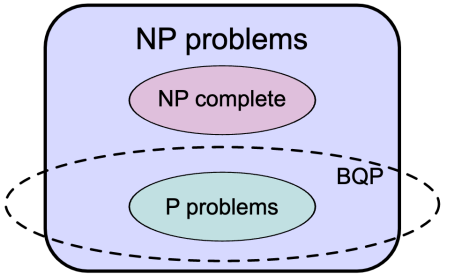
Trapped ion quantum computing

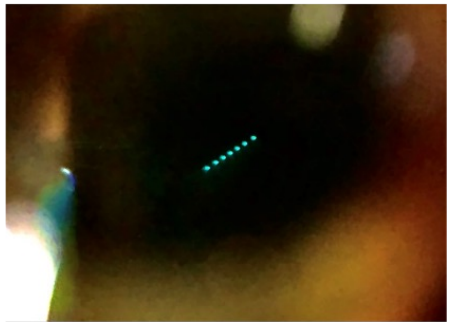
Matt Grau

Old Dominion University

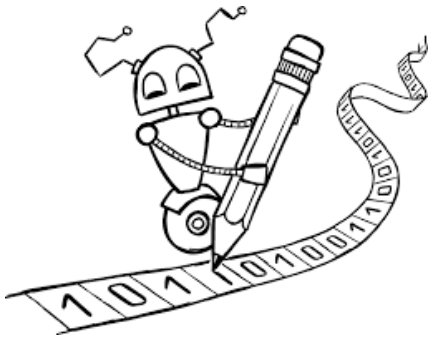
Outline

- Quantum Computers
- DiVincenzo's criteria
- Trapped Ion platform





Computer

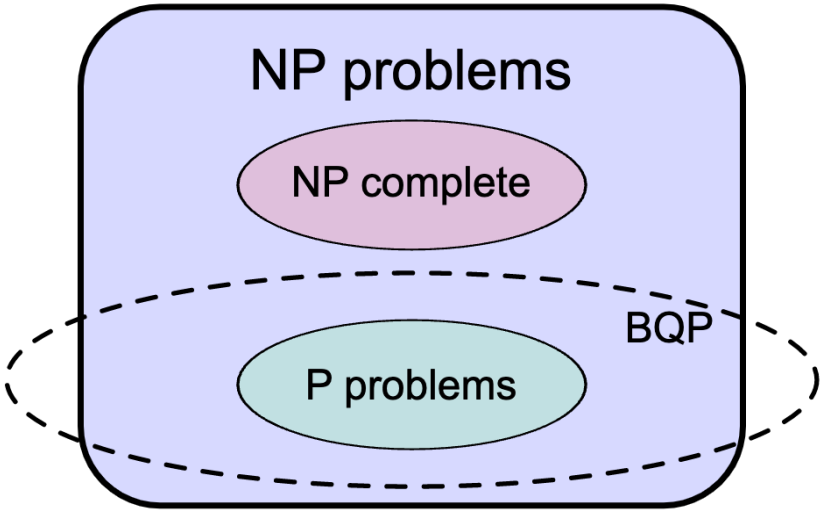


- Solves problems that are "computable"
  - What is the shortest path? ✓
  - ~~What is the answer to the ultimate question of life, the universe, and everything?~~
- Church-Turing → computable

TEX

Quantum Computer

- Physically different model of computation
  - Bounded-error quantum polynomial time
- Appears to violate "extended Church-Turing thesis"
  - BQP > P ??
- Quantum Algorithms
  - Fourier Transform $O(2^n) \rightarrow O(n^2)$
  - Search $O(n) \rightarrow O(\sqrt{n})$
  - Linear Equations $O(n) \rightarrow O(\log(n))$
  - Variational Eigensolver
  - Quantum Simulation



Bits vs. Qubits

True 1

False 0

“5” : 0101

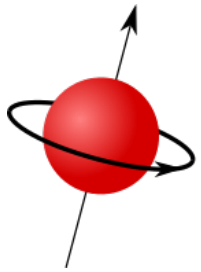
+

“6” : 0110

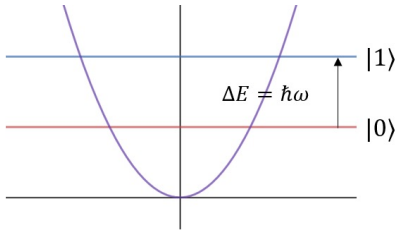
=

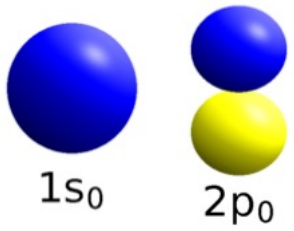
“11” : 1011

Bits vs. Qubits

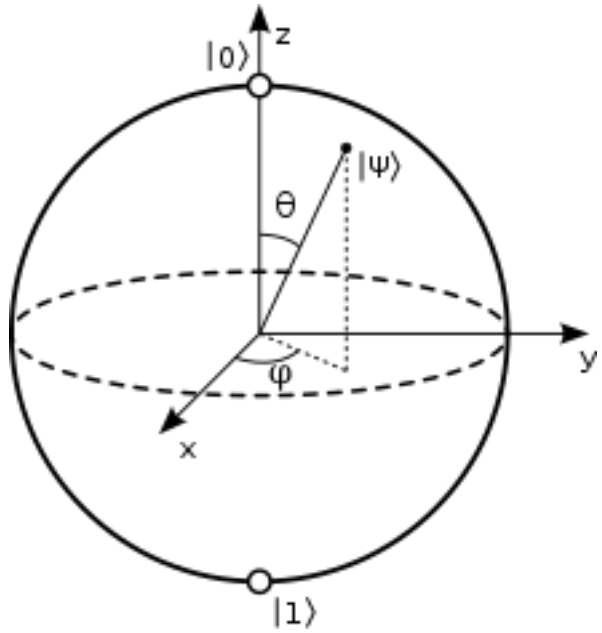


$|\downarrow\rangle \quad |1\rangle$





$|\uparrow\rangle \quad |0\rangle$



$$|\psi\rangle = \cos(\theta)\,|0\rangle + e^{i\phi}\sin(\theta)\,|1\rangle$$

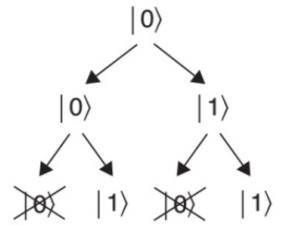
Qubits

- Superposition $|\psi\rangle = \cos(\theta)\,|0\rangle + e^{i\phi}\sin(\theta)\,|1\rangle$
- Entanglement 001, 010, 100 n^2

$|000\rangle, |001\rangle, |010\rangle, |100\rangle, |011\rangle, |101\rangle, |110\rangle, |111\rangle$ 2^n

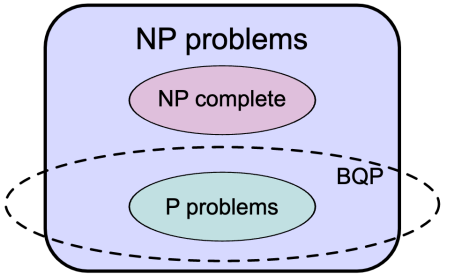
- Interference

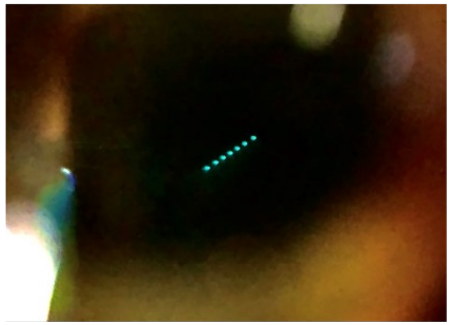
$$|0\rangle \rightarrow \frac{1}{\sqrt{2}}(|1\rangle + |0\rangle) \rightarrow |1\rangle$$



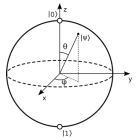
Outline

- Quantum Computers
- DiVincenzo's criteria
- Trapped Ion platform



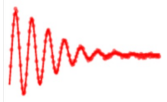


DiVincenzo's criteria

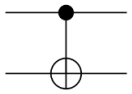


1. Scalable and well-characterized qubit

$|\psi\rangle \rightarrow |0\rangle$ 2. Initialization



3. Long coherence times



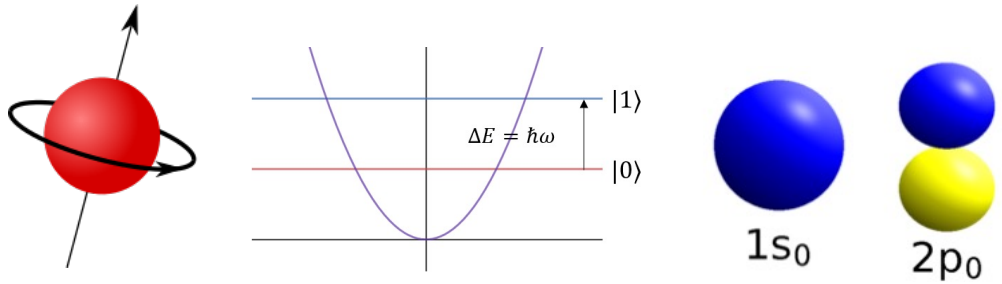
4. Universal set of gates

5. Measurement

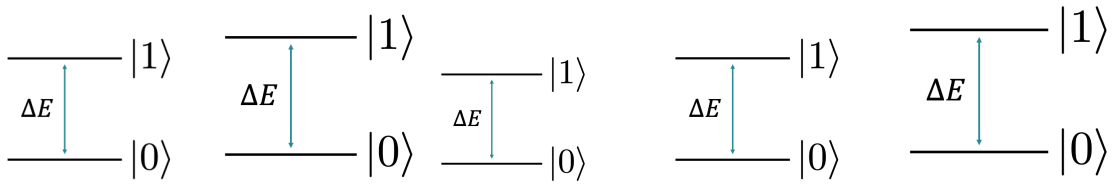
D. P. DiVincenzo, Fortschr. Phys. **48**, 771 (2000).

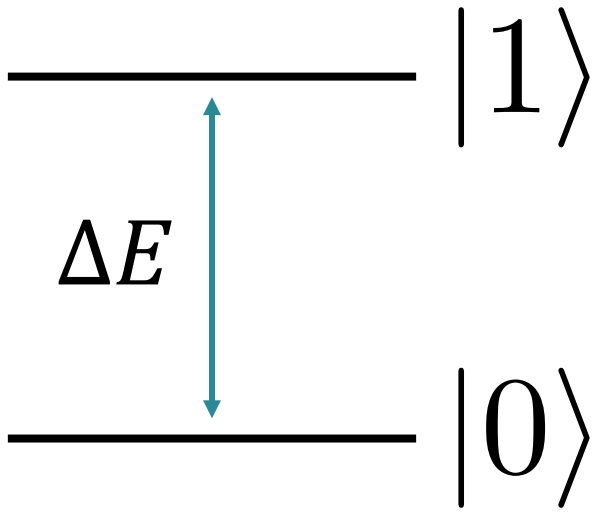
Scalable and well-characterized

- 2 dimensional Hilbert space
  - Closed
  - Gapped ΔE
  - Control



- Scalable
  - Can you make lots?
  - Are they identical?





Initialization (State Preparation)

- Prepare the system in a well known initial state
  - Optical pumping
  - Measurement and feedback
  - annealing
- Introduces Error
- Requires controlled dissipation

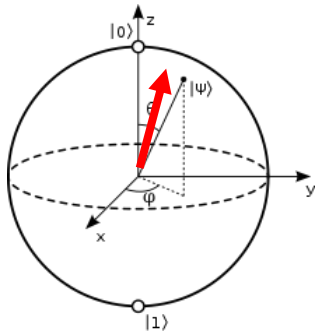
$$|\psi\rangle \rightarrow |000\ldots\rangle$$

$$|\psi\rangle \rightarrow (1-\epsilon)\,|0\rangle + \epsilon\,|1\rangle$$

Coherence Time

- "storage time" of quantum information
- Decoherence mechanisms:
  - Phase decoherence

$$|1\rangle + e^{i\phi}|0\rangle \rightarrow |1\rangle + e^{i(\phi+\epsilon)}|0\rangle$$

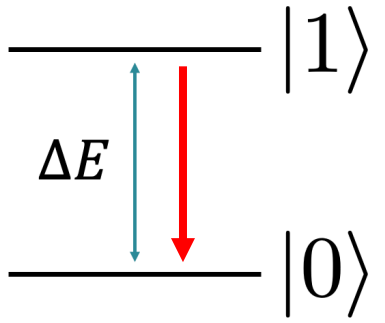


  - Measurement

$$\alpha|1\rangle + \beta|0\rangle \rightarrow P(|1\rangle) = |\alpha|^2 \text{ and } P(|0\rangle) = |\beta|^2$$

