Quantum Technologies, risks and prospects

Morten Hjorth-Jensen

Department of Physics and Center for Computing in Science Education, University of Oslo, Norway

40th Nordic Conference on Law and IT – Regulating for Complexity, November 5-7, 2025

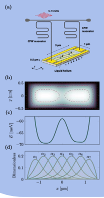
What is this talk about?

The main emphasis is to give you a short and hopefully pedestrian introduction to the whys and hows of quantum technologies. And why this could (or should) be of interest.

Quantum technology and machine learning/AI are tighly interwoven

Quantum Hardware

- Quantum control and sensors
- Quantum computers
- Catalysis



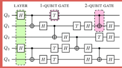
AI for Quantum Technology

- Quantum mechanical many-body theories
- Molecular dynamics
- Density functional theory

Quantum Technology and AI

Quantum Algorithms for AI

- Quantum computing
- Quantum algorithms
- Quantum machine learning
- Quantum inspired classical computing



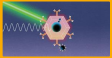
Societal impact and products

New medicines

Better shipping

Financial innovation

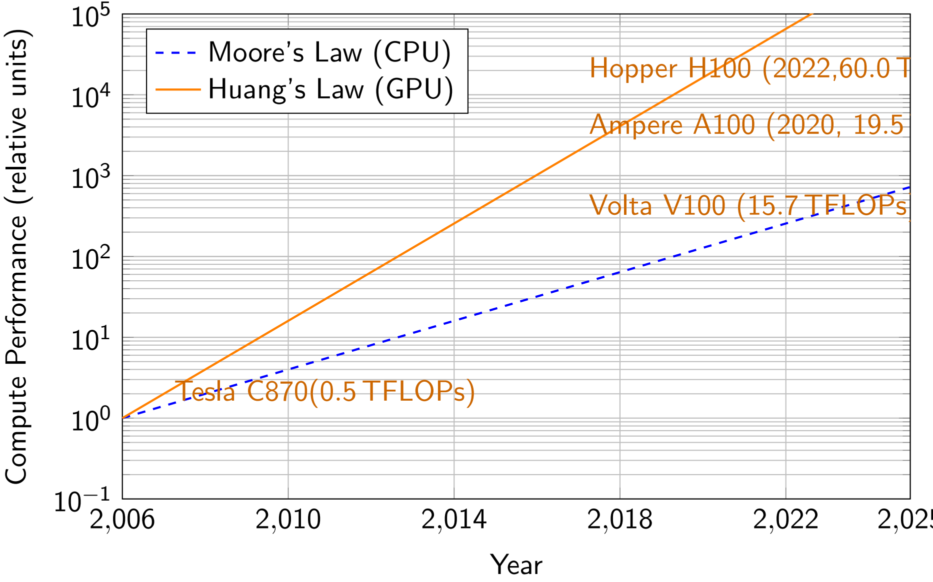
Quantum readiness



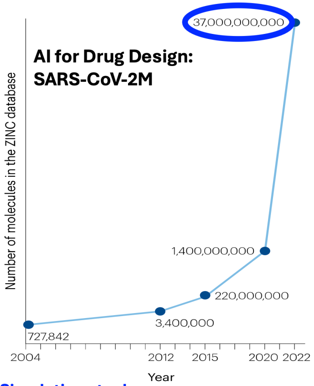
Quantum sensors and computers

- Drug discovery
- Quantum sensing
- Supply chain optimization
- Financial market modelling and risk analysis
- Material discovery

From Moore's law to Huang's law



Machine learning and AI models are computationally expensive



Simulations took:

90 days on **250 GPUs & 640 cpu-core**
1 day on **27000 GPU** Summit supercomputer

Nature Reviews Drug Discovery **23**, 141–155 (2024)

