Building Blocks for Quantum Computing Part IV

Design and Construction of the Trapped Ion Quantum Computer (TIQC)

Patrick Dreher

CSC801 – Seminar on Quantum Computing

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Goal Is To Understand The Principles And Operation of the Trapped Ion Quantum Computer (TIQC)

- Building Blocks for Quantum Computing Part I
- Building Blocks for Quantum Computing Part II
- Building Blocks for Quantum Computing Part III
  Quantum Mechanics Primer
- Building Blocks for Quantum Computing
  Design and Construction of the TIQC – Part IV
- Building Blocks for Quantum Computing
  Operation of the TIQC – Part V

Review

- In Lecture I reviewed the basic properties of linear algebra and the postulates of quantum mechanics
- In Lecture II showed that
  - using standard logic gate inputs and outputs did not satisfy the unitarity postulate of quantum mechanics
  - Modified the gate behavior so that unitarity was satisfied
  - Studied 1 qubit properties and the Bloch sphere and constructed/categorized a set of 1 qubit gates
  - Constructed a 2 qubit universal quantum gate (CNOT)
- In Lecture III the minimum relevant quantum mechanics and atomic physics was presented and summarized in preparation for designing, building and operating a universal quantum computer

Build an Experimental Apparatus That Functions as a Universal Quantum Computer

- Goal for Lecture IV and V is to design construct and operate an experimental apparatus that can
  1) Take 1 qubit inputs and produce outputs that reflect the properties of 1 qubit gates
  2) Take 2 qubit inputs and produce outputs that reflect the properties of 2 qubit gates
- Validating an experimental apparatus that satisfies goals 1) and 2) above will form the basis for a universal quantum computer
- This process of building and operating a TIQC universal quantum computer will now be developed in detail

The Design Plan for Building a Trapped Ion Quantum Computer

Trapped Ion Component Primer

- Start with the basic building blocks described in Part III
  - Atoms and Materials
  - Electromagnetic fields
  - Lasers
  - Cryostat holding the experimental apparatus that is capable of operating at milli-Kelvin temperatures

Functional Design Requirements - TIQC

- Build an experimental apparatus that will perform quantum computing operations with two distinct qubits
  - Model the apparatus so that it behaves as a CNOT gate using two independent ions as the 2 qubits
  - Allow each physical qubit to change states according to the postulates of quantum mechanics without collapsing the wavefunction to a definite classical state in the middle of the programmed quantum computation
  - Develop a method to measure the final TIQC state

Specific Design Requirements Cold Temperature Apparatus

2. This level of control of the ion interactions requires that the experimental apparatus in which the ions are placed be cooled to temperatures close to absolute zero
3. At these ultra cold temperatures identify a Hilbert space of internal atomic (spin) states of the ion and the lowest level vibrational excitation among the ions (phonon) as representing the two individual qubits of information about the system
4. Develop a method that couples interactions between the ion spin and phonon oscillations of the total linear ion chain as a controlled two qubit system

Specific Design Requirements
Operational requirements

5. Demonstrate that multiple single qubit operations (unitary transformations) can be performed separately on the individual ion spin and the phonon states
6. Program a set of quantum computing instructions (gates and unitary transformations of the qubits) that will transform the initial state of the two qubit system to a final system state through interactions between the ion spin and ion chain phonon states
7. Implement a technique to measure the final aggregated set of quantum gate manipulations (unitary transformations) that represents the output of the quantum computing calculation

Operational Challenges

- The biggest challenges are
  - Construct conditions to allow a unitary transformation of the states being measured
  - Maintain experimental apparatus near absolute zero
  - Suppress conditions that lead to de-coherence of the system wavefunction
- Record measurements can be attributed to have the most significant probability of the largest expectation value
- Measure the final state information

Suggested TIQC Design

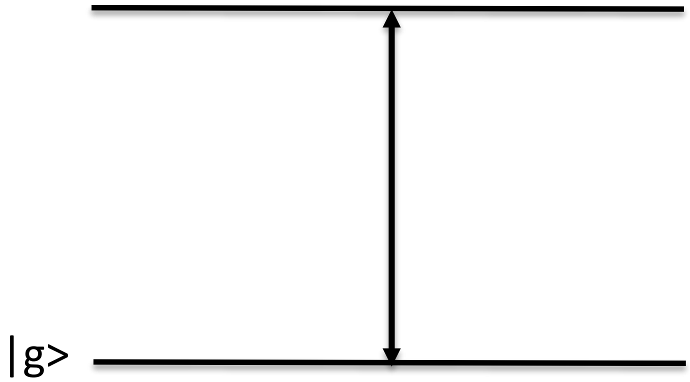
Simple Model of a Two Qubit Quantum Computer

- Construct a 2 level spin system interacting with an electromagnetic field
- Spin interactions controlled by a spin rotation in response to a laser
- Spin is physically confined within a harmonic potential
- States are quantized with energy of scale hν
- These harmonic oscillator bound states are identified as center of mass phonon vibrations

2 Qubit Example of a Quantum Computer Ion Trap

Two level Ion

Harmonic Trap



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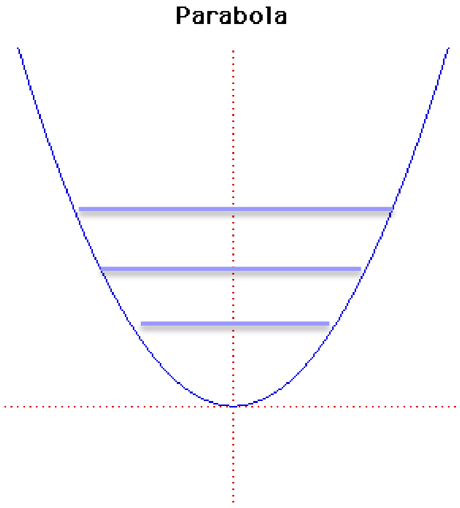


Ion Spin States

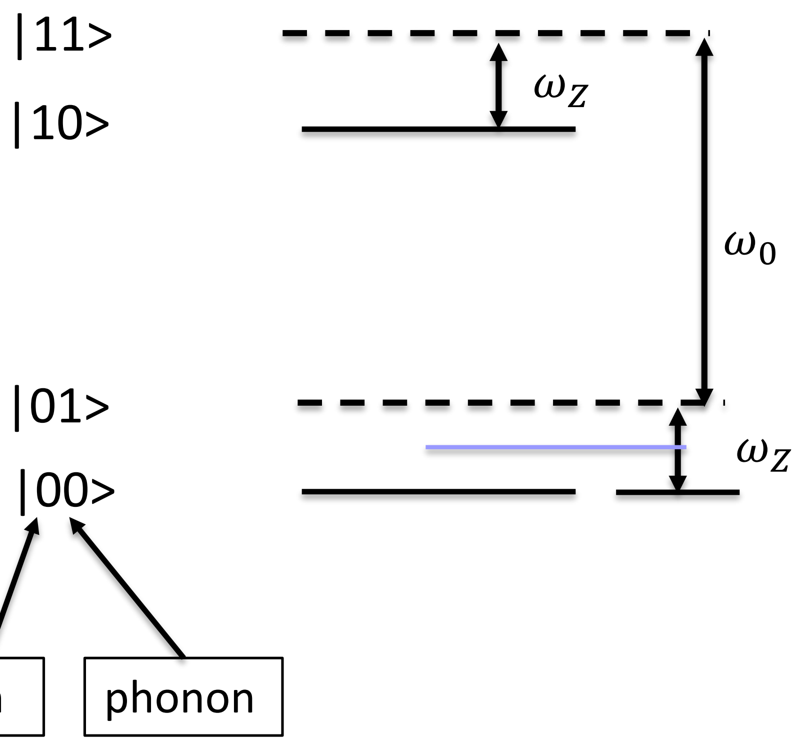
- Choose electromagnetic field (laser pulse) of appropriate frequency and duration
- Use the rotation operator to view the pulse as a unitary transformation allowing a one qubit transformation to be performed on the spin state

