Chip Scale Atomic Clocks Sources

Working principles

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Agenda

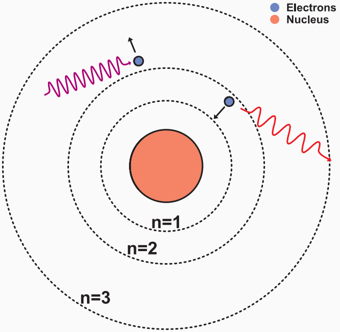
1. Toolbox
2. CSAC Block Diagram
3. Physics Package based on Microwave Optical Double-Resonance (MODR)
4. Physics Package based on Coherent Population Trapping (CPT)
5. Control loop
6. Local Oscillator

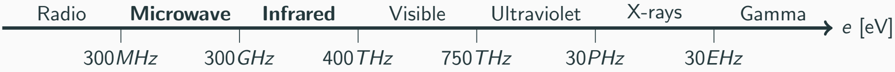
Toolbox

Electromagnetic Spectrum

The energy of a photon is given by the **Planck's relation**[1]:

$$e = hf \quad [\text{eV or J}] \qquad (1)$$





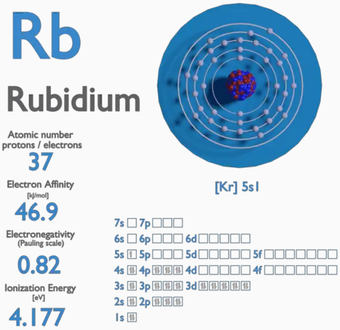
Our working frame will be in the **microwave** and **infrared** regions.

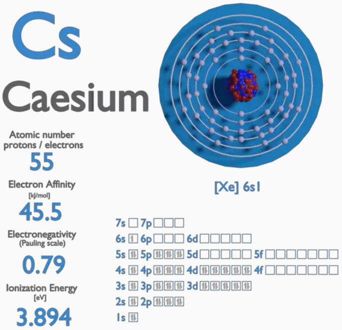
[1] Planck's constant $h = 6.62607015 \times 10^{-34}$ J s

Rubidium and Cesium

We will deal with Rubidium (isotopes ^{85}Rb & ^{87}Rb) and Cesium (^{133}Cs).

- They are both alkali metals with a single valence electron.
- Their first ionization energy is low.





Quantum levels

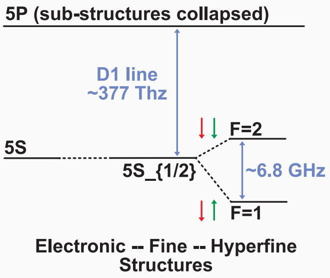


Figure 1: ^{87}Rb quantum levels.

Elementary energy level ($n = 1, 2, 3, \ldots$), can further be split.[1]

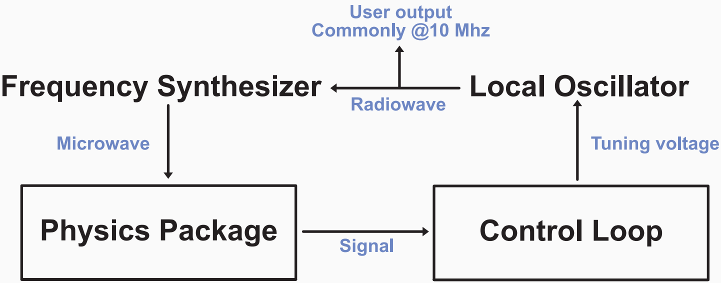
Substructures are due to various quantum phenomena acting inside the atom domain.

- Electronic str.: classical orbital levels.
- Fine str.: electronic spin-orbit coupling.
- Hyperfine str.: nuclear spin-electron spin coupling.

[1] For the purpose of the CSACs, we can consider the sub-5P structures as collapsed into a single one.

CSAC Block Diagram

Block diagram of a generic CSAC

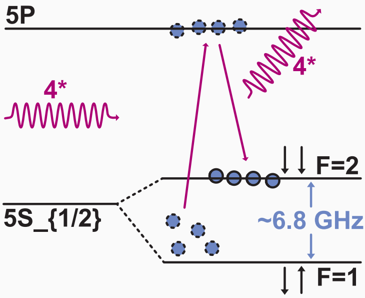


In the following slides, we are going to see:

- Physics Package
  - Based on Microwave Optical Double-Resonance (MODR)
  - Based on Coherent Population Trapping (CPT)
- Control loop
- Local Oscillator

Physics Package based on Microwave Optical Double-Resonance (MODR)

At the heart of a MODR based CSAC, we find a ^{87}Rb reference cell.