TOP4 Powerful Supercomputers as of Nov 2024

Rank	System	Cores	Rmax (PFlop/s)	Rpeak (PFlop/s)	Power (kW)
1	**El Capitan** - HPE Cray EX255a, AMD 4th Gen EPYC 24C 1.8GHz, AMD Instinct MI300A, Slingshot-11, TOSS, HPE DOE/NNSA/LLNL United States	11,039,616	1,742.00	2,746.38	29,581
		76	1,353.00	2,055.72	24,607
	Max, Slingshot-11, Intel DOE/SC/Argonne National Laboratory United States				
4	**Eagle** - Microsoft NDv5, Xeon Platinum 8480C 48C 2GHz, NVIDIA H100, NVIDIA Infiniband NDR, Microsoft Azure Microsoft Azure United States	2,073,600	561.20	846.84	

Advance nuclear weapon science and scientific discovery.

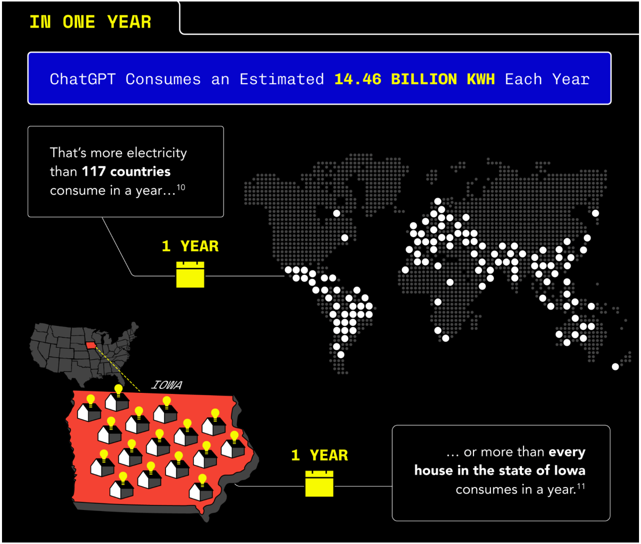
US$600 million

nature reviews drug discovery

Perspective | Published: 08 December 2023

Integrating QSAR modelling and deep learning in drug discovery: the emergence of deep QSAR

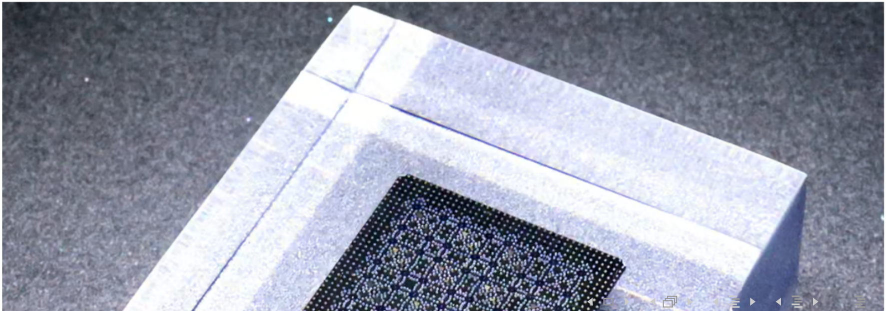
And power greedy, perhaps quantum computers can reduce the impact?



Taken from https://www.businessenergyuk.com/knowledge-hub/

Google hails breakthrough as quantum computer surpasses ability of supercomputers

Algorithm performed task beyond capability of classical computers, although experts say real-world application still years away



What is Quantum Computing?

Quantum computing leverages principles of quantum mechanics to perform computations beyond classical capabilities.

Key Concepts:

- **Superposition:** Qubits can exist in a combination of states.
- **Entanglement:** Correlation between qubits regardless of distance.
- **Quantum Interference:** Probability amplitudes interfere to solve problems.

Qubit Representation:

$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle\,, \quad |\alpha|^2 + |\beta|^2 = 1$$

What is Quantum Machine Learning?

Quantum Machine Learning (QML) integrates quantum computing with machine learning algorithms to exploit quantum advantages.

Motivation:

- High-dimensional Hilbert spaces for better feature representation.
- Quantum parallelism for faster computation.
- Quantum entanglement for richer data encoding.

Quantum Speedups

Why Quantum?

- **Quantum Parallelism:** Process multiple states simultaneously.
- **Quantum Entanglement:** Correlated states for richer information.
- **Quantum Interference:** Constructive and destructive interference to enhance solutions.

Example - Grover's Algorithm:

$$\text{Quantum Search Complexity: } O(\sqrt{N}) \text{ vs. } O(N)$$

Advantage: - Speedups in high-dimensional optimization and linear algebra problems.

Challenges and Limitations

1. **Quantum Hardware Limitations:**
   - Noisy Intermediate-Scale Quantum (NISQ) devices.
   - Decoherence and limited qubit coherence times.
2. **Data Encoding:**
   - Efficient embedding of classical data into quantum states.
3. **Scalability:**
   - Difficult to scale circuits to large datasets.

What is Quantum Entanglement?

Quantum Entanglement is a quantum phenomenon where two or more particles become correlated in such a way that the state of one particle directly affects the state of the other, regardless of distance.

Key Features:

- Non-local correlations
- No classical analog
- Violates Bell's inequalities

Entangled State Example:

$$\left|\Phi^+\right\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

1. Quantum Communication

Quantum Teleportation:

- Entanglement enables the transmission of quantum states using classical communication.
- No need to send the physical quantum particle.

Advantage:

- Instantaneous state transfer within quantum mechanics constraints.
- Quantum networks rely on entanglement for secure communication.

2. Quantum Cryptography

Quantum Key Distribution:

- Entanglement ensures secure communication.
- Eavesdropping disturbs quantum states, revealing interception attempts.
- Any measurement by a third party collapses the wavefunction.
- Ensures security based on quantum mechanics, not computational hardness.

Advantage: Unconditional security guaranteed by the laws of physics.

Speedup in Quantum Algorithms:

- Entanglement provides exponential state space.
- Quantum parallelism arises from entangled qubits.

Grover's Algorithm:

$$\mathcal{O}(\sqrt{N}) \text{ vs. } \mathcal{O}(N)$$

Shor's Algorithm:

$$\text{Factoring in } \mathcal{O}((\log N)^3)$$

4. Quantum Metrology

Quantum Metrology:

- Uses entangled states for ultra-precise measurements.
- Overcomes the classical shot-noise limit.

Heisenberg Limit:

$$\Delta\theta \geq \frac{1}{N},$$

where N is the number of entangled particles.

Advantage:

- Quantum entanglement improves sensitivity beyond classical limits.

Challenges of Quantum Entanglement

Decoherence:

- Entangled states are fragile.
- Interaction with the environment collapses the wavefunction.

Scalability:

- Difficult to entangle large numbers of qubits.
- Error correction requires complex protocols.

Measurement Problem:

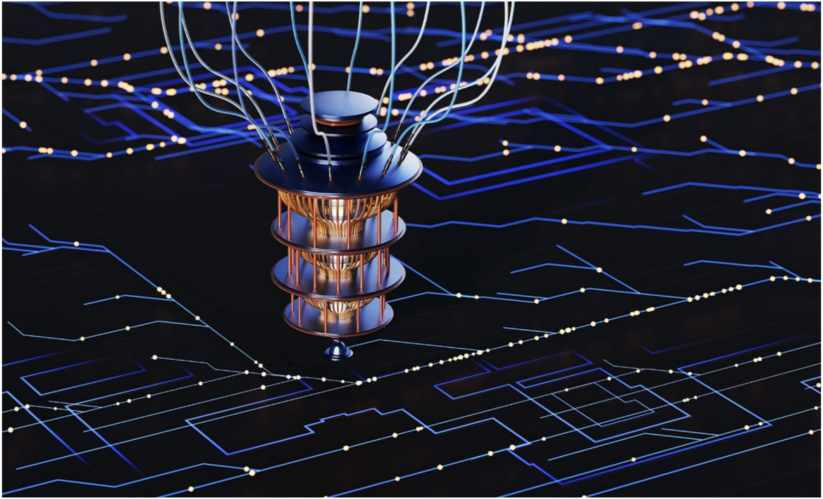
- Measurement destroys entanglement.
- Trade-off between information gain and entanglement preservation.

Di Vincenzo criteria

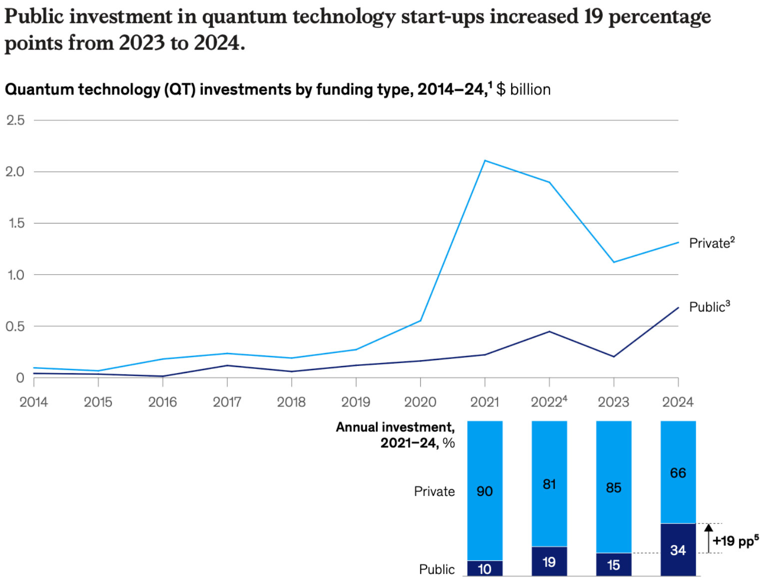
Quantum computing requirements

1. A scalable physical system with well-characterized qubit
2. The ability to initialize the state of the qubits to a simple fiducial state
3. Long relevant Quantum coherence times longer than the gate operation time
4. A **universal** set of quantum gates
5. A qubit-specific measurement capability

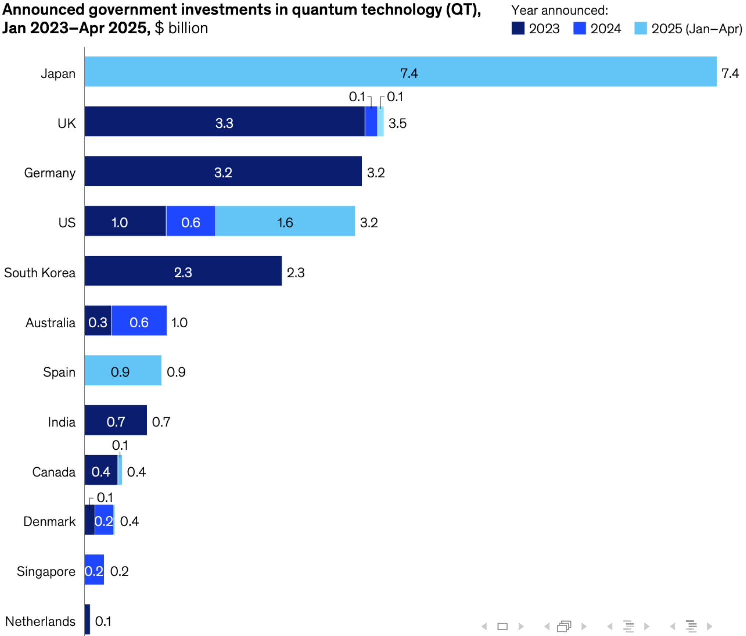
Considerable investements (add source)



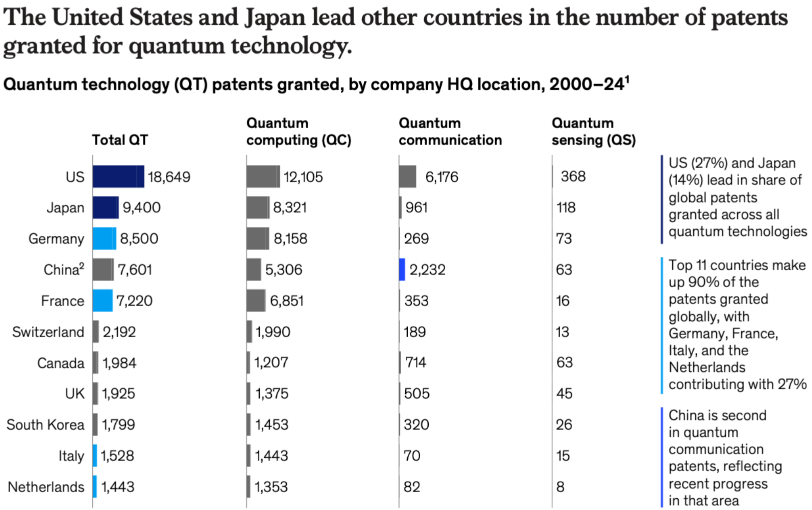
Considerable investements (add source)



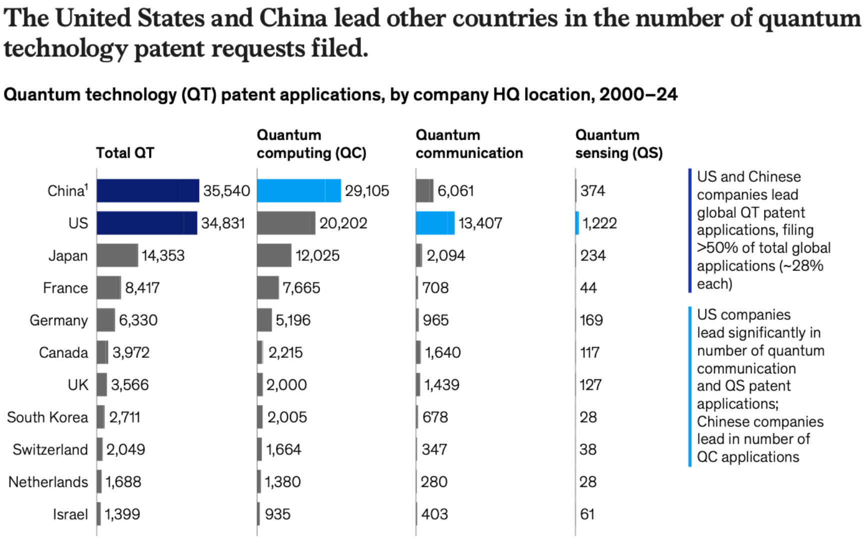
Considerable investements (add source)



Considerable investements (add source)

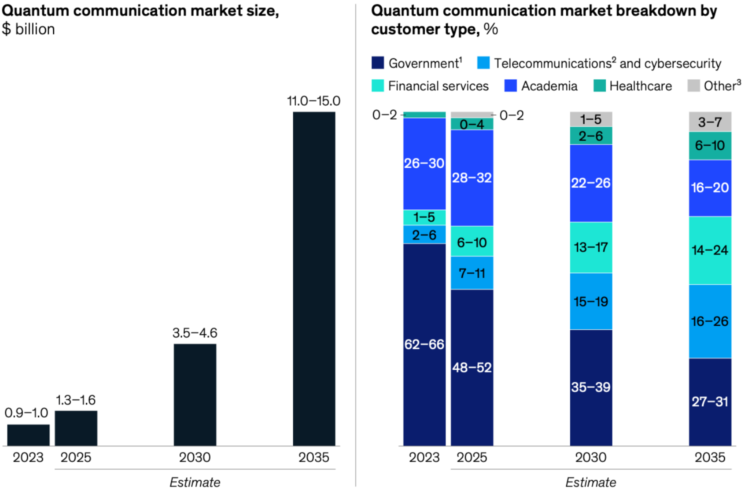


Considerable investements (add source)



Considerable investements (add source)

The quantum communication market is projected to reach $11 billion to $15 billion by 2035.