  - Decay

$$\alpha|1\rangle + \beta|0\rangle \rightarrow |0\rangle$$



Gates

- Single qubit gates
  - Turn on resonant interaction between $|0\rangle$ and $|1\rangle$ for a single qubit

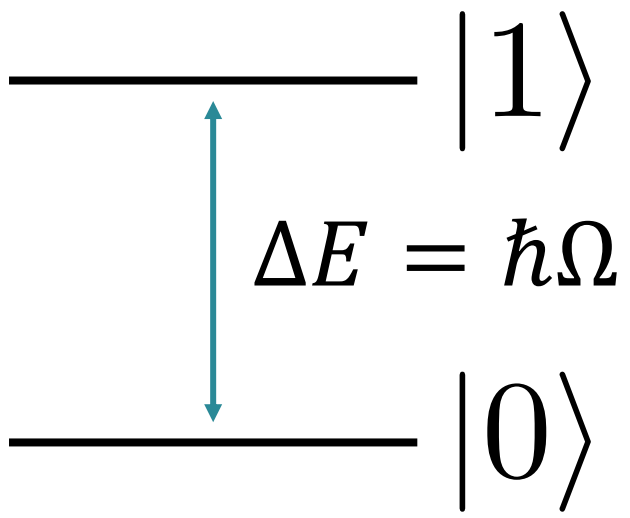
$$H = \Omega(|1\rangle\langle 0| + |0\rangle\langle 1|)$$

  - Drives $|0\rangle \rightarrow |1\rangle$

$$|1\rangle \rightarrow |0\rangle$$

$$\alpha|1\rangle + \beta|0\rangle \rightarrow \alpha|0\rangle + \beta|1\rangle$$

$$t = \pi/\Omega$$

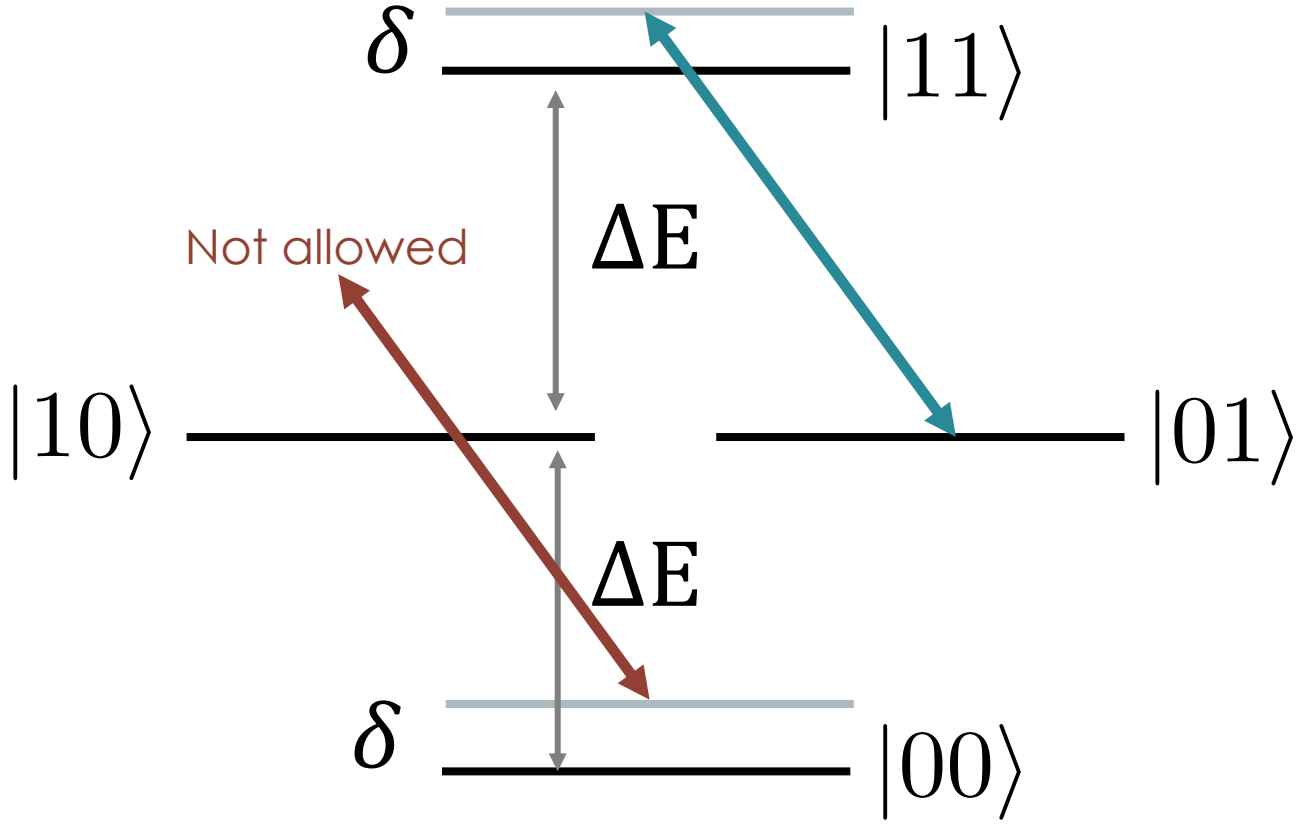


Gates

- Two qubit gates
  - Requires some spin dependent interaction

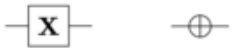
$$H = \delta(|11\rangle + |00\rangle)$$

  - Together with a single qubit gate you can "flip" one qubit dependent on another



Gates

- Many different one- and two-qubit gates
- "Universal set" needed to be able to do any computation
- One such set:
  - One-qubit rotations, phase
  - Two-qubit CNOT

Operator	Gate(s)	Matrix
Pauli-X (X)		$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)		$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)		$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)		$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)		$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
$\pi/8$ (T)		$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$
Controlled Not (CNOT, CX)		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$
Controlled Z (CZ)		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$
SWAP		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)		$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$

Measurement

- "Project" qubit into either basis with probability P

$$\cos(\theta)\,|1\rangle + \sin(\theta)\,|0\rangle \rightarrow P(|1\rangle) = |\cos(\theta)|^2 \text{ and } P(|0\rangle) = |\sin(\theta)|^2$$

- Perform on each qubit individually
- Each measurement: 1 bit of information about θ
- Perform N identical computations, uncertainty on θ goes like $\sqrt{N}$

Metrics of a Quantum Computer

- Fidelities of:
  - State Preparation
  - Measurement
  - One-qubit gates
  - Two-qubit gates
- Depth of circuit = (Coherence Time)/(Gate Time)
- "Clock speed": circuit time vs. $\sqrt{N}$ measurement time

