Building Blocks for Quantum Computing Part III

"Quantum Mechanics and Atomic Physics " Primer

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CSC801 – Seminar on Quantum Computing

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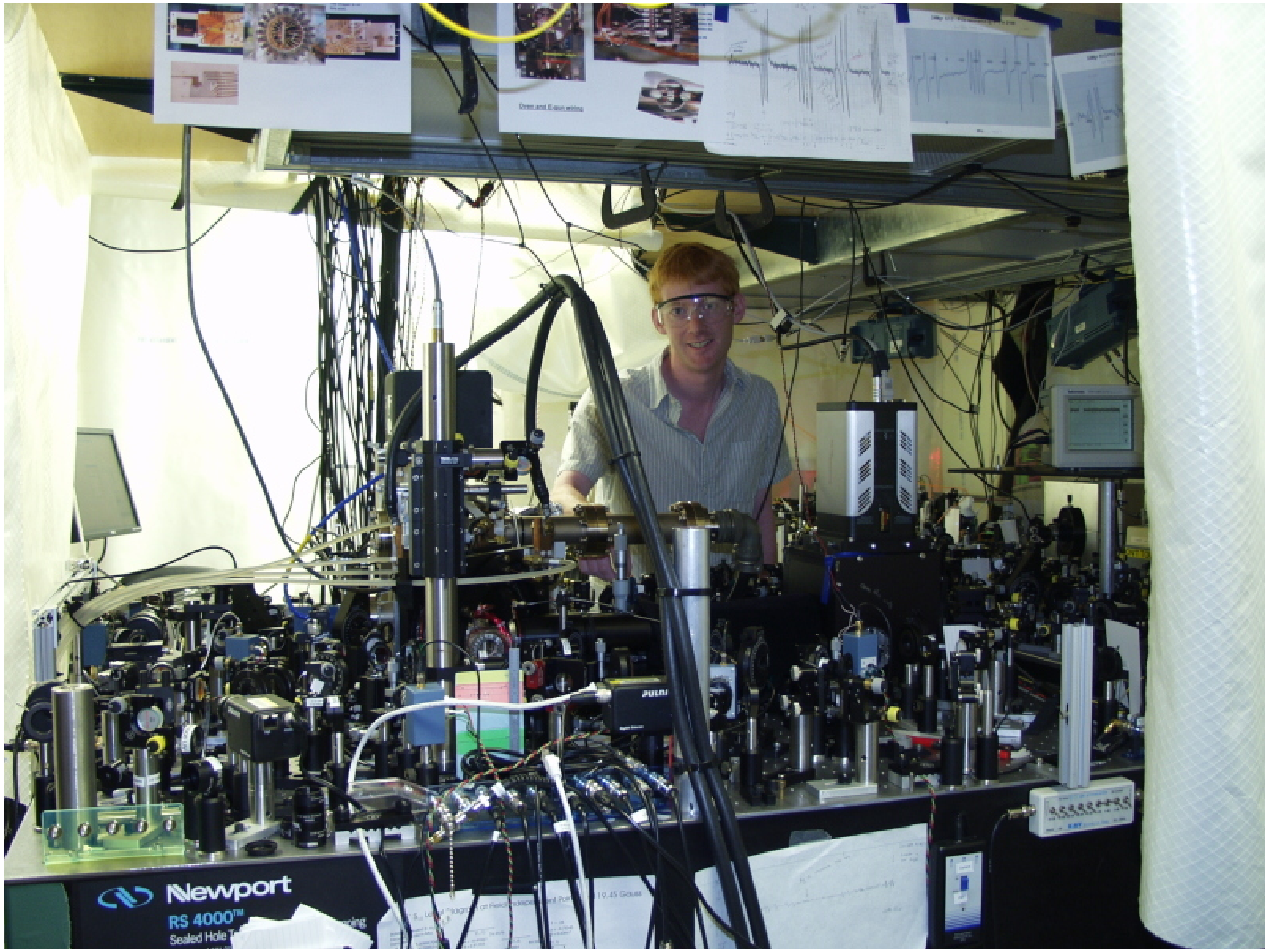
Goal Is To Understand The Principles And Operation of the Trapped Ion Quantum Computer (TIQC)

- 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

What Components are Included in the Experimental Apparatus of an Ion Trap QC



NIST Ion Trap Apparatus

Key Components in a TIQC

- To discern how a Trapped Ion Quantum Computer (TIQC) works need to identify key components
  - Atoms and Materials
  - Electromagnetic fields
  - Lasers
  - Experimental samples are deposited in extremely low temperature experimental chambers (cryostats)
- Examine these components one at a time to understand their role in a TIQC

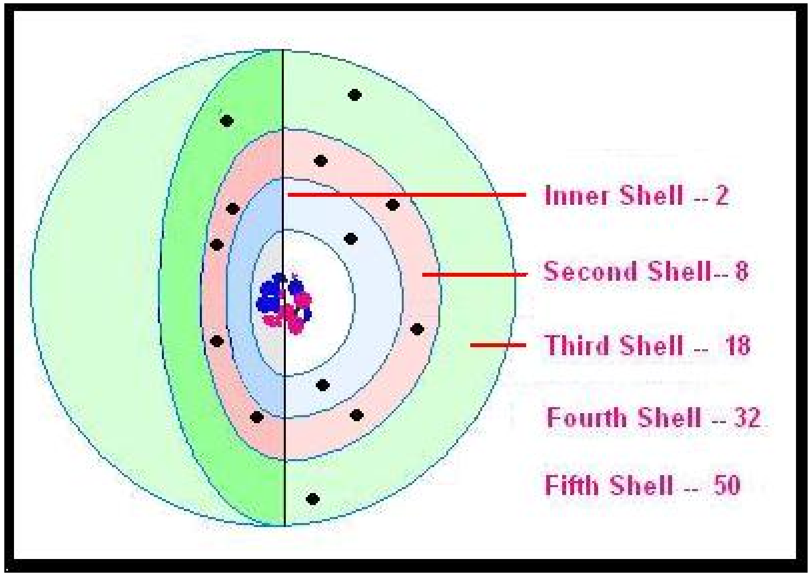
“Quantum Mechanics Primer” for Atoms and Materials

