

Building Blocks for Quantum Computing Part III

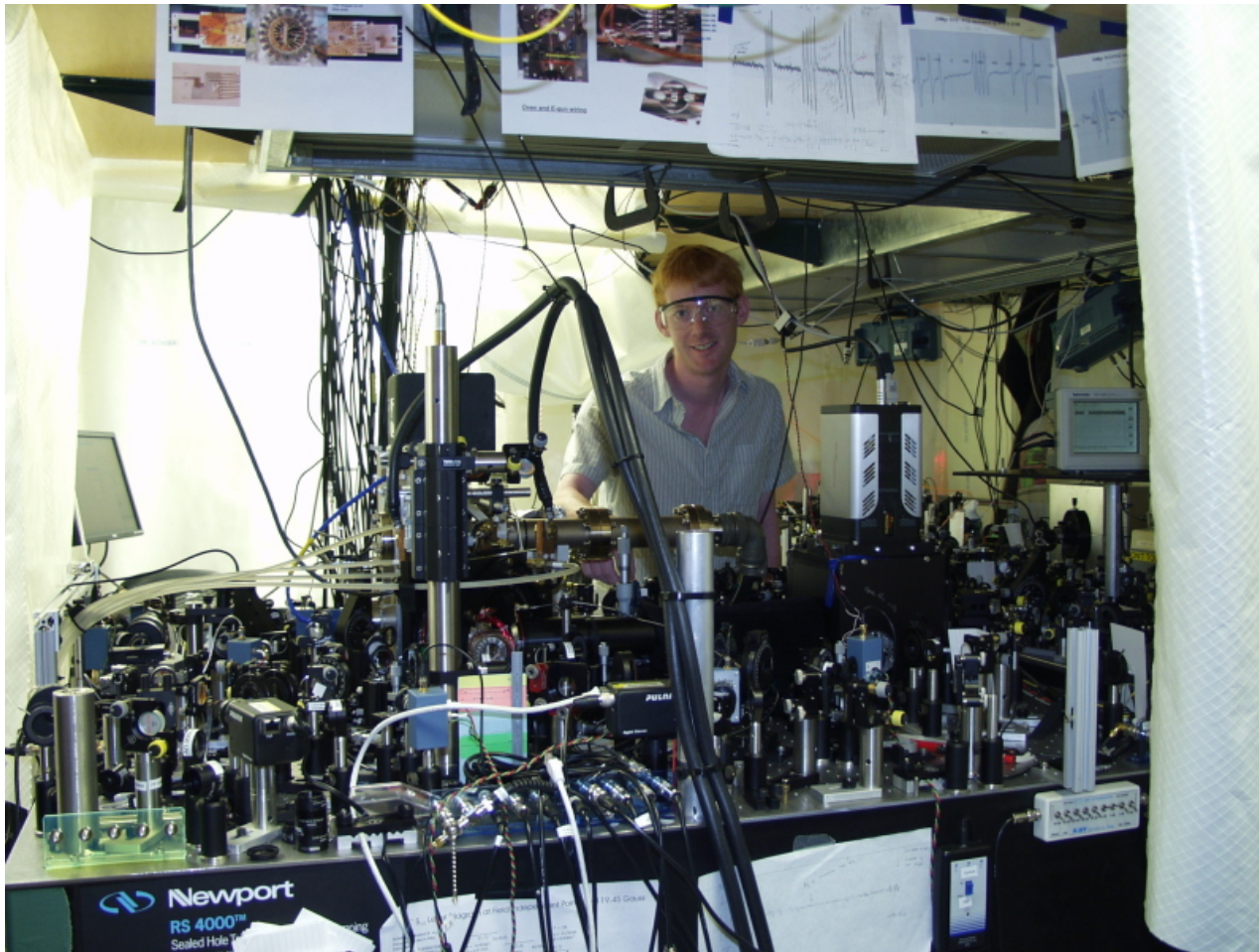
“Quantum Mechanics and Atomic Physics” Primer

Patrick Dreher
CSC801 – Seminar on Quantum Computing
Spring 2018

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

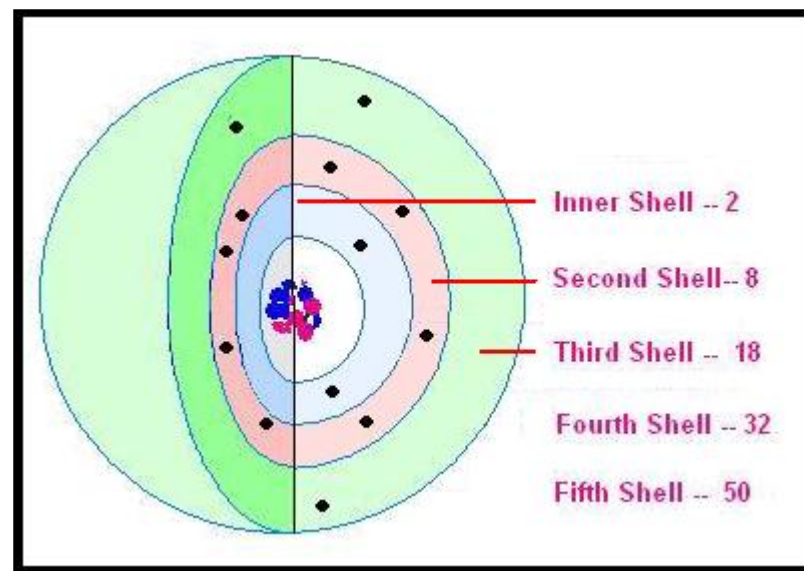
“Quantum Mechanics Primer” for Atoms and Materials