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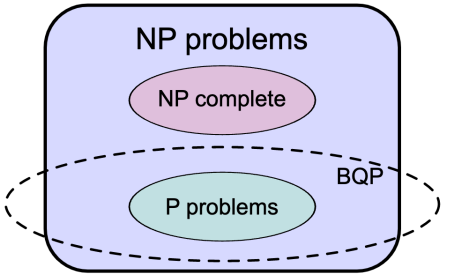
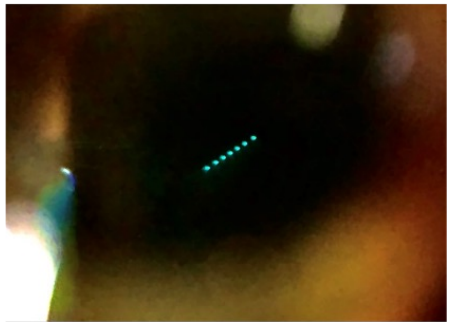




Not a sales pitch

Not a sales pitch

QUANTINUUM

SCIENCE LED AND ENTERPRISE DRIVEN, WE'RE ACCELERATING QUANTUM COMPUTING

oxford ionics

Unparalleled performance

The world's most powerful quantum computer

AQT

::: TURN-KEY QUANTUM

AQT realizes the first general-purpose Quantum Computer.

Q

Can we build a million qubit quantum computer?

Universal Quantum

Not a

IONQ (NYSE: IONQ)

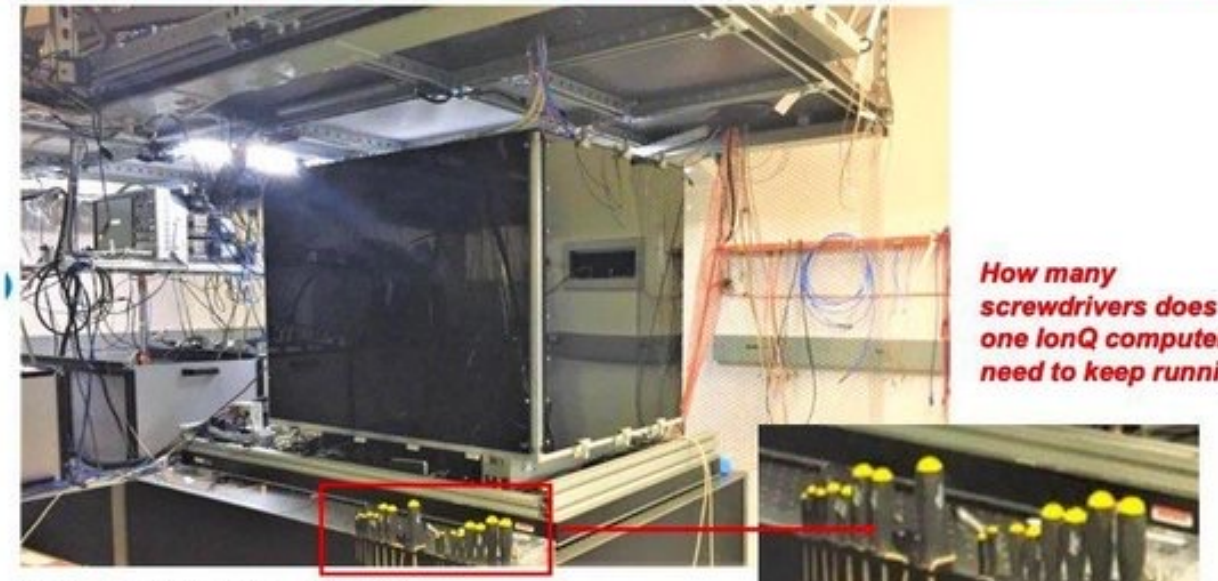
The "World's Most Powerful Quantum Computer" Is A Hoax With Staged Nikola-Style Photos – An Absurd VC Pump With A Recent Lock-Up Expiration Takes SPAC Abuses To New Extremes

- A part-time side-hustle run by two academics who barely show up, dressed up as a "company"
- A useless toy that can't even add 1+1, as revealed by experiments we hired experts to run
- Fictitious "revenue" via sham transactions and related-party round-tripping
- A scam built on phony statements about nearly all key aspects of the technology and business
- CEO appears to be making up his MIT educational credentials

QUAN

SCIENCE LED AND ENTERPRISE DRIVEN. WE'RE
ACCELERATING QUANT

June 2020 research paper. Photo caption says "Trapped-ion quantum computer; Source: IonQ"



How many screwdrivers does one IonQ computer need to keep running?

Trapped-ion quantum computer; Source: IonQ

70

AQT

::: TURN-KEY

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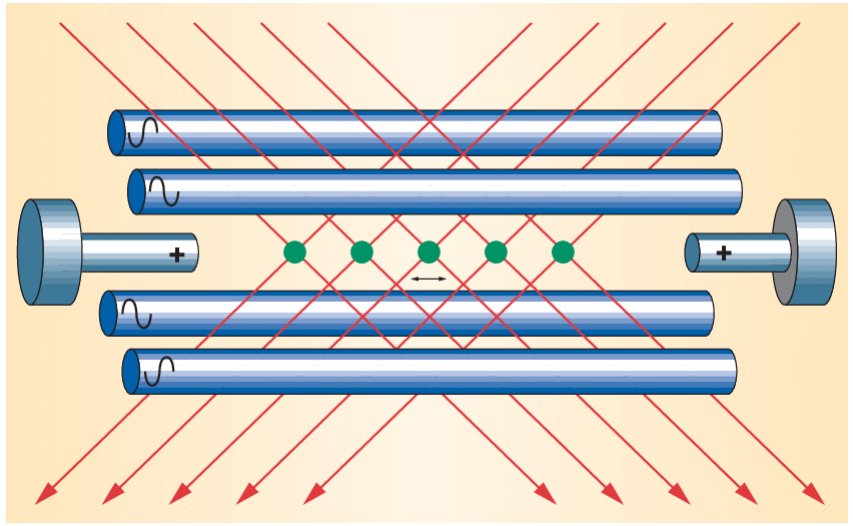
bit
puter?

Trapped Ions

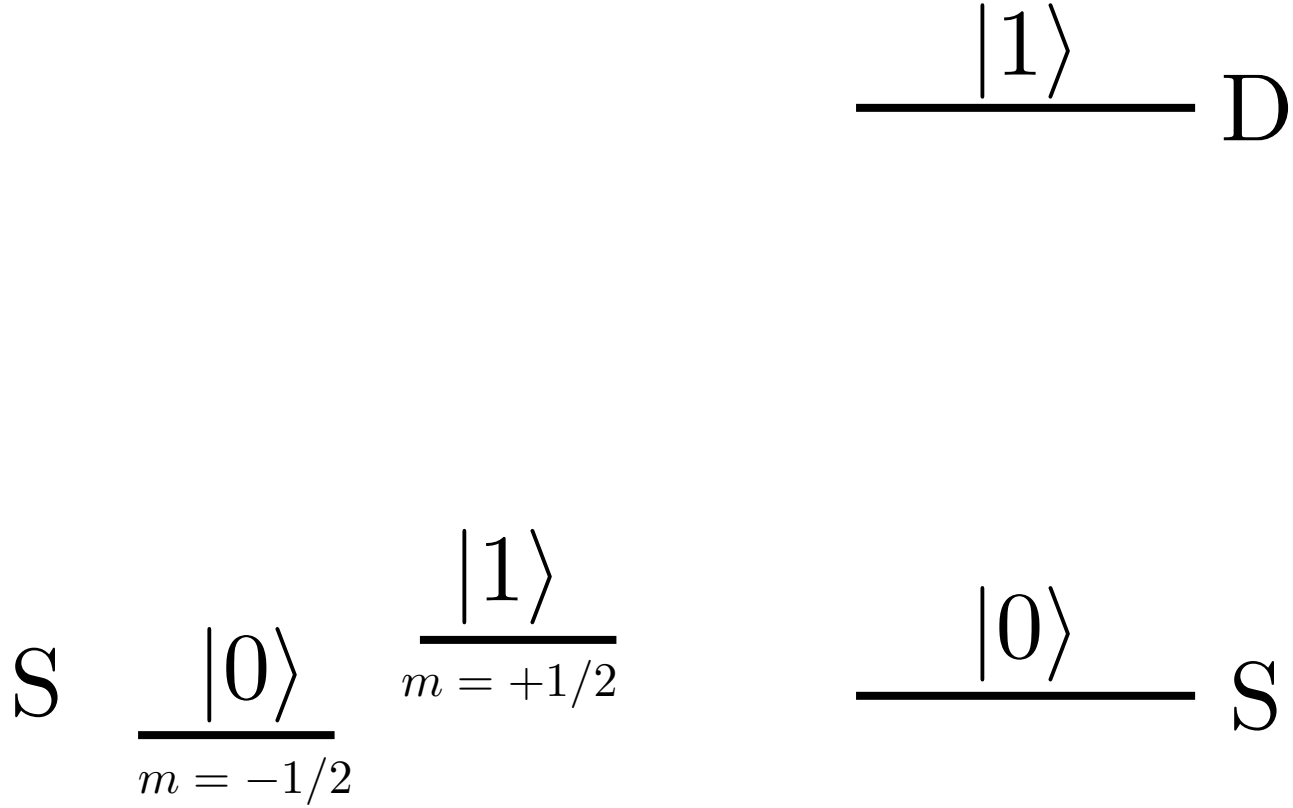
- Singly charged atoms confined with electric fields
- Laser-cooling
- Fluorescence readout
- Addressed via lasers



Ion Qubits

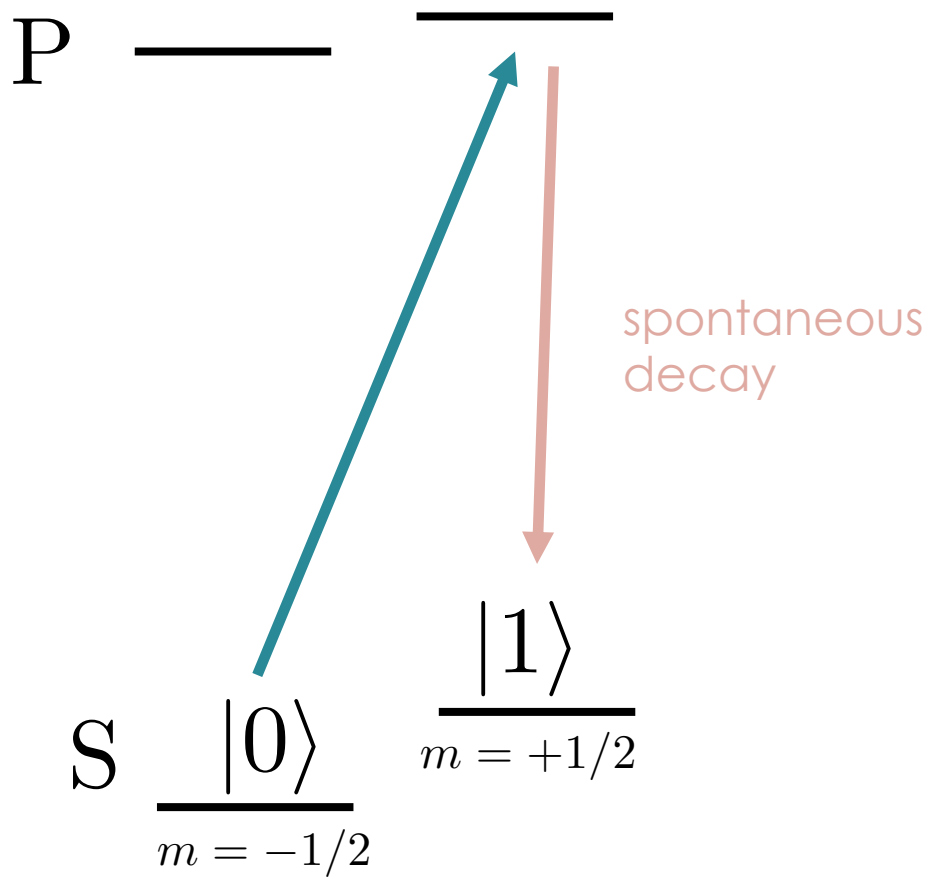
- Singly charged atoms with a single valence electron
  - Ca^+, Sr^+, Yb^+, etc.

- Every atom identical
  - Electron spin
  - Electron orbital
  - Nuclear spin



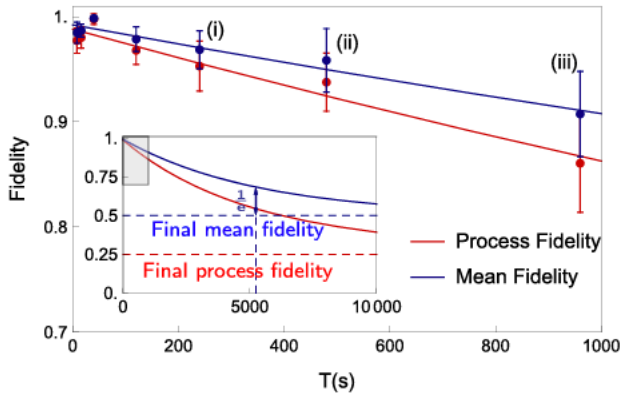
State Preparation

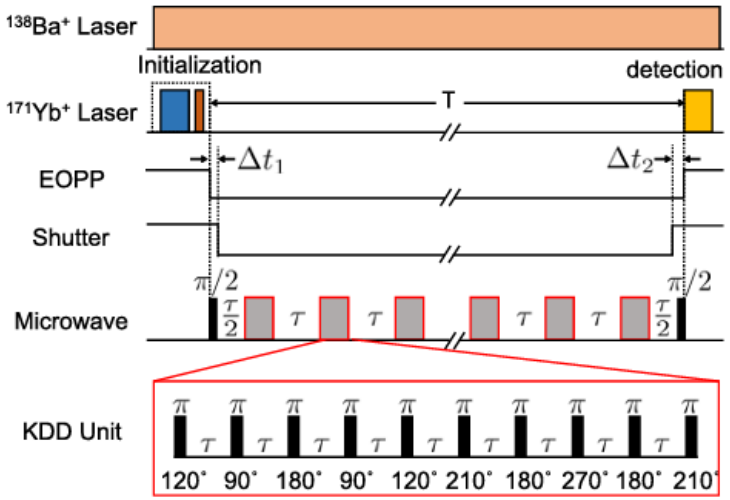
- Optical pumping
- Dissipation via laser coupling to excited state
- Best fidelity: 0.9992



Coherence Time

- Ions can be stored for months
- Isolation of qubit spins from environment enables long coherence time:
  - Electron spin : seconds
  - Nuclear spin : hours



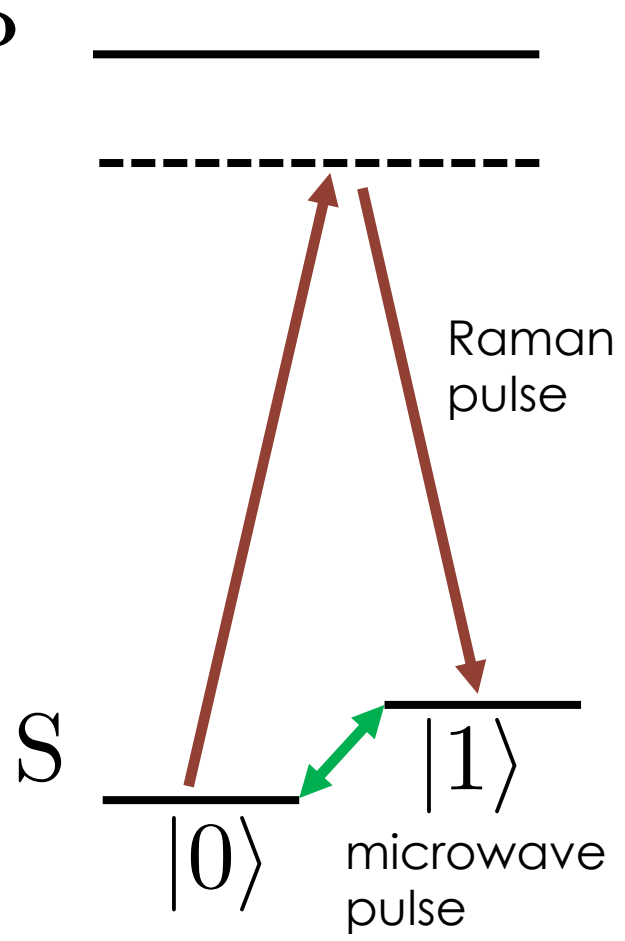


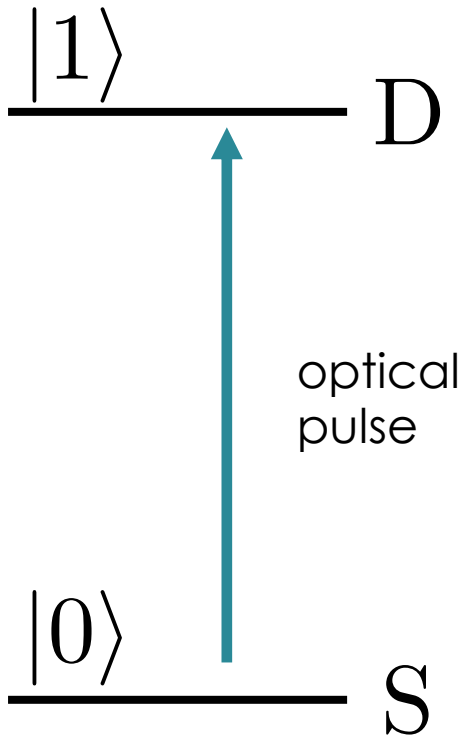
Wang, P., Luan, CY., Qiao, M. *et al.* Single ion qubit with estimated coherence time exceeding one hour. *Nat Commun* **12,** 233 (2021).

Single-qubit gates

- Resonant laser pulse (optical qubit)
- Resonant microwave (hyperfine qubit)
- Raman laser pulse (hyperfine qubit)

- Best fidelity: 0.999999

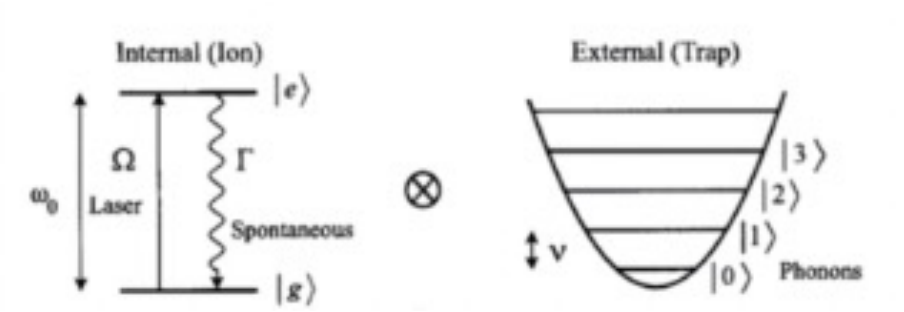


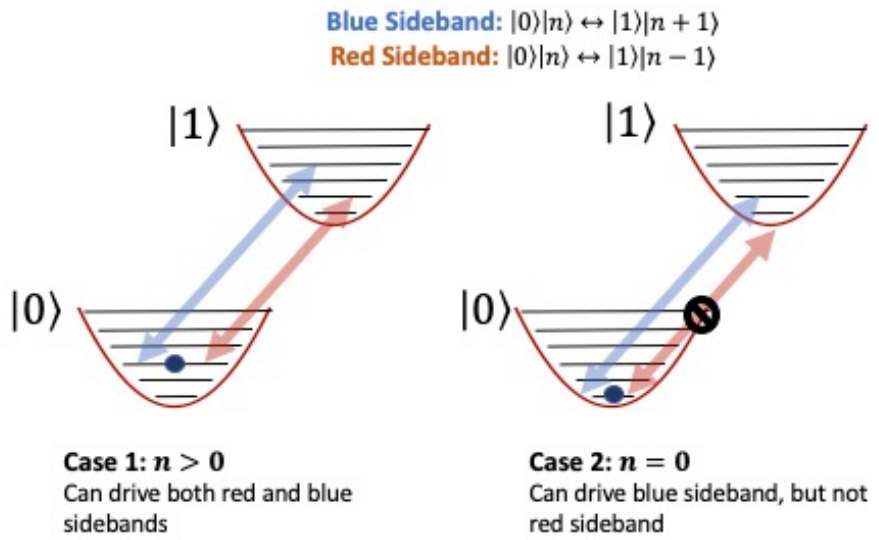


T. P. Harty, D. T. C. Allcock, C. J. Ballance, L. Guidoni, H. A. Janacek, N. M. Linke, D. N. Stacey, and D. M. Lucas
Phys. Rev. Lett. **113**, 220501

Two-qubit gates

- Resolved motional sidebands generate spin-dependent force
  - Cirac-Zoller gate
  - Mølmer–Sørensen gate
- Best fidelity: 0.997



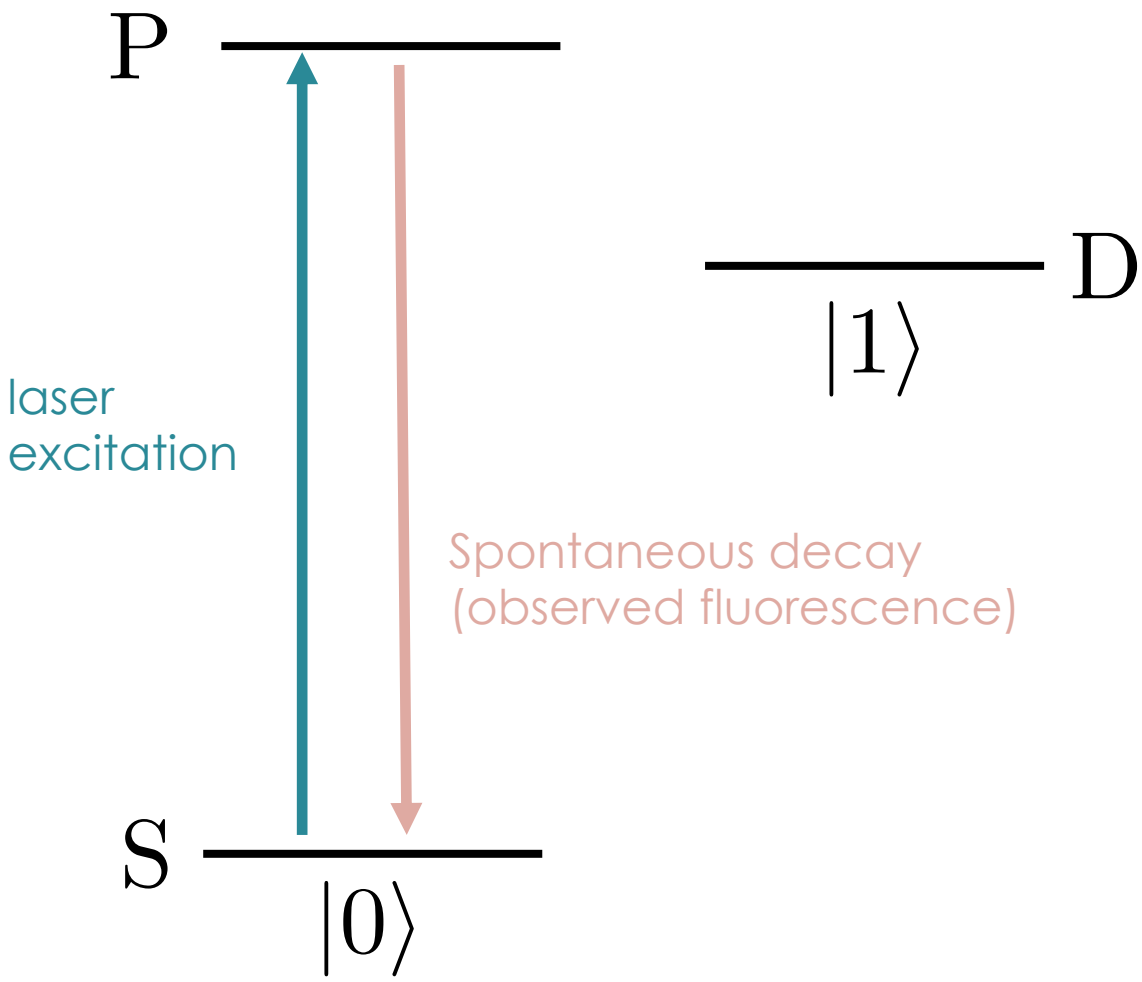


$$|1\rangle\,|n=1\rangle \rightarrow |0\rangle\,|n=0\rangle$$
$$|1\rangle\,|n=0\rangle \rightarrow X$$
$$|0\rangle\,|n=1\rangle \rightarrow X$$

Srinivas, R., Burd, S.C., Knaack, H.M. *et al.* High-fidelity laser-free universal control of trapped ion qubits. *Nature* **597,** 209–213 (2021)

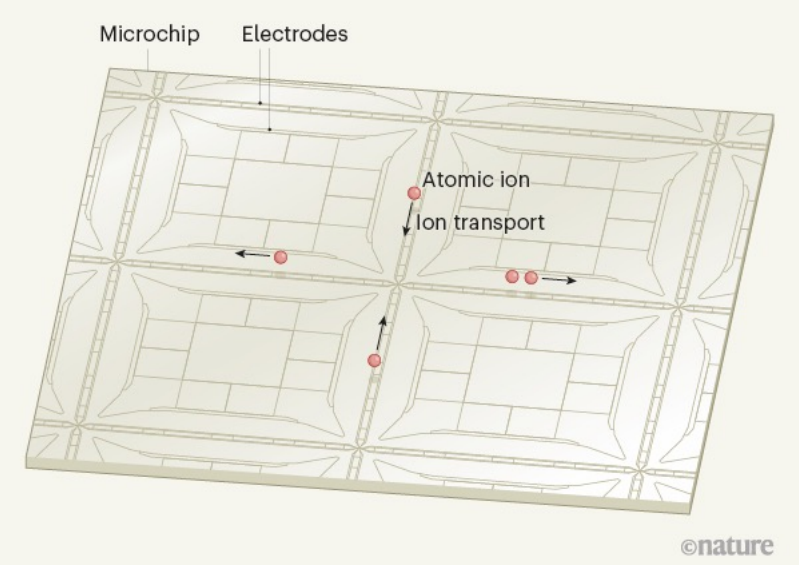
Measurement

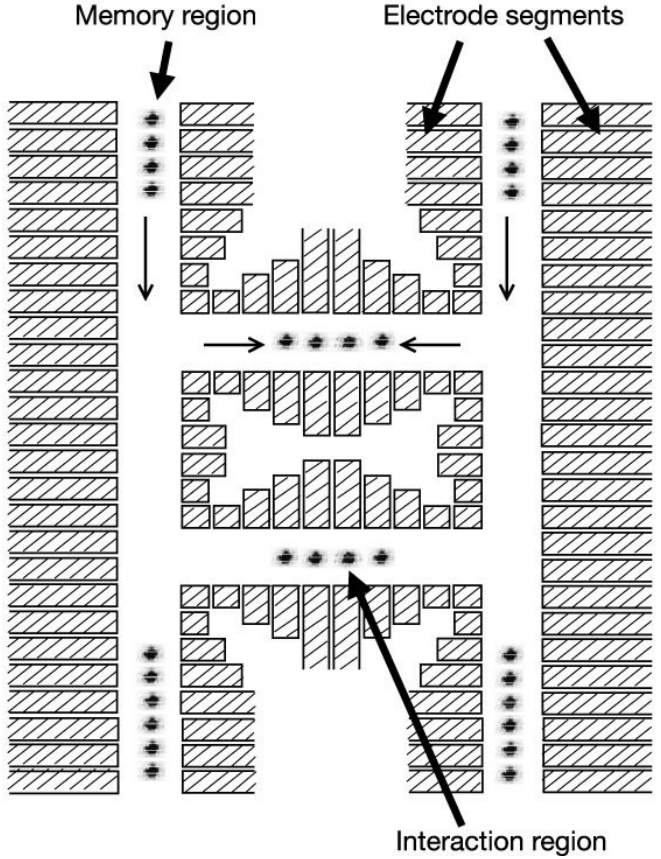
- Map qubit states onto "dark" and "bright" states



Other Advantages

- Ions can be moved around to change connectivity



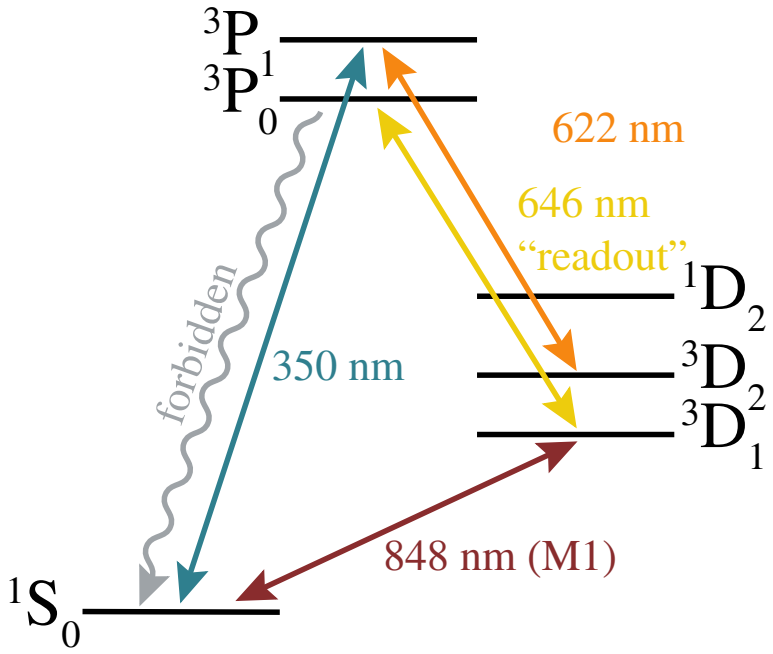


Kielpinski, D., Monroe, C. & Wineland, D. Architecture for a large-scale ion-trap quantum computer. *Nature* **417,** 709–711 (2002)

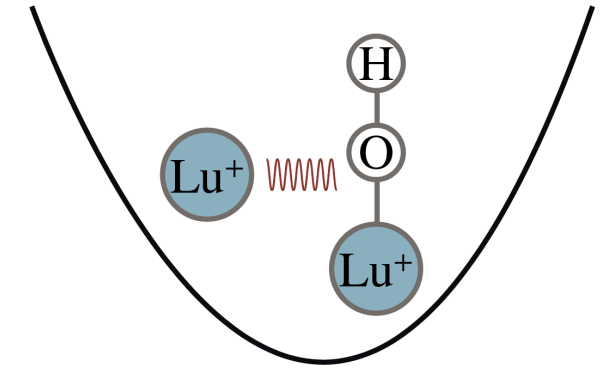
Small sales pitch (Graulab)

- Local trapped ion setup at ODU
- Working with
  - Ba^+ (qubits)
  - Lu^+ (qubits, atomic clocks)
  - $LuOH^+$ (fundamental physics)

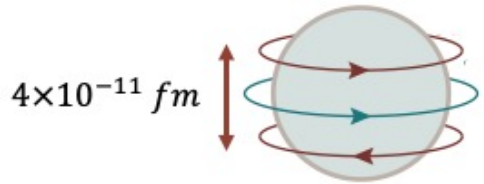
Investigating Lu^+ as a novel divalent trapped ion qubit



Search for nuclear CP violation Using quantum logic spectroscopy of molecular ions



$\sim 4\times10^{26}$ μN cm



Summary

- Quantum Computers
- DiVincenzo's criteria
- Trapped Ion platform