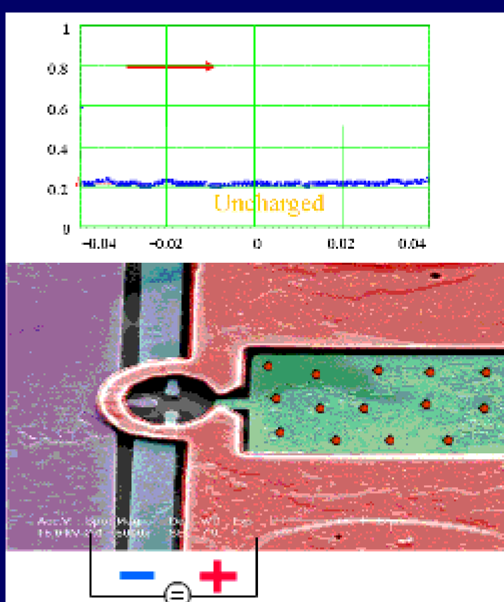
Electrons on Liquid Helium

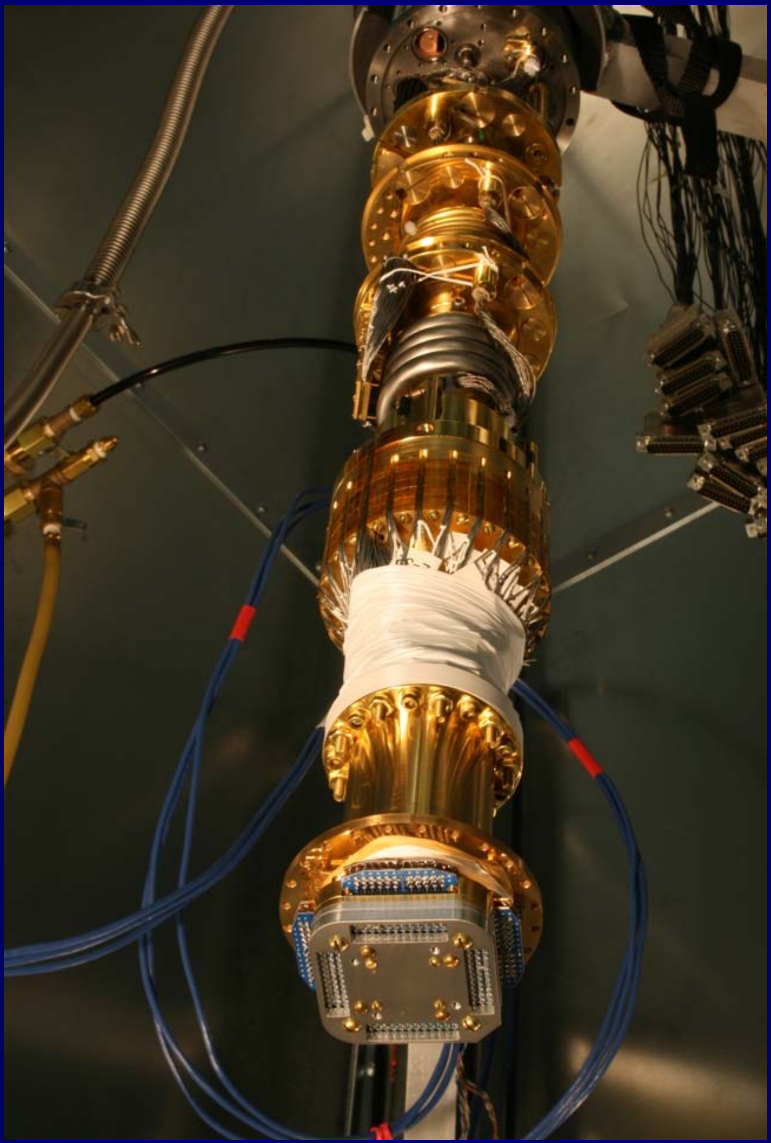


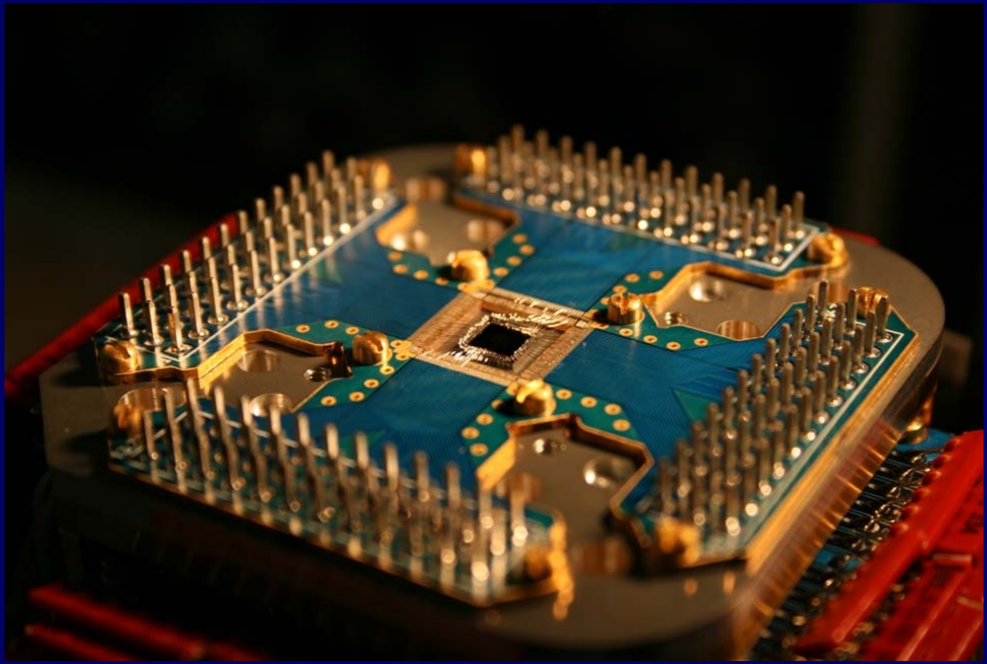
http://www-drecam.cea.fr/Images/astImg/375_1.gif

Unique qubits

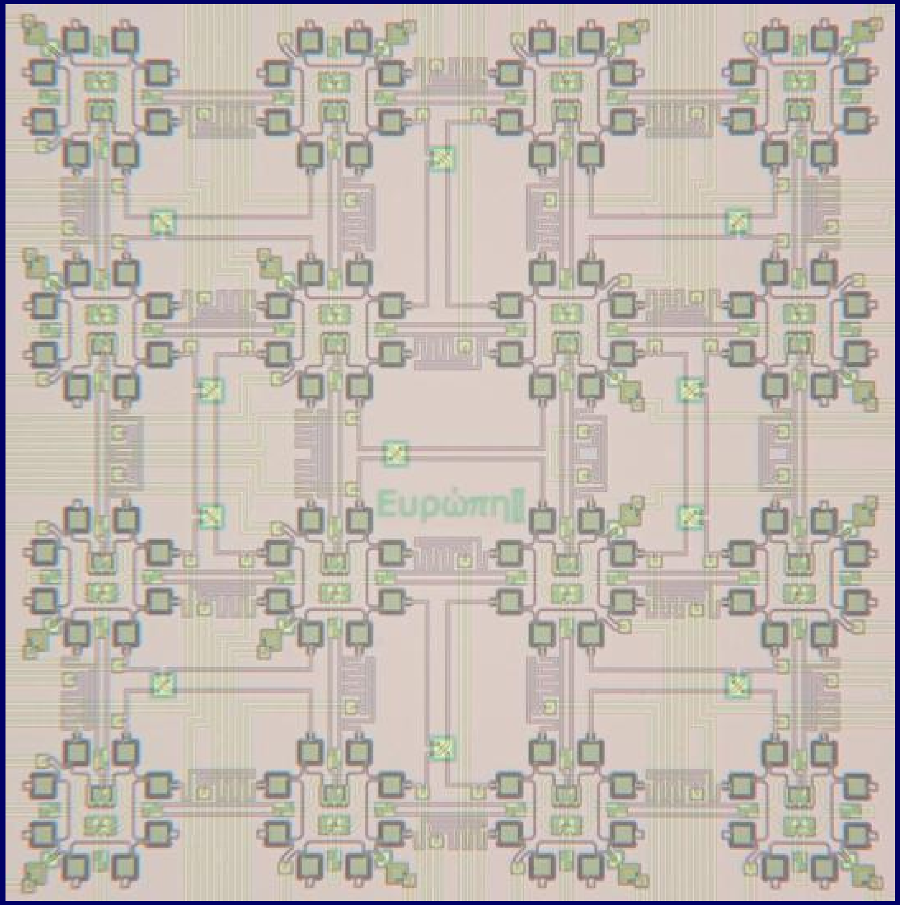
D:Wave

The Quantum Computing Company™





The D-Wave "Orion" chip



Is this a quantum computer?

The Orion system is a hardware accelerator designed to solve a particular NP-complete problem called the two dimensional Ising model in a magnetic field. It is built around a 16-qubit superconducting adiabatic quantum computer processor. The system is designed to be used in concert with a conventional front end for any application that requires the solution of an NP-complete problem. (from Geordie Rose's blog dwave.wordpress.com)

The D-Wave "Orion" chip is supposed to perform adiabatic quantum computation.

Standard QC is a sequence of unitary operations involving many energy levels, superpositions and entanglement.

Adiabatic QC works by keeping the system near the (instantaneous) ground state of the Hamiltonian, which varies slowly (adiabatically) with time.

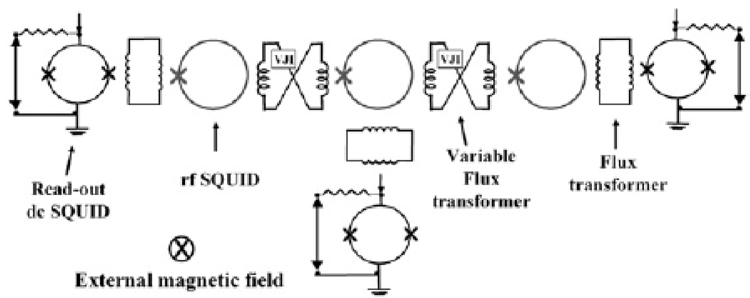
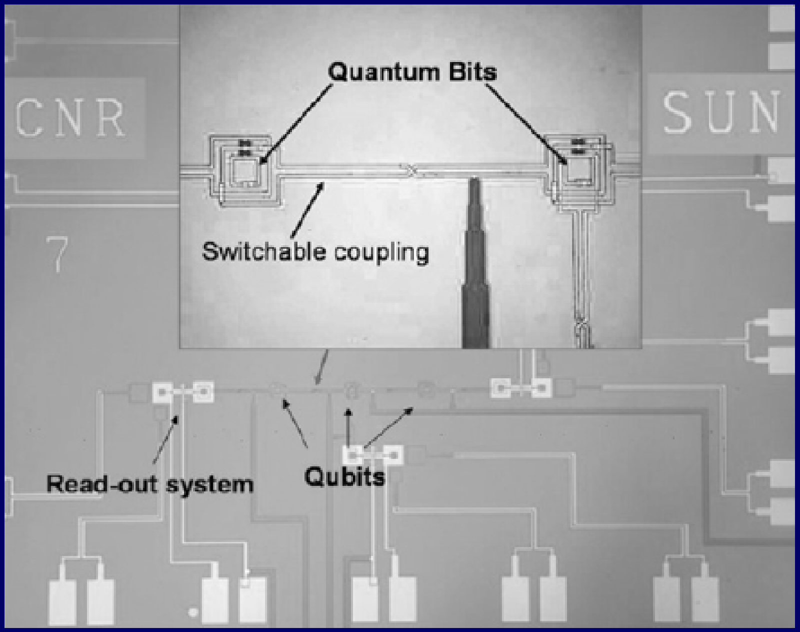


Figure 3. Sketch of the experimental design of a multi-qubit system, driven by the external magnetic flux Φ_x. Rf SQUIDs are coupled through a switchable flux transformer guaranteeing the antiferromagnetic coupling. Each qubit signal is read by a dc SQUID sensor.



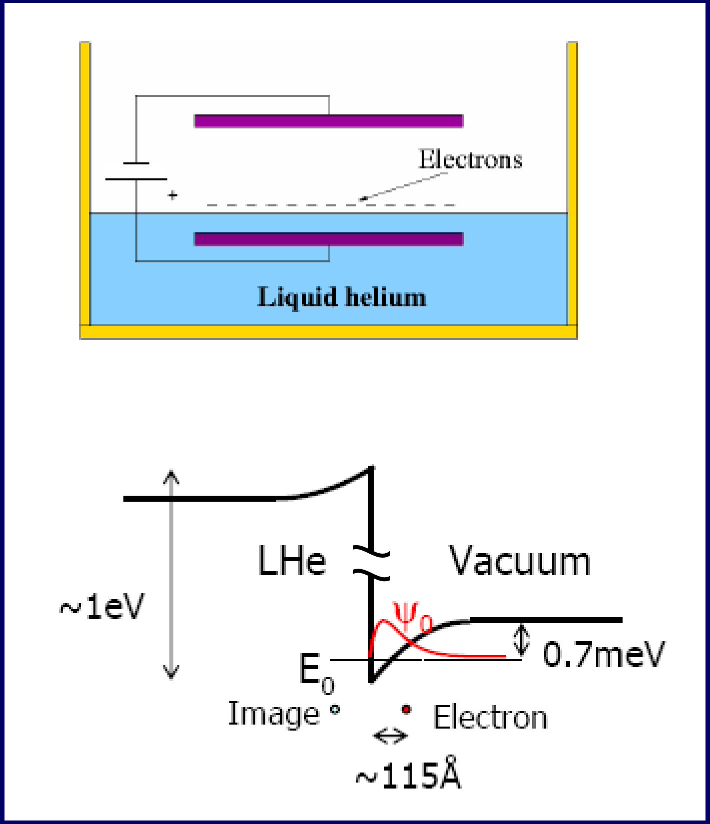
V Corato et al., proceedings of 7th European Conference on Applied Superconductivity (2006)

Electrons on Helium

Electrons are weakly attracted by the image charge (ε = 1.057 for LHe); the 1-D image potential along z is:

$$-\Sigma/z\ ,\quad \text{where } \Sigma = (\varepsilon-1)e^2/4(\varepsilon+1)$$

They are prevented from penetrating helium surface by a high (~ 1eV) barrier.



Bound states in this potential in 1-D look like hydrogen:

$E_n = -R/n^2$ (n = 1, 2, . . .), $R = \Sigma^2 m/2\hbar^2$

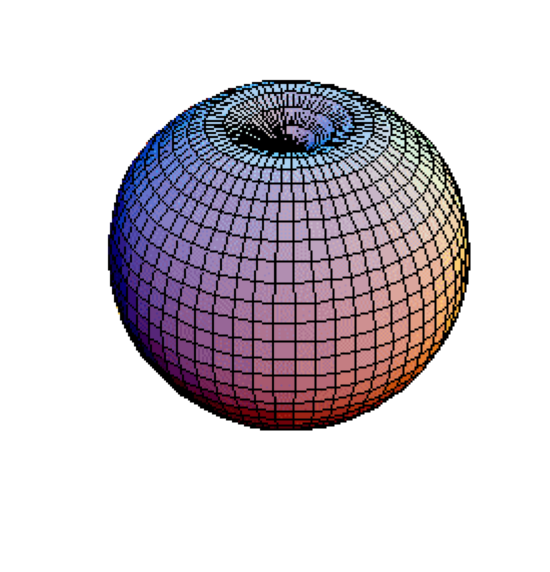
Rydberg energy is about 8K, and the effective Bohr radius is about 8 nm.

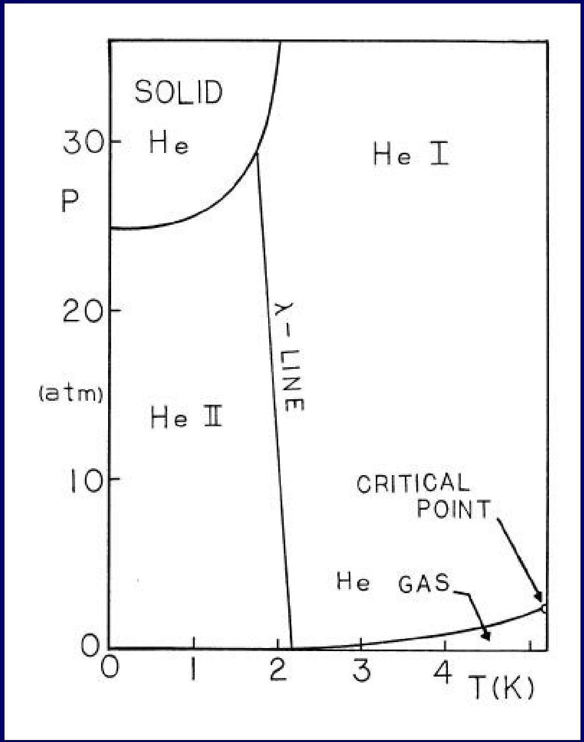
Electrons on Helium - 2

Liquid helium film must be cooled down to mK temperatures in order to reduce the vapor pressure (which would otherwise wreak havoc with among the electrons)

It is well known that below about 2.2 K He-4 turns superfluid. At few mK it is pure He II.

These features are crucial for the QC proposal with electrons on LHe. The main source of noise (heating) for the electrons trapped on the surface is the ripplons.





http://silvera.physics.harvard.edu/bubbles.htm

The original proposal

"Quantum Computing with Electrons Floating on Liquid Helium"
P. M. Platzman, M. I. Dykman, Science **284** pp. 1967 – 1969 (1999).

The qubit is formed by the two lowest energy states of the trapped electron. Given R = 8K = 170 GHz, the n = 1 and the n = 2 levels are split by about 125 GHz.

Presence of electric fields from bias electrodes introduces Stark shift of the levels.

Single qubit operations are performed by applying microwaves at the Stark-shifted frequency. Expected Rabi frequencies of the order of hundreds of MHz

Patterned bottom electrodes

Electrons on surface of LHe of thickness d (typically about 1 micron) will form a 2-D solid with lattice constant approximately equal to d. (This is because the Coulomb energy e^2/d is of the order 20 K » $k_b T$ at 10 mK).

In order to control the locations of the electrons, as well as to be able to individually address each qubits, the bottom electrode of the capacitor is patterned. This also provides confinement in the plane of the LHe film.

Electrons can be physically raised and lowered by controlling the voltages on the patterned electrodes.

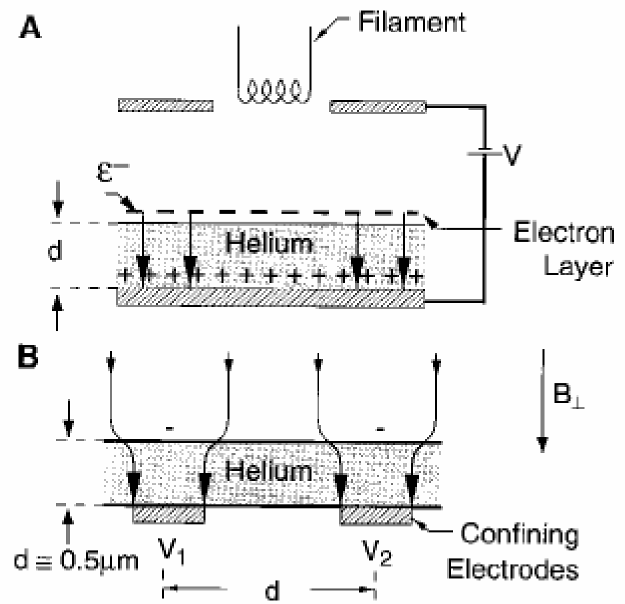


Fig. 2. (**A**) The parallel plate capacitor arrangement for confining a uniform layer of electrons. The holding field $\mathscr{E}_{-}$ and the filament for charging are shown. (**B**) The geometry for a pair of electrons on a patterned substrate. The rough dimensions, the shape of the field lines, and the control gate are included.

Two-qubit gates

Two-qubit gates via dipole-dipole interaction (similar to the liquid state NMR QC).

For a dipole moment (er), the interaction energy between qubits separated by distance d is $(er)^2/d^3$. At 1 micron separation the interaction energy is estimated to be about 10 MHz.

The frequency of the coupling is qubit state-dependent (because (er) is state-dependent). This forms the basis of the quantum logic gates like the CNOT gate.

However, it is strongly distance-dependent. Thus, interactions are limited to nearest neighbors.

The readout

"In order to read out the wave function at some time t_f, when the computation is completed, we apply a reverse field E_+ to the capacitor..."

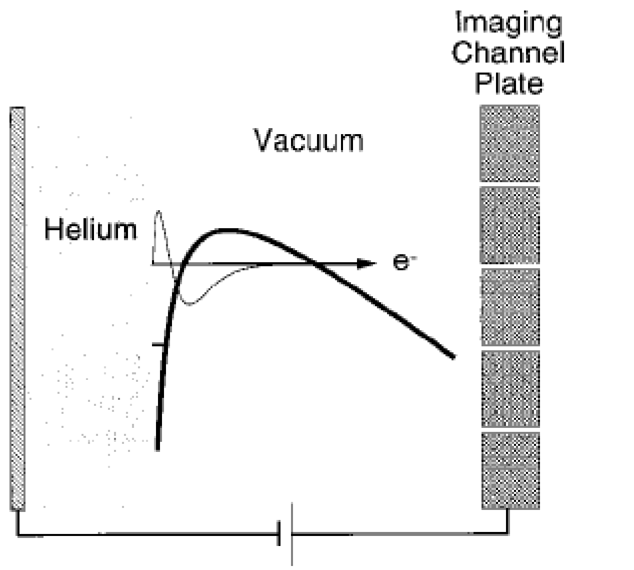


Fig. 3. The read-out configuration. The potential leading to tunneling when a reverse field is shown, along with a schematic of the position-sensitive channel plate.

Qubit readout relies on state-dependent electron tunneling when a reversed bias field is applied to the capacitor.

This tunneling readout scheme is similar to the readout of superconducting flux qubits.

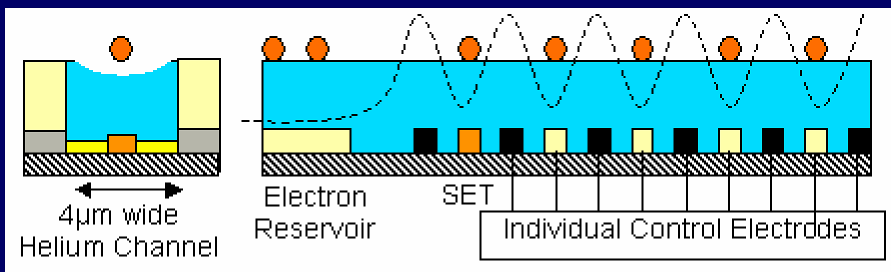
In this proposal, a multi-channel plate detector is envisioned. An SET can be used, too.

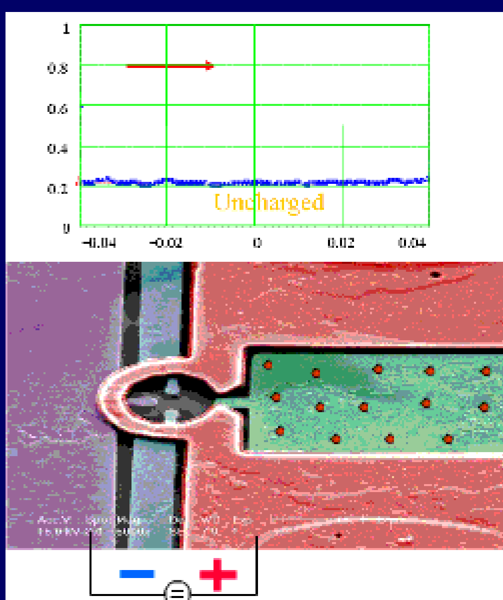
Problems: reading out the whole system at once; need to detect single electrons reliably

Current state-of-the-art

Planar structures with SET readout

Mike Lea, Royal Holloway University of London





Surface tension in the channel defined LHe depth; control electrodes on the bottom define individual traps.

The readout is performed by a SET at the end of the channel. The electrons are ionized first if they are in the higher energy state, then read out one by one.

Trapping and controlling individual e^-

Phil Platzman (Lucent) and John Goodkind (UC San Diego)

Developing a cold-cathode source of electrons.

Microfabricated pattern of micron-sized pillars to trap individual electrons

Readout by ionizing the upper state electrons and using bolometry ~2 mm above the surface

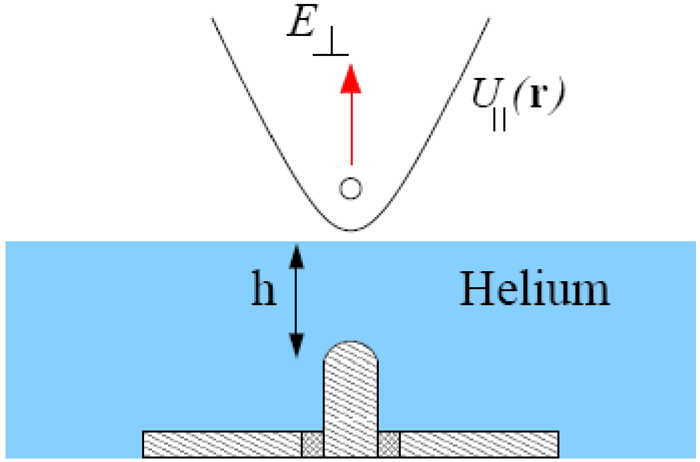
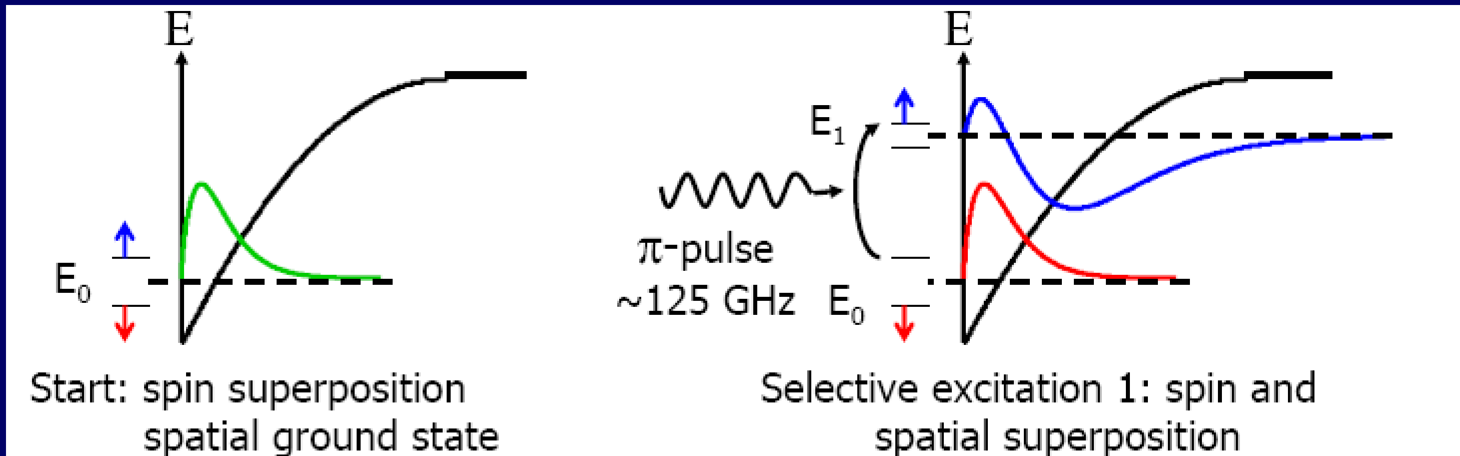


FIG. 1: A sketch of a micro-electrode submerged by the depth $h \sim 0.5\,\mu$m beneath the helium surface, with an electron localized above it. The electron is driven by a field $E_\perp$ normal to the surface. This field comes from the electrode and the parallel-plate capacitor (only the lower plate of the capacitor is shown). The in-plane electron potential $U_{||}(\mathbf{r})$ is parabolic near the minimum, with curvature determined by the electrode potential ($\mathbf{r} = (x, y)$ is the in-plane position vector).

Spin-based qubits with EoH

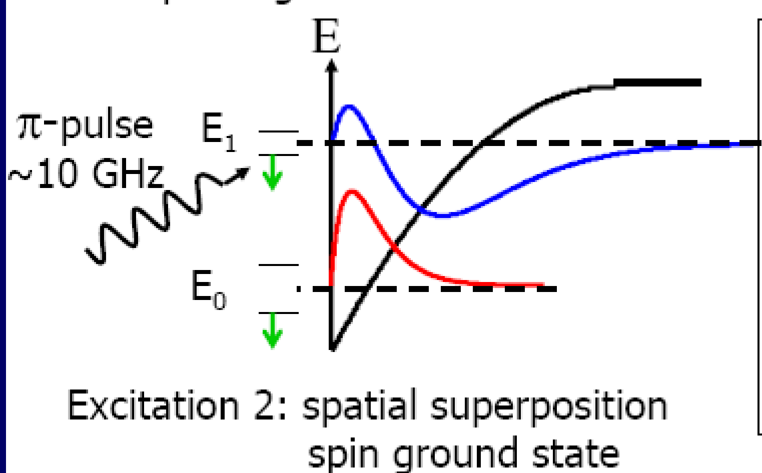
Spin qubit coherence times are longer; may be better suited for QC than the motion states (charge qubit).

Spins coupled mapping on motion states, then performing dipole-dipole gates as in the original proposal



Start: spin superposition
spatial ground state

Selective excitation 1: spin and
spatial superposition



Excitation 2: spatial superposition
spin ground state

Can interchange spin and spatial superpositions – analogous to ions

1. Convert spin to space
2. Use Platzman-Dykman 2-qubit interactions (electric dipole-dipole)
3. Convert back to spin

$\Rightarrow$ A few μs

Steve Lyon
(Princeton)

Conclusions....

- A "neat" and certainly very unique approach
- Builds on ideas from the superconducting qubits, trapped ions, quantum dots
- The experiment is harder than theory. Some theoretical predictions unrealistic.