Polarized Helium-3: Why and How

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PHY 554 Guest Lecture

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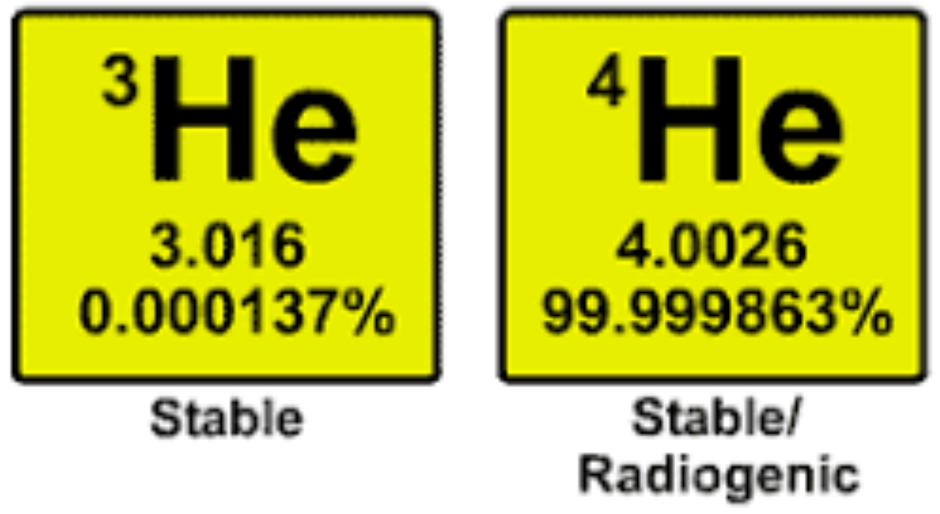
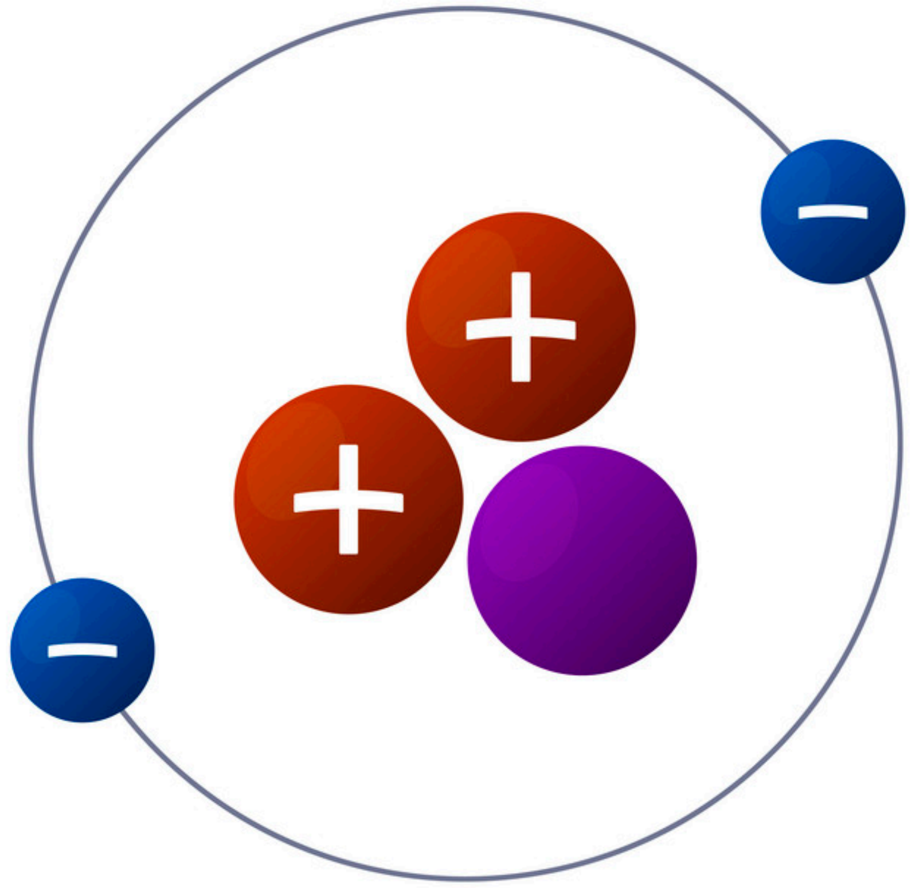
Why (Polarized)Helium-3?

What is helium-3?



Helium-3 is one of two *stable helium isotopes*:

Atomic structure:

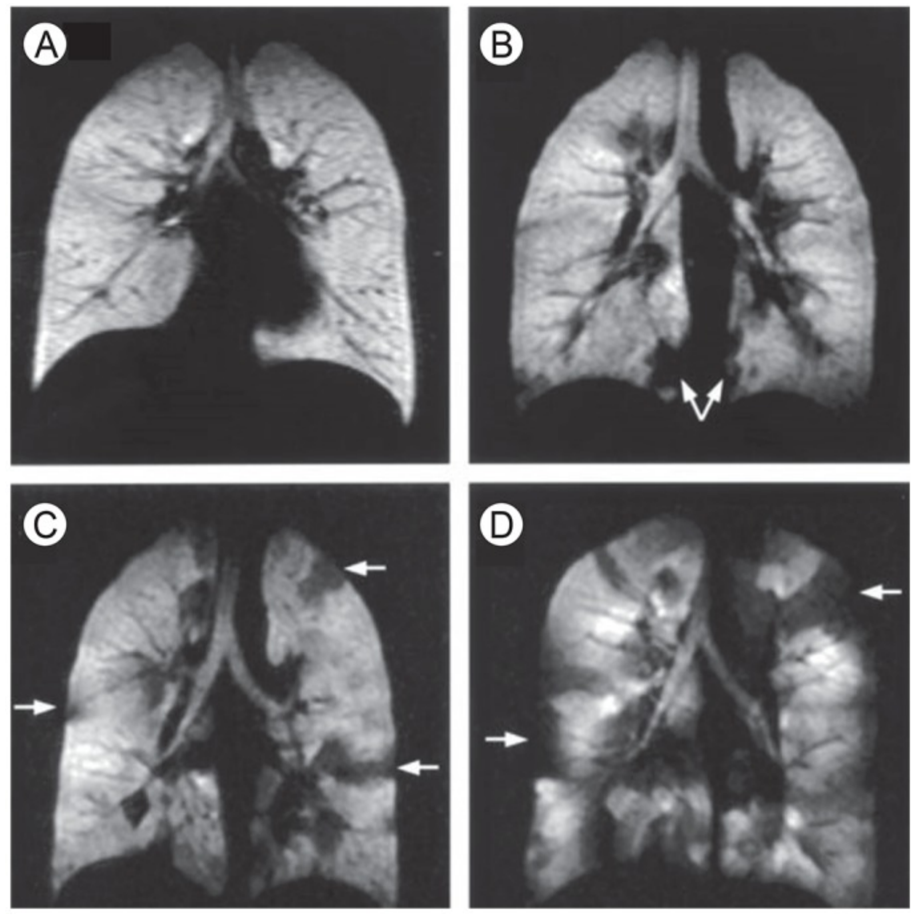


^{3}He

Helium-3 is a noble gas ➪ chemically inert!!

- If spin-polarized it can be used for medical imagining:

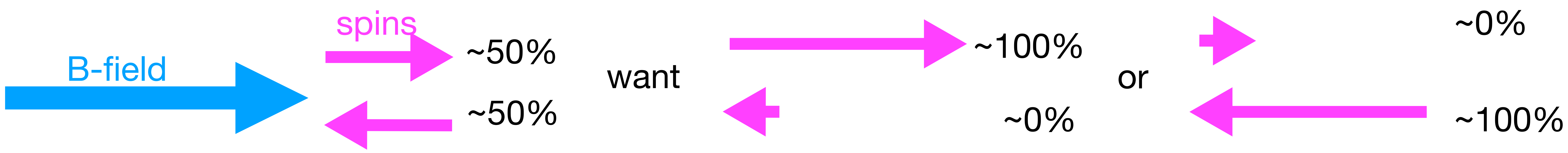
Human lungs

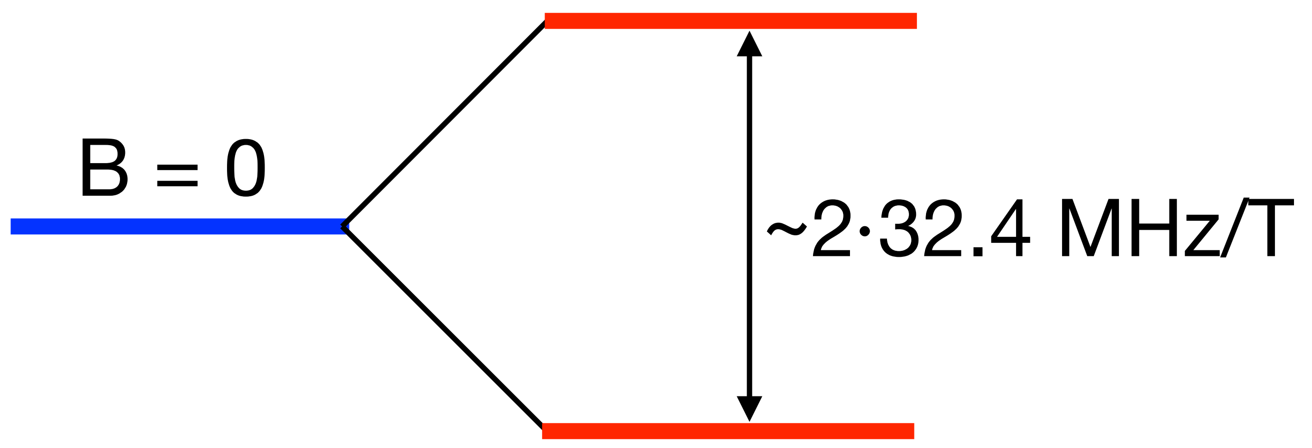


- Use spin-polarized ^{3}He nucleus as an effective polarized neutron
  - Neutrons are unstable $\tau_n \sim 880$ s
  - magnetic moments: $\mu_{3He} = -2.12\ \mu_N$, $\mu_n = -1.91\ \mu_N$
    - ➪ very little contribution from protons
    - ➪ study contributions of quark and gluons to neutron spin

- Use spin-polarized 3He as a neutron polarizer:
  - At T ~ 300K: $n\uparrow + {}^{3}He\downarrow \Longrightarrow {}^{4}He \quad \sigma_{abs} = 11{,}000$ barn
  - whereas: $n\uparrow + {}^{3}He\uparrow \Longrightarrow \quad \sigma_{abs} \sim 0$ barn
    - ➪ neutron polarizer/analyzer

How to (Spin-)Polarize Helium-3?





Brute force polarization: gyromagnetic ratio for 3He: $|\gamma_{3He}| = 20.3789473 \times 10^7$ rad/s/T

Recall: $\mu = \gamma \cdot I$ (μ = magnetic moment, I = spin of the nucleus)

Typically we have in the laboratory: T ~ 300 K, B = 20 G = 2 mT

Thermodynamics: $$P = \frac{N_+ - N_-}{N_+ + N_-} = \frac{exp(\frac{\mu B}{kT}) - exp(-\frac{\mu B}{kT})}{exp(\frac{\mu B}{kT}) + exp(-\frac{\mu B}{kT})} = tanh\left(\frac{\mu_{^3He} \cdot B}{kT}\right) \approx 1.0 \times 10^{-8}$$ 😟

Cooling the sample? Large B-fields?
Use: 100 mK, B = 2 T ☞ P ~ 0.30

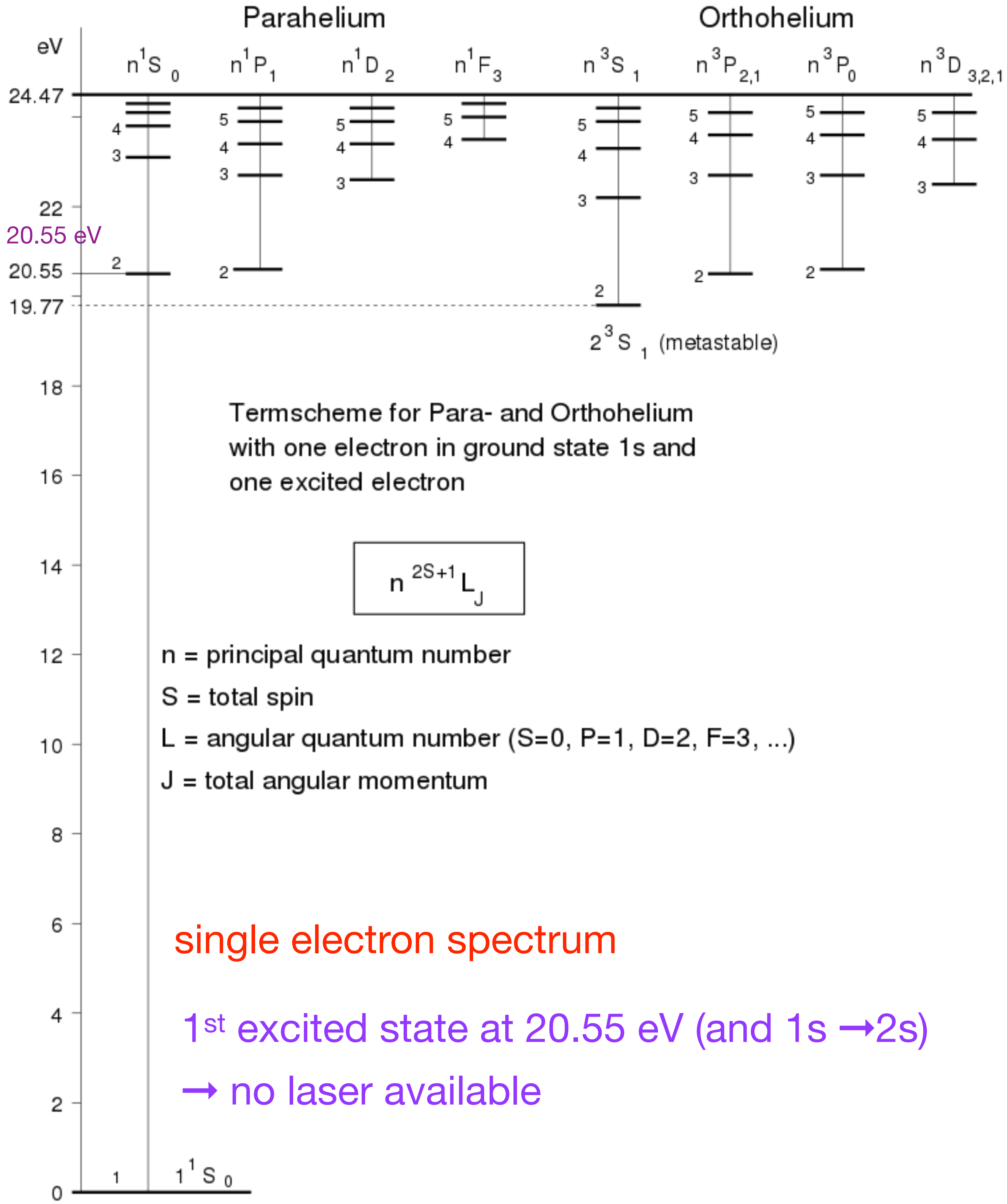
- Polarization ok, but technically hard to accomplish ($$$)
- Impossible to use in an accelerator environment, e.g. electron beam

Somehow we either have to add or remove angular momentum from the system!

Three possibilities to polarize helium-3:

- Metastability exchange optical pumping (MEOP)
  - difficult to produce dense gas targets ($p \lesssim 1$ atm)
  - pure targets, $P \lesssim 80\%$
- Spin exchange optical pumping (SEOP)
  - other “impurities” (polarizing atoms, N_2) present in target, $P \lesssim 70\%$
  - relatively easy to work at high pressures ($p \lesssim 10$ atm)
  - used here at UK
- Stern-Gerlach apparatus (atomic beam source)
  - very low densities ($p \lesssim 1$ mbar), $P \lesssim 95\%$
  - expensive

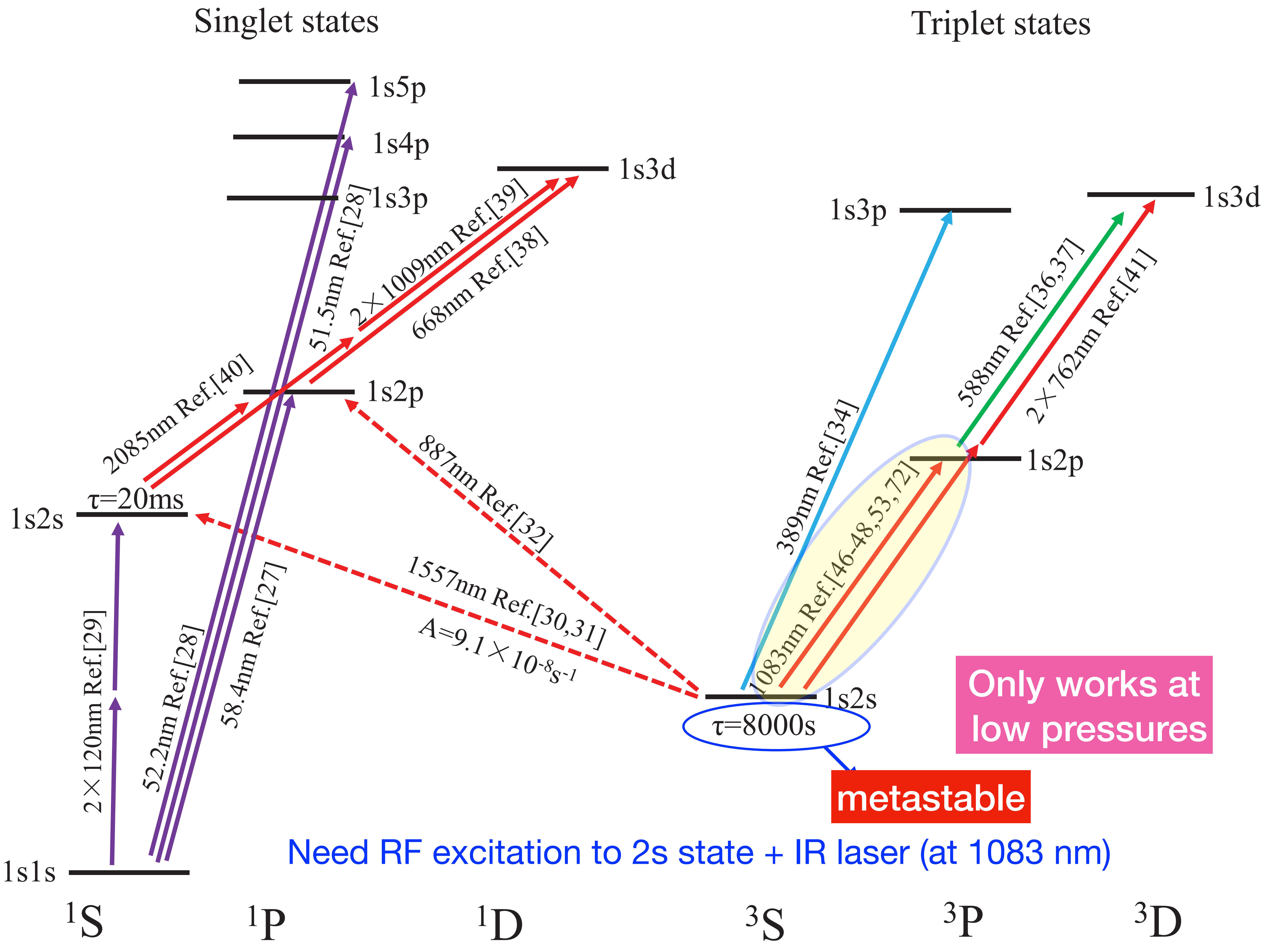
The problem with MEOP



single electron spectrum

1st excited state at 20.55 eV (and 1s →2s)

→ no laser available



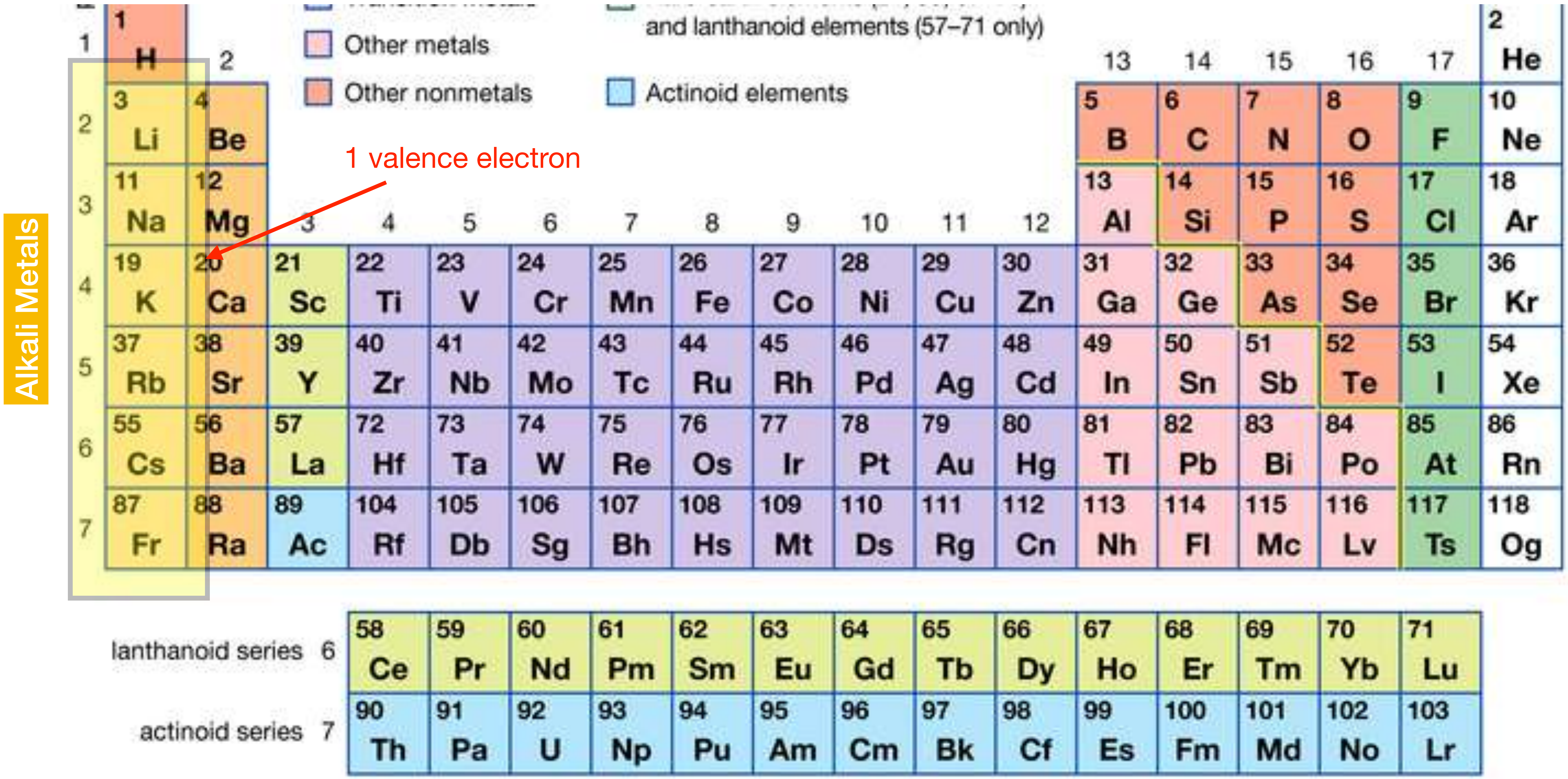
Only works at low pressures

metastable

Need RF excitation to 2s state + IR laser (at 1083 nm)

How about SEOP?

Helium-3 nucleus gets polarized via “spin-spin” (hyperfine) interaction with an alkali metal



*Numbering system adopted by the International Union of Pure and Applied Chemistry (IUPAC).

A look at Rubidium

Natural abundance: ^{85}Rb = 0.72   I= 5/2-, J = 1/2 → F = I±J = 3,2 → m_F = -3, -2, -1, 0, 1, 2, 3 and m_F = -2,-1, 0, 1, 2

^{87}Rb = 0.28   I = 3/2-, J = 1/2 → F= I±J = 2,1 → m_F = - -2, -1, 0, 1, 2 and m_F= -1,0,1

Look at ^{87}Rb: groundstate: $5\ ^2S_{1/2}$
first excited states: $5\ ^2P_{1/2}$
$5\ ^2P_{3/2}$

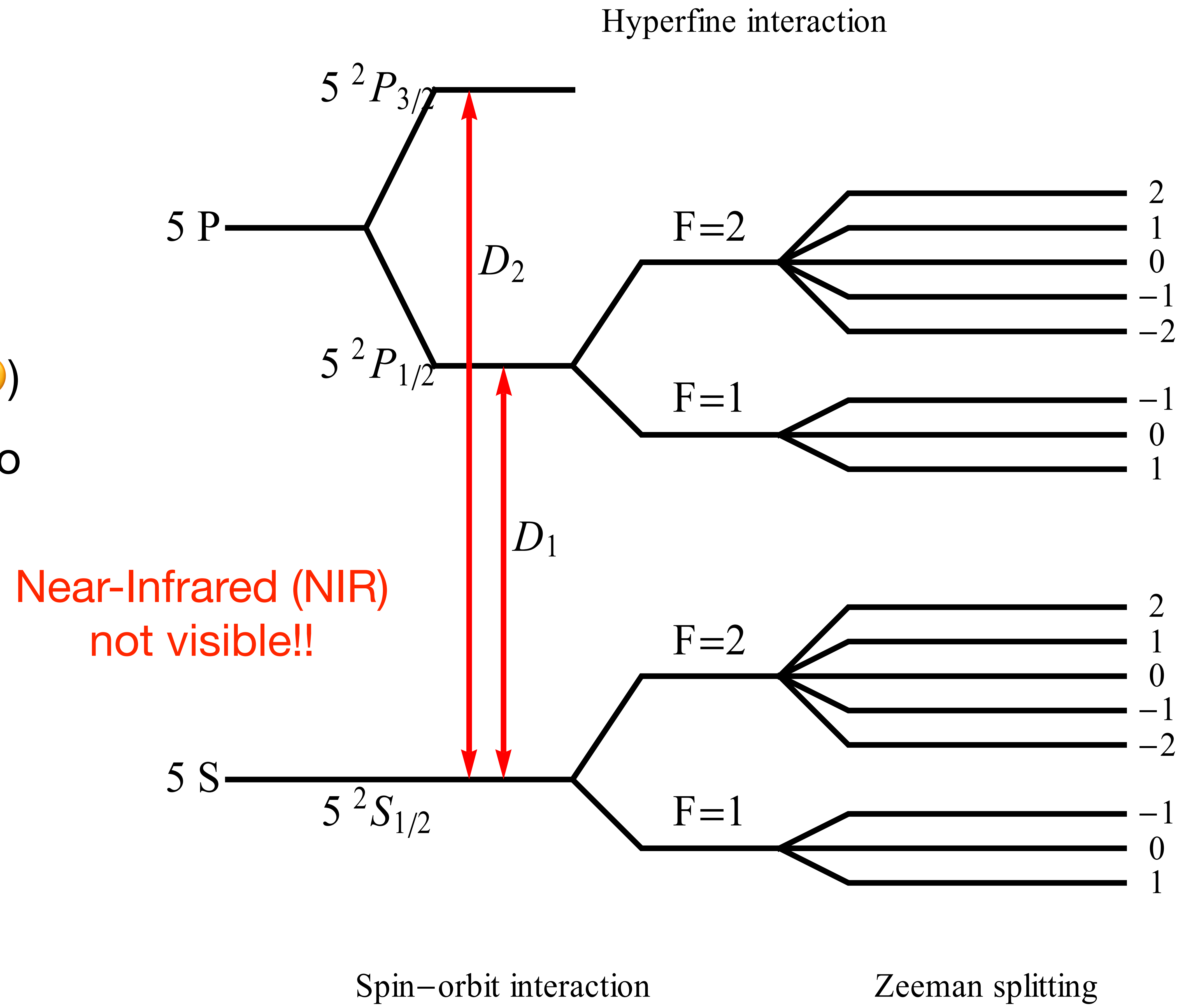
Two optical dipole transitions:

$5\ ^2S_{1/2} \rightarrow 5\ ^2P_{1/2} \rightarrow$ D1 transition (λ_1 = 795 nm - powerful lasers available 😀)

$5\ ^2S_{1/2} \rightarrow 5\ ^2P_{3/2} \rightarrow$ D2 transition (λ_2 = 780 nm - somewhat more difficult to optically pump)

Typical frequencies:

5 S → 5 P:	~3.8×10^{14} Hz (few 100 THz)
$5\ P_{1/2} \rightarrow 5\ P_{3/2}$:	~7×10^{12} Hz (7 THz)
F=1 → F=2 (S-state):	~ 6.8×10^9 Hz (6.8 GHz)
F=1 → F=2 (P-state):	~ 0.8×10^9 Hz (0.8 GHz)
Δm_F transition:	few 10^6 Hz (few MHz)



Alkali atoms in external magnetic fields:

General Hamiltonian: $H_B = \frac{\mu_B}{\hbar}(g_s \mathbf{S} + g_L \mathbf{L} + g_I \mathbf{I}) \cdot \mathbf{B} \;\; = \frac{\mu_B}{\hbar}(g_s S_z + g_L L_z + g_I I_z) B_z$ (choosing B-field along z-axis) *(strong field)*

g-factors: $g_s,\ g_L,\ g_I$ are theoretically or experimentally determined constants (e.g. due to anomalous moments)

If ΔE shift due to B-field is small compared to fine-structure: $H_B = \frac{\mu_B}{\hbar}(g_J J_z + g_I I_z) B_z$ with

g_J is the Landé (fine-structure) g-factor:

$$g_J = g_L \frac{J(J+1) - S(S+1) + L(L+1)}{2J(J+1)} + g_S \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$$ *(medium field)*

If ΔE shift due to B-field is small compared to hyperfine-structure: $H_B = \frac{\mu_B}{\hbar} g_F F_z B_z$ with

g_F is the Landé (hyperfine-structure) g-factor:

$$g_F = g_J \frac{F(F+1) - I(I+1) + J(J+1)}{2F(F+1)} + g_I \frac{F(F+1) + I(I+1) - J(J+1)}{2F(F+1)}$$ *(weak field)*

For any atom with total electronic orbital momentum J = 1/2 ħ the energy eigenvalues can be calculated exactly: → Breit Rabi formula

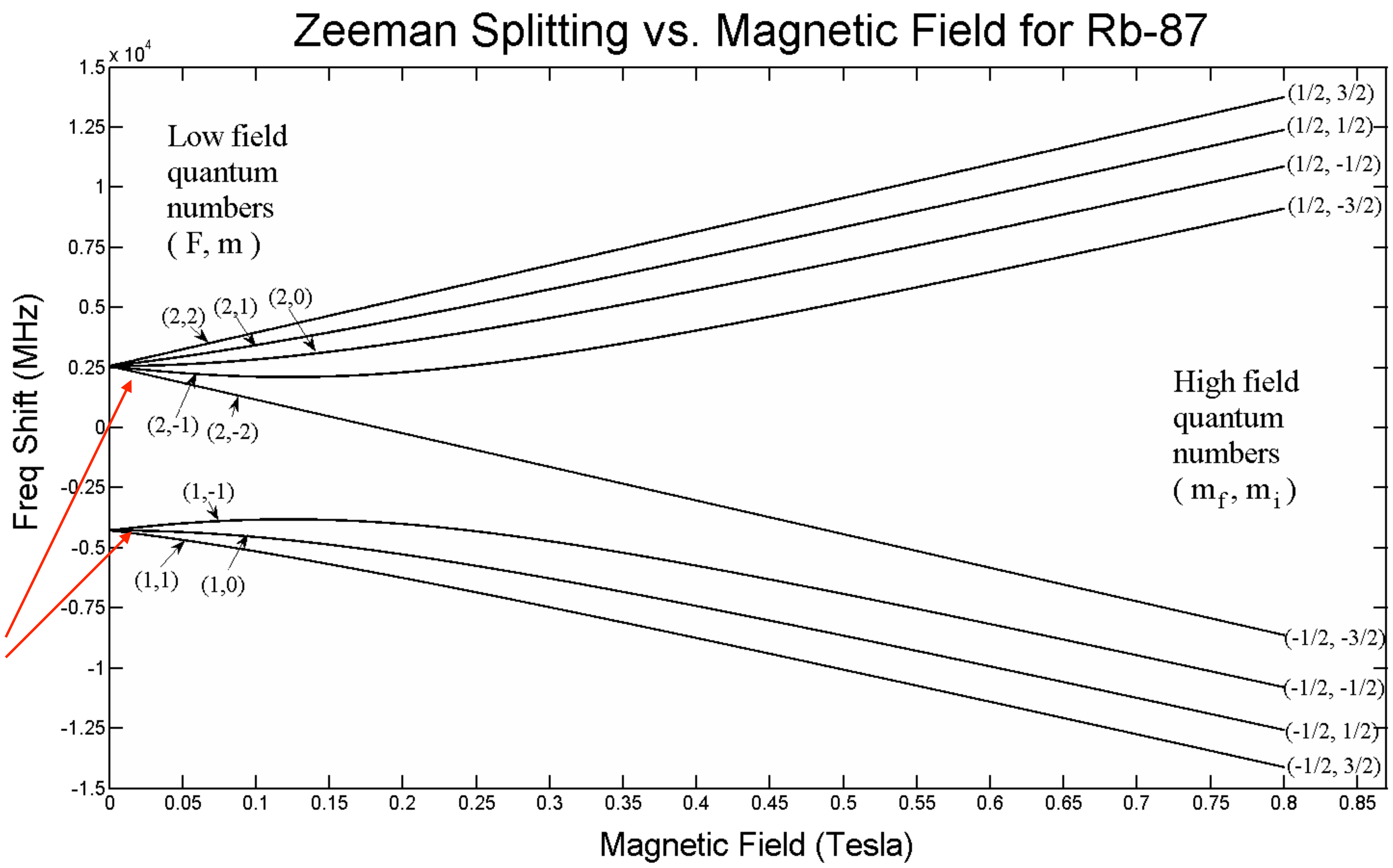
$$\boxed{E(J=1/2, m_J, I, m_I) = -\frac{\Delta E_{HFS}}{2(2J+1)} + g_I \mu_B m B_z \pm \frac{\Delta E_{HFS}}{2}\left(1 + \frac{4mx}{2I+1} + x^2\right)^{1/2}}$$

$$m = m_I \pm m_J = m_I \pm \frac{1}{2} \qquad x = \frac{(g_J - g_I)\mu_B B_z}{\Delta E_{HFS}}$$

$$\Delta E_{HFS} = A_{HFS}\left(I + \frac{1}{2}\right) \qquad A_{HFS} = h \cdot 3.417341305452145(45)\ GHz\ (^{87}Rb\ ground\ state)$$

^{87}Rb: I = 3/2 ħ, S = 1/2 ħ

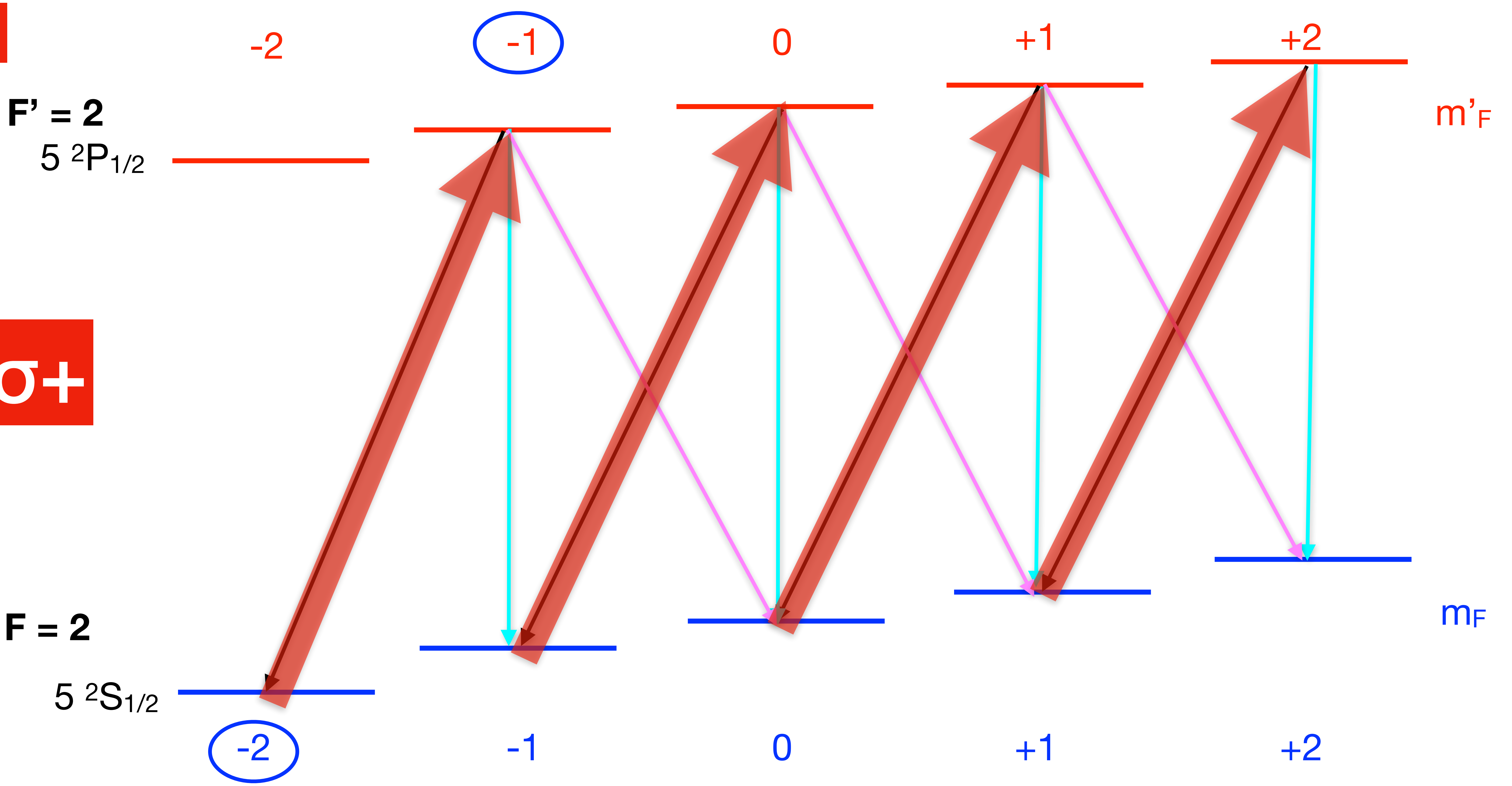
➔ F = 2,1



Polarizing ^{87}Rb via Optical Pumping:

Typically: Pumping D1 transitions (795 nm)

σ+



Fat red arrows: σ+ laser light ➔ induces $\Delta m_F = +1$ transitions (electric dipole transitions)

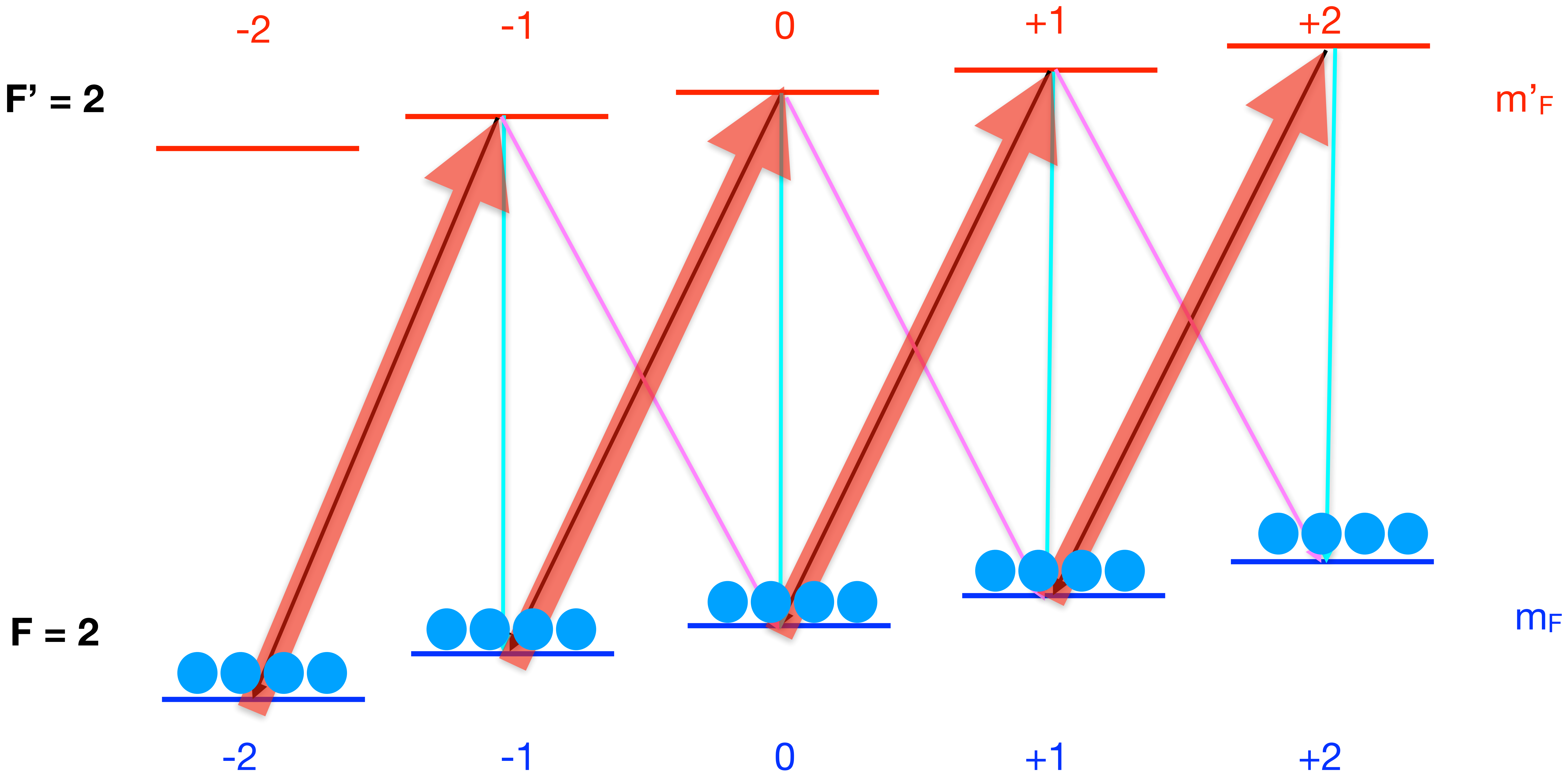
Skinny arrows: radiative decay $\Delta m_F = -1, 0, +1$ (transition probabilities → Clebsch Gordan coefficients)

Clebsch Gordon coefficients: $\langle F_f, m_f | (|J_{photon}, m_{photon}\rangle \oplus |F_i, m_i\rangle) = \langle F_f, m_f | (|1, m_{photon}\rangle \oplus |F_i, m_i\rangle)$

Nice exercise!!

