



THE UNIVERSITY OF
MELBOURNE

Optical Pumping of Rubidium

Part 3 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. As a preliminary investigation, you will measure the absorption cross-section of Rb gas. You will then begin a series of tests of quantum theory. 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. Time permitting, you will measure the quadratic Zeeman effect. If this is either enticing or confusing, read on.

2 Some words about third year labs

These notes **don't** contain all the information you need - they're here to define the terms for you, and to give you an idea of the direction you should be taking. You'll find that you need to go foraging for more detailed information in other places - often in the references, and even more often in the rubble of your demonstrators' minds. You're going to learn a lot while you're doing that, so don't waste the effort - share all the work you're doing with us in your report! Remember that your report has to be self-contained. It doesn't have to be beautiful, but it should be clear and detailed. Perhaps the most important thing to remember is that when you write your report you're trying to **teach** your reader what you did, why you did it, and what you learned. That way, we get to learn something too! Enjoy!

By the way, these notes have recently undergone a major revision, and may be littered with typos (and possibly more serious errors). We in part3 would love it if you could bring any mistakes to the attention of your demonstrators, or email suggestions to part3@physics.unimelb.edu.au

3 Theory

3.1 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 \mathbf{I} is the spin of the atomic nucleus. Again, the vector addition of the quantum numbers \mathbf{I} and \mathbf{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 \mathbf{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 $\mathbf{F} = \mathbf{I} + \mathbf{J}$ where $I = 3/2$ and $J = 1/2$. Do the same for ^{85}Rb , where $I = 5/2$. (Reference [1] again)*

3.2 The Zeeman Effect

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

$$\Delta E = g_F \mu_0 B M_F \quad (1)$$

Where:

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

and:

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

and μ_0 is the Bohr magneton.

These energy splittings are characterised by a new quantum number, M_F , which takes the values $-F, -F+1, \dots, 0, \dots, F-1, F$. 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 5).

3.3 Absorption

In passing through a volume of gas, light is attenuated. The outgoing flux, I , of photons can be related to the ingoing flux, I_0 , by the relation

$$I = I_0 e^{-\sigma_0 \rho l} \quad (4)$$

Where:

σ_0 is the maximum absorption cross section measured at the centre of atomic resonance

ρ the density of Rb gas

and l is the path length (distance travelled through gas).

If we used particles instead of light we would think of a geometrical cross section (σ). That is, the cross section represents the area over which the particles interact with the atom (usually the cross sectional area of the atom $(10^{-10})^2 \text{m}^2$.) In the case of light, the cross section may be significantly different to the geometrical cross section because of the process of resonance. We would expect the strength of the interaction to be greater. In fact, the cross section is found to be of the order of λ^2 .

3.4 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 \mathbf{E} field rotates about the optical axis (direction of propagation.) We can do this by using a 1/4 waveplate (see section 4.1) 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 $\Delta M_F = +1$ (or lower $\Delta M_F = -1$) angular momentum states. If we look at the energy level diagram of ^{87}Rb and exclusively apply the selection rule $\Delta M_F = +1$ 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.

Question 4 *Which state is optically pumped if the σ light is polarised such that $\Delta M_F = -1$?*

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

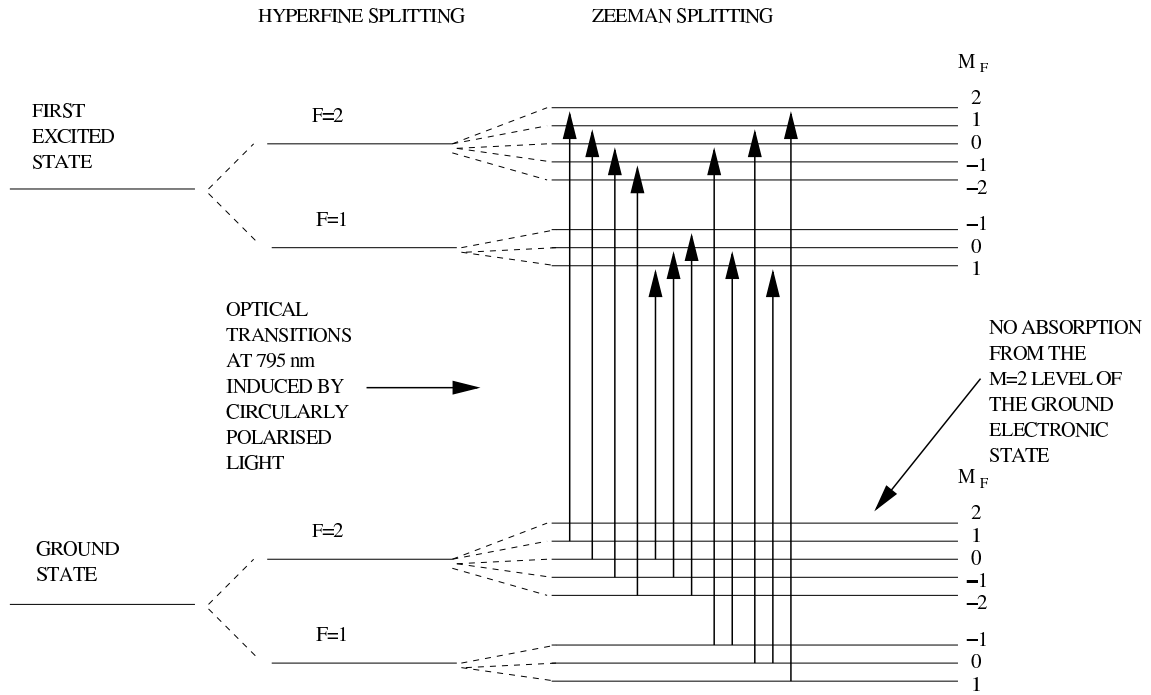


Figure 1: Transitions involved in the optical pumping of ^{87}Rb (not to scale.) In the absence of collisions, spontaneous emission will eventually drive the atomic population into the $M_F = 2$ level of the ground state.

rules for magnetic dipole transitions are $\Delta F=0$ and $\Delta M_F=\pm 1$. This will produce transitions between the magnetic (Zeeman) sub-levels. This will tend to re-distribute the electrons from the optically pumped state.

4 Experiment

4.1 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 5 *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 $\mathbf{B} = \mathbf{0}$ resonance. The currents going through the horizontal 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.

4.2 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.2.

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 5cm 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

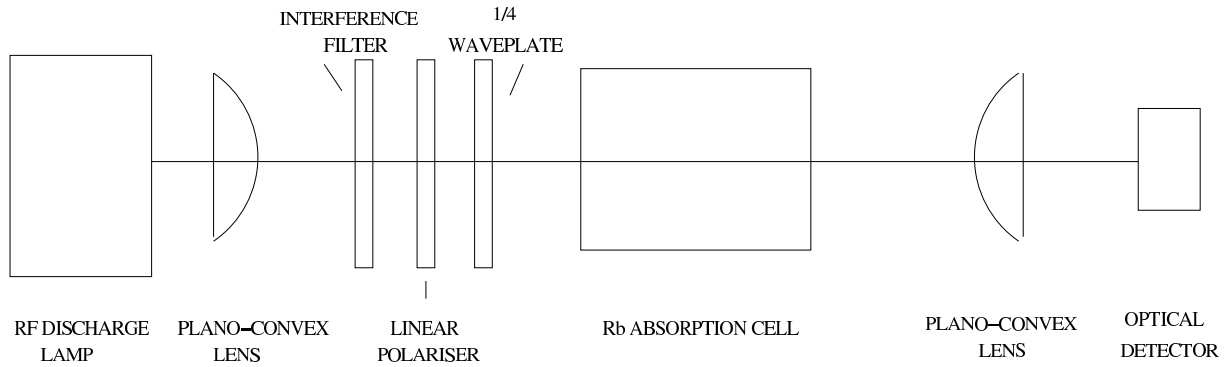


Figure 2: Alignment of optics.

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 magnetic 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 $10M\Omega$. It may need to be reduced to $1M\Omega$ if the signal is off scale. The Detector Amplifier Gain should be set to 1. Gain Mult. should be x1, Time Constant = 100ms, 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 $\mathbf{B} = \mathbf{0}$ dip then you are ready to go on with the rest of the experiment.

4.3 Absorption Cross-Section

The first experiment you will do will be a measurement of the absorption cross-section of Rb as a function on temperature.

The optical set-up should be as in Fig.2 *without* the 1/4 waveplate and polariser.

Put the detector gains back to their original settings. Set the cell heater to 300 K, and allow 30 minutes for thermal equilibrium to be established. You may find after this that the detector is saturated. You can de-focus the beam using the detector lens if necessary.

Question 6 *The galvanometer gives readings that are not in units of intensity. If we are to use Equation (1) to find σ_0 , do we need to know I and I_0 ? Why or why not?*

Once you have a non-saturated reading on the galvanometer, record it. Now change the set temperature to 310 K. Wait until thermal equilibrium is reached, that is, all readings are stable, and record the reading. Keep going in 10 degree increments until 370 K. The cell heater can't go much higher than 100°C.

The density of Rb in the bulb as a function of temperature is given by the table on page 4-2 of the TeachSpin manual. With this knowledge you can now plot the graph of density versus intensity. Fit the graph with Excel or Sigmaplot. The path length is 2.5 cm. Calculate σ_0 .

4.4 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:

$$B(\text{gauss}) = 8.991 \times 10^{-3} \frac{IN}{R} \quad (5)$$

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 1Ω resistor (1 V means 1 A). Find the zero field resonance again. Calculate the residual magnetic field using Eq. 5.

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

You can measure the RF current, which is proportional to the RF field, at the two electrodes on the connector on the cell holder. The signal is developed over a 50Ω resistor and is therefore proportional to the amplitude of the RF field.

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.

4.4.1 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.

4.4.2 Sweep Field Calibration

OK, now we're going to backtrack a bit. In order to do the next section we are going to need a calibration of the magnetic fields. 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 a calibration for the sweep coils.

4.4.3 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 0.5Ω 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.

5 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:

$$\nu = g_F \mu_0 B / h \quad (6)$$

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.

Extra Extra Work.

The interaction energy is given by the Breit-Rabi equation:

$$W(F, M_F) = -\frac{\Delta W}{2(2I+1)} = \frac{\mu_I}{I} B M_F \pm \frac{\Delta W}{2} [1 + \frac{4M_F}{2I+1} x + x^2]^{1/2} \quad (7)$$

where

$$x = (g_J - g_I) \frac{\mu_0 B}{\Delta W} \quad (8)$$

and

$$g_I = -\frac{\mu_I}{I \mu_0} \quad (9)$$

Solve the Breit-Rabi equation for the particular values of B you chose. It can't be solved analytically so you will have to use a program like Mathematica or Maple 5.

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.

References

- [1] B. H. Bransden and C. J. Joachain. *Physics of atoms and molecules*.

Safety in the third year laboratory

This is to certify that the undersigned person has completed the following:

- they have read and understood the "General Safety notes" for the overall third year experimental laboratories;
- they have read and understood the safety notes specific to the experiment listed below;
- they have been trained in the use of specialised equipment used in this experiment by the demonstrator listed below.

Experiment:

Specialised equipment:

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Demonstrator:

Print name

Signature

Student:

Print name

Signature

Date: