

Measuring Optical Pumping of Rubidium Vapor

Shawn Westerdale*
MIT Department of Physics
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Optical pumping is a process that stochastically increases the energy levels of atoms in a magnetic field to their highest Zeeman energy state. This technique is important for its applications in applied atomic and molecular physics, particularly in the construction of lasers. In this paper, we will construct a model of optical pumping for the case of rubidium atoms and will use experimental results to determine the Landé g-factors for the two stable isotopes of rubidium and measure the relaxation time for pumped rubidium. We will then show how the relaxation time constant varies with temperature and pumping light intensity. Lastly, we will use our model and observations to determine the mean free path of 7948 Å photons through rubidium vapor at 41.8°C.

1. INTRODUCTION

In the 1950s A. Kastler developed the process known as optical pumping, for which he later received the Nobel prize. Optical pumping is the excitation of atoms with a resonant light source and the stochastically biasing of the transitions in order to migrate the atoms into the highest energy Zeeman state. Rubidium vapor was used in this experiment due to its well understood hyperfine levels. The use of rubidium also simplifies the physics, since there are only two stable isotopes of rubidium, ^{85}Rb and ^{87}Rb ; the effects of nuclear spin can therefore be easily accounted for.

1.1. Angular Momenta and Energy Level Splittings

In the presence of a magnetic field \vec{B} , the spin-orbit coupling of electrons around the nucleus becomes significant. For an electron with orbital angular momentum \vec{L} and spin \vec{S} , we find a change in the energy equal to $\Delta E = \frac{e}{2m_e} (\vec{L} + 2\vec{S}) \cdot \vec{B}$. By considering the total angular momentum $\vec{J} = \vec{L} + \vec{S}$ we can reduce this equation to $\Delta E = g_J \mu_B m_j B$ where m_j is the component of the total angular momentum parallel to the magnetic field, μ_B is the Bohr magneton, and g_J is the Landé g-factor, given by,

$$g_J = 1 + \frac{j(j+1) + s(s+1) - l(l+1)}{2j(j+1)} \quad (1)$$

For a more in-depth derivation of these formulae, see [1].

To a higher order, there is also energy level splitting due to the interactions of electronic angular momenta with the nuclear angular momentum \vec{I} . To determine the effects of \vec{I} on the energy level splitting, we follow a very similar procedure to what we did for the spin-orbit coupling. Defining the total angular momentum

vector $\vec{F} = \vec{I} + \vec{J}$, we arrive at the conclusion that $\Delta E = g_f m_f \mu_B B$, where g_f is given by,

$$g_f \approx g_J \frac{f(f+1) + j(j+1) - i(i+1)}{2f(f+1)} \quad (2)$$

Note that f , j , and i are the eigenvalues of F , J , and I , respectively.

1.1.1. g-Factors for Rubidium

We can use equation (2) to determine the g-factors for the two isotopes of Rb used in this experiment. Considering that both isotopes have the same electronic shell configuration, with ground state valence electron in $5^2S_{\frac{1}{2}}$, where $j = \frac{1}{2}$, the two isotopes will differ only in their nuclear angular momentum. The nuclear angular momentum quantum numbers for ^{85}Rb and ^{87}Rb are $i = \frac{5}{2}$ and $i = \frac{3}{2}$, respectively[2]. When combining j and i to determine the possible values for f , we find that for ^{85}Rb , $f = 2, 3$ and that for ^{87}Rb , $f = 1, 2$. The g-factors found using equations (2) and (1) are $\pm\frac{1}{3}$ for ^{85}Rb and $\pm\frac{1}{2}$ for ^{87}Rb .

1.2. Optical Pumping

In the presence of a weak magnetic field on the order of milligauss, the energy differences between hyperfine levels splits as described above. In the case of ^{87}Rb , the $5S$ orbital splits into eight states according to their possible values for m_f , their total angular momentum parallel to the magnetic field.

When a photon with angular momentum +1 and energy equal to the transition energy between the $5S$ and $5P$ states interacts with an electron in the $5S$ state, it excites the atom into the $5P$ state and increases its angular momentum quantum number m_f by one unit. As the atom decays back down to a lower energy state, the electron dropping down may change its angular momentum according to the selection rule $\Delta m_f = 0, \pm 1$. In this way, there is a $\frac{2}{3}$ chance that the electron end up with a net

*Electronic address: shawest@mit.edu

increase in m_f and a $\frac{1}{3}$ chance that it will stay the same. Over time, after continued exposure to these photons, we would therefore expect the value of m_f to continually climb. However, the highest angular momentum state available in the $5P$ state has $m_f = +2$. For this reason, if an electron in $5S$ with $m_f = +2$ were to interact with a photon, it would have no angular momentum state to jump into, rendering the electron incapable of absorbing the photon. The atoms in this state will therefore appear transparent to the light. As a result, the electrons will be pumped into the $m_f = +2$ state.

2. THE APPARATUS

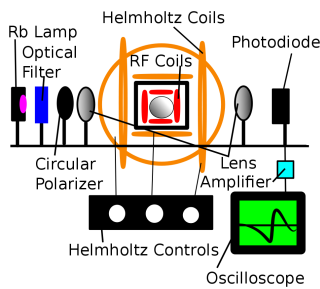


FIG. 1: The experimental setup

Figure 1 shows the experimental apparatus we used. In the center of the apparatus is a bulb containing a rubidium sample. The Helmholtz coils around the bulb allow us to control the magnetic field that the sample feels, while the RF coils pulse the atoms with depolarizing photons to move some of the atoms that it resonates with out of the polarized state. The rubidium lamp provided the light driving the pumping, which passes through a filter to ensure that only light of the desired frequency interacts with the sample. The circular polarizer ensures that all of the photons arriving at the sample will have angular momentum $m_f = +1$ by blocking the $m_j = -1$ photons, ensuring that the pumping is uniformly towards a higher state. The photons then pass through a collimating lens which, along with the lens on the opposite side of the bulb, ensures that we are using as much of the light as possible to pump the sample. After passing the second lens, the light hits the photodiode, where it passes through an amplifier and provides a signal to the oscilloscope to be measured.

Not shown in figure 1 is the heat control system. The heat control system allowed us to heat the rubidium to a higher temperature so that it would be above its boiling point, thereby increasing the concentration of rubidium vapor.

3. AMBIENT MAGNETIC FIELD CORRECTION

Since the Zeeman splitting that is significant in optical pumping requires a magnetic field of the same order as the earth's magnetic field, it is important to determine the ambient magnetic field in order to appropriately buck it out. To do so, we ramp through a range of RF frequencies and observe the trace on the oscilloscope at a constant magnetic field. Assuming the vapor is fully pumped by the lamp, ramping over a wide range of RF frequencies allows us to observe the resonant frequencies of the split energy levels. The magnitude of the magnetic field B is related to the resonant frequency by $f = \frac{1}{\hbar} g_f \mu_B B$. By adjusting the magnetic field along each axis, we can plot the frequency versus the magnetic field applied to each coil. Figure 2 is the resonant frequency

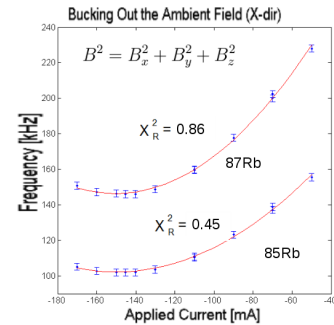


FIG. 2: The applied magnetic field versus resonant frequency along the X-axis

versus applied magnetic field curve for bucking out the field along the X-axis. Since there is still an ambient field present in the Y- and Z-directions, the curve looks hyperbolic. The minimum of this curve represents the magnetic field at which the X-axis is completely bucked out. By minimizing the fields in all three directions, we were able to measure the Earth's local geomagnetic field to be 52540 ± 740 nT, which is about $.5\sigma$ from the accepted value of 52820 nT[4].

4. RELATIVE ISOTOPIC ABUNDANCES

After having bucked out the magnetic field, we were able to vary the magnetic field in the Z-direction while holding the RF frequency constant. During this process, whenever the magnetic field changes the Zeeman splitting to resonate with the RF signal, a dip appeared in the photodiode voltage as the atoms briefly became depolarized. The size of this dip is proportional to the population of the rubidium isotope we are resonating with. As a result, we were able to estimate the relative abundances of the two isotopes by taking the ratio of the two dip depths. We found the sample to be a roughly equal mixture of both isotopes. This measurement differs significantly from the known natural relative abundances

which predicts 72% of the atoms to be ^{87}Rb ; we conclude that our sample is not representative of naturally occurring rubidium.

5. LANDÉ G-FACTORS

Additionally, we were able to measure the change in resonant frequency as we increased magnetic field. As the relation $f = \frac{1}{\hbar}g_f\mu_B B_z$ predicts, we found that the change in resonant frequency varied linearly with the magnetic field. Figure 3 is a plot of this change for both isotopes. Taking μ_B to be known, we were able to measure the slope of these lines and calculate the corresponding Landé g-factor. We found the Landé g-factor of ^{85}Rb to be

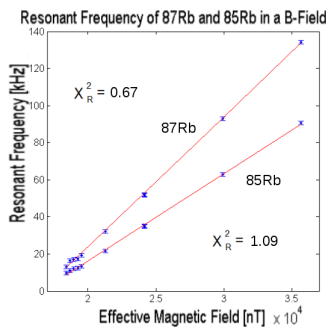


FIG. 3: The resonant frequencies of the two isotopes varied with a very strong linear relationship proportional to their Landé g-factors

$0.446 \pm .004$, within $.1\sigma$ of the known value, and ^{87}Rb to be 0.500 ± 0.009 , equal to the known value.

6. CONSTRUCTING A MODEL

Optical pumping is most conveniently observed by exposing the Rb vapor in a glass bulb to a lamp whose photons have frequencies that resonate with the desired transition. While this is happening, the atoms that are not in the $|5S, m_j = +2\rangle$ state may absorb the photons, and therefore appear opaque to the photodiode, while the electrons that are in the $|5S, m_j = +2\rangle$ state will transmit the light completely.

To construct a model that we can test, we will base it around the experiment where we maintain a constant RF frequency and apply a square wave centered around zero to the Z-axis Helmholtz coil. By giving the square wave a sufficiently large period, we allow the sample to reach an equilibrium point between its pumping rate and depolarizing rates. When the magnetic field switches direction, the roles of the $m = +1$ and $m = -1$ states switch, putting the sample back into an unpumped state for pumping to begin fresh. Depolarization occurs through two dominating processes: depolarizing collisions and interacting with the RF photons.

Considering the pragmatic effects of changing the magnetic field, an extra time constant is introduced due to the time evolution of the rubidium atoms as they feel the effects of the changing magnetic field and the more significant effect of the inductive time constant of the Helmholtz coils. Taking this into account, we may construct a three state system given by,

$$s'_+ = -Rs_+ + Ps_u \quad (3)$$

$$s'_u = -Ps_u + Rs_+ + To \quad (4)$$

$$o' = -To \quad (5)$$

where s_+ is the population of the pumped state, s_u is the population of all of the unpumped states, o is the population of the “original” state that has not yet felt the change in magnetic field, R is the depolarizing collision rate constant, P is the pumping rate constant, and T is the rate constant for atoms to feel the change in magnetic field. Since s_u is the only state that blocks light, this is the only one relevant to this experiment. Solving the system in (5) with the conditions that there are a total of n atoms, m of which are still unpumped in the equilibrium state, and $n - m$ of which are in state o when the fields switch and in s_+ at equilibrium, we find that

$$s_u(t) = \frac{7(m-n)R(P+R-T) + 7(m-n)P(T-R)e^{-Tt} + P(m(P+8R-8T) + 7n(T-R))e^{-(P+R)t}}{7P(P+R-T)}$$

Since our observations are all in terms of transmission intensity, we use the relation $I = I_0 e^{k\rho x} \approx I_0(1 + e^{k\rho x})$, where k is the opacity of the unpumped atoms, ρ is their density, and x is the diameter of the bulb. Using stoichiometry to relate ρ to s_u and collapsing the constants into fitting parameters, we find,

$$I = A - Be^{-Qt} + Ce^{-Tt} \quad (6)$$

where I is the intensity of the light upon the photodiode, A, B , and C are fitting parameters, determined by constants and terms found in s_u , and $Q = P + R$ is the repolarization time constant.

6.1. Confirmation

Plotting the data and fitting our model to the data results in figure 4. The model has a χ^2/NDF of .68,

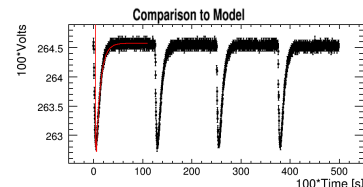


FIG. 4: The repolarization of pumped rubidium atoms indicating that it fits the data very well.

7. INTENSITY DEPENDENCE

By placing neutral density filters in front of the lamp, we were able to reduce the intensity of the beam incident on the sample. Maintaining a constant temperature at $43.3 \pm .5^\circ\text{C}$, we calculated the repolarization constant for several different intensities. In this case, the quantity of interest is $\tau = \frac{1}{Q}$, the characteristic time scale for repolarization. Figure 5 shows the variation of τ with lamp intensity. Here, we expect the time constant to

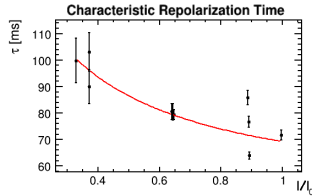


FIG. 5: Repolarization time scale decreases with intensity, indicating that a higher photon flux pumps the sample faster

follow a general form of $T + \frac{A}{I/I_0 + B}$ due to the resonant nature of the light. Fitting this to curve to the data yields a $\chi^2/\text{NDF} = 10$. We also find that as the intensity approaches zero, the repolarization time scale approaches 207 ± 16 ms. This number represents the characteristic spin relaxation time of the rubidium isotopes.

8. TEMPERATURE DEPENDENCE

We then varied the temperature of the bulb by heating it up to a high temperature and repeatedly observing the optical pumping as the temperature decreased. Figure 6 shows how the time constant τ varied with bulb temperature above the boiling point. We observe that the time constant decreases as the temperature increases, leveling off around the melting point at 38.5°C .

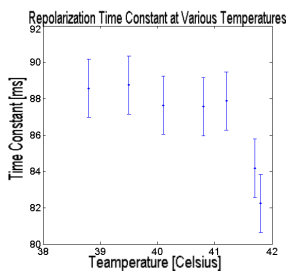


FIG. 6: The temperature dependence of τ

9. MEAN FREE PATH OF LIGHT

By fitting equation 6 to the data, we were able to manipulate the parameters based off of their intrinsic value from their definition out of s_u and the constants associated with the attenuation of light with opacity k in order to measure the mean free path of 7948\AA photons through rubidium vapor. Doing this at 41.8°C yields a mean free path of $29 \pm 4.2\text{mm}$. M. chevrollier et al. published a range of mean free paths for rubidium in [3]. The range they found went from 50 mm at 20°C to 5 mm at 47°C . Our measurement falls within this range. However, given that the temperature is close to 47°C , the measured mean free path is still high. This might be able to be accounted for by an unknown systematic error in our measurement of I_0 , the intensity of the incident beam. Since we could not remove the rubidium bulb from the apparatus, we measured I_0 by placing the photodiode directly in front of the filters. This means the attenuations of the light due to its passing through the Plexiglas container surrounding the bulb as well as the bulb itself (both of which were rather dirty) were not taken into account.

10. ERROR ANALYSIS AND DISCUSSION

The dominating source of error throughout this experiment was the statistical fitting error. In determining the ambient field, our dominating source of error was from the width of the peak giving uncertainty in our measured frequency of about 1.5%, accounting for all of our error in our ambient field measurement. In determining the mean free path of light in rubidium, there was an additional source of statistical error of about 1.2% in our measurement of the bulb diameter. This accounted for about 9% of the total error; fitting errors accounted for the other 91% of the known error. However, there was also an unknown systematic error in the intensity of the light, as discussed above. In the rest of our data, statistical discretization error from the oscilloscope came to about 10% in voltage and .25% in time. These errors translated into errors in our fitting parameters which accounted for roughly the entire error in the rest of our measurements.

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