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

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18													
1	H Hydrogen 1.00794																		2	He Helium 4.002602											
2	Li Lithium 6.941	Be Beryllium 9.012182																		3	B Boron 10.811	4	C Carbon 12.0107	5	N Nitrogen 14.0067	6	O Oxygen 15.9994	7	F Fluorine 18.9984032	8	Ne Neon 20.1797
3	Na Sodium 22.98976928	Mg Magnesium 24.3050																		13	Al Aluminum 26.9815386	14	Si Silicon 28.0855	15	P Phosphorus 30.973762	16	S Sulfur 32.065	17	Cl Chlorine 35.453	18	Ar Argon 39.948
4	K Potassium 39.0983	Ca Calcium 40.078	Sc Scandium 44.955912	Ti Titanium 47.887	V Vanadium 50.9415	Cr Chromium 51.9961	Mn Manganese 54.938045	Fe Iron 55.845	Co Cobalt 58.933195	Ni Nickel 58.6934	Cu Copper 63.546	Zn Zinc 65.38	Ga Gallium 69.723	Ge Germanium 72.64	As Arsenic 74.92160	Se Selenium 78.96	Br Bromine 79.904	Kr Krypton 83.798													
5	Rb Rubidium 85.4678	Sr Strontium 87.62	Y Yttrium 88.90585	Zr Zirconium 91.224	Nb Niobium 92.90638	Mo Molybdenum 95.96	Tc Technetium (97.9072)	Ru Ruthenium 101.07	Rh Rhodium 102.90550	Pd Palladium 106.42	Ag Silver 107.8682	Cd Cadmium 112.411	In Indium 114.818	Sn Tin 118.710	Sb Antimony 121.760	Te Tellurium 127.60	I Iodine 126.90447	Xe Xenon 131.293													
6	Cs Cesium 132.9054519	Ba Barium (137.327)	57-71		Hf Hafnium 178.49	Ta Tantalum 180.94738	W Tungsten 183.84	Re Rhenium 186.207	Os Osmium 190.23	Ir Iridium 192.217	Pt Platinum 195.084	Au Gold 196.966569	Hg Mercury 200.59	Tl Thallium 204.3833	Pb Lead 207.2	Bi Bismuth 208.98040	Po Polonium (209)	At Astatine (210)	Rn Radon (222)												
7	Fr Francium (223)	Ra Radium (226)	89-103		Rf Rutherfordium (261)	Db Dubnium (262)	Sg Seaborgium (266)	Bh Bohrium (264)	Hs Hassium (277)	Mt Meitnerium (268)	Ds Darmstadtium (271)	Rg Roentgenium (272)	Uub Ununbium (285)	Uut Ununtrium (284)	Uuq Ununquadium (289)	Uup Ununpentium (288)	Uuh Ununhexium (292)	Uus Ununseptium (294)	Uuo Ununoctium (294)												

C Solid
Hg Liquid
H Gas
Rf Unknown

Metals
 Alkali metals
 Alkaline earth metals
 Lanthanoids
 Actinoids
 Transition metals
 Poor metals
Nonmetals
 Other nonmetals
 Noble gases

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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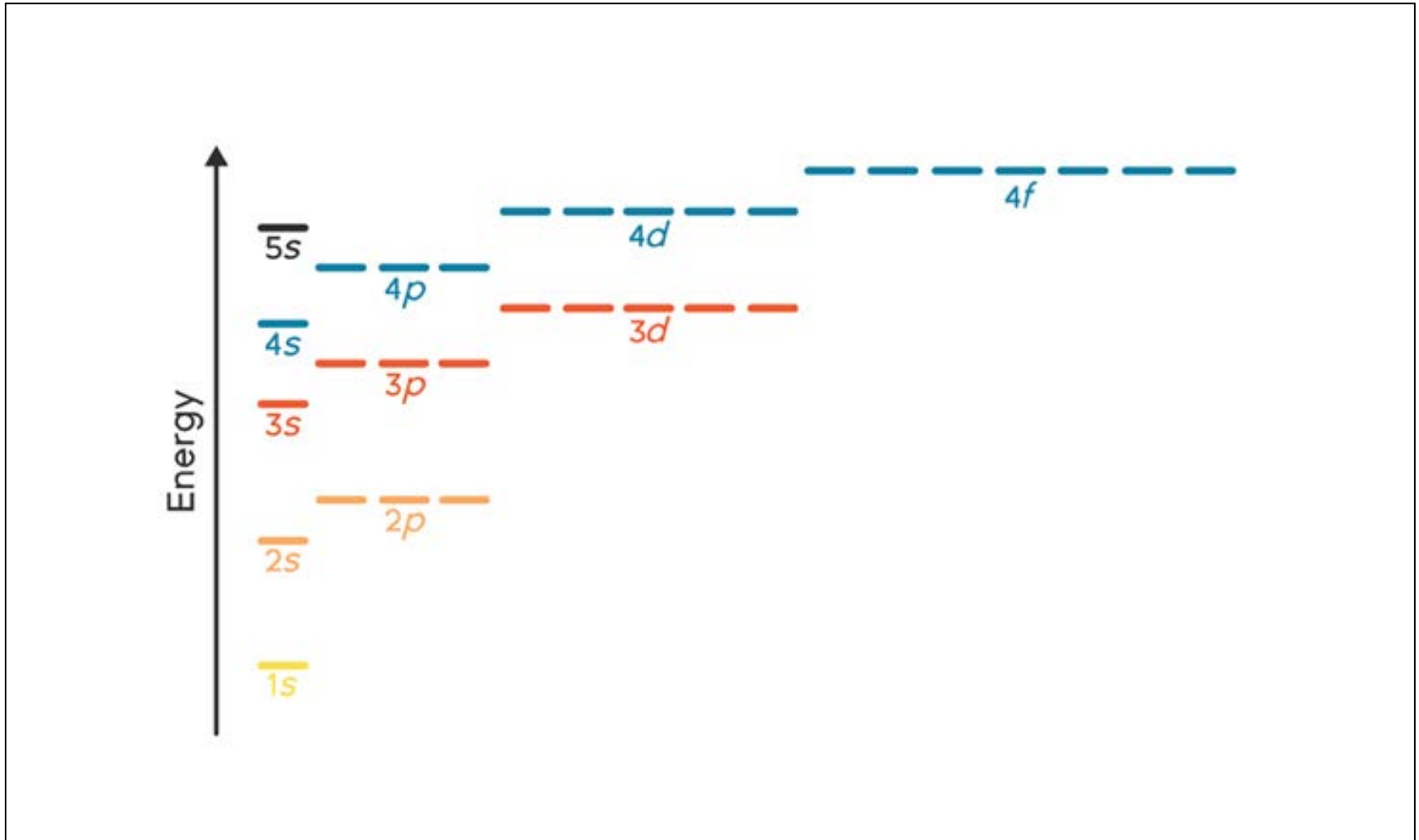


