Optical Pumping of Rubidium

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I. INTRODUCTION

Optical Pumping, which received a Nobel prize in the 1950's, refers to a process in which light is used to 'pump' or raise electrons from a lower energy level within its fine or hyperfine structure to a higher one. This is done using resonance radiation correlating to the individual isotopes of targeted atoms. By unusually simple experimental techniques, only partially disrupted by elevators and the NYC subway system, we are able to measure the fine and hyperfine structure of atoms, magnetic moments of nuclei, and additional other fundamental attributes of free ions and electrons to eventually produce useful polarization of atoms, nuclei, and electrons. We are capable of gaining accurate results that illustrate fundamental principles of quantum theory and atomic structure.

The techniques discussed have led to the development of coherent light generator, or the laser, atomic clocks, magnetometers, and countless other mechanical developments. The technique is so simple, yet now ubiquitous, that Carver, in his original paper describing Optical Pumping in the journal Science, even states the techniques are "so obvious that one cannot but wonder why they were not exploited earlier."

II. THEORY

A. Structure and Interaction of Atoms

In this experiment we observe the absorption of light by rubidium atoms. In order to do so we must consider the atomic structure of rubidium, its interaction with external magnetic fields, and photons of it's resonance frequency.

Rubidium atoms can be described in terms of their energy levels which can be described by angular momentum and respective wave functions described in perturbation theory. Many properties of the rubidium atom are dependent on a single valence electron in the outer shell of the atom. We can completely neglect the presence of inner shell electrons and consider rubidium as if it were a simple Hydrogen atom.

The outer electron is described by $\vec{L}$, the angular momentum, $\vec{S}$, a spin angular momentum, and total non-nuclear angular momentum $\vec{J}$. The total angular momentum can be written $\vec{J} = \vec{L}+\vec{S}$. In the ground state we take $L = 0$, like the hydrogen atom. Since a single electron has an intrinsic spin angular momentum of $\frac{\hbar}{2}$, the value of $S = \frac{1}{2}$. In perturbation theory the state is written $^{2S+1}L_J$ so the ground state of the rubidium atom is denoted $^2S_{\frac{1}{2}}$. The L values correspond to different shells which can be described within electron configuration notation $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 5s$. In the L=P state, the total angular momentum J can only have values $L + S$ and $L - S$. This leads us to having two P states $^2P_{\frac{1}{2}}$ and $^2P_{\frac{3}{2}}$. This splitting of different energies is called the fine structure.

The crux of optical pumping comes from our discussion of the properties that lie within the nucleus, so within one can almost say they are intrinsic. The nuclear magnetic moment is coupled with the electronic magnetic dipole moment associated with the total non-nuclear angular momentum of the atom to form its overall angular momentum value $\vec{F}$. The nuclear spin, denoted by $\vec{I}$ leads to further splitting of the energy levels called the Hyperfine Structure. This is characterized with the Hamiltonian $H = ha\vec{I} \cdot \vec{J}$, where h is the Planck constant and a is dependent on the atom.

In our experiment we consider a weak external magnetic field acting on the rubidium atoms to produce the Zeeman Effect, or further splitting of energy levels. The rubidium atom has values of $\vec{J} = \frac{1}{2}$ and $\vec{I} = \frac{1}{2}$ which allow us to calculate the energy levels in the closed form of quantum mechanics using the Breit-Rabi equation. The atom magnetic field interaction leads $\vec{F}$ to process around the magnetic field at the Larmour frequency. The single valence electron, with spin of $\frac{1}{2}$ gives rise to a magnetic dipole moment equal to the Bohr magneton μ_o. The effective magnetic moment is described by the Lande g-factor. We use the vector model of the nucleus to write an equation for the magnetic energy

$$\frac{M[\vec{L} + 2\vec{S}]\vec{J}}{J^2}\mu_o B = g_j \mu_o M B$$

where B is the magnitude of the magnetic field applied and M is the component of electron spin along the field. g_j the Lande-g factor is

$$g_j = \frac{[\vec{L} + 2\vec{S}]\vec{J}}{J^2}$$

this can be further evaluated as

$$g_j = 1 + \frac{J(J+1+S(S+1) - L(L+1)}{2J(J+1)}$$

. The interaction energey of the magnetic field is expressed as

$$W = -g_j \mu_o B M$$

. For rubidium the Lande-g factor is 2.00232. When we consider the nucleus we have,

$$g_f = g_j \frac{F(F+1) + J(J+1) - I(I+1)}{2F(F+1)}$$

and the interaction energy is now

$$W = g_f \mu_o B M$$

.

B. Manipulation of Energy levels

Optical pumping occurs when absorption of light produces a saturated population of an energy level different from the usual Boltzmann distribution. We irradiate the rubidium with the circularly polarized photons induced by the rubidium lamp. These photons can induce $5^2S_{\frac{1}{2}} \rightarrow 5^2P_{\frac{1}{2}}$ transitions because of a carefully planned optical train.

In perturbation theory if incident photons have an angular momentum of $\hbar$ the only allowed transition are a change of the quantum number $\delta m_f = 1$. This leads to every absorption exciting an electron by one state, or one more unit of angular momentum. The random emission of photons however only have the restriction of $\delta m_f = 0$ or $\delta m_f = \pm 1$. This leads to a trend of increasing m_f values and leads the rubidium atoms to be artificially "pumped". Eventually, there will no longer be atoms in a state which can absorb additional photons to reach a higher state. This will lead to the intensity of the transmitted beam to increase thus leading to a higher current detected by the photodiode.

In the TeachSpin experiment, the magnetic fields produced by the Helmholtz coils are manipulated. Radio photons of the resonance frequency of rubidium are induced so that populations of rubidium are kept relatively neutral with respect to their energy levels. The resonant frequency, which can be discovered by monitoring the change in opacity of the beam and changes in magnetic field can allow us to derive the magnetic moment of the rubidium atom.

III. Apparatus

A. The Optical Rail

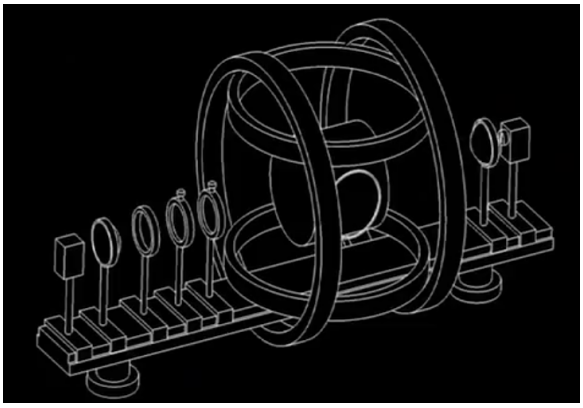

Fig. 1. A Schematic of of the Optical Rail.

The following describes the Optical Rail shown in Fig.1. from left to right.

1) Rubidium Lamp: We obtain photons with the energies of a range which can induce $5S_{\frac{1}{2}} \rightarrow 5P_{\frac{1}{2}}$ transitions from the lamp excited by a radio frequency generator we operate. The RF creates a rapidly oscillating high amplitude electric field which creates an 'RF discharge' which causes free electrons to oscillate between energy levels and maintain a state of partial ionization and causes valence electrons to be excited to the 5^2P states and higher. Relaxation of the atoms in the excited state by spontaneous emission results in observed radiation from the lamp in the form of photons.

2) Filter, Polarizer, Quarter Wave Plate: Photons of the lowest energy of the D-line doublet which are needed in the aforementioned $5S_{\frac{1}{2}} \rightarrow 5P_{\frac{1}{2}}$ transition are able to pass through the narrow-band interference filter. These photons then pass through a linear polarizer and a quarter-wave plate to restrict waves to right handed circular polarity. This is done so that the angular momentum of each photon is equal to $\pm\hbar$.

3) Rubidium Chamber and RF Coil: The rubidium is encased in a temperature controlled chamber allows for the control of the pressure of the rubidium. The chamber is kept at $38.5°C$, the boiling point of rubidium. The chamber also contains a buffer gas to restrict the amount to which the different isotopes contained interfere with each other within the chamber. The RF coil irradiates the vapor with low RF photons to depolarize the pumped rubidium atoms. This is the heart of our experiment.