Use ground state as initial state and excited state as final state. For example: $(|2,-2\rangle \oplus |1,+1\rangle) \rightarrow |2,-1\rangle \rightarrow CG: -\sqrt{\frac{1}{3}}$

Polarizing ^{87}Rb via Optical Pumping:



Initially all ground states are ~equally occupied

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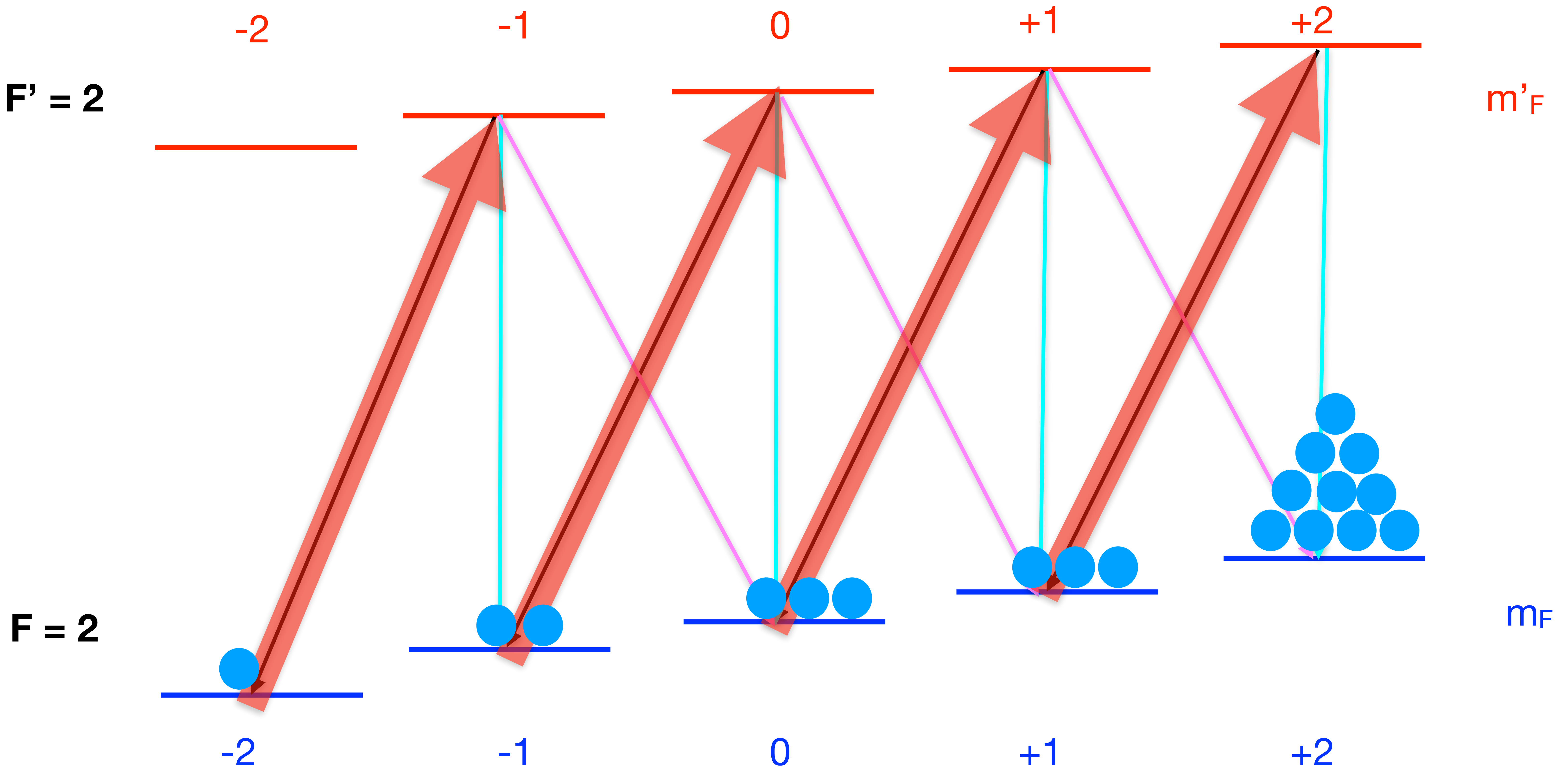

After a few pumping cycles

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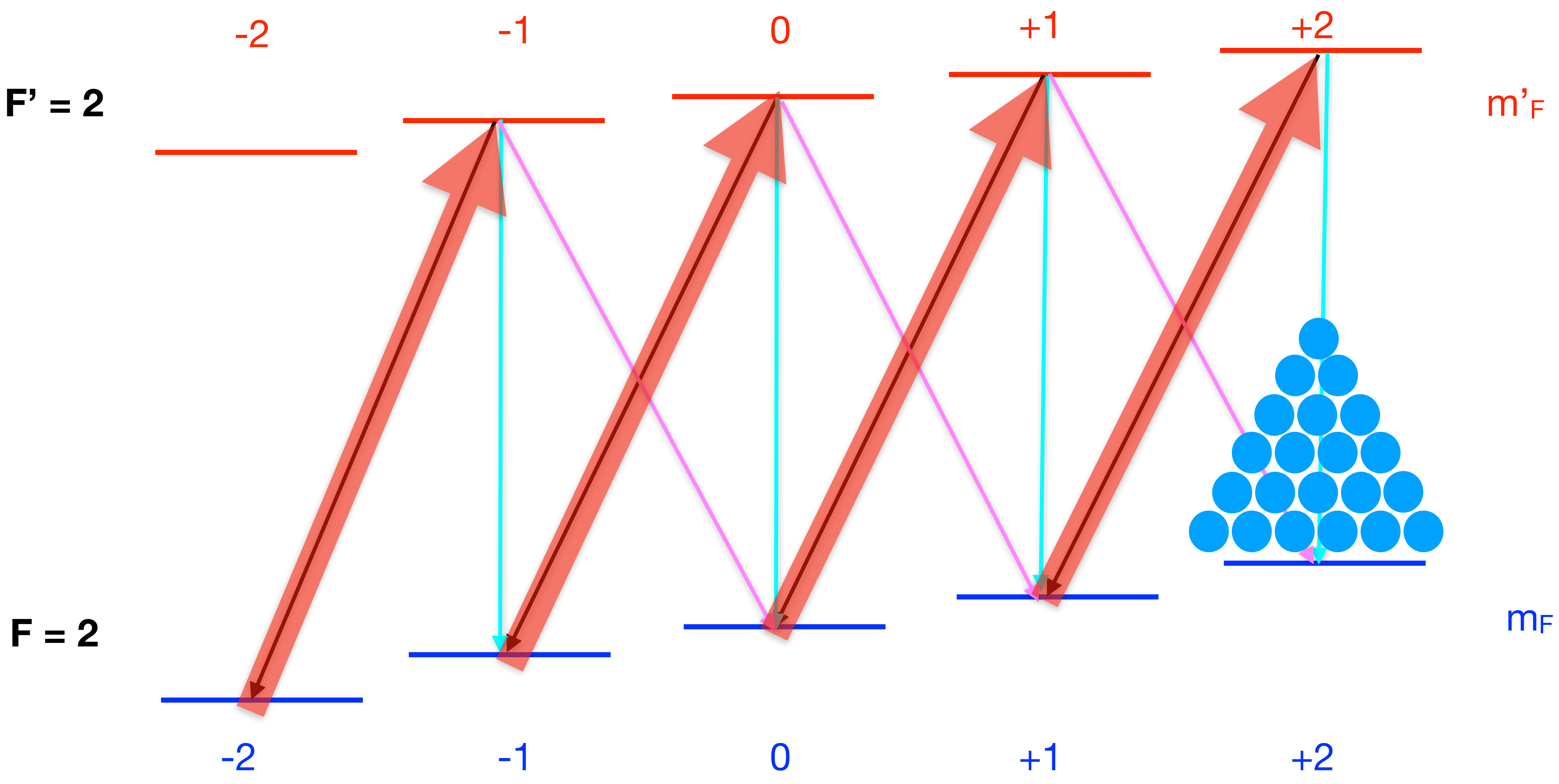
Polarizing ^{87}Rb via Optical Pumping:



After a few pumping cycles
(ms time scale)

P_{Rb} ~ 100% !!

Fat red arrows: σ+ laser light ➔ induces $\Delta m_F = +1$ transitions (electric dipole transitions)

Skinny arrows: radiative decay $\Delta m_F = -1, 0, +1$ (transition probabilities ➞ Clebsch Gordan coefficients)

After a few cycles the Rb atoms are ~100% polarized in either the $|2,+2\rangle$ state or the $|2,-2\rangle$ state.

That's good, but *we want to polarize ^{3}He*?

Idea: Mix ^{3}He and $^{87/85}$Rb and transfer electron polarization of the Rb atoms to the ^{3}He nuclei!!

How does this transfer happen?

Main mechanism: Transfer polarization via hyperfine interaction between alkali atom and ^{3}He nucleus in "spin exchange collisions":

$$H_{SE} = -2\gamma_n \mu_N \mu_B \frac{8\pi}{3} \delta(R)\ \mathbf{S}_e^{Rb} \cdot \mathbf{I}_N^{He}$$

→ dipole-dipole interaction, just like the H-atom

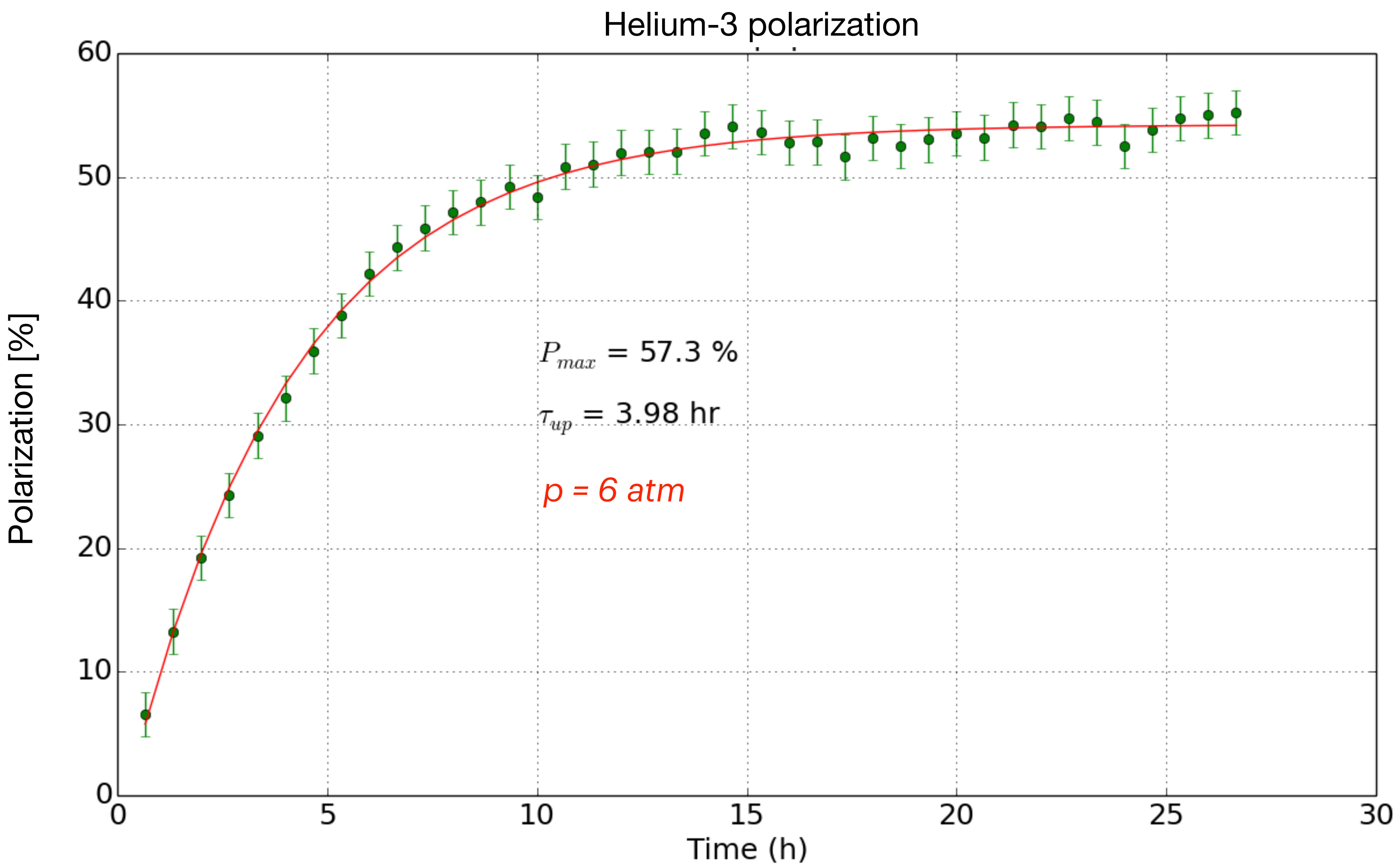
R = distance between (Rb) valence electron and (He) nucleus.

Rb spin flips → Rb polarization is reduced → keep lasers running and continue optical pumping.

Does it really work?

Important:

- Storage vessel (glass cell) has to be very clean
- Keep (transverse) field gradients small (< 2 mT/cm)



How we actually measure the ^{3}He polarization?

Multiple methods:

Nuclear Magnetic Resonance (NMR) - relative

Electron Paramagnetic Resonance (EPR) - absolute

EPR: Measure shift of energy levels in Rb due to the local B-field generated by the polarized ^{3}He nuclei → Zeeman shift

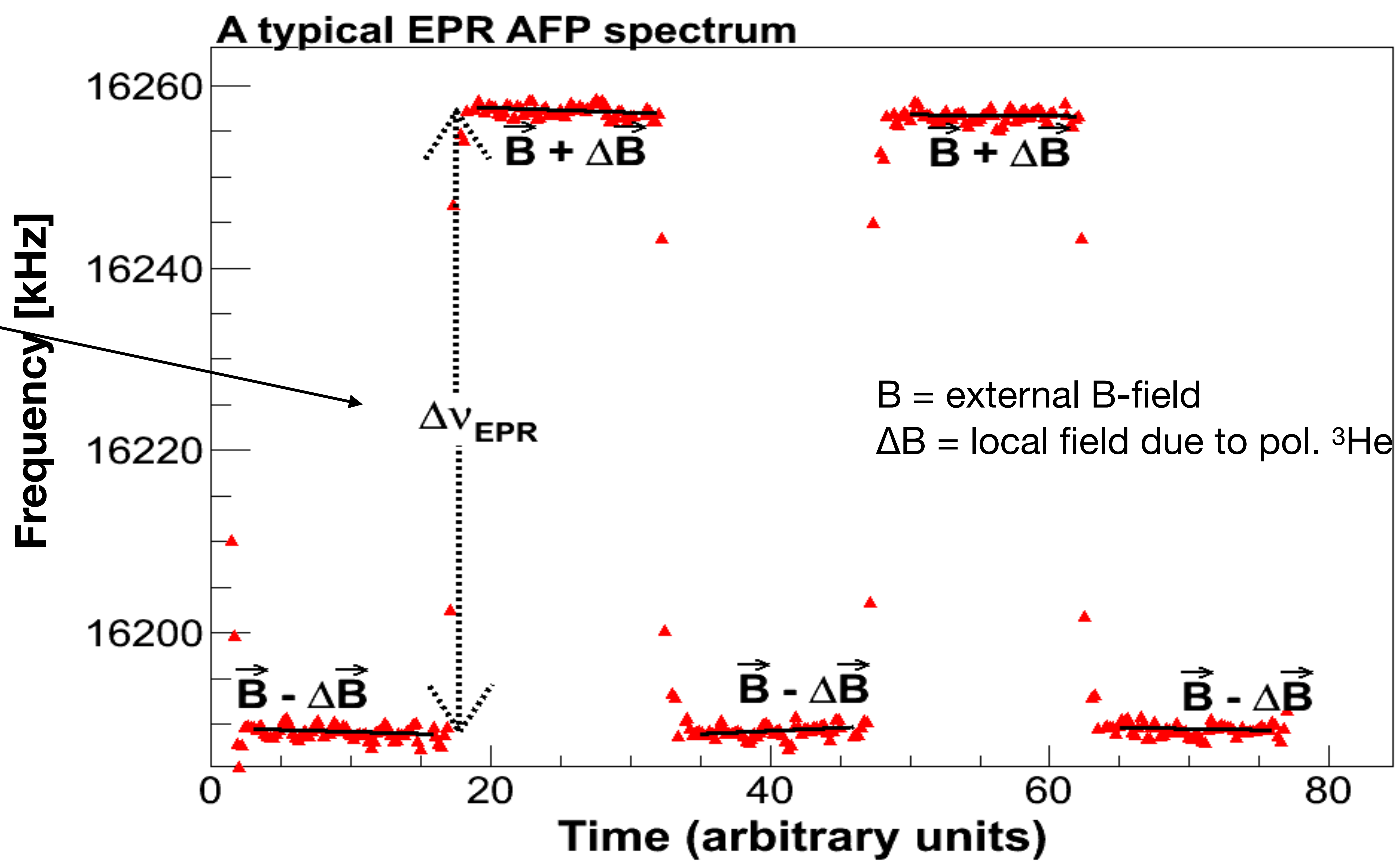
☞ Magnetized sphere or cylinder

$\Delta\nu_{EPR}$ is the frequency shift induced by the polarized ^{3}He nuclei on Rb ground state atoms

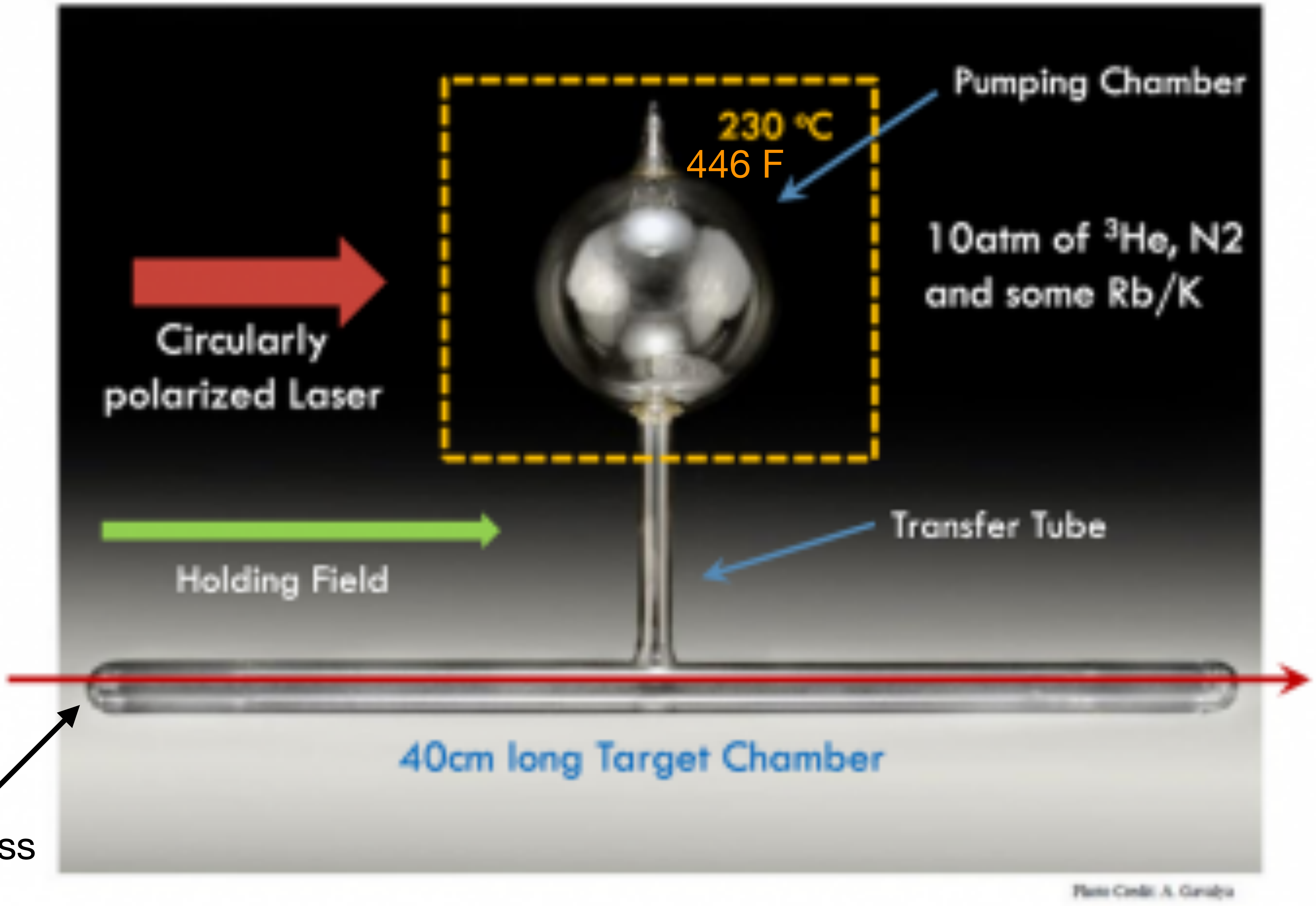
P ~ 1kHz/% (@ 6 atm)

Resolution: <100 Hz (out of ~20 MHz)

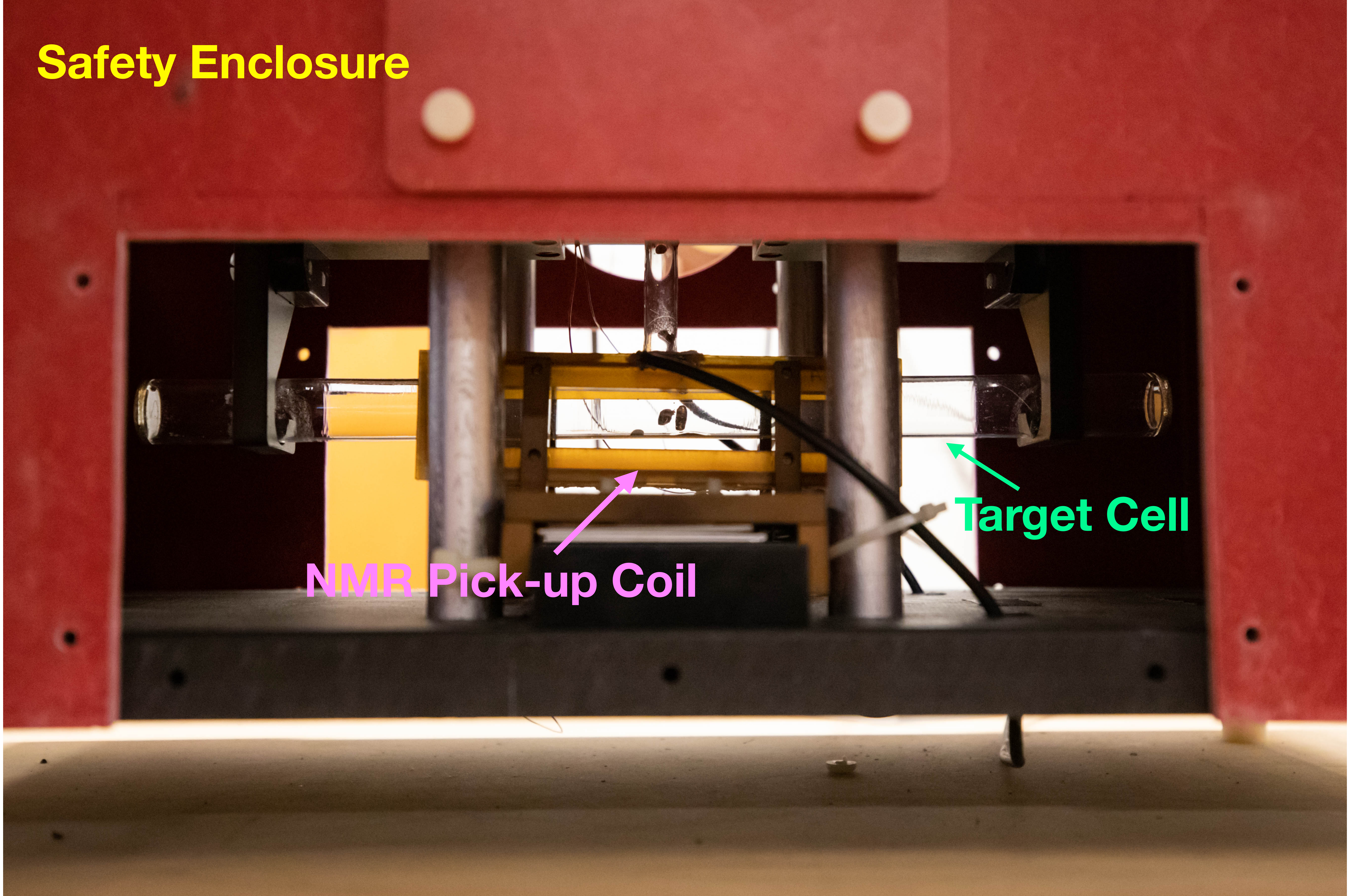
$$\frac{\Delta f}{f} \leq 5 \times 10^{-6}$$



A typical target cell



end window thickness
~0.1-0.2 mm


Safety Enclosure
Target Cell
NMR Pick-up Coil


Homemade: 100 W of NIR-CW laser
Safety goggles required!!
Laser linewidth: Δλ~0.2 nm
→ well matched to Rb Doppler profile.


WALKER

Summary

- High values of polarization (> ~60-70%) can be produced via SEOP at high densities (up to p ~10 atm):
  - Used at Jefferson Lab (11 GeV electron accelerator) to study the spin-dependent quark gluon structure of neutrons
  - Spin precession of polarized ^{3}He (+SQUIDs) is used to monitor the stability of B-fields (search for a permanent EDM of the neutron at ORNL)
  - Used to generate high-resolution lung images
  - Neutron spin filters
  - Used to study magnetically induced Faraday rotation
  - Many more applications .....