Q>100,000)
- High-homogeneity magnetic field ($2x10^{-6}$ /cm^3)

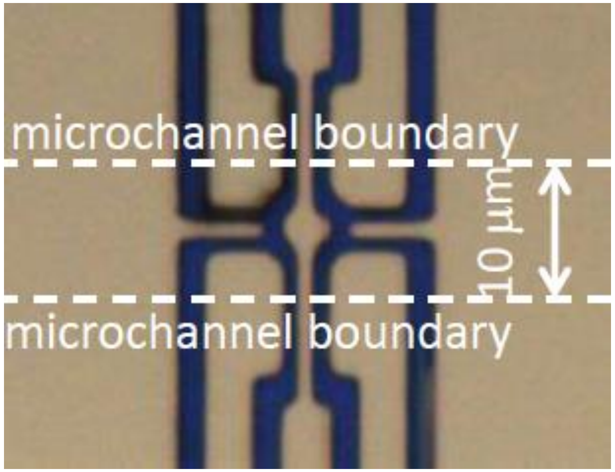
in progress (help from Sergey Vasiliev, Turku University)

Towards single-electron detection

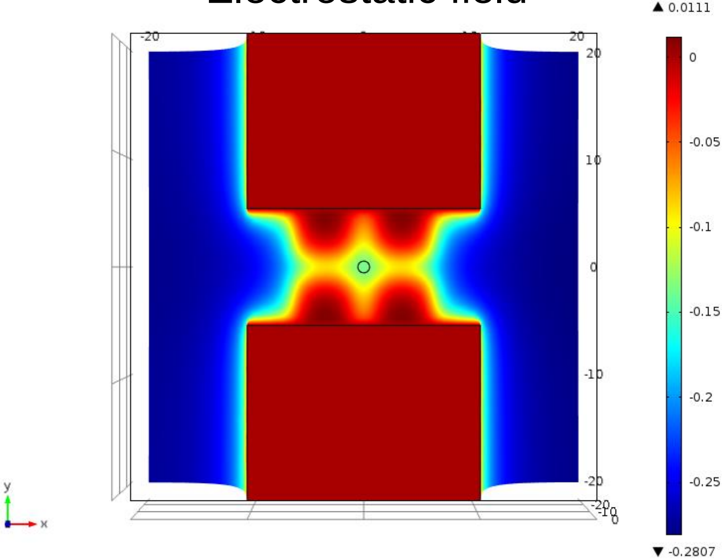
- Trapping of single electron in a 2D electrostatic potential
- Detection using transport measurements through the microchannel
- Detection and manipulation using SET

Device layout





Electrostatic field



in progress (collaboration with David Rees, National Chiao Tung University)

Summary

- Electrons on helium: unique model system

- Promising candidate for qubit implementation

- 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..

- A lot of work still needs to be done!