Optical Pumping of Rubidium

3rd year Physics Laboratories

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1 Introduction

In this prac you will study the "optical pumping" of rubidium (Rb) atoms. Optical pumping produces a non-equilibrium distribution of energy states in a collection of atoms. This is done by shining resonant radiation (of optical or near-optical frequencies) at the ensemble. Another way of manipulating energy states is by the use of RF (radio frequency) radiation. This has the effect of de-pumping the ensemble.

On the whole, there are not too many commercial applications for the optical pumping of rubidium! What this prac is all about is making fundamental measurements in atomic physics. In particular, you will be testing the Zeeman effect as it relates to the splitting of energy levels in the hyperfine structure of Rb. You will also measure the spins of the various isotopes of the Rb nucleus, and investigate the quantum mechanical phenomenon of Rabi oscillations. Time permitting, you will examine the quadratic Zeeman effect. If this is either enticing or confusing, read on.

2 Theory

2.1 Quantum Theory of Hydrogenic Atoms

Rubidium is a hydrogen-like atom. Its inner 36 electrons are paired off in closed shells and we will ignore them. The 37th electron (5s) produces most of the properties of the atom. The first property we will look at will be fine structure. The orbital angular momentum of the electron (**L**) produces a dipole moment which interacts with the spin (**S**) of the electron. These vectors add to give a total angular momentum of the electron, $\mathbf{J} = \mathbf{L} + \mathbf{S}$. Now, each vector has an associated quantum number; S,L and J. J can take on different values even for the same S and L because **L** and **S** can point in different directions. These different J values split the gross structure into corresponding energy levels.

Question 1 *What is spectroscopic notation? I want to designate a state with n=5, S=1/2, L=0 and J=1/2. How do I do that? What if n=5, S=1/2, L=1 and J=1/2? How do I represent that? (Reference [1], or any 3rd year quantum text.)*

In the following discussion, consider the former state in Question 1 as the ground state and the latter as the excited state. The approximate wavelength of light needed to excite electrons from the lower to the upper state is 795 nm.

These sub-levels can be further split in a process called Hyperfine Splitting. Hyperfine structure is caused by the interaction of the electron with the nucleus. This is regulated by a vector, $\mathbf{F} = \mathbf{I} + \mathbf{J}$, where **I** is the spin of the atomic nucleus. Again, the vector addition of the quantum numbers I and J tells us the possible number of splittings. Note well that in this prac we have two isotopes, ^{85}Rb and ^{87}Rb, which have different I values (a nice little complication!)

Question 2 *We have been talking a lot about the 'vector addition' of quantum numbers. State the generic rule for adding two angular momenta. What are the possible values of the final quantum number? Apply this for ^{87}Rb, using $\boldsymbol{F} = \boldsymbol{I} + \boldsymbol{J}$ where I = 3/2 and J = 1/2. Do the same for ^{85}Rb, where I = 5/2. (Reference [1] again)*

2.2 The Zeeman Effect

The Zeeman Effect, as you may recall, is the splitting of electronic energy levels in a magnetic (**B**) field. For small fields, that is, fields which produce a small splitting in comparison to the hyperfine splitting, the splitting increases linearly in B=|**B**|. The splitting is given by:

$$\Delta E = g_F \mu_B B M_F \tag{1}$$

Where:

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

and:

$$g_J = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)} \tag{3}$$

and μ_0 is the Bohr magneton.

These energy splittings are characterised by a new quantum number, M_F, which takes the values -F,-F+1,...,0,...,F-1,F. Hence, for a hyperfine energy level designated by the quantum number F there are 2F + 1 Zeeman sub-levels. To make it blatantly obvious, if F = 2 then M_F takes the values -2,-1,0,1 and 2. Refer to Fig. 1 for a schematic of the energy levels. Note that the spacings of The Zeeman levels are equal. This is not the case for high magnetic fields (see section 4).