57	La Lanthanum 138.90547	58	Ce Cerium 140.116	59	Pr Praseodymium 140.90765	60	Nd Neodymium 144.242	61	Pm Promethium (145)	62	Sm Samarium 150.36	63	Eu Europium 151.964	64	Gd Gadolinium 157.25	65	Tb Terbium 158.92535	66	Dy Dysprosium 162.500	67	Ho Holmium 164.93032	68	Er Erbium 167.259	69	Tm Thulium 168.93421	70	Yb Ytterbium 173.054	71	Lu Lutetium 174.9688
89	Ac Actinium (227)	90	Th Thorium 232.03806	91	Pa Protactinium 231.03688	92	U Uranium 238.02891	93	Np Neptunium (237)	94	Pu Plutonium (244)	95	Am Americium (243)	96	Cm Curium (247)	97	Bk Berkelium (247)	98	Cf Californium (251)	99	Es Einsteinium (252)	100	Fm Fermium (257)	101	Md Mendelevium (258)	102	No Nobelium (259)	103	Lr Lawrencium (262)

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 ($n = 1, 2, 3, \dots$) 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

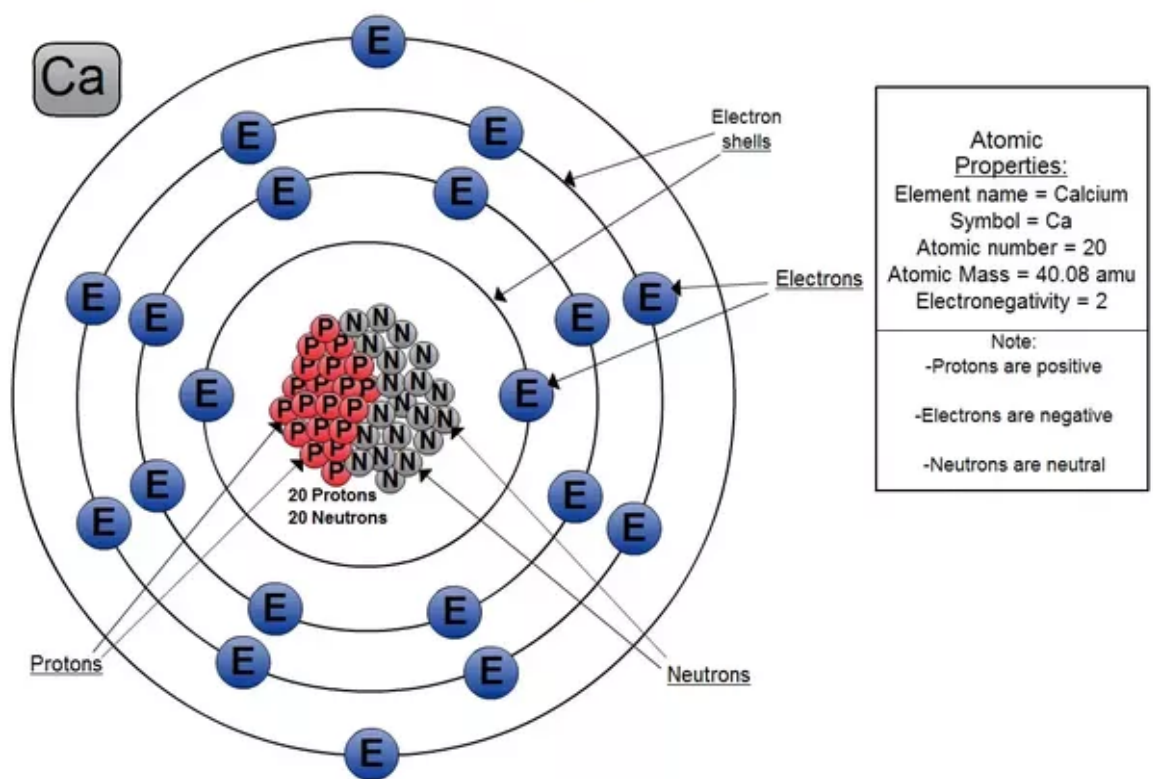


Picking an Element for a TIQC

- 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

Calcium Atom Diagram



(online diagramming & design) createiy.com

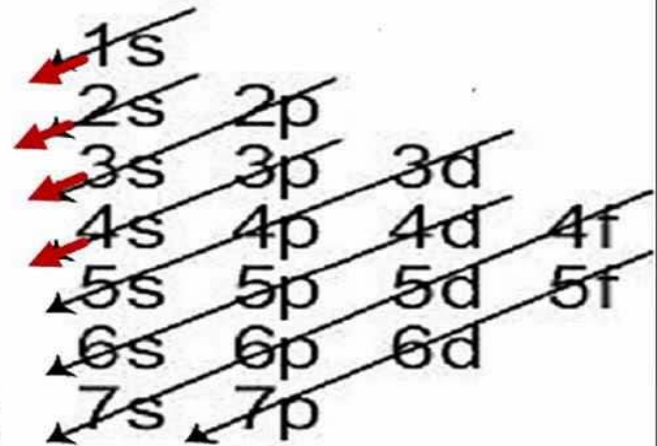
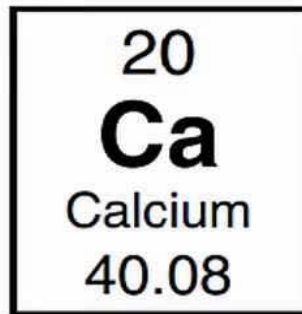
Order of Electron Filling of Energy Levels in Calcium Atom

