

# Optical Pumping and the Hyperfine Structure of Rubidium 87

Laboratory Manual for Physics 3081

THOMAS DUMITRESCU\*, SOLOMON ENDLICH†

May 2007

## Abstract

In this experiment you will learn about the powerful experimental technique of optical pumping, and apply it to investigate the hyperfine structure of Rubidium in an applied external magnetic field. The main goal of the experiment is to measure the hyperfine splitting of the ground state of Rubidium 87 at zero external magnetic field.

*Note: In this lab manual, Gaussian units are used throughout. See [4] for the relation between Gaussian and SI units.*

---

\*email: td2135@columbia.edu

†email: sge2104@columbia.edu

# 1 Hyperfine Structure of Rubidium

In this experiment you will study the optical pumping of Rubidium in an external magnetic field to determine its hyperfine structure. In the following, we give a brief outline of the hyperfine structure of Rubidium and its Zeeman splitting in an external magnetic field. The main goal of this section is to motivate the Breit-Rabi formula, which gives the Zeeman splitting of the Hyperfine levels. For a thorough and enlightening discussion of these topics we refer to the excellent article by Benumof [1].

The ground state of alkali atoms - of which Rubidium is one - consists of a number of closed shells and one s-state valence electron in the next shell. Recall that the total angular momentum of a closed atomic shell is zero, so the total angular momentum of the Rubidium atom is the sum of three angular momenta: the orbital and spin angular momenta  $\mathbf{L}$  and  $\mathbf{S}$  of the valence electron, and the nuclear angular momentum  $\mathbf{I}$ . Since Rubidium has a fairly large number of electrons and the closed shells are spherically symmetric, we can treat the valence electron in mean field theory: the closed shells just give an effective screening contribution to the spherically symmetric Coulomb potential of the nucleus and can otherwise be neglected. Thus the only players in our discussion will be the nucleus and the valence electron.

To determine the hyperfine structure of this effective one-electron problem we have to solve the Schrödinger equation

$$(H_0 + H_{h,f})\psi = E\psi$$

where  $H_0$  is the effective Hamiltonian describing the kinetic energy and Coulomb interaction of the electron, and  $H_{h,f}$  is the hyperfine Hamiltonian

$$H_{h,f} = \eta \mathbf{I} \cdot \mathbf{J} - \boldsymbol{\mu}_J \cdot \mathbf{B} - \boldsymbol{\mu}_I \cdot \mathbf{B}$$

Here  $\mathbf{J} = \mathbf{L} + \mathbf{S}$  is the total electron angular momentum,  $\eta$  is a proportionality constant and  $\boldsymbol{\mu}_J$ ,  $\boldsymbol{\mu}_I$  are the electron and nuclear magnetic moments respectively. Note that since we are only investigating the hyperfine structure of the s-wave ground state, we can neglect spin-orbit coupling. The magnetic moments are written in the form

$$\boldsymbol{\mu}_J = -g_J \frac{e}{2mc} \mathbf{J} \quad \text{and} \quad \boldsymbol{\mu}_I = g_I \frac{e}{2mc} \mathbf{I}$$

where  $m$  is the mass of the electron,  $-e$  is the charge of the electron,  $c$  is the speed of light, and  $g_J$ ,  $g_I$  are the electron and nuclear gyromagnetic ratios. Note that in terms of orders of magnitude  $g_I \sim \frac{m}{M}g_J \sim \frac{1}{1836}g_J$ , where  $M$  is the mass of a nucleon. One of the goals of this experiment will be to measure  $g_I$ . It will also be convenient to introduce the total angular momentum  $\mathbf{F} = \mathbf{J} + \mathbf{I}$  of the entire atom. In the ground state, the allowed values of  $F$  are just  $F = I \pm S = I \pm 1/2$ . The solution of the full quantum mechanical problem is not difficult - it is essentially a first-order time-independent perturbation theory problem - but somewhat lengthy. A careful derivation is given in [1]; for further reading, see also [2]. At non-zero external magnetic field, the degeneracy of the hyperfine structure is completely broken (this is the Zeeman effect) and each allowed value of  $m_F = -F, -F + 1, \dots, F - 1, F$  corresponds to a different energy eigenvalue; here  $m_F$  is the component of  $\mathbf{F}$  parallel to  $\mathbf{B}$ . Relative to a convenient reference level, the hyperfine energies are given by the celebrated Breit-Rabi formula, which is usually written in terms of angular frequencies rather than energies:

$$\omega_{m_F}^{F=I\pm 1/2} = -\mu_B g_I m_F B \pm \frac{\Delta_{hf}}{2} \left( 1 + \frac{4m_F x}{2I+1} + x^2 \right)^{1/2}$$