$$R_x(\theta) = \exp(-i\theta S_x)$$

$$R_y(\theta) = \exp\left(-i\theta S_y\right)$$

Phonon Vibration States

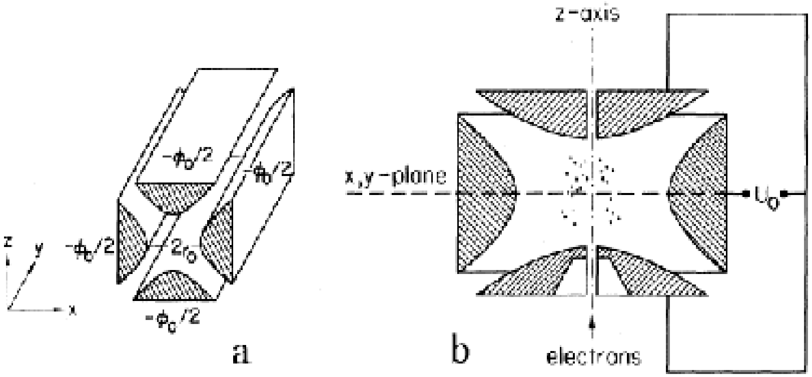
- Assume particle is cooled so that it is near its lowest vibrational state
- Have a ladder of these harmonic oscillator states

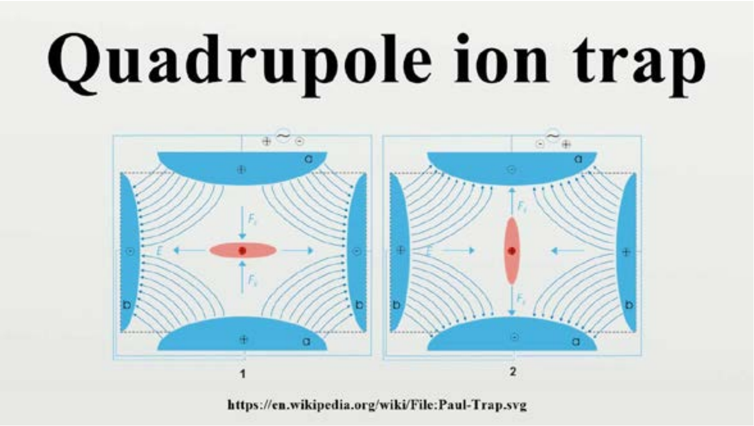


Construction of the TIQC Experimental Apparatus

1- Experimental Apparatus

- Construct an apparatus that will confine ions along one dimension of the system
- 1st design idea is to consider and electromagnetic trap consisting of 4 cylinders as shown below
- The ends of the cylinders are biased at different dc voltages from the cylinder center so that the charged ions are axially confined




Quadrupole ion trap

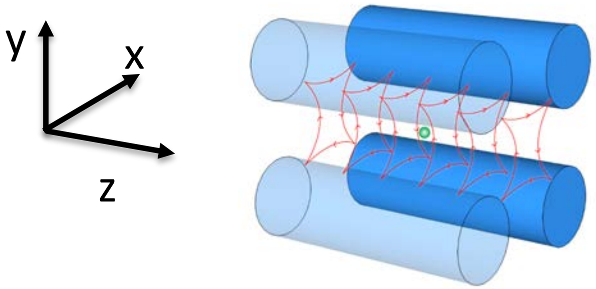
https://en.wikipedia.org/wiki/File:Paul-Trap.svg

Model an Ion in a Stationary Quadrupole Field*

* You tube video (stationary saddle) https://www.youtube.com/watch?v=XTJznUkAmIY

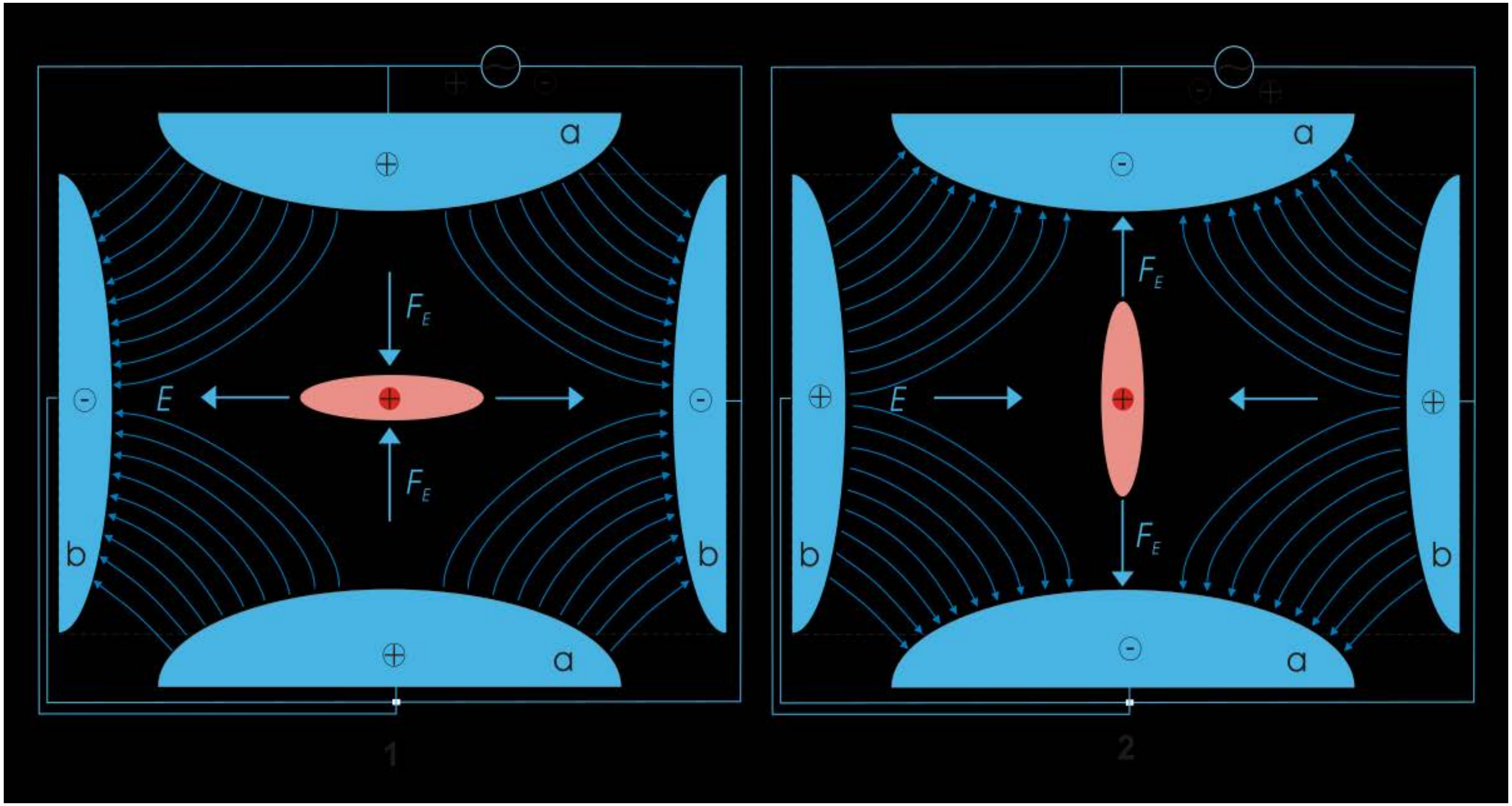
Experimental Apparatus
Design Shortcoming