Start by Selecting a Material for the TIQC

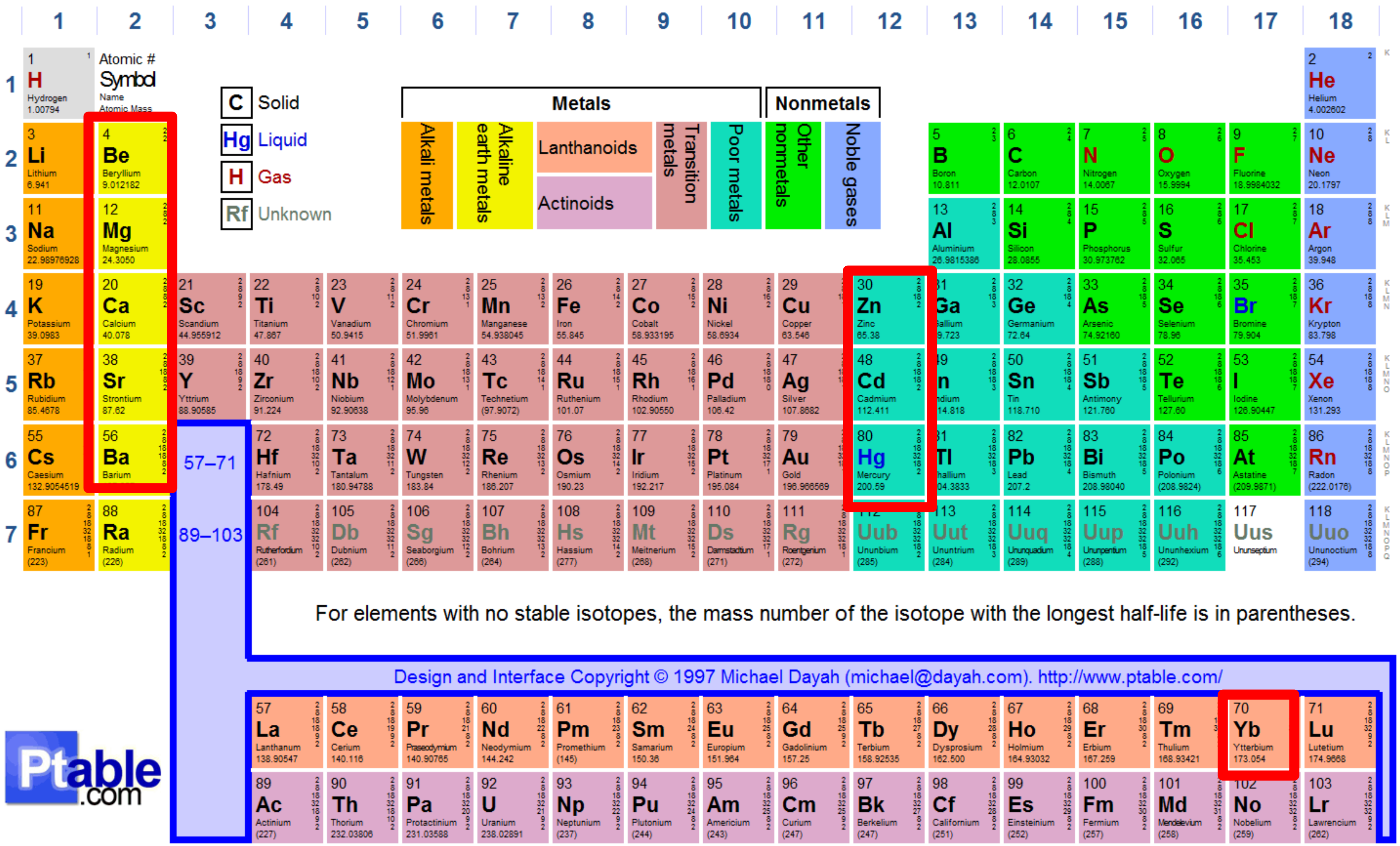
- Experimentalists select specific elements because
  - Unique atomic properties when interacting with electromagnetic waves
  - Various properties of the atom can be mapped to the operations of a qubit
- Questions
  - What is the selection criteria for specific materials?
  - How and why do they work in a TIQC?

Properties of All Materials

- All materials are atoms that are made of protons, neutrons and electrons
- Protons and neutrons form the nucleus of the atom
- Electrons surrounding nucleus reside in atom's energy levels
- Electrons occupy energy shells surrounding the nucleus
- Inner shells will fill first
- All types of atoms are globally classified and organized in a Periodic Table of the Elements



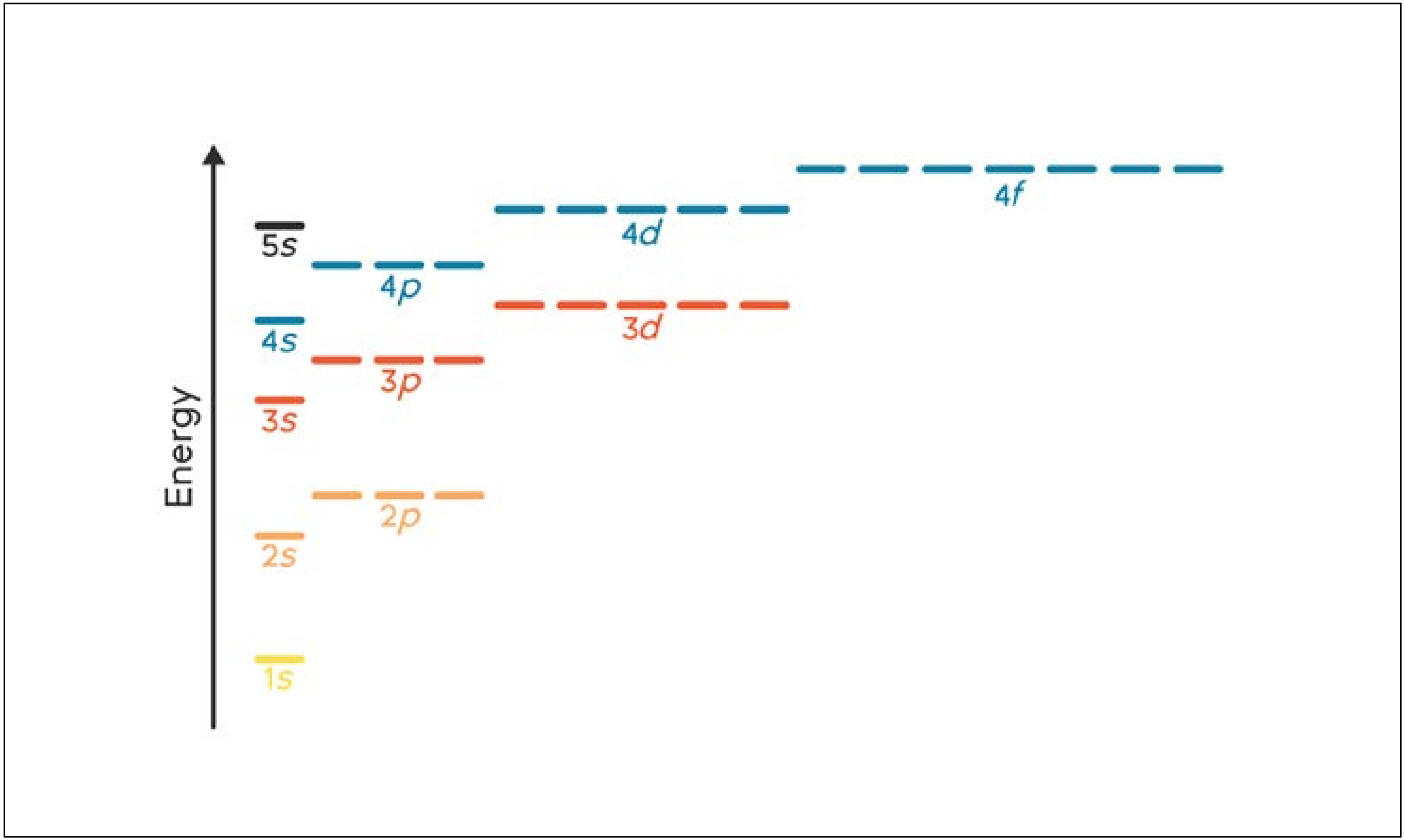
Periodic Table of Elements



Bound States of Each Element

- Each element in the Periodic Table has protons (and neutrons) in a nucleus and an equal number of electrons in bound states surrounding that nucleus
- There are different energy levels (n = 1, 2, 3, …) that have bound states labelled as S, P, D, F, …
- The electrons fill these bound states in a specific order
  - S state – takes 2 electrons
  - P state – takes 6 electrons
  - D state – takes 10 electrons