4) Photodiode: The intensity difference of the transmitted beam are measured by the photodiode. The current obtained is used to collect most of the data this experiment.

B. Oscilloscope and Control Unit

The output of the photodiode to observe intensity among other things was viewed using an Oscilloscope. We used a function generator to serve as an RF source. The temperature of the chamber and the magnetic fields were controlled using the optical pumping control panel. These are all on the oscilloscope and are controlled on different axis through several orientations of different cords. The apparatus to which the oscilloscope was connected was changed at least 6 times in the experiment and is therefore not tracked exactly. On the oscilloscope we are able to change the time base using an X-Y basis and a Y-T basis.

We use two oscilloscopes to combine the accuracy of one with the noise reduction of the other using a simple test to determine a conversion constant for measured values. Although one oscilloscope is in German, Sophie serves as a translator. The oscilloscope used to measure experimental data records current, voltage, and alternating magnetic fields. Additionally, the TeachSpin control unit serves to control the temperature of the rubidium chamber, the magnetic field strength, and more. Additionally, the RF trigger which has is one of the most important functions within the oscilloscope. This enables the scope to display an image that is available for us to capture.

IV. Methods

A. Low Field Resonance

To start we must apply a weak magnetic field along the optical axis of the apparatus. To do so, we have to make sure the residual magnetic field of the earth, and the subway system, and the elevators, is as uniform as possible.

1) Zero Field Transition: The magnetic field is swept around zero. We apply no oscillating RF. This is observed on an oscilloscope with intensity on the vertical axis and voltage on the horizontal axis which is then converted to magnetic field intensity using a different oscilloscope to reduce noise and increase accuracy. The rubidium chamber is set to 320K.

Our goal is to achieve minimum width of the zero field transition by manipulating the different magnetic fields around the spot where the magnetic field is zero. The point at which the magnetic field is zero is important for us to observe because it is the point at which there is no splitting of states and when most rubidium isotopes are in the lowest energy shell. This allows any old photon of any frequency to excite the rubidium atoms which decreases the intensity of the beam detected by the photodiode compared to other magnetic field values where there is in fact splitting of energy states. This is observed by locating a dramatic dip in the intensity recorded.

2) Measurement of Nuclear Spins: The two isotopes of rubidium in the chamber have different nuclear spins. We are able to calculate them via measurement of the g_f values. We do so by observing the independent resonant frequency at which the different isotopes of rubidium are "depumped". These are also referred to as Zeeman resonances.

We determine the value of the magnetic field produced by the Helmholtz coils using basic electricity and magnetism theory and geometry. By varying the RF frequency used, we obtain different magnetic field values for which there is a Zeeman resonance identified. Again, we identify the magnetic field value with respect to our zero at the largest blip using the current which corresponds to each resonance at each frequency. We plot the magnetic field vs the corresponding frequencies for each isotope and find the slope of the line which is proportional to the g_f value. We then compare our data to theory using principles of quantum mechanics.

B. Transient Effects

One of the most interesting parts of the optical pumping lab is the way in which we are able to very clearly observe the pumping and depumping of rubidium atoms. These are called the transient effects.

Zeeman levels are mixed and no optical pumping takes place when the RF is totally on. Therefore, the transmitted light intensity is at a minimum because there is no absorption of photons. We therefore may turn the RF off to allow for pumping. We will see an exponential increase until the maximum value of light intensity is met. The time constant measured from this exponential growth is a measure of optical pumping time. When the RF is turned on once again we are able to observe transitions between the Zeeman sublevels while the population of these levels are being driven toward equilibrium.

To measure this curve for isotope 85, chosen because of the consistency in magnetic field values, we sit on the corresponding Zeeman resonance causing magnetic field value and then switch our oscilloscope view to light intensity vs time. We keep the RF at a constant value of approximately 300 kHZ and turn the RF on and off to observe the transient effect. We record the curve and from this obtain a time constant using mathematical methods contained within the exponential function explained later.

Additionally, we engineer a part of the experiment to gain more data to record time constants with since we would like to see a trend in increasing time constants due to a larger maximum intensity. We turn the rubidium lamp off long enough for it to cool down and proceed to repeat the above measurement except repeatedly as the temperature, which is proportional to the intensity of the bulb, increases. We observe an increase in time constants as the maximum intensity of the light increases.

Finally, since the rise of the RF envelope observed is short enough the rubidium populations will overshoot the absorption of photons and ring around equilibrium. These are known as Rabi Oscillations. We record the period of these oscillations for several amplitudes of the RF for both isotopes of rubidium and observe a trend between the two.

C. Rabi Oscillations

When light interacts with our quantum two or multiple level system, consisting of the ground and several excited states, this leads to a periodic exchange of energy between the system and photons. We can think of these as a periodic change between absorption and simulated emission of photons. The angular frequency of these oscillations is the Rabi frequency. This is proportional to the amplitude and not the optical intensity. When we wish to observe the cyclic behavior of the system we observe the Rabi Oscillations.

To observe them, we must have the RF field strength and horizontal magnetic field strength at resonance frequencies. If we suddenly turn the RF field on, the atoms will cyclically absorb photons and re-emit them, in a cycle known as the Rabi cycle. If we look on a short enough time scale, we can observe these oscillations on an oscilloscope.

V. Results

A. Low Field Resonances

As discussed, for varying frequencies we collect data points, in current, for which a Zeeman resonance is detected. This is converted to the magnetic field affiliated using the formula provided for the geometry of the coil

$$B = \frac{8.991 \cdot 10^{-3} IN}{\overline{R}}$$

where the mean radius of the coils is $\overline{R} = 0.1639m$, I is the current of the Zeeman frequency in amps and the number of turns on each side is $N = 11$. The calculated fields for Rubidium 87 and Rubidium 85 are shown in tables 1 and 2 respectively.

where the mean radius of the coils is $\overline{R} = 0.1639m$, I is the current of the Zeeman frequency in amps and the number of turns on each side is $N = 11$.

The g_f factor is found for each isotope. Frequencies are plotted against the magnetic field and data for each isotope was fit to a line $\nu = a + m \cdot B$ from which we find the slope.

TABLE I

RUBIDIUM 87

RF (kHz)	Current of Resonance (A)	Magnetic Field (Gauss)
100	0.192 ± 0.001	0.1159 ± 0.0006
150	0.288 ± 0.001	0.1738 ± 0.0006
160	0.352 ± 0.001	0.2124 ± 0.0006
200	0.416 ± 0.001	0.2510 ± 0.0006
250	0.544 ± 0.001	0.3283 ± 0.0006
300	0.672 ± 0.001	0.4055 ± 0.0006

TABLE II

RUBIDIUM 85

RF (kHz)	Current of Resonance (A)	Magnetic Field (Gauss)
100	0.288 ± 0.001	0.1738 ± 0.0006
150	0.448 ± 0.001	0.2703 ± 0.0006
160	0.512 ± 0.001	0.3090 ± 0.0006
200	0.608 ± 0.001	0.3669 ± 0.0006
250	0.832 ± 0.001	0.5020 ± 0.0006
300	0.992 ± 0.001	0.5986 ± 0.0006

The relationship that

$$\nu = \frac{g_f \cdot \mu_B}{h} \cdot B$$

where μ_B is the Bohr magneton and h is Planck's constant, allows us to ignore the constant calculated for the line fit and use the value of the slope to find g_f. We can set we can set

$$g_f = \frac{m \cdot h}{\mu_B}$$

.

To mathematically fit the data to a line and calculate the slope we use Mathematica as a calculator and Python to graph.

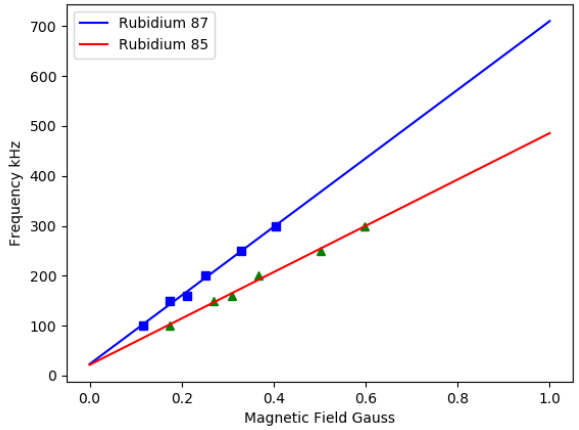

Fig. 2. Rubidium 87 and 85 Data

The calculated fit for isotope 87 and isotope 85 respectively were

$$\nu = 23 + 686 \pm 23 * B$$

and

$$\nu = 21 + 463 \pm 16 * B$$

From this, we obtain values of $g_f = 0.49 \pm 0.3$ for isotope 87 and $g_f = 0.33 \pm 0.5$ for isotope 85. This compared to our theoretical values of $\frac{1}{2}$ and $\frac{1}{3}$ respectively are incredibly precise!

B. Transient Effects

1) Rabi Oscillations: The period of discussed Rabi oscillations is plotted against the amplitude of the RF. As the RF is decreased in amplitude and triggered on, we can observe that the period of the oscillations is increased. We learn that with a higher RF the emission and absorption of photons takes longer to stabilize as discussed in the theory section, with a stronger oscillatory field there is more separation from the equilibrium. When we wish to observe the cyclic behavior of the system we observe the Rabi Oscillations. On the oscilloscope we use 1 $\frac{ms}{div}$.

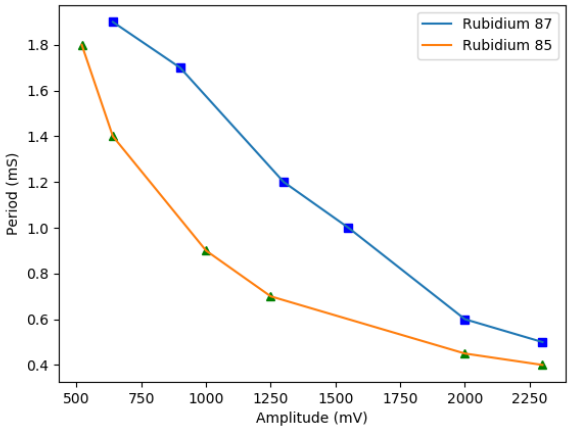

Fig. 3. Rabi Oscillations

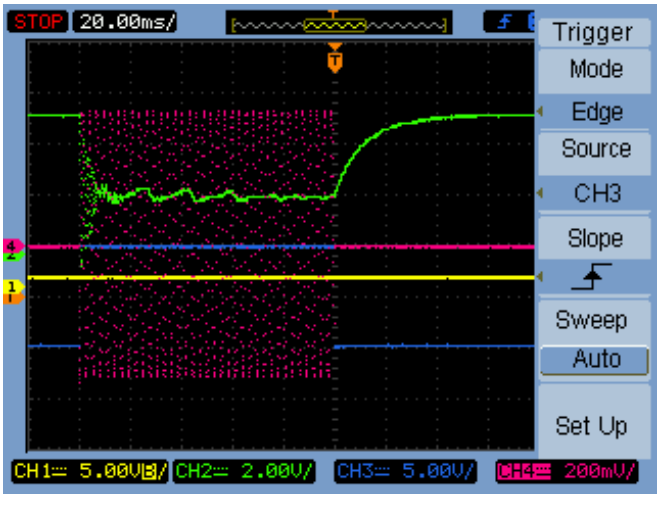

Fig. 4. Time Dependence of the Transmitted Light Intensity on RF

2) Time Constant: As discussed we gather 5 graphs for the time constants shown. One of these is gathered by turning the RF on and off, or triggering on and the others by

turning the rubidium lamp off and repeating the experiment at different temperatures while it heats up. We can observe from this trend that the hotter the heat lamp is, the faster we are able to saturate our rubidium atoms. This makes sense when considering the relationship between intensity, temperature, and the Stefan-Boltzmann constant. The higher the temperature, the higher the light intensity or number of photons available to saturate the rubidium chamber. The oscilloscope is set to 20 $\frac{ms}{div}$

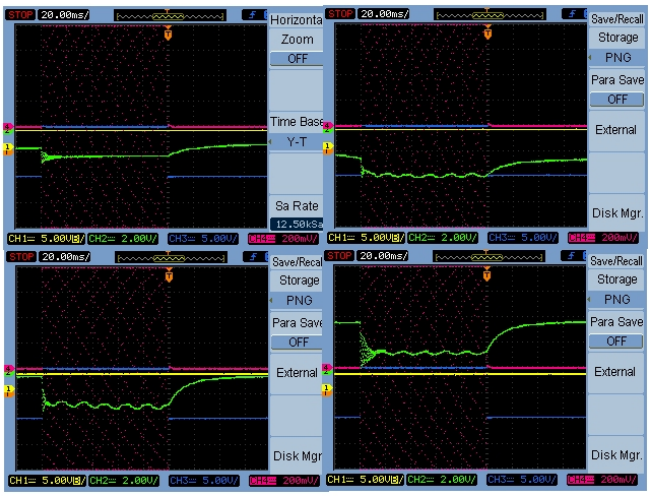

Fig. 5. More Time Dependence of the Transmitted Light Intensity on RF

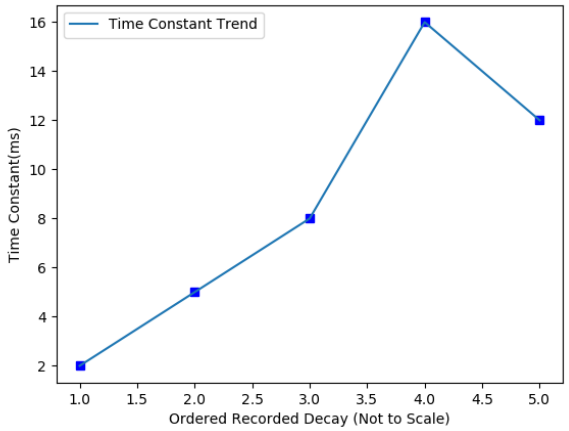

Fig. 6. Time Constants

To find the time constant from each graph displayed we find the time at which the intensity detected by the photodiode was equal to 63.2% of the maximum. This is because $1 - e^{-t/\tau} = 0.632$ when $t = \tau$. These are graphed below.

It seems that the time constant increases with temperature, however, since the images were captured haphazardly since the lamp heated up very quickly towards the end, it became difficult to measure distinct time constants and our data may be partially lucky.

VI. CONCLUSIONS

The two experimental procedures explored here provided by TeachSpin allow us to measure and receive quite accurate results described in the data section for values of nuclear spin of rubidium as well as allow us to observe and quantitatively analyze the Zeeman effect and Rabi Oscillations. The measurements made, apart from problems with the oscilloscope were pretty straight forward to attain once the apparatus was understood.

Throughout the experiment constant decisions needed to be made about how to correct for the lack of theoretical explanation and qualitative instruction provided by the lab manual. It seemed that though the lab manual was long and a lot of information was provided it was not clear and well organized which is to be expected from an experimental guide meant to teach. Although I had a fun time digging through four papers and three lab manuals looking for what experimental procedures to follow, at times, it held my lab partner and I back when we wished we to be progressing in the pursuit of observation of quantum phenomenon. However, with perseverance and strong will we managed to complete half of the TeachSpin procedures. If this experiment were repeated I would recommend following the procedure documented in our report in addition to measurements that can be collected from section 4B of the manual because that is what seems most interesting.

In terms of phenomenon, I wish I was currently enrolled in Quantum II alongside this lab! I was fortunate enough to have Sophie as a lab partner and was able to direct questions on theoretical aspects of this lab to Andrew Haas and the Quantum text used in Quantum II.

In the future I would like to further explore how Optical Pumping situates itself in contemporary research. I am currently working with David Grier to apply what I learned here in my understanding of the laser used in the Holographic Video Microscope I have built over the last two years.

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