2.3 Optical Pumping

Now we are approaching the crux of the prac. Normally light is polarised in random orientations. We can use a polariser to select one of these orientations. In this case, the light is said to be linearly polarised (π-polarised). Light can also be circularly polarised (σ-polarised). This means that the **E** field rotates about the optical axis (direction of propagation). We can do this by using a 1/4 waveplate (see section 3.1) in front of the linear polariser. The interesting thing about circularly polarised light is that it has angular momentum. In fact, whenever an electron de-excites and happens to change its angular momentum, it gives off a photon with the opposite angular momentum to the change (conservation of angular momentum).

Question 3 *What is a selection rule? What are the selection rules for the change in M_F?*

If we can get a beam of σ-polarised light to have photons of a particular angular momentum, we can force the electrons to be excited into higher ΔM_F = +1 (or lower ΔM_F = -1) angular momentum states. If we look at the energy level diagram of ^{87}Rb and exclusively apply the selection rule ΔM_F = +1 then it can be seen (Fig. 1) that the ground state M_F = +2 state cannot be excited. Any electron starting in this state is essentially stuck. Over time, electrons will decay into this level and it will become highly populated at the expense of the other levels. This is OPTICAL PUMPING.

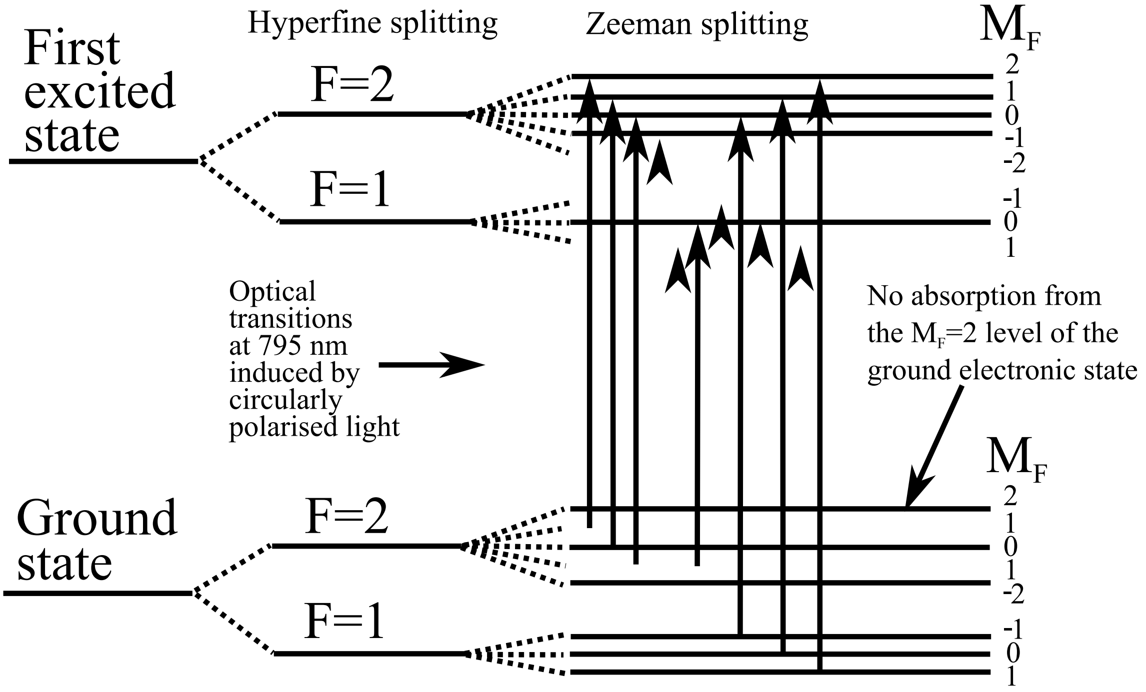

Figure 1: Transitions involved in the optical pumping of ^{87}Rb (not to scale). In the absence of collisions, spontaneous emission will eventually drive the atomic population into the M$_F$ = 2 level of the ground state.

Question 4 *Which state is optically pumped if the σ light is polarised such that ΔM_F=-1?*

The above discussion has been about *electric* dipole transitions. If we apply a RF magnetic field we can induce *magnetic* dipole radiation. In the set-up of this experiment the selection rules for magnetic dipole transitions are ΔF=0 and ΔM_F=± 1. This will produce transitions between the magnetic (Zeeman) sub-levels. This will tend to re-distribute the electrons from the optically pumped state.

2.4 Population of Energy States

In the absence of any applied radiation to pump or de-pump the levels, the population of energy states at thermal equilibrium will be given by the Boltzmann distribution law:

$$\frac{n_2}{n_1} = e^{-\frac{(E_2 - E_1)}{k_B T}} \tag{4}$$

where n_1 and n_2 represent the population of two levels with energies E_1 and E_2.

Question 5 *The circularly polarized light we use to promote electrons into the excited state has a wavelength of 795 nm. In the absence of this stimulus, what proportion of the electron population would we expect to find naturally in an excited state at room temperature?*

Now consider the Zeeman-split magnetic sublevels of the ground state. We will be investigating their resonant behaviour at applied magnetic fields of around 1 Gauss. For Rb^{87}, what would we expect the population distribution to look like at room temperature, for an applied field of this strength?

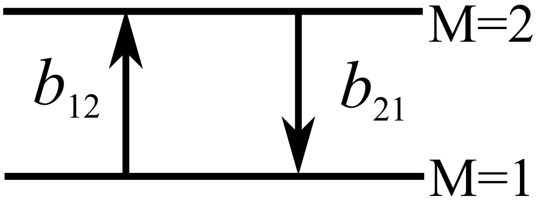

Figure 2: RF transitions between the $M = 2$ and the $M = 1$ magnetic sublevels

From the calculation above, it can be seen that in thermal equilibrium we expect our magnetic sublevels to have populations that are essentially equal (this shows what a tiny perturbation Zeeman splitting really is!). When optical pumping occurs, however, the system will be driven from equilibrium by the application of an external field, and the population of the magnetic sublevels will become unequal.

If this pumping process was all that was happening, the result would be a very large increase in the population of the $M = 2$ ground state. However, we must also consider collisional processes between the pumped atoms and other Rb atoms, as well as with the atoms of the buffer gas and the walls of the cell. These collisions will result in transitions between the magnetic sublevels, and as such will tend to equalize the population of the states.

This means that the actual amount of pumping that will occur will be determined by a balance between the rate of transitions into a pumped state, and the rate at which atoms are removed by collisional relaxation processes. After the pumping light has been on for a sufficient time (usually on the order of ms), a new equilibrium will be established, and the intensity of the detected light will reflect this new equilibrium. If an RF field is now applied, transitions with $\Delta m = \pm 1$ will tend to drive the system back to its original distribution.

To understand the nature of this decay back to an equalized population, we can use basic rate equations to simulate the situation. To simplify things, let's consider only the $M = 2$ and $M = 1$ magnetic sublevels, and make the assumption that the effects of collisional relaxation will be negligible.

In Figure 2, the arrows labelled b_{12} and b_{21} represent the transition probabilities from the $M = 1$ to the $M = 2$ and the $M = 2$ to the $M = 1$ sublevels respectively. The rate equations are:

$$\frac{dp_2}{dt} = -b_{21}p_2 + b_{12}p_1 \tag{5}$$

$$\frac{dp_1}{dt} = -b_{12}p_1 + b_{21}p_2 \tag{6}$$

Since in this approximation we are dealing with a two-level system, further simplifications can be applied. Two conditions that must be true in this case are $b_{12} = b_{21} = b$, and $p_1 + p_2 = 1$.