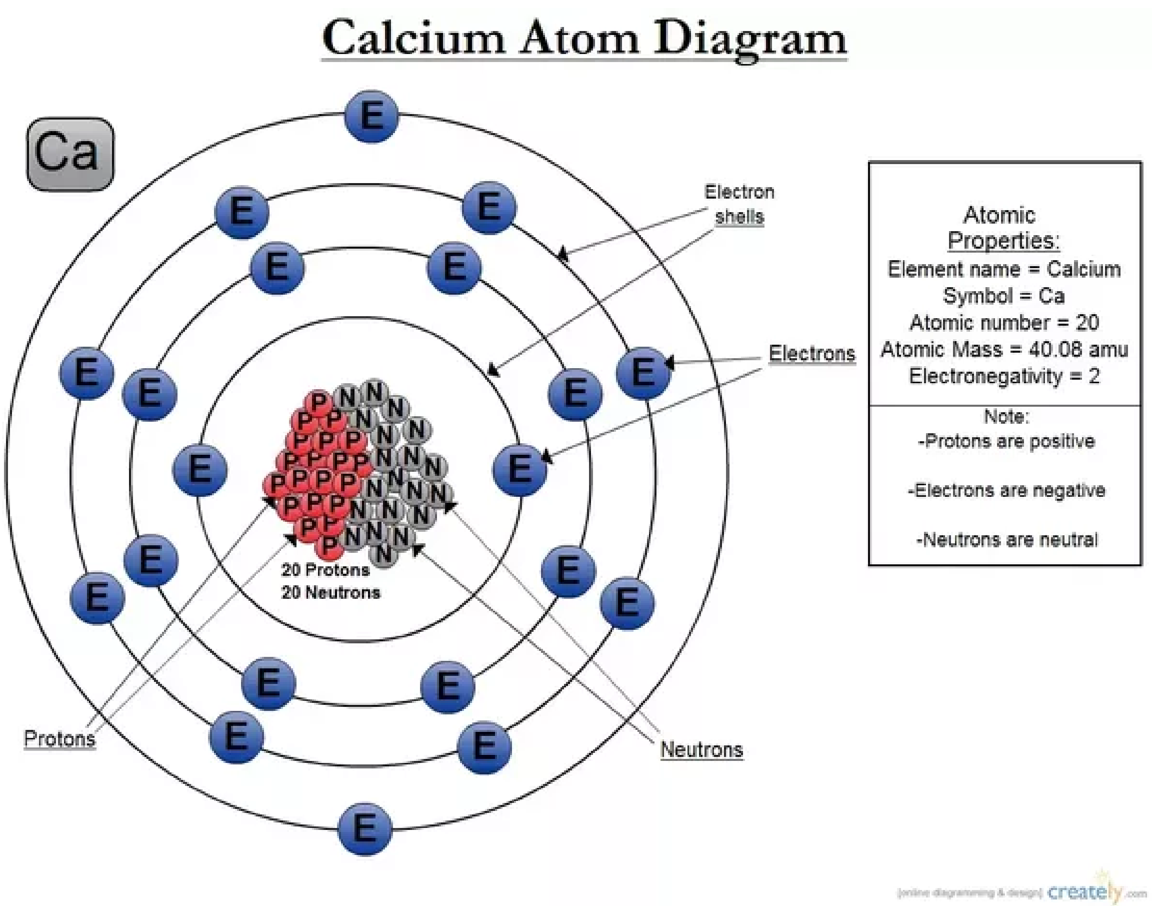
Order of Filling of Shells



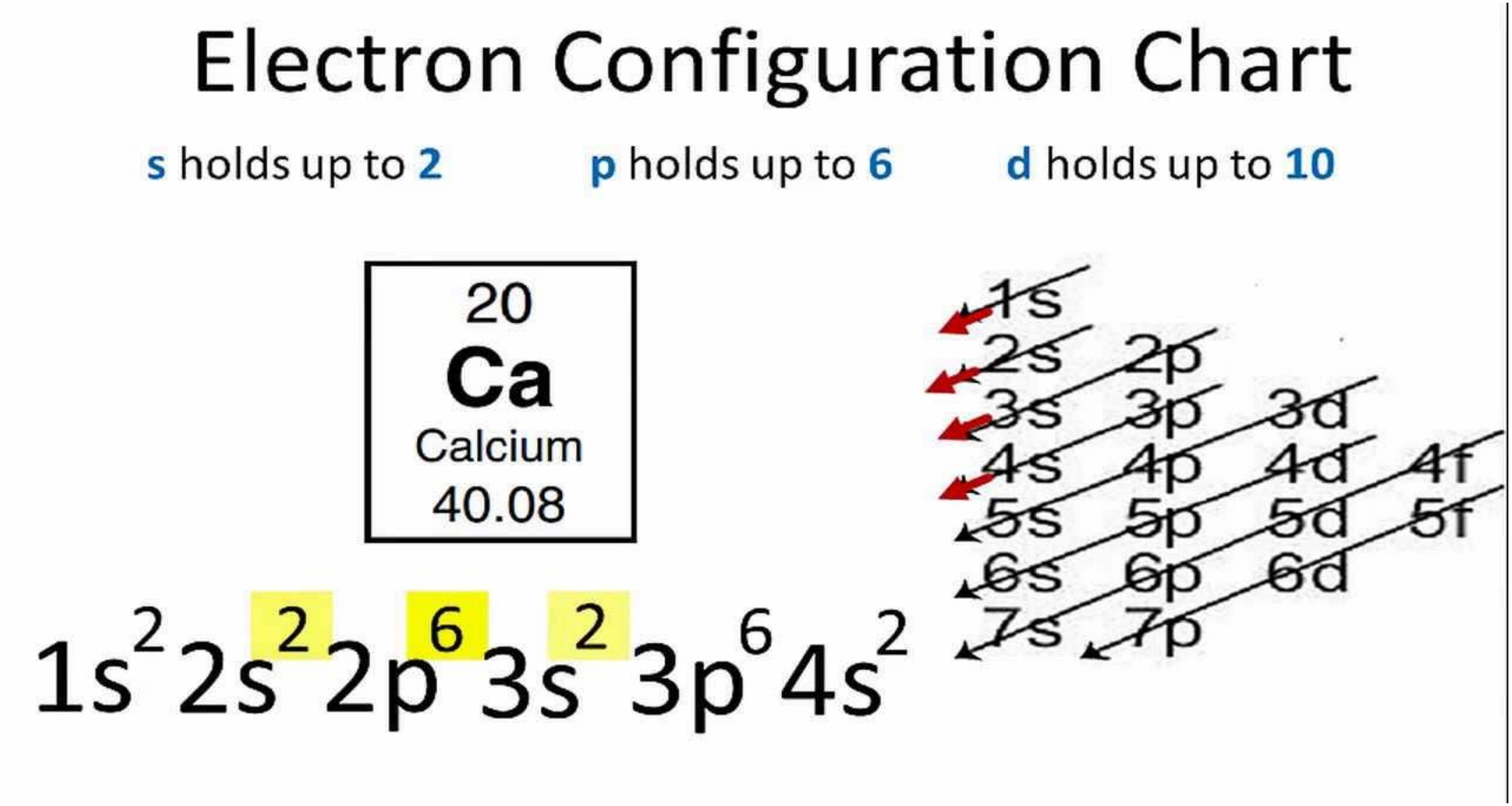
Picking an Element for a TIQC

- Choose Calcium in the 2nd column of the periodic table
- Calcium (Ca) has atomic number 20 (20 protons in the nucleus and 20 electrons filled in distinct energy bound state shells surrounding the nucleus)
- Interactions mainly occur among electrons in the partially filled outer shells
- Examine the atomic properties of Ca

Examine the Atomic Structure of a Calcium Atom



Order of Electron Filling of Energy Levels in Calcium Atom



Electromagnetic Fields

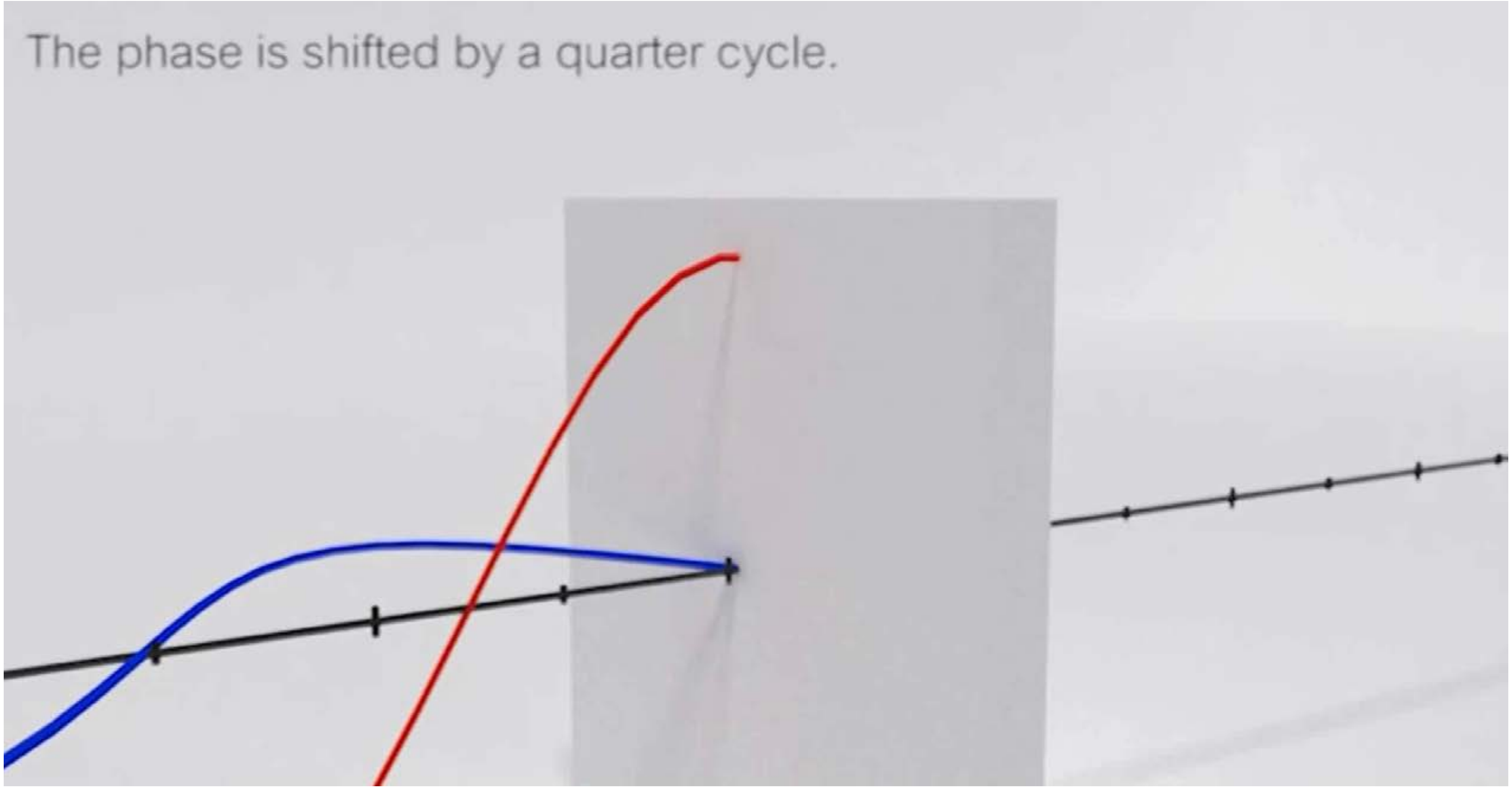
Electromagnetic Fields

- Electromagnetic fields
  - Carry energy and angular momentum
  - Interact with electrons in atoms
- Key properties of atoms and electromagnetic fields

✓ **Bound state electrons in an atom will absorb and emit discrete quantities of energy and units of angular momentum**

✓ **Electromagnetic fields are a primary source that transfers energy and angular momentum to electrons in the atom**

Propagation of Electromagnetic Fields



Transferring Energy to/from Bound State Electrons in an Atom

- The amount of energy that an electron absorbs/emits to change from an initial state to a different state is determined by
  - Difference between the two bound state energy levels
  - The initial and final angular momentum state (S, P, D, F,)
- The total angular momentum of the electron is determined by the combination of both the electron’s orbital angular momentum and an “internal” angular momentum called “spin”

Transferring Energy to/from Bound State Electrons in a Material

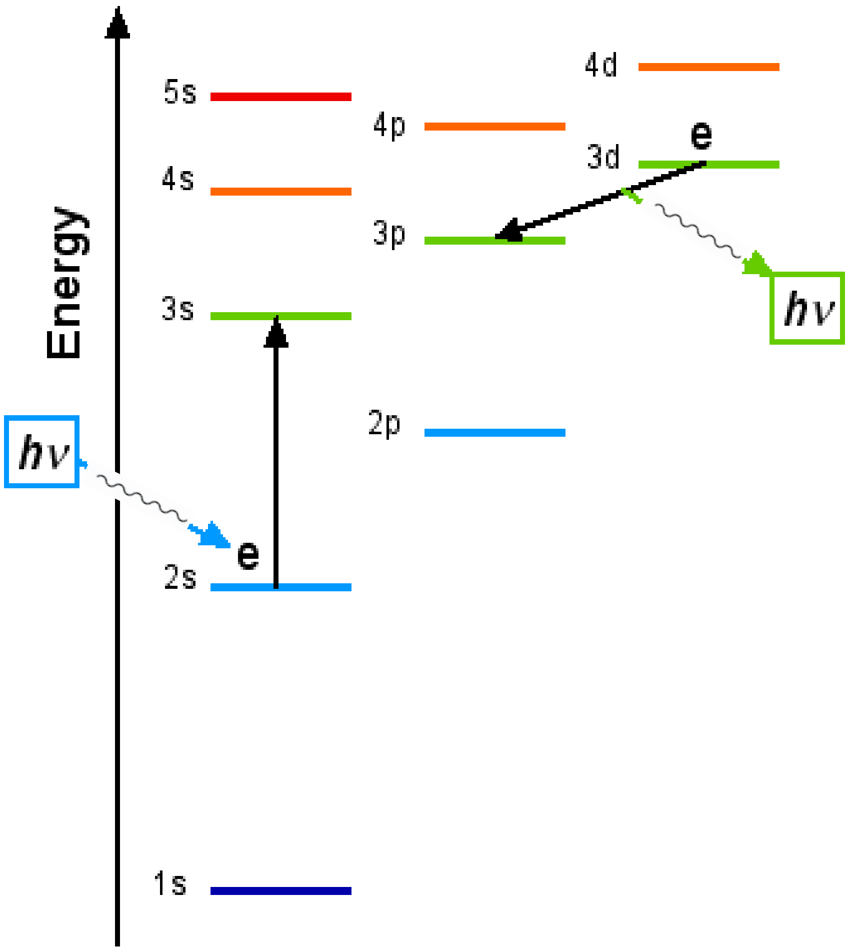
- By selecting a specific frequency of electromagnetic radiation it transfers energy and discrete units of angular momentum into an electron
- Results in an electron transitioning from an initial state to a different state
- There are specific “quantum mechanics” rules constraining transitions between energy levels based on the transition energy and change in angular momentum
- Rules are based on an electron’s total angular momentum J (sum of orbital angular momentum (L) and internal spin angular momentum (S))
- Rules summarized as “Selection Rules”

Selection Rules for Atomic Spectra

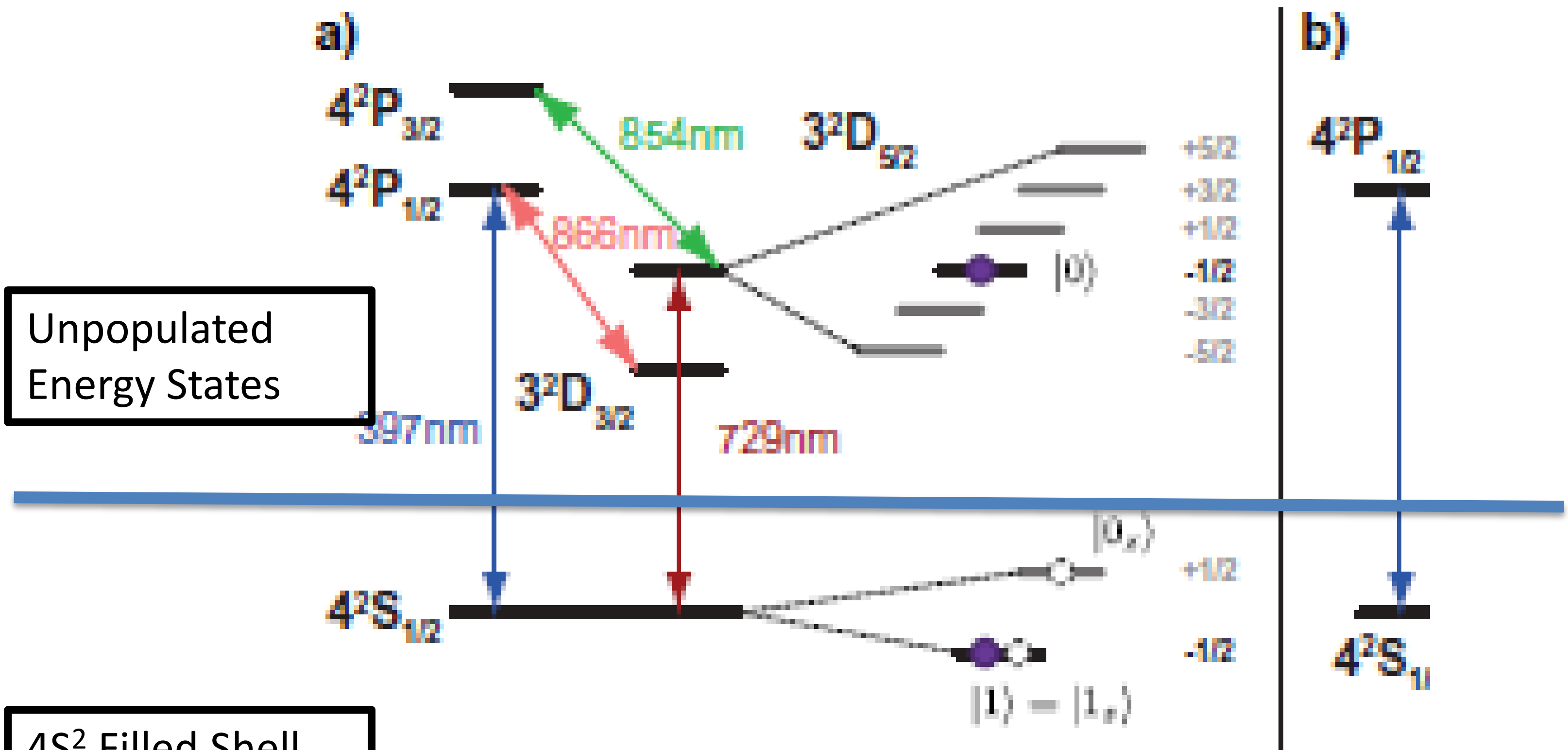
Electric dipole (allowed)		Magnetic dipole (forbidden)	Electric quadrupole (forbidden)
(1) $\Delta J = 0, \pm 1$		$\Delta J = 0, \pm 1$	$\Delta J = 0, \pm 1, \pm 2$
$(0 \nleftrightarrow 0)$	*Rigorous*	$(0 \nleftrightarrow 0)$	$(0 \nleftrightarrow 0, \frac{1}{2} \nleftrightarrow \frac{1}{2}, 0 \nleftrightarrow 1)$
(2) $\Delta M = 0, \pm 1$		$\Delta M = 0, \pm 1$	$\Delta M = 0, \pm 1, \pm 2$
(3) Parity change		No parity change	No parity change
(4) One electron jump		No electron jump	One or no electron jump
$\Delta l = \pm 1$		$\Delta l = 0$	$\Delta l = 0, \pm 2$
For L – S coupling	*LS*	$\Delta n = 0$	
(5) $\Delta S = 0$		$\Delta S = 0$	$\Delta S = 0$
(6) $\Delta L = 0, \pm 1$		$\Delta L = 0$	$\Delta L = 0, \pm 1, \pm 2$
$(0 \nleftrightarrow 0)$			$(0 \nleftrightarrow 0, 0 \nleftrightarrow 1)$

Energy Levels and Transitions in Materials

- Electrons can change energy states by transitioning among different quantized energy levels
- Electrons absorb and emit discrete quantities of energy and angular momentum when undergoing these transitions



Focus on the Atomic Spectra of Calcium



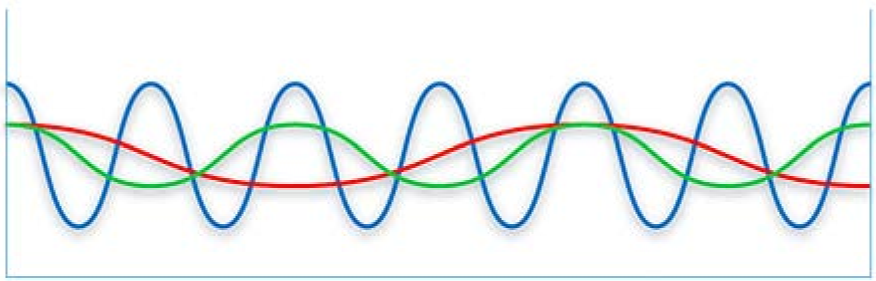
Unpopulated Energy States

$4S^2$ Filled Shell Energy States

Lasers

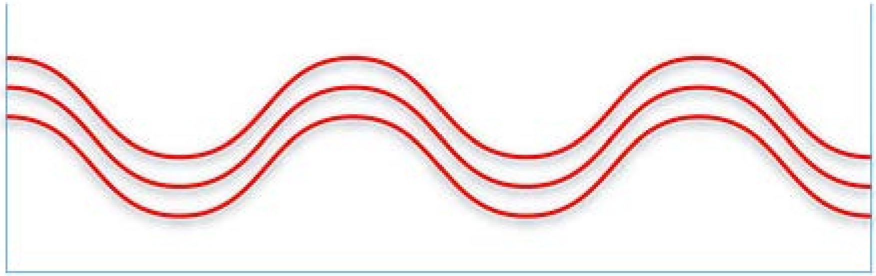
Electromagnetic Radiation Properties

- Light is composed of many electromagnetic fields of many different energies (frequencies)



