

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

UNIVERSITÄT HEIDELBERG Physikalisches Institut

FORTGESCHRITTENEN-PRAKTIKUM VERSUCH: PREPARATORY MATERIAL

Magneto-optische Falle

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Part I History

Manual Versions:

- 2014/03/05 First version of pdf document, fully synchronized with Wiki. (V. Gavryusev)
- 2020/08/12 Second version of the pdf document. Update of the manual with the new interface which allows to remote connection to the PC in FP-lab. The PC controls all the key tunable parameters of the experiment. This interface is described in the current manual.
- 2022/02 Third version of the pdf document. Document is since then on overleaf
- 2023/03/16 Small changes: typos, correction remaining statements about the old laser setup, add beam walk explanation, add additional explanation of the crossover effect in spectroscopy

In autumn 2009 the magneto-optical trap of the F20 experiment was completely revised, improved and adapted to high safety standards. This included a complete renewal of the experimental setup which was done by Marc Repp, Christoph Hofmann, Silvânia Alves de Carvalho, Kristina Meyer, and Dominic Litsch. A new and interactive