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Group P3

Advanced Lab Course: Rubidium Magneto Optical Trap A248

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Contents

1. Theory

1.1. Optical Cooling

Atoms in an ensemble move in random direction. These scattered atoms when subjected to radiation pressure by a LASER beam that is very much in resonant with the atoms transitions, the atoms absorb and emit the momentum carrying photon. During absorption the atoms gets a momentum kick and hence experiences a force $< F >= \hbar k R$ where R is the rate of absorption. Where as the spontaneous emission by the atoms are isotropic, thus the net force will be zero. Hence the atoms will experience an average force because of absorption. The average force is given by

$$< F >= \frac{\hbar k}{2} \frac{(\frac{I}{I_s})}{1 + (\frac{I}{I_s}) + (\frac{\delta}{\Gamma})}$$

where I is the intensity of the beam, I_s is the saturation intensity, δ is detuning term and the natural line width Γ. This force can be used to control the atoms and decrease their velocity near to zero. To cool the atoms we need to ensure the scattering rate of the photon is dependent on the Doppler effect. Here we consider atoms either moving towards or away from the photons direction, the atoms moving towards the photons sees the photon to be blue shifted. Hence to ensure cooling the atoms and atoms in the direction of photon doesn't get accelerated, we use red detuned LASER beam.

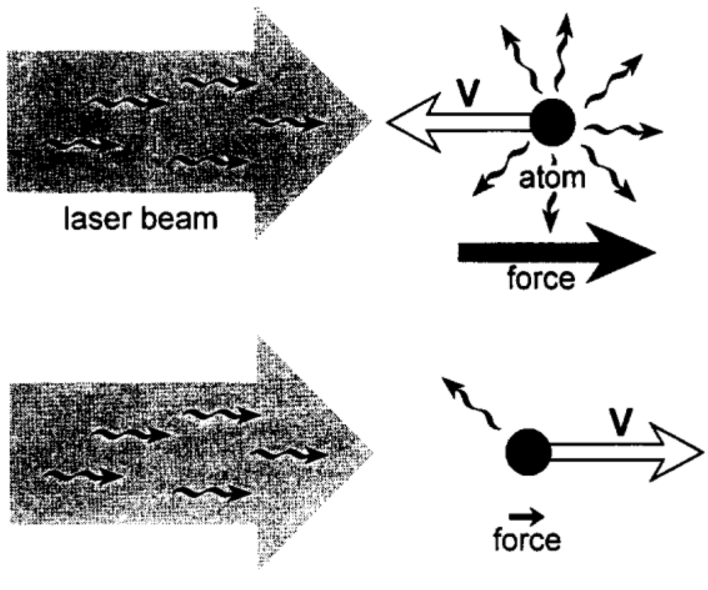


Figure 1.1.: LASER and Atom interaction. [2]

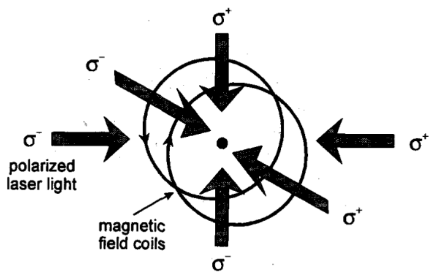
1.2. Optical Molasses

As we have seen in the above section a single beam of LASER can only employed to slow down the atoms velocity in one direction, we use three pairs of beams in orthogonal axes with each in counter propagating direction. This configuration will slow down atoms and make the move towards the centre forming a clump called as Optical Molasses. This formed clump of atoms are not stable because of the background heat and also the spontaneous emission photons by the atoms the atoms generates heat internally causing them to defuse out. As a result it ceases our limit of cooling temperature called the Doppler temperature T_D where the cooling is balanced with the natural heating. The Doppler temperature is given by

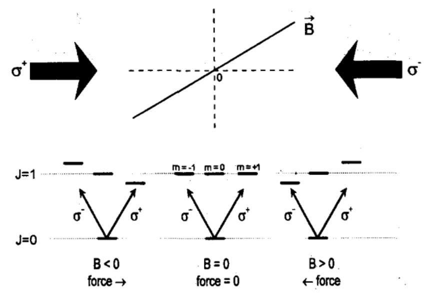
$$T_D = \frac{\hbar\Gamma}{2K_B}$$

1.3. Magneto Optic Trap

To ensure trapping of atoms along with optical molasses we apply quadrupole magnetic field using an aniti-helmholtz configuration[Fig 1.2(a)]. The magnetic field applied is linear[Fig 1.2(b)] in nature in the neighbourhood of the origin. Due to the magnetic field the Zeeman splits occur and hence making their scattering rate dependent on position. The split energy levels(m_f) are linearly dependent with the radial distance. Hence the atoms that move away from the origin become more resonant(detuning decreases) with beam and forced to the centre.



(a) Anti-Helmholtz configuration. [2]



(b) One dimensional explanation of the MOT.Circularly polarized laser beams with oppsite angular momenta impinge on an atom from opposite directions. The lasers excites the $J = 0$ to $J = 1$ transition. The laser from the right only excites to $m = -1$ excited state,, and the laser from the left only excites to the $m = +1$ state. .[2]

Figure 1.2.

In our experiment we use Rubidium atoms(^{85}Rb and ^{87}Rb). Our aim is to trap ^{85}Rb as it makes up major population is 72.2% of the sample.For cooling and trapping we red tune one our laser to the resonant frequency of the transition $F = 3 \rightarrow F_{\prime=2}$. This does not imply a closed trasition, since other transitions like $F = 3 \rightarrow F_{\prime 2}$ and $F = 2 \rightarrow F_{\prime=2}$ are also possible and also from these non resonant states atoms can decay into $F = 2$ state, This state is called as the dark state as it does not interact with our cooling laser. To ensure that atoms interact with the cooling laser we make use of repumping laser tuned at transition of $F = 2 \rightarrow F_{\prime=3}$ state as this state decays to $F = 3$ state.

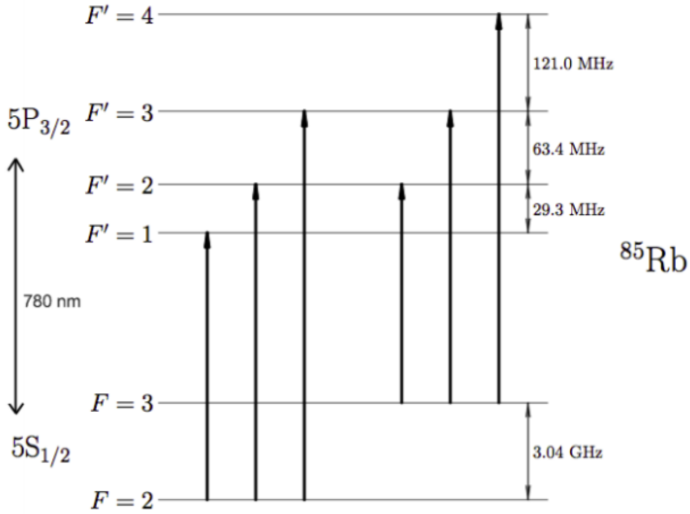


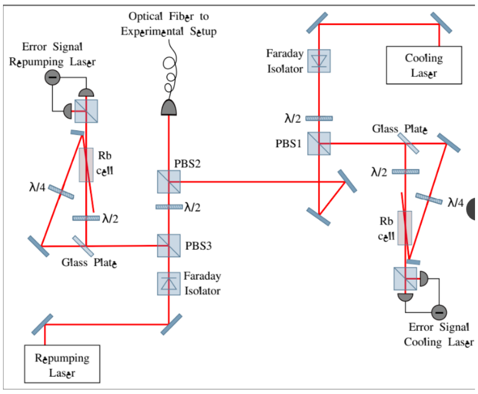
Figure 1.3.: Transitions of Rubidium atom ^{85}Rb [1]

1.4. Spectroscopy

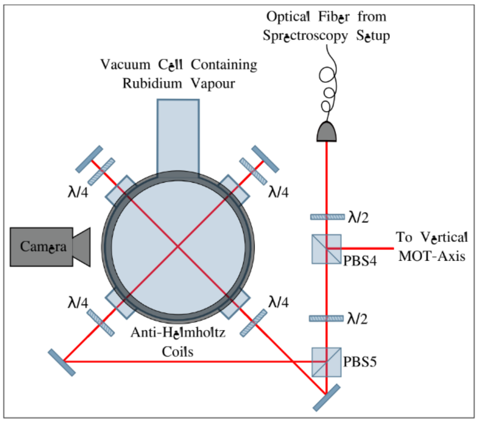
In the saturation absorption spectroscopy, fluorescence of the sample interacting with laser beams are observed through a photodiode to get the absorption spectroscopy. Because of atoms in the sample have different velocities the Intensity vs frequency plot shows a normal distribution with dip at zero detuning this is called the Lamb dip. Where as in multilevel atoms we see more intense peaks than their energy levels.This is because of the various upper and lower energy levels of the these have close energy gaps and hence causing Doppler broadened profiles to overlap also called as cross-over peaks.

2. Experimental setup

MOT set up consists of Rubidium vapour in vacuum chamber at very low pressure. The trapping chamber is surrounded by an anti-Helmholtz configuration that produces the desired magnetic field.The cooling and re pumping lasers first pass through the Rubidium cells where the polarization spectroscopy is employed to find the Rb spectrum.Then these lasers travel through an optical fiber and are split into beams in each spatial direction propagating in opposite directions. The opposite circular polarization on these beams are achieved through quarter wave plates. Now, these beams are aligned on to the center of the MOT cell. The cooling and re pumping lasers were locked in with their corresponding transitions. By turning on the magnetic field, MOT was detected via a bright spot seen on the secondary camera. A power meter and a photo diode is used for measurements.



(a) Experimental set up of polarization spectroscopy. [1]



(b) Experimental set up of MOT.[1]

Figure 2.1.

3. Experiment and Characteristics of MOT

3.1. Beam Diameter

We measure the power of beam with a photodiode using knife edge technique. The power of the beam at different position of the knife edge is recorded and the data is plotted with fit function

$$f(x) = a.Erfc\left[\frac{x-b}{\sqrt{2.\sigma^2}}\right]$$

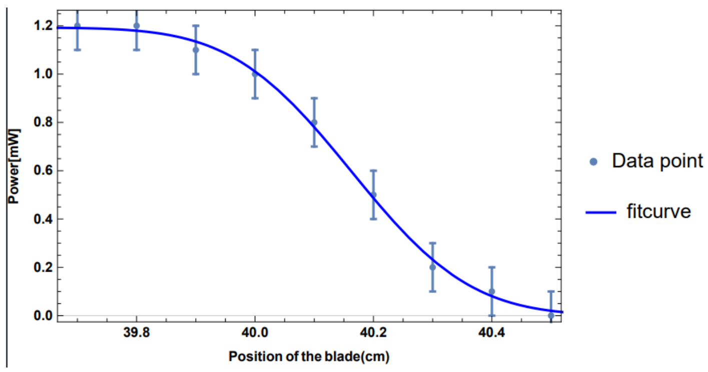


Figure 3.1.: Plot of position of blade vs the power of the beam

The beam diameter is calculated using

$$Beam \ = 4.\sigma$$

$$Beam \ diameter = 6.3 \pm 0.03mm$$

3.2. MOT size

The size of the MOT couldn't be determined as the image of the ruler was very poor in quality compared to the MOT image and it was not possible for us to read any data after superimposing the two image. The MOT image is shown in the figure below

3.3. Influence of quater wave plate

Here we see how the MOT population(power) is influenced my the quarter wave plate. The dependency of the MOT power for two beams one incoming and the reflected beam by the quarter wave plate. We first optimize our MOT then one of the axis is chosen and the quarter wave plate of the incoming beam is changed in steps of 10° and the co-responding fluorescence power is recorded and same is done with the reflected beam.

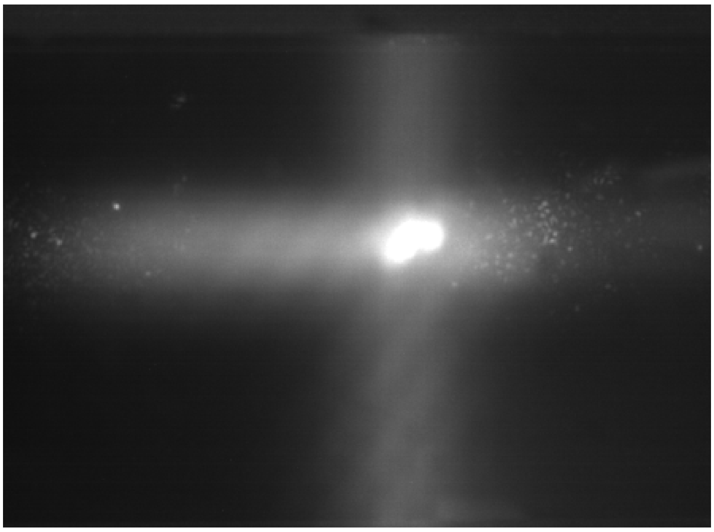


Figure 3.2.: MOT image captured using the digital camera

3.3.1. Quarter wave plate-incoming beam

The recorded data is plotted and as we know the fit curve should be the relation from Malus law, the power dependency fit function as below is curve fitted with the data. As we can see the fit is in good match with the data

$$P(\theta) = P_{bg} + P_{max}.cos^2(\theta - b)$$

where P_{bg} is the background fluorescence and P_{max} is the maximum power of the MOT.

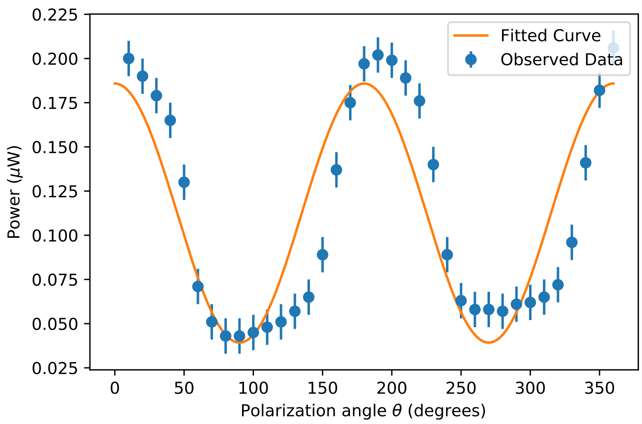


Figure 3.3.: Angle of the quarter wave plate vs the Power of the MOT

3.3.2. Quarter wave plate-reflected beam

The dependency of the quarter wave plate of the reflected beam and power is plotted and best fit is implied, shown in figure 3.3. As expected polarization of the reflected beam was independent of the polarization angle of the quarter wave plate.

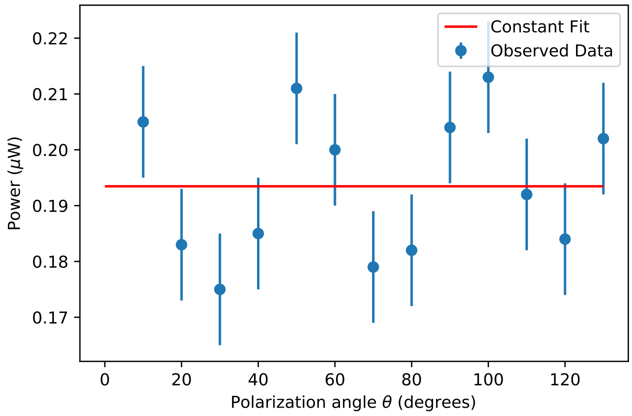


Figure 3.4.: Measured power of the MOT flourscence vs polarization angle of quarter wave plate for the reflected beam

3.4. Dependence on the magnetic field strength

Here we examine how the MOT population is dependent on the strength of the magnetic quadrupole field applied. This is done by changing the current through the coil in steps of 0.2 μW and the corresponding power readings are noted and plotted as below. We have fitted two curve fit to the plot, the fit 2 is very promising to consider as it reflects the linear dependency of the MOT population on the magnetic field strength.

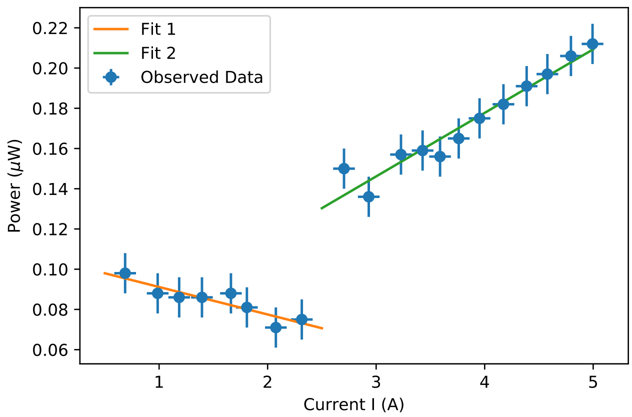


Figure 3.5.: Current through the coil vs MOT flourescence

3.5. Loading behaviour

The data for loading behaviour is measured by replacing the power meter by photo diode connecting to a digital oscilloscope. Since the photo diode collects both light from the MOT and the background. Hence to see the loading behaviour we turn off and on the current through the coil,as the current is turned off MOT is destroyed and when the current through the coil is turned on MOT reloads and hence the loading behaviour is observed in terms of the rising fluorescence. The data is collected and plotted with the theoretical loading behaviour fit function which is shown below, the plot is shown inn the figure 3.5.

$$f(t) = a.\left(1 - e^{-(\frac{t-t_0}{\tau})}\right)$$

In our experiment we have taken six readings in order to reduce the statistical uncertainty and the data is tabulated in the table and the average $\bar{\tau}$ is calculated from the six readings using the formula

$$\bar{\tau} = \frac{\sum_{n=1}^{n=7}(\Delta\bar{\tau}_n^{-2}.\tau_n)}{\sum_{n=1}^{n=7}\Delta\bar{\tau}_n^{-2}}$$

and the uncertainty is calculated using

$$\Delta\bar{\tau} = \sqrt{\frac{1}{\sum_{n=1}^{n=7}\Delta\bar{\tau}_n^{-2}}}$$

The loading average is calculated and found to be

$$\bar{\tau} = 0.0459 \pm 0.0005s$$

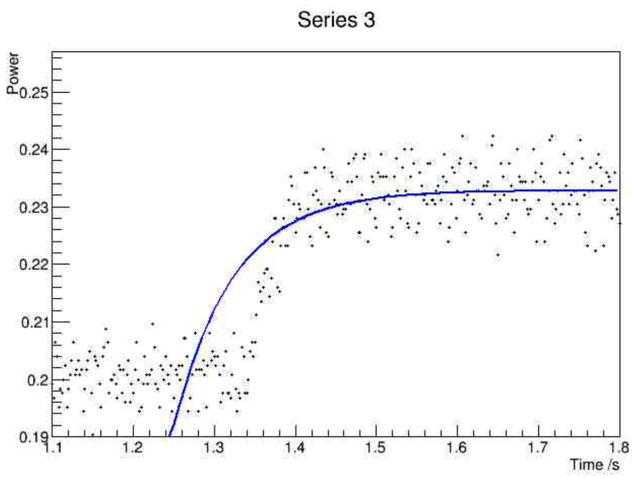


Figure 3.6.: Loading Behaviour of the MOT

Rest of the loading behaviour plot is included in the appendix.

3.6. Rb-Rb cross section

After finding the loading time one can calculate the Rb-Rb cross section by the relation

$$\frac{1}{\bar{\tau}} = n_{Rb}.\sigma_{Rb}.v_{Rb}$$

where n_{Rb} is the density of the Rb atoms, v_{Rb} velocity of the Rb atoms and σ_{Rb} cross section for Rb-Rb collisions. The density is calculated using the formula given below, Where $P = (4.35 \pm 0.01).10^{-8} mbar$

pressure of the vaccum chamber and $T = 299.5 \pm 0.1K$ is the temperature and the mass of Rb atom is $m_{Rb} = 1.419.10^{-25}kg$

$$n_{Rb} = \frac{P}{k_B.T} = (1.05 \pm 0.02).10^{15}m^{-3}$$

$$\Delta n_{Rb} = n_{Rb}.\sqrt{\left(\frac{\Delta P}{P}\right)^2 + \left(\frac{\Delta T}{T}\right)^2}$$

and the velocity is calculated using

$$V_{Rb} = \sqrt{\frac{3k_B}{m_{Rb}}}.\Delta T = 295.6 \pm 0.07ms^{-1}$$

$$\Delta V_{Rb} = \sqrt{\frac{3k_B}{2m_{Rb}T}}.\Delta T$$

The Rb cross section is calculated to be,

$$\sigma_{Rb} = (7.019 \pm 0.08).10^{-17}m^2$$

3.7. Detuning

In order to find the detuning of the laser we measure the fluorescence signal and the spectrum signal of the laser by the digital oscilloscope. During the measurement we keep the mot in optimum and one of the lasers is locked and other is set to scan over the Rb spectrum.We set scan frequency < 1Hz in order to for the MOT have enough time to load the atoms.

3.7.1. Detuning of the cooling laser

The cooling laser spectral signal and the fluorescence signal is shown below. The peaks of both spectral signal and fluorescence signal are fitted with function

$$U(t) = a.exp\left[\frac{-(t-b)^2}{2c^2}\right] + d$$

The peak positions for spectral signal are found to be

$$t_{3\to4} = (2.974 \pm 0.002)s$$

$$t_{3\to3,4} = (2.560 \pm 0.003)s$$

$$t_{3\to2,4} = (2.356 \pm 0.003)s$$

The florescence peak is found out to be $t_f = (2..900 \pm 0.002)s$. And from the peak positions obtained the time distance between the peaks are found

$$\Delta t_{3\to3,4} = t_{3\to4} - t_{3\to3,4}(0.414 \pm 0.002)s$$

$$\Delta t_{3\to2,4} = t_{3\to4} - t_{3\to2,4}(0.618 \pm 0.002)s$$

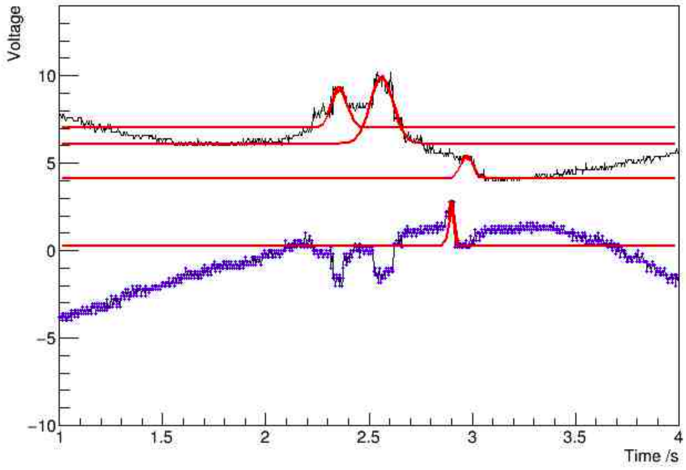


Figure 3.7.: Spectral and flourescence signal of MOT

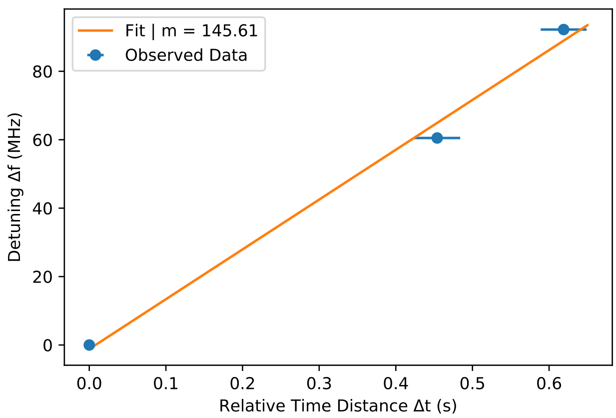


Figure 3.8.: Calibration plot for the time scale of the oscilloscope, the error bars on Δt_i is scaled by x10

We now calibrate the peaks with frequency, for this we plot the frequency difference of the cooling transition of the laser to the corresponding time difference transition. The calibration graph is plotted and the calibration constant is determined

$$m = 145.61 Mhz/s$$

Using the calibration constant we can find the detuning δ_{col} of the cooling laser

$$\delta_{col} = \omega_0 - \omega = (t_{3\to4} - t_f).m = 10.77 \pm 0.3$$

3.7.2. Detuning of the repumping laser

We couldn't do a proper curve fit for the repumping laser and hence our analysis for the repumping laser couldn't be done.

3.8. Population of MOT

The MOT population can be calculated by knowing the total power of the fluorescence and the scattering rate that are calculated in the below sections.

3.8.1. MOT Fluorescence

The MOT power reading is taken through a power meter at distance $d = (18.5 \pm 2)cm$ The power is measured only the light falling on the lens of the power meter of radius $r_{lens} = 1.27cm$ and the measured power is $P_m eter = (0.212 \pm 0.01)\mu W$. The MOT power is calculated using the relation

$$P_{MOT} = P_{meter} . \frac{4\pi d^2}{\pi r_{lens}^2}$$

$$P_{MOT} = (558.21 \pm 7.2)\mu W$$

We used Gaussian error propagation to calculate the error.

3.8.2. Scattering rate

The scattering rate R equation is given by

$$R = \frac{\left(\frac{I}{I_s}\right)\pi\Gamma}{1 + \left(\frac{I}{I_s}\right) + 4\left(\frac{\delta}{\Gamma}\right)^2}$$

Where I is the intensity of the laser, $I_s = 4.1 mW/cm^2$[2] is the saturation intensity, $\delta 10.77 \pm 0.3$ detuning and $\Gamma = 6 MHz$[2]. The intensity is calculated using the formula

$$I = \frac{P}{\pi(d_{beam}/2)^2}$$

where $P = 1.2 \pm 0.1\mu W$ is the power measured to calculate the beam diameter($d_{beam} = 6.3 \pm 0.03$)

$$I = (38.5 \pm 4) mW/cm^2$$

and hence the scattering rate is calculated and found to be

$$R = 17.04 \pm 3.2 MHz$$

3.8.3. MOT population

The MOT population is calculated us the formula

$$N = \frac{P_{MOT}}{R.E}$$

Where N is the number of atoms in MOT and E is the energy of the cooling transition where$E = \frac{hc}{\lambda} = 2.55.10^{-19} J$ hence the number of atoms found to be

$$N = (1.28 \pm 0.2)10^{8} atoms$$

4. Conclusion

In this experiment we were able to set up MOT. We could analyze most of our data. The detuning for the cooling laser was done successfully by using the Gaussian profile to fit the peaks but for the repumping laser we were unable to curve fit the peaks. The characteristics of MOT were also calculated for the most of them but for the MOT size the scale image we captured was not a good quality image and we had to assume a value for the MOT size. Regardless of the drawbacks we could estimate a realistic number of atoms in the MOT.

A. Appendix

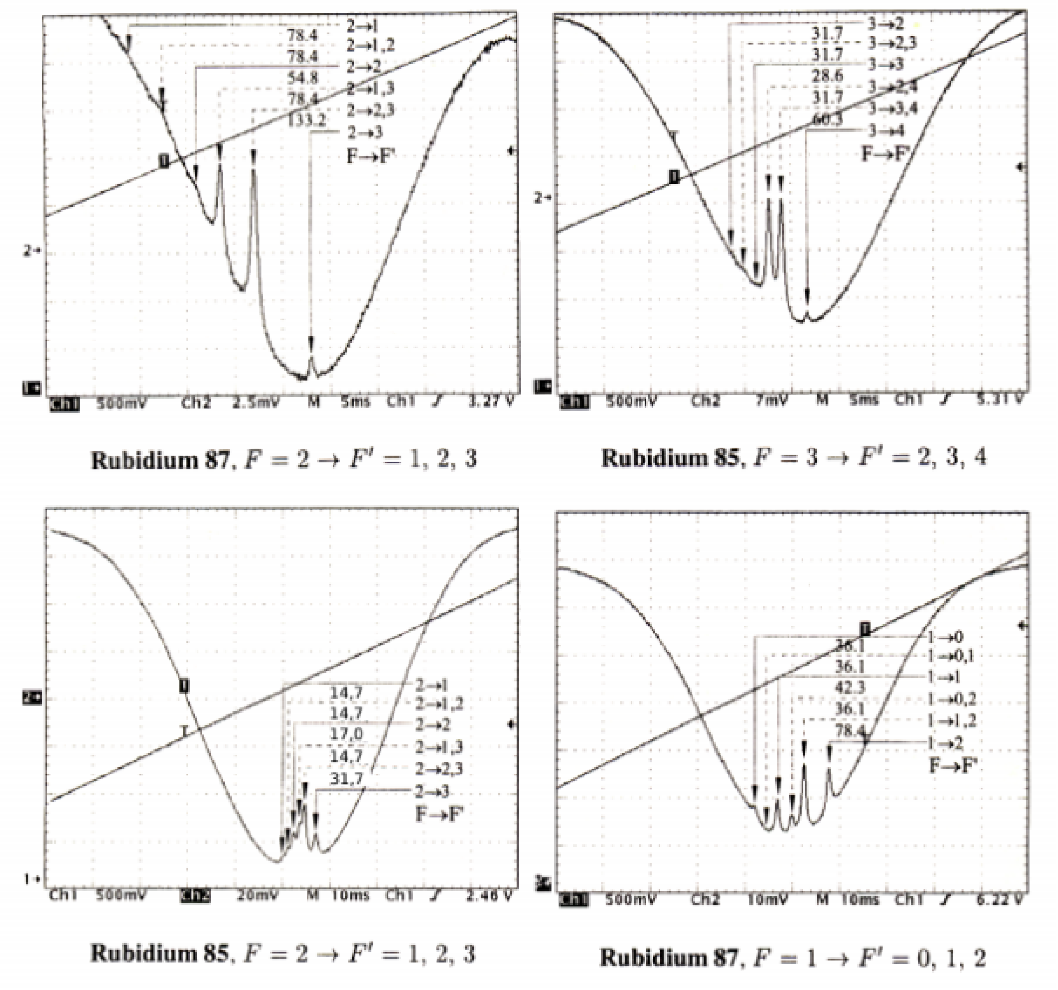


Figure A.1.: Spectrum of Rb atoms

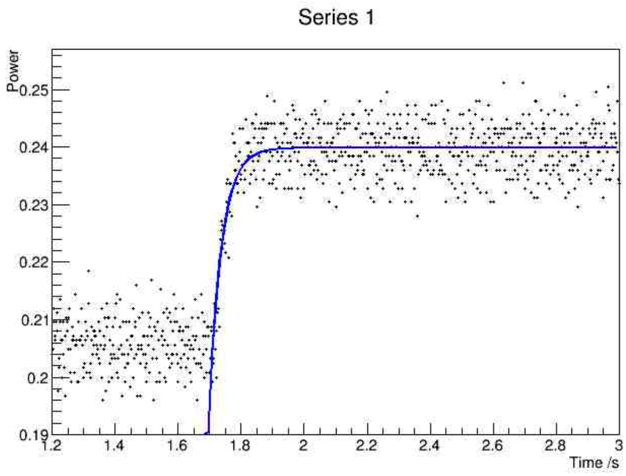
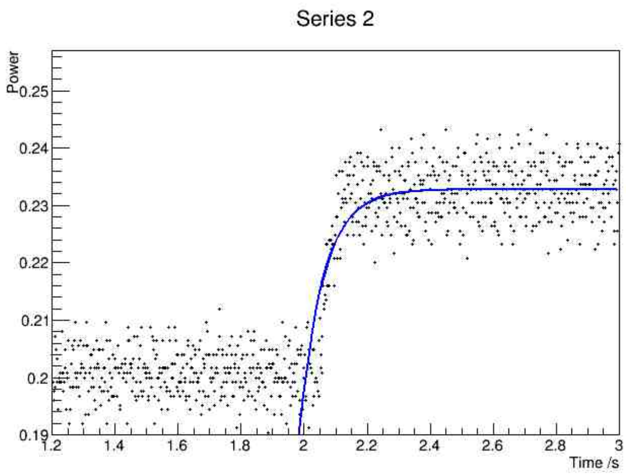


Figure A.2.: Loading Behaviour of the MOT



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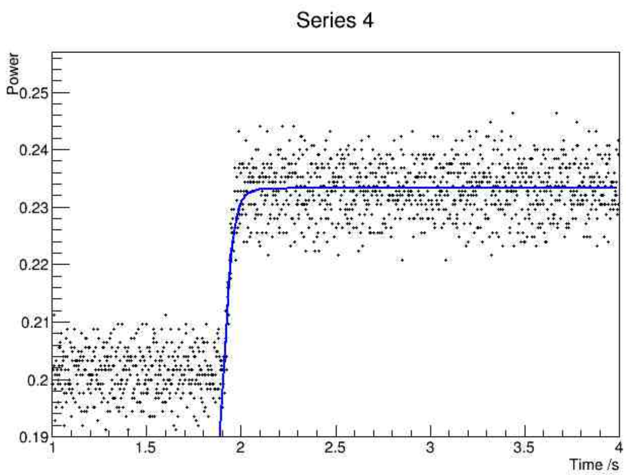

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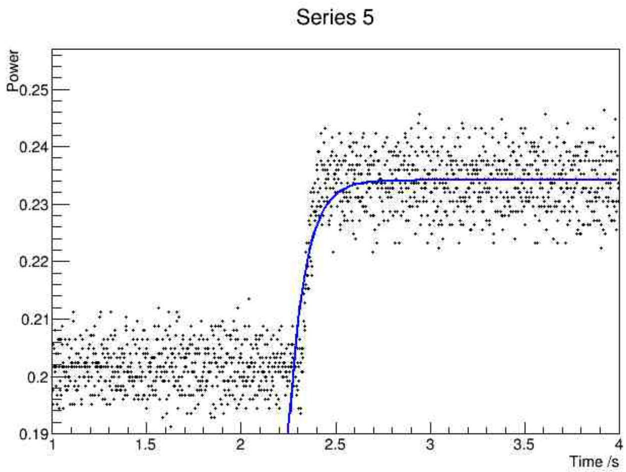

Figure A.5.: Loading Behaviour of the MOT

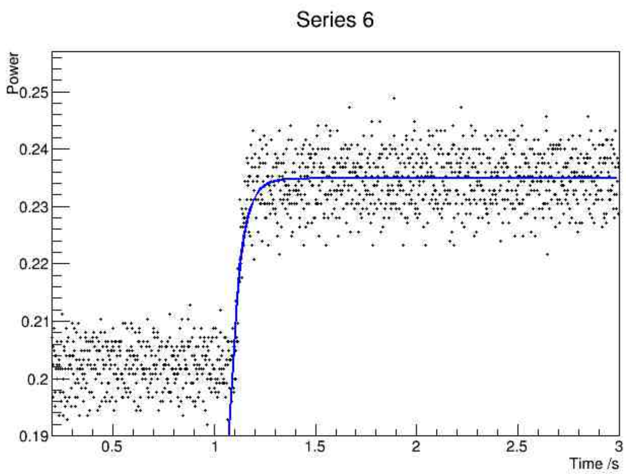

Figure A.6.: Loading Behaviour of the MOT

Bibliography

[1] University of Bonn: *A248 Material - ALC-Instructions MOT* , 2017

[2] University of Bonn: *A248 Material - Wieman - Inexpensive laser cooling and trapping experiment for undergraduate laboratories*