

Fortgeschrittenen Praktikum Teil 2: PI

Versuch 3: Optisches Pumpen

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1 Target

In our experiment concerning optical pumping, we want to evaluate the different energy states of an atom and its details of Rubidium. We want to show, how they can be changed into another and especially, how the magnetic moments of gas atoms can be aligned in the same direction. This is useful for different, for example medical and physical uses. In the first part we measure the time it needs to polarize the gas atoms in the same direction to its maximal amount, while we evaluate the splitting energy of Zeeman-states in the second part. Additional results will be the relaxation time of the polarized gas and the Landé-factor.

2 Theoretical

2.1 Energy States of Rubidium and Zeemann-Effect

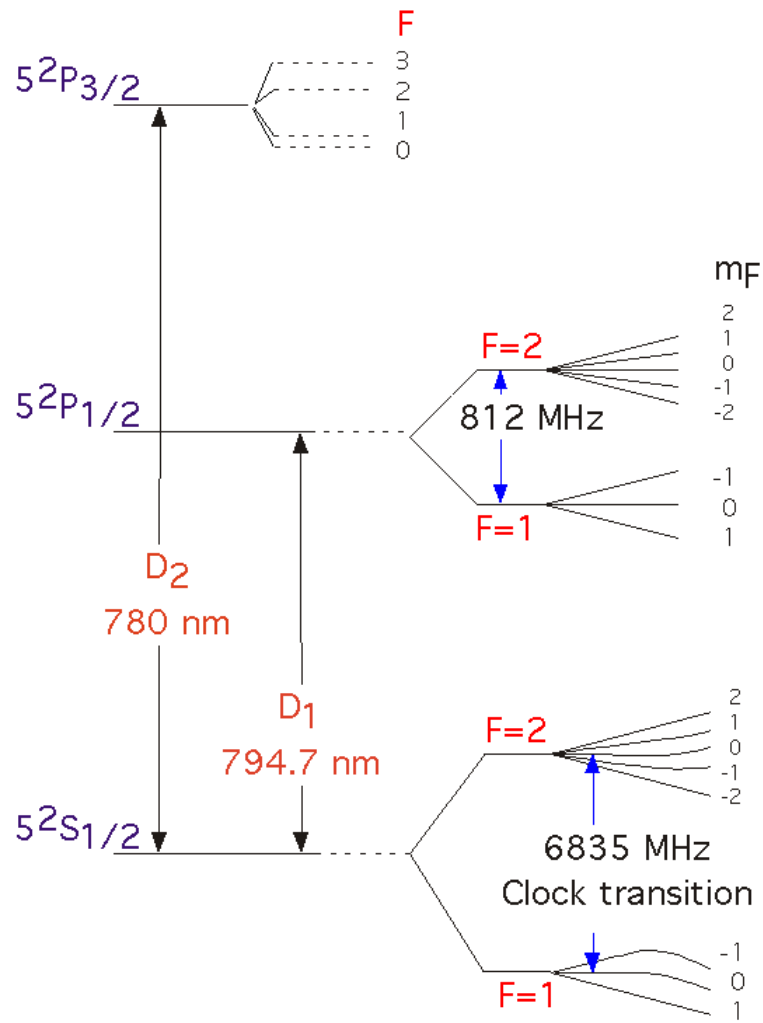
According to rules of Quantum Mechanics, every atom has its own quantized energy states, in which the electrons are positioned. The states are described by some quantum numbers, which are called n , l and s . n is the energy quantum number, l describes the angular momentum and s shows the electron spin and obviously is $s = \frac{1}{2}$. We notate these states as 1S, 2S, 2P and so on. The angular momentum and spin couple to the so-called finestructure. This are some energy corrections to the states, which also can split up through this coupling. Mathematically, we add the quantum numbers l and s to the total angular momentum j . Because the directions of l and s can be the same or different, we get in the case of $l=1$ two different possibilities for J , which are generated by $J = \frac{1}{2}$ and $J = \frac{3}{2}$ and have different energy niveaus. Our notations changes so to $1S_{\frac{1}{2}}, 2S_{\frac{1}{2}}, 2P_{\frac{1}{2}}, \dots$.

For the complete correct energy niveaus, we have to add another quantum number, which describes the spin of the atomcore. It is called I and counts $I = \frac{3}{2}$ in our case, as we work with $^{87}\text{Rubidium}$. The angular momentum I therefore adds to the total angular momentum J to another total angular momentum called F . The resulting energy states are called hyperfinestructure.

In Figure 1 are plotted the S and P states of Rb. Additionally there are marked the wavelenghts for the energy difference of the different states and the magnetic quantum number m , which always appear with an angular momentum quantum number. In our case, the resulting angular momentum quantum number is F and m_f always runs from $-F$ to F , so the figure can be understood well. Without external fields, the energy of all states with different values of m is exactly the same, so usually there is no such splitting seen.

The existence of these magnetic quantum numbers is responsible for the so-called zeeman-effect, which appears if we put our atom in a small magnetic field. It is possible to calculate the energy correction effect of the magnetic coupling of external field and orbital angular momentum. The correction counts $E_Z = g_F \mu_0 B m_f$ According to that, we now have different energx levels for different values of m_f . Our old energy states is so split up in $2F + 1$ states with different energies, which are separated by the same energy

^{87}Rb Ground and First Excited State Structure



levelDiag87.CNV

Figure 1: Energy states of ^{87}Rb [Phi18]

difference. g_F is the Landé-factor, which is different in every state of the hyperfine structure can be calculated by [Bla11]:

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

And continued:

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

2.2 Optical Pumping

If there is light of a certain wavelength (794.7nm), the electrons in the Rubidium atom can be raised from the groundstate $^2S_{1/2}$ to the first excited state $^2P_{1/2}$. But for this transition there is a transition rule that has to be followed. A circularly polarized photon has an angular momentum of an amount of $1\hbar$. We will call the light σ^+ if the photons have a positive angular momentum relative to the direction of the applied magnetic field. Similarly we call the light σ^- if the photons have a negative angular momentum relative to the magnetic field [Ben63]. As an example right-polarized light parallel to the magnetic field would be σ^+ . At last linearly polarized light is called π and does not have an angular momentum.

Now you can look at the absorption of an σ^+ -photon in the Rubidium 87 gas. The photon vanishes and for the conservation of angular momentum the angular momentum of the electron has to increase by 1. This means to the quantum number m_f has to be added 1, if it is possible. There do not exist states with $m_f = +3$, so the atoms in the $+2$ state do not absorb σ^+ -photons. For σ^- m_f decreases by 1 and π doesn't change the quantum number m_f . Due to spontaneous radiation emission the atoms can return to the groundstate. Within this process they are emitting π, σ^+ or σ^- photons so that all groundstate sublevels can be populated again.

Now we only have σ^+ pumping light and because of the continual absorption and emission the quantum numbers m_f of the atoms will be raised gradually until they reach $+2$. There the atoms are trapped and a nonthermal distribution is achieved. Processes where a nonthermal distribution is achieved by light is called optical pumping in general.

When the maximum population of $m_f = +2$ is reached the excitation of the atoms by the σ^+ photons is at minimum and so the Rubidium gas becomes the most transparent for the light. The intensity after the light has passed the gas can be used to measure the degree of polarization of the gas. There are always some radiative transitions to the groundstate, but this doesn't compensate the absorption. Additionally there can be nonradiative transitions as an effect of collisions which also lead the atoms in the ground state. So even when the gas has reached its most transparent phase, the gas still absorbs some light.

2.3 Stimulated emission

As we learned in the pervious section, we can raise electrons to an upper energy state by light with a certain wavelength. If all electrons are raised in the upper energy state with $m_f = 2$ and we continue to radiate light with wavelength of the energy difference of the states, we can also get another effect called stimulated emission. Thereby, the incoming photon is not absorbed, but induces another photon with the same wavelength, which is emitted. The electron then loses energy and is dropped back to the old lower energy state. The two or more photons are coherent and have exactly the same wavelength, so the built radioation can be used for example to build a laser. This effect can also be reached by an alternating magnetic field, which oscillates with the frequency of $\nu = g_F \frac{e}{4\pi m_f} B$.

3 Construction of Experiment and used Devices

Central part of our experiment is a cell with the rubidium gas in it, which we want to investigate. In its normal compound, natural rubidium consists of 72% ^{85}Rb and 28% ^{87}Rb , so we have both isotopes in the cell.

We also need a lamp, from which we radiate the light to the rubidium cell. In the direct opposite of the lamp, we have a detector to measure the incoming and therefore not absorbed radiation. The signal of the detector is shown by an oscilloscope, where we can do our measurements of the signal. Of course, we have to use polarized light of a special wavelength for optical pumping, while the light of the lamp is unpolarized. So we have three filters in the beam between the lamp and the Rb-cell. This and the following setup can be seen in figure 2 The first filter selects one special wavelength wich can pass the filter, other wavelengths are deflected. The next filter polarizes the incoming light linearly, so it can be polarized circular more easily. That can be reached by the third filter, which is a so-called $\frac{\lambda}{4}$ -plate. This is mainly a cristal with a special grid distance, which delays one part of the radiation wave and has no effect to the other part. After that filter, we have a right-handed circular polarized light of a certain wavelength, as we need to realize optical pumping. Also, our beam is focused twice by lenses, once for aiming the radiation in the Rb-cell and afterwards to be focused in the detector.

In our experiment, we need different magnetic fields, so we have three pairs of helmholtz coils around the rubidium cell. One of it generates a field in vertical direction, while the other two pairs generate horizontal fields. The coil pairs are driven either by a programmable DC power supply or a function generator for AC currents. Depending on the connected device, we can generate constant or oscillating magnetic fields.

Additionally, we heat our Rb-cell with a little heating system, so the Rb-atoms are completely in gas state.

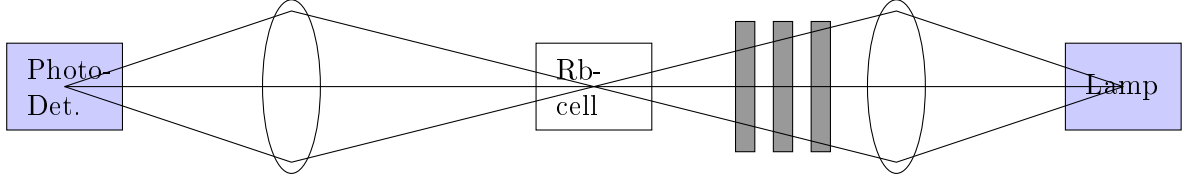


Figure 2: Schematical setup of the experiment

4 Execution and results

4.1 Optical pumping and relaxation time

In the first part of our experiment we want to measure the optical pumping time, which it takes to trap all electrons in the $m_f = 2$ -state. If we then turn off the magnetic field, all of the different m_f -states collapse to the same energy level and lose their polarization too. This takes some time, which is called relaxation time and which we want to measure, too.

If we simply would turn on magnetic field and radiation, the $m_f = 2$ - state would be reached so fast, that we would not see anything in our detector. So we have to distort the system so we can see the optical pumping process on the oscilloscope. For that, we apply an alternating current of the function generator to one of the horizontal Helmholtz coils, which generates a small alternating magnetic field. Additionally we put the alternating current signal to the oscilloscope so we can trigger our detector signal in reference to the magnetic field.

Before we can start our measurement, we need to compensate the earth magnetic field which otherwise would distort our results and even could make the measurement impossible because of its strenght. The earth magnetic field values are $B_h = 20\mu T$ and $B_v = 44\mu T$, while the magnetic field of a pair of helmholtz coils can be calculated by:

$$B = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0 n I}{R} \quad (3)$$

Where n is the number of windigs in the Helmholtz coils and R the radius of the coils. The characteristic values and the calculated current for the helmholtz coils are found in Table 1.

Table 1: Values of Helmholtz coils

| | B in μT | R in m | n | I in A |
|-------|--------------|--------|-----|--------|
| B_h | 20 | 0,15 | 400 | 0,005 |
| B_v | 44 | 0,2 | 20 | 0,302 |

With a so scaled DC current through the pairs of Helmholtz coils, we can start our measurement and apply an alternating current through the third helmholtz coils. With

that, we see a characteristic trace on the oscilloscope with a raise due to optical pumping and a fall due to the zero-point of the magnetic field and the decrease of polarization. The values for the measured charactersistic times are:

$$t_{opticalpumping} = 19,6ms \quad (4)$$

$$t_{relaxation} = 11,6ms \quad (5)$$

4.2 Energy splitting of Zeeman - states

In the second part of the experiment we want to measure the energy splitting of the different m_f -states which occur with a applied constant magnetic field. For this we apply a constant current to one of the helmholtz coils used for compensating the earth field in the first part. Important is to choose a field strenght much higher than the earth field, so its effect can be neglected.

To measure the Zeeman-splitting, we use the described effect of stimulated emission. Because of the very small energy difference between the Zeeman-states, we need a radiation with a high wavelenght in radiofrequency area. We realize this again by a alternating current, which we put directly on an antenne placed in the Rb-cell. The theoretical value of Zeeman-splitting can be calculated by:

$$E = g_f \left(\frac{e\hbar}{2m} \right) B m_f \quad (6)$$

The Landé-factor g_f can be calculate by the formula in the theoreticals part. As we have our atoms in the $^2s_{1/2}$ -state, we have $L = 0$, $S = \frac{1}{2}$ and $J = \frac{1}{2}$. For the nuclei-spins we have $I = \frac{3}{2}$ for ^{87}Rb and $I = \frac{5}{2}$ for ^{85}Rb . With that, we can calculate the theoretical Zeeman-splitting for both Rb-isotopes. With the relation $E = h\nu$ we can calculate our theoretical frequency, with which we need to apply the AC-current. Since we have different tolerances in our experiment which distort our measurements, we pick up three values for the applied magnetic fields (e.G. the applied DC current) and look for the resonant frequency which shows the appearing stimulated emission. The used currents and the calculated magnetic fields, frequencies and found frequencies for both Rb-isotopes are found in table 2.

The values for g_f for both Rb-isotopes are:

$$g_f (^{85}Rb) = \frac{1}{3} \quad (7)$$

$$g_f (^{87}Rb) = \frac{1}{2} \quad (8)$$

According to that, we calculate the experimental energy values and the average for both isotopes:

Table 2: Zeeman-splitting frequencies

| | B in $10^{-4}T$ | $\nu_{theo.} (^{87}Rb)$ | $\nu_{theo.} (^{85}Rb)$ | $\nu_{exp.} (^{87}Rb)$ | $\nu_{exp.} (^{85}Rb)$ |
|-------------|-----------------|-------------------------|-------------------------|------------------------|------------------------|
| $I = 0,07A$ | 1,68 | 1,17 MHz | 0,78 MHz | 1,03 MHz | 0,68 MHz |
| $I = 0,09A$ | 2,16 | 1,51 MHz | 1,01 MHz | 1,35 MHz | 0,84 MHz |
| $I = 0,11A$ | 2,64 | 1,85 MHz | 1,23 MHz | 1,66 MHz | 1,11 MHz |

Table 3: Calculated Zeeman-splitting energies

| | ΔE_{I1} in eV | ΔE_{I2} in eV | ΔE_{I3} in eV |
|-----------|-----------------------|-----------------------|-----------------------|
| ^{85}Rb | $2,83 \cdot 10^{-9}$ | $3,47 \cdot 10^{-9}$ | $4,59 \cdot 10^{-9}$ |
| ^{87}Rb | $4,26 \cdot 10^{-9}$ | $5,58 \cdot 10^{-9}$ | $6,87 \cdot 10^{-9}$ |

The experimental value for the Landé-factor can be calculated by using this formula:

$$g_F = \frac{\Delta E}{B} \cdot \frac{2m_e}{e\hbar} \quad (9)$$

m_e is the electron mass, e is the elementary electric charge and \hbar is the Planck constant. For the 3 different values of the magnetic field you get these Landé-factors: This error of

Table 4: The experimental Landé-factors for ^{87}Rb and ^{85}Rb

| | $g_F(^{87}Rb)$ | $g_F(^{85}Rb)$ |
|---------------|----------------|----------------|
| $B = 0,168mT$ | 0,44 | 0,29 |
| $B = 0,216mT$ | 0,45 | 0,28 |
| $B = 0,264mT$ | 0,45 | 0,30 |
| Average | 0,45 | 0,29 |

more than 10% cannot be the consequence of the additional earth magnetic field, because it is much smaller than the applied magnetic field. But the error might be explained by the fact that the actual magnetic field might differ from the value calculated by equation (3). If the magnetic field is slightly smaller than calculated by the formula, it results in higher Landé-factors, which would be more accurate in both cases.

5 Conclusion

In conclusion one can say that this experiment has roughly confirmed the expectations. The characteristic times for the optical pumping and the relaxation are in the milliseconds range which are reasonable values. In the second part the aim was to compare the theoretical g-factors which can be calculated to the measured g-factors from the experiment. The experimental values differ quite a bit from the theoretical values, but cannot be a statistical error, because all the values for different magnetic fields are quite the same. One possible explanation was given, as the calculation of the magnetic field does not match the real magnetic field in the gas.

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