Electron Configuration Chart

s holds up to 2

p holds up to 6

d holds up to 10

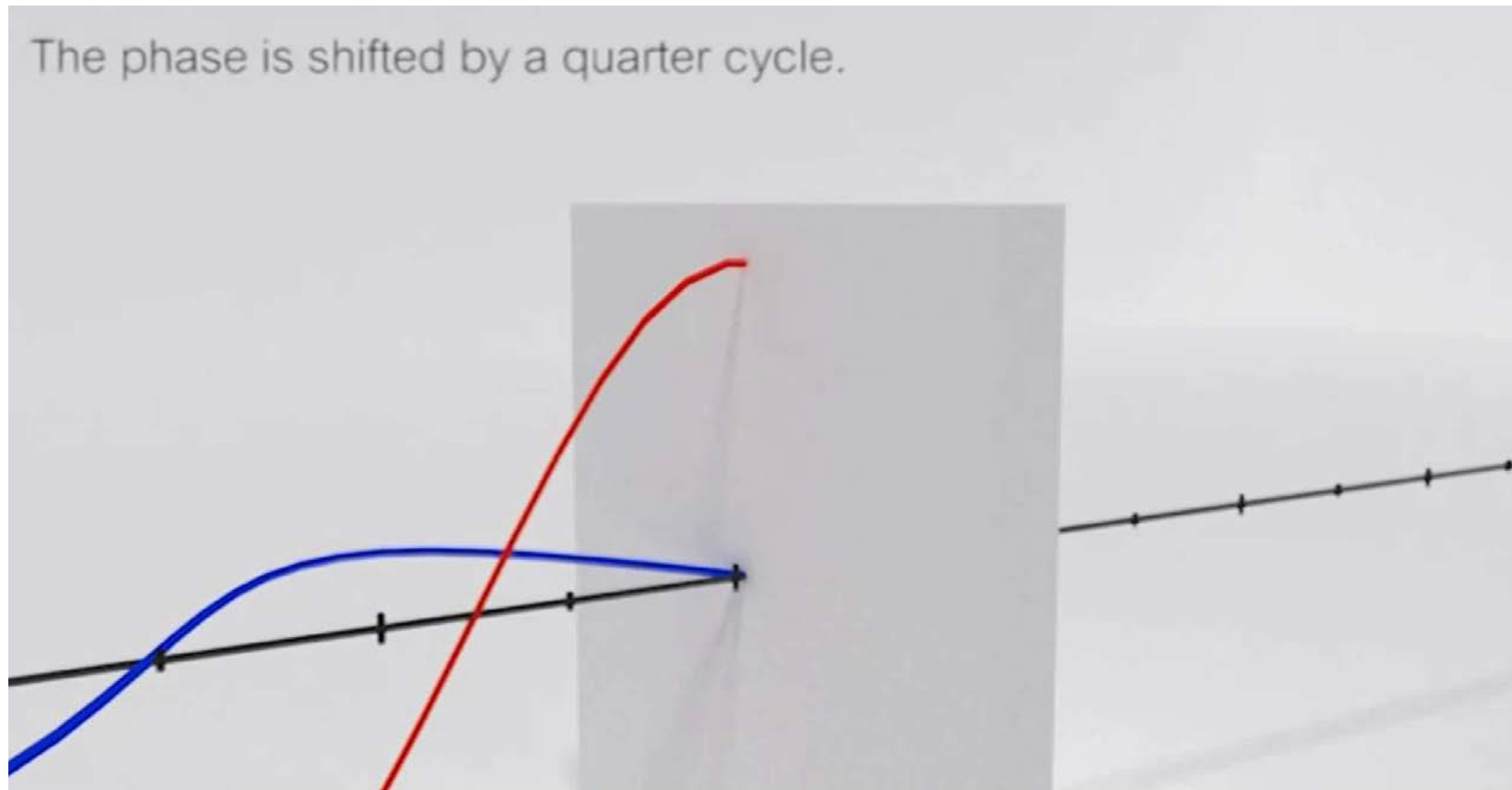


Electromagnetic Fields

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

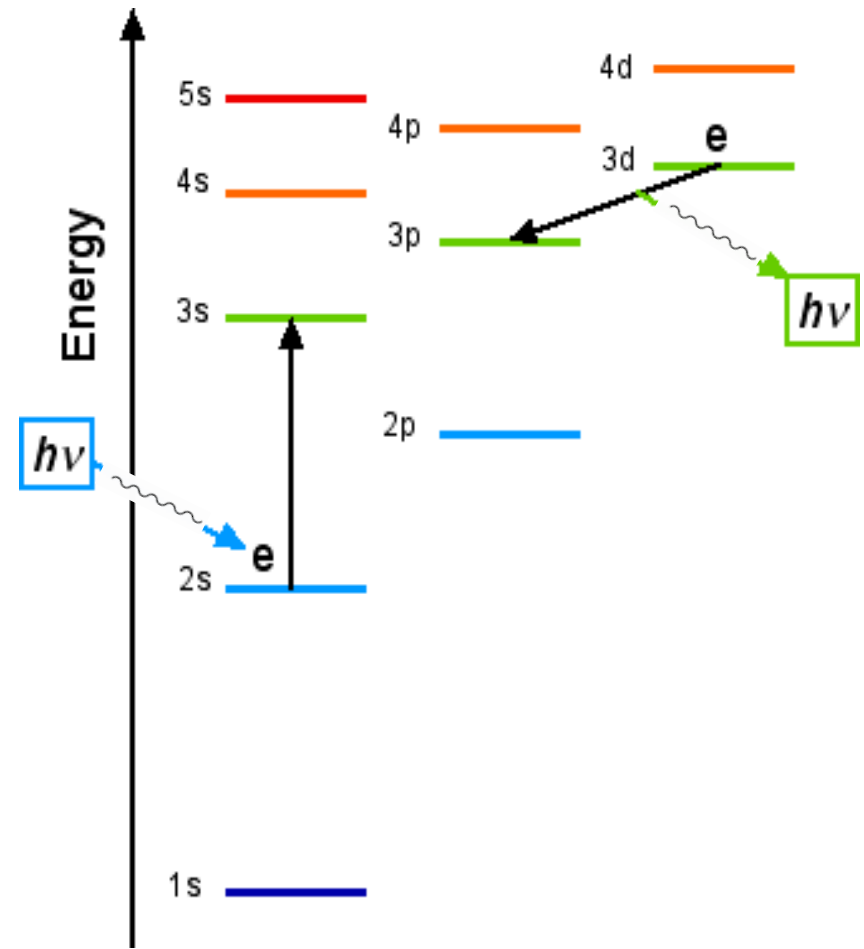
Electric dipole (allowed)	Magnetic dipole (forbidden)	Electric quadrupole (forbidden)
(1) $\Delta J = 0, \pm 1$ ($0 \nleftrightarrow 0$)	$\Delta J = 0, \pm 1$ ($0 \nleftrightarrow 0$)	$\Delta J = 0, \pm 1, \pm 2$ ($0 \nleftrightarrow 0, \frac{1}{2} \nleftrightarrow \frac{1}{2}, 0 \nleftrightarrow 1$)
(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 $\Delta l = \pm 1$ For L - S coupling	No electron jump $\Delta l = 0$	One or no electron jump $\Delta l = 0, \pm 2$
(5) $\Delta S = 0$	$\Delta S = 0$	$\Delta S = 0$
(6) $\Delta L = 0, \pm 1$ ($0 \nleftrightarrow 0$)	$\Delta L = 0$	$\Delta L = 0, \pm 1, \pm 2$ ($0 \nleftrightarrow 0, 0 \nleftrightarrow 1$)

Rigorous (bracketed next to rules 1-3)