We can distinguish 3 processes:

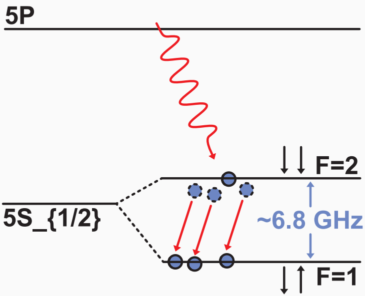
1. **Optical Pumping (Population Inversion)**

Ground state population $F = |1\rangle$ gets pumped to $5P$ and then decay to both $F = |1\rangle$ & $F = |2\rangle$.

Over time, the population will accumulate in the $F = |2\rangle$ state.

^{87}Rb Reference Cell

At the heart of a MODR based CSAC, we find a ^{87}Rb reference cell.



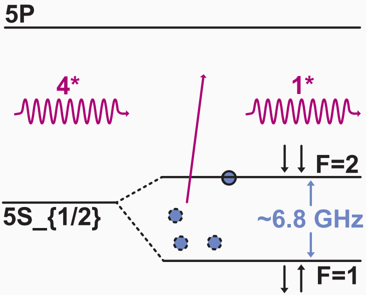
We can distinguish 3 processes:

1. Optical Pumping (Population Inversion)
2. **Microwave Excitation**

Microwave tuned at the atomic resonance frequency ($\approx$ 6.8 GHz) brings part of the population back to $F = |1\rangle$.

^{87}Rb Reference Cell

At the heart of a MODR based CSAC, we find a ^{87}Rb reference cell.

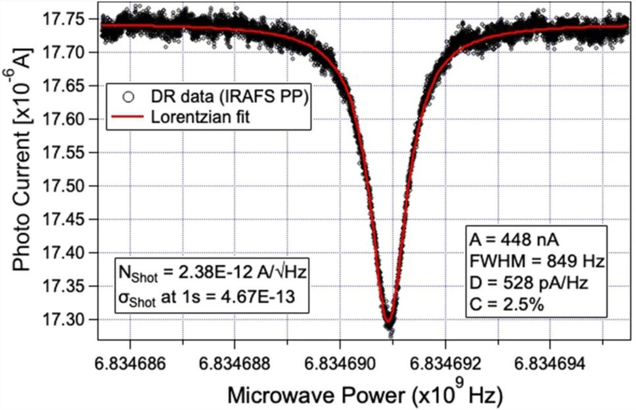


We can distinguish 3 processes:

1. Optical Pumping (Population Inversion)
2. Microwave Excitation
3. **Optical Pumping (Interrogation)**

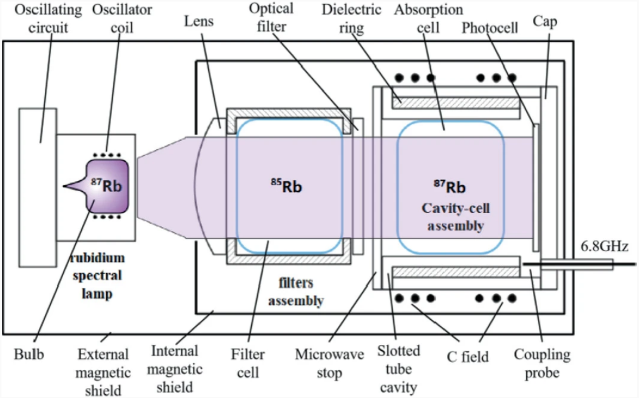
Depending on the intensity of the transmitted radiation, **we can infer if the microwave frequency was in resonance or not**.

At the end of the cell, a photodiode is used to measure the intensity of the transmitted radiation.



Our target is to stay at the dip of the transmission curve.

Complete Physics Package for a MODR-based CSAC



Other notable components are:

- ^{87}Rb Bulb: high frequency radiation source.
- ^{85}Rb Filter cell: because of overlapping hyperfine levels, it filters out the unwanted transitions frequencies from the lamp.
- Microwave cavity: enhances the interaction between radiation and atoms.

Design bottleneck

...goal of developing an ultra-miniaturized, low-power, atomic time and frequency reference units...

In case of a MODR-based CSAC, we can recognize multiple problematic areas:

- **Size**: microwave cavity imposes a low limit ($L_{min} = \frac{c}{2f_{transition}} \approx 2.2cm$).
- **Power consumption**: high ($\approx 10W$) due to thermal stabilization ($\approx$ 70% of the total).
- **Optical instabilities**: internal wall gas collision[1], Zeeman effects[1], Stark shifts.

[1] More on this in the "Extra slides" section.

Physics Package based on Coherent Population Trapping (CPT)

Superposition of Quantum States (concept)

Before exploring the CPT itself, it's important to understand the concept of superposition of quantum states by using the Bloch sphere representation.

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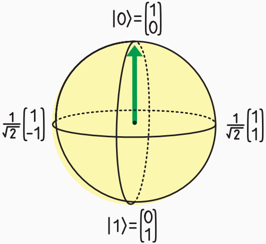

Figure 2: Ground state

Superposition of Quantum States (concept)

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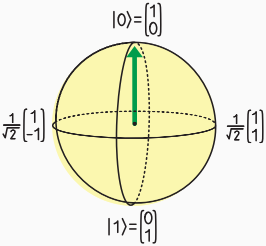


Figure 2: Ground state

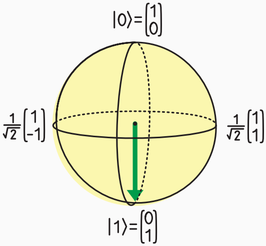


Figure 4: Excited state

Total Energy of the system increases

Superposition of Quantum States (concept)

Before exploring the CPT itself, it's important to understand the concept of superposition of quantum states by using the Bloch sphere representation.

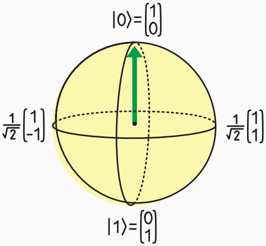


Figure 2: Ground state

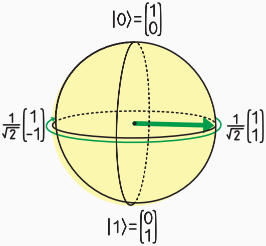


Figure 3: Superposition of states

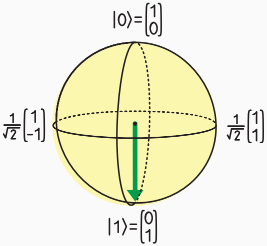


Figure 4: Excited state

Total Energy of the system increases

Dark state & Λ-system

"In atomic physics, a dark state refers to a state of an atom or molecule that cannot absorb (or emit) photons."

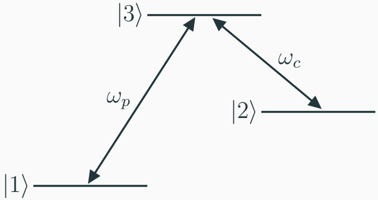


Figure 5: Λ-system.

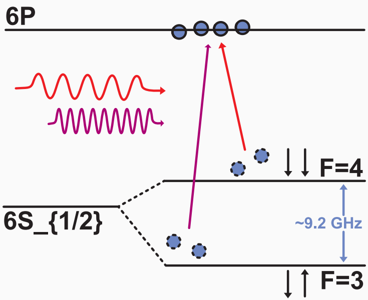
$$\text{Allowed transitions:} \begin{cases} |1\rangle \leftrightarrow |3\rangle \\ |2\rangle \leftrightarrow |3\rangle \end{cases} \tag{2}$$

$$\text{Forbidden transition:} \left\{ |1\rangle \leftrightarrow |2\rangle \right. \tag{3}$$

In this case the dark state happens to be a superposition of $|1\rangle$ and $|2\rangle$.

^{133}Cs Reference Cell

At the heart of a CPT based CSAC, we find a ^{133}Cs reference cell.



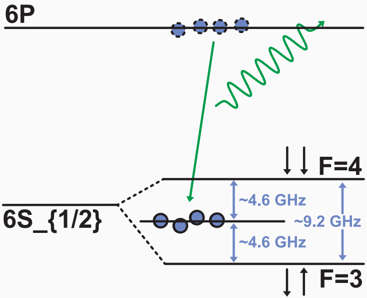
We can distinguish 3 processes:

1. **Optical Pumping (Population Inversion)**

A dual-frequency laser is used to pump the population from both $F = |1\rangle$ and $F = |2\rangle$ to $6P$.

^{133}Cs Reference Cell

At the heart of a CPT based CSAC, we find a ^{133}Cs reference cell.



We can distinguish 3 processes:

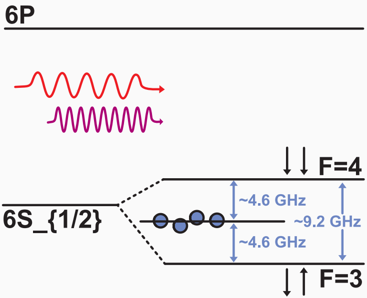
1. Optical Pumping (Population Inversion)
2. **Decay to the dark state (superposition state)**

Because of the particular beat frequency and phase of the laser, the population will (over time) fall into a superposition state.

$$|\psi\rangle = |Dark\rangle = \frac{1}{\sqrt{2}}\left(|3\rangle + |4\rangle\right) \tag{4}$$

^{133}Cs Reference Cell

At the heart of a CPT based CSAC, we find a ^{133}Cs reference cell.



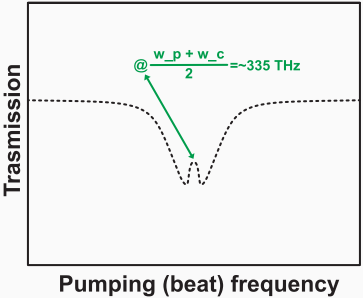
We can distinguish 3 processes:

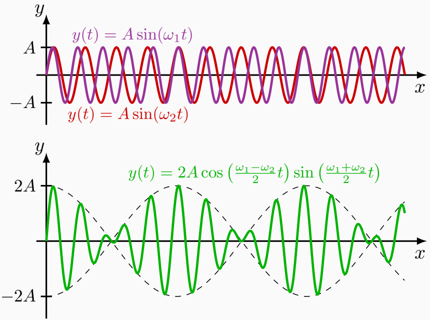
1. Optical Pumping (Population Inversion)
2. Decay to the dark state (superposition state)
3. **Optical Pumping (Interrogation)**

Being in a superposition state $|\psi\rangle$, the population will not absorb the pumping laser radiation anymore. **Electrons are now trapped.**

Photodetection

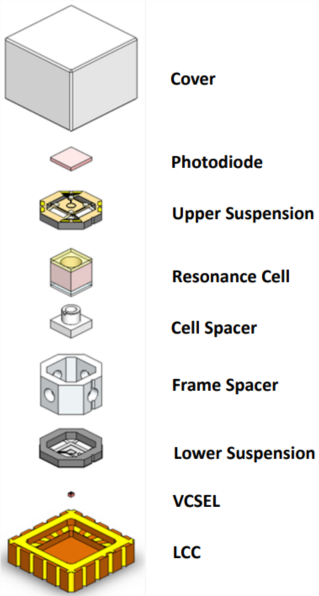
At the end of the cell, a photodiode is used to measure the intensity of the transmitted radiation.





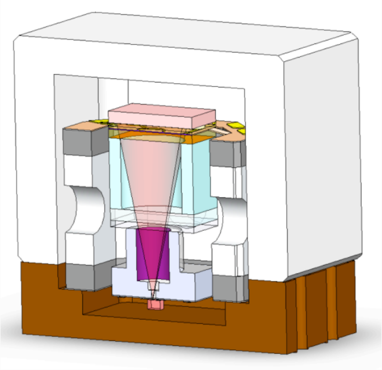
Our target is to stay at the peak in the middle of the valley in the transmission curve.

Complete Physics Package for a CPT-based CSAC



Power consumption[1]: $\approx 10mW$.

Volume: $\approx 0.35cm^3$.



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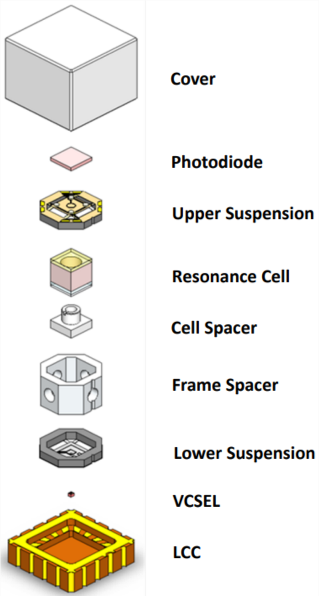
[a] The entire package is vacuum sealed to minimize the heating power required (to stabilize).