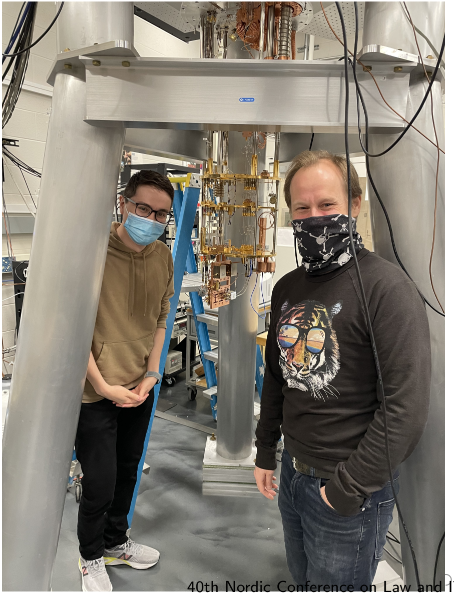


Quantum platforms

1. Superconduting qubits
2. Ion traps
3. Quantum dot systems (in semiconductors)
4. more text to come

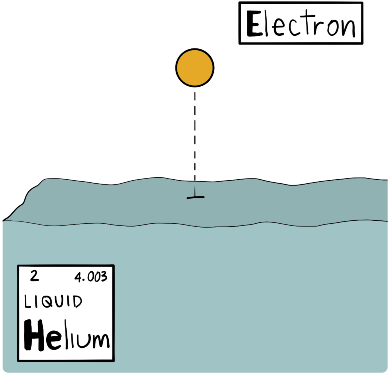
Important properties, electrons on helium

1. Long coherence times
2. Highly connect qubits
3. Many qubits in a small area
4. CMOS compatible
5. Fast gates

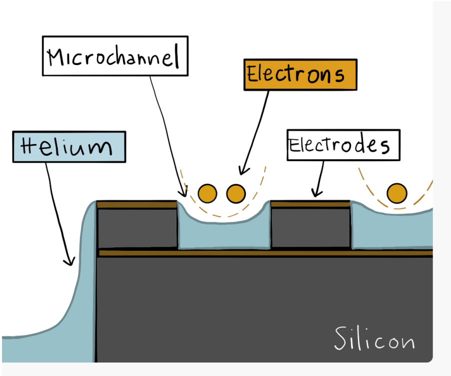


Single electrons can make great qubits

At the heart is the trapping and control of individual electrons floating above pools of superfluid helium. These electrons form the qubits of our quantum computer, and the purity of the superfluid helium protects the intrinsic quantum properties of each electron. The ultimate goal is to build a large-scale quantum computer based on quantum magnetic (spin) state of these trapped electrons.

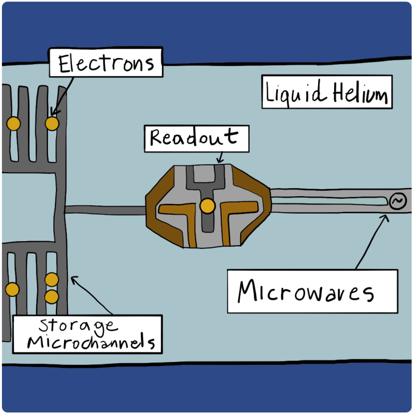


Microchannels fabricated into silicon wafers are filled with superfluid helium and energized electrodes. Together with the natural electron trapping properties of superfluid helium, these allow for the precision trapping of individual or multiple electrons. The microchannels are only a few micrometers in size, or about five times smaller than the diameter of a human hair.



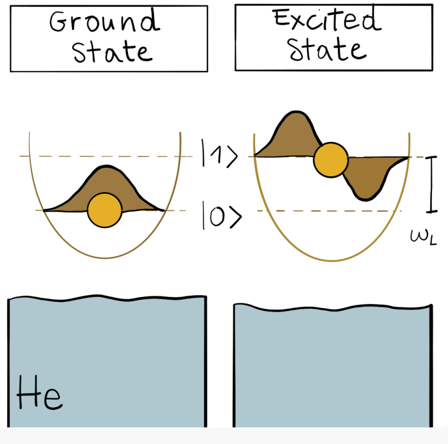
Control and readout

Microchannel regions can store thousands of electrons, from which one can be plucked and transported to the single electron control and readout area. In this region, microwave signals will interact with the electron to perform quantum logic gate operations, which will be readout via extremely fast electronics.

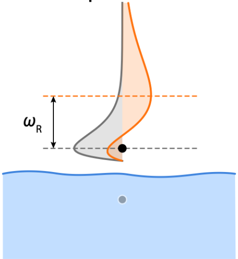


Operations for quantum computing

Quantum information can be encoded in a number of ways using single electrons. Currently, we are working with the side-to-side(lateral) quantum motion of the electron in the engineered trap. This motion can either be in its lowest energy state, the ground state, or in a number of higher-energy excited states. This electron motion also provides the readout capabilities for the ultimate goal of building a large-scale quantum computer based on the electron's magnetic moment (spin).



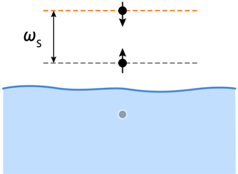
Qubit platforms with electrons on helium



Rydberg states

$\omega_R/2\pi = 120$ GHz

P.M. Platzman and M.I. Dykman
Science **284**(5422), pp.1967 (1999)

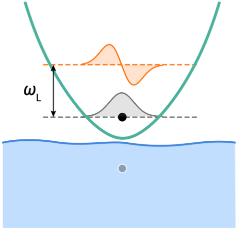


Spin states

$\omega_s/2\pi = 5$ GHz at $B = 0.2$ T

$(T_2 \approx 1.5$ s$)$

S. A. Lyon, *Phys. Rev. A* **74**, 052338 (2006)



Lateral motional states

$\omega_s/2\pi = 5$ GHz

D.I. Schuster et al., *Phys. Rev. Lett.* **105**, 040503 (20

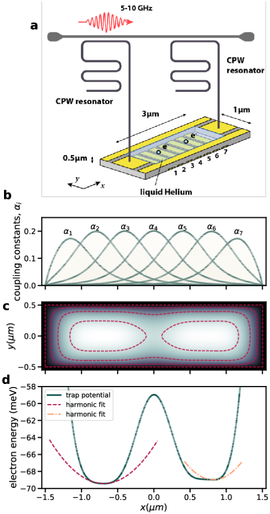
D. Konstantinov - OIST (Okinawa)
A.Chepelianskii - Universite Paris-Sud

S. Lyon - Princeton
E. Kawakami - RIKEN

D. Schuster - University of Chicago
J. Pollanen - EeroQ/MSU

Final experimental setup

1. (a) Microdevice where two electrons are trapped in a double-well potential created by electrodes 1-7. The read-out is provided by two superconducting resonators dispersively coupled to electron's in-plane motional states.
2. (b) Coupling constants from each individual electrode beneath the helium layer.
3. (c+d) The electron's energy in a double-well electrostatic potential.



Export control

Technology/Component	**Export Sensitivity Category**	**Reason for Sensitiv**
Superconducting CPW resonator (6.04 GHz)	Dual-Use (Quantum computing/EAR)	High-frequency super
Single-electron trap (gated microchannel)	Dual-Use (Quantum hardware/EAR)	Precision single-elect
Superconducting electrodes (Nb films)	Dual-Use (Superconducting electronics/EAR)	Superconducting ma
Pumped ^{4}He cryostat (1.1 K)	Dual-Use (Cryogenic systems/EAR)	High-capacity cryoge
Superfluid ^{4}He substrate	Dual-Use (Cryogenic medium/EAR)	Specialized cryogenic
Cryogenic RF components	Dual-Use (RF electronics/EAR)	GHz-range passive c
Low-noise RF amplifiers		Specialized amplifiers
On-chip LC filters	Dual-Use (RF filter technology/EAR)	Engineered filtering f
Electron-on-helium qubit platform	Dual-Use (Quantum computing/EAR)	Emerging quantum i