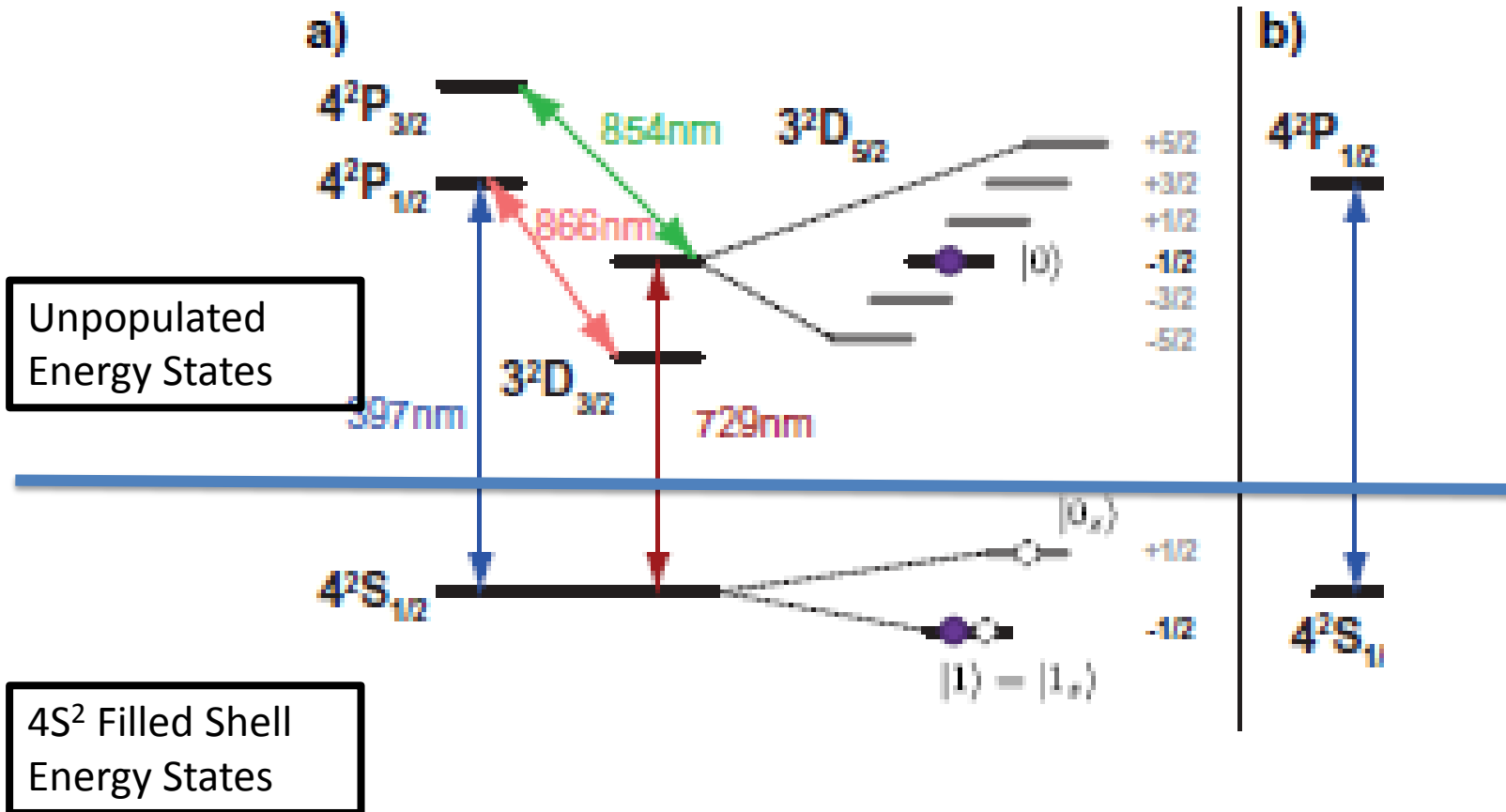
LS (bracketed next to rules 4-6)

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



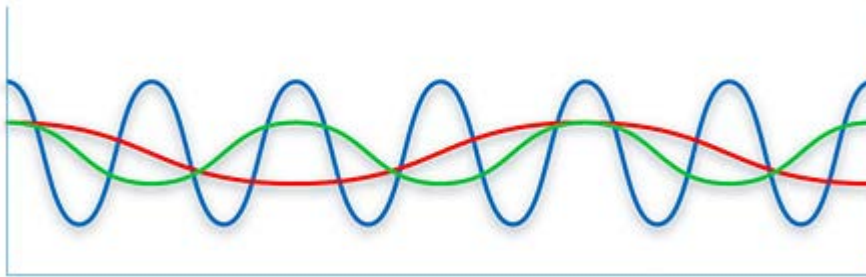
Focus on the Atomic Spectra of Calcium



Lasers

Electromagnetic Radiation Properties

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



Incoherent Light

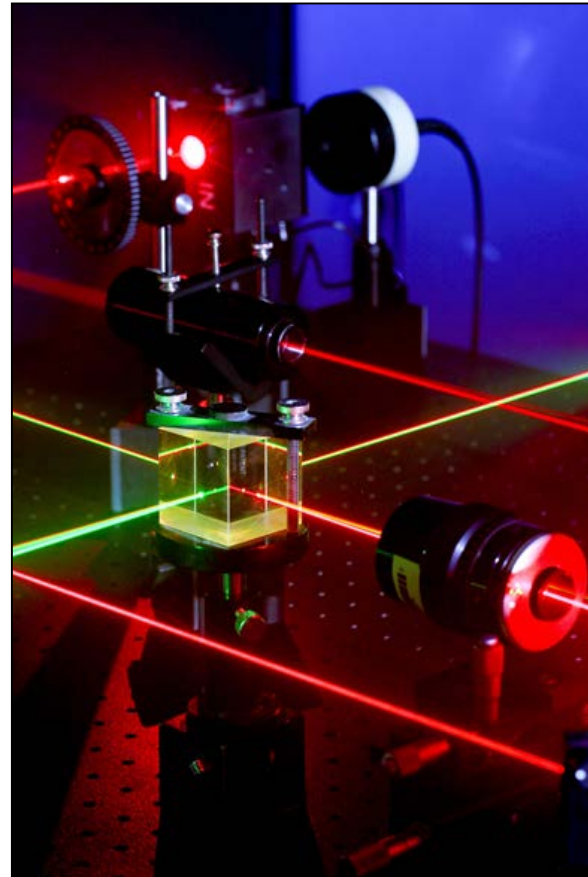
- Need light with properties of coherence (light with specific frequency and common phase)