[b] LCC: Leadless Chip Carrier.

[c] VCSEL: Vertical-Cavity Surface-Emitting Laser.

Complete Physics Package for a CPT-based CSAC



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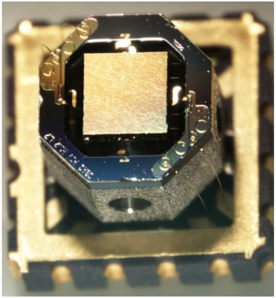
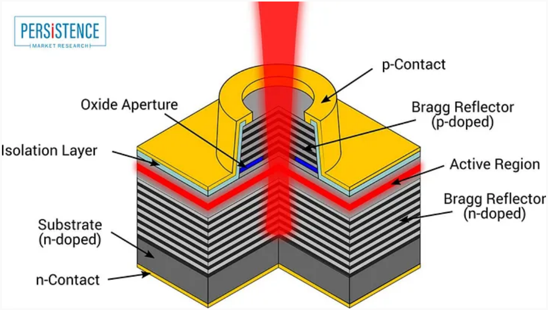


Figure 6: Microchip SA.45s physics package.

[a]The entire package is vacuum sealed to minimize the heating power required (to stabilize).
[b]LCC: Leadless Chip Carrier.
[c]VCSEL: Vertical-Cavity Surface-Emitting Laser.

Vertical-Cavity Surface-Emitting Laser (VCSEL)

VCSELs are a type of semiconductor laser diode with laser beam emission perpendicular to the chip surface.



In CPT-based CSACs, the VCSEL is used as the radiation source:

- Stability in the emitted frequency.
- Flexibility in the choice of the optical wavelength.
- Low power consumption ($\approx 3mW$).

Design bottleneck

CPT-based CSACs partially solve the bottleneck of size and power consumption of the MODR-based CSACs.

Still, we can recognize some area of improvements:

- Working temperature range[1] (currently $\approx [-40; 80]^\circ C$).
- High sensitivity to temperature and voltage fluctuations.
- Short-term frequency stability (currently $\approx 3 \times 10^{-10} @ \tau = 1s$).

[1] Mainly due to degradation in performance of the resonance cell (buffer gas pressure).

Control loop

Control loop

Close-loop approach to **lock the LO[1] frequency to the atomic transition**.

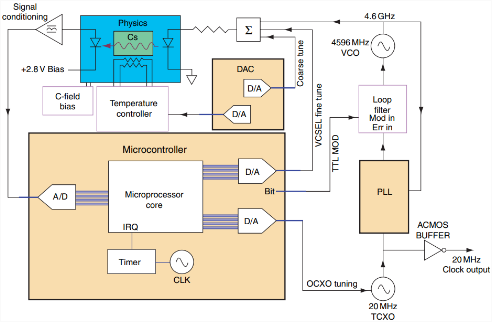


Figure 7: Control loop block diagram.

PI[2] controllers are used to minimize the error between the target and the actual value.

Indispensable targets:

- LO frequency
- Laser frequency
- Laser temperature
- Cell temperature

[1] LO: Local Oscillator
[2] PI: Proportional-Integral

Electronics

Here are some possible problematic areas:

- Stability in voltage and current provided to VCO and VCSEL (highly sensitive components)
- Cross-talk between different control loops
- Noise from the electronics
- Power consumption ($\approx 10\%$ of the total)

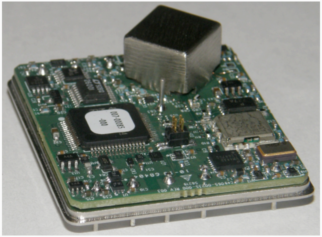


Figure 8: CSAC SA.45s from Microchip.

Local Oscillator

Local Oscillator

Normally, the local oscillator in a CSAC is a quartz crystal oscillator (XO).

There exist many versions of the XO, differentiated based on the environmental correction type applied to enhance stability:

- **TCXO**: Temperature Compensated Crystal Oscillator
- **MCXO**: Microcomputer Compensated Crystal Oscillator
- **OCXO**: Oven Controlled Crystal Oscillator

Quartz Crystal Oscillator

At short time scales, the quartz crystal oscillator is the main source of instability in a CSAC due to its phase noise.

Here are some other problematic areas:

- High temperature sensitivity
- Power consumption (due to thermal control to enhance stability)
- Aging and frequency drift

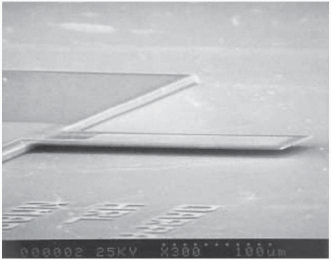


Figure 9: Resonator with 2-mm quartz thickness[1].

In the end, the choice of a local oscillator is a trade-off between stability and power consumption.

[1]Photograph taken using Scanning Electron Microscope (SEM) technique.

Extra slides

Reference cell (buffer gas & cell size)

Collision with untreated walls of the reference cell can depolarize the spin of electrons, forcing them to return to the ground state.

To avoid this, we can either **add a buffer gas to reduce the number of collisions** composed of a mixture of N_2, Ne, Ar, and He or **reduce the mean free path of atoms (larger cell)**.

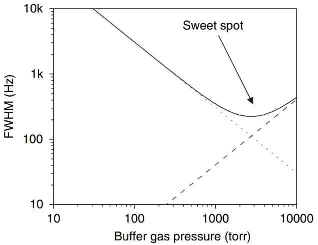


Figure 10: Result of diffusion to the walls (red dotted line) and buffer gas collisions (dashed blue line).

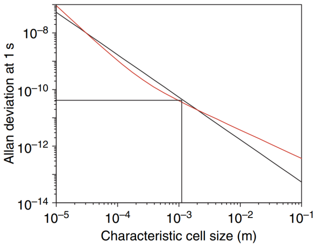


Figure 11: Cell with a $100kPa$ nitrogen buffer gas (red) or a paraffin wall coating (black).

[0]FWHM: Full Width at Half Maximum

Quantum levels of ^{133}Cs and ^{87}Rb

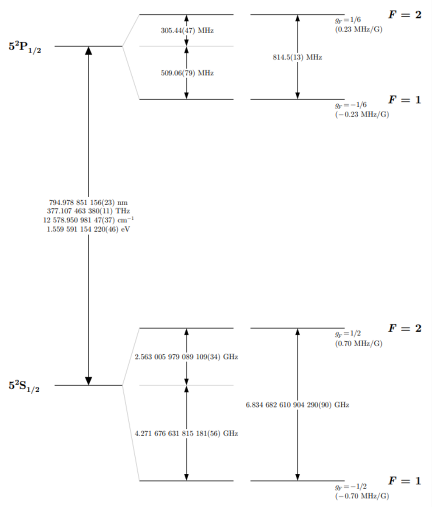


Figure 12: ^{87}Rb quantum level.

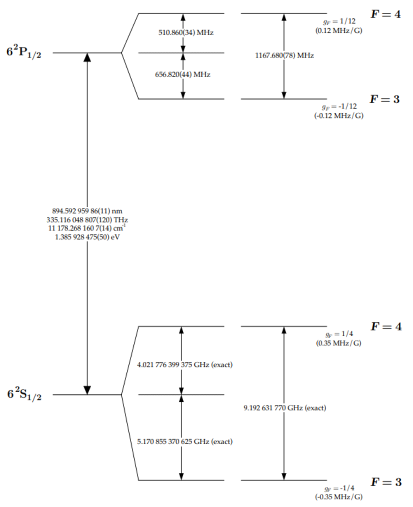


Figure 13: ^{133}Cs quantum level.

Zeeman effect and c-field for clock calibration

The Zeeman effect is the splitting of atomic energy levels due to the presence of an external magnetic field.

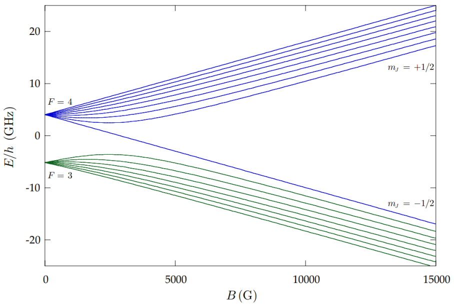


Figure 14: $^{133}Cs\ 6S_{1/2}$ (ground) level hyperfine structure in an external magnetic field

A fine calibration of the clock can be done by applying a c-field (controlled magnetic field) to the reference cell.

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Questions?

Thank you!