Question 6 *From this information, it should be possible for you to obtain a differential equation for* p_2*, which you can then solve to obtain the population level of the* $M = 2$ *state as a function of time. According to this model, what does the behaviour of a decay from an optically pumped state with initial population* p_0 *look like?*

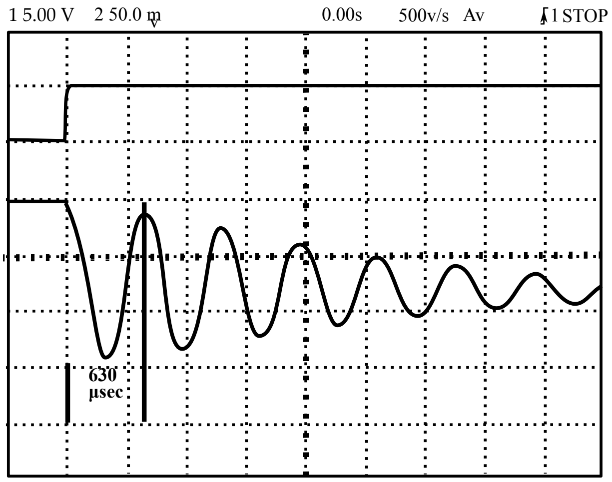

Figure 3: Damped Rabi oscillations of an optically pumped state in an applied RF field

2.5 Transient Effects

While the application of a resonant RF field will indeed lead to an equalized population distribution, over the short term the decay behaviour of the system will not correspond to the simplistic situation we described in our rate equations. This is because we have been considering our two-level system purely as a classical problem, whereas in reality we are dealing with a quantum mechanical system.

If you examine the two-state system using a full quantum mechanical treatment of the atom - based on the probability of a transition taking place at a given time - the result you obtain is that the system will undergo cyclic probability oscillations between the two magnetic sublevels, in a process known as Rabi oscillation. The interesting thing to note is that the quantum calculation tells us that there will be times when the entire population of atoms can be in either of the two states (which contradicts the classical rate equation result, since only half of the population could decay back into the $M = 1$ state, but no more than this).

In the ideal case, this oscillating cycle of excitation and de-excitation would continue indefinitely, so long as the applied RF field remained constant. However, in reality we are not dealing with an ideal system, since the interaction of our two-level system with the outside environment will tend to disturb this quantum mechanical behaviour. The result of this will be a continuous damping of the oscillating probability signal, known as 'decoherence', until the quantum effects disappear and the system decays to the classical equilibrium value given by our rate equations in the section above. (The fact that the quantum mechanical result will decay into its classical counterpart after decoherence is a good example of Bohr's correspondance principle!)

In terms of our experiment, the Rabi oscillations will be observed as a damped sinusoidal oscillation of the intensity of the detected light just after the RF field has been applied. We expect this signal to then decohere rapidly to a central intensity point which characterizes an equalized population distribution and the establishment of a new equilibrium (see Figure 3).

In state-of-the-art optical pumping experiments, the atoms are kept in a special paraffin-coated glass cell, which prevents them from depolarizing when they collide with the cell walls. Using methods like this, physicists have been able to extend the coherence time of Rabi oscillations to around the 1 second mark. Of course, since our system is not exactly 'state-of-the-art', our coherence time is likely to be substantially less than this!

One of the major aims of this prac will be to study the transient behaviour of an optically pumped state. We will try to observe the Rabi oscillations that occur when depumping begins, and use them to confirm results we obtained from resonance measurements on the two Rb isotopes.

3 Experiment

3.1 Apparatus

Rubidium discharge lamp - a bulb filled with Rb gas and a xenon buffer gas. Stray ions in the gas are accelerated by an RF electric field. Collisions between these atoms and the buffer gas cause further ionisation or excitation. The bulb is heated to increase the vapour pressure (more collisions).

Lenses - the first lens, placed directly after the lamp, is to collimate the beam (necessary for the waveplate). The second lens, placed just before the detector, is to focus the beam onto the detector.

Filter - gets rid of all discharge lines from the lamp except the 795 nm line. This line is in the near-infrared and is not visible. The purple-pink discharge you see is from other rubidium lines and xenon lines.

Polariser and 1/4 waveplate - a polariser is necessary to allow the waveplate to work. The waveplate will produce circularly polarised light of one type - there are two types: left handed and right handed - only if illuminated by linearly polarised light.

Question 7 *How is it possible to check, using a second polariser, whether outcoming light from the waveplate is circularly polarised?*

Cell and heater - the cell is an insulated perspex cylinder with a bulb of rubidium and neon buffer gas. The bulb can be heated to change the Rb pressure and density.

Magnetic field coils - The vertical field is to cancel the local field due to the Earth's magnetic field. The horizontal field is for the Zeeman effect and the sweep field is for viewing the **B =0** resonance. The currents going through the horizonatal coils can be measured at the tip jacks on the electronics box, using the voltmeter and converting to Amps using V=IR and the value of the resistor. All these fields are controlled by the electronics box. (NB: DO NOT have a situation where the sum of the sweep field currents (Range + Start Field controls) is above 1 Amp.)

RF coils and signal generator - the RF magnetic field coils are located on the cell. The field is produced by a signal generator plugged into the electronics box.

3.2 Zero Field Resonance

Align the optical bench with the detector facing magnetic North. This makes it easier for the Helmholtz coils to cancel the residual magnetic field.

Familiarise yourself with the equipment and make sure all the wires are in the right places. You can do this by checking the labels on the wires or tracing them to the components on the optical bench. If you are still lost, refer to page 5-3 of the TeachSpin manual. Now turn on the electronics box at the back. Check that the set temperature of the cell is 50°C. This can be done by pushing the SCROLL key on the regulator (LED display) twice. Then press the ENTER key. The up and down keys can change the set point. Push SCROLL twice again until RUN appears. The lamp will take 15-20 minutes to warm up. You should see the purple-pink discharge after a few minutes. Wait for the full 20 minutes before you try to maximise the output.

The optics should be set up thus as in Fig.4.

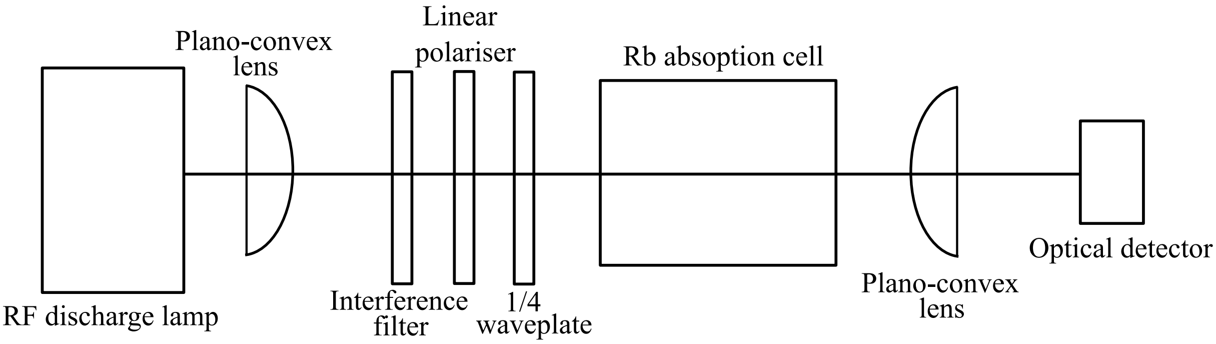

Figure 4: Alignment of optics.

Notes:

- The linear polariser should be set at 45°.
- The 1/4 waveplate should be set at 0°.
- The lenses should have the flat sides about 5 cm from the lamp and detector respectively.

Once the optics are set up you can look for the alignment that gives maximum detector signal. Maximum signal means the galvanometer on the electronics box produces a high reading. This should not be a problem since the source is very bright. The most important thing is that the height of all the components is centred at the height of the centre of the cell.

Initially all the magentic fields should be set to zero (knobs fully counter-clockwise.) There should be no RF field applied. The gain on the detector (set by toggle switch at the detector) should be 10 MΩ. It may need to be reduced to 1 MΩ if the signal is off scale. The Detector Amplifier Gain should be set to 1. Gain Mult. should be x1, Time Constant = 100 ms, Meter Multiplier = x1. Test what happens when you block the beam. The signal should go to zero. If the signal is still off scale, change the Meter Multiplier to x2. If worst comes to worst, defocus the detector lens.

Next, we need to adjust the Gains on the detector so that we can pick up a very small variation in intensity. The zero field resonance reduces the intensity by only about 2%. Adjust the DC offset so the meter reads zero then turn up the Gain to 20. Make sure the meter is not off-scale. Adjust the Gain as necessary.

Now set the vertical field to 0.33 Amps (3.0 on the dial.) This is enough to cancel the vertical component of the Earth's field in Buffalo, NY. The field may need to be at a different strength, but this is a good starting number. Now let's figure out what the Sweep Field does. Plug the X-axis on the CRO into the Horizontal Sweep field Recorder Output. The output should appear as a horizontal line if the CRO is in Y-T mode. You may have to adjust a few things to get it. Explore. Look at the Sweep field controls. Set the Start field to an arbitrary number (make it low). Do the same for the Range. Observe what happens to the line if you have the ‘start/reset’ toggle on ‘reset’ and switch it to ‘start’. What difference does the ‘single/continuous’ toggle make? Make your conclusions about what the Start field, Range and Recorder offset do.

We will now try to observe the zero-field resonance. When the magnetic field is zero, there should be a dip in the transmitted light because there is no Zeeman effect, hence no optical pumping, and there are more electrons available to absorb light. We use the Sweep field to cancel the horizontal component of the Earth’s field. We produce a time dependent horizontal field which, if swept slowly enough, will at some stage cancel the Earth’s field and produce a resonance.

Plug the detector output into the Y-input of the CRO and switch the CRO to X-Y mode. Make sure both outputs are DC coupled. Now the output is a dot. Find it. Now, to track this dot you can select ‘display’ on the CRO then ‘persist’ and ‘infinite’. Return the Start field and Range settings to zero. Set the ‘start/reset’ toggle to ‘reset’ and slowly increase the Start field. You expect to see a broad dip in intensity (around 3 or 4 on the Sweep field dial.) If you do not see it, try adjusting the vertical field by one unit, then sweeping again. If this is not working, try swapping the banana plugs (i.e. reversing polarity) on either the vertical or horizontal Sweep fields. It is possible that the local magnetic field in the room is affecting the cell more than the Earth’s field.

Once you have found the dip you will want to minimise its width. Adjust the Start field so it is at the side of the dip, then adjust the vertical field and the position of the optical bench to maximise the signal. Get it?

If you are happy with your **B = 0** dip then you are ready to go on with the rest of the experiment.

3.3 Nuclear Spins measured via the Zeeman Effect.

Set the cell temperature to 320 K. Replace the linear polariser and 1/4 waveplate.

We will now pretend we don’t know the nuclear spins of ^{85}Rb and ^{87}Rb and proceed to measure them. In order to do this we will need to find out the g_F values. The magnetic field can be determined approximately from the geometry of the field coils. Since nuclear spins are either integral or half-integral we only need an approximate value the field.

The coils we will use will be the Sweep field coils. They have the following parameters:

$$B(gauss) = 8.991x10^{-3}\frac{IN}{R} \tag{7}$$

Mean radius R=0.1639 m, N=11 turns on each side.

Disconnect the main horizontal field coils. We will only be using the sweep coils for this part. Remember to measure the sweep coil current using the voltmeter over the 1 Ω resistor (1 V means 1 A). Find the zero field resonance again. Calculate the residual magnetic field using Eq. 7.

Now, apply an RF field of about 150 kHz. The amplitude is not important at the moment. You can check the frequency on the CRO. Sweep the horizontal sweep field slowly from zero and record the

B field current of any Zeeman resonances you see.

Question 8 *How do we know which isotope the resonances come from?* Hint: draw a graph of ΔE versus B for each isotope.

Observe what happens to the RF transitions when you alter the RF amplitude. Determine the value that give maximum transition probability and use that value for the rest of this section.

3.3.1 Low field Zeeman effect

Now measure the sweep coil current for the resonances at different frequencies of RF field, for example, between 0 and 200kHz. Plot RF frequency on the Y-axis of a graph and resonant field current on the X-axis. You should produce a straight line for each isotope. The ratio of the gradients of the lines should be the ratio of the g_F-factors. How do these compare with theory?

You now have enough information to find the g_F-factors using the ΔE equation at a particular energy. You will have two sweep field resonance values at this energy - one for each isotope. *Be careful: you need to subtract the residual field from your resonant field values.* From these g_F-factors you can find the nuclear spins.

3.3.2 Sweep Field Calibration

Rather than subtracting a residual field from every measurement we take, it would be nice to instead be able to convert our current readings directly into a magnetic field strength.

Now that we have worked out the g_F-factors for the two isotopes, this can easily be achieved. We are going to use the ΔE equation to find B, using the known values of g_F. We will then plot this against the sweep coil current. This will provide us with a calibration equation for the sweep coils that automatically takes the residual field into account.

3.4 Rabi oscillations

So far we have only been investigating optical pumping as a static phenomenon; that is, when our system has already reached thermal equilibrium. What we want to do now is to study the system as a function of time, as it is transitioning from one equilibrium point to another.

To achieve this, we are going to turn the RF field on and off rapidly while tuned to the centre of a low field resonance, and observe the transmitted light intensity as a function of time. To start, set the cell heater to $50°$C, and allow around 30 minutes for the temperature to stabilize. Apply an RF frequency of 100 kHz, and tune the magnetic sweep field until you are positioned at the bottom of the first resonance dip. In order to observe the Rabi oscillations, we will want to keep our experiment covered with a cloth at all times (or alternatively, you could just turn off the lights).

Question 9 *Why do you think this particular part of the experiment is so sensitive to the presence of light, while in contrast we were able to complete all our previous measurements with the optical pumping stage uncovered?*

Now turn on the pulse generator, and set it to generate square waves with a frequency of around 5 Hz and a height of less than 5 V (check this on the CRO). Connect the square wave output both to the RF modulation input on the electronics box, and to the EXT channel of the CRO (use a T-junction). The CRO should be set back to YT-mode, and the detector output cable plugged into channel 1 on the CRO. The recorder output can be disconnected, as we won't be needing it in this experiment.

What we are doing here is pulsing the applied RF field on and off several times a second, and setting the CRO to begin its trace just as each pulse has been applied. In this way we are able to see the transient response of the detected intensity signal before it has had time to reach thermal equilibrium. Using a frequency of only 5 Hz allows the signal enough time to achieve thermal equilibrium before the next pulse is applied. You should also decrease the time constant on the pumping box to 1 ms, as this will allow the signal to be processed quickly enough to capture the intensity oscillations we are looking for.

We can set the CRO to trigger either on the rising or falling edge of our square wave pulses. In this way, we can get the CRO to display the behaviour of the system either just after the RF pulse has been turned on, or alternatively, just after it has been turned off and pumping resumes. To do this, we go into the Trig menu on the CRO, and change the source to EXT. Now choose Edge triggering, and set the CRO to trigger either on a rising or a falling slope, depending on what you want to observe.

We'll start by examining the signal as it is being optical pumped (i.e. when the RF pulse has just been turned off). Unlike the quantum effects we expect to observe with the application of an RF field, the one-way nature of the pumping process ensures that the transient pumping signal will behave classically, so its behaviour should be similar to that described by the rate equations we worked out earlier. As such, optical pumping will be a simple exponential process, with the time constant of this exponential being defined as the 'pumping time'. You can estimate this by measuring the time it takes for the intensity signal to reach $1 - 1/e$ of its maximum value. (The pumping time will be proportional to the intensity of the pumping light that is applied).

It is now time to try to observe the Rabi oscillations that occur during depumping. The timescale on the CRO will have to be made much smaller in order to view them properly. Note that even with a cloth to cover the experiment, the signal is still likely to be quite jumpy and sometimes irregular. If the signal starts to drift off resonance, smearing out the oscillations, you will have to tweak the applied sweep field slightly to correct for this. As the Rabi oscillation signal is very weak, it can easily be swamped by electronic noise and interference from the outside environment.

Since the signal is unlikely to remain steady for very long, the easiest way to take measurements of the oscillations is to use the 'Single Seq' button on the CRO. This will take a snapshot of the screen at a single moment in time, so you can keep pressing this until a good signal appears. Measurements can then be done on that static image of the waveform. The best way to handle this is to use the Cursor menu on the CRO. This will create two vertical lines, which can be positioned with the vertical and horizontal positioning knobs to measure the period of the oscillations. You can press the 'Run/Stop' button at any time to resume normal CRO operation.

We will be plotting the period of the Rabi oscillations as a function of the applied RF voltage. In Section 2G of the Teachspin manual, it is demonstrated that the period of oscillation between the two sublevels will be given by:

$$T = \frac{1}{g_F \mu_0 B_{rf}/\hbar} \tag{8}$$

where B_{rf} is the applied RF magnetic field. Obviously, the greater the amplitude of the RF field we apply, the faster the depumping will occur, and hence the faster the population distributions will equalize and the system will reach its new equilibrium. Since the RF voltage is proportional to this applied RF field, this means that the period of the oscillations should be inversely proportional to the applied RF voltage, V_{rf}.

Question 10 *From the information given above, it can be shown that for a given* V_{rf} *value, the ratio of the periods of oscillation for the two isotopes should be equal to the ratio of their g-factors. Prove this.*

You can measure the RF voltage at the two electrodes on the connector on the cell holder. Use the specialized cable with two alligator clips on one end and a BNC connector on the other for this, and view the signal on the spare channel of the CRO. Plotting the period against the inverse of the voltage for each isotope, we can obtain a gradient for both curves, and this should enable us to verify the ratio of the two g_F-factors we obtained through our earlier resonance experiments.

4 Extra Work

The *quadratic* Zeeman Effect is where the Zeeman Effect is no longer linear in B (ie. a strong **B** field.) The spacings between the Zeeman levels are no longer equal. Hence there will be 2F resonances for each isotope (6 for I=3/2 and 10 for I=5/2.)

The magnetic field at which these resonances can be seen is approximately:

$$\nu = g_F \mu_0 B / h \tag{9}$$

In order to take quantative measurements of the quadratic Zeeman Effect, we will first have to calibrate the main field coils.

4.1 Main Field Calibration

Connect up the main field coils so that their field is in the same direction as that of the sweep coils. The current control for the main coils is too coarse to allow the resonances to be centred well using it alone. It will be necessary to use both the main coils and the sweep coils for this calibration. The voltage presented by the main coil monitor on the front panel (which is developed across a 0.5 Ω resistor) is one half of the main coil current in amps. Use this voltage as a measure of the main coil current.

Use both sets of coils to make measurements at resonance frequencies up to about 1 MHz, and use the sweep coil calibration to correct the measured fields for the residual field. Plot the data and fit a line to it. If you are lost, please refer to page 4-11 of the TeachSpin manual.

4.2 Quadratic Zeeman Effect

You can use your calibration to choose the correct current. Start with the main field current at zero, and set the sweep field current to the centre of the zero field transition. Then set the main field to the desired value, and use the sweep field to observe the resonances. For a given frequency, measure the sweep field current corresponding to each resonance, and calculate the total magnetic field. If the first frequency you try does not yield resolved resonances go to a higher frequency. See sample data from pages 4-12 to 4-16 of the TeachSpin manual.

Acknowledgements

These notes draw heavily from the TeachSpin Manual (Copyright TeachSpin Inc, Buffalo NY).
First version of these notes generated by Matthew Norman in 2004.
Second version of these notes generated by Toby Hopf in 2005.

References

[1] B H Bransden and C J Joachain. *Physics of Atoms and Molecules; 2nd ed.* Prentice-Hall, Harlow, 2003.