Coherent Light

Need a Focused Source of Energy - Lasers -

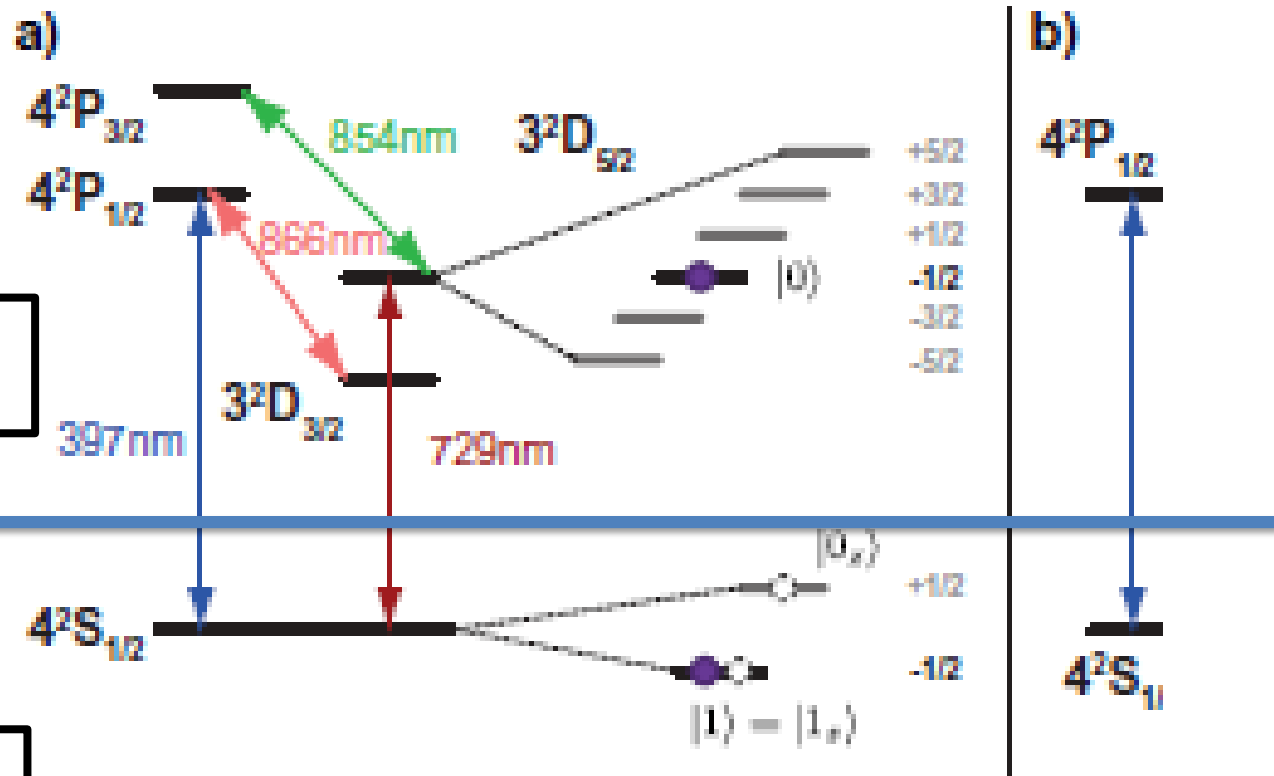
- It would be far more efficient to “dial-up” a specific energy difference that will cause the electron to transition (resonate) between two different energy levels
- Requires a coherent light source tuned to a specific frequency



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

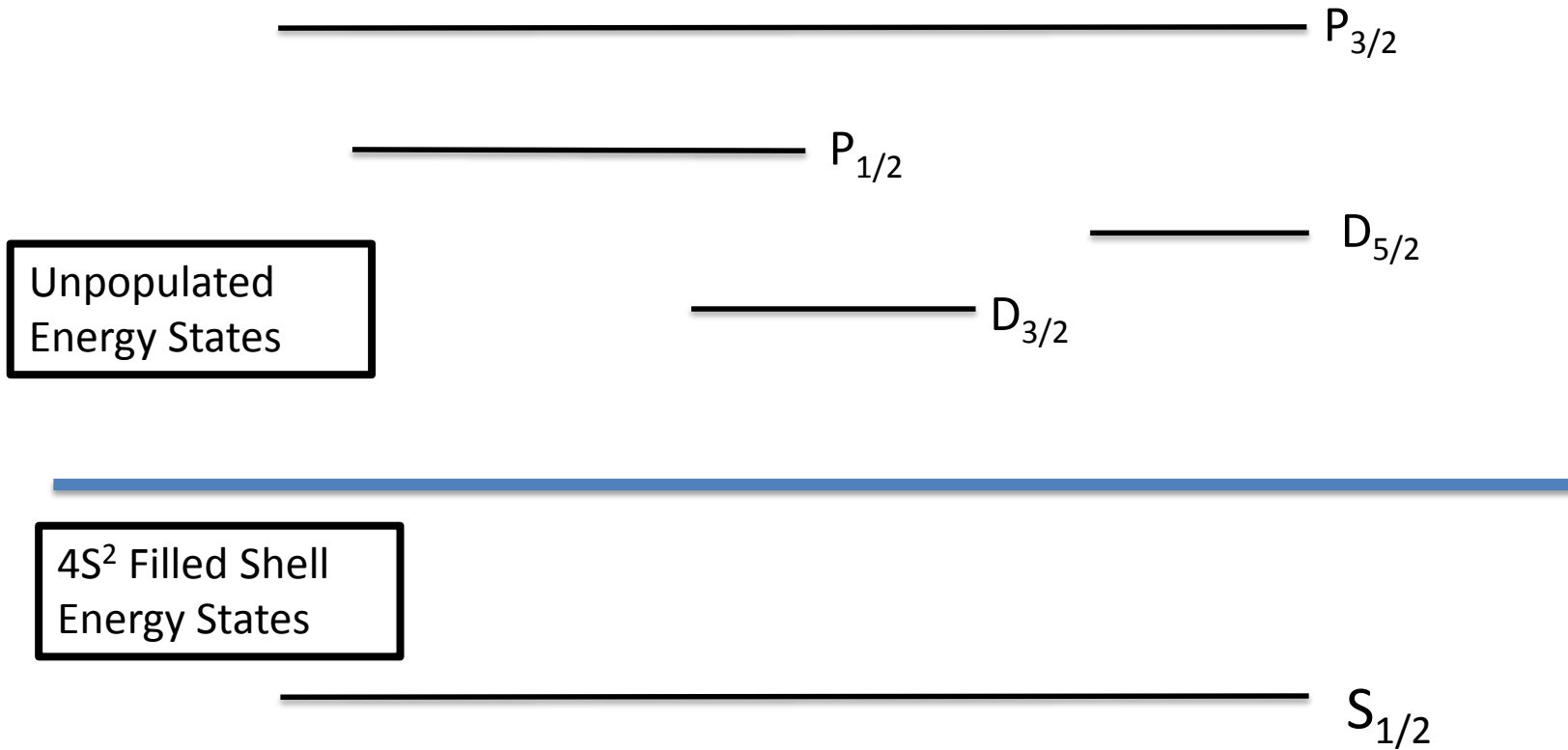
Calcium Atom Spectra



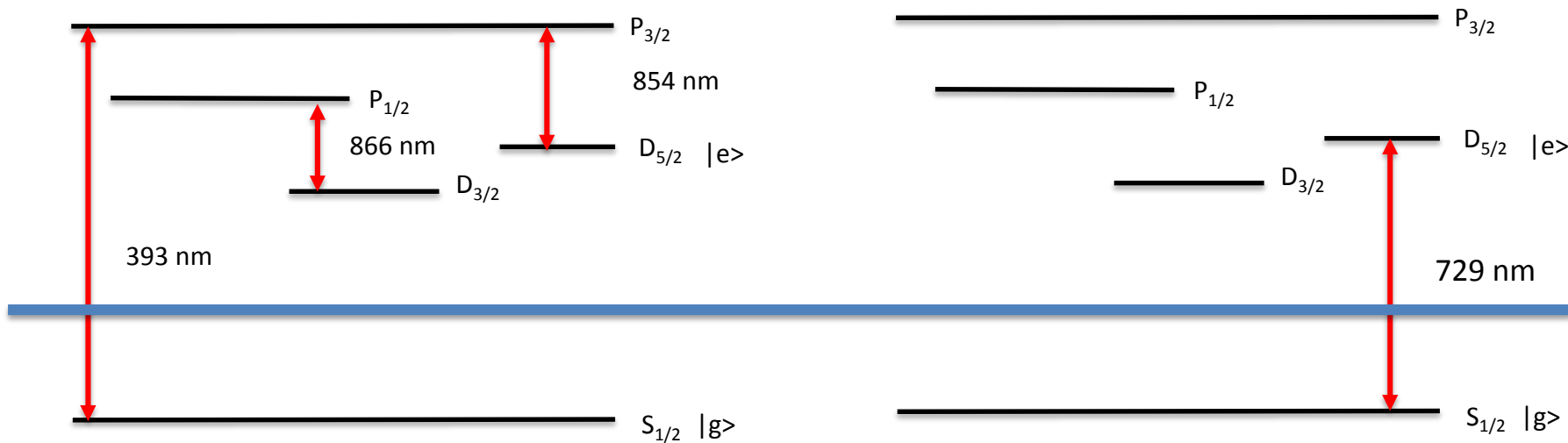
Unpopulated Energy States

4S² 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

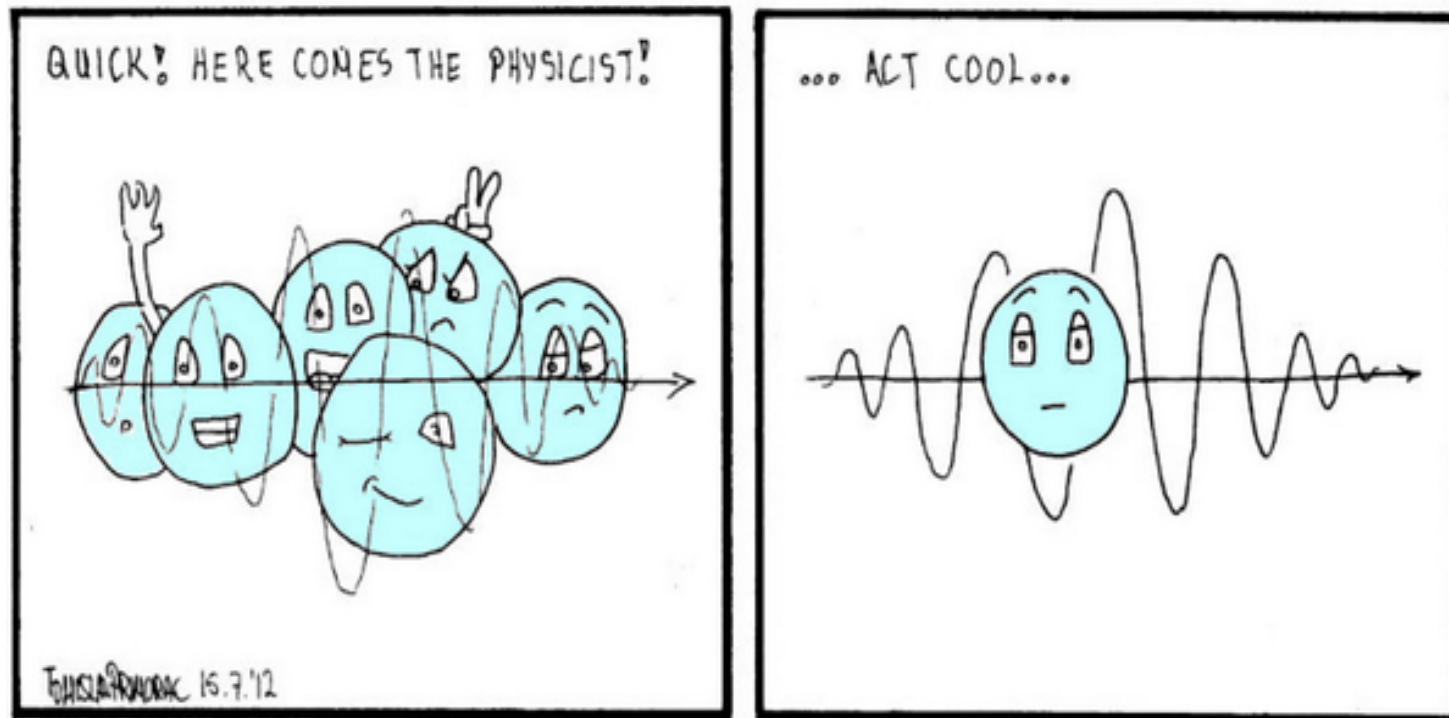
IBM Q Cryostat



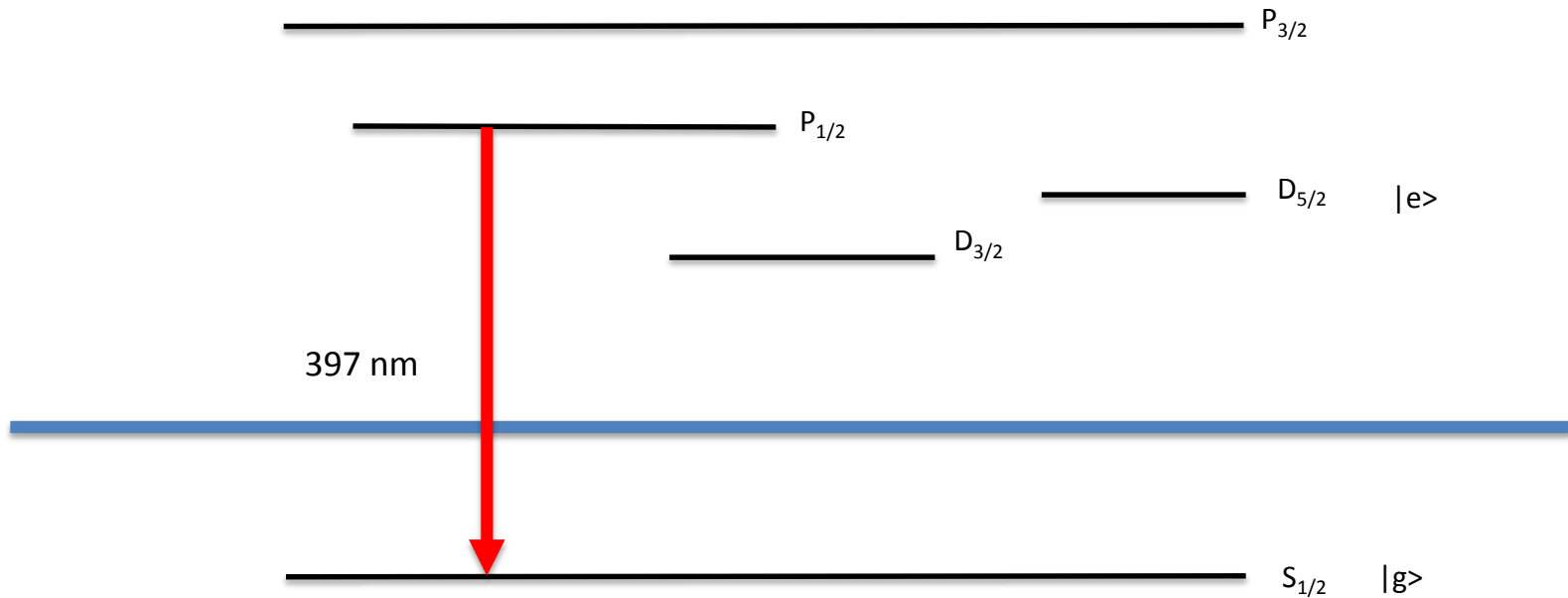
Requirement for Low Temperature Environment for the Experiment

- 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

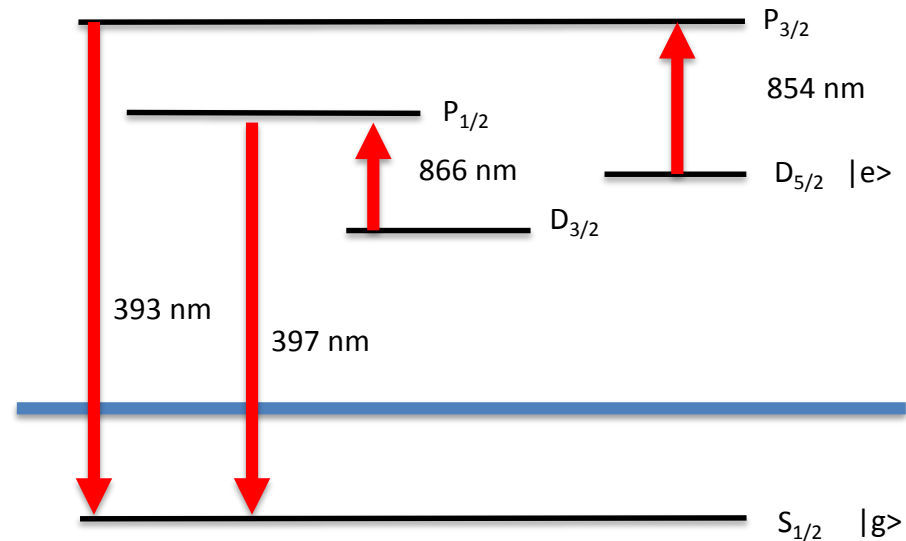


Cool the Apparatus to Limit the Size of the Hilbert Space Available to the Qubit



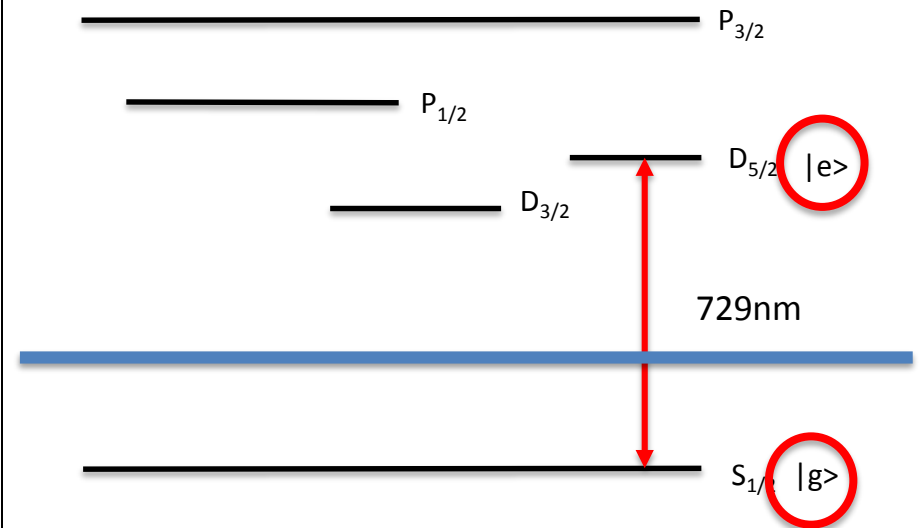
Removing Unwanted Excited States to Prepare the Ion to Initially Only be in the $S_{1/2}$ Ground State

- Depopulate the $P_{1/2} \leftrightarrow D_{3/2}$ transition that can contaminate the $D \leftrightarrow S$ 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 $|e\rangle$ from the $S_{1/2}$ ground state $|g\rangle$
- 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) \rightarrow 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