OPTICAL PUMPING

Objectives

1. To optically pump a sample of rubidium (Rb) atoms into a non-equilibrium state in which the atoms no longer absorb light and thus the sample becomes transparent.

2. To use optical pumping to measure atomic parameters of rubidium.

3. To use the optical pumping cell as a magnetometer to measure the local magnetic field.

Introduction

The "ground state" of an atom may have several hyperfine-structure levels that arise from magnetic interactions of the electrons with the nuclear magnetic moment. In addition, a magnetic field splits each hyperfine level into several Zeeman substates with different values of quantum number *m*. The energy differences between these levels are all very small in comparison to *kT* at room temperature. Consequently, all the hyperfine levels and all the magnetic substates are *equally populated* for a sample of atoms in thermal equilibrium.

By taking advantage of quantum mechanical selection rules, you are going to use polarized light to move atoms from some magnetic substates to others, creating a non-equilibrium population distribution. The process is called **optical pumping** because the light "pumps" atoms from one state to another, then keeps them there as long as the light remains on.

The version of optical pumping you'll be doing was developed in the 1950s. It has been used to make many precision tests of quantum mechanics and led to several Nobel prizes. More recently, optical pumping with lasers is an essential part of how optical traps work and how Bose-Einstein condensation is created in atomic gases – discoveries that have generated more Nobel prizes. It's safe to say that optical pumping is one of the most important experimental techniques of the last 50 years, and its importance for the controlled manipulation of atoms continues unabated.

References

An excellent description on optical pumping by Arnold Bloom appeared in Scientific American in the 1960s. It is on the web, and you should definitely read it. It may seem "old," but it meshes nicely with the simple version of optical pumping that you'll be doing. Reviewing atomic structure, fine structure, and hyperfine structure (with quantum numbers *L, S, J, I, F*) in your modern physics book is a good idea as well.

Acknowledgments

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The Rubidium Atomic Model

There are two stable isotopes of rubidium: ^{85}Rb ($\approx$70%) and ^{87}Rb ($\approx$30%). Figure 1 shows the energy level diagram of ^{85}Rb; Figure 2 shows ^{87}Rb. Rubidium, like sodium and the other alkali

metals, has one electron outside closed shells and thus acts in many ways rather like a hydrogen atom. For rubidium, the $n = 4$ shell is closed, so the valence electron has $n = 5$. The ground state is 5S and the first excited state is 5P. Selection rules allow transitions between these states, with the emission and absorption of photons.

This hydrogen-like understanding is only a rough approximation, and we have to look more closely at the energy-level structure to understand optical pumping. There are three key atomic interactions: spin-orbit coupling, electron-nuclear coupling, and the Zeeman effect.
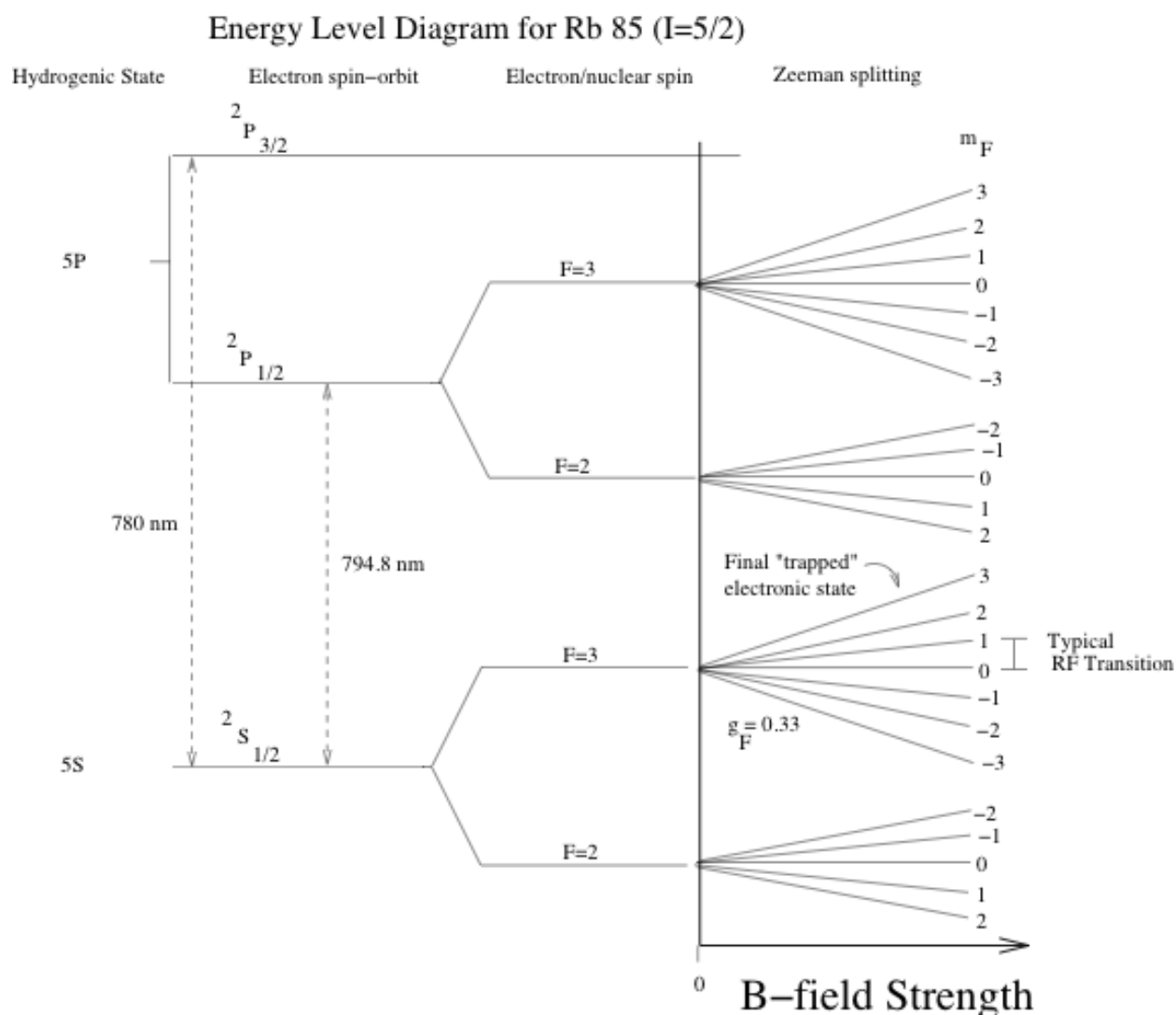
Energy Level Diagram for Rb 85 (I=5/2)

Figure 1: Structure of the ^{85}Rb isotope (not to scale).
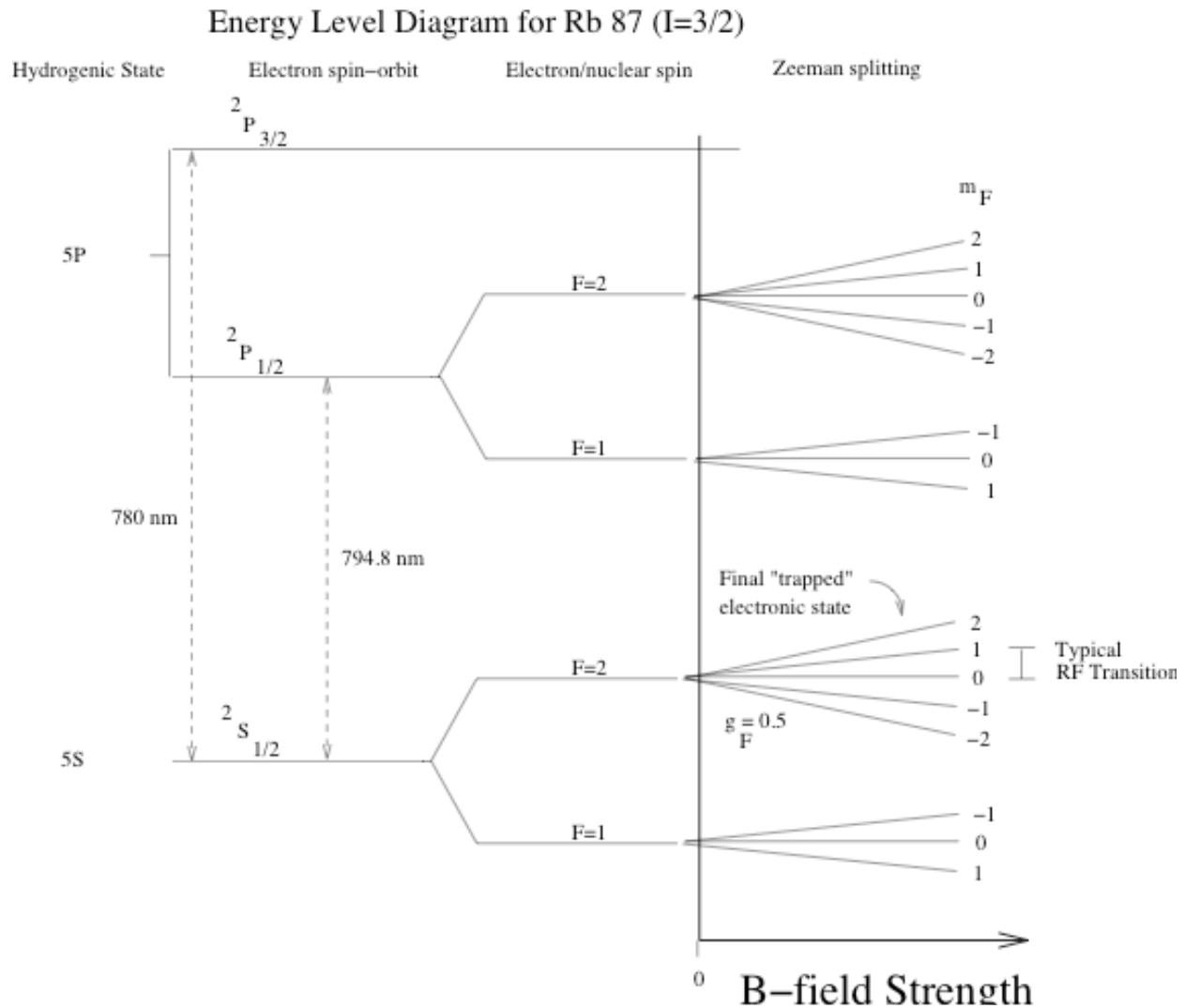
Energy Level Diagram for Rb 87 (I=3/2)

Figure 2: Structure of the ^{87}Rb isotope (not to scale).

Electron spin-orbit coupling: In quantum mechanics, interactions are called **couplings**. The orbital motion of the electrons creates a magnetic moment. (It's a little current loop.) The electron spin means that the electron has an inherent magnetic moment. These two magnetic moments interact, just like two neighboring bar magnets, and this interaction is called **spin-orbit coupling**. This interaction changes the atom's energy because two bar magnets are in a lower energy state if they are anti-aligned (one up and one down with the N pole of one facing the S pole of the other). Two aligned bar magnets have facing N poles (and facing S poles) and thus are in a higher energy state. The splitting of energy levels due to the interaction between orbital and spin magnetic moments is called **fine structure**.

The orbiting electrons have orbital angular momentum $\vec{L}$ with quantum number L. The electron spin is angular momentum $\vec{S}$ with quantum number $S = 1/2$. If the electron spin did not interact with the orbital magnetic moment, then both orbital and spin angular momentum would separately be conserved. But the interaction – the spin-orbit coupling – means that the

orbital magnetic moment puts a small torque on the electron spin while the spin magnetic moment puts a small torque on the orbital motion. Torques change angular momentum, so neither $\vec{L}$ nor $\vec{S}$ is conserved. However, their sum $\vec{J} = \vec{L} + \vec{S}$, which is the **total electron angular momentum**, *is* conserved because there is no external torque on the entire electron cloud (ignoring, for the moment, nuclear effects). Because angular momentum must be quantized, we introduce a new quantum number J for total electron angular momentum.

The 5S ground state has no orbital angular momentum ($L = 0$), so it has no spin-orbit interaction. The total electron angular momentum is just the spin: $J = S = 1/2$. In the second column of Figures 1 and 2 you can see that the ground state has been labeled $5S_{1/2}$, where we use the subscript to give the value of J, but it's energy hasn't changed. In the 5P state, the spin can be aligned with the orbital angular momentum to give a higher energy state $J = L + S = 3/2$, or anti-aligned to give a lower energy state $J = L - S = 1/2$. These two states are labeled $5P_{3/2}$ and $5P_{1/2}$, and the energy difference between them is the energy of the magnetic interaction inside the atom.

You probably recall the famous "sodium doublet," the yellow line in the sodium spectrum that, upon higher resolution, turns out to be two lines at 589 nm and 596 nm. The doublet arises from the spin-orbit interaction in the P state of sodium. Similarly, transitions are allowed in rubidium from the $5S_{1/2}$ ground state to both the 5P states, giving rise to what we might call the "rubidium doublet." However, the spin-orbit interaction increases in strength for heavier atoms, so the two wavelengths are much farther apart in rubidium than in sodium: 780 nm and 795 nm. These wavelengths are in the near infrared. Our experiment will use a filter to allow only light very close to 795 nm to pass through the rubidium cell, so our optical pumping will be based on the $5S_{1/2}$ to $5P_{1/2}$ transition.

Aside: At this level of detail of atomic structure, J is called a "good" quantum number while L and S are "approximate" quantum numbers. That is, the spin-orbit interaction is weak enough that we can continue to use L and S to label the states, but we have to keep in mind that the 5P state is not a "pure" state with exactly $L = 1$. If you've had PHYS 405, you know that a wave function can be written as a superposition of basis states. The $5P_{1/2}$ state is actually a superposition of *all* atomic states having $J = 1/2$ (the "good" quantum number). That is, the wave function is a superposition of $5S_{1/2}$, $5P_{1/2}$, $5D_{1/2}$, and so on. But because the spin-orbit interaction is weak, the $5P_{1/2}$ component is by far the largest, so we can still use P as an "approximate" quantum number.

Electron-nuclear coupling: It's now straightforward to take the next step. The total angular momentum of the electrons has a magnetic moment. Most nuclei also have a nuclear magnetic moment – the basis of the NMR experiment. Once again, these magnetic moments interact, and that adds new structure to the atomic energy levels. The splitting of energy levels due to coupling between the electron magnetic moment and the nuclear magnetic moment is called **hyperfine structure**. It is a *much* smaller effect than the fine structure, producing a splitting of spectral lines that is visible only with very large spectrometers having incredibly high resolution.

Nuclei with a magnetic moment also have nuclear angular momentum, called $\vec{I}$, with quantum number I. Because of the electron-nuclear coupling, neither the electron's $\vec{J}$ nor the nucleus' $\vec{I}$ is conserved, but their sum $\vec{F} = \vec{J} + \vec{I}$ is. $\vec{F}$ is the **total atomic angular**

momentum, with quantum number F. With nuclear couplings included, F is a "good" quantum number while J becomes only an approximate quantum number. However, the nuclear coupling is so much weaker than the spin-orbit coupling that it's quite valid to continue to think of J as a good quantum number.

The isotopes ^{85}Rb and ^{87}Rb have different nuclei with different nuclear spins. For ^{85}Rb, $I = 5/2$, and for ^{87}Rb, $I = 3/2$. When combined with the 1/2 unit of electron angular momentum of either the $5S_{1/2}$ or the $5P_{1/2}$ state, the alignment or anti-alignment of the electron and nuclear magnetic moments produces hyperfine states with $F = 2$ and 3 (for ^{85}Rb) and with $F = 1$ and 2 (for ^{87}Rb). Notice these states in the third column of Figures 1 and 2. The energy differences represent the very small magnetic interaction between the electrons and the nucleus. Also notice that the figure caption says "not to scale." The hyperfine structure is shown large so that we can see it, but it is *extremely small* in comparison to the fine-structure. If this figure were drawn to scale, we wouldn't even see the hyperfine structure.

Zeeman Splitting. Earlier you observed and measured the Zeeman shift in cadmium. The states involved had no net spin ($S = 0$), so only orbital angular momentum was involved. In that case, the energies of the Zeeman splitting are $E = m\mu_B B$, with m the magnetic quantum number, and the energy difference between adjacent states was

Rubidium is similar, but with the inclusion of electron and nuclear spins the levels split according to their _____ values, where _____ is the projection of F along the z-axis. It ranges from $-F$ to $+F$, as shown in Figures 1 and 2. Now the Zeeman effect is more complex because there are three magnetic moments (orbiting electrons, electron spin, and nuclear spin) interacting with the magnetic field, but for low magnetic fields the results of a quantum analysis are straightforward:

$$E = g_F m_F \mu_B B \tag{1}$$

where the g-factor, like the g-factors in the NMR experiment, tells us how strong the atoms' *net* magnetic moment – the combination of the three individual moments – is. Because two adjacent states have $\Delta m_F = 1$, their energy difference, which is what you'll measure, is

$$\Delta E_{\text{Zeeman}} = g_F \mu_B B \tag{2}$$

Equations (1) and (2) predict that the spacing increases linearly with magnetic field, which is a good approximation at low fields, but at higher fields the straight lines in Figures 1 and 2 start to curve. We'll restrict ourselves to low fields in this experiment, but an interesting senior project would be to study optical pumping at higher field strengths.

If L, and S are treated as "good" quantum numbers, then one can show that

$$g_F = g_J \frac{F(F+1) + J(J+1) - I(I+1)}{2F(F+1)}, \tag{3}$$

where

$$g_J = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}. \tag{4}$$

is called the Lande g-factor. You will be measuring g_F in this experiment for both isotopes. If your measured values agree with these predictions, then you'll have evidence that the spin-

orbit and electron-nuclear interactions in rubidium are small enough for L and S to be good quantum numbers. If your g_F differs, then you'll know that these interactions are strong and that our labeling of states with definitive values of L and S was only an approximation.

The interaction between Rb atoms and electromagnetic radiation

You know that an atom will absorb or emit a photon when the photon energy $E = hf$ equals the energy spacing between two states in an atom. But not all possible transitions occur. Not only must energy be conserved, but the atom must also obey quantum mechanical *selection rules*:

- Photons carry one unit of angular momentum, or $1\hbar$. Angular momentum must also be conserved when a photon excites an atom, so an excitation process requires $\Delta L = \pm 1$. We're looking at S ($L = 0$) to P ($L = 1$) transitions, so this selection rule is obeyed.

- *C*ircularly polarized* photons carry an additional selection rule: the m_F quantum number must change by $\Delta m_F = \pm 1$. It must change by +1 if the photon is right circularly polarized (σ^+), or by −1 if the photon is left circularly polarized (σ^-). *In this experiment, all light entering the rubidium cell is right circularly polarized, so photons can be absorbed only in transitions for which $\Delta m_F = +1$.* This selection rule is critical for optical pumping.

- When an atom emits a photon, jumping from the 5P level back to 5S, L decreases by 1, which is OK, and m_F may change by −1, 0, or 1. That is, emitted photons can be linearly or circularly polarized without restrictions.

What Optical Pumping Is All About

Pumping

At 50°C, the density of rubidium atoms is high enough that most 795 nm radiation is absorbed while passing the cell by the $5S_{1/2}$ to $5P_{1/2}$ transition. That is, the cell is very nearly opaque to 795 nm light. In general, all the hyperfine and Zeeman levels of the $5S_{1/2}$ ground state are equally populated. But suppose we could arrange it so that *all* the ^{85}Rb atoms were in *one* state, the $5S_{1/2}$, $F=3$, $m_F = +3$ state (see Figure 1). Further, suppose the incoming 795 light has been right circularly polarized. Given what you now know from the previous section about selection rules, how would the rubidium gas appear to the excitation light?

If you answered "completely transparent," you would be correct. Why? Remember the excitation light is right circularly polarized. Any absorption of these photons by rubidium atoms requires $\Delta m_F = +1$. But an atom in the $m_F = +3$ state cannot absorb a photon because the $5P_{1/2}$ level has no $m_F = +4$ state for it to enter! If *all* the atoms are in the $m_F = +3$ state, then no photon absorption can occur. The same scenario applies to the ^{87}Rb isotope if all the atoms are in $m_F = +2$, since no $m_F = +3$ state is available in the $5P_{1/2}$ level. For both isotopes, ground state atoms with the maximum possible value of m_F are unable to absorb 795 nm light if the light has been right circularly polarized.

So what? We noted earlier that, in thermal equilibrium, all the different states are equally populated. In general, atoms with other values of m_F can absorb light, which is why the sample is opaque to 795 nm light. To make the gas transparent, we would need to get *all* the atoms into the state of maximum m_F, a very non-equilibrium situation. But that's what optical pumping does.

Consider shining right circular polarized 795 nm light on a gas of rubidum atoms in thermal equilibrium. We'll focus on ^{85}Rb atoms, but the same thing happens for ^{87}Rb. Initially, all the states are equally populated. An atom with $m_F = -3$ can absorb a photon, but to do so it has to obey the $\Delta m_F = +1$ selection rule and go to $5P_{1/2}$, $F = 2$ or 3, $m_F = -2$. A short time after being excited, the atom is going to emit a photon and jump back to the ground state. The emitted photon can have $\Delta m_F = -1, 0, +1$, so the atom can drop back to a state with $m_F = -3, -2$, or -1. Because not all atoms return to the $m_F = -3$ state, where they started, there's been a net "upward" transfer of atoms to states with higher m_F. **This is the essence of optical pumping.**

Now continue this absorption/re-emission process over and over. During each up-down cycle, an atom can increase its value of m_F, but it can never decrease m_F. **Make sure you understand this, because it's the key idea.** It's like a ratchet that can turn one way but not the other. After many cycles, the entire population has been "pumped" into the state of maximum m_F, and there it's "trapped" because the selection rules now prevent any further absorption of photons. **This is what optical pumping is all about: trapping the atomic population in a non-equilibrium state where is it restricted from further photon excitation by selection rules.** And once all the atoms are in the state of maximum m_F, the atomic gas – which is no longer absorbing photons – becomes transparent. You'll measure how long the pumping process takes, but it's typically 10–20 ms.

De-pumping

Suppose you have an optically pumped sample. The sample is transparent to right circularly polarized 795 nm radiation, so a photo-detector behind the gas has a maximum signal. Now suppose you do something to the system that moves atoms into states with lower values of m_F. That is, you force atoms to "leak" out of their $m_F = m_{F\text{max}}$ states. What would happen?

The photo-detector signal would abruptly drop, because you will have created a whole set of atoms that do not have $m_F = m_{F\text{max}}$. These atoms are available to absorb light, so the amount of light passing through the sample decreases. We say that you have **de-pumped** the sample.

Although there are various ways to de-pump the sample, in this experiment we are going to do so using radio-frequency (RF) photons to cause transitions between neighboring Zeeman states. If you look at Figures 1 and 2, you'll see transitions between neighboring Zeeman states ($\Delta m_F = \pm 1$) labeled as "typical RF transitions." At the magnetic fields you'll be using, these level spacing correspond to frequencies of roughly 100 kHz, which are easily generated. After you've pumped all the atoms to the state of maximum m_F, and the gas has become transparent, turning on the RF at the correct frequency will drive some atoms back to the $m_{F\text{max}} - 1$ state, where they will start absorbing photons. The loss of photo-detector signal will be the indication that the applied RF is in resonance with the atomic transition. Accurate measurements of the transition frequencies at various magnetic fields will allow you to measure g_F for both isotopes of rubidium.

The Apparatus

There are two core components of the apparatus: the wooden **control panel** with all of the knobs on it, and the stand-alone **pumping unit,** with multiple pairs of Helmholtz coils.

Pumping Unit

The pumping unit consists of an optical rail containing various optical components, four sets of Helmholtz coils, a rubidium lamp, a glass cell containing rubidium atoms, and a sensitive photodiode (light intensity detector). Remove the black drape to take look at everything and make any notes/sketches you need for your report.

Optical rail

It's easiest to understand the pumping unit by traversing along the optical rail from one end to another. Both ends of the rail have blue metal boxes. Start at the end with the larger of the two boxes. This is a rubidium lamp that emits light when a high-frequency field is applied to it. This is automatic and happens when you turn the control panel on. All the spectral lines of rubidium are emitted, but the 5S–5P transitions at 780 nm and 795 nm are most intense. These are not visible wavelengths, so the lamp looks dim to your eye even though it is actually very bright.

In front is a large $f = 50$ mm lens used to collect light from the lamp and form a parallel beam through the gas cell. The lens is followed by an interference filter that transmits only the 795 nm light (so in this experiment, you will only be using the 795 nm light). Next, there is a polarizer that converts the unpolarized light from the lamp into linearly polarized light. Lastly, there's a quarter wave plate that converts the linearly polarized light into right circularly polarized light.

Skipping the volume enclosed by the Helmholtz coils for a moment, there's another $f = 50$ mm converging lens to collect light passing through the system and focus it onto the detector. The smaller blue box on this end of the optical rail is an amplified photo-detector. It outputs a voltage proportional to the incident light intensity.

All of this should be set up, adjusted, and ready to go. If you have any reason to think something along the rail is not correct, please inform your instructor rather than trying to fix it yourself.

Helmholtz coil volume

Examine the Helmholtz coils, and the volume straddled by them. As you probably know (and will test in the ESR experiment), a Helmholtz coil-pair can create a uniform magnetic field in a volume near the center of the coils. In this apparatus, there are four Helmholtz coil pairs. Be sure to identify them all.

1. **Horizontal Magnetic Field Coils.** The horizontal magnetic field coils have an axis parallel to the optical rail and are connected to the `Horizontal Field` connector on the control panel. Current is provided by a DC current supply, controlled by the `Horizontal Magnetic Field` knob on the control panel. (**Go ahead and locate these on the control panel.**) These coils/field are not to be confused with the `Horizontal Magnetic Field Sweep` (see below). Data: Radius $R = 15.8$ cm, $N = 154$ turns.

2. **Horizontal Magnetic Field Sweep Coils.** Independently wrapped on top of the Horizontal field windings (using the same supports) are additional windings connected to the `Horizontal Magnetic Field Sweep` output on the control panel. The `Start Field` and `Range` knobs (**find these!**) allow you to set an initial field B and a range ΔB, over which you want to sweep. The horizontal sweep field then starts at B and sweeps to $B+\Delta B$ in a time set by the `Time` knob. Data: $R = 16.3$ cm, $N = 11$ turns.

3. **Vertical Magnetic Field Coils.** These coils create a vertical magnetic field. Their current is controlled via the `Vertical Magnetic Field` knob. Data: $R = 11.7$ cm, $N = 20$ turns.

4. **RF Magnetic Field Coil.** The cylindrical Plexiglas tank in the center of the Helmholtz volume has two sets of reddish-colored windings on it. These are a Helmholtz pair used to generate an oscillating magnetic field at the RF frequency of 100 kHz to 5 MHz. These are connected to the `RF Amplifier Output` connector on the control panel. In the upper left corner of the panel is the `RF Amplifier Gain` knob. Data: $R = 3.22$ cm, $N = 3$ turns.

Note: For this experiment, the horizontal magnetic field coils are turned off. You'll control the horizontal field using only the horizontal magnetic field sweep coils

Rubidium cell

Buried in the very center of the Helmholtz volume (inside of the Plexiglas housing) is a small glass cell containing rubidium. Rubidium has a high vapor pressure and becomes an atomic gas at modest temperatures. The cell can be heated and maintained at a given temperature using the `Cell Heater/Controller`. You should have no need to change this.

Control Panel

The control panel is the table-top unit with all of the knobs on it. It controls all magnetic fields and measures the incoming signal from the light detector. The rightmost third of the control panel is dedicated to the light detector. The large analog meter shows you the signal from the detector (light intensity). The `Gain/Gain Multiplier` knobs are used to set the amplification factor on the detector amplifier. The `DC-Offset/Offset Fine` knobs add or subtract a DC voltage from the detector output voltage. The `Time Constant` knob is wired to an internal resistor of a low-pass filter. The smaller the time setting, the more bandwidth is available for amplification. The 10 ms setting seems adequate for most of this lab.

Procedure

The rubidium lamp and the rubidium cell heater require about 15 minutes to warm up. Turn on the control box *now*, as you continue reading through the procedures, so that they can be warming. The switch is on the *back* of the control panel. The cell temperature, shown on the large green LED display, should climb and hold steady at $50^{o}C$ before you begin your experiment.

Next, move all metal chairs or metal equipment *far* away from the apparatus. The experiment is *very* sensitive to distortions in the magnetic field from anything that is iron.

Where the data come from

The light detector measures how much 795 nm light from the rubidium lamp successfully passes through the rubidium cell. If the rubidium cell were completely empty, you'd get a maximum amount of light striking the detector. If light is absorbed in the cell, less light will strike the detector and the signal will decrease.

In this experiment, the only mechanism that can cause less light to hit the detector is absorption by rubidium atoms in the cell. Whenever you see a dip, or drop in the detector's signal, you may correctly conclude that rubidium atoms are absorbing light. Optical pumping is all about when rubidium atoms can or can't absorb 795 nm photons, as a function of the net magnetic field they are immersed in. So all of your raw data today is "light intensity striking the detector" vs. "net magnetic field the rubidium atoms experience."

Finding a zero magnetic field Environment

When you're ready to start, and everything is warmed up, turn off the room lights long enough to verify that you can see a dull glow coming from the rubidium lamp. Turn the room lights back on, which will generate a signal from the detector, and adjust the DC offset on the control panel so that the meter needle is near the middle. Block the detector with a piece of dark paper and verify that the meter changes. After verifying that the light source and detector are working, cover up the pumping unit with the black drape so that you can work with room lights on. Then re-adjust the DC offset to that the meter needle is near the middle.

At this point, you are optically pumping the atoms and the cell is transparent to 795 nm light! The reason is that the light you're sending through is right circularly polarized, so, as described earlier, it is pumping all the atoms into the state of maximum m_F. From there, selection rules prevent any addition absorption, so the cell becomes transparent. You're going to be looking for signal *decreases* when you do things (de-pumping) that destroy the optical pumping.

The results of your experiment are critically dependent on the net magnetic field in which the rubidium atoms are immersed. You must be able to carefully control the magnetic field in the cell that contains the rubidium atoms, but to do so you need to "tune out" the Earth's magnetic field and/or any residual magnetic fields that exists because of the local environment. In the northern hemisphere, the Earth's magnetic field points down and to the north. If you align the apparatus along a north-south axis, the Earth's field will have a vertical component and a horizontal component parallel to the optical rail, but no horizontal component perpendicular to the rail. So to create a "zero field environment," which is your reference point, you can use careful alignment to eliminate one component of the Earth's field, then use the vertical and horizontal Helmholtz coils to generate fields that are exactly equal and opposite to the Earth's field.

To begin, get a compass and verify that the optical rail points along the direction of the local magnetic field. (This may not be exactly north since any iron or steel in the building distorts the Earth's field.) Physically rotate the apparatus if you need to. You'll make finer alignment adjustments in a minute, after acquiring a signal.

Set the scope to XY mode (use the Main/Delayed button menu) with the channel 1 (or A) – the X channel – at 2 V/div and channel 2 (or B) – the Y channel – at 100 mV/div. Then:

- Connect the `Recorder Output` connector to Channel X and the `Detector Amplifier Output` to Channel Y. The `Recorder Output` is proportional to the horizontal magnetic field; it is calibrated so that 50 mV = 1 mG (0.1 μT).

- *Disconnect* the Hewlett Packward function generator is from the `RF-Input`.

- Turn the `Start Field` knob to zero (full CCW), the `Range` knob to maximum (full CW).

- Set the `Time` of the horizontal sweep to 1 second.

- Set the `Detector Gain` to 5 and the `Amplifier Time Constant` to 10 ms.

- Toggle the switch from `Start` to `Reset`, then back to `Start` again. The other toggle switch should be on `Continuous`. You should see the trace on the oscilloscope scan from left to right, once per second, as the horizontal magnetic field scans through its full range.

- Set the oscilloscope to "persistence" mode. (This is on the Display button menu.) Select persistence time of about 3 s.

- Adjust the oscilloscope (not the control panel) so the entire sweep range appears within the bounds of the display.

- Watch what happens on the scope as you change the `Start Field`, the `Range`, and the `Time`. Make sure you understand what's going on because these are the kinds of changes you'll need to make to do the experiment. Then return to zero start field, maximum range, and a 1 s time.

With these settings, the horizontal coils are creating a magnetic field that sweeps from zero to some maximum value. Some yet unknown value of this field will cancel the horizontal component of the Earth's magnetic field.

Next, set the `Vertical Magnetic Field` knob to 3.7, which corresponds to 0.37 A of DC current delivered to the vertical field Helmholtz coils. You should see the oscilloscope trace forming a dip, although at first the dip might be very gradual. This dip corresponds to the rubidium atoms existing in a zero magnetic field environment. Why?

As noted, you're already optically pumping the atoms, so the cell is transparent to 795 nm light. But optical pumping can't occur at $B = 0$ (zero field) because in zero field there's no distinction between the different magnetic substates (different m_F). Reducing the field to zero destroys the optical pumping, so atoms are again able to absorb photons and the amount of light passing through the cell decreases – hence the dip. (By telling you to set the `Vertical Magnetic Field` knob to 3.7, we've given you a setting that nearly cancels the Earth's vertical field. Without this information, you would have had to search through a wide range of vertical magnetic fields looking for the initial dip in the trace.) Once the sweep has passed through zero field, optical pumping resumes, the gas again becomes transparent, and the signal goes back up.

The oscilloscope trace shown in Figure 3 is what you're trying to achieve. To make the dip as deep and narrow as possible:

- First make small adjustments in the vertical magnetic field.

- Next, physically (and carefully) rotate the entire pumping unit to optimize the north-south orientation of the unit, ensuring the rubidium atoms experience only vertical and longitudinal

magnetic components due to the Earth's field. **This is the most critical adjustment, and it will take time and very tiny rotations to get the best dip.**

• As the dip gets narrower, increase the horizontal field start value, reduce the horizontal field sweep range, and change the scale on the scope X-axis to 1 V/div and eventually to 500 mV/div so that the dip has sufficient width to easily measure.

• Go back and forth between these three types of adjustments until the dip is as narrow as you can make it. Then change the sweep time to 5 s and try some more. (The 1 s sweep time is a little fast compared to the detector's time constant, which artificially broadens the dip and makes it somewhat asymmetrical.)
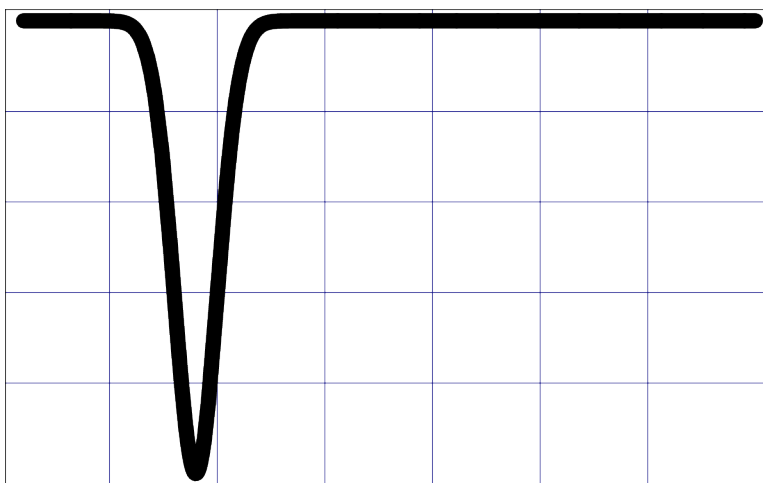

Figure 3: A sample oscilloscope trace illustrating the zero-field resonance.

Recall that the gain on the `Recorder Output` is 50 mV≈ 1 mG (0.1 µT). **You should be able to achieve a minimum width (FWHM) of about 3 mG for this zero field transition.** Note that you can see the needle on the analog meter deflect abruptly as the field passes through zero.

• When done, return the start field to zero, the range to maximum, the time to 1 s, and the scope to display the full sweep.

Running the Main Experiment

Initial observations

Once you have minimized the width of the zero-field transition, you are ready to begin optically pumping experiments.

• Connect <u>Low Output</u> terminal of the Hewlett-Packard function generator to the `RF Input` on the control panel. Make sure the function generator is set to sine waves, set the frequency to ≈100 KHz, then turn up the amplitude knob to ≈75% of maximum. Be sure the `Output` of the `RF Amplifier` is connected to the appropriate cable leading to the pumping apparatus.

• Also connect the function generator to the LG Sweep Function Generator input. Make sure that (1) the INT/EXT switch on the LG is set to EXT, and (2) the output of the LG (second row of BNC connectors) is NOT connected to the modulation input on the control panel. The

LG is now functioning as a frequency meter. Use it for frequency measurements; don't use the much less precise scale on the function generator.

- The oscilloscope should now look roughly like the trace shown in Figure 4. (Use the `Recorder Offset` to move the peaks as far left as possible, and adjust the scope if needed to get everything in one sweep.)

- Adjust the function generator amplitude and/or the RF amplifier gain to make the two new dips as strong as possible without broadening them. As you turn up the amplitude, starting from zero, you should see dips grow in amplitude. But there comes a point where additional RF starts making the dips broader (if you look carefully) but no larger. At this point you've *saturated* the transition. Back off on the RF amplitude to where the dips are just reaching maximum amplitude.

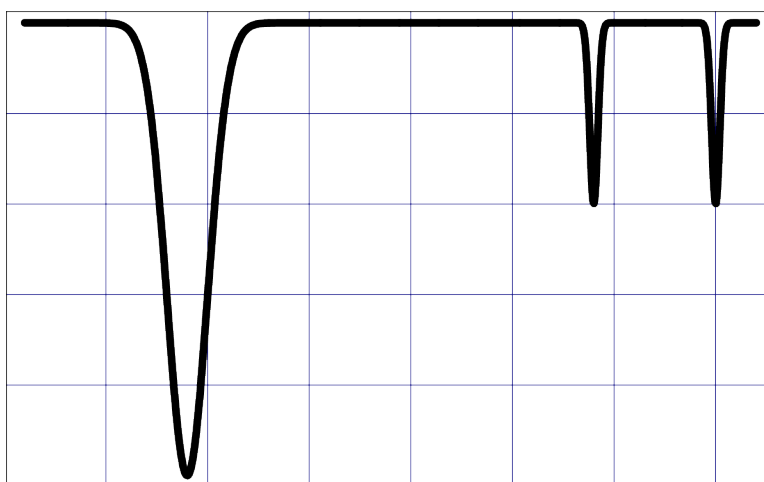You should obtain a data file of this oscilloscope trace for your lab report.

Figure 4: A sample oscilloscope trace illustrating the zero-field resonance (leftmost dip), and RF resonances due to ^{87}Rb (middle peak) and ^{85}Rb (rightmost peak)

You can still see the zero-field peak to the left, but now a pair of peaks on the right have become visible. The left peak of the pair is from ^{87}Rb and the right peak is from ^{85}Rb. Recall that a dip in the light level means that the rubidium atoms are suddenly absorbing light. As the magnetic field increases, it brings the Zeeman splitting ΔE_{Zeeman} of the ^{87}Rb atoms into resonance with the RF frequency. As discussed earlier, the RF "depumps" the trapped electronic population into lower m_F levels. Now the atoms can absorb light, and the signal decreases. The same thing happens for ^{87}Rb atoms at a somewhat higher field. Now you're beginning to manipulate the atoms in a very controlled way.

Explore and report on what happens as you change the RF frequency. Why?

Atomic structure of rubidium

The goal of this section is to measure g_F for both isotopes of rubidium and to compare your measured values to the theoretical values based on an assumption (an atomic model) that L and S are good quantum numbers. Equation 2, along with $E_{\text{photon}} = hf$, is the key relationship for making this measurement.

Experimentally, you need to make an accurate determination of the magnetic field at resonance. Here's how:

- Stop the `Horizontal Sweep Field` from sweeping, by changing the `Start/Reset` toggle switch to `Reset`. This means the horizontal magnetic field will stay set at a constant B controlled by the `Start Field` knob. Set the `Start Field` knob to zero.

- Connect a volt meter to the `Horizontal Sweep Field Monitor`. This is a 1.00 Ω precision resistor that the current flows through on its way to the horizontal field coils. Read the voltage, then use Ohm's law to deduce the current through the coils. As you turn up the `Start Field` knob, the voltage across this resistor should increase.

- Manually turn the `Start Field` knob while watching the scope. The scope trace will be the same as before, but you're now controlling the horizontal position on the trace. The signal should decrease dramatically as you cross the $B=0$ resonance (i.e., the current at which the horizontal Helmholtz coils cancel the Earth's horizontal field component). Optimize the knob setting to be at the absolute minimum and record the current I through the coils. The B-field at the center of Helmholtz coils of radius R, N turns, and current I can be computed from

$$(5)$$

  Data on the sweep-field coils was given earlier. Call the calculated B-field for the zero-field transition B_H This is the horizontal B-field the apparatus must produce to cancel the Earth's horizontal field component. (You'll later measure B_V, the vertical component.)

- Keep turning the knob, increasing the current. Eventually the scope trace and the needle on the meter will dip when you pass through the ^{87}Rb resonance. The dip is very sharp, so work carefully. When you find the dip, optimize the current to give minimum signal. Remember what is happening: at the B-field you now have set with the Helmholtz coils, RF photons, at the RF frequency f, are in resonance with the splitting between the m_F levels. **You are continually "depumping" the rubidium atoms and so they are continually absorbing light; the photo-detector signal drops.** Record the frequency, the current, and calculate the B-field.

- Keep increasing the current until you find the ^{85}Rb resonance. Make the same measurements.

Now devise and carry out an experimental procedure for determining g_F for both isotopes of rubidium.

Optical Pumping as a Magnetometer

Geophysicists use "rubidium magnetometers" to make precise measurements of the Earth's magnetic field. They work just like the experiment you're doing. You've already determined the horizontal component of the local magnetic field, B_H. What about the vertical field?

You've already adjusted the vertical field of the Helmholtz coils to match (and cancel) the vertical component of the local field. To determine its field, using Equation (5), you need to

known how much current is going through the coils. The `Vertical Magnetic Field` knob is approximately 10 times the actual current (i.e., a setting of 1.6 means ≈0.16 A of current), but you can get a better value by measuring the voltage across a pair of terminals on the <u>back</u> of the control panel. The current to the coils passes through a 1.00 Ω precision resistor, so you can use Ohm's law to deduce the current. Call the vertical component of the Earth's field B_V.

Determine the magnitude of the local field, in gauss, and the angle of the field below horizontal. This angle is called the **dip angle**. How does it compare with the Earth's field at the location of San Luis Obispo, a quantity you should be able to find on the internet? Our location on Earth is 35°17′ N, 120°40′ W. Because we're in a building with lots of steel, the local field will not be exactly the "true" value, but it won't be far off.

You can place a magnetic "dip meter" near your work area to directly measured value for the angle of the local magnetic field. And you might want to take the dip meter outside for comparison.

Transient Effects

"Transient" refers to time-dependent changes that do not persist.

Optical pumping time

Suppose the rubidium lamp was off and the rubidium gas was in complete thermal equilibrium. If you suddenly turned on the lamp, how long would it take the rubidium gas to reach the transparent, optically pumped state? This is the **optical pumping time**. It is analogous to the time needed to charge a capacitor.

Rather than turn the lamp off and on, which we can't do quickly, we'll turn the RF off and on while sitting on a resonance. When the RF comes on, de-pumping destroys the optical pumping. When the RF goes off, the optical pumping process starts. By monitoring the time dependence of the signal, you can watch the system evolve from opaque to transparent and measure the time constant for this process.

- Set the RF frequency to ≈150 kHz. Record the frequency, then disconnect the RF function generator from the LG Sweep Function Generator. (Keep it connected to the `RF Input`.)

- Temporarily unplug the cable that goes from the `RF Amplifier Output` to the Helmholtz coils. Connect this amplifier output to scope channel 2 (or B) and verify that you have a sine wave oscillation at the RF frequency. (You'll have to go out of XY mode to normal scope operation.) This is the RF that causes de-pumping when you're on resonance.

- Set the LG to INT and connect the TTL output to the `RF Modulation Input` on the left side of the control panel. A square-wave at this input causes the RF field to be turned off and on. Also connect the LG to scope channel 1 (or A). Set the frequency to ≈10 Hz, set the scope to trigger on channel 1, and verify on the scope that you're making TTL pulses (0 to roughly 3V) at ≈10 Hz.

- Now observe the RF amplifier signal (channel 2) on the scope. You should see that it's going off and on as the TTL signal goes up and down. (You can't see the individual oscillations on this time scale.) Note which TTL level (high or low) causes the RF to go OFF – you'll need

this information in a few minutes. Once you've verified that the RF is being modulated, switch the `RF Amplifier Output` from the scope back to the Helmholtz coils.

- Temporarily unplug the modulation signal (from the LG) from both the `RF Modulation Input` and the scope. Return to your earlier XY scope set up with the `Recorder Output` on Channel X and the `Detector Amplifier Output` on Channel Y. As you manually change the horizontal magnetic field, you should again see that you're passing across the zero-field resonance and, at higher fields, the resonances of the two isotopes. Choose the isotope giving the larger signal, and tune the horizontal-field current to be as close to on resonance as you can. You have to be on resonance for the RF modulation to have any effect.

- Once you're on resonance, plug the modulation signal (from the LG) back into the `RF Modulation Input` and into scope channel 1 (or A). Leave the detector signal on scope channel 2 (or B). Switch the scope back to time base mode, trigger on channel 1 (the TTL signal), and set it to trigger on the edge (low-to-high or high-to-low) that you earlier noted turns OFF the RF. Turning OFF the RF turns ON the optical pumping, which is what you want to see. You should now be seeing a signal rather like Figure 5, but probably not as clear. The reason is that you're probably not *exactly* on resonance. <u>Very slightly</u> tweak the horizontal magnetic field to maximize the signal amplitude. Maximum amplitude occurs at exact resonance.
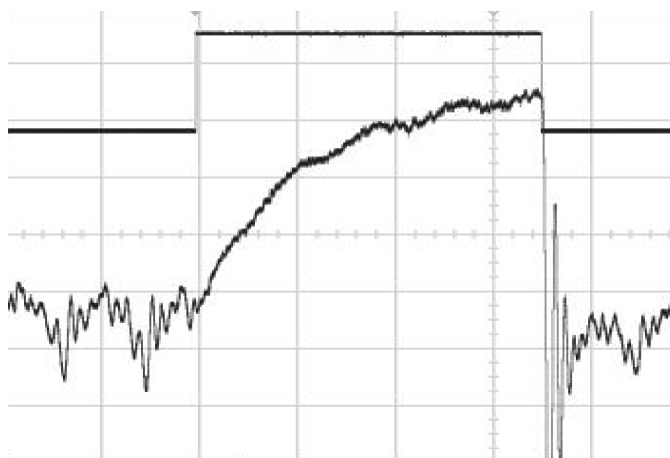

Figure 5: Photodiode response as a function of time when the RF
field is abruptly shut off by a square-wave modulation input.

- Further optimize the signal using the photodetector gain and the `Amplifier Time Constant`. You earlier had the time constant set to 10 ms. The larger the time constant, the better the noise reduction – but too large a time constant distorts the signal you want to measure. Choose the largest time constant that doesn't distort the signal. You'll probably want to observe the effect of changing the *modulation* frequency (<u>not</u> the RF frequency).

- Acquire and save a data file that you can later fit to an exponential equation to determine the time constant – this is the optical pumping time. (The equation that models the growing signal has exactly the same mathematical form as the equation for charging a capacitor.)

Rapid Field Switching

Look again carefully at Figure 5, in particular at the photodiode signal during the falling edge of the TTL pulse. Do you see the large oscillations that rapidly damp out? Zoom in on this feature until you have a display that resembles Figure 6. Another very small tweak of the horizontal field will probably be needed to optimize the oscillations.

Now change the amplitude of the RF field by slowly turning the `Gain` knob on the `RF Amplifier` (the upper, leftmost knob). Notice that *the oscillation period* of the signal changes. The oscillation period versus RF amplitude is what you now want to measure.
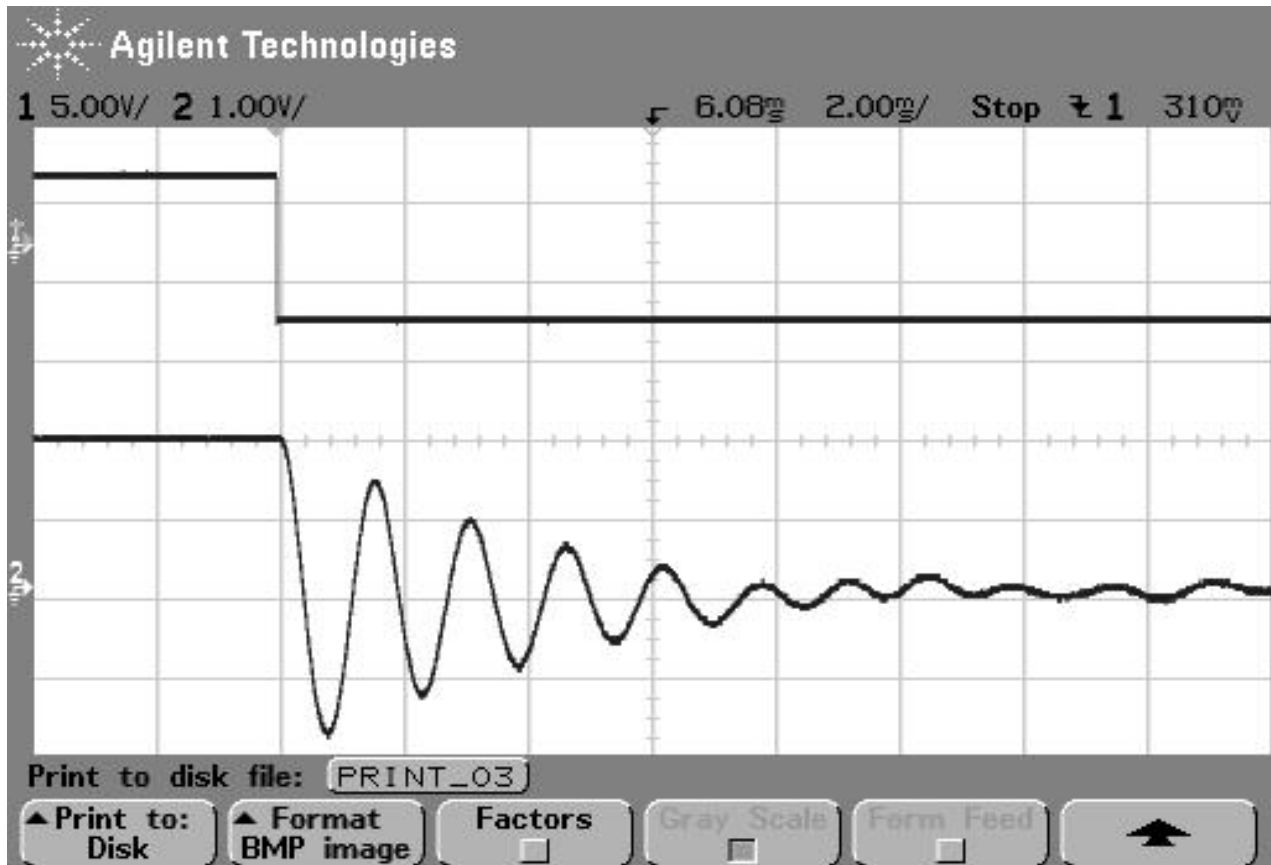

Figure 6: Photodiode response when the RF field is turned on.

The RF is too high a frequency to read the voltage with a voltmeter, but you can measure it on the scope. There's cable with a banana-plug-to-BNC adapter that comes out from underneath the pumping station. (If you're unsure, follow it to see that it comes from a blue box underneath the RF Helmholtz coils.) Plug this temporarily into scope channel 2 and measure the *amplitude* (not peak-to-peak) voltage V_{RF}. This voltage is across a 50 Ω resistor, so the current in the coils can be found from $I_{RF} = V_{RF}/50$. Once the current is known, the strength B_{RF} of the RF magnetic field can be found from Equation (5).

• Measure the oscillation period T for several different values of the RF field strength B_{RF}. (You'll have to keep switching scope channel 2 back and forth between the RF voltage and the photo-detector signal.)

- Repeat this for the other isotope. You'll first have to go back the XY mode so that you can change the horizontal field current to locate the other resonance. Then tweak the current to optimize the oscillations.
- For each isotope, plot the oscillation frequency $1/T$ versus B_{RF}. Although we given no reason, it turns out that the graphs should be straight lines. Further, theory predicts that ratio of the slopes should equal the ratio of the g_F factors that you measured earlier. Does it?

What explains this? Why does the signal oscillate when the RF is turned on? Why is there a dependence of the oscillation period on B_{RF}? How does the ratio of the g-factors come from the ratio of the slopes?

Why the oscillation? When the RF is off and gas is optically pumped, the gas as a whole is *polarized* with all the atoms in the $m_{F\max}$ state. That is, all the angular momenta have the same orientation. When the RF is suddenly turned on, with the RF on resonance, many transitions are made out of the $m_{F\max}$ state. This causes a sudden decrease in the transparency of the Rb gas, resulting in a drop in the photodiode signal, thus explaining the initial decrease in the signal as the RF is turn on.

Remember that the RF frequency is set to be in resonance with two adjacent m-states, $m_{F\max}$ and $m_{F\max} - 1$. The RF initially transfers population out of the abundantly populated $m_{F\max}$ state into the $m_{F\max} - 1$ state, leaving the gas with an abundance of atoms in the $m_{F\max} - 1$ state. Then, because the RF is in resonance, there is no reason why it can't drive the population back up to the $m_{F\max}$ state, which it does! Consequently, the gas starts becoming more transparent again, resulting in a rise of the photodiode signal again. As this the process repeat, the oscillation has begun!

There is a steady decrease in amplitude of the oscillation because not all population driven out of the original optically pumped state will make it back to the optically pumped state. Transitions also drive some of the atoms from the $m_{F\max} - 1$ state to the $m_{F\max} - 2$ state, and then to the $m_{F\max} - 3$ state, and so on. And because this is a gas and because the magnetic field is not perfectly uniform, motion of the gas atoms may move some into a slightly different magnetic field where they are no longer resonant with the RF.

Oscillation period and $\mathbf{B_{RF}}$: The details are complicated, but common sense suggests that a stronger RF magnetic field will be more effective than a weak RF magnetic field at driving the population from $m_{F\max}$ to $m_{F\max} - 1$ and then back to $m_{F\max}$. That is, increasing the RF magnetic field should increase the frequency of the population oscillations that you're observing. That the increase is linear, rather than, say, quadratic, is a detail best left to a more advanced theoretical analysis.

Why does the ratio of the slopes give the ratio of the g-factors? The g_F factor tells us the net magnetic moment of the atom – the combination of the orbital, spin, and nuclear magnetic moments. An atom with a larger magnetic moment interacts more strongly with the RF magnetic field and thus oscillates more quickly between the states. Again, the details are complicated, but this tells us that an atom with a larger g_F should have a larger slope than one with smaller g_F.

Report

This is a complex experiment. The Background section of your report should demonstrate that you understand the basic ideas of optical pumping, but you should summarize that understanding in a couple of pages. Please don't write a 10-page background section! Focus on the big picture of what's happening, not all the details.

The experimental section has asked you to do quite a number of things. Think carefully about how to report all this in a way that makes sense to your audience. This is an experiment that your assumed audience – upper division physics majors – is *not* familiar with, so you'll need a very logical, coherent presentation with quite a few explanations of what it's all about and what you're learning.

And There's More . . .

You've barely begun to explore the many measurements this apparatus can make. And if you take PHYS 342, you'll be doing some related laser spectroscopy experiments with rubidium. If you find these interesting, there are senior-project opportunities to use this apparatus to go further into optical pumping.