Optical Pumping of ^{85}Rb and ^{87}Rb

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Atoms both emit and absorb light at very specific wavelengths. These wavelengths are determined by the quantum mechanical energy levels in the atoms. In principle, the light emitted by one atom can be absorbed by another atom of the same species, so long as the absorbing atom is in the same state as the state as the final state of the emitting atom.

In practice, though, the situation is not so simple because the wavelengths involved are very precise, so a small perturbation in the absorbing atom, say, can shift the energy levels enough so that absorption is not possible. Very small magnetic fields, on the order of 1 Gauss, are enough to perturb the absorbing atom states so that absorption does not happen. Note that the Earth's magnetic field is on the order of 1 Gauss.

Another complication comes from the angular momentum carried by the light. When a magnetic field "splits" the atomic energy levels by their angular momentum quantum numbers, only some transitions will be possible. This is especially true if the light is "circularly polarized" in which case it only carries very specific angular momentum quantum numbers.

You will observe all of these phenomena in this experiment, using atoms of the alkali element rubidium. Ultimately, you will observe something called *Optical Pumping* because the circularly polarized light drives all the split atomic states into one state, due to the characteristics of absorption and emission of the atoms in the absorption cell.

This is a challenging experiment. There is a lot of physics to grasp, and the apparatus is quite involved. It will be very helpful if you review what you've learned in Quantum Mechanics regarding the hydrogen atom and perturbation theory. If you learned about alkali atoms, that's a bonus, but I will document those specifics for you.

1 Energy Levels of Rubidium Atoms

Rubidium is an example of an *alkali metal*, which make up the first column of the periodic table. These elements all have one electron outside a closed shell, so they share a lot of properties with the hydrogen atom. In the case of hydrogen, there is one electron in a strict Coulomb potential, and it turns out this leads to an additional quantum mechanical symmetry which in turn implies a high degree of degeneracy in the energy levels.

We'll review some of the basic properties of the energy levels of "one-electron" atoms before getting into the rubidium states in detail.

1.1 Review of Hydrogen Atom Energy Levels

You should be familiar with the hydrogen atom from your Quantum Mechanics courses. You should also be familiar with how the degeneracies are lifted by internal and external magnetic fields. If this physics is unfamiliar to you, we can discuss the physics together. You can also look in just about any Quantum Mechanics textbook, but it will often be covered in various different sections, including a discussion of perturbation theory. For example, you can check out Modern Quantum Mechanics, Third Edition, by Sakurai and Napolitano, in Sections 3.7.4, 4.1.4, and 5.3.

Very briefly, the energy levels of hydrogen (not including perturbations) are determined by a single quantum number $n = 1, 2, 3 \ldots$. Each of these levels are highly degenerate (that is, actually consisting of several different levels with different quantum numbers). The most glaring is that each n contains sub-levels of different orbital angular momenta $\ell = 0, 1, \ldots, n-1$. This degeneracy is associated with the additional symmetry of the Coulomb potential.

Each of those ℓ states have their own sub-levels according to the "magnetic" quantum number $m = -\ell, -\ell+1, \ldots, \ell$. On top of this, there is a degeneracy factor of 2 from the electron spin, and another factor of two from the proton spin. The degeneracies in orbital and electron spin angular momentum are lifted by the internal magnetic field of the "spin-orbit" interaction or by external magnetic fields (the "Zeeman effect.") The effect of the proton spin is very small, called "hyperfine splitting", because its magnetic moment is much smaller than that of the electron.

1.2 Characteristic Energy Levels of Alkali Atoms

Most of these degeneracies remain in the alkali atoms because of the spherical symmetry of the closed shell, but the strict dependence on n alone is gone. In particular, in this experiment, you will focus on the infrared transition between the lowest lying $\ell = 1 \to \ell = 0$ states of rubidium, both with $n = 5$.

The lowest lying energy levels are labeled by the value of n that is one larger than the levels in the closed shell. We have $n = 2$ for lithium, $n = 3$ for sodium, $n = 4$ for potassium, and $n = 5$ for rubidium. The two lowest lying levels correspond to $\ell = 0$ (an "S" state) and $\ell = 1$ ("P" state), and their energy difference corresponds roughly to light of a visible wavelength.

The spin-orbit interaction splits the $\ell = 1$ state into states with total angular quantum number $j = \ell \pm 1/2 = 1/2$ and $3/2$. This splitting is much smaller than the difference between the S and P states and therefore "splits" the wavelength of the emitted light into two

Table 1: Properties of the stable isotopes of rubidium

Isotope	Atomic Mass (amu)	Abundance	Spin	Mag Moment (μ_N)	Allowed values of f for $j = 1/2$	$j = 3/2$
^{85}Rb	84.911794	72.17%	5/2	+1.3530	2,3	1,2,3,4
^{87}Rb	86.909187	27.83%	3/2	+2.7512	1,2	0,1,2,3

closely spaced spectral lines. (You might be familiar[1] with the famous bright yellow "sodium D-lines" which are from the $3P_{1/2} \to 3S_{1/2}$ and $3P_{3/2} \to 3S_{1/2}$ transitions in sodium.)