In this formula  $\mu_B = e\hbar/2mc = 1.40\text{MHz/Gauss}$  is the Bohr magneton,  $B = |\mathbf{B}|$ ,  $\Delta_{hf}$  is the magnitude of the hyperfine splitting of the  $F = I - 1/2$  and  $F = I + 1/2$  levels at zero external magnetic field (this is another thing we want to measure in this experiment), and

$$x = \frac{(g_J + g_I)\mu_B B}{\Delta_{hf}}$$

This formula depends on the sign conventions we chose for the gyromagnetic ratios; in our conventions, both  $g_J$  and  $g_I$  are positive. As an aside, it is interesting to point out that  $\Delta_{hf} = \eta\hbar^2(I + \frac{1}{2})$  depends only on the coefficient of  $\mathbf{I} \cdot \mathbf{J}$  in the hyperfine Hamiltonian, as is expected for the hyperfine splitting at zero external field. In this experiment we will be dealing exclusively with Rubidium 87, which has  $I = 3/2$  and consequently has  $F = 1$  or  $F = 2$ . The hyperfine splitting between these two levels at zero external field is given by  $\Delta_{hf} = 6834.7\text{MHz}$ . The nuclear gyromagnetic ratio of Rubidium 87 is  $g_I = 0.000999$ . Although the purpose of this experiment is to measure  $\Delta_{hf}$  and  $g_I$ , it will be useful to plug the literature values into the Breit-Rabi formula, so that you can calculate the expected hyperfine transition frequencies. For Rubidium 87, the frequency in MHz of a hyperfine transition between a state

with  $m_F$  and a state with  $m_F - 1$  for  $F = I \pm 1/2$  is given by

$$\nu = 3417.34 \left( (1 + m_F x + x^2)^{1/2} - (1 + (m_F - 1)x + x^2)^{1/2} \right) \mp 0.0013978B$$

where

$$x = 9.2302 \cdot 10^4 B$$

and in both of these formulas  $B$  is measured in Gauss. For the given experimental setup, it is also true that  $B \simeq 19.53I_{el}$ , where again  $B$  is measured in Gauss and  $I_{el}$  is current generating the magnetic field measured in A. Note that for Rubidium 87 there should be a total of 6 transitions given by the formula above: for  $F = 1$  the possible transitions are  $1 \leftrightarrow 0$  and  $0 \leftrightarrow -1$ , and for  $F = 2$  the possible transitions are  $2 \leftrightarrow 1$ ,  $1 \leftrightarrow 0$ ,  $0 \leftrightarrow -1$  and  $-1 \leftrightarrow -2$ . The information given above is sufficient to calculate the expected hyperfine transition frequencies and to analyze the data you will obtain in order to determine  $\Delta_{hf}$  and  $g_I$ ; this will be discussed further below. For further reading we again refer to [1] and [2]. Figure 1 shows the hyperfine structure of Rubidium 87 as a function of the external magnetic field.

## 2 Principles of Optical Pumping

In this experiment, light from a Rubidium lamp is used to optically pump Rubidium 87 vapor. In the following, we briefly outline the mechanism of optical pumping, and explain how it can be used to measure hyperfine transition frequencies. As discussed further below, the most important part of the experimental setup consists of a linear arrangement of the Rubidium lamp, an optical filter and polarizer, the Rubidium vapor bulb and an optical detector. The light from the Rubidium lamp is filtered to only allow photons of wavelength 7947.6 Å to pass through the Rubidium vapor bulb. These photons are exactly of the right energy to cause a transition of the valence electron from its  $^2S_{1/2}$  ground state to the  $^2P_{1/2}$  first excited state (see Figure 1). These filtered photons are then passed through a polarizer (a quarter wave plate) to convert them into photons of right circular polarization (or positive helicity); we refer to such photons as  $\sigma^+$  photons. If the external magnetic field is parallel to their direction of propagation, these  $\sigma^+$  photons can affect  $^2S_{1/2} \rightarrow ^2P_{1/2}$  transitions according to the following dipole selection rules (these give the dominant transition processes):

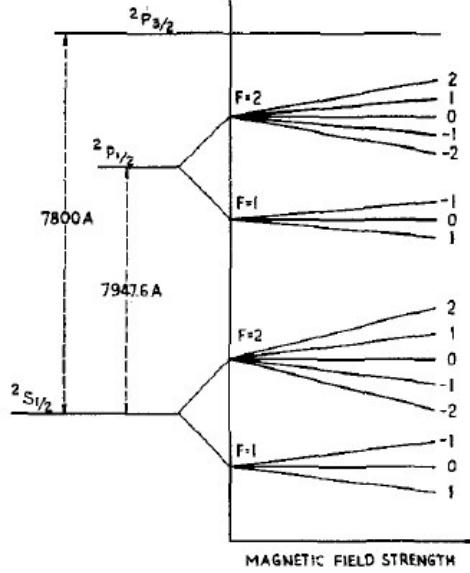


Figure 1: Hyperfine Structure of the Low-Lying States of  $\text{Rb}^{87}$  (Source: [1])

$$\Delta L = \pm 1 \quad \Delta J = 0, \pm 1 \quad \Delta F = 0, \pm 1 \quad \Delta m_F = +1$$

Note that  $\sigma^+$  photons can only cause  $\Delta m_F = +1$  transitions. Likewise, photons of negative helicity - so-called  $\sigma^-$  photons - can only cause  $\Delta m_F = -1$  transitions, with otherwise identical selection rules. So when a  $\sigma^+$  photon hits a Rubidium 87 atom, it not only excites the electron to the  $2P_{1/2}$  level, but also raises its  $m_F$  by one unit. Of course, the excited state is unstable and spontaneously decays back to the ground state by emitting another photon. However, the spontaneously emitted photon has arbitrary polarization and the decay can have  $\Delta m_F = 0, \pm 1$ . Thus, on average we have  $\Delta m_F = +1$  for the excitation by  $\sigma^+$  photons, but  $\Delta m_F = 0$  for the spontaneous decay, giving a net average  $\Delta m_F = +1$ : on average, the electrons will migrate into states of higher and higher  $m_F$ . This phenomenon is referred to as optical pumping. Of course  $m_F = -F, -F + 1, \dots, F - 1, F$ , so this process eventually has to stop. At this point the vast majority of electrons in the Rubidium 87 vapor are in the ground state of highest allowed  $m_F$  (due to the close spacing of the hyperfine levels, thermal effects prevent a complete depletion of the lower-lying  $m_F$  states). This process is illustrated in Figure 2. It is important to note that when the external magnetic field

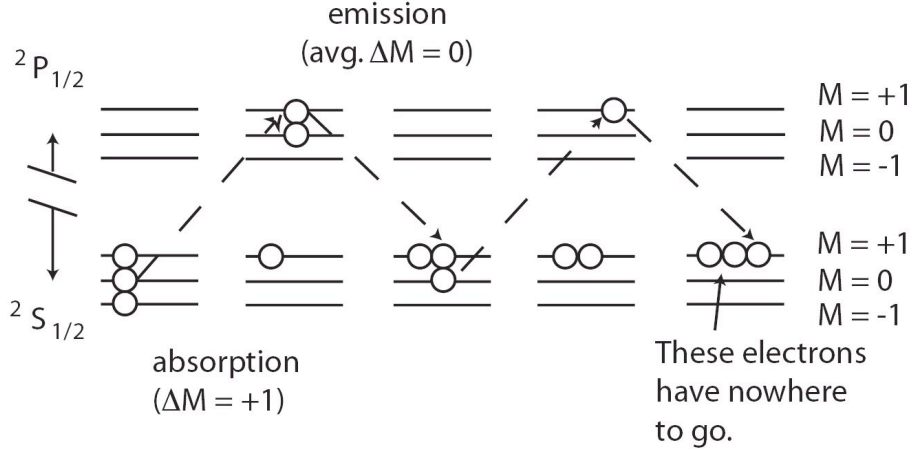


Figure 2: The Optical Pumping Mechanism at Work (Source: Eric D. Black, *Optical Pumping*, <http://www.pma.caltech.edu/~ph77/labs/>)

is antiparallel to the photon direction of propagation the selection rules for  $\sigma^+$  photons and  $\sigma^-$  photons switch:  $\sigma^+$  photons act like  $\sigma^-$  photons (the pump electrons to the state of lowest  $m_F$ ) and vice versa.

Physically, the fact that the electrons are being pumped into a state of maximal  $m_F$  means that their magnetic dipole moments orient themselves parallel to the external magnetic field. In a state of maximal  $m_F$ , dipole selection rules prohibit the atoms from absorbing any more  $\sigma^+$  photons, and thus these photons pass through the Rubidium vapor bulb unaffected: in its fully pumped state the bulb is transparent. Now imagine that there was - loosely speaking - a way to disorient the magnetic moments we just talked about. Then the Rubidium gas would not be in its fully pumped state anymore and could again absorb  $\sigma^+$  photons: it would temporarily become opaque. By monitoring the depletion of the incident beam of  $\sigma^+$  photons using the optical detector behind the Rubidium vapor bulb, we can thus tell when the Rubidium vapor is in its fully pumped state and when it has become temporarily disoriented: temporary opacity shows up as a dip in the intensity of the incident photon beam measured by the optical detector. This is the key idea which makes optical pumping a powerful experimental technique: we can use it to tell when the Rubidium vapor becomes temporarily disoriented.

In this experiment you will use two methods of disorienting the Rubidium atoms. The simpler method consists of applying a slowly varying longitudinal magnetic field (along the direction of the photon beam) which is driven by a triangle waveform. At nonzero values of the field, the Rubidium atoms will be optically pumped into a state of magnetic alignment. However, as the triangle passes through zero and the magnetic field switches direction, the atoms become temporarily disoriented as they start to get pumped in the opposite direction. This is visible as a single dip in the optical detector signal exactly at the moment when the magnetic field passes through zero, and is known as zero-crossing. The dip is followed by an exponential recovery corresponding to the gradual re-pumping of the Rubidium atoms in the opposite direction. Note that the dip is often followed by an overshoot in the signal. The second method of disorienting the Rubidium atoms is slightly more complicated. First we apply a DC (i.e. time-independent) longitudinal magnetic field to Zeeman-split the hyperfine levels of the Rubidium atoms. Optical pumping happens as before; most electrons end up in the state of highest  $m_F$ . We now apply a second magnetic field transverse to the first longitudinal field. This transverse field is sinusoidally driven at radio frequencies (on the order of tens of MHz), and is called an RF field. If the frequency of the RF field is very close or equal to the splitting between two adjacent hyperfine levels, it can cause a hyperfine transition between these levels (this is a resonance effect very similar to the one in nuclear magnetic resonance). This disorients the Rubidium atoms, which again makes the Rubidium vapor temporarily opaque and causes a dip in the detector signal. Using this method, one can determine the hyperfine splitting of Rubidium 87 by looking for those RF frequencies at which a dip is visible in the detector output. This is the method used in this experiment (for purely technical reasons, a third magnetic field is used to sweep in and out of resonance; this is discussed below).

### 3 Equipment and Experimental Setup

The amount of equipment involved in this experiment is substantial, and it is worth your time to spend a while becoming familiar with the various components and how they are connected to each other, before beginning the experiment. The entire setup is succinctly summarized in Figure 3.

The main part of the experimental setup is the straight-line configuration of Rubidium bulb, polarizer and filter, Rubidium vapor bulb and optical

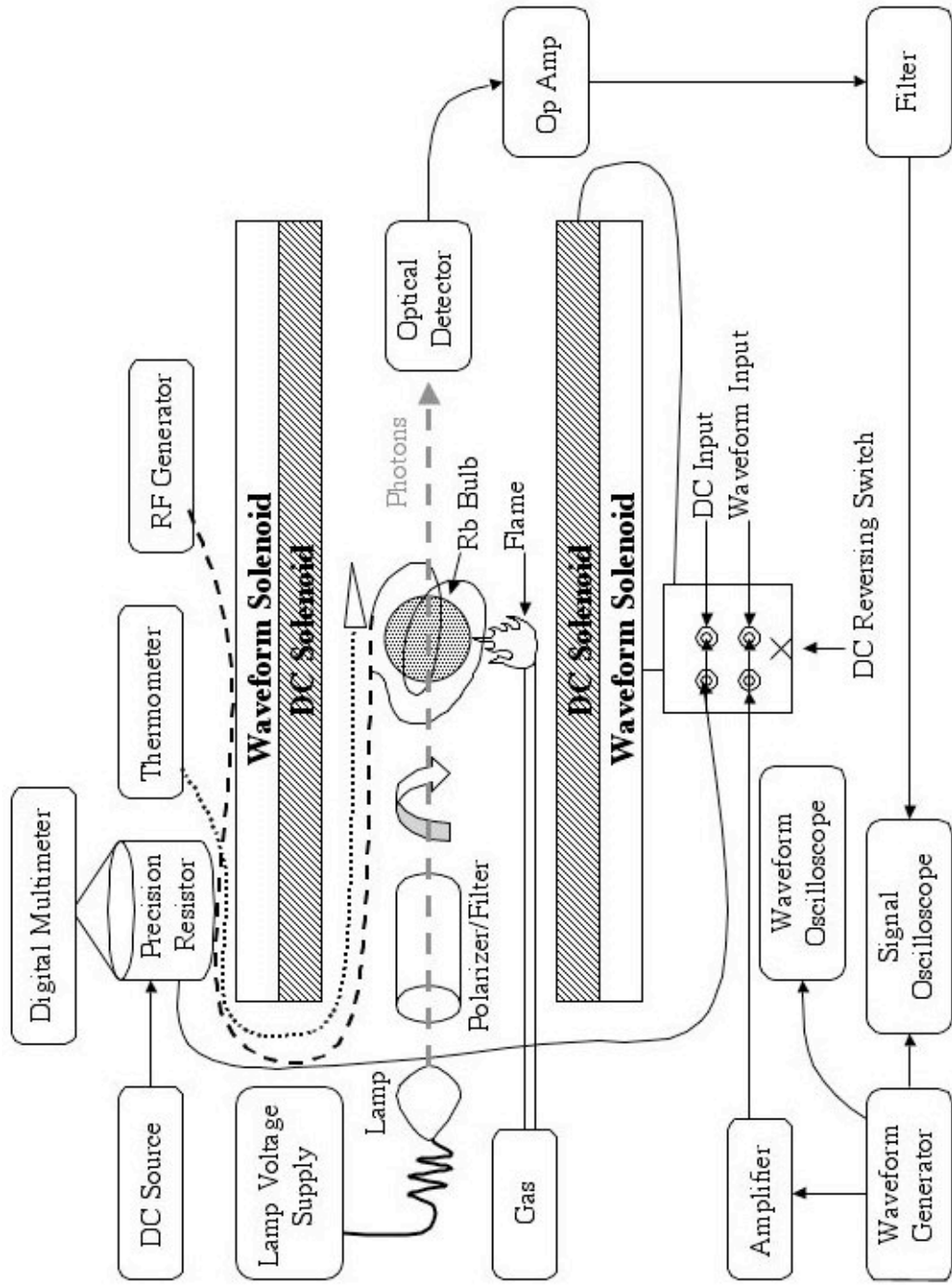


Figure 3: Experimental Setup for Optical Pumping



detector located inside the two large longitudinal solenoids. The lamp is powered independently, and the current supplied by the lamp voltage source should not exceed 25 mA; in our experience higher currents lead to better signals. The lamp should be warmed up on standby before turning it on. The Rubidium bulb is heated with a gas burner, as the Rubidium needs to be in its vaporized state filling the bulb to undergo optical pumping; if, however, the Rubidium becomes too hot, constant collisions with the bulb rapidly disorient the Rubidium atoms and greatly reduce the signal quality. A suggested operating temperature, which can be monitored with the thermometer attached to the bulb, is around  $60^\circ\text{C}$ , although in our experience higher temperatures around  $\sim 75^\circ\text{C}$  have yielded the best results. It is also advisable to heat the sample to the desired temperature and then keep a small flame burning throughout the experiment to maintain the bulb at constant operating temperature, since the signal quality is strongly affected by temperature fluctuations. Finally, it is important that the optical detector is carefully aligned along the lamp-bulb axis.

The parts of the experiment described above are enclosed in two concentric, longitudinal solenoids which are shielded from the Earth's magnetic field by magnetically soft  $\mu$ -metal on the outside of the solenoids. The DC coil is 74 cm long, 23 cm in diameter, and has 1164 turns. It is powered by a high-voltage power source which generates a stable, high DC current (up to  $\sim 3\text{A}$ ). For this experiment, the relation between the DC current and the magnetic field at the center of the solenoid is given by  $B \simeq 19.53I_{el}$ , where  $B$  is in Gauss and  $I_{el}$  in A. The current powering the DC coil is determined by measuring the voltage drop across a  $(1 \pm 0.01) \cdot 10^{-2}\Omega$  precision resistor using a digital multimeter. During the measurement of the hyperfine transition frequencies, it is important to keep the DC current very stable, as those frequencies are sensitive to the DC magnetic field. The second coil - referred to as the waveform coil - has the same dimensions as the DC coil, but has 1940 turns. It is connected to a waveform generator whose output is amplified before connecting to the coil. The waveform generator can generate several waveforms, but the most useful for this experiment is a triangle wave of low frequency ( $\sim 0.5\text{Hz}$ ). The waveform coil provides the triangle magnetic field for the zero-crossing part of the experiment, and also plays an important part in the measurement of the hyperfine transition frequencies (see below). The output from the waveform generator is monitored on the waveform oscilloscope. This output is also used to control the X-channel of the signal oscilloscope, so that the oscilloscope trace moves horizontally

back and forth across the screen together with the triangle, and crosses the center of the screen exactly when the triangle field passes through zero. It is advisable to set the amplitude of the waveform generator to a high value and correspondingly adjust the oscilloscope screen so that the trace is exactly confined to the screen and does not overshoot on either side. Finally, the transverse RF field is directly controlled by a separate RF generator, which can generate sinusoidal RF waves over a wide range of frequencies with high precision. To improve the signal quality it helps to set the amplitude of the RF generator to a value close to the allowed maximum. Note that during the experiment, the  $\mu$ -metal shielding mentioned above acquires a small amount of magnetization which biases the apparatus. For this reason the entire experiment needs to be performed with the DC longitudinal field both parallel and anti-parallel to the light beam from the Rubidium lamp. This reversal can be easily effected by the DC reversing switch next to the DC and waveform input sockets.

The signal from the optical detector is passed through an operational amplifier and then through a low-pass filter before connecting to the Y-channel of the signal oscilloscope. Thus the signal oscilloscope output is synchronized in a way that the zero-crossing dip, which occurs when the triangle magnetic field passes through zero, occurs at the center of the oscilloscope screen. There is a significant amount of optical noise (disruptive light sources) and electromagnetic noise (inductive couplings between different pieces of equipment) which can reduce the quality of the signal. The optical noise is reduced by covering the entire apparatus with a piece of thick black cloth, closing the blinds on the windows, and turning off the light (yes, this experiment is performed in the dark). Turning off the lights is especially important, since they flicker with the standard AC frequency of 60 Hz and introduce a significant amount of optical noise. Since the signals which we would like to measure in this experiment - the dips which occur when the Rubidium atoms become temporarily disoriented - are of a relatively low frequency (on the order of a couple of Hz), the filter has a relatively steep rolloff at  $\sim 30$  Hz. In particular, this rolloff is chosen to eliminate the standard AC frequency of 60 Hz, which might enter the experiment through various sources. While the filter is a useful tool for this experiment, you should try to perform the experiment both with and without the filter, and compare results. Keep in mind that very low-pass filters such as this one can have a considerable effect on the shape of the signal. The definitive reference for filter electronics is [3].

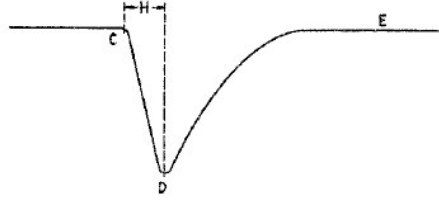


Figure 4: Characteristic Shape of the Zero-Crossing Dip (Source: [1])

## 4 The Experiment

The first part of this experiment consists of setting up the apparatus and observing the zero-crossing. For this part of the experiment there is no DC and no RF magnetic field; only the triangle field from the waveform generator is present. You should observe a single dip on the oscilloscope whenever the trace passes through the center of the screen. If everything is aligned properly and the system is allowed some time to reach equilibrium, you should observe a zero-crossing signal of amplitude  $\sim 20$  mV without the filter present. If you are using the filter, the signal will be somewhat reduced. The characteristic shape of the zero-crossing (and also the dips during the second part of the experiment) is shown in Figure 4 for the case when the oscilloscope trace is sweeping from left to right. The rapid drop CD occurs when the triangle field passes through zero and the atoms become disoriented. If the field were entirely uniform throughout the bulb, this drop would be instantaneous, and thus the width H is a measure of the non-uniformity of the field in the bulb. The exponentially rising curve DE corresponds to the re-pumping of the Rubidium atoms in the other direction; the time constant of this exponential is a good measure of the re-pumping time. In order to correctly perform the second part of the experiment, you need to once and for all pick a direction for the oscilloscope trace which you are going to use for your measurements. For example, you could decide to only read the trace as it goes from left to right (alternatively you could set the waveform generator to only ramp from left to right instead of generating a triangle, but in our experience it is easier to just stick with the triangle). The reason you have to make this choice is that the magnetic bias caused by the  $\mu$ -metal shielding causes an asymmetry between left-to-right and right-to-left sweeps. If you look at your zero-crossing signal, you should notice that the sharp drop CD does not occur at exactly the same place for the two directions. Once you have picked a direction, you should shift your

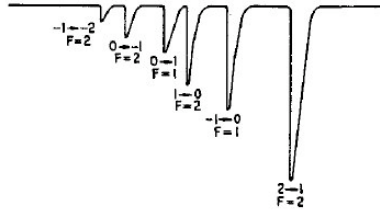


Figure 5: Characteristic Oscilloscope Trace in the Measurement of the Hyperfine Transition Frequencies (Source: [1])

oscilloscope display, so that the nearly vertical line CD exactly matches up with the Y-axis of your oscilloscope; then you can be confident that the center of the screen corresponds to zero total magnetic field (i.e. the field from the waveform generator and the residual  $\mu$ -metal field exactly cancel at this point). Now you can move on and perform the second part of the experiment. As mentioned above you will have to perform the second part with both possible orientations for the DC magnetic field. After you switch the direction of the DC field you should realign your zero-crossing just as described above. Note that you should not change the direction in which you are reading your signal, but only the DC magnetic field.

The second part of the experiment - measuring the hyperfine transition frequencies of Rubidium 87 - involves the full apparatus. You now also have to turn on the DC and RF magnetic fields **in addition** to the triangle field. For a given value of the total longitudinal field, a specific hyperfine transition has a given frequency. The 6 hyperfine transitions for Rubidium 87 lie sufficiently close together that by slightly altering the longitudinal field, each individual transition can be tuned to a common frequency (of course this cannot be done for all transitions simultaneously). In order to make all 6 transitions visible at once, you tune the RF frequency to correspond to one of the transition frequencies for the given value of the DC magnetic field calculated from the formulas discussed in Section 1. The longitudinal triangle field superimposed on the DC field then slightly shifts the total longitudinal field back and forth so that the individual hyperfine transitions alter their frequencies in a way that one hyperfine transition is always in resonance with the RF field. Thus the 6 hyperfine transitions are shifted in an out of resonance, and what appears on the oscilloscope is a sequence of 6 dips as the triangle sweeps back and forth. This trace is schematically shown in Figure 5. You can test your understanding of

what has been discussed so far by trying to figure out whether the trace in Figure 5 is moving from left to right or vice versa, and in which direction the DC magnetic field is pointing. Now that all 6 transition dips have been made visible, you can precisely measure the frequency of each by tuning the RF frequency so that the dip you want to measure has its sharp dropoff at exactly the center of the oscilloscope screen. From the first part of the experiment, we know that this corresponds to zero triangle and residual magnetic field; at this point, only the DC field is acting. Thus for a given value of the DC field, this allows you to accurately measure the frequencies of all 6 hyperfine transitions. It is important to note that for this part of the experiment, the initial drop in each dip will be considerably less sharp than in the zero crossing case (this is true whether or not you use the filter). Therefore, an important systematic is your choice on which part of the drop to center the oscilloscope screen; a reasonable choice is the middle of drop (halfway between C and D in Figure 4). You should measure all transitions for several values of the DC magnetic field. A good range of DC currents to use is  $\sim 1.0$  A to  $\sim 3.0$  A in steps of  $\sim 0.25$  A. At lower magnetic fields, the 6 dips meld into one another and become impossible to discern. Finally, as discussed above, you should repeat all measurements after reversing the direction of the DC field.

## 5 Notes on Data Analysis and Further Investigations

The data analysis for this experiment is comparatively straightforward. In principle, the measured hyperfine transition frequencies and the Breit-Rabi formula immediately allow you to calculate  $\Delta_{hf}$  and  $g_I$ . In practice, two extra steps are necessary. Firstly, the transition frequencies for the two orientations of the DC field will in general differ and should be averaged. Secondly, unavoidable systematic errors should be eliminated by working with the hyperfine transition frequencies relative to one specific transition frequency (e.g. the lowest one). This should allow you to calculate  $\Delta_{hf}$  quite accurately ( $\sim 3\%$ ). The error in  $g_I$  tends to be larger, as it is the small difference between two large quantities.

While you should expect to see only 6 dips corresponding to the 6 hyperfine transitions in the second part of the experiment, a seventh, spurious dip has consistently appeared in our experience. This dip becomes very pronounced at high DC magnetic fields, at which it is virtually indistinguishable

from the other dips, and melds with the neighboring dips as the DC field is reduced. While it is likely that this spurious dip is caused by the instrumentation, its origin remains unclear. If you measure an additional dip, you should compare your data with the predictions from the Brei-Rabi formula to determine which dip is spurious and neglect it in your data analysis. However, if you have completed the measurement of the hyperfine transition frequencies, you might want to spend some time to further investigate this spurious dip, and how it behaves as various experimental parameters are changed; this might yield some insight into its origin.

Finally, the optical pumping experiment is in a continual state of development and improvement. In particular, efforts to improve the signal filter and the RF coil surrounding the Rubidium bulb are currently planned, which should considerably improve the signal quality. A new digital signal scope has already been ordered but is not yet fully integrated into the experiment. Also, the Rubidium bulb currently used essentially only contains Rubidium 87; a future replacement bulb is likely to contain both Rubidium 87 and Rubidium 85, both of whose hyperfine structures can be accurately measured using the techniques described above. The calculations in Section 1 trivially generalize to the case of Rubidium 85. You should consult your lab instructor regarding the status of these improvements.

## 6 Acknowledgments

We would like to thank Prof. Morgan May for the opportunity to spend a considerable amount of time with the optical pumping experiment, and for his support in our efforts to improve it. Special thanks go to David Tam who enthusiastically supervised our tinkering and provided invaluable help by designing and building a new low-pass filter. Finally, we thank Clay Cordova and Claire Lackner, who resurrected this experiment from its dysfunctional state and provided us with valuable advice.

## References

- [1] Reuben Benumof. Optical pumping theory and experiments. *American Journal of Physics*, 33:151–160, 1965.
- [2] Robert Bernheim. *Optical Pumping - An Introduction*. W.A. Benjamin, New York, 1965.
- [3] Paul Horowitz and Winfield Hill. *The Art of Electronics*. Second edition.
- [4] John David Jackson. *Classical Electrodynamics*. Third edition.