- Static electric field confinement of the atoms in three dimensions is not possible because of the divergence theorem for the electric field
- Div **E** = 0 → no net inward force to constrain motion of the atoms
- force cannot be inward in all directions → at least one direction where ions can escape



Experimental Apparatus
Dynamic Ion Trap Option

- One solution is to consider dynamic traps
- A dynamic trap is a design where two of the electrodes are grounded and the other two are driven by an RF voltage
- The RF voltage generates a periodic rotation of the shape of the field lines as seen by the ion
- Set the rotation of the parabolic electric field lines at a rate that the atom periodically feels parabolic constraining force and then a parabolic un-constraining force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Dynamic Ion Trap Option

- As the atom starts to feel unconstrained and accelerate away from the center, the applied RF voltage rotates the field lines with a timing such that the atom starts to feel the parabolic constraining field lines
- The atom then starts falling in a direction 90º to the original direction of motion
- As it starts to fall in the direction the field lines have rotated so that the ion now feels a parabolic constraining force preventing its un-constraining motion
- The period of rotation of the RF is adjusted so that the fields lines permanently keep the ion trapped

Brain Teaser Time

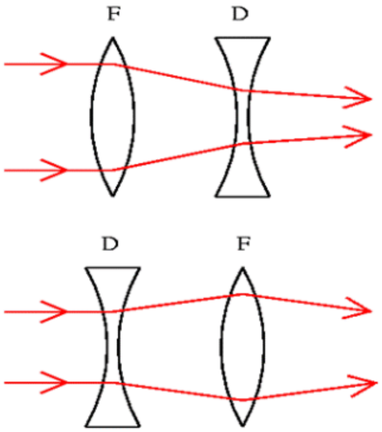
- How does this applied rf field provide a net attractive force confining the ion in the trap?
- If ω is the frequency of the applied rf then applied force on the ion over one period has the form proportional to

$$\sim \int_{0}^{2\pi} \cos(\omega t)dt$$

- What is the value of this integral over the period [0, 2π]?
- How can this provide a net confinement of the ion over time?

The Principle of Strong Focusing*

- This principle of physics has been the basis for the design of all alternate gradient synchrotron particles accelerators since the middle of the 20th Century



*Beam Optics and Lattice Design for Particle Accelerators
https://arxiv.org/ftp/arxiv/papers/1303/1303.6514.pdf

The Principle of Strong Focusing

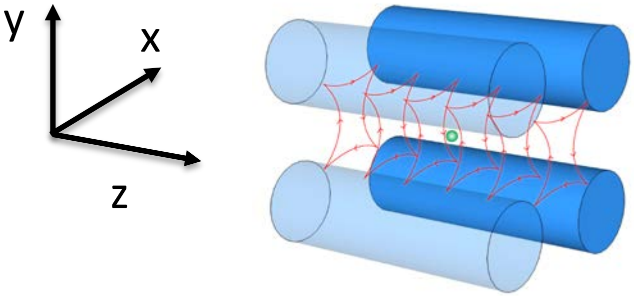
- The shape of the rotating quadrapole field provides a time dependent alternate focusing and de-focusing field
- If a path is traced at a constant distance from the center through 1 period of oscillation the force felt by the ion is zero
- If a trace of the particle’s path through the particle’s actual trajectory passing through the focusing and de-focusing fields is followed the result is that there is a net focused (confining) trajectory for the particle (ion) [using appropriate optics physics equations to calculate the trajectory of the ion as in passes through these lens (fields)]

Rotating Saddle Point Surface*

* You tube video https://www.youtube.com/watch?v=rJ13qwRYs

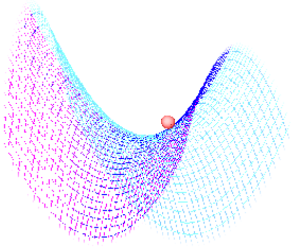
Additional Effect of the Periodic RF Potential

- Net effect produces a combined effect
  - The combination of the RF and DC voltages also produce a harmonic potential
  - The electrostatic repulsion of each ion creates a string of ions trapped along the z-axis of the trap



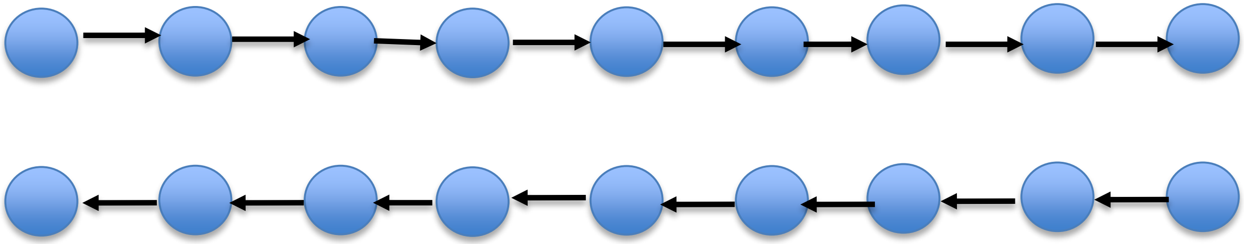
Design of a 1-D Harmonic Oscillator Within the Experimental Apparatus

- This process isolates and traps a small number of atoms (in this discussion they are $^{40}Ca^+$)
- Cool the ions to a temperature where they can be sufficiently decoupled from the surrounding environment
  - (ex. minimum amount of spurious electromagnetic fields that can cause random transitions between energy eigenstates)
- Under these conditions the motion of the confined ions becomes quantized as a 1-dimensional harmonic oscillator with equally spaced energy levels $\hbar\omega$



Phonons

- These phonons are center of mass energy eigenstates that represent the coupled vibrational modes of the entire lattice of ions



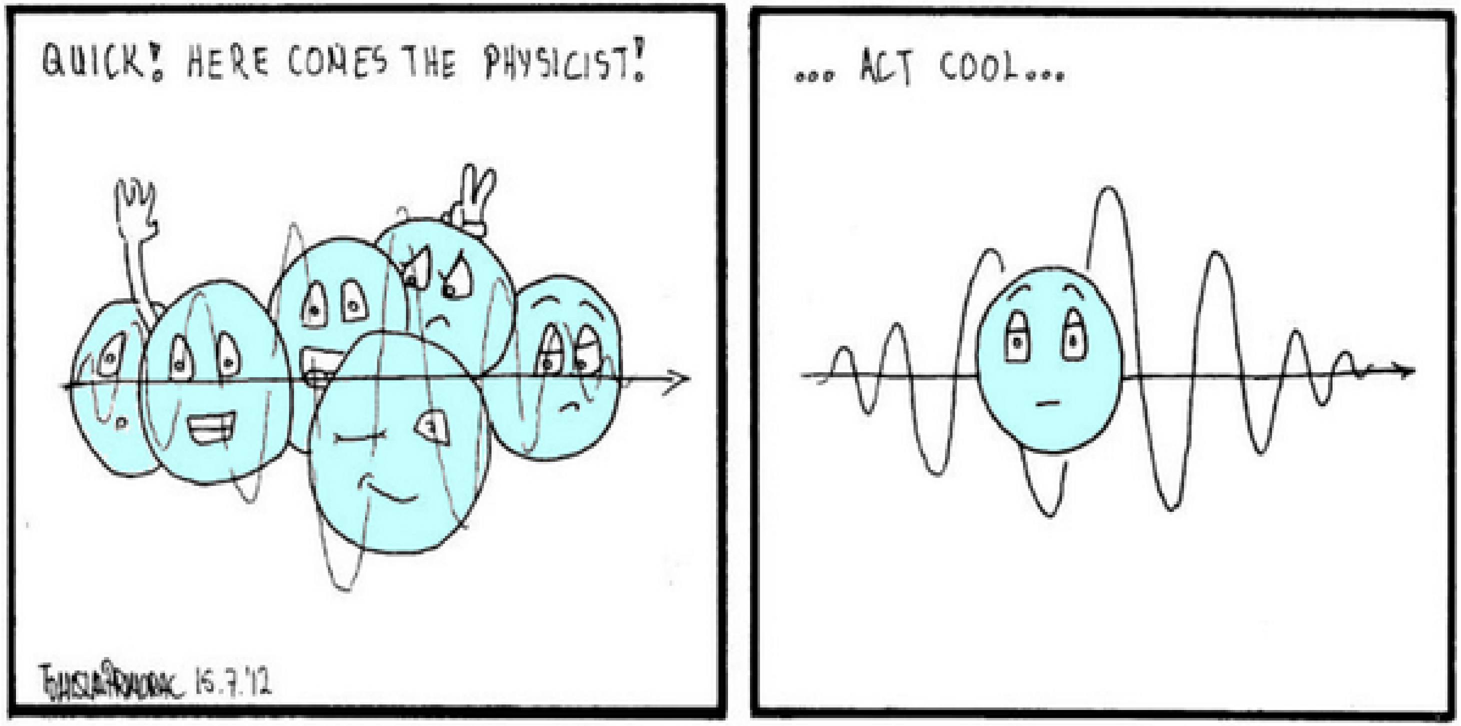
- These ions are at room temp and have many thermal vibrational modes

Construction of the TIQC Experimental Apparatus

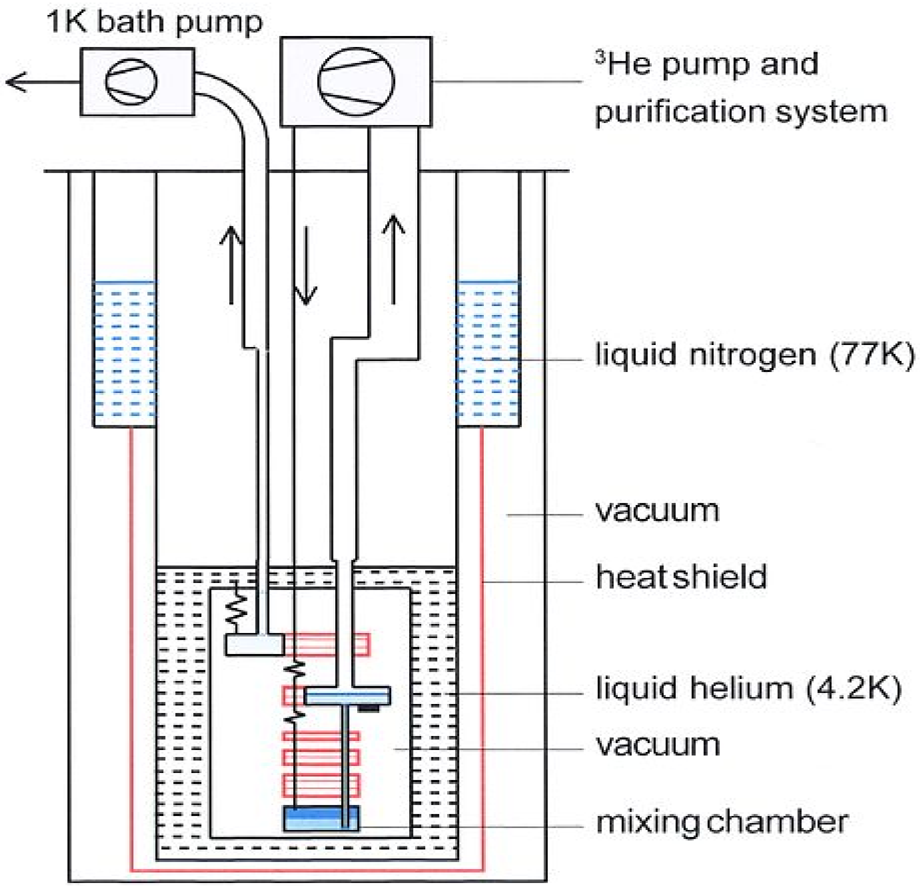
Requirement for Low Temperature Environment for the Experiment

- At room temperature the electrons are subject to many types of energy fluctuations
- Above the filled electron shells, there are many unfilled bound states to which the electron can transition (unwanted volunteers)
- Want to suppress this “jitter” so that the transitions that number and type of transitions between bound states in the Ca atom is minimized

Minimize The Number and Type of Atomic Transitions in a Material by Cooling The Experimental Apparatus To Almost "Absolute Zero" Temperature



Dilution Refrigerator *



* Image from http://www.wikiwand.com/en/Dilution_refrigerator

Cooling the Experimental Samples

- The experimental chamber is cooled to about 4^{O} Kelvin with standard refrigeration technology
- To get to lower temperatures specialized techniques are required
  - Doppler Cooling
  - Sideband Cooling

Cooling Methods That Extend Beyond the Dilution Refrigerator Capability

- The two cooling methods are
  - Doppler cooling - light with frequency tuned slightly below an electronic transition in an atom sent in the opposite direction to the motion of the atom. In each absorption, the atom loses momentum equal to the momentum of the photon
  - Sideband cooling – incrementally cool the ion by sending laser pulses the step down the hyperfine state from higher to lower energy hyperfine state

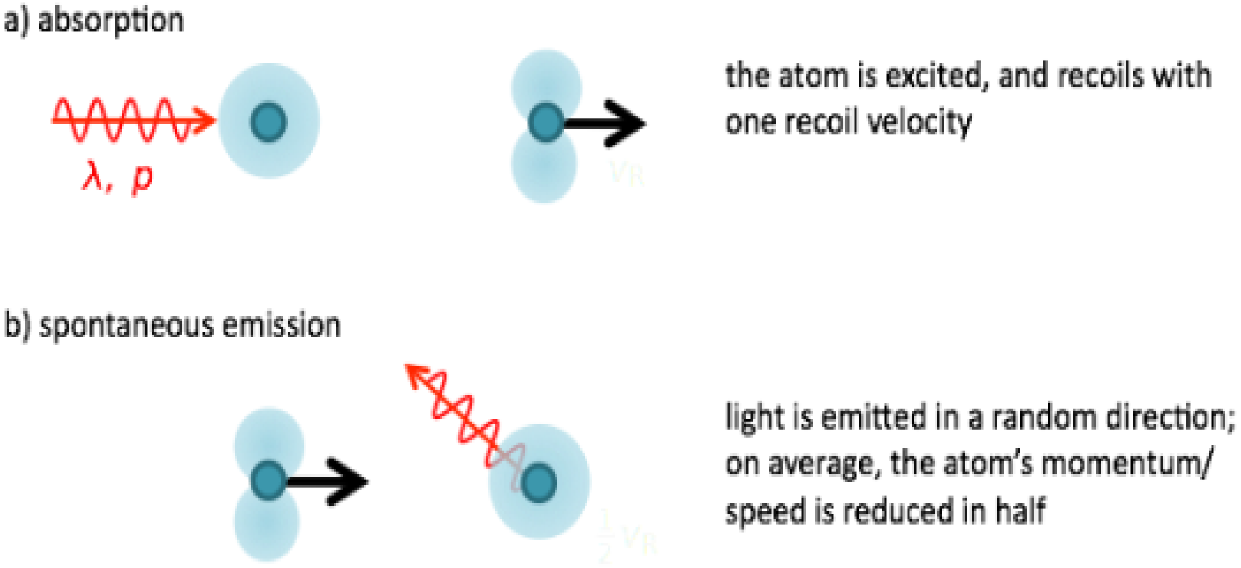
Doppler Cooling

- Doppler cooling operates through the concept of momentum transfer as a result of a head-on impact collision between an ion and photon in the apparatus
- Laser light with frequency tuned slightly below an electronic transition in an atom (detuned to the "red“) is directed to the atom
- The atom absorbs more photons if it is moving toward the light source (Doppler effect)
- If light is applied from two opposite directions, the atoms will always absorb more photons from the laser beam pointing opposite to atom’s direction of motion
- In each absorption event, the atom loses momentum equal to the momentum of the photon