On top of this is the hyperfine splitting from the (very weak) magnetic moment of the atomic nucleus, associated with a nuclear spin quantum number I. The resulting states are specified in terms of total angular momentum quantum number F. The degeneracy of the magnetic quantum numbers remains, however, but can be lifted by applying an external magnetic field which destroys the overall spherical symmetry of the atom.

1.3 Specifics for ^{85}Rb and ^{87}Rb

Let's now illustrate all this with the rubidium atom. Table 1 gives a little bit of data on this atom. (See `https://physics.nist.gov/PhysRefData/Handbook/atomic_number.htm` for more complete data.) It is important to note that natural rubidium comes in two isotopes, that is atoms with two different nuclei. (The different atomic masses mean that the $5P \to 5S$ transition energies will differ slightly because of the different reduced masses, but this effect is negligible for our purposes because the nuclei are very massive.)

Find detailed figures of the low lying energy levels at `https://steck.us/alkalidata/`, and a complete set of data, but see Figure 1 for a schematic. Note that the spin-orbit splitting is much smaller than the $5P - 5S$ excitation, and the hyperfine splitting (which differs for the two isotopes because of the different nuclear spins and magnetic moments) is much smaller than the spin-orbit splitting.

At this point, it is instructive to put in some numbers. The difference between energy levels are given in Figure 1 in energy units. However, these transitions correspond to the emission and absorption of electromagnetic radiation in the form of light or radio frequency (RF) energy. Therefore, it is useful to consider these energies in wavelength or frequency units.

You know that the energy level difference $\Delta E = h\nu$ and $\lambda\nu = c$ where h is Planck's constant

[1] These lines had a lot to do with Joseph von Fraunhofer's discovery of elements in the Sun.

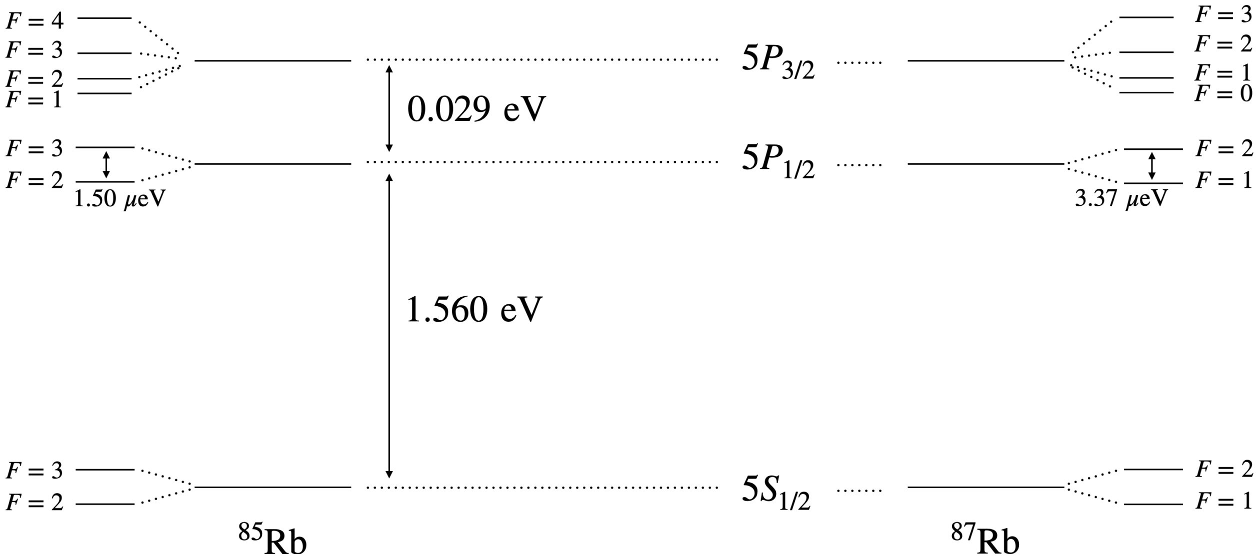

Figure 1: Schematic diagram of the energy levels of the rubidium atoms for the two natural isotopes. **The level spacings are not drawn to scale.** Only two specific values of the hyperfine splitting are indicated; see the Steck reference for all of the numbers.

and c is the speed of light. Therefore, the wavelengths of the two optical lines are

$$\lambda = \frac{hc}{1.560 \text{ eV}} = 794.7 \text{ nm} \qquad \text{and} \qquad \lambda = \frac{hc}{1.560 \text{ eV} + 0.029 \text{ eV}} = 780.3 \text{ nm}$$

These wavelengths are in the near infrared, so don't expect to observe this radiation with your eyes in the optical setup. Most people are unable to see light at this wavelength.

We can also calculate the frequencies of the radiation emitted from the two transitions:

$$(1.560 \text{ eV})/h = 3.772 \times 10^5 \text{ GHz} \qquad \text{and} \qquad (1.560 \text{ eV} + 0.029 \text{ eV})/h = 3.842 \times 10^5 \text{ GHz}$$

These are extremely high frequencies, much higher than anything you can make in a laboratory using oscillating magnetic field coils, for example. The level splitting is much smaller, around 7000 GHz, but still very large. However, transitions between the $5P_{1/2}$ hyperfine levels in ^{87}Rb correspond to a frequency

$$(3.37 \ \mu\text{eV})/h = 815 \text{ MHz}$$

which is still very large, and not easily obtained using field coils. However, applying an external magnetic field splits the F levels into $2F+1$ eigenstates $|F, M\rangle$, and these splittings correspond to reachable RF frequencies.

Broadly speaking, this experiment is about using light emitted from a source of rubidium atoms to excite rubidium atoms in a cell where they can be manipulated using externally applied magnetic fields. The magnetic fields will be either static (such as the Earth's field and coils where the current is varied only slowly) or fields which oscillate at radio frequencies. You will be measuring the degree of absorption by the atoms in the cell as a function of the current producing the static fields and/or as a function of the RF frequency.

1.4 Splitting in an External Magnetic Field

Let's take a moment to step back and review where we are so far. For a ground state principle quantum number n in an alkali atom ($n = 5$ for rubidium), the $l = 0$ (i.e. S) state is lower than the $l = 1$ (i.e. P) state. The spin-orbit interaction splits the P state into two states with $j = \ell \pm 1/2 = 1/2, 3/2$, namely $5P_{1/2}$ and $5P_{3/2}$ for rubidium. (With $\ell = 0$, there is only one state, $5S_{1/2}$.) The $P \to S$ transition emits an optical photon (with wavelength 795 nm for $5P_{1/2} \to 5S_{1/2}$ and 780 nm for $5P_{3/2} \to 5S_{1/2}$ in rubidium, which are in the infrared). Including the hyperfine interaction between the electron and the nuclear magnetic moment, these three states each split according to the "total" angular quantum number F which ranges from $|I - j|$ to $I + j$ where I is the spin of the nucleus.[2] At each of these steps, the energy splitting decreases by orders of magnitude. See Figure 1.

At this point, the $2F + 1$ states $|F, M\rangle$ are all degenerate in energy, because the system still has rotational symmetry. This degeneracy is lifted by the application of an external magnetic field (which therefore breaks the rotational symmetry). We say the magnetic field is "weak" if the splitting is much less than the difference between energies of nearby states with different F, in which case we determine the energy changes using perturbation theory on the $|F, M\rangle$ states. For a "strong" magnetic field, we use the $5S_{1/2}$, $5P_{1/2}$, or $5S_{3/2}$ states.

The splittings in an external field (as well as the spin-orbit and hyperfine splittings) can be calculated using degenerate perturbation theory. Most quantum mechanics textbooks cover this when discussing the Zeeman effect in hydrogen. (See, for example, Section 5.3.3 in Modern Quantum Mechanics, 3e.) The proper way to find the perturbing Hamiltonian H_B is to make the replacement $\mathbf{p} \to \mathbf{p} - e\mathbf{A}/c$ where $\mathbf{A}$ is the vector potential for a static field, and square out the kinetic energy term. If the field is not so large as to need the quadratic term, you find

$$\begin{aligned} H_B &= \frac{\mu_B}{\hbar}\left(g_\ell \mathbf{L} + g_s \mathbf{S} + g_I \mathbf{I}\right) \cdot \mathbf{B} \\ &= \frac{\mu_B}{\hbar}\left(g_\ell L_z + g_s S_z + g_I I_z\right) B \end{aligned} \tag{1}$$

for a magnetic field $\mathbf{B}$ in the z-direction, where μ_B is the Bohr magneton and the "g-factors" g_ℓ, g_s, and g_I relate their respective angular momentum operators to magnetic moment

[2] I apologize for a slight notation change. Most textbooks I know use capital letters like $\mathbf{L}$, $\mathbf{S}$, and $\mathbf{J}$, to refer to (vector) angular momentum operators, and lower case letters like ℓ, s, and j to refer to their eigenvalues. However, the references I see on optical pumping use the non-bold capital letter to refer to the eigenvalues, hence $\mathbf{I}$ and $\mathbf{F}$ for the nuclear and total spin operators, and I and F to refer to their eigenvalues.

operators. To a very good approximation $g_\ell = 1$ and $g_s = 2$, while g_I is much smaller so we ignore the third term in Equation (1). (See Table 6 in Steck's ^{87}Rb document for precise values.) Equation (1) is the classical energy $\boldsymbol{\mu} \cdot \mathbf{B}$ of a magnetic dipole in a magnetic field.

1.4.1 Weak Magnetic Field

If the field is weak, we diagonalize H_B in the $|F, M\rangle$ basis. Using $g_\ell = 1$ and $g_s = 2$, while ignoring the g_I term, the resulting energy shifts are

$$\Delta E = \mu_B g_F M B \tag{2}$$

where

$$\begin{aligned} g_F &= g_J \frac{F(F+1) - I(I+1) + j(j+1)}{2F(F+1)} \\ \text{and} \qquad g_J &= 1 + \frac{j(j+1) + s(s+1) - \ell(\ell+1)}{2j(j+1)} \end{aligned} \tag{3}$$

Note that, using the approximations we've made, the splitting (2) is proportional to M. This means that the energy difference between all M states is the same, namely $\mu_B g_F B$.