Incoherent Light

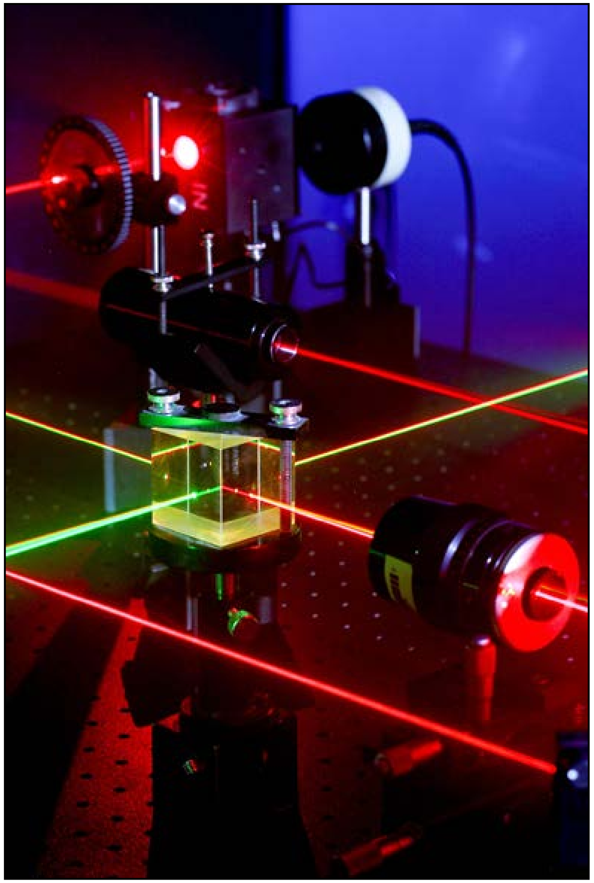
- Need light with properties of coherence (light with specific frequency and common phase)



Coherent Light

Need a Focused Source of Energy - Lasers -

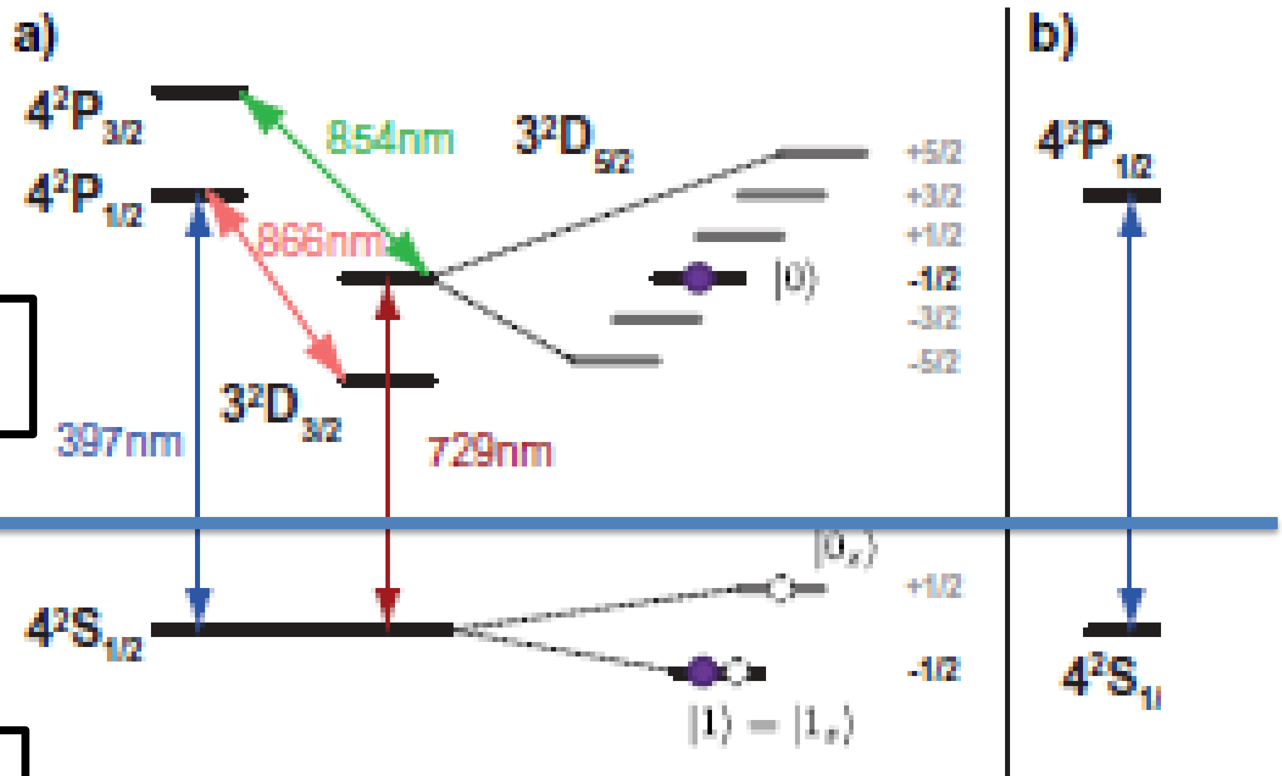
- It would be far more efficient to "dial-up" a specific energy difference that will cause the electron to transition (resonate) between two different energy levels
- Requires a coherent light source tuned to a specific frequency



Lasers in the Experimental Apparatus

- Electromagnetic radiation from a laser will interact with the electronic structure of these particular atoms
- Laser can
  - Produce electromagnetic radiation across a spectrum of frequencies from infrared through ultraviolet
  - Be tuned to specific electron transition energies
- By varying the polarization, phase, wavelength, and duration of the laser light pulse the behavior of the electron can be controlled
- From a QC perspective this effectively created rotations and transformations of the qubit states

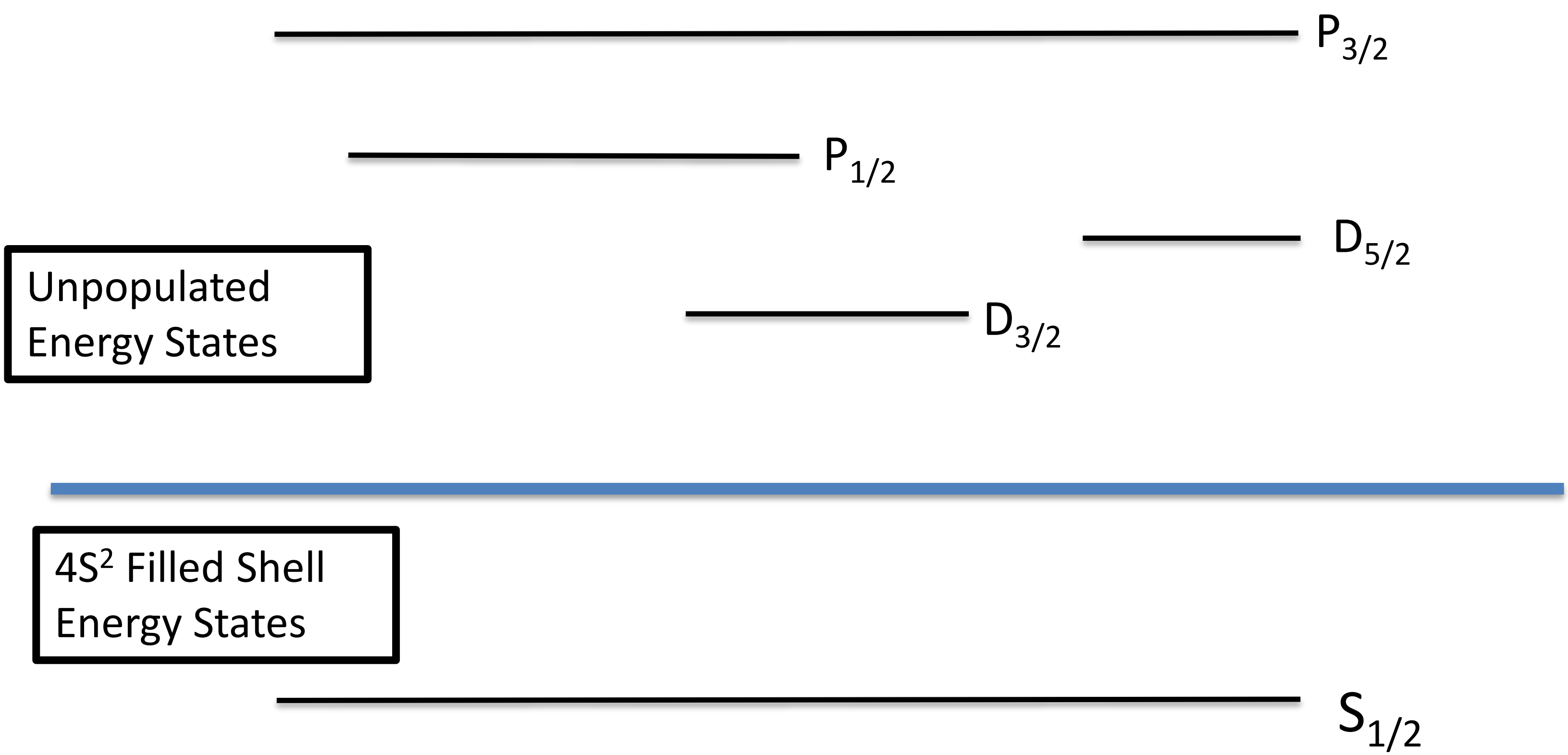
Calcium Atom Spectra



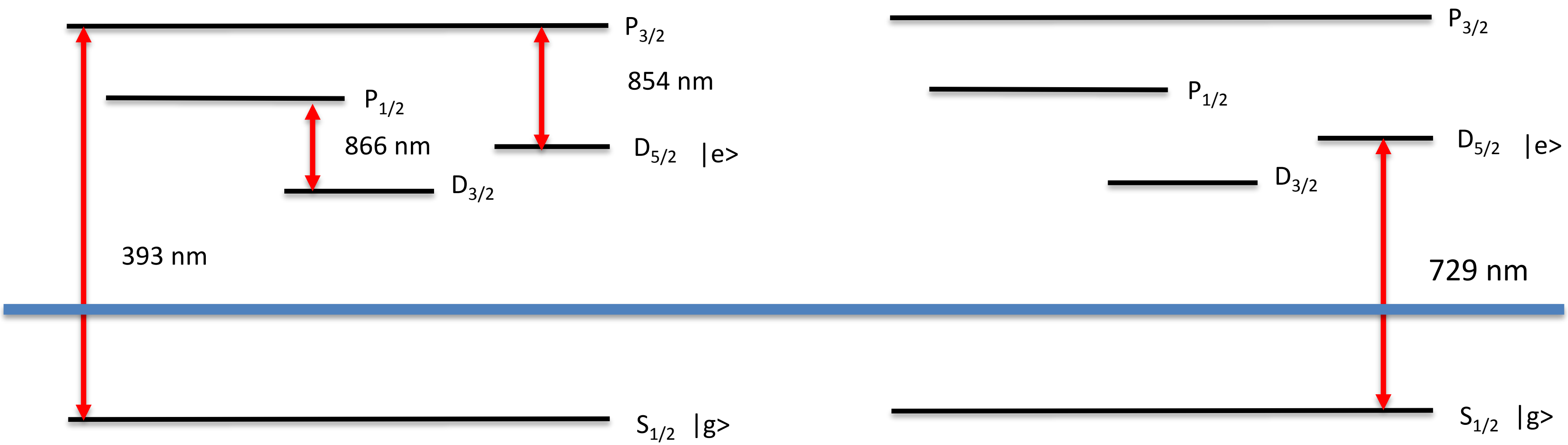
Unpopulated Energy States

$4S^2$ Filled Shell Energy States

Consider the States Of ^{40}Ca Just Below And Above The Fully Filled Shells



Several Types of ^{40}Ca Energy Level Transitions That Can be Identified



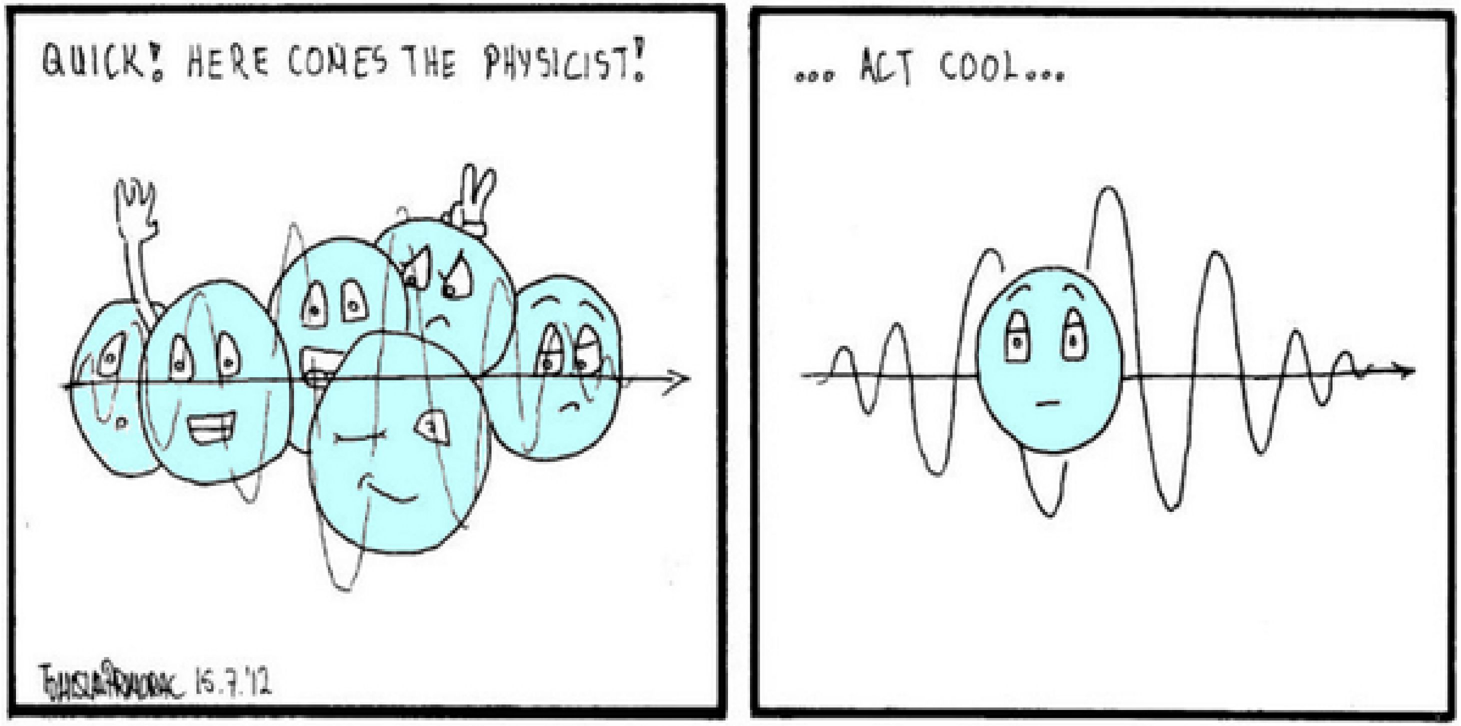
Low Temperature Experimental Apparatus

IBM Q Cryostat

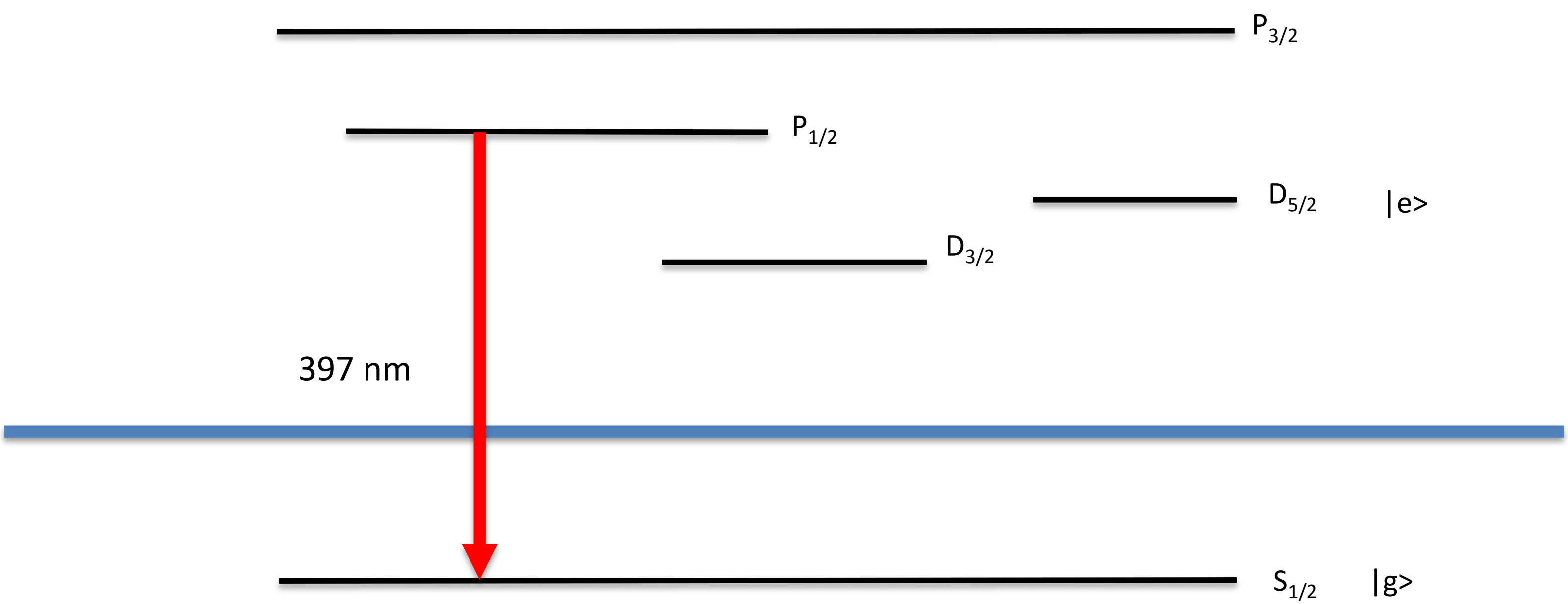
Requirement for Low Temperature Environment for the Experiment

- At room temperature the electrons are subject to many types of thermal fluctuations
- Above the filled electron shells, there are many unfilled bound states to which the electron can transition (unwanted volunteers)
- Want to suppress this “thermal jitter” so that the transitions between bound and excited states in the ^{40}Ca atom is minimized

Minimize The Atomic Transitions in a Material by Cooling the Experimental Apparatus To Almost "Absolute Zero" Temperature

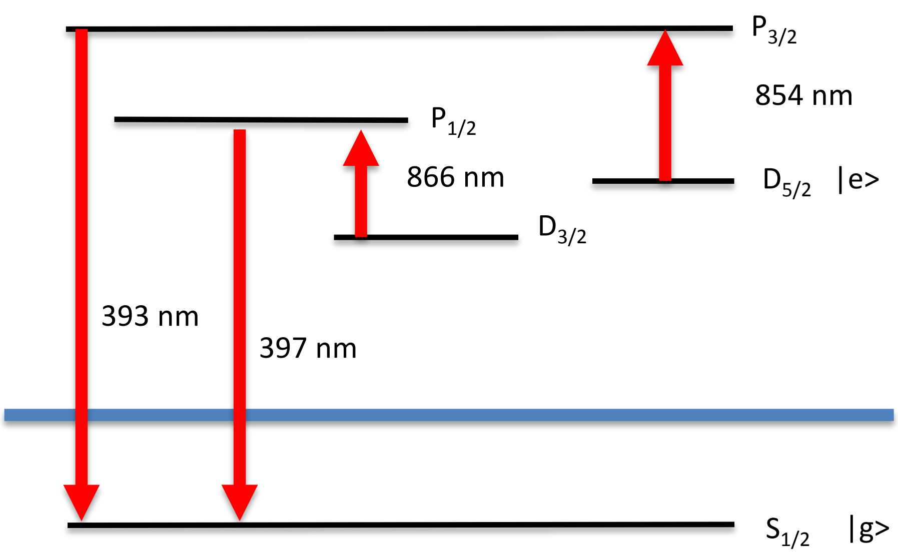


Cool the Apparatus to Limit the Size of the Hilbert Space Available to the Qubit



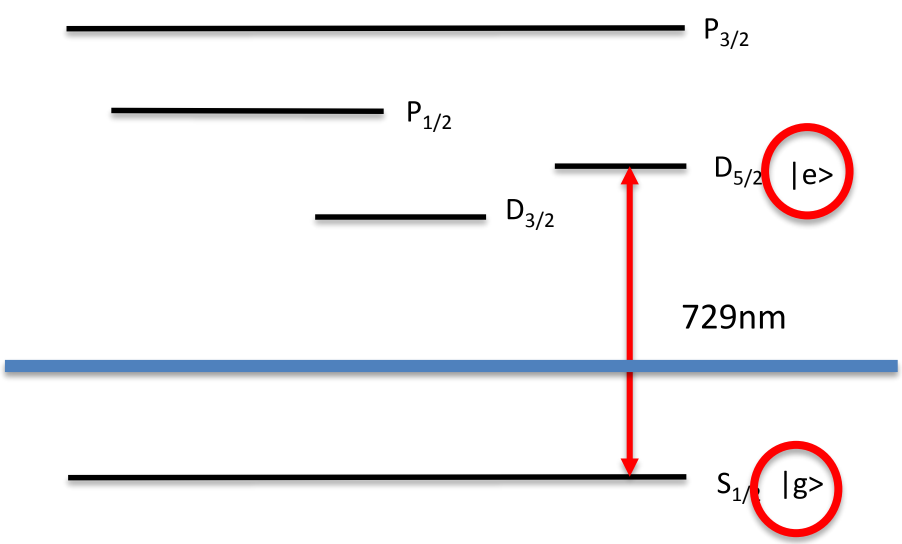
Removing Unwanted Excited States to Prepare the Ion to Initially Only be in the $S_{1/2}$ Ground State

- Depopulate the $P_{1/2}$ ←→ $D_{3/2}$ transition that can contaminate the D ←→ S long lived state for a qubit
- Also need to de-populate the $D_{5/2}$ state
- Need 2 new lasers (854 nm and 866 nm) to pump electrons to the $P_{1/2}$ and $P_{3/2}$ states that can then drain to the $S_{1/2}$ ground state



Building a Long Lived Ion Qubit State

- Now use another laser tuned to the resonant wavelength of (729 nm) to force an excited state population into the $D_{5/2}$ state |e> from the $S_{1/2}$ ground state |g>
- From laws of QM this is a forbidden transition and so the excited state will be long lived (~1 sec) compared to the lifetime of an allowed transition (~ 1 nanosecond) → stable qubit
- Now have constructed a long-lived stable qubit



Toward The Construction of a Trapped Ion Quantum Computer

Goal of an Experimental TIQC

- Goal is to construct 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
- Demonstrating 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 be described in detail in Lectures IV and V

Last Slide