Doppler Cooling

- If the atom (which is now in the excited state), emits a photon spontaneously, it will be kicked by the same amount of momentum but in a random direction
- The result of the absorption and emission process is a reduced speed of the atom, (provided its initial speed is larger than the recoil velocity from scattering a single photon)
- If the absorption and emission are repeated many times, the mean velocity, (i.e. the kinetic energy of the atom) will be reduced
- Because the temperature of an ensemble of atoms is a measure of the random internal kinetic energy, thermodynamically this is equivalent to cooling the atoms

Diagram* - Doppler Cooling



a) absorption

the atom is excited, and recoils with one recoil velocity

b) spontaneous emission

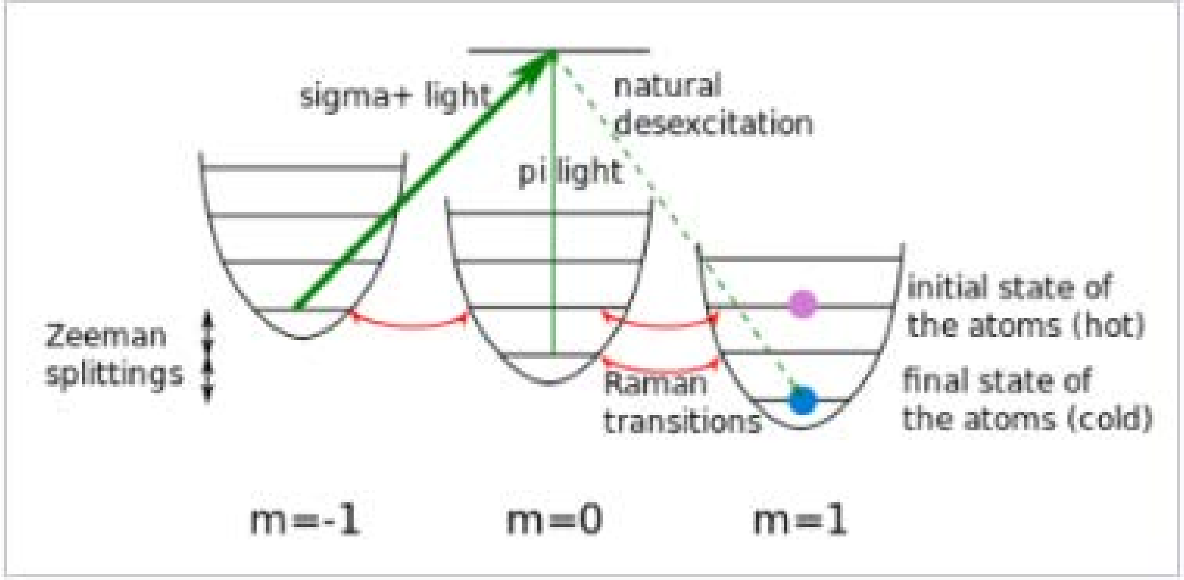
light is emitted in a random direction; on average, the atom's momentum/ speed is reduced in half

* Figure from https://sites.ualberta.ca/~ljleblan/background/laser-cooling.html

Sideband Cooling

- **Raman cooling** is a sub-recoil cooling technique that allows the cooling of atoms using optical methods below the limitations of Doppler cooling.
- Uses the techniques of Raman scattering
- Optical lasers
- Magnetic field that splits the hyperfine state into its z components
- limited by the recoil energy of a photon given to an atom.

Sideband Cooling



Raman side-band cooling

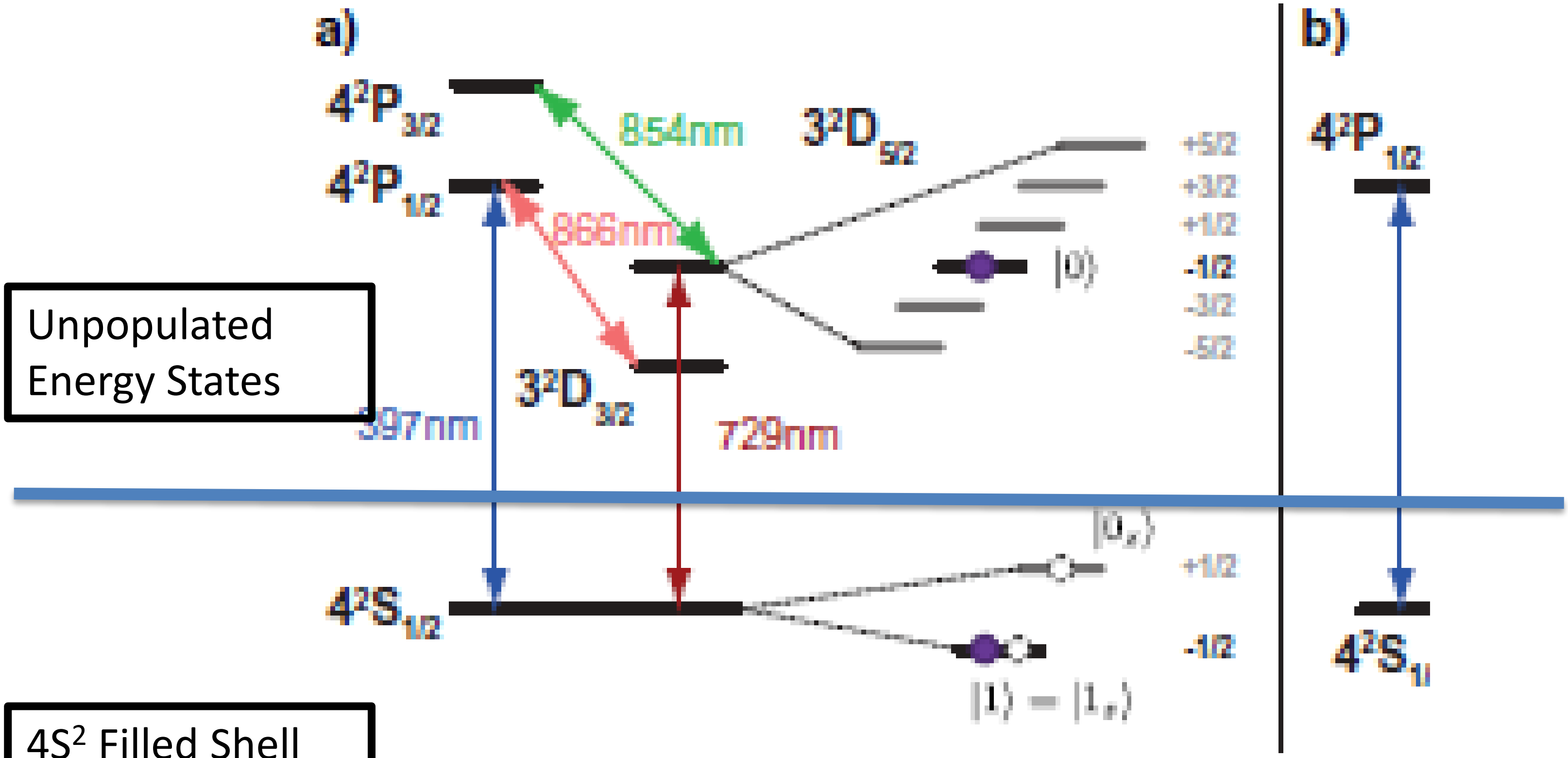
Figure from Wikipedia – Raman Cooling
https://en.wikipedia.org/wiki/Raman_cooling

Select the Atomic Material from the Periodic Table

Sample Material Selected is ^{40}Ca

- Material selected for the TIQC experimental sample is ^{40}Ca
- Examine the filled bound state electron shells and the unfilled shells just above the filled shells
- Measure the energy differences between the highest filled shell and the next few unfilled shell

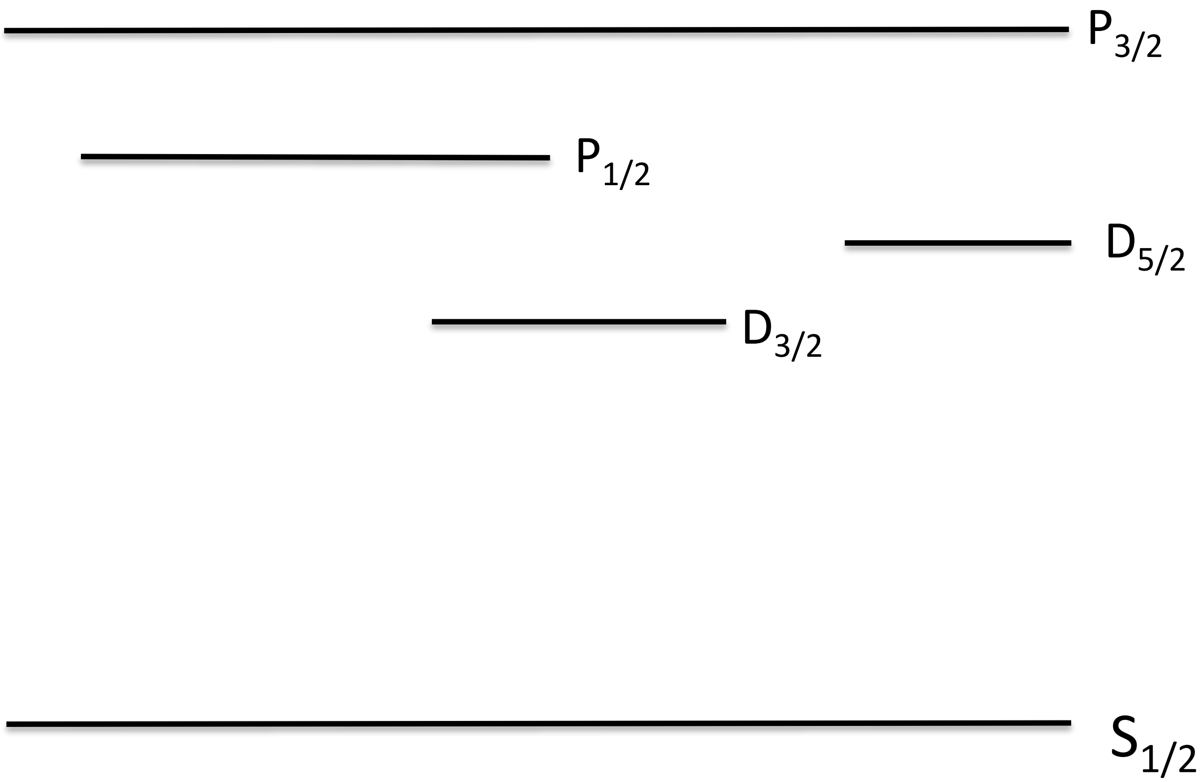
Focus on the Atomic Spectra of Calcium



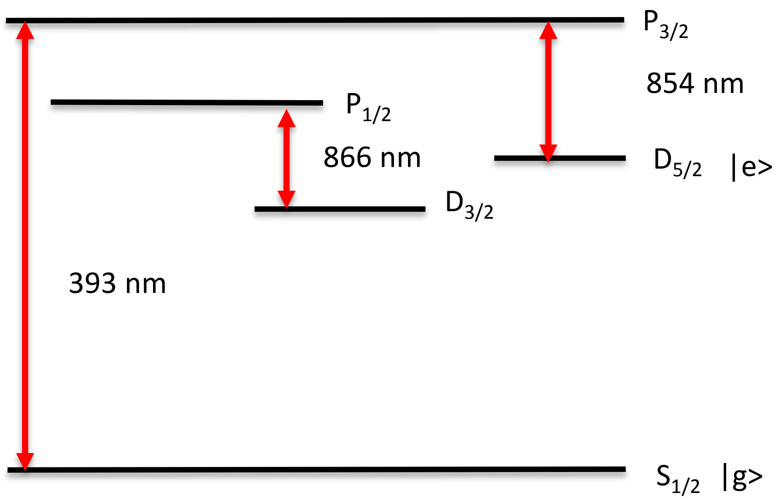
Unpopulated
Energy States

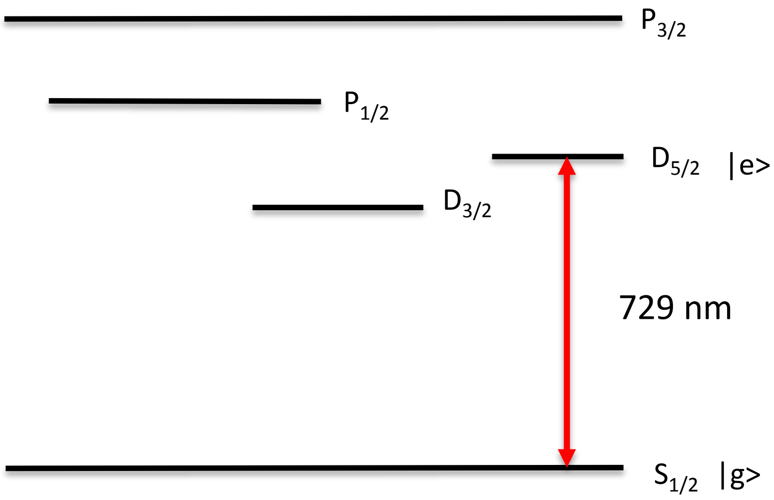
$4S^2$ Filled Shell
Energy States

Identify the Signature States Of Ca Just Below And Above The Fully Filled Shells



- Several Types of Ca Energy Level Transitions That Can be Identified
- Measure the energy differences between the highest filled shell and the next few unfilled shells





Lasers

Lasers in the Experimental Apparatus

- Light from a laser will interact with the electronic structure of these particular atoms
- Laser can
  - produce very narrow bands of radiation that can be detected in the frequency range of visible light
  - Tuned to specific electron transition energies
- By varying the polarization, phase, wavelength, and duration of the laser light pulse the behavior of the qubit can be controlled
- This effectively created rotations and transformations of the qubit states

Specific Laser Tuned Outputs

- There are 4 separate identified energy differences between these bound states
  - 393 nm
  - 854 nm
  - 866 nm
  - 729 nm
- This indicates that lasers that can produce outputs tuned to these wavelengths need to be part of the experimental apparatus

Rabi Frequency

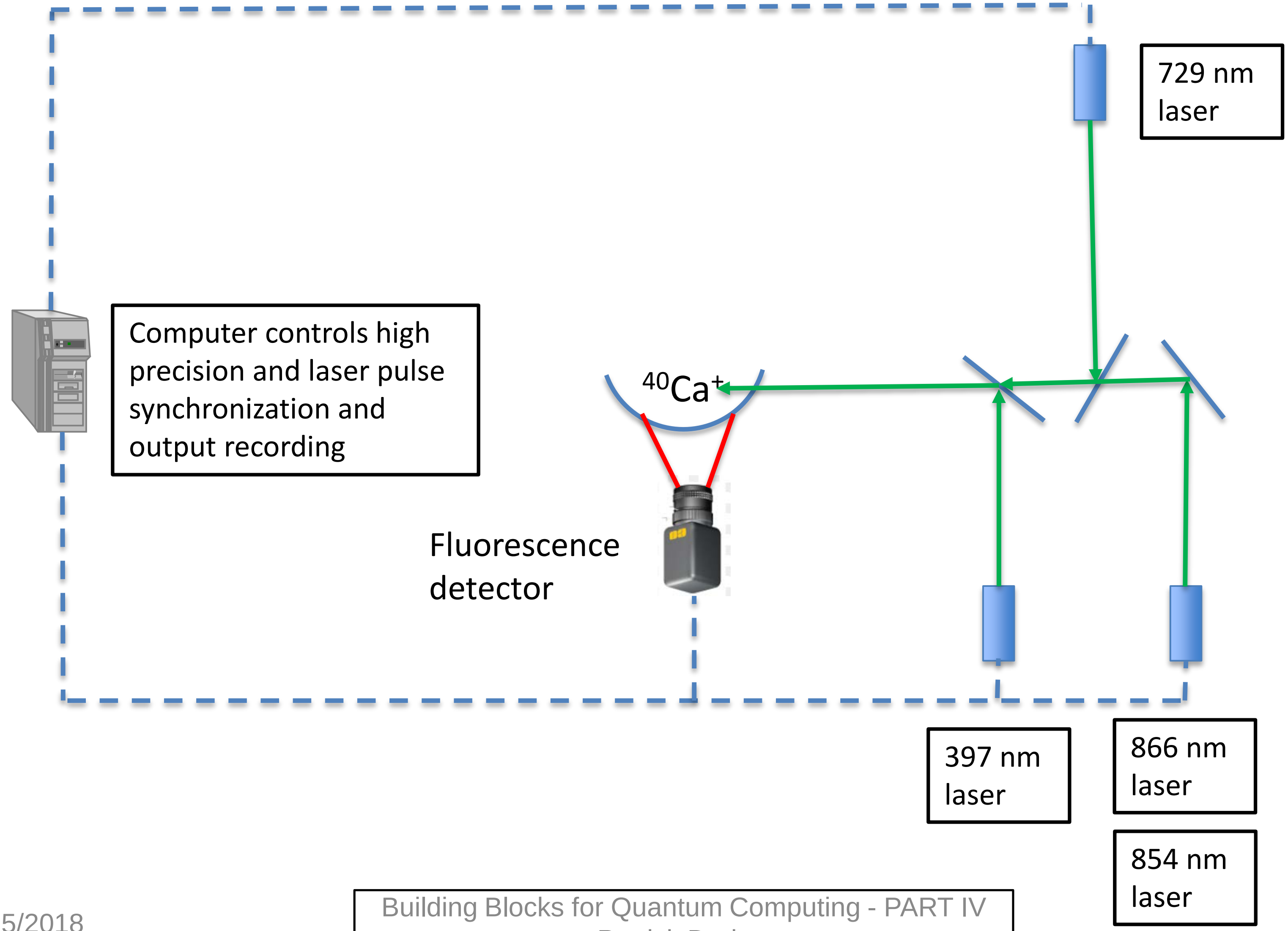
- The ^{40}CA has transitions that will allow an electron to oscillate between a bound state and excited state
- Use the lasers to induce two state excitations of the electron driven by a forcing field (laser)
- Rabi frequency is a quantity that occurs between the levels of a 2-level system illuminated with light exactly resonant with the transition
- Associated with oscillations of the quantum mechanical expectation values of level populations and photon numbers
- This transition will play a role in the operational aspect of a TIQC

Control Electronics and Detector

- Need to have electronics to precisely control the firing of each laser
  - Timing of each laser pulse
  - Timing between laser pulses
  - Sequencing of pulses among the lasers
  - Duration
  - Phase
- Detector (Fluorescence* is the technique that will measure the final TIQC state
  - Fluorescence detector to sample the final states of the ions

* Luminescence that is caused by the absorption of radiation at one wavelength followed by nearly immediate re-radiation usually at a different wavelength

Generic Block Diagram of a TIQC



Computer controls high precision and laser pulse synchronization and output recording

Fluorescence detector

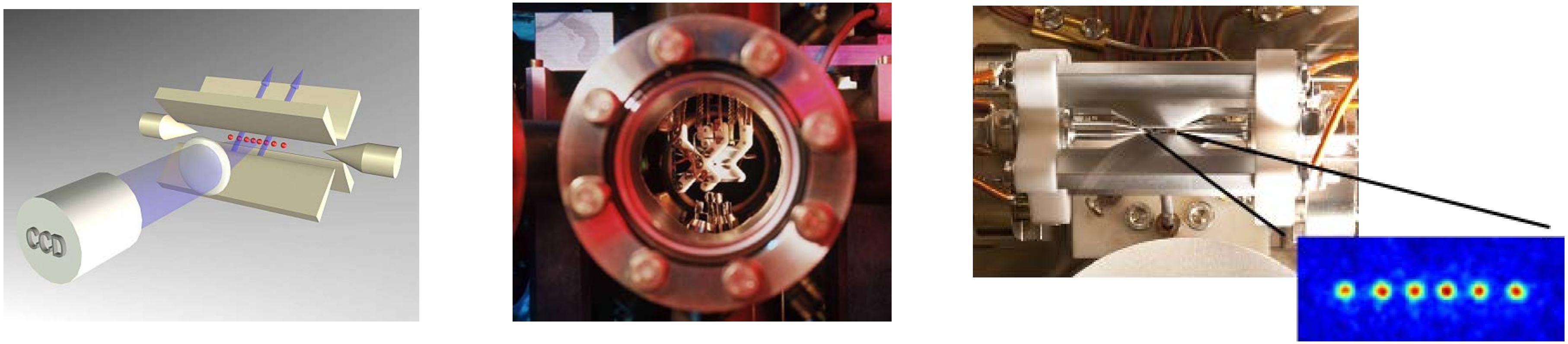
729 nm laser

397 nm laser

866 nm laser

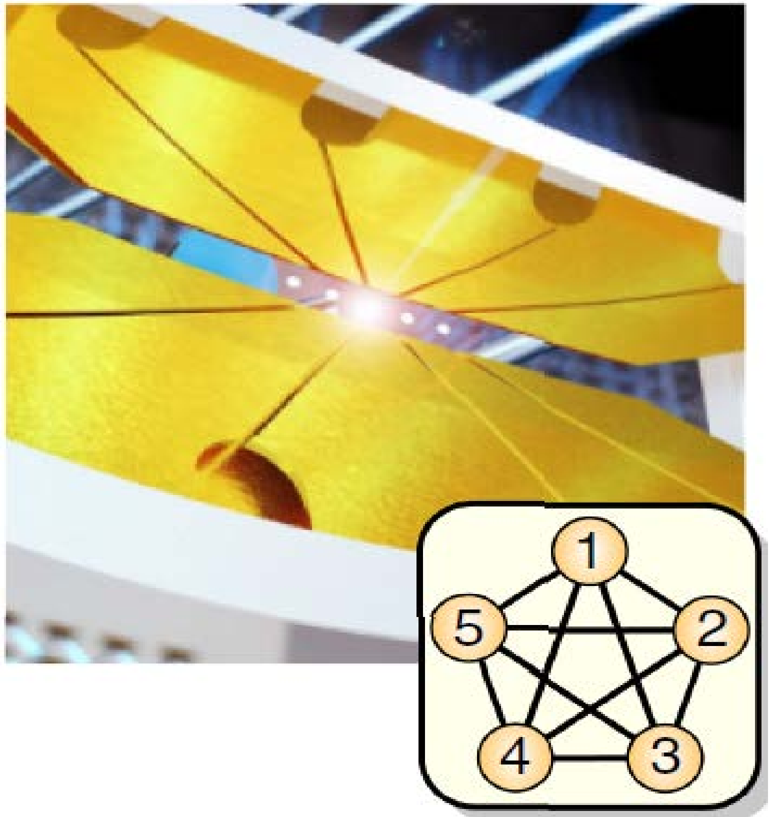
854 nm laser

Diagram and Photos of an Ion Trap*



* https://quantumoptics.at/en/research/lintrap.html Institut fur Experimentalphysik Universitat Innsbruck

- In the Ion Trap architecture all ions partake in the collective motion of the chain, gates between any pair can be invoked in this way
- The addressing during operations and the distinction between qubits during readout are both achieved by spatially resolving the ions



Trapped Ions mediated by laser pulse interactions

Comments Regarding Equivalent Quantum Computer Architectures

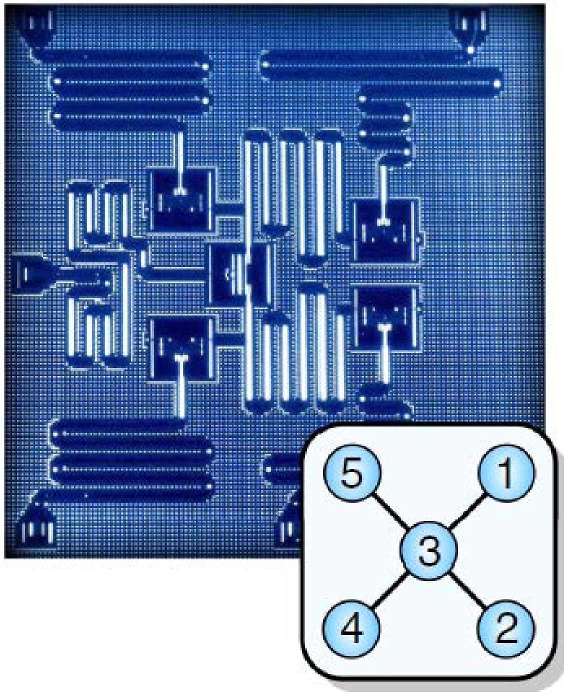
Other Universal Quantum Computers

- The trapped Ion Quantum Computer is not the only universal quantum computer that is in operation at the present time
- IBM has a different design to build rotation and CNOT gates for qubits using microwave resonators

IBM Q Transom Architecture

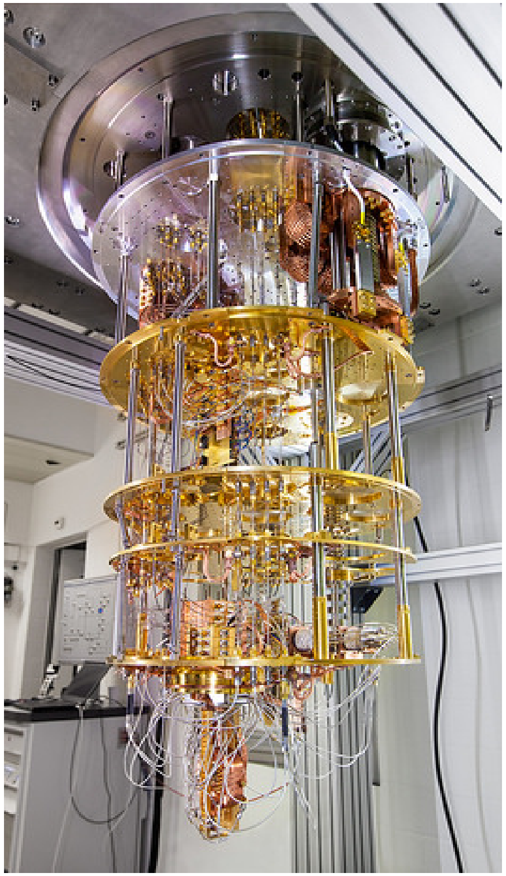
- “artificial atoms” constructed by making devices having superconducting islands connected by Josephson junctions and shunt capacitors
- provide superpositions of charge states that are insensitive to charge fluctuations
- qubits are connected to each other and the classical control system by microwave resonators
- State preparation and readout are achieved by applying tailored microwave signals to this network and measuring the response

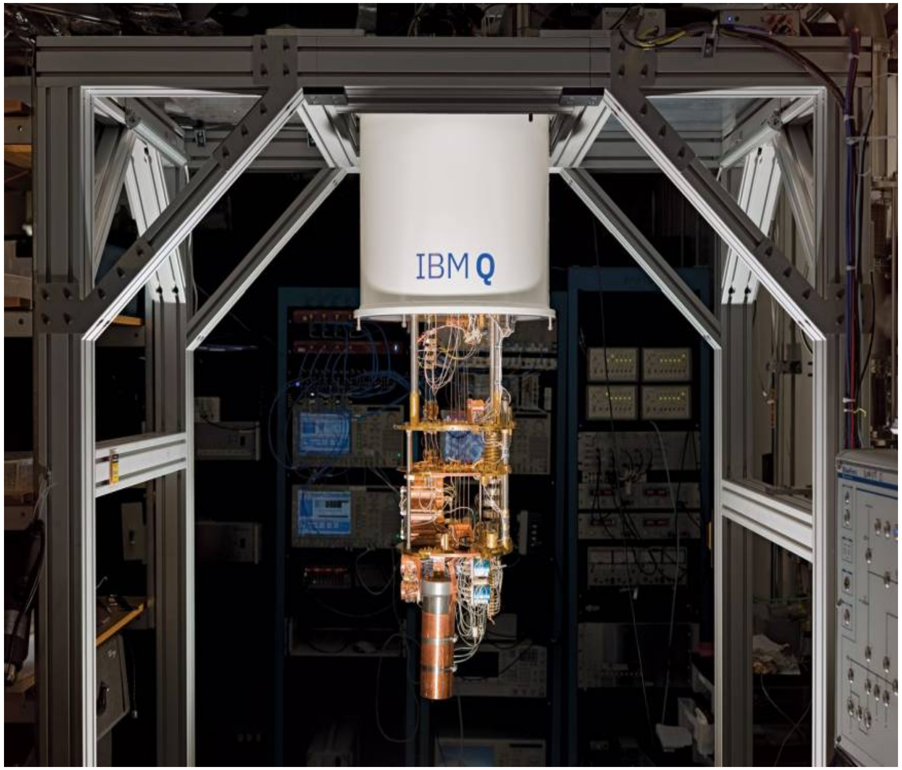
- In, the qubits are connected in a star-shaped pattern that provides four 2-qubit interactions which are controlled-NOT (CNOT) gates targeting the central qubit.



Superconducting qubits connected by microwave resonators (credit IBM research)

IBM Quantum Computer





Images credit IBM Research

IBM Q Cryostat for Quantum Computer

Images credit IBM Research

Additional Comments and Summary Comparing Different Universal Quantum Computers Will Be Discussed at the Conclusion of Lecture V

Last Slide - PART IV