Let's put in some numbers for the $5S_{1/2}$ ($\ell = 0$, $s = 1/2$, $j = 1/2$) states for the two rubidium isotopes. It is handy to know that $\mu_B = 1.4h$ MHz/G $= 5.8$ neV/G where h is Planck's constant. From Table 1, $I = 5/2$ for ^{85}Rb and $I = 3/2$ for ^{87}Rb. We therefore have

Isotope	F	g_F	$\mu_B g_F$ (neV/G)	$\mu_B g_F/h$ (MHz/G)
^{85}Rb	2	$-1/3$	-1.9	-0.47
	3	$+1/3$	1.9	0.47
^{87}Rb	1	$-1/2$	-2.9	-0.70
	2	$+1/2$	2.9	0.70

(These values agree with those in the level diagrams given by Steck.) Notice that for fields on the order of Gauss, the splittings are much less than the order of μeV shown in Figure 1. That is, fields on the order of Gauss are indeed "weak."

1.4.2 Strong Magnetic Field

For stronger fields, we not only have to perform degenerate perturbation theory instead on the spin-orbit split states (because the different hyperfine states are now effectively degenerate with each other), but we also need to take into account the quadratic term in the magnetic field. This is a complicated calculation, but can be done analytically for the $S_{1/2}$ (ground) state, which is the one we care about in optical pumping. That is, we carry out a calculation on the state $|j = 1/2, m_j, I, M_I\rangle$ using the full perturbing Hamiltonian. The result is

$$\Delta E = -\frac{\Delta E_{\text{hfs}}}{2(2I+1)} + g_\ell \mu_B m B \pm \frac{\Delta E_{\text{hfs}}}{2}\left(1 + \frac{4mx}{2I+1} + x^2\right)^{1/2} \tag{4}$$

where $\Delta E_{\text{hfs}} = A_{\text{hfs}}(I + 1/2)$ is the hyperfine splitting (with $A_{\text{hfs}} = h \cdot 1.012$ GHz for ^{85}Rb and $A_{\text{hfs}} = h \cdot 3.417$ GHz for ^{87}Rb); $m = m_I \pm m_j = m_I \pm 1/2$; and

$$x = \frac{(g_j - g_I)\mu_B B}{\Delta E_{\text{hfs}}}$$

You should take the time to make plots of these energies as a function of magnetic field. (You can check your result by comparing to the plots in the Steck documentation.) Note that the hyperfine splitting is $3.0h$ GHz $= 12$ μeV in ^{87}Rb and $6.8h$ GHz $= 28$ μeV in ^{87}Rb. Considering the values of $\mu_B g_F$, a "strong" field is on the order of several hundred Gauss.

2 Passage of Light through Alkali Atomic Vapor

There are many processes by which light might be absorbed or scattered while passing through an atomic vapor. However, if the light is of a wavelength than can be absorbed by a transition between states, that process will dominate over other processes.

In this experiment, 795 nm light from the $5P_{1/2} \to 5S_{1/2}$ transition in rubidium will pass through an absorption cell of rubidium vapor. Therefore, resonant absorption will dominate. However, magnetic fields as small as the Earth's field will shift the levels in the absorption cell enough so that absorption is not possible. Furthermore, the phenomenon of "optical pumping" will also spoil the ability to absorb light.

After discussing some preliminary physics below, we will describe the optical pumping process and how you can observe it by repopulating the energy levels using radio frequency (RF) electromagnetic fields.

2.1 Photon Absorption by Alkali Atoms

This will essentially be Section 2C from the TeachSpin documentation.

2.1.1 Electric Dipole Selection Rules

Although, in principle, light at the appropriate wavelength can be emitted or absorbed between any two energy levels, in practice transitions only occur between states that follow specific rules based on their quantum numbers, along with the angular momentum carried by the light. This is because by far the strongest transitions are for what is called *electric dipole radiation* because the wavelengths are much larger than the size of the atoms. (You can learn more about the "long wavelength approximation" in any quantum mechanics textbook covering time-dependent perturbation theory.)

The electric dipole selection rules are as follows:

- $\Delta s = 0$, $\Delta j = 0, \pm 1$
- $\Delta l = 0, \pm 1$ but no $\ell = 0$ to $\ell = 0$
- $\Delta F = 0, \pm 1$
- $\Delta M = 0, \pm 1$

A very important point, which makes optical pumping possible, is that "circularly polarized" light can only be absorbed in $\Delta M = \pm 1$ transitions, where the sign depends on the sense of the circular polarization.

2.2 Linear and Circularly Polarized Light

This is a good point to discuss certain polarization states of light. This is a very brief description. You can learn more from any number of good websites, or any textbook that covers the fundamentals of optics.

Light is an electromagnetic wave, which we will treat as a plane wave. In this case, both the electric and magnetic fields are perpendicular to the direction of propagation, as well as perpendicular to each other. The plane in which the electric field vector oscillates therefore provides a lot of information about the light wave. In fact, for this experiment, this is enough information for us to fully describe the wave.

If light emerges from some kind of thermal source, as in this experiment, the electric field planes are oriented in random directions. We refer to this light as *unpolarized*. If the light passes through a polarizer, then the only waves that pass through have their electric field planes oriented in just one direction. Such light is said to be *linearly polarized*. Of course, we can write any electric field vector as the sum of two perpendicular components, so when unpolarized light passes through a polarizing filter, the intensity is cut in half.

Now imagine a *birefringent* crystal material, where the speed of light passing through it depends on the angle of the electric field plane relative to some axis. If linearly polarized light passes through with the polarization plane at 45° to the birefringent axis, then half of the wave propagates and a different speed than then other half. If we precisely make the crystal thickness so that one component of the light emerges 90° phase out of phase with the other, the electric field vector of the light will rotate in a circular fashion. (Such a device is called a "quarter wave plate.") The light is now said to be *circularly polarized*.

This is not hard to write down mathematically. A plane polarized light wave propagating $\hat{\mathbf{z}}$ direction and polarized in the direction $\hat{\mathbf{n}} \perp \hat{\mathbf{z}}$ has an electric field vector

$$\mathbf{E}(z,t) = E_0 \hat{\mathbf{n}} \cos(kz - \omega t)$$

Now let the birefringent axes of the quarter wave plate be in the $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ directions. Then the electric field vector of the wave emerging from the linear polarizer is

$$\mathbf{E}(z,t) = E_0 \left(\frac{1}{\sqrt{2}} \hat{\mathbf{x}} + \frac{1}{\sqrt{2}} \hat{\mathbf{y}} \right) \cos(kz - \omega t)$$

As it passes through the quarter wave plate, the value of $k = 2\pi/\lambda$ are different for the $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ components. The plate is manufactured precisely so that one of them, say $\hat{\mathbf{y}}$ lags behind the other by one quarter of a wavelength, which corresponds to a phase difference of $90° = \pi/2$. Therefore, the wave emerging from the quarter wave plate is

$$\begin{aligned} \mathbf{E}(z,t) &= E_0 \frac{1}{\sqrt{2}} \hat{\mathbf{x}} \cos(kz - \omega t) + E_0 \frac{1}{\sqrt{2}} \hat{\mathbf{y}} \cos(kz - \omega t - \pi/2) \\ &= E_0 \frac{1}{\sqrt{2}} \left[\hat{\mathbf{x}} \cos(kz - \omega t) + \hat{\mathbf{y}} \sin(kz - \omega t) \right] \end{aligned}$$

It is easy to see that at any particular position, say $z = 0$, the direction of the electric field rotates in time about the z-axis with a fixed amplitude and constant frequency ω. This is why we use the term "circular polarization."

2.3 Optical Pumping

Now, finally, we can understand the optical pumping process. See the paper *Optical Pumping*, by R.L. de Zafra, American Journal of Physics 28(1960)646.

Recall that the quantum number F can take on the values $|i - I|$ up to $j + I$. For each F, there are $2F + 1$ sublevels, specified by $M = -F, -F + 1, \ldots, +F$. In the absence of an external magnetic field, all of the M sublevels are degenerate in energy. The application of a "weak" magnetic field leads to a splitting of the sublevels proportional to M. Left handed circularly polarized light only allows selected absorption between levels of different M where

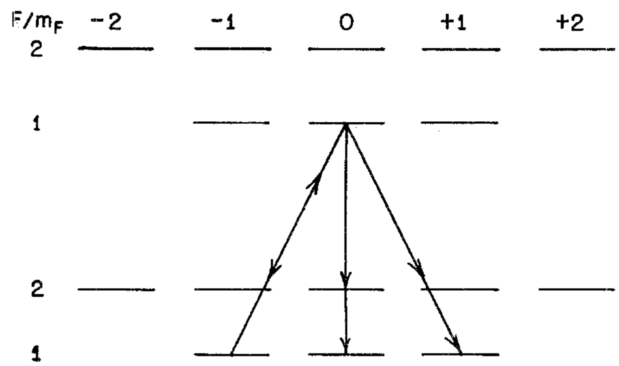

Figure 2: Possible transitions between the $S_{1/2}$ and $P_{1/2}$ states for absorption of left handed circularly polarized light. From deZafra (1960).

$\Delta M = +1$. See Figure 2. Therefore, light absorbed by the $S_{1/2}$, $M = -1$ state can only go to the $M = 0$ state of the $P_{1/2}$ level. However, the radiation from the $P_{1/2}$, $M = 0$ state can go equally to the three $S_{1/2}$ states. That is, atoms in the $S_{1/2}$, $M = -1$ are "pumped" into the $S_{1/2}$, $M = 0, +1$ states, and similarly for atoms in the $S_{1/2}$, $M = 0$ until all of the atoms are pumped up into the $S_{1/2}$, $M = +1$, and there can be no more absorption.

To detect this effect, the $S_{1/2}$, $M = +1$ can be "mixed" with the $S_{1/2}$, $M = 0, -1$ states with RF radiation at the appropriate frequency, given the value of the magnetic field. When you hit that resonances, absorption occurs.

This RF field drives transitions between any two states where $\Delta M = \pm 1$ because the linearly polarized field used in the experiment is actually the combination of both senses of circular polarization. This is easy to see. The horizontal RF field is generated by a pair of coils oriented so that the field is perpendicular to the polarization direction. If we call the polarization direction $\hat{\mathbf{z}}$ and the RF field direction $\hat{\mathbf{x}}$, then the RF magnetic field is

$$\begin{aligned} \mathbf{B}(t) &= B_0 \hat{\mathbf{x}} \cos \omega t \\ &= \frac{B_0}{2} \left[\hat{\mathbf{x}} \cos \omega t + \hat{\mathbf{z}} \sin \omega t \right] + \frac{B_0}{2} \left[\hat{\mathbf{x}} \cos \omega t - \hat{\mathbf{z}} \sin \omega t \right] \end{aligned}$$

which is just the sum of a right handed component with a left handed component.

2.3.1 Rate for Optical Pumping

There is some stuff in Section 2D in the TeachSpin manual, but I want to work out more detail here.

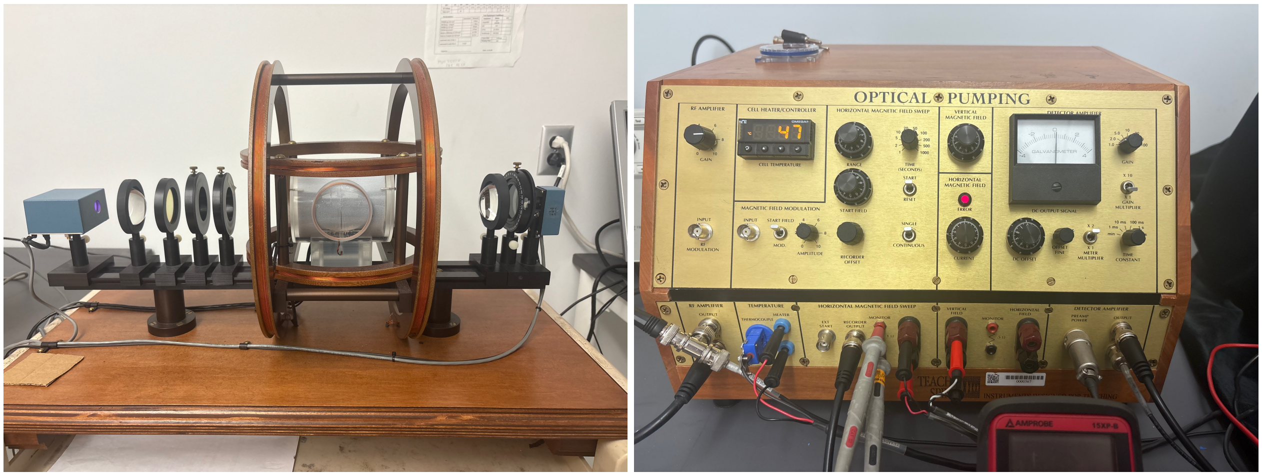

Figure 3: Photographs of the TeachSpin Optical Pumping apparatus.

3 The Apparatus

All of the measurements for this laboratory involve taking light from the de-excitation of rubidium atoms, passing it through a cell filled with rubidium vapor, and detecting the light that makes it through the cell. A set of adjustable static ("DC" for "Direct Current") and oscillating ("AC" for "Alternating Current") magnetic fields affect the atomic states in the cell, which changes the rate of absorption, thereby modifying the intensity at the detector. The detected intensity also depends on the density of vapor in the cell and the orientation of the polarizers inserted before and after the cell.

This section describes the apparatus and the preliminary measurements you need to make in order to get it set up. Figure 3 shows two photographs of this experiment in the laboratory at Temple. One photo shows the optical rail that holds the components, and the other is of the control box that you will use to adjust (most of the) experiment parameters and take your data. In addition to these, you will make use of a digital oscilloscope and a computer interface to record the data.

3.1 Schematic of the Optical Components

Figure 4 shows a schematic of the optical components. The lamp emits light from excited natural rubidium and xenon atoms. The lenses focus light onto the absorption cell and then onto the detector. The interference filter is designed to remove the 780 nm light from ^{85}Rb, so your measurements will be done using the 795 nm light. (See page 2-11 in the TeachSpin manual, and also Section 1.3 above.) The linear polarizer followed by the quarter wave plate makes the light circularly polarized, and the analyzer allows only one linear polarization

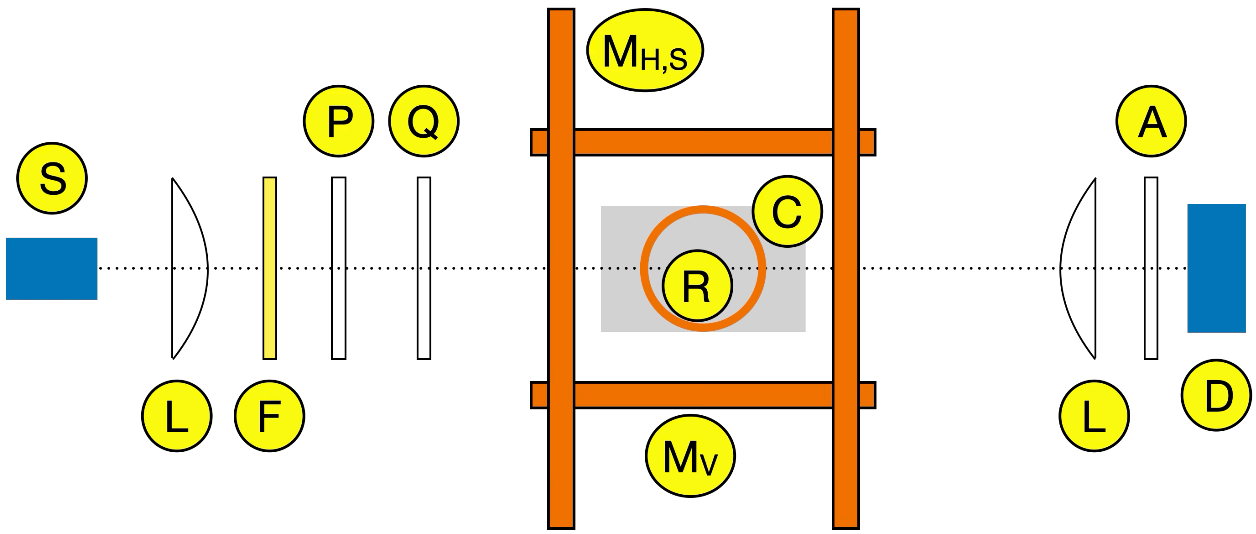

Figure 4: Schematic diagram of the optical components, relative to the optical axis (dotted line) using the following labels. *Note that for some of your measurements, certain components will be removed and particular magnets will not be energized.*

S: The rubidium vapor light source "lamp."

L: Pair of plano-convex lenses to focus light on the rubidium absorption cell and detector.

F: Interference filter.

P: Linear polarizer.

Q: Quarter wave plate.

A: Second linear polarizer used as an analyzer for polarized light.

D: Photodiode light detector. *Note that there is a control switch on the detector housing.*

$M_{H,S}$: Two Helmholtz coils (combined) for the "horizontal" and "sweep" magnetic fields.

M_V: Vertical magnetic field Helmholtz coils.

R: Radio Frequency (RF) magnetic field coils (orange circle).

C: Rubidium vapor absorption cell (gray box).

state to reach the detector.

The TeachSpin manual includes lots of detail about the current-to-voltage preamplifier for the photodiode, but the only thing you need to be aware of is the gain setting control on the detector box.

The DC magnetic fields are setup by three Helmholtz coils[3] which we refer to as "horizontal", "sweep", and "vertical" fields. The specifications of the coils are given in Table 3E-1 in the TeachSpin manual. The horizontal and sweep fields are would onto the same bobbin. That is, the actual horizontal field is given by the sum of the fields from the horizontal and sweep coils. The vertical coils are used to null out the remaining field of the Earth.

You need to pay attention to the direction of these fields as well as their magnitude. You can change the field direction by switching the leads in the output box.

The RF coils are affixed to the sides of the rubidium absorption cell. They are not in Helmholtz geometry, but uniformity of magnetic field is not so important in this case.

3.2 Details of the Control Box and Output Panel

An annotated photograph of the control box and output panel is shown in Figure 5. Except for the preamplifier switch on the detector housing, all of the adjustments for your measurements will use the control box. The output panel supplies power to all the coils, interfaces to the detector, supplies current to heat vaporize the rubidium in the cell and monitor its temperature, and provide outputs of the detector intensity and sweep signal to the oscilloscope.

Most of the labels on the control box are self explanatory, and they will be described in more detail when we go through the various measurements. There are a lot of options for controlling the horizontal sweep field, including ways to control the range and time dependence of the sweep. The detector amplifier also has a number of different settings that mainly control the gain and shape of the preamplified signal. Note that the "galvanometer" indicates the value amplified detector signal, which should agree with the output BNC connector on the output port just below that section of the control box.

The connections on the output panel are also mostly self explanatory. Note that the cable terminations are labeled so that it is straightforward to see what gets plugged into where.

[3]Magnet coils in a Helmholtz geometry are designed to produce a particularly uniform field at the geometric center by zeroing out the second derivative. You should review the relevant physics, which you can find in any calculus-based introductory physics textbook.

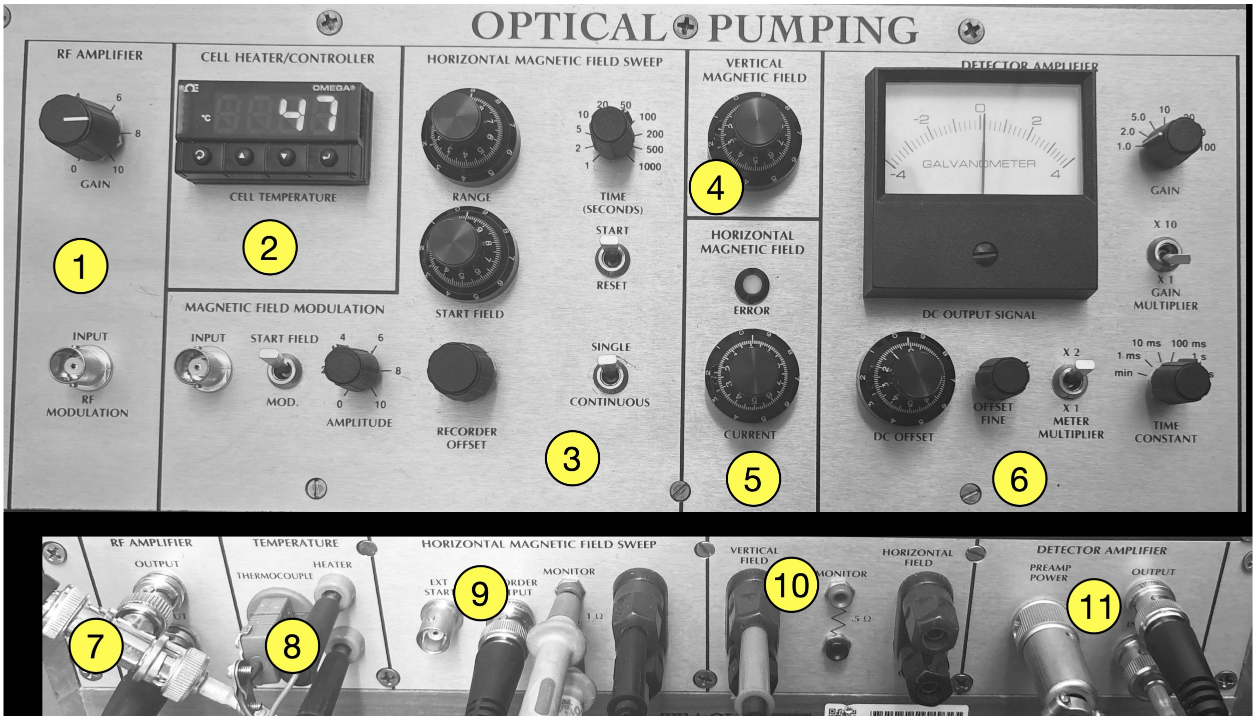

Figure 5: Front panel of the control box including output ports. Not all of the output connections are in place.

1: Input and amplifier controls for RF coils.

2: Heater control for the rubidium absorption cell.

3: Controls for the horizontal sweep magnetic field coils.

4: Control for the vertical magnetic field coils.

5: Control for the main horizontal magnetic field coils.

6: Gain, DC offset, shaping time, and meter controls for the detector preamplifier signal.

7: RF amplifier output.

8: Cell heater output and input for temperature gauge.

9: Sweep field power output, monitor, and sweep signal

10: Power outputs for the main horizontal and vertical field coils.

11: Detector preamplifier power, detector input, and amplified detector output.

3.3 Aligning the Optical Components

3.4 Orienting the Polarizer and Analyzer

3.5 Demonstrating Absorption as a Function of Density

4 Measurements and Analysis

This section describes the various measurements you can make with the apparatus.

4.1 Observing the Zero Field Transition

The basic physics here is simple. Circularly polarized light of a specific wavelength passes through the absorption cell which should absorb light at exactly that wavelength. However, an applied magnetic field splits the levels of the atoms in the cel, so the light is no longer absorbed, decreasing the detected intensity as magnetic field is swept across zero.

The observation itself is not so simple, so you need to be careful of several things. One is the direction and magnitude of the Earthy's magnetic field, which adds to the sweep field. You can look up the Earth's field at any particular location using the following web based application:

https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml#igrfwmm

At the location of the laboratory at Temple, the field has a westward horizontal component of 21 μT and a downward vertical component of 46 μT. This means you need to orient the polarity of the sweep magnet so that it nulls out the horizontal component at the appropriate sweep value. (The magnets and optical coils are on a roller cart, so use the compass provided to orient the apparatus.) You also want to adjust the vertical field so that you make the absorption signal as narrow as possible, but nulling out the vertical field. It is worth taking some time to calculate the fields from the coils using the specifications in the TeachSpin manual, and comparing them to the values of the Earth's field.

The procedure is described pretty well in the TeachSpin manual, Section (5i) on page 5-4, except that we found with our setup that the recorder output offset is zero with a full *clockwise* turn, not counterclockwise. The BNL Digital Oscilloscope serves as your "storage scope" when run in XY mode, and you can extract the data from the scope into the computer provided and make your plots externally.

Figure. . . shows our result for the zero field transition with the following parameters: