Ph 77 - Advanced Physics Laboratory

Department of Physics, California Institute of Technology

- Atomic Track -

Optical Pumping

Introduction

The Optical Pumping experiment will introduce you to the general field of AMO physics (a.k.a. Atomic/Molecular/Optical physics), which describes the detailed structures of atoms and molecules and their interaction with light. Current research in AMO physics includes advances in spectroscopy, laser technology, quantum optics, laser cooling & trapping, Bose-Einstein condensation, atomic clocks, quantum entanglement, and searches for physics beyond the Standard Model … just to name a few. In the Optical Pumping experiment you will learn about atomic energy levels, optical and radio-frequency transitions between levels, Zeeman splittings, manipulating level populations, and some experimental techniques used broadly in AMO physics. Good stuff!

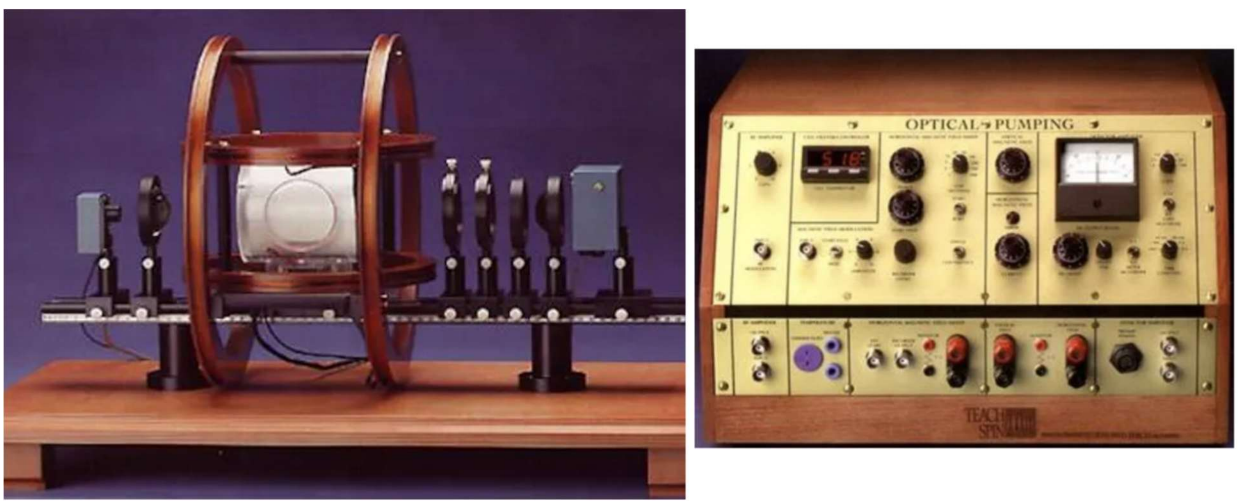

Figure 1. The Optical Pumping optical setup (left) and chassis (right), located in the Ph77 lab in 210 East Bridge.

Rubidium atomic structure

Our optical-pumping experiment focuses on Rubidium atoms, as Rb has proven to be a useful atomic case study, demonstrating many general physical principles by example. Rubidium is relatively easy to work with in the lab, and it has a single valence electron, giving it a relatively simple hydrogen-like atomic structure. Because Rb acts much like hydrogen in its spectroscopic behavior, choosing this atom simplifies the problem enormously right from the start. In natural rubidium the isotopes ^{85}Rb and ^{87}Rb occur in the ratio 72:28 percent.

Your first task is to review the atomic level structure of the Rubidium isotopes. If you have not taken Ph125, much of this material may be unfamiliar to you. If you have taken Ph125, you may soon find that one course in QM is not nearly enough to fully understand atomic spectroscopy (it's definitely not). In any case, we mostly state the relevant results here, without delving into their QM origins.

The occupied electron orbitals of a rubidium atom are

$$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 5s$$

and the first 36 electrons are in closed shells with zero total angular momentum. The 5s electron therefore acts much like the sole electron in a hydrogen atom. Next consider the electronic energy levels of this sole electron, referring to the level diagrams in Figures 2 and 3. These show just the lowest-energy S and P levels, as the higher levels are unimportant for this lab.

Starting on the left in these diagrams, the ground state is an S state with an orbital angular momentum of L = 0, and the upper state is a P state with L = 1. Adding spin-orbit coupling gives

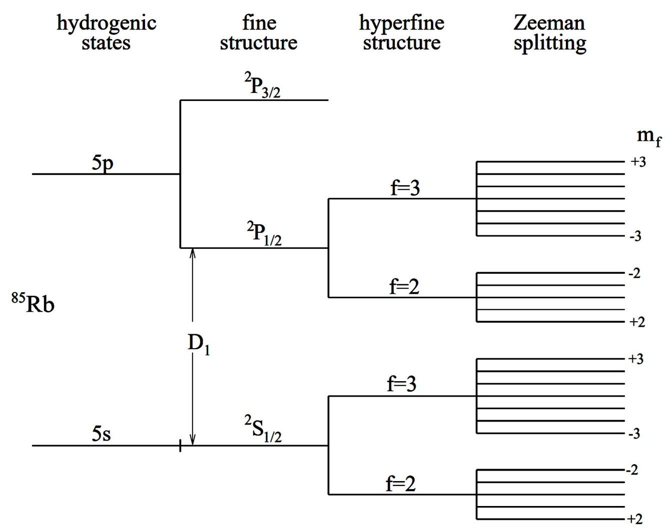

Figure 2. The ^{85}Rb level diagram, focusing on the D1 line at 795 nm.

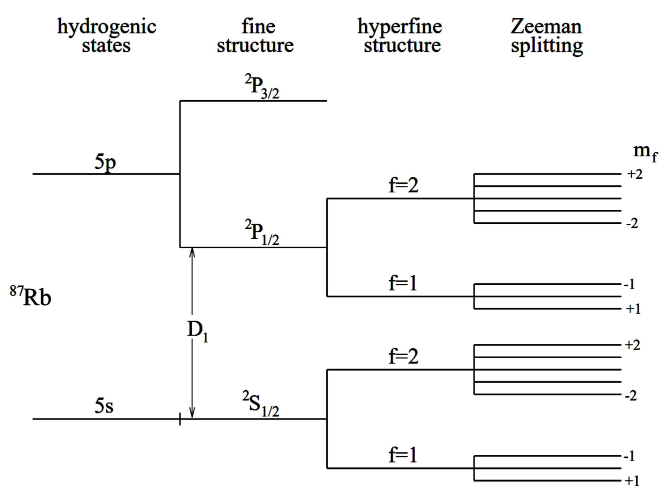

Figure 3. The ^{87}Rb level diagram, focusing on the D1 line at 795 nm.

the second "fine structure" column in both diagrams, with the levels shown in the usual Russell-Saunders notation $^{2S+1}L_J$, where S represents the total spin angular momentum (S = 1/2 for a single electron), L specifies the total orbital angular momentum (designated S, P, D, etc. for L = 0, 1, 2 respectively … alas, this S is different from the total-spin S), and J refers to the total angular momentum. You learned about the quantum physics underlying spin-orbit coupling in Ph125, so we will not discuss the matter further here. Consider this handout as a good opportunity to refresh your memory and take a deeper dive into a specific case study.

After adding spin-orbit coupling, there are two optical transitions to consider, conventionally called D1 and D2 for alkali atoms (only D1 is labeled in the diagrams, as this is the transition we will be using). For rubidium, the wavelengths of these transitions are 795 nm (D1 line) and 780 nm (D2 line), and these are in the near-infrared optical spectrum. In the Optical Pumping apparatus, we suppress the D2 line using a narrow-band optical filter, so we will only be exciting the D1 transition using optical photons.

Next we add nuclear spin, equal to I = 5/2 for ^{85}Rb and I = 3/2 for ^{87}Rb, giving the third "hyperfine structure" column in the diagrams. Here F shows the angular-momentum sum of J and I, and the energy splitting arises because the electron and nuclear magnetic moments interact with one another (again, see Ph125 for details). Looking at the ground-state $^2S_{1/2}$ levels, we have L = 0, so spin-orbit coupling gives simply J = S = ½. Further adding the nuclear spin I, the only two possibilities are F = I ± ½.

Note that the different energy-level splittings are *not* to scale in these figures. The hydrogenic states are separated by about 1 eV, the spin-orbit splittings (between $P_{1/2}$ and $P_{3/2}$ states) are separated by about 10^{-3} eV, and the hyperfine splittings are of order 10^{-6} eV. Putting in some numbers, the D1 and D2 lines have transition frequencies of 377 THz (795 nm) and 384 THz (780 nm), while the ground-state hyperfine splittings are 3035.73 MHz for ^{85}Rb and 6834.68 MHz for ^{87}Rb. The upper-state hyperfine splittings are smaller, equal to about 361 MHz and 816 MHz and for the $P_{1/2}$ states of ^{85}Rb and ^{87}Rb, respectively.

We note in passing that it is quite difficult to accurately calculate any of these numbers, owing to the complexities of many-body quantum-mechanical models. Spectroscopic measurements can be made with great precision, however, so all the transition frequencies are known to many significant digits. Remember that even the hydrogen atom is not easy to solve with high precision. The finite size and mass of the proton, relativistic effects, the Lamb shift (from QED), and other factors present theoretical and computational challenges. If you want to understand *everything* about atomic spectroscopy, that is a tall order! The only way to get your head around the problem in a finite time is to make lots of simplifications, ignoring small perturbations whenever possible. Therefore, the discussion that follows is approximate and focuses mainly on the physics needed to understand the Optical Pumping experiment.

Proceeding to the final column in Figures 2 and 3, adding an external magnetic field produces Zeeman splittings that lift the m_F degeneracy of the hyperfine states as shown. For low magnetic field strengths (Zeeman splitting << hyperfine splitting), the Zeeman levels are shifted by

$$\Delta E \approx g_F \mu_B B m_F \tag{1}$$

where B is the magnetic field strength, $\mu_B = e\hbar/2m_e \approx 1.40$ MHz/Gauss is the Bohr magneton, and the Landé g-factor is given by (see Ph125)

$$g_F \approx g_J \frac{F(F+1)+J(J+1)-I(I+1)}{2F(F+1)} \tag{2}$$

with

$$g_J \approx 1 + \frac{J(J+1)+S(S+1)-L(L+1)}{2J(J+1)} \tag{3}$$

and these expressions ignore the contribution of the nuclear magnetic moment (because it is about 2000x smaller than the electron magnetic moment).

Simplifications for Rubidium

Now is a good time to pause and think about what all this means. It is helpful to have a specific case study in mind, so consider only the ground state $^2S_{1/2}$ levels of ^{85}Rb (because this lab mainly focuses on just these levels). The hyperfine states reflect the angular-momentum addition of one electron spin (S = 1/2) with the ^{85}Rb nuclear spin (I=5/2), giving two ground states with F = 2 and F = 3. We will often narrow our focus even more and consider just the F = 3 manifold.

Note that we refer to all the $^2S_{1/2}$ levels as "ground states" because these levels are essentially equally populated in thermal equilibrium. In contrast, the P levels are generally unpopulated, because they quickly decay (in ~ 30 nanoseconds) to the ground states. In a gas of Rb atoms, atomic collisions will soon "mix" the ground states, which tends to equalize the level populations. At room temperature we have $kT \approx 0.025$ eV, so collisions have more than enough energy to scramble the hyperfine levels separated by a measly 10^{-6} eV. But thermal collisions are not nearly energetic enough to excite the P levels. So this is the normal state of affairs in a Rb gas – nothing in the P levels, while all the $^2S_{1/2}$ ground states are all equally populated.

Moving on to the Zeeman levels for ^{85}Rb, the ground state $^2S_{1/2}$ levels have S = J = 1/2 and L = 0, so substituting into the above equations gives $g_J = 2$. This is just the "bare" Lande g-factor of the electron, call it g_e. If we set I = 0 for a moment, then F = J = S = 1/2 and the above expressions give $g_F = g_J = 2$. In this fictitious hyperfine-free atom, the ground state has only two Zeeman levels with $m_F = \pm 1/2$, and the Zeeman splitting is just the $\mu \cdot B$ energy of the electron in a magnetic field. The energy shift $\Delta E \approx g_F \mu_B B m_F$ given above means that the two $m_F = \pm 1/2$ levels are separated by $\Delta E \approx 2\mu_B B$, giving a transition frequency $\nu_{Zeeman} = \Delta E/h \approx 28$ GHz/Tesla ≈ 2.8 MHz/Gauss. So, in the absence of nuclear spin, the Zeeman splitting arises entirely from the magnetic moment of the sole valence electron.

[Alas, because nothing can ever be simple in quantum mechanics, the "bare" Lande g-factor of the electron is not the whole story. Quantum electrodynamics (QED) adds a small correction, so real electrons have $g_e \approx 2.0023193043626$. Both theory and experiment provide all these significant digits, and they both agree! This fact is an amazing triumph of 20^{th} century physics. But we digress... $g_e \approx 2$ is adequate for this lab.]

Returning to the ground state $^2S_{1/2}$ levels of ^{85}Rb, we see that Equation (2) is overly general for our needs. For these ground states we just showed $g_J = 2$, and hyperfine coupling for one-electron atoms simply gives F = I ± 1/2. Plugging this into Equation (2) then yields

$$g_F \approx \pm \frac{g_e}{2I+1} \approx \pm \frac{2}{2I+1} \tag{4}$$

where the plus sign applies to F = I+1/2 and the minus sign applies to F = I–1/2. Again, this expression applies in the limit $g_I \approx 0$, because the electron magnetic moment dominates the Zeeman splitting.

For ^{85}Rb, we see that $g_F \approx \pm 1/3$, where the plus sign applies to the F = 3 manifold and the minus sign applies to the F = 2 manifold. As you can see in Figure 2, the F = 2 Zeeman manifold is indeed inverted from the "normal" F = 3 manifold.

Interestingly, we see that both the F = 2 and F = 3 manifolds have the same magnitude for the Zeeman splitting, because $|g_F| \approx 1/3$ for both. This makes sense because the low-field Zeeman splitting all comes from the electron spin, and there is only one electron in this problem. Also, the maximum value of $m_F = 3$ (for the ^{85}Rb ground states) gives $\Delta E \approx \mu_B B$. Thus the maximum m_F value means the electron magnetic moment is aligned along the applied B field. Similarly, the minimum value $m_F = -3$ means the electron is aligned anti-parallel to the applied B field.

In the lab, we will use RF (radio frequency) radiation to drive transitions between the different Zeeman levels. Optical radiation is needed to excite the atoms from the S to P states, with frequencies of several hundred THz. But the Zeeman splittings are much smaller, so we only need electromagnetic radiation with a frequency

$$\nu_{Zeeman} = g_F \frac{\mu_B}{h} B \tag{5}$$

with $\mu_B/h = 1.3996245$ MHz/Gauss. Moreover, quantum selection rules inhibit RF transitions except between Zeeman levels separated by Δm = ±1. (See Ph125 and beyond for more about selection rules; it's complicated, so we only state the results here.)

Exercise 1. Put in some numbers to show that driving Δm = ±1 Zeeman transitions in the ^{85}Rb ground states require RF radiation with $\nu_{Zeeman}/B = 467$ kHz/Gauss. Similarly, show that ^{87}Rb has $g_F = \pm 1/2$, giving $\nu_{Zeeman}/B = 700$ kHz/Gauss. These values for the two Rb isotopes are particularly important in this lab, as you will see.

Strong-field Zeeman splitting

If the magnetic field is strong enough, then the Zeeman splitting starts to become comparable to the hyperfine splitting, and then Equation (1) is no longer an accurate representation of the energy levels. A better treatment of the Zeeman effect yields what is called the *Breit-Rabi equation.* For the special case of ground-state alkali atoms (with S=1/2, L=0, J=1/2, and F = I±1/2), Breit-Rabi becomes

$$\Delta E_{Zeeman} = g_I \mu_B B m_F \pm \frac{\Delta E_{hf}}{2} \sqrt{1 + \frac{4m_F}{2I+1} x + x^2} \tag{6}$$

where g_I is the small nuclear g-factor (previously neglected), ΔE_{hf} is the hyperfine splitting of the $^2S_{1/2}$ level, the ± in this expression refers to the upper (+) and lower (-) hyperfine levels, and the dimensionless factor x is

$$x = (g_J - g_I) \frac{\mu_B B}{\Delta E_{hf}} \tag{7}$$

Evaluating Breit-Rabi gives the results in Figure 4, which show the Zeeman energy levels for the Rb ground states.

Exercise 2. Ignoring the nuclear Zeeman splitting (set $g_I = 0$), verify that the Breit-Rabi equation becomes Equation (1) for both of the ^{85}Rb ground states when $x \ll 1$. (Hint: remember that for the special case of single-valence-electron atoms like Rb, the two hyperfine ground states have F = I±1/2.) Our apparatus can only supply B fields up to about 20 Gauss. At this field strength, how large is the dimensionless parameter x for ^{85}Rb?

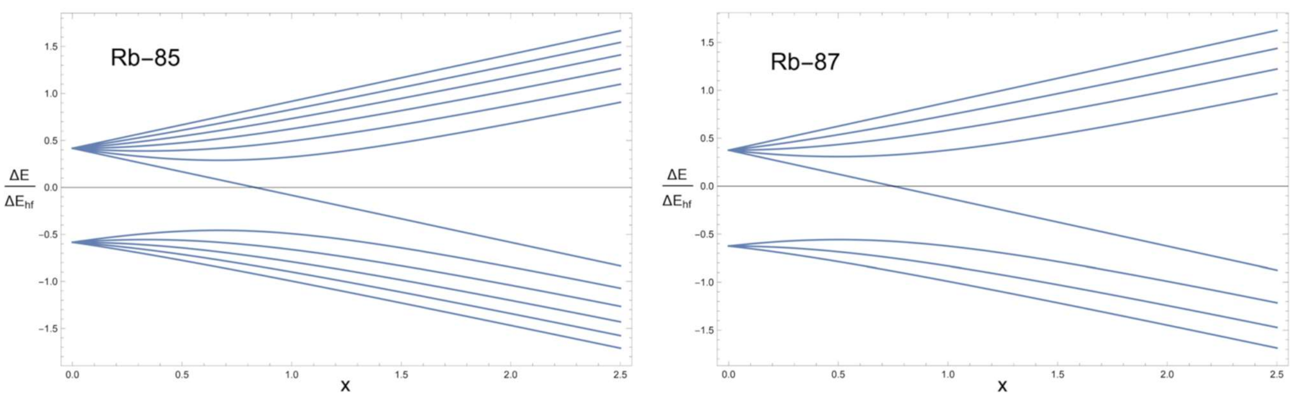

Figure 4. The Zeeman energy levels for the $2S_{1/2}$ ground states of Rb85 (left) and Rb87 (right) according to the Breit-Rabi formula, plotting $\Delta E / \Delta E_{hf}$ as a function of $x = g_J \mu_B m_F B / \Delta E_{hf}$. We can observe nonlinear Zeeman splittings in the Optical Pumping lab, but the instrument capabilities are confined to the far left in these diagrams.

Important parameters for this lab. We will mainly focus on the ^{85}Rb ground states in this lab, and here are some parameters that often come up:

I = 5/2	= ^{85}Rb nuclear spin
$\Delta E_{hf}/h = 3035.73$ MHz	= ground state hyperfine splitting
$\nu_{Zeeman}/B = 467$ kHz/Gauss	= low-field Zeeman splitting
$g_J \approx 2$	= electronic g-factor
$g_I \approx -2.936 \times 10^{-4}$	= nuclear g-factor

Optical pumping

Now that you have a basic picture of the energy level diagrams for both Rubidium isotopes, the next step is to examine how light can be used to manipulate the populations of the various atomic states, a process that is sometimes called *quantum-state engineering*. The phenomenon of optical pumping is a staple of AMO physics experiments, used in laser cooling of atomic gases, trapping atoms and molecules in optical potentials, AMO searches for fundamental physics beyond the Standard Model, quantum entanglement, quantum computing, and other applications. Once again, our goal here is to present a case study using our Optical Pumping apparatus, as this relatively inexpensive experiment demonstrates many aspects of the essential physics you will find in modern AMO research labs.

Level populations and transitions

In the Optical Pumping (OP) experiment, we use optical radiation near 795nm to excite the D1 transition shown in Figures 2 and 3. This is an "allowed" electric-dipole transition, restricted by the quantum selection rules ΔL = $\pm$1, ΔF = 0 or $\pm$1 (except F = 0 to F = 0 is not allowed), and Δm = 0 or $\pm$1. Once an atom has been excited from $S_{1/2}$ to $P_{1/2}$, the upper state rapidly decays back to the ground state by emitting a photon, with a decay time of about 30 nsec, with the selection rule Δm = 0 or $\pm$1.

The lamp in this experiment provides somewhat broadband radiation near 795nm, so these photons will readily excite all the D1 transitions that are allowed by the selection rules. The energy differences between the various hyperfine and Zeeman energy splittings are inconsequential when considering excitations of the D1 transitions in this experiment. Modern AMO experiments generally use lasers that can select individual transitions (see the Ph77 Rb Spectroscopy lab). But the OP lamp is cheaper, and laser goggles are not needed in the OP lab.

Because the hyperfine splittings are small compared to kT, all the ground-state hyperfine levels are roughly equally populated in thermal equilibrium. In contrast, the $P_{1/2}$ state population is essentially zero in thermal equilibrium. This provides the starting point for the OP experiment – when no light is shining on the Rb atoms, they are in the $S_{1/2}$ state, equally distributed among the various hyperfine ground states.

This situation does not change much if *unpolarized* 795nm light is shining on the Rb atoms. These photons excite all the allowed D1 transitions, and the excited states decay rapidly back down, yielding the same uniformly populated hyperfine states. The excited-state $P_{1/2}$ state population is always very low compared to the ground-state $S_{1/2}$ population.

Light polarization & angular momentum

The ground-state level populations can change, however, if *circularly polarized light* is used to excite the D1 transition. Because photons are spin-1 massless particles, they carry angular momentum equal to $\pm\hbar$, and this angular momentum can be transferred to the atom depending on the polarization of the incident light wave. Any polarization state can be expressed as a linear combination of the usual horizontal $|H\rangle$ and vertical $|V\rangle$ polarization states, because these two states provide an orthogonal basis set. The electric field vector is confined to the horizonal plane for $|H\rangle$ and the vertical plane for $|V\rangle$.

Alternatively, any polarization state can be expressed as a linear combination of right-circular $|RC\rangle$ and left-circular $|LC\rangle$ polarization, because these two "helical" states also provide an orthogonal basis set. If you are not already familiar with these polarization terms, you can (and should) quickly research them online.

What is important for our present discussion is that light in the $|LC\rangle$ polarization state will only drive a so-called σ^+ transition, which increases the m_F value of the atomic state, as measured along the propagation direction of the light beam. Put another way, a single σ^+ photon will engage the $\Delta m = +1$ selection rule, and only that rule; light in the σ^+ polarization state will *not* engage the $\Delta m = 0$ or $\Delta m = -1$ selection rules. The same applies for σ^- photons, except these decrease m_F, as you would expect.

If we apply an external magnetic field along the optical axis, then this field establishes the stable Zeeman states in the system. It is important to define a coordinate system for this discussion, and this is fixed by the on-axis magnetic field. In this coordinate basis, the m_F states will be eigenstates of the system, so they will be stable in time if unperturbed. You can see why this is the case in classical physics by considering a ^{85}Rb atom in the F = 3 ground state with $m_F = +3$. In this maximal state, the electron spin is fully aligned with the magnetic field, so the magnetic dipole moment of the electron is also aligned as well. Classically, a magnetic dipole in a magnetic field will precess about the B field; but a dipole along B does not precess. This is a classical-physics picture of why the $m_F = +3$ state is stable. The quantum-physics view is simply that this state (as well as all the other m_F states) are eigenstates of the Hamiltonian.

Note also that linearly polarized light contains equal amounts of $|RC\rangle$ and $|LC\rangle$ states because both $|H\rangle$ and $|V\rangle$ can be written as linear combinations of $|RC\rangle$ and $|LC\rangle$. If you are unfamiliar with this notation, please look up the *Jones calculus* representation of polarization states. Unpolarized light will also contain equal amounts of $|RC\rangle$ and $|LC\rangle$ states.

Optical pumping

Putting all this together, Figure 6 sketches the basic layout of the OP experiment, and Figure 5 describes the essential physics involved in optical pumping. Together these diagrams illustrate the most important concepts in this lab. Note that the incident light in Figure 6 has a σ^+ polarization, which means the optical excitations are restricted to $\Delta m = +1$. But subsequent decays are allowed for $\Delta m = 0$ and $\Delta m = \pm 1$.

As seen in Figure 5, each upward σ^+ transition increases m_F by $\Delta m = +1$, while the subsequent decay of the upper state leaves the value of m_F statistically unchanged (approximately). After many σ^+ transitions have occurred, the atoms will inevitably end up with the maximum m_F value of the ground state. From this state, however, there are no longer any σ^+ transitions. This maximum m_F state is often called a "dark state" in AMO jargon because atoms in this state cannot absorb (and thereby scatter) any of the incoming σ^+ light. For the present experiment, it might be better to say that the optically pumped atoms are "transparent", because their presence reduces the overall absorption of σ^+ light, thus increasing the amount of light striking the photodetector in Figure 6.

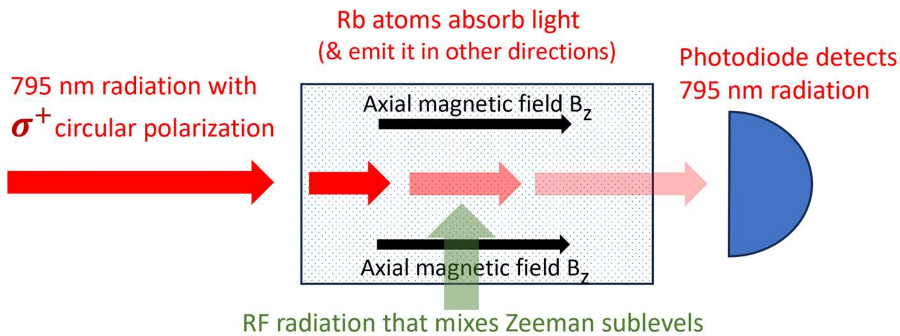

Figure 6. The essential operation of the Optical Pumping optics. A lamp produces a beam of circularly polarized σ^+ light that passes through the Rb vapor cell and is measured by a photodiode. Some of the light is absorbed by Rb vapor in the cell and does not reach the detector. An axial magnetic field B_z (called the Horizontal field on the OP controller) is applied along the optical axis. An additional wire coil is used to apply RF radiation to the Rb atoms. If the RF frequency equals the Zeeman splitting, then the RF radiation will mix the Rb ground-state Zeeman levels.

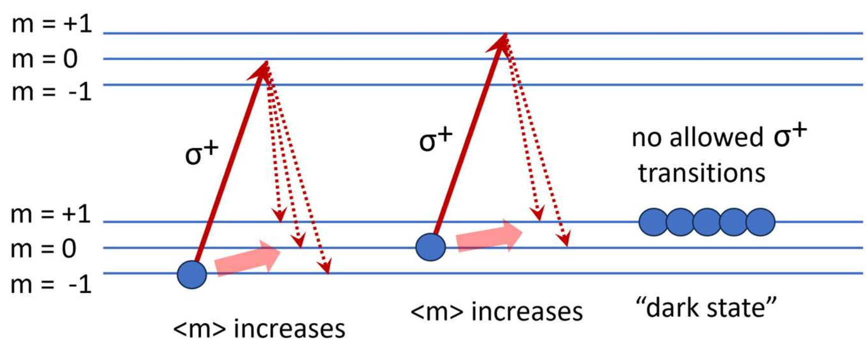

Figure 5. The essential physics of optical pumping, illustrated using an F=1 to F=1 transition. When circular polarized light drives only σ^+ transitions, these generally increase the m_f value of the ground state. After multiple excitations and decays, the atoms all end up "pumped" into the m=+1 ground state. This is called a "dark" state because it can no longer be excited by σ^+ photons. If the light is turned off, the ground states will slowly repopulate (via collisions or other factors) to their equilibrium populations.

What optical pumping does is manipulate the populations of the ground-state atoms in the Rb vapor cell. With no optical pumping, the different ground-state Zeeman levels are all populated equally (in a statistical sense). With optical pumping, more atoms are in the maximum m_F state, where they absorb less incident light. Thus the amount of light hitting the photodiode in Figure 6 can be used to measure the degree of optical pumping that is present.

If you are having trouble absorbing all this, that's because the optical-pumping phenomenon involves a lot of physical concepts all mixed together. In your theory classes like Ph125, you isolate each new concept and examine it in isolation. In the real world, stuff is all happening at once. If you are puzzled, ask questions. We will try to answer as best we can. In the lab, comparing theory and experiments is often an excellent way to solidify one's physical understanding, so….

Laboratory Exercises

This section of the handout begins with a quick step-by-step guide to the set-up process, and many aspects of the hardware have been pre-built and pre-assembled. Once you have a first signal on the oscilloscope, we will come back to talking about the physics and the hardware in detail.

Begin by uncovering the Optical Pumping (OP) apparatus so you can have a good look at the optics. The instrument can remain uncovered during operation, but keeping air currents off the heated elements tends to yield better data. Please replace the cloth cover when you leave the lab. Turn the controller on (the power switch is in the back, just to the left of the power cord) and note that the *Cell Heater/Controller* shows you the temperature of the Rb vapor cell in degrees C. If you see a small illuminated "1" on this controller, this means the cell is heating up, and you don't want that now. If you see the "1", change the set point of the controller to a temperature below 20 C. Instructions for doing this are on top of the chassis. If no illuminated "1" is present, then continue to the next step.

You will also see a red *Error* light on the controller; this part of the apparatus is defective, so you can ignore this error indicator. You can also ignore the entire *Detector Amplifier* section of the OP chassis; we replaced this with a better detector/amplifier system.

A quick note on eye safety. The Rb lamp produces a light intensity of about 100 μW/cm^2 at a distance of about 10 cm from the lamp. Even if you put an eye quite close to the lamp, you would only get about 10 μW hitting your retina. For comparison, staring at the Sun sends about 1 mW to your retina. Thus, although the light from the Rb lamp is effectively invisible, it is about 100x too dim to present any eye-safety issues.

While the Rb lamp is warming up (which takes a few minutes), this is a good opportunity to examine the various parts of the apparatus, sketched in Figure 7. The Rb lamp consists of a heated glass cell containing Rb vapor along with an inert buffer gas. An electrical discharge inside the lamp excites the Rb atoms into higher electronic states, from which they decay back down to the ground state… the same basic operation as a neon light. The Rb lamp emits light from many atomic transitions, but the brightest components are the D1 (795 nm) and D2 (780 nm) lines, which are a deep red color, just beyond the range of human vision.

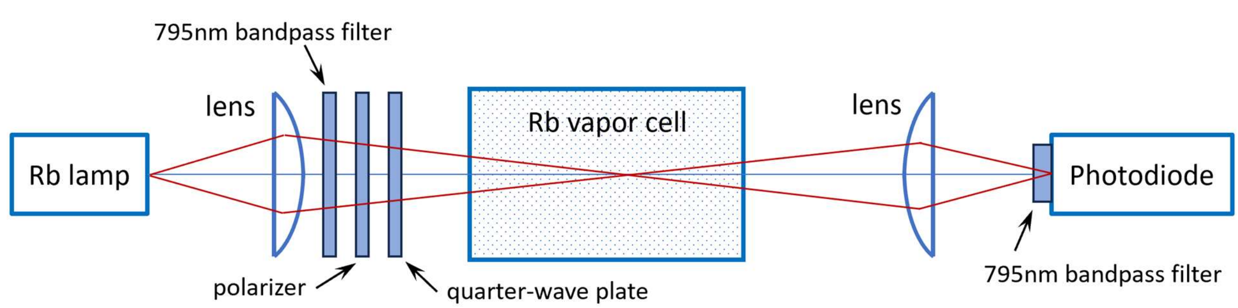

Figure 7. The end-to-end optical layout of the Optical Pumping apparatus. The optics have been preset and pre-aligned to maximize your optical-pumping signals, so you probably do not need to readjust any of these optical elements.

The lamp light goes through a collimating lens, then a 795-nm bandpass filter that transmits only light near the D1 line, then a linear polarizer, and then a quarter-wave plate. The polarizer and quarter-wave plate together produce circularly polarized that then passes through the main Rb vapor cell. The polarizer is set to zero degrees and the quarter-wave plate is set near 45 degrees, as these are the typical operating settings for producing σ^+ light.

The walls of the Rb vapor cell have a light coating of Rb metal on the inside surfaces, which is thermal equilibrium with Rb vapor in the cell. Heating the cell produces more vapor, and the buffer gas reduces the net motion of the Rb atoms. (Thermal velocities are about 1 km/second, so a free Rb atom would only spend about 10 μsec in the optically active central part of the cell. Collisions with the buffer gas increase this time.) After passing through the Rb cell, the light passes through a second focusing lens and a second 795-nm bandpass filter that blocks the room lights.

The optics have already been set up and aligned for optimal performance, so you should not need to adjust any of the optical elements at this time. Similarly, the OP controller and the other electronics equipment nearby to all the heavy lifting in terms of regulating the lamp, driving the various magnetic-field coils, and amplifying the photodiode signals. From an educational perspective, it is quite useful (and interesting!) to delve into these aspects of the apparatus, but there is a time and place for that – namely in the Electronics Track and the Optics Track in Ph77. In this Atomic Track, however, our focus is more on the underlying AMO physics, as that is already a significant challenge.

As described above, Figure 6 illustrates the essential components of the OP apparatus: the lamp produces a beam of 795-nm σ^+ light that passes through the Rb cell and is detected by a photodetector, the axial magnetic field establishes the Zeeman axis, and RF radiation is supplied to mix the Zeeman sub-levels of the Rb ground states. Figure 6 gives the conceptual picture for understanding the atomic physics, while Figure 7 sketches the actual hardware implementation.

Now that the instrument is nicely warmed up, your next task is to set up the connections shown in Figure 8 to observe the basic optical-pumping signal. Remember that our goal at this point is just to produce a first signal. Once a signal appears on the oscilloscope, it becomes much easier to talk about what the signal is, how it responds to changes in settings, etc. Don't worry if some of these steps are confusing now; they will make more sense once you have a first signal set up.

Note that many electrical connections are not shown in the figure, as these are (hopefully) already set up for you. Many of these parts of the controller provide access for debugging when the

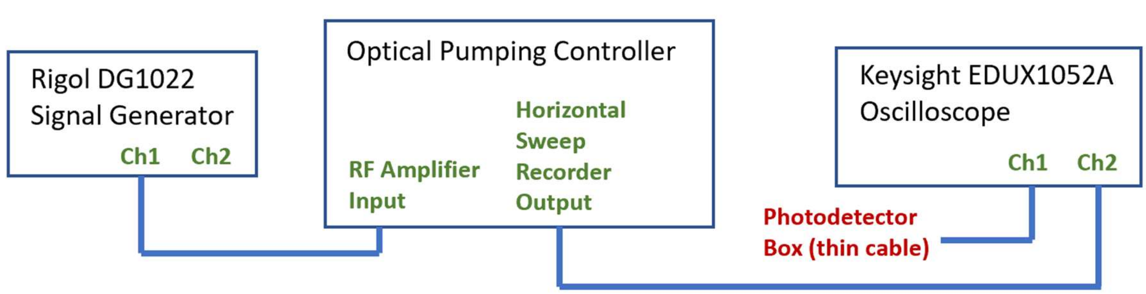

Figure 8. Use this electronics layout to observe the low-field optical-pumping signal. The photodetector box is at the back end of the optical pumping optics.

instrument needs repairs, plus one can perform some additional experiments not described in this handout. When things are working, however, these connections rarely change.

Once the connections shown in Figure 8 have been made, you will then need to reproduce several instrument settings to obtain the desired optical-pumping signal:

1) Set up the Horizontal Magnetic Field Sweep. On this panel, set the Time Constant to 1 second (the fastest sweep time), set the two switches to Start and Continuous, set the Range to 5.0 on the dial, and set the Start Field to zero. Set the RF Amplitude knob so it points vertically, at the center of its range.
2) To see the ch2 signal on the oscilloscope, use the ‘scope Trigger menu to trigger from ch2, with a negative (falling) slope, and set the trigger mode to Auto. Make sure ch2 is DC coupled and adjust the ‘scope to see a sawtooth signal. If you do not see a ramp signal on the oscilloscope, toggle the Start/Reset switch down & up to reset the system. What this ramp trace shows is the value of the axial B_z field as a function of time. Note, however, that there is an unknown voltage offset, so zero volts does not mean $B_z = 0$.
3) At this point the ramp signal will be wandering across the screen because the frequency is too slow to use Auto trigger mode. Switch to Normal triggering mode to produce a nice stable sawtooth signal like that shown in Figure 9. You may need to adjust the trigger level so it lies in the range of the sawtooth range. Throughout this lab, it is important to have the ‘scope triggering properly, so work with the ‘scope settings until you produce a stable sawtooth signal. Note that the Recorder Offset knob can be used to center the signal around zero volts; use this knob to eliminate any “clipping” distortion of the sawtooth signal. Make sure you display one full upward sweep of the ch2 signal, as you see in Figure 9.
4) Next adjust the ch1 settings to find the OP signal (which will only have a single dip at this point). This dip occurs when the axial magnetic field goes through $B_z = 0$, and we will talk about the physics of this below.
5) Next set up the signal generator to produce a 40 kHz sine-wave signal with an amplitude of 200 mVrms. Now you should see something that looks roughly like that in Figure 9. Adjust the Horizontal Range knob to place the center dip at the center of the ‘scope screen.

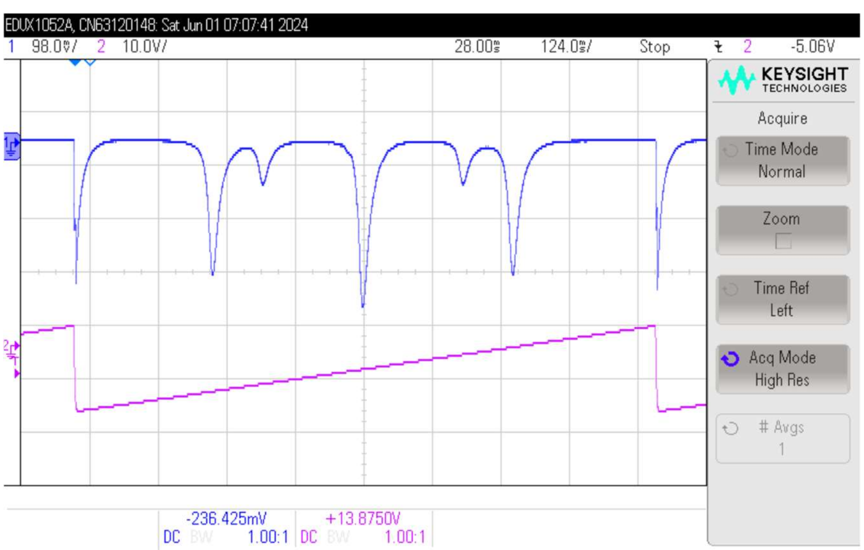

Figure 9. A typical oscilloscope screen once you have the ‘scope triggering well with the optical-pumping signal placed nicely on the screen. The bottom trace (red) shows the linear ramp of axial magnetic field, with B = 0 at the center of the screen. The top trace shows the photodiode signal. Note that abrupt B-field transitions affect the photodiode amplifier electronics, and this produces spurious dips at these transitions.

6) At this point, the central dip may not be as narrow as shown in Figure 9. A wide dip means that while $B_z = 0$, either B_x or B_y (or both) are not zero. B_y comes mostly from the vertical component of the Earth's magnetic field, and you can adjust the Vertical Magnetic Field knob to change B_y. This sends current through a coil that changes B_y. Try it. Similarly, B_x comes from the horizontal component of the Earth's magnetic field, and we have no knob to adjust that. Instead, you rotate the apparatus on the table so that the optical axis is perpendicular to the horizontal component of the Earth's field. Try it. Not surprisingly, the dip width is lowest when the optical axis points a bit east of due north).

Now that you have this signal displayed, let us pause and try to understand what's going on in detail. First of all, turn the RF off and on using the signal generator and you will see that four "RF dips" are clearly caused by the RF radiation illustrated in Figure 6. The large central dip (present with or without RF) is called the "B = 0" dip because it happens when the B_z field ramp goes through $B_z = 0$ (so the axial B_z field changes sign when it goes through the $B_z = 0$ point). And you can ignore the dips in the signal that happen when the B field jumps abruptly at the beginning and end of the sweep; these result from some kind of electronic pickup.

To understand the OP signal you have displayed on the 'scope, consider the simplified level diagrams shown in Figures 10 and 11. These are basically like the diagrams in Figures 2 and 3, except stripped down to the bare essentials for the case of ^{85}Rb. Figure 10 shows the basic optical pumping phenomenon, while Figure 11 shows why mixing the Zeeman levels using RF radiation reduces the signal seen by the photodiode.

As the B_z field goes through its ramp, the photodiode (PD) signal mostly stays at a constant high level (except at the dips, obviously). This high PD level establishes the signal in the presence of strong optical pumping, as described in Figure 10. [Note also that zero PD voltage does not refer to zero light level. The electronics sends the PD signal through a long-period high-pass filter that removes the DC component of the signal. In fact, the dips you see in Figure 9 are quite small compared to the large DC offset.]

The RF Dips

With the RF signal back on, consider the RF dips shown in Figure 9. These appear when the RF radiation drives transitions between the different Zeeman levels, as illustrated in Figure 11. Selection rules limit the transitions to $\Delta m = \pm 1$, so a single RF photon will only mix adjacent Zeeman levels. But many RF transitions will soon mix all the states, roughly equilibrating the level populations.

As described in Figure 11, the RF-induced transitions scramble the Zeeman levels and thus disrupt the optical-pumping process. This results in fewer optically pumped "transparent" atoms (compared to the no-RF situation shown in Figure 10), thus yielding more absorption that makes RF dips in the OP signal. The dips only occur when Equation (5) is satisfied, and the observed dips are for the two Rb isotopes (which have different g-values). The RF dips are symmetrically placed about $B_z = 0$ because optical pumping works for either sign of B_z. (Think about it.)

If this does not make sense, ask someone, or read through the above discussion again. Understanding the RF dips is central to understanding optical pumping.

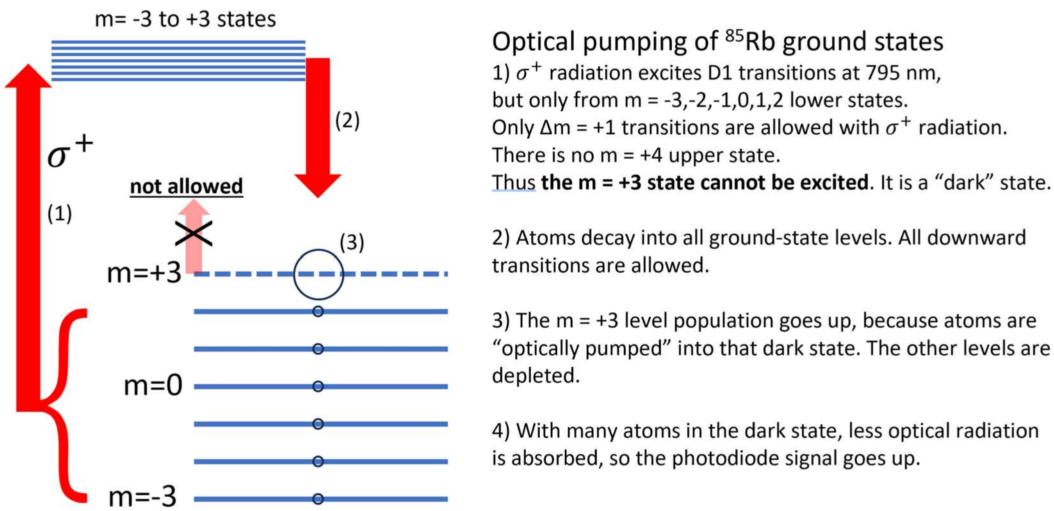

Figure 10. The essential optical-pumping phenomenon as applied to the Rb-85 ground states when there is no mixing of the different Zeeman levels. With many atoms in m = +3 ground state (which cannot absorb σ^+ photons), the photodiode signal is high.

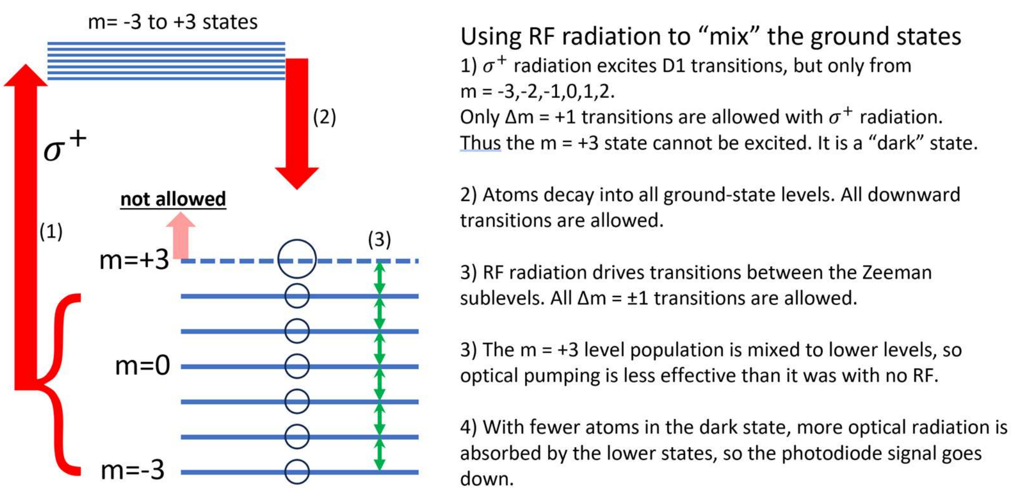

Figure 11. The optical-pumping phenomenon as applied to the Rb-85 ground states when RF radiation is used to mix the different Zeeman levels. With fewer atoms in the m = +3 state, the photodiode signal is low.

Exercise 3. You calculated the Zeeman splittings for both Rb isotopes in Exercise 1, and you know the RF frequency you are applying in the OP apparatus. Given this, what are the B-field values at the four RF dips shown in Figure 9, in Gauss?

The B=0 Dip

If you turn off the RF signal, then all you have left is the central dip, which happens when the horizontal B_z magnetic field goes through zero. In theoretically perfect world, having $B_z = 0$ would not change the optical-pumping process shown in Figure 10. The Zeeman levels are degenerate when

$B_z = 0$, but optical pumping would still work. In the real world, however, there are always some stray magnetic fields present, and this matters. Referring to Figure 10, optical pumping sends Rb atoms into the m = +3 state, and this maximum m_F value means that the electron spins are aligned along the optical axis. If we have a nonzero B_z, then these electrons precess around B_z, but this does nothing because the spins are aligned along B_z.

But consider what happens when $B_z = 0$ and we add a small $B_y \neq 0$ field. Now the tiny electron gyroscopes (possessing both a spin and magnet moment, both pointing in the same direction) will precess about B_y. And the precession is fast, with precession frequencies of order ~1MHz/Gauss. So, as soon as optical pumping aligns the atomic magnetic moments along the z direction, precession from stray transverse magnetic fields mixes the level populations almost immediately. This fast precession means that the dark-state (transparent) population is less than it is at nonzero B_z, reducing the amount of transmitted light. Thus, we have the "zero-field" dip.

In principle, you could eliminate the B_x and B_y fields completely, and people have tried this in carefully controlled experiments. And the $B_z = 0$ dip does go away in this ideal situation, as theory predicts. Alas, we cannot achieve $B_x = B_y = 0$ to see this happen in the Ph77 lab. But we can *increase* the transverse fields quite easily. Adjust the Vertical Magnetic Field knob and you will see how this affects the $B_z = 0$ dip. When you rotate the OP apparatus, that is like applying a small transverse horizontal field – namely that component of the Earth's magnetic field. You can eliminate this transverse field by pointing the OP apparatus toward the magnetic pole, which is just east of due north.

If you adjust the Vertical Magnetic Field knob, you can see that the depth of the B = 0 dip is roughly independent of the vertical B_y field. Try it. Why is that the case? Well, once you have scrambled the Zeeman levels, scrambling them more doesn't do much, so the dip depth only gets so deep.

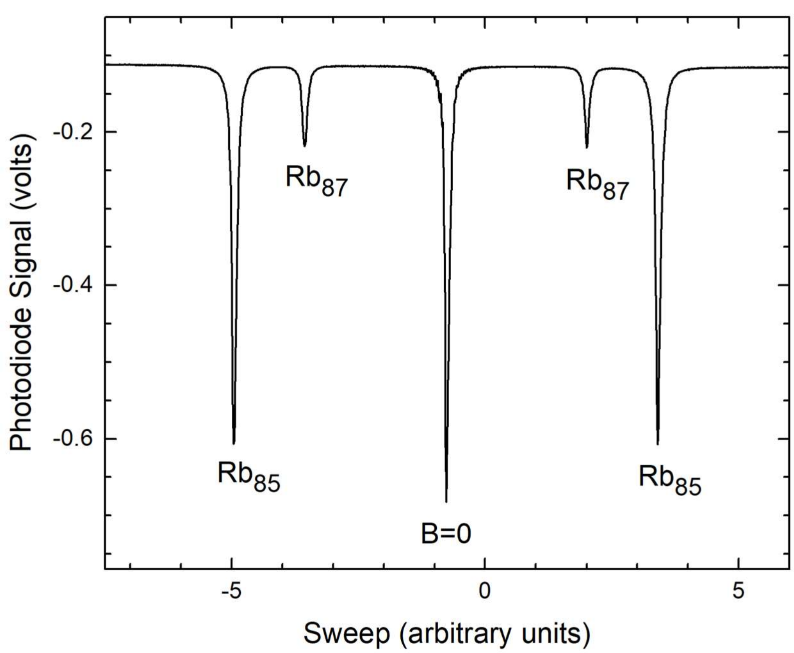

Figure 12. Saving the 'scope data to a .csv file can give you a cleaner plot than what you see on the 'scope screen, because the screen resolution is lower than what you get with the digital data. And the improved resolution allows more accurate measurements of the dip positions. To make the dips especially sharp, change the sweep time from 1 second to 2 seconds, or even 5 seconds.

Exercise 4. Starting with a trace like that in Figure 9, minimize the width of the $B_z = 0$ dip. Go back and forth between the B_x and B_y adjustments to find the global minimum of the central dip width. This is a slow process at one second per sweep, so take your time. Set the 'scope Acquire mode to High-Resolution to reduce the voltage noise (this mode smooths the data by averaging adjacent pixels). And remember you can press the Horizontal knob on the 'scope to toggle between coarse and fine adjustment. Save a .csv file and make a plot like that in Figure 12. Record your optimal Vertical Field knob setting for later reference.

Exercise 5. Using your digital data, measure the positions (along the sweep axis) of the B=0 dip and both sets of ^{85}Rb and ^{87}Rb dips. Do this with some care and estimate the uncertainties in your measurements. (There is typically no obvious formula or procedure for estimating uncertainties, so use common sense along with your understanding of the data. In this case you could do a nonlinear fit to the dips, but an eyeball estimate is adequate. Looking at the raw data numbers is useful for this.)

Because $g_F = 1/2$ for ^{87}Rb and $g_F = 1/3$ for ^{85}Rb, you expect that these dips should present a ratio of 1.5. Measure the ratios twice for the two sets of dips, and report both measurements in your e-notebook. Note that there may be nonlinearities and/or offsets in the B-field sweep, and these may yield ratios that are not exactly in agreement with theory.

Exercise 6. From your data, measure the width of the B = 0 dip in Gauss (using the RF dips to convert the 'scope time base to Gauss. What percentage of the Earth's field is this?

Next try changing the RF frequency to see the RF dips move. No surprises there. With the RF at 40kHz and 200mVrms, move the OP signal to the lower part of the 'scope screen and save a Reference trace on the 'scope. (This feature is buried in the 'scope menus. Go to Analyze/Features/R1, then Save/Clear.) Now offset the ch1 trace so you can see it along with R1 and change the RF frequency to 20kHz. Your screen should look something like that in Figure 13.

Now turn the RF amplitude up to 1Vrms and you will see the 20kHz dips broaden (focus on the outer Rb-85 dips, because these are the most prominent.) This happens because even slightly-off-resonant RF can mix the Zeeman levels if the amplitude is high enough. Again, not surprising.

If you turn the RF amplitude up higher, you may see additional dips appear (try it with 10kHz, 5Vrms). These happen because at high RF amplitudes the RF signal is no longer a pure sine wave, but includes higher harmonics created by electronic distortion in the RF amplifier. There is no new atomic physics here; just electronic distortion. This is a problem you often face in the experimental physics world; sometimes new signals mean new and interesting physics, sometimes not.

Exercise 7. Save a screenshot like that in Figure 13 for your e-notebook, just for the record.

Exercise 8. Go back to an RF frequency of 40 kHz and use the 'scope cursors to measure the depth of the Rb-85 dip as a function of RF amplitude. Cover a large range of amplitudes, including very low values when the dip is small. But stay below 2Vrms. Take plenty of data points where the dip

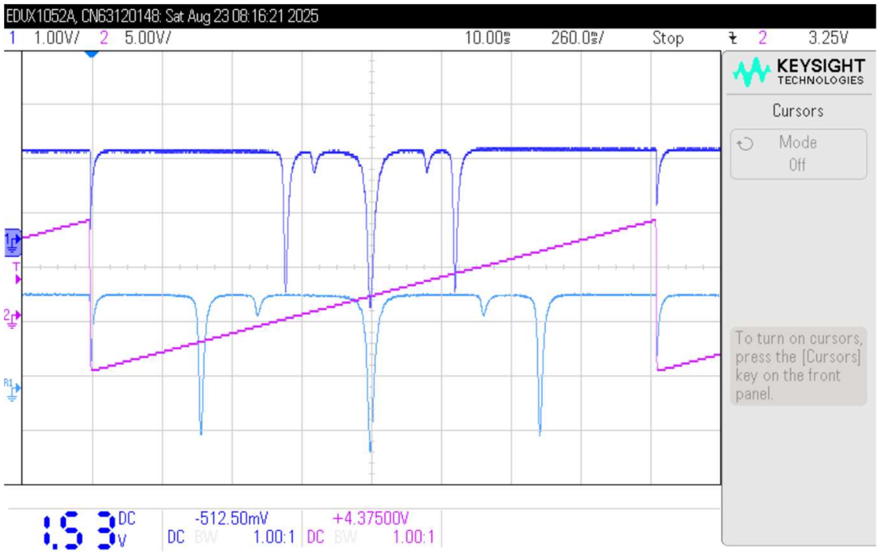

Figure 13. The top trace here shows the OP signal with the RF frequency at 20kHz. The lower Reference trace shows the same signal with the RF frequency at 40kHz.

depth is changing rapidly with RF amplitude, fewer where it is not. Display your data on a log-log plot. Theory says the dip depth should vary linearly with the RF power (power being proportional to the amplitude squared) until the dip depth saturates at high powers. Draw a chi-by-eye fit line through your data using the functional form $D = D_{max}\{1 - \exp[(-A/A_0)^2]\}$, where D is the dip depth and A is the RF amplitude.

Why this functional form? At low RF amplitude, the depth of the dip is roughly proportional to the RF transition probability between Zeeman levels, and these are *magnetic-dipole transitions*. In this case, theory tells us that the transition probability scales with the RF power, so the square of the RF amplitude. And you can verify that $D \sim A^2$ for low A in the above expression.

At high RF amplitudes, the RF mixes all the Zeeman states very quickly, which thwarts the optical-pumping process, thus reducing the amount of transmitted light and making a deep dip. Once the Zeeman levels are completely mixed, however, further mixing doesn't change things. Thus the depth of the dip saturates above some RF amplitude.

Note that the theory behind this is not precise, because the depth of the RF dips depends on how the light intensity varies along the axis of the Rb cell, all the minute details of the optical pumping mechanism, etc. When you work on QM theory, you can isolate a single atom in a known EM field and work that out in precise detail. In the lab, one often has a lot of processes happening in concert, and the best one can do is make imperfect models of what is going on.

Rabi Oscillations

You next task is to have a quick look at what happens to the optical-pumping signal when the RF signal is abruptly turned off and on. This exercise requires that you apply a 40kHz RF signal like before, but not with a B-field sweep. This time you must set up a constant B-field so the RF resonates with the ^{85}Rb Zeeman splitting. Here is how you can set that up.

To begin, make sure the Rb cell temperature is still set to below 20 C (unchanged from before). Then reproduce the signal shown in Figure 9 once again, with a B-field sweep time of 1 second, an RF frequency of 40kHz, and an RF amplitude of 400 mVrms. Same as above; nothing new yet.

From this starting point, next turn up the Start Field until the first ^{85}Rb dip happens right at the beginning of the B-field sweep. This is typically with the Start Field dial at about 0.93. Then stop the B-field sweep by setting the B-field Sweep switch from Start to Reset. Now the B-field is no longer sweeping, and the ‘scope no longer has a signal to trigger on. So set the ‘scope to Acquire/Roll and the ‘scope trace will just be on continuously. And both traces are flat.

If you turn the Start Field dial back and forth quickly, and you will see the ^{85}Rb dip. By moving the dial, you are doing a manual B-field sweep. By watching the trace on the ‘scope, adjust the Start Field dial until you are sitting at the ^{85}Rb dip. Remember that the photodiode signal is going through a high-pass filter, so you have to create an AC signal to see where you sit in relation to the ^{85}Rb dip.

Once you are confident that you are sitting at the ^{85}Rb dip with a stationary B-field, set up the system using the circuit diagram shown in Figure 14. Leave the ch1 RF signal alone and set ch2 up on the signal generator to produce a 10Hz square wave with Vmin = 0 and Vmax = 3V. (If you press the Amplitude button on the signal generator, it will change from Amplitude/Offset to Vmax/Vmin, which is convenient here.) When RF Modulation input goes high, the RF applied magnetic fields are turned off. And when the modulation signal goes low, the RF fields are turned on.

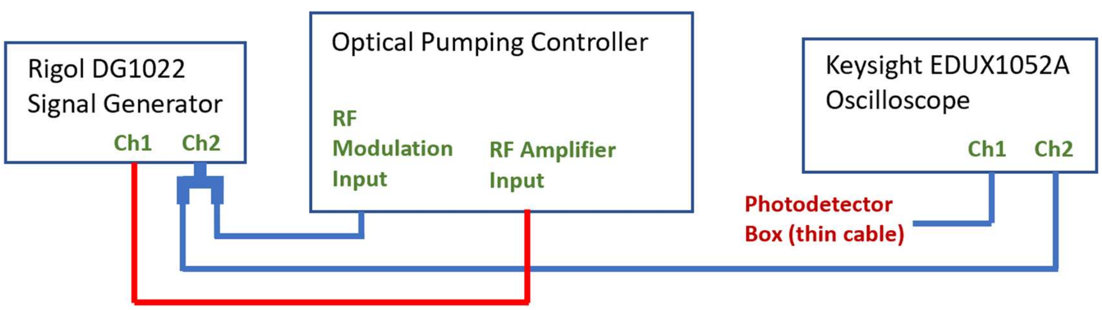

Figure 14. Use this electronic setup to observe transient optical-pumping signals when the RF fields are abruptly turned on and off.

This on/off modulation of the RF B-fields lets you look at the transient responses of the optical-pumping signal. Go back to Acquire/Normal to trigger the ‘scope, set the trigger level to 1V, and turn the ch2 scale to 1V/division. You should be able to adjust the ‘scope settings to get something like the screen in Figure 15. If you see the oscillations at all, you can adjust the Start Field to optimize their amplitude. The oscillations are greatest when the RF is tuned to the ^{85}Rb Zeeman splittings. If you need help, ask. If you really get lost, you may have to go back to Figure 9 and start over (not a problem; after you do this a few times and start to understand the instrument better, executing a reset can go quite quickly).

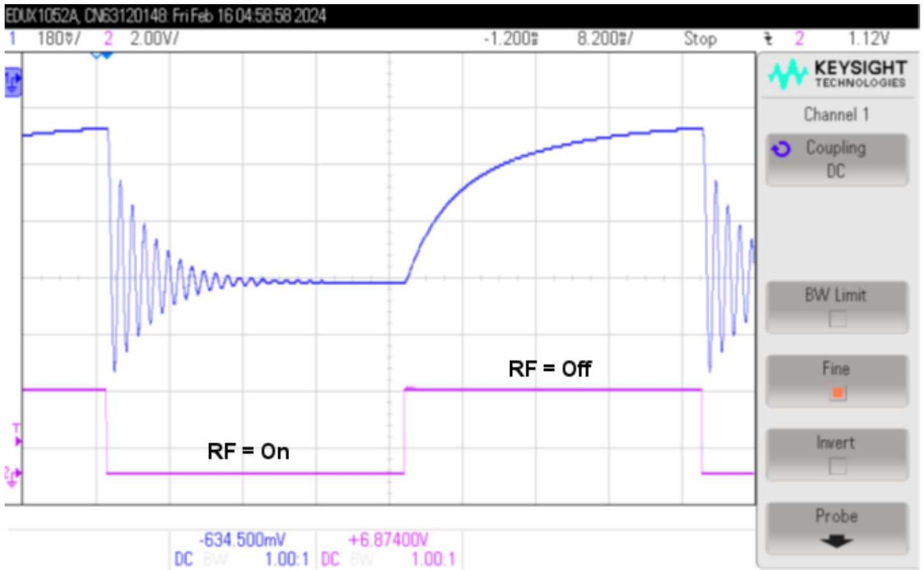

Figure 15. A close look at what happens to the optical-pumping signal (top trace) when the RF fields are turned on and off. Note that ch2 low here means that the RF is on.

Exercise 9. Save a screenshot that looks something like Figure 15 and add it to your e-notebook.

Once again, now that we have a signal on the ‘scope, let us pause and consider what is happening in Figure 15. Near the center of the screenshot, the RF turns abruptly off (ch2 goes high). With the RF suddenly off, the Rb atoms start to optically pump into the dark state, so the photodiode signal rises. Looking at the horizontal scale in Figure 15 (8.2 msec/division), you see that it takes about 10 msec for optical pumping to take place, giving a smooth exponential relaxation to the optical-pumping-on state (high signal).

At the other transition, the sudden turn-on of the RF signal produces a couple of effects. At timescales longer than the oscillation period, the RF thwarts the optical pumping mechanism (remember we are sitting right on the ^{85}Rb dip), so the OP signal goes down when the RF turns on. The overall relaxation timescale is again determined by the optical pumping process, so the long-term rise and fall times are about 10 msec.

Now consider what happens right before and after the RF switches on. When the RF is off, the OP signal is high, and this means that optical pumping has driven many atoms into the $m_F = F$ dark state. And, in turn, this means that many atoms are polarized along the z direction. In other words, when OP is active (RF = off), the atoms have a net dipole moment along the z axis.

When the RF signal turns on, the result is just like what you saw in the NMR experiment. The RF signal is just like the A pulse in the NMR apparatus, except that the RF goes on and stays on. So, like in NMR, the RF signal causes the atomic magnetic dipoles to rotate downward as they precess about B_z. So the z-component of the magnetic dipoles first rotates by 90 degrees (like a $\pi/2$ pulse in NMR), then it rotates further to 180 degrees (like a π pulse in NMR). As long as the RF remains on, the dipole moment will rotate around indefinitely, flipping back and forth from along B_z to along $-B_z$ and back.

And how does this affect the OP signal? Well, with no spin rotation (0 degrees), the dipoles are aligned along B_z and the OP signal is high. When the spins rotate down 180 degrees, they are then aligned along $-B_z$, and in this orientation they absorb a lot of σ^+ photons, yielding an especially low OP signal. In the $-B_z$ orientation, the atoms are in an "anti-dark" state, so they absorb even more than unpolarized atoms. In the anti-dark state, the OP signal drops below the unpolarized level, as can be seen in Figure 15.

And so it proceeds… the OP signal is high when the dipoles are aligned along B_z, and low when they are aligned along $-B_z$. And after about ten oscillations in Figure 15, the coherence is lost and the normal RF dip is restored.

One thing to notice is that the precession frequency of polarized Rb atoms in a magnetic field is equal to the Zeeman splitting frequency. The same was true for the protons in the NMR experiment, so the OP experiment and the NMR experiments share some of the same physical concepts. There is a deep truth in all this that relates quantum-mechanical Zeeman splittings to classical dipole precession frequencies in a magnetic field.

Of course, there is a lot going on here, so it takes a fair bit of time to get your head around all of it. But if you think about it for a while, this observation does a marvelous job of connecting the OP experiment to the NMR experiment. Both involve atomic spins, their accompanying magnetic moments, and precession around applied B fields. These themes permeate many aspects of AMO physics.

From a theory perspective, we examined this process classically in the NMR experiment, treating protons as small magnetic gyroscopes precessing around B_z. One can also look at the problem quantum-mechanically, and this is usually done for the simpler case of a two-level system. If you apply a resonant signal, the system will oscillate back and forth between the lower and upper states indefinitely, and these are called *Rabi oscillations*. The math is more difficult for multi-level systems, but it can be done. Of course, when you are working with a statistical ensemble of atoms, the two theoretical approaches give the same results.

Exercise 10. Theory (either quantum or classical) predicts that the oscillations observed in this signal should have a frequency that is roughly proportional to the RF amplitude (at least at low amplitudes). Use the 'scope cursors to measure the oscillation frequencies as a function of RF voltage and see how well this theory holds up.

Strong-field Zeeman splitting

Your next task is to observe RF Zeeman transitions in the nonlinear strong-field regime. Begin by setting the Rb cell temperature to 50C so it has time to warm up. The physics we will be exploring goes back to Figure 12, where you saw the ^{85}Rb and ^{87}Rb dips in the weak-field regime. Focusing on the ^{85}Rb dip at positive B-field, this dip was caused by all the available $\Delta m = \pm 1$ transitions, because these all occurred at essentially the same frequency given by Equation (5). This is the

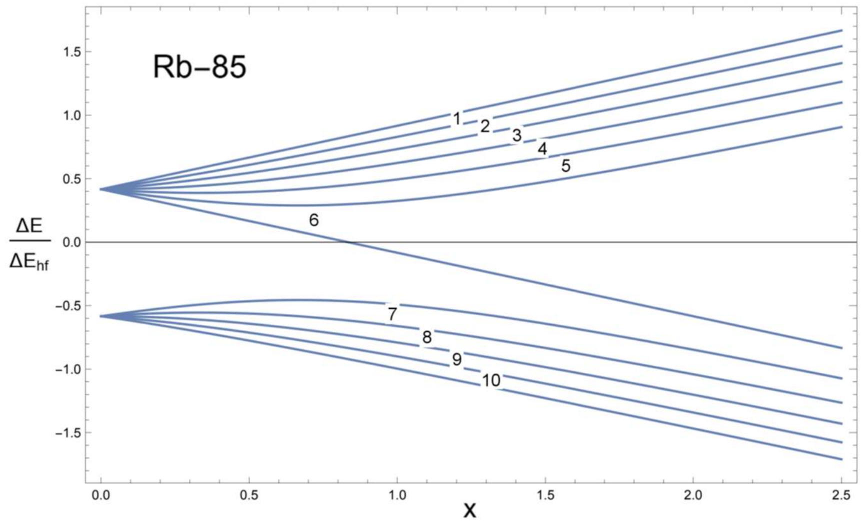

Figure 16. The Zeeman sublevels of Rb-85, calculated using the Breit-Rabi formula. The ten relevant Δm=1 transitions have been numbered. We only sample up to x ≈ 0.02 in this lab, but that already enough to see nonlinear effects.

situation at the far-left side of Figure 16. In this linear regime ($x < 0.01$), a single RF frequency will excite any of the $\Delta \mathrm{m} = \pm 1$ transitions.

As the B field increases, however, the various Zeeman levels no longer change linearly with x. And this means that the ten available $\Delta \mathrm{m} = \pm 1$ transitions are no longer excited by a single RF frequency f_{RF}. A close look at Figure 16 reveals that transition #1 has the lowest energy gap while transition #6 has the highest. And you can observe all ten of these transitions using optical pumping.

The best way to observe the strong-field Zeeman splitting is to apply a large, constant B_z field and then sweep the RF frequency. Above we swept the B-field while keeping f_{RF} constant, but now we are going to keep B constant while we sweep f_{RF}. Here are some settings to get you started, with the connection diagram in Figure 17:

1) As the Rb cell is stabilizing at 50C, produce the same OP signal you did previously, as shown in Figure 9. This is always the starting point in this lab.
2) Then turn off the B-field sweep by moving the Start/Reset switch to Reset. Set the Start Field knob to 2.6 on the dial, as this gives $B_z \approx 0$.

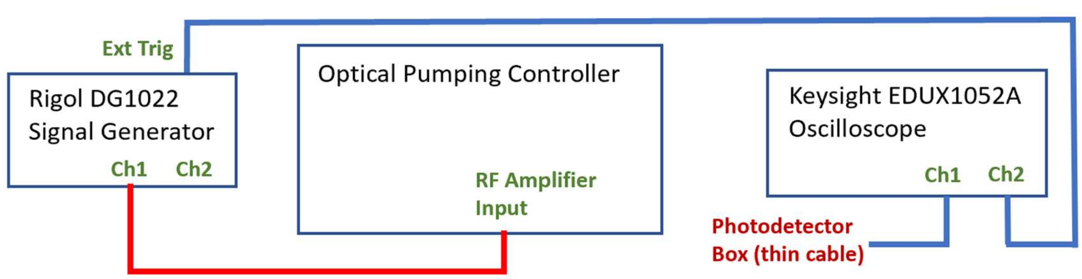

Figure 17. A partial connection diagram for observing the strong-field Zeeman splitting.

3) Next drive the main horizontal B-field coils using the external power supply found on the shelf above the OP controller. Make sure the red banana plug is plugged into the positive (red) terminal on the power supply and send 1.000A to the coils. This produces a relatively large B_z field, about 8 Gauss. Be sure to set the power supply so it produces constant current, not constant voltage. Why is this better?... because we want a stable B-field, and B scales with the coil current. (And the coil resistance will drift slightly with temperature.)
4) On the signal generator, press the Sweep button and use a Linear sweep of the RF frequency. Begin with Start = 3.5MHz and Stop = 4.5MHz, and use a sweep Time = 1 second. Set up a sine-wave signal with an amplitude of 100 mVrms and turn the signal on.
5) Again in the Sweep menu, select Trigger/Trigout/TriggerUp. This will produce a triggering signal at the Ext Trigger port on the back of the signal generator. Send this signal to ch2 on the ‘scope. Set the ‘scope trigger to Normal mode and trigger on ch2, with the trigger level at about 2V. Adjust things so you see one complete square-wave signal on the ‘scope, as shown in Figure 18 (only ch2 will look like the figure at this point). Excellent; now you have a swept-frequency RF signal going to the RF coils, and the ch2 signal shows you where the Start and Stop frequencies occur: 3.5 MHz on the left and 4.5 MHz on the right. Make sure you see a complete sweep on the ‘scope, stably triggered, with both the RFstart and RFstop transitions as shown in Figure 18. If necessary, change the trigger up/down setting so your screen looks just like that in the figure, with the trigger flag on the left side of the screen (Acquire/Time Ref/Left).
6) The RF dips will be small, and it takes maybe 10 minutes for the cell to stabilize.

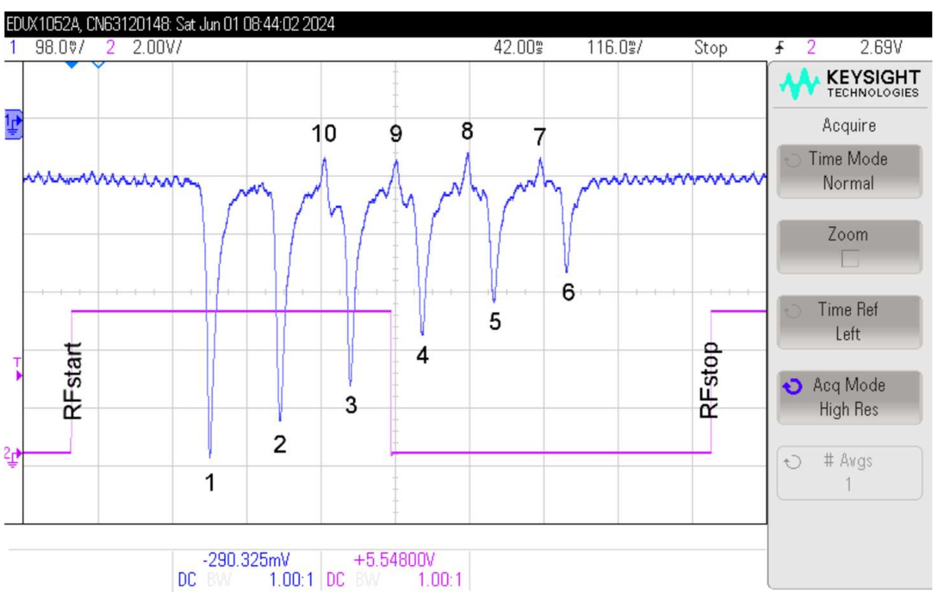

Figure 18. The Rb-85 OP signal during a swept RF drive signal, with a total sweep here of 100kHz. The linear frequency sweep starts at the first downward transition in ch2, and it ends at the second downward transition. The ch1 OP signal should take up more than half of the RF sweep and be centered in the screen. The Zeeman dips are labeled in accordance with the diagram in Figure 16.

7) In the Sweep menu, press the Start button a few times to toggle between Start/Stop frequencies and Center/Sweep. The latter is usually easier to use. Change the RF sweep settings to zoom in on the ^{85}Rb dips, giving a screen that looks something like Figure 18.

Exercise 11. Adjust your settings until you get a screen that looks quite similar to Figure 18. You should be able to see all ten transitions, although 7-10 will be weak. Make sure you are using Acquire/High Res to improve the signal-to-noise ratio (SNR). Save a screenshot and add it to your e-notebook.

Once again, it is beneficial to pause at this point and consider what is happening here. Mostly you just increased B_z and then increased f_{RF} (from 40 kHz to about 4 MHz) to keep the ^{85}Rb dip on the screen. And you switched from sweeping the B field to sweeping the RF frequency instead. However, as mentioned above, the higher B-field (now constant) causes the Zeeman sublevels to shift according to the Breit-Rabi formula, and the available transitions are numbered in Figure 16 and Figure 18. As the RF frequency sweeps from RFstart to RFstop, you see ten peaks on the 'scope, now separated because we are in the nonlinear strong-field Zeeman regime. This can be confusing at first, so ask questions. Having a conversation is the best way to understand things.

Next consider the different depths of the large dips (#1 to #6 in Figure 18). Remember that optical pumping tends to send atoms to the $(F, m_F) = (3, +3)$ state, which is the dark state, thus increasing the OP signal level. Because RF transition #1 directly connects to the dark state, this transition produces the largest dip in the OP signal. If the dark state is overpopulated by optical pumping, then #1 transition is most effective at depopulating it.

Transitions 2-6 are progressively weaker because they are, in a sense, farther away from the dark state. And transitions 7-10 are confined to a completely different hyperfine manifold, so these have a much smaller effect on the OP signal.

You might be wondering why transitions 7-10 are not dips. Good question...hard to answer. If you change the cell temperature to 70C (don't do this now; it takes a long time to stabilize), these transitions also become small dips. At 50C, they are best described as small peaks sometimes followed by small dips. Developing a model of how these various transitions affect the OP signal is quite a challenging problem, so we will not delve into the question here. Instead, just focus on the 1-6 transitions for now.

Exercise 12. Try adjusting the RF amplitude to see how that affects the OP signal. The peaks are smaller when the RF amplitude is lower (makes sense), but when you get to about 300mVrms you will see two-photon transitions that couple states with Δm=2. If you think about how this works, you will see that the new two-photon dips must appear between the Δm=1 dips. For example, the first Δm=2 dip will be exactly halfway between peaks 1 and 2 in Figure 18. (Not making sense? Try sketching the energy levels. Or ask!) Take a nice screenshot showing the Δm=2 dips and add it to your e-notebook.

Exercise 13. To produce an especially clean signal, switch to a 2-second sweep and maybe average a few traces to improve the SNR. Set the RF amplitude as high as possible without adding any two-photon dips. When you have a nice screen like that shown in Figure 19, save a .csv file and plot the signal *as a function of RF frequency.* Note that you will need to know the RF start and stop frequencies (see Figure 18) to convert your 'scope data to RF frequency. So be sure to record those values, and make sure the full square-wave signal is on the 'scope, as you see in Figure 18. When you are sure you have a good plot, *please change the Rb cell temperature set point* to below 20C before you turn off the instrument.

Exercise 14. (Optional) Figure out what RF center frequency you need to view the ^{87}Rb dips (instead of ^{85}Rb). Go to this frequency, find the dips (increase the sweep range at first), and zoom in on the dips as you did above. Once again, adjust your settings until you get something that looks similar to Figure 19, and add it to your e-notebook. Does the number of dips meet your expectations?

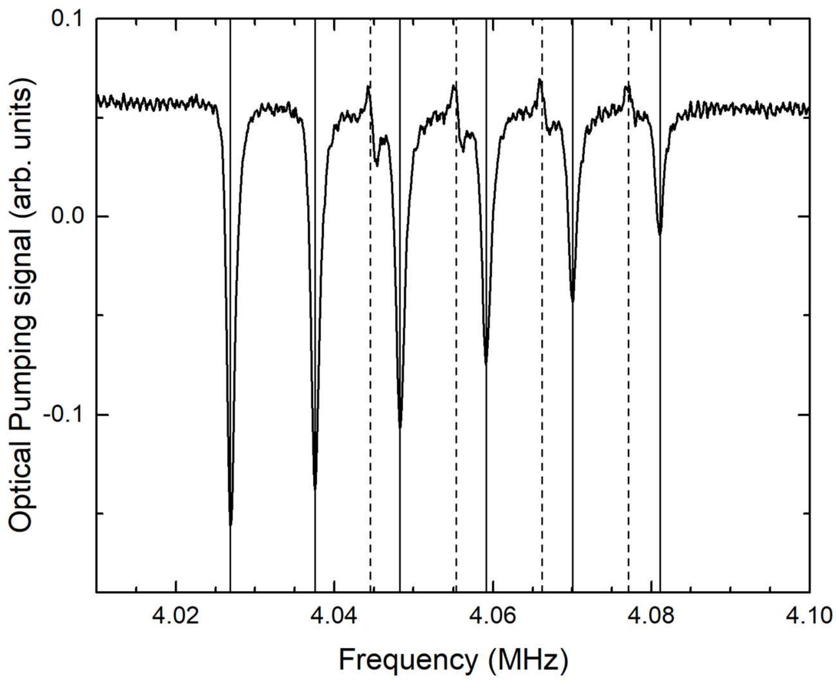

Figure 19. A high-resolution OP spectrum of the Rb-85 Zeeman dips near 4 MHz.

Analyzing the high-field Zeeman data

Now that you have explored the OP signal to some extent, your next task is to model the locations of the various OP dips. Start by measuring the frequencies of the first six dips in your version of Figure 19. These dips are clearly defined, so fitting algorithms should give you accurate dip positions. But an eyeball estimate is fine for now (but do try to be accurate).

There are many ways to go about building a model that reproduces these frequency measurements, and Figure 20 shows a handy "spreadsheet" approach that you may not have encountered for doing physics calculations. Referring to this spreadsheet, **F** and **mf** are the Zeeman quantum numbers, entered by hand. **B** is the magnetic field in Gauss, which is an adjustable input parameter in the model. Column **x** is calculated using Equation (7), and **Emf** is calculated using Equation (6), Column **dE** is the calculated difference of **Emf** values, with **dE** is converted to RF frequency. **Nt** refers to the peak numbering shown in Figure 16, entered by hand. And **measured** gives the measured dip frequencies, again entered by hand. Finally, **diff** lists the differences between the measured and calculated frequencies. If the model is a good one, then all the **diff** numbers should be small.

You should derive these expressions yourself, but the columns in Figure 20 were defined using
x = (gJ-gI)*(1.39962/3035.73)*col(B) with gJ = 2 and gI = -2.936e-4.
Emf = gI*uB*col(B)[1]*col(mf)+hfs*(col(F)-2.5)*sqrt(1 + (4/6)*col(mf)*col(x)[1] + col(x)[1]^2) with
uB = 1.39962, gI = = -2.9e-4, and hfs = 3035.73.

F(Y)	mf(Y)	B(Y)	x(Y)	Emf(Y)	dE(Y)	Nt(Y)	measured(Y)	diff(Y)
		Gauss		MHz	MHz		MHz	kHz
3	3	8.8136	8.1281E-03	1.5301915E+03	4.08112	1	4.08123	-0.11478
3	2			1.5261103E+03	4.09208	2	4.09205	0.02762
3	1			1.5220183E+03	4.10313	3	4.10311	0.01876
3	0			1.5179151E+03	4.11427	4	4.11428	-0.01016
3	-1			1.5138009E+03	4.12550	5	4.12548	0.02209
3	-2			1.5096754E+03	4.13683	6	4.13672	0.10675
3	-3			1.5055385E+03	3015.19942	--		--
2	-2			-1.5096609E+03	4.13275	7		--
2	-1			-1.5137936E+03	4.12151	8		--
2	0			-1.5179151E+03	4.11037	9		--
2	1			-1.5220255E+03	4.09932	10		--
2	2			-1.5261248E+03	--			--

Figure 20. A "spreadsheet" model for reproducing the frequencies of the Rb-85 OP dips. This computational method provides a straightforward structure for making step-by-step calculations, and it provides a quick-and-easy approach for analyzing simple data sets.

Once this spreadsheet is set up, you can then input different values of **B** to minimize the frequency differences. This quickly allows you to find a value that fits the data reasonably well, and you can watch how the frequencies change with **B**. Plot the **diff** values as a function of **measured** and adjust **B** to minimize the **diff** values as best you can. Of course, you do not have to use a spreadsheet to make these calculations; you can always write a short program to serve the same purpose. However, the spreadsheet method is quite intuitive for short problems like this, plus it displays the results nicely without having to write any code.

Exercise 15. Develop this model of your data and document the results in your e-notebook. If you are not a fan of spreadsheets, you are welcome to do the analysis using whatever technique you choose. But do make a table of numbers like that shown in Figure 20, and plot your best **diff** values as a function of **measured**. If you compare the model values for transitions 7-10, you should see that fit the data quite well (see the dotted lines in Figure 19), even though the 7-10 "dips" are a bit odd looking. (Why? Because optical pumping puts most of the Rb atoms in the highest Zeeman level in Figure 16. Mixing via the #1 transition is most effective at reducing the optical pumping process, so this dip is the deepest. The 7-10 transitions are far removed from the main optical pumping process, so these transitions produce only small signals.)

As a final thought, imagine for a moment that you are a physicist in the 1950s when optical pumping was first discovered. Atomic physics was not much developed at that time; Zeeman spectroscopy was crude, NMR was unknown, and of course lasers had not yet been invented. Nevertheless, with just this simple optical-pumping apparatus, a great many fascinating atomic-physics phenomena could now be observed and compared with detailed predictions from quantum mechanics. This was an exciting time in AMO physics! So it is no surprise that the Nobel Prize in Physics in 1966 was awarded to Alfred Kastler "for the discovery and development of optical methods for studying Hertzian resonances in atoms" (i.e., for the discovery and development of optical pumping techniques).

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