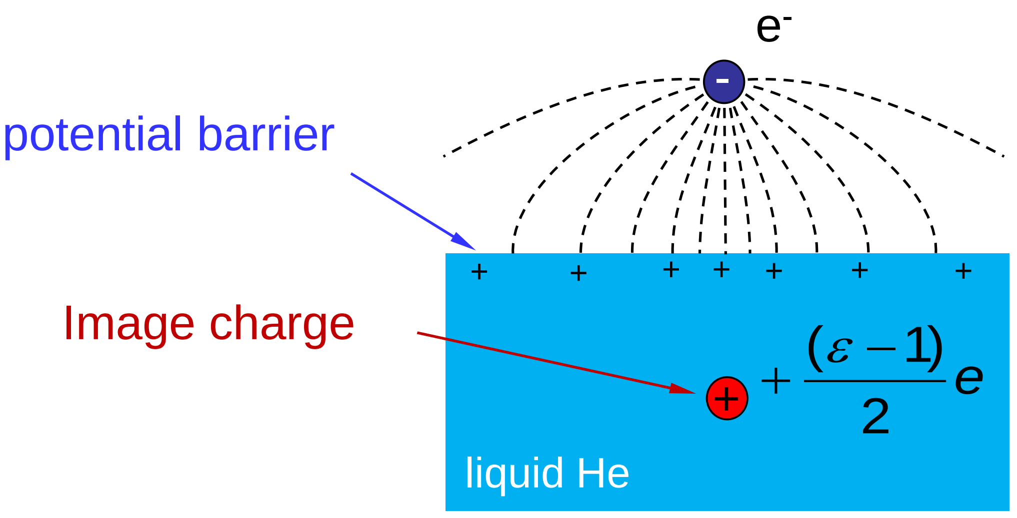
Realization of spin qubits using electrons on the surface of superfluid helium

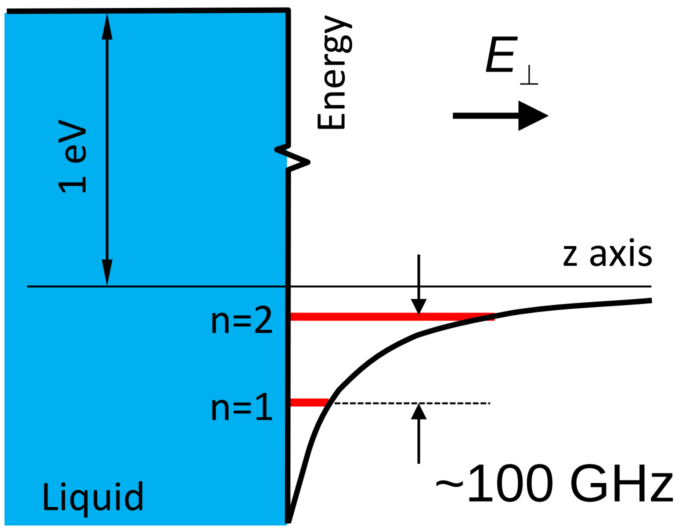
Denis Konstantinov, Quantum Dynamics Unit
OIST Graduate University

OKINAWA INSTITUTE OF SCIENCE AND TECHNOLOGY GRADUATE UNIVERSITY

APTQS 2022

Surface States of Electrons on Helium (EonHe)





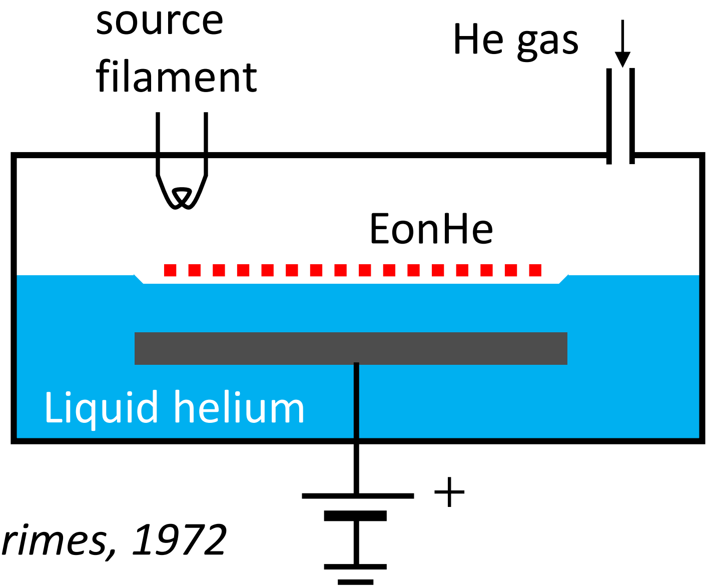
Hydrogen-like (Rydberg) spectrum: $\boxed{E_n = -\frac{R_y}{n^2},\ \ n = 1, 2, \ldots}$

Small Rydberg energy: $\boxed{R_y = \frac{(\varepsilon-1)^2 m_e^2 e^2}{16\hbar^2} \approx 10^{-3}\ \text{eV} = 10\ \text{K}}$

Linear Stark shift: $\boxed{\Delta E_n = eE_\perp z_{nn}}$

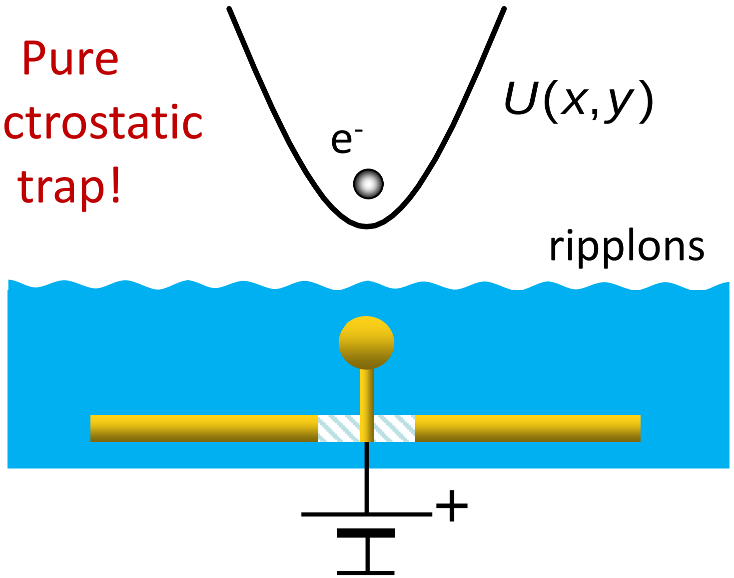
2D electron system

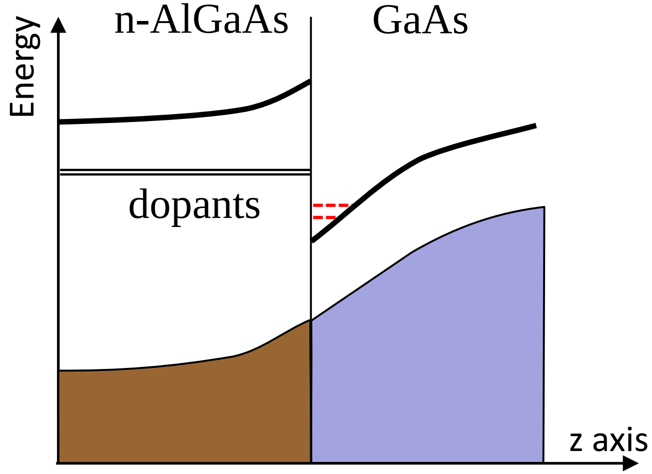
T<1 K



Brown and Grimes, 1972

Pure
electrostatic
trap!

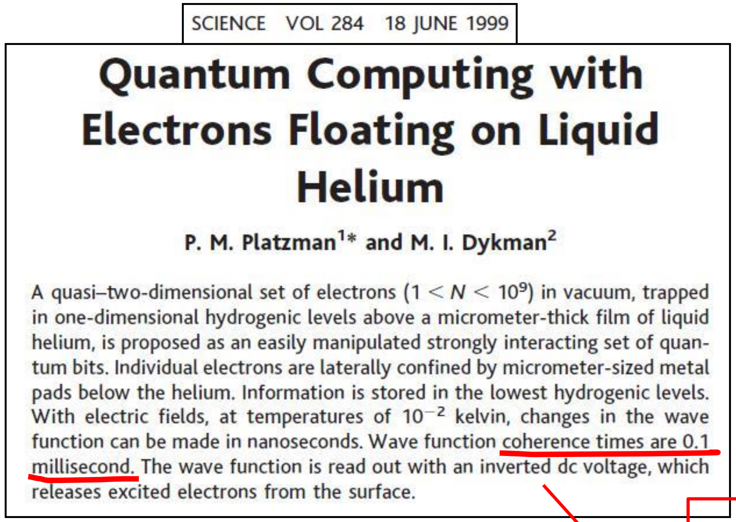




Why liquid helium?

- Remains liquid down to T=0
- Smooth surface, no defects
- Interaction only with ripplons

Quantum computing using Rydberg states



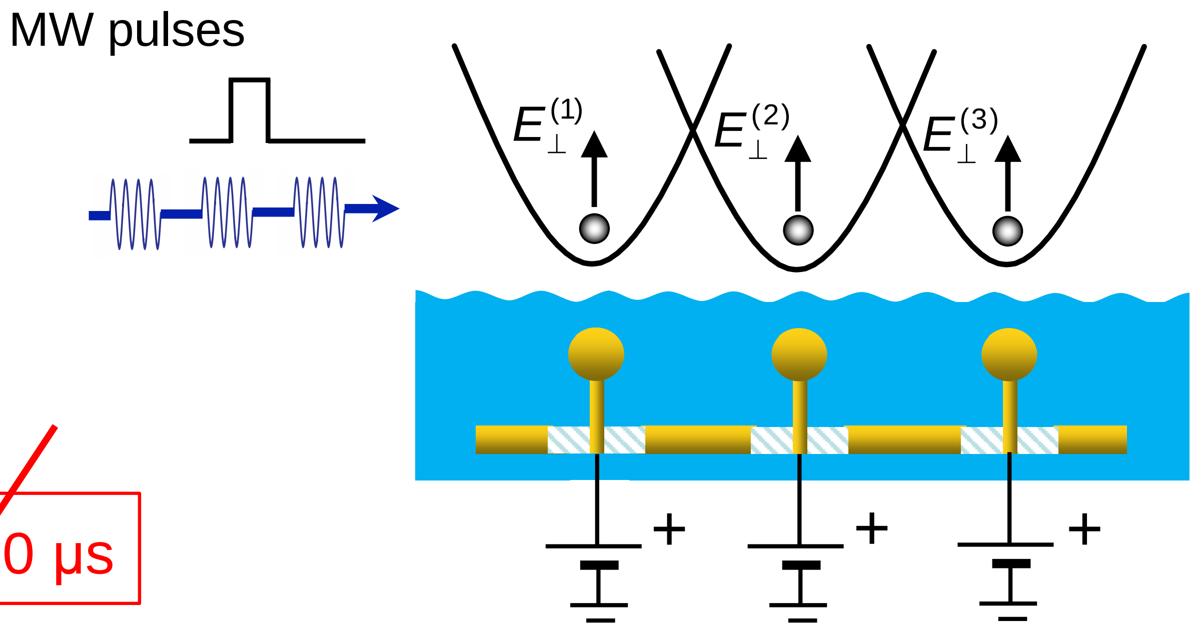
SCIENCE VOL 284 18 JUNE 1999

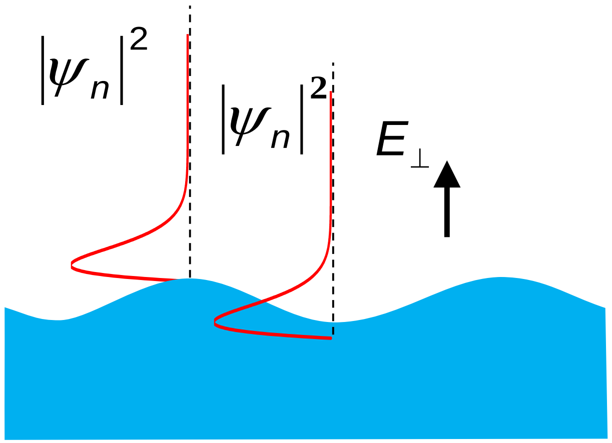
Quantum Computing with Electrons Floating on Liquid Helium

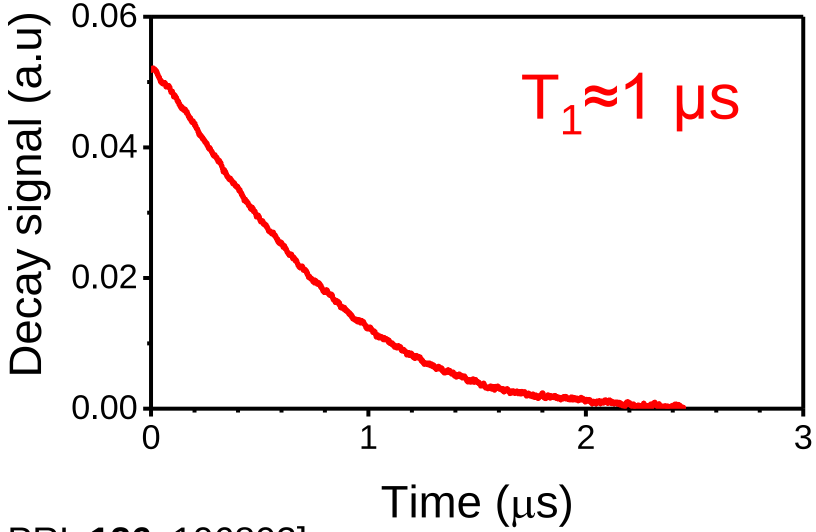
P. M. Platzman[1]* and M. I. Dykman[2]

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~~

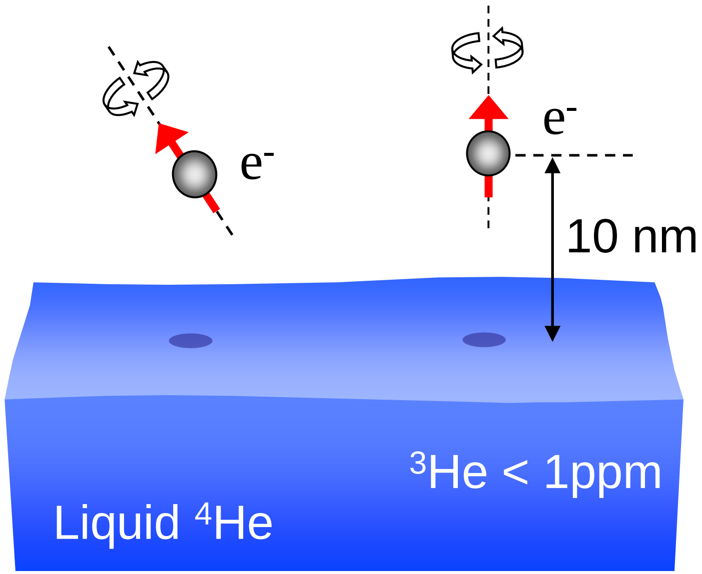




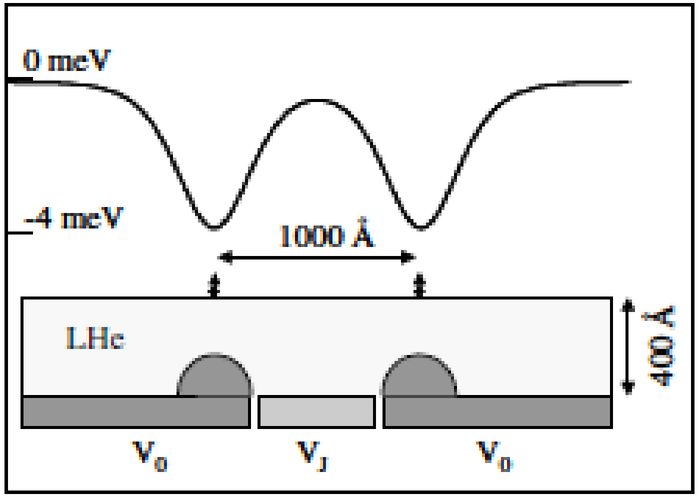


[E. Kawakami *et al.*, PRL **126**, 106802]

Quantum computing using spins



Steve Lyon, 2004



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

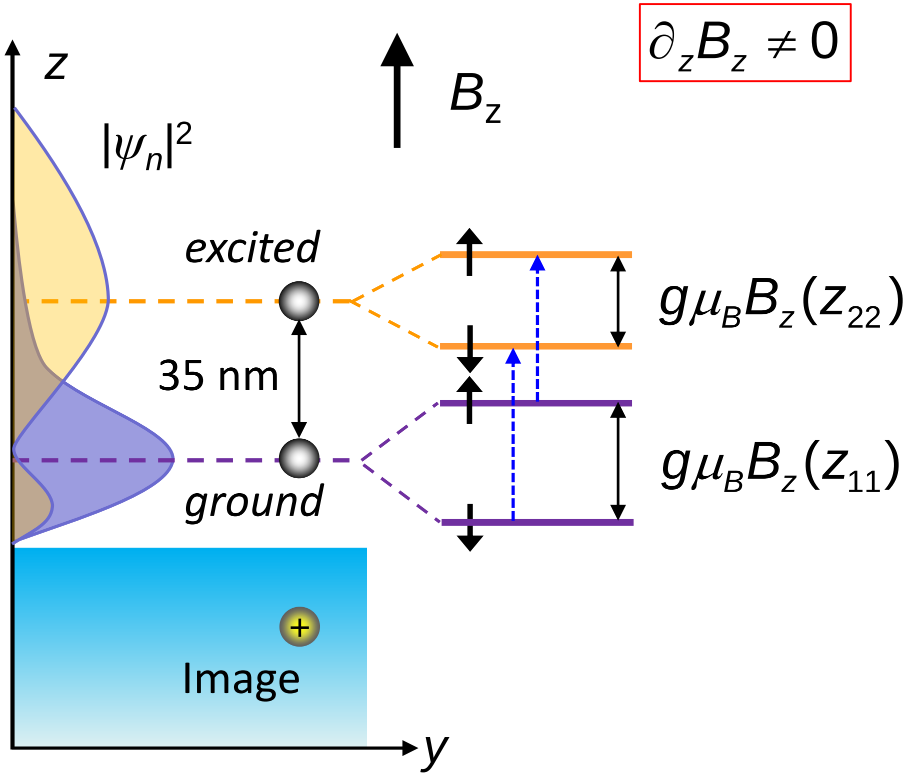
Spin coherence time >100 s!

- Negligible SO interaction
- Magnetic-impurity-free environment
- Negligible noise from electrodes

How to control spin states?

- Very week dipole interaction
- Slow spin rotations
- Spin state readout?

Introduce SO coupling (Spin-Rydberg)



Erika Kawakami

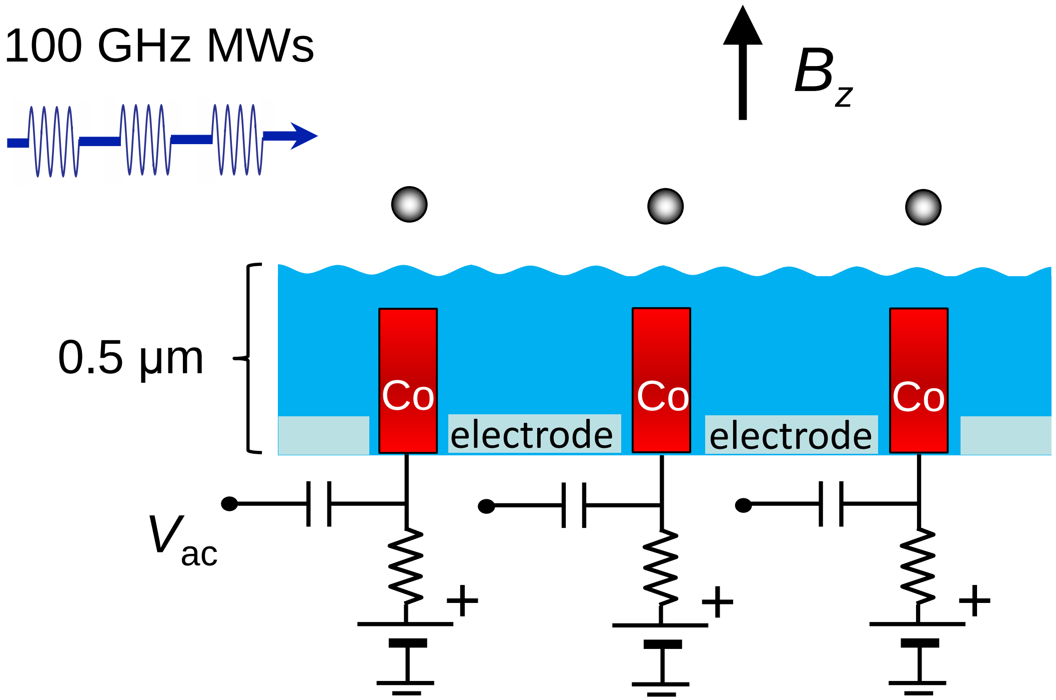
Spin-orbit (SO) interaction:

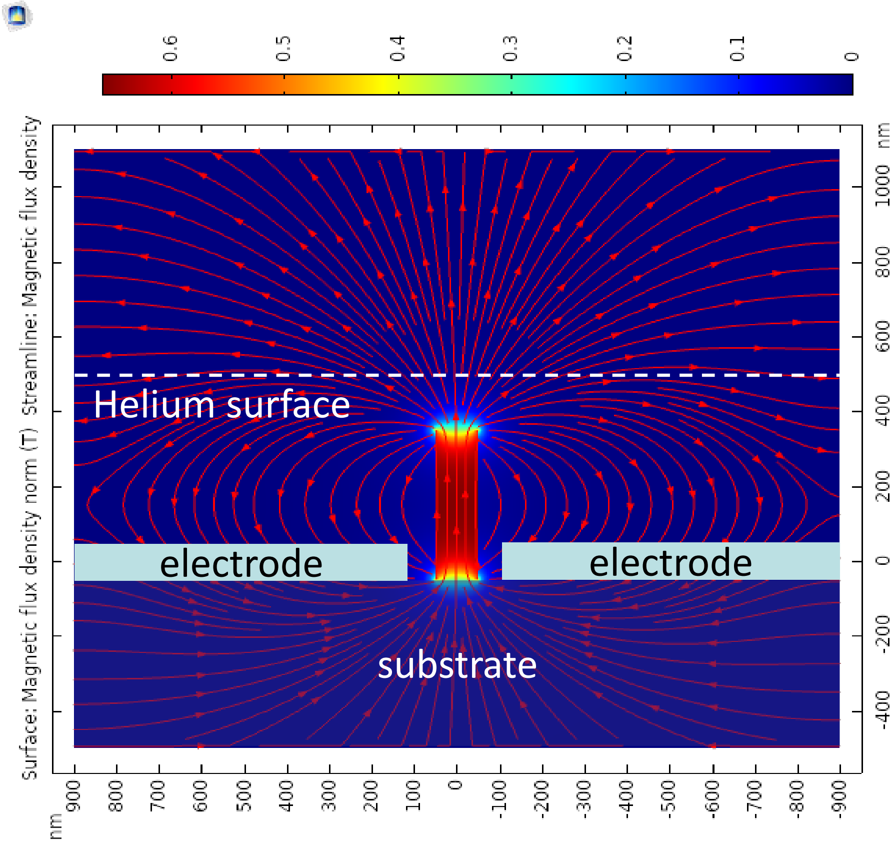
$$\boxed{H_{SO} = \gamma_e \left(\frac{\partial B_z}{\partial z} \right) z s_z}$$

Different Zeeman splitting for
ground and excited Rydberg states!

- Fast spin rotations (single-q gate)
- Spin-state readout (q-readout)
- Spin-spin coupling (two-q gate)

EonHe-Spin quantum computer





Difference in Zeeman splitting:

$$\boxed{g\mu_B\left(\frac{\partial B_z}{\partial z}\right)(z_{22}-z_{11})\approx 100\,\mathrm{MHz}}$$

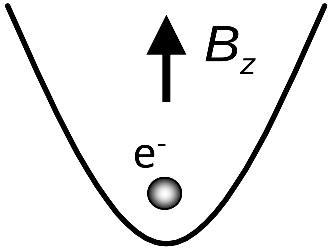
Magnetic field gradient:

$$\boxed{\frac{\partial B_x}{\partial z}\approx 0.14\,\mathrm{mT/nm}}$$

Decoherence of spin states

SO coupling will decrease coherence of spin states!

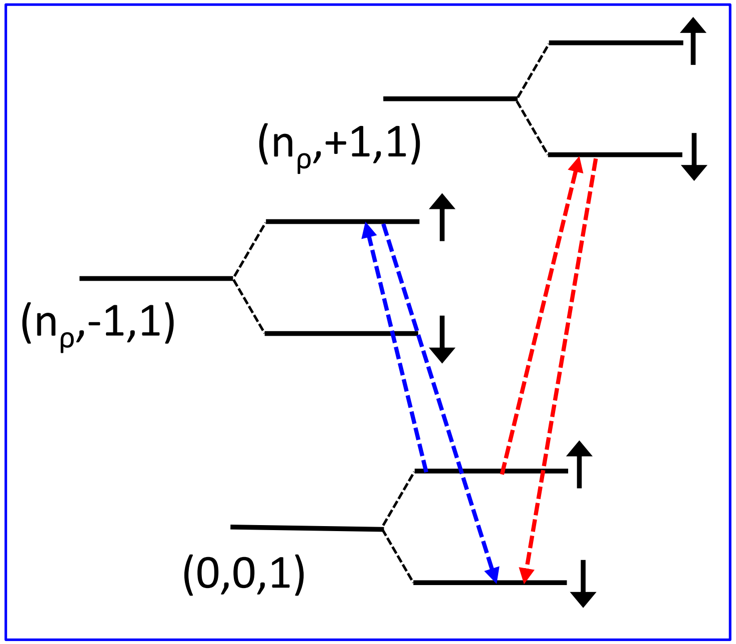
① Spin relaxation



$$\boxed{H = H_{Fock-Darwin} + H_z + H_s + H_{SO} + H_{e-ripplons}}$$

$$\underbrace{H_{Fock-Darwin}}_{\text{in-plane motion}} \quad \underbrace{H_z}_{\text{vertical motion}} \quad \underbrace{H_s}_{\text{spin}} \quad \underbrace{H_{SO} + H_{e-ripplons}}_{\text{perturbation}}$$

Virtual transitions to orbital states



Second order perturbation theory:

$$\boxed{T_1^{-1} \approx \Gamma_{\text{orbital}} \left(\gamma_c l_B \left(\frac{\partial B_\rho}{\partial \rho} \right) \frac{\sqrt{\omega_c^2 + \omega_0^2}}{8\omega_0^2} \right)^2 \approx 10\ \text{s}^{-1}}$$

Decoherence of spin states

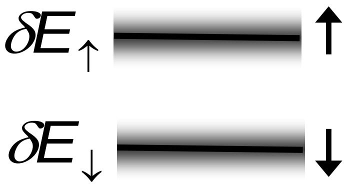
SO coupling will decrease coherence of spin states!

② Spin dephasing

$$\boxed{H = H_{Fock-Darwin} + H_z + H_s + H_{SO} + H_{e-ripplons}}$$

$$\underbrace{H_{Fock-Darwin}}_{\text{in-plane motion}} + \underbrace{H_z}_{\text{vertical motion}} + \underbrace{H_s}_{\text{spin}} + \underbrace{H_{SO} + H_{e-ripplons}}_{\text{perturbation}}$$

$$\boxed{\left\langle [\varphi(t) - \varphi(0)]^2 \right\rangle = \frac{1}{\hbar^2} \int \int_0^t dt_1 dt_2 \left\langle \delta E_{\uparrow\downarrow}(t_1) \delta E_{\uparrow\downarrow}(t_2) \right\rangle}$$

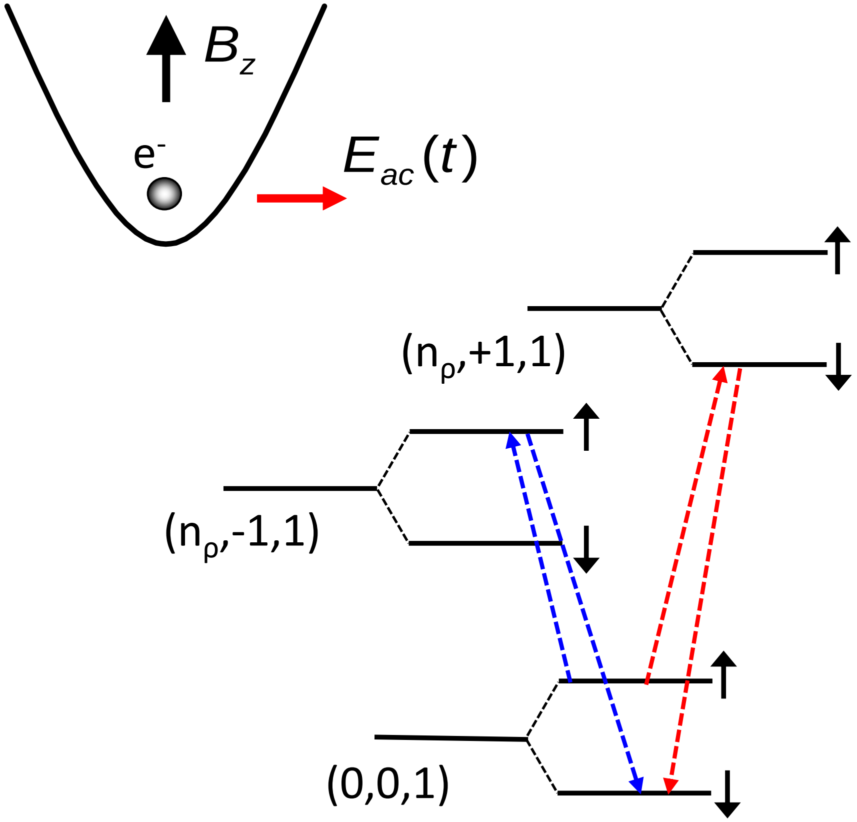


Second order perturbation theory:

$$\boxed{\Gamma_\varphi(T) \approx 10^{-2}\ \mathrm{s}^{-1}}$$ @ T=100 mK

Spin rotation by RF electric field

$$\boxed{H = \underbrace{H_{Fock-Darwin}}_{\textit{orbital motion}} + H_z + \underbrace{H_s}_{\textit{spin}} + \underbrace{H_{SO}}_{\textit{SO interaction}} + H(t)}$$



Electrical dipole approximation:

$$\boxed{H(t) = Ve^{-i\omega t} + V_+ e^{i\omega t},\ V = eE_{ac}x}$$

Second order perturbation theory:

$$\boxed{\Omega_{rot} \approx \Omega_{dipole}\gamma_c l_B \left(\frac{\partial B_z}{\partial \rho}\right)\left(\frac{\sqrt{\omega_c^2 + \omega_0^2}}{4\omega_0^2}\right) \approx 20\,\text{MHz}}$$

@ E_{ac}=1 V/mm

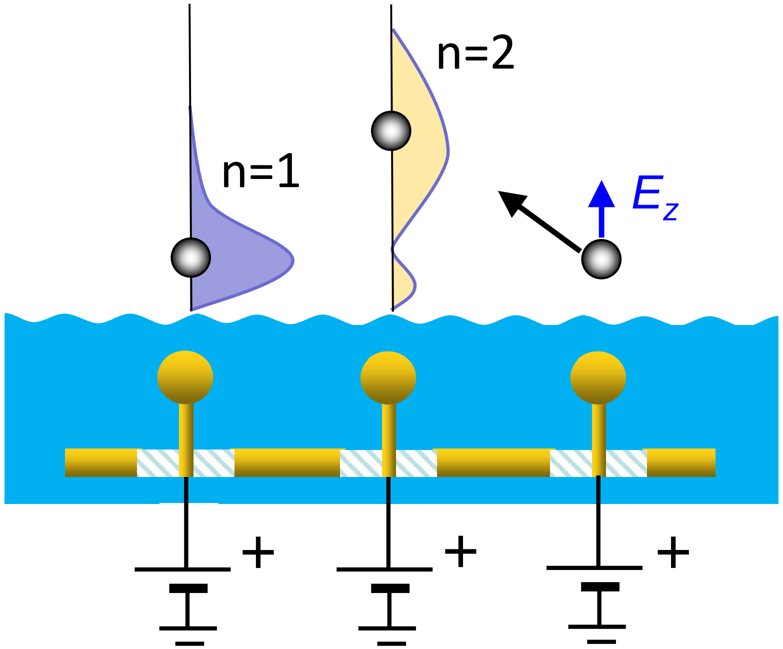
Electron-electron interaction

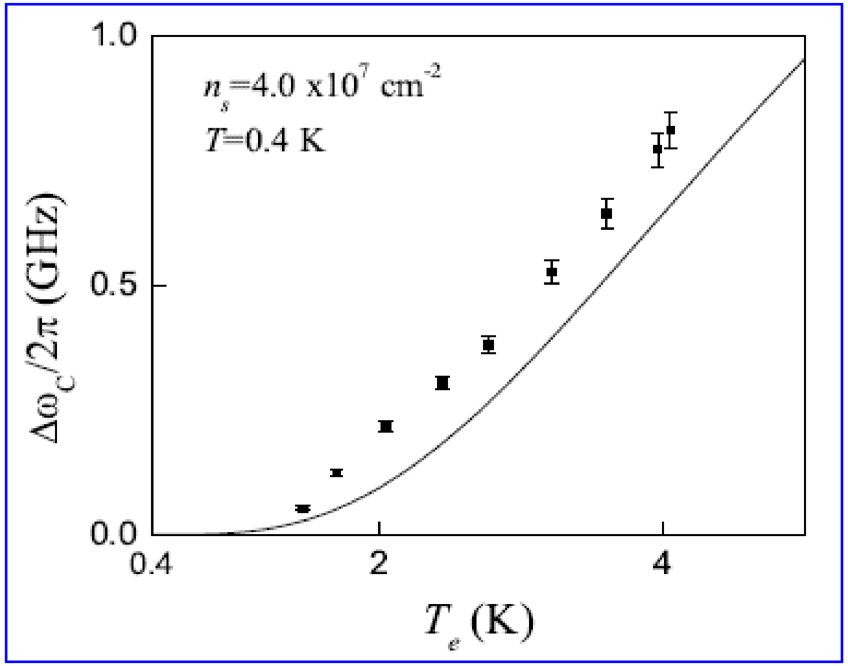
- Spin relaxation (T_1=100 ms)
- Spin dephasing (T_2^*>1 s)
- Spin rotations (Ω_{rot}~10 MHz)

Two-qubit gate?

The Coulomb interaction!

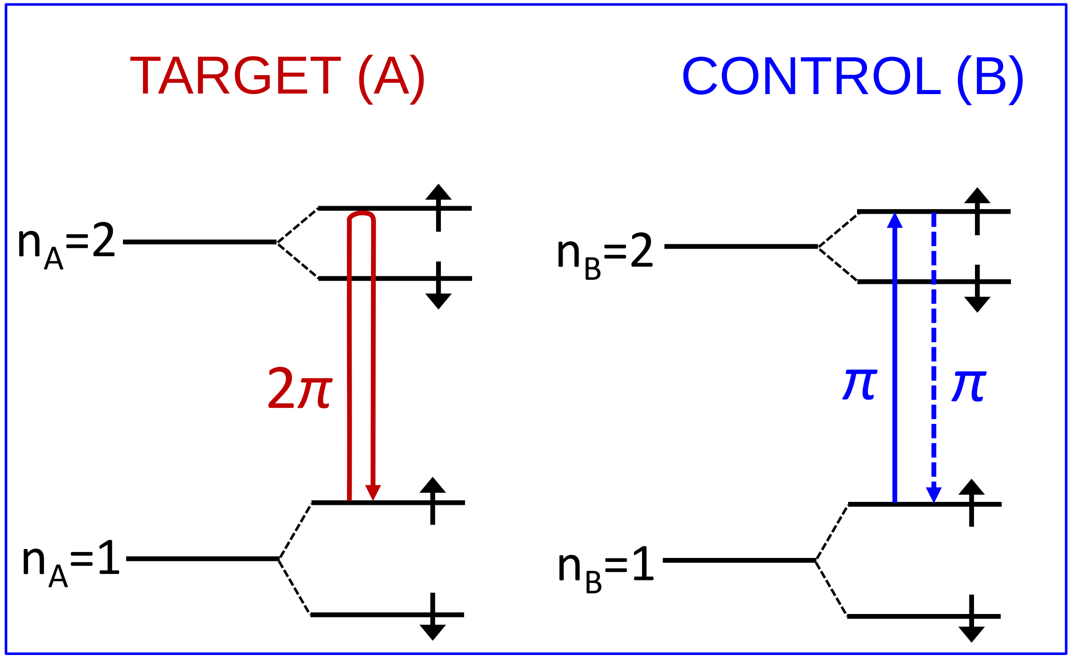
Coulomb shift of Rydberg energies:

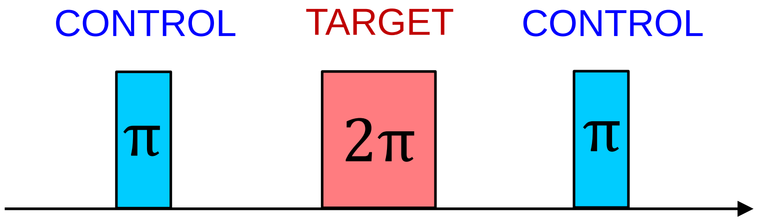




[DK *et al.*, PRL **103**, 096801]

Two-qubit gate





$$\begin{aligned}
&|11\rangle|\downarrow\downarrow\rangle \rightarrow |11\rangle|\downarrow\downarrow\rangle \rightarrow |11\rangle|\downarrow\downarrow\rangle \rightarrow |11\rangle|\downarrow\downarrow\rangle \\
&|11\rangle|\uparrow\downarrow\rangle \rightarrow |11\rangle|\uparrow\downarrow\rangle \rightarrow |11\rangle|\uparrow\downarrow\rangle \rightarrow |11\rangle|\uparrow\downarrow\rangle \\
&|11\rangle|\downarrow\uparrow\rangle \rightarrow -i|12\rangle|\downarrow\uparrow\rangle \rightarrow -i|12\rangle|\downarrow\uparrow\rangle \rightarrow |11\rangle|\downarrow\uparrow\rangle \\
&|11\rangle|\uparrow\uparrow\rangle \rightarrow -i|12\rangle|\uparrow\uparrow\rangle \rightarrow i|12\rangle|\uparrow\uparrow\rangle \rightarrow -|11\rangle|\uparrow\uparrow\rangle
\end{aligned}$$

Controlled-phase gate

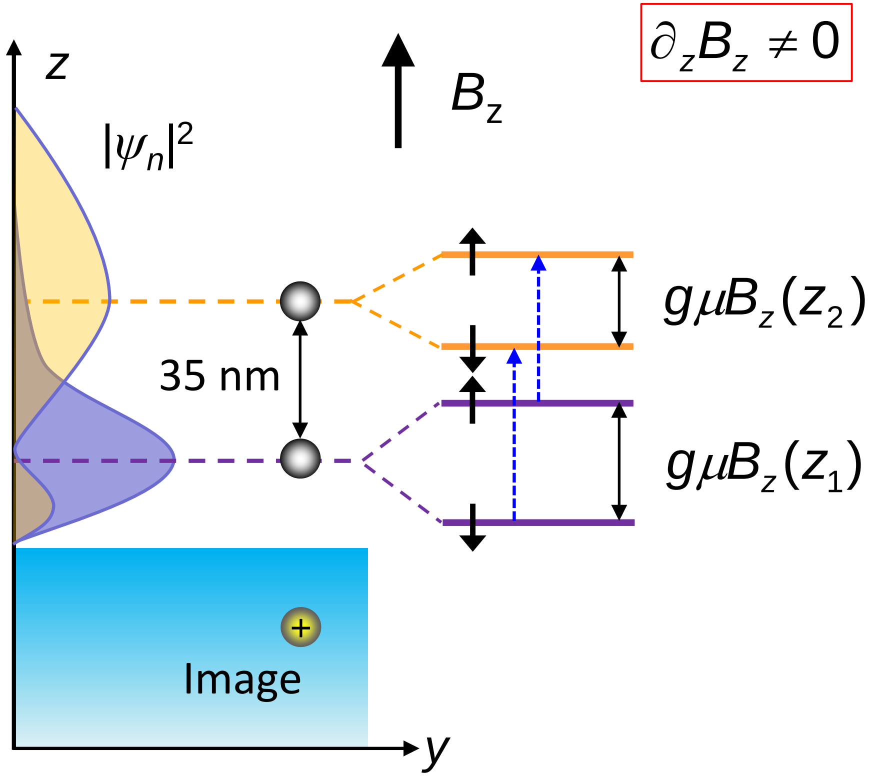
[Cirac and Zoller, PRL **74**, 4091]

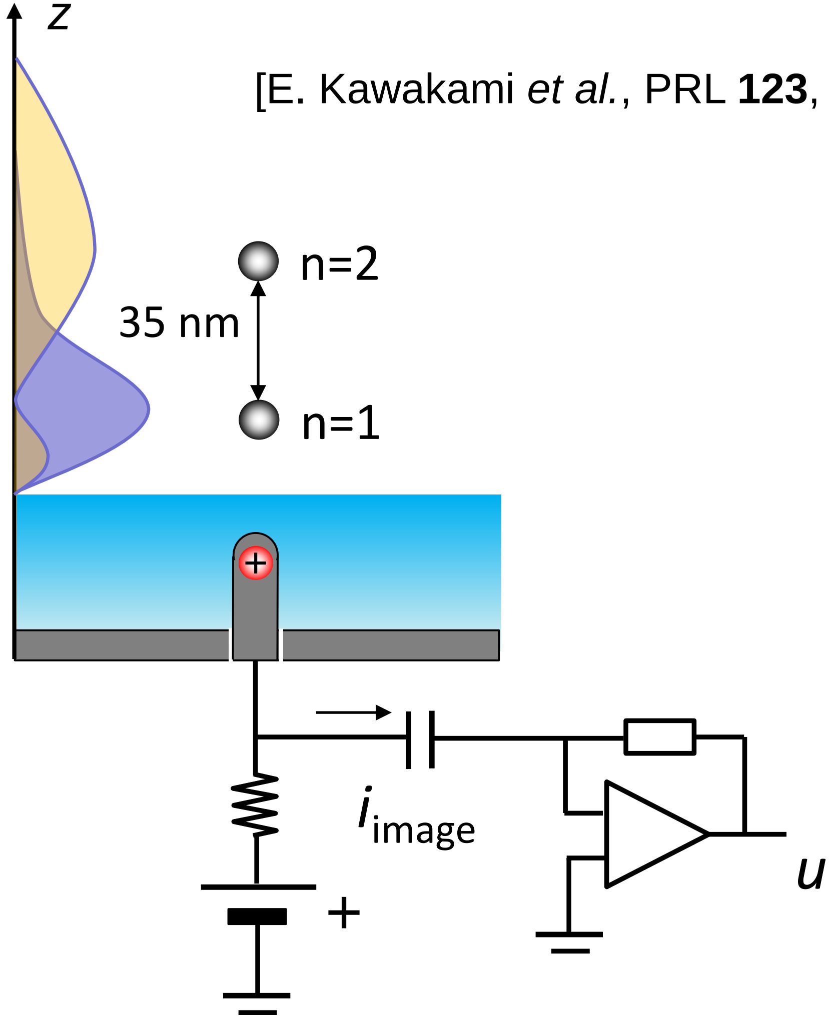
All rotations are on Rydberg states

$\boxed{\Omega_{dipole} \sim 100\ \text{MHz}}$

Spin-state readout

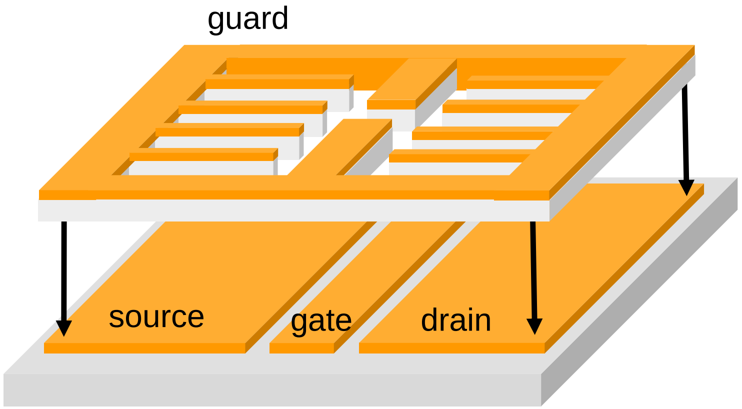
Detect the Rydberg transition $\overset{\text{SO}}{\Longrightarrow}$ know the spin state!

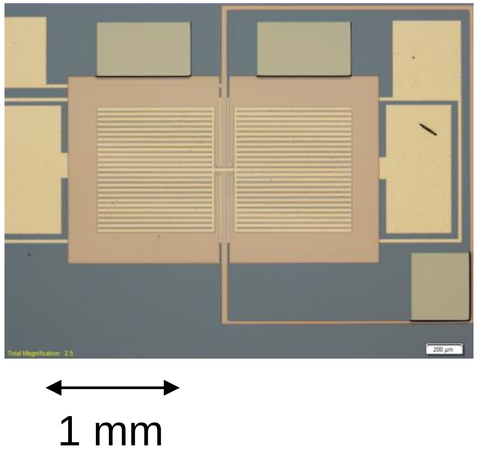




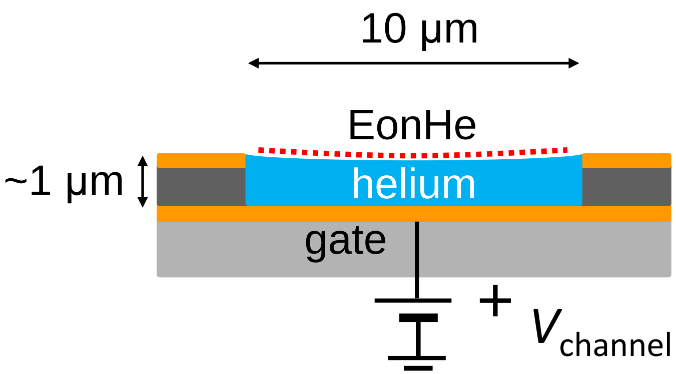
[E. Kawakami *et al.*, PRL **123**, 086801]

Electrons in Microchannel Devices

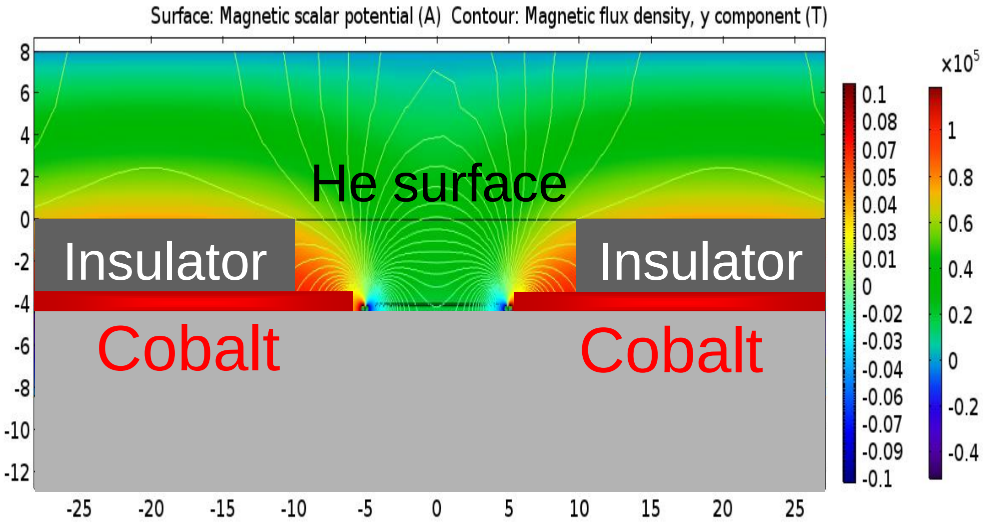


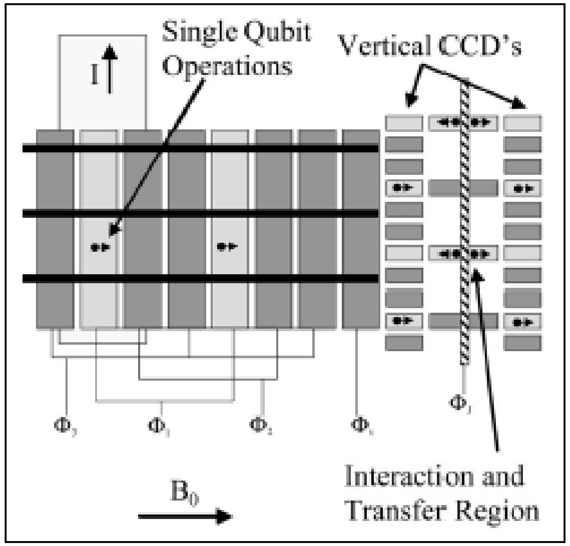


Central Channel



B-field gradient:

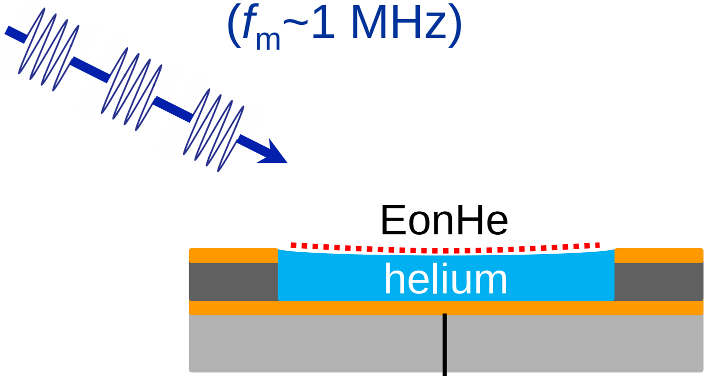


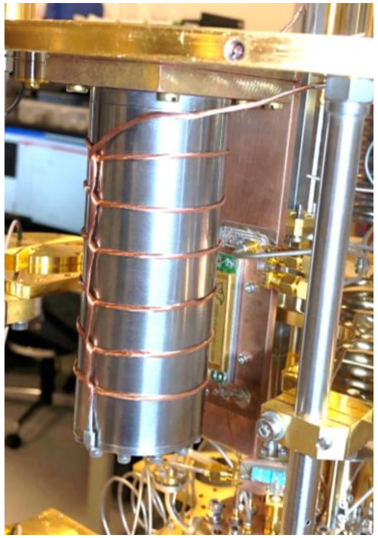


[S. A. Lyon, Phys. Rev. A, **74**, 052338]

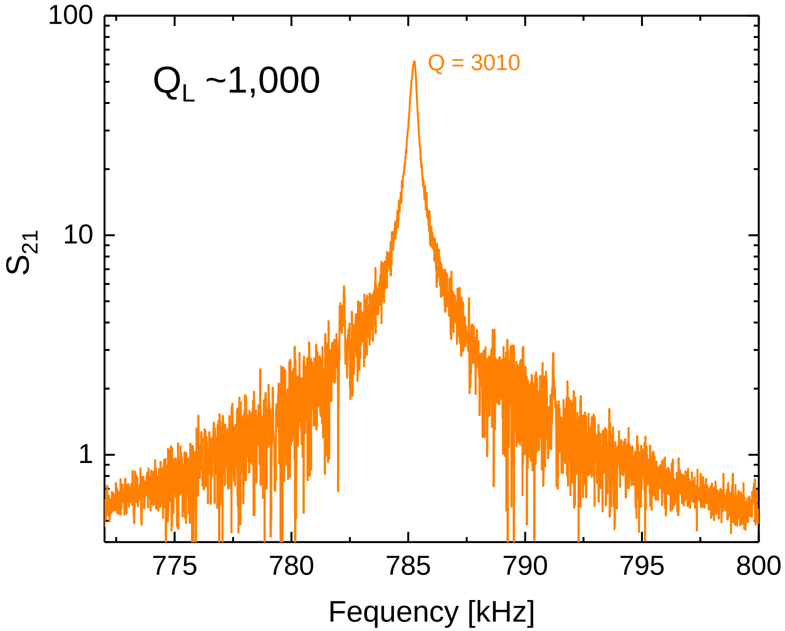
Detection of Rydberg transition of EonHe in a microchannel

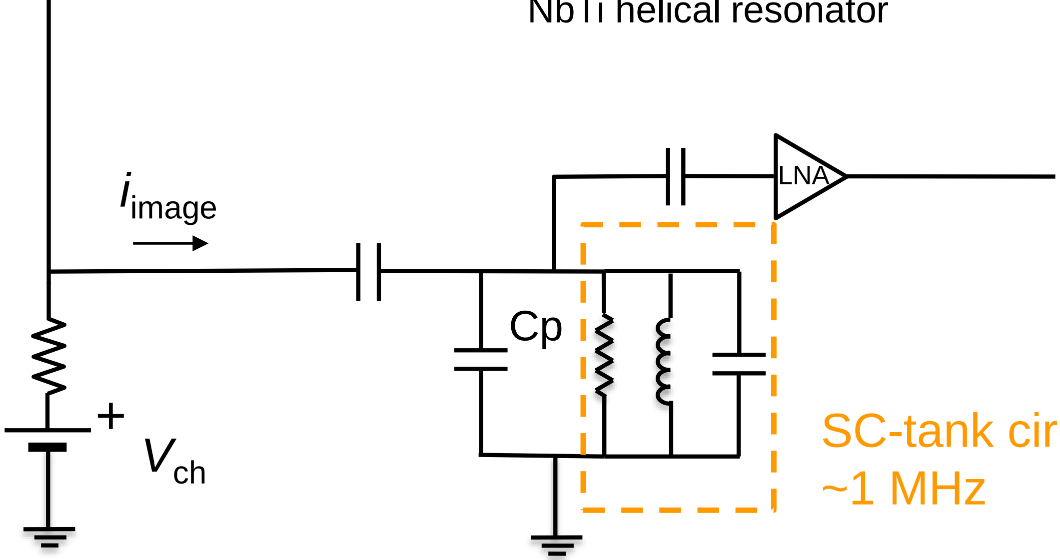
Pulse-modulated
100 GHz excitation
(f_m~1 MHz)





NbTi helical resonator



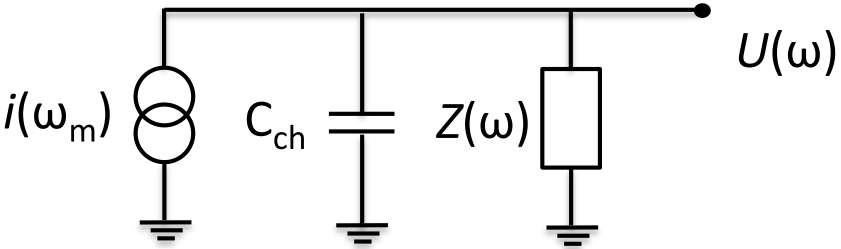


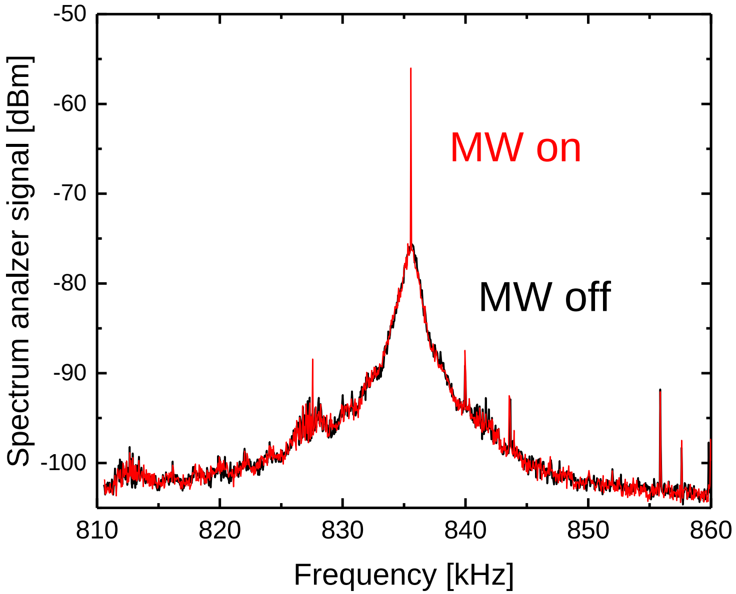
To room-temperature
electronics

SC-tank circuit
~1 MHz

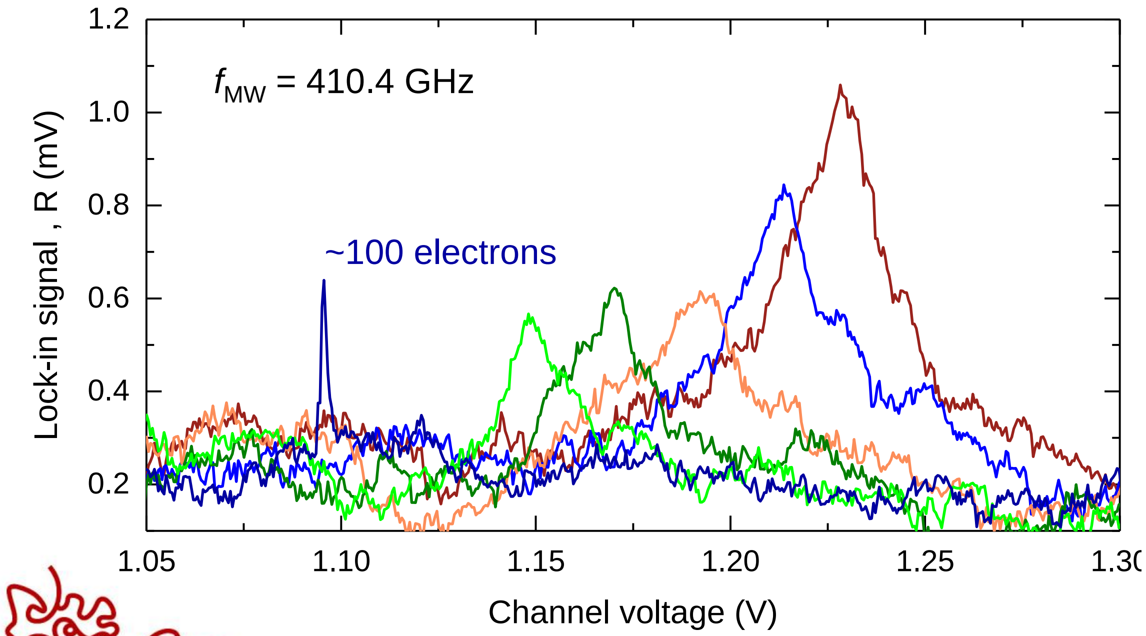
[Wineland and Dehmelt, J. Appl. Phys. **46**, 919]

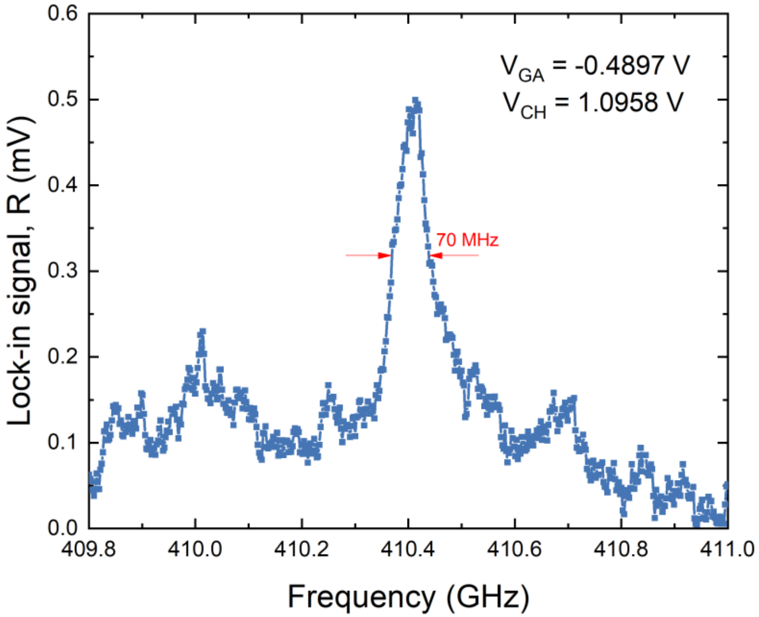
Rydberg transition





Stark-tuning to resonance:





Summary

Introduce SO coupling to control spin states of EonHe

Suitable for quantum computing

- Slow spin decoherence (T_1=100 ms)
- Fast spin rotations (Ω_{rot}~10 MHz)
- Fast 2-qubit gate (Ω_{dipole}~100 MHz)
- Spin readout by image current

Microchannel devices: scalability, mobile qubits, QCCD architecture..

Acknowledgement

Erika Kawakami
(former postdoc)

Floating-Electron-Based
Quantum Information (PI)
RIKEN

Shan Zou
(PhD student)

OIST

Mikhail
Belianchikov
(Postdoc)

OIST

https://www.groups.oist.jp/qdu

https://www.oist.jp

<u>Funding:</u>

OIST

KAKENHI MEXT

科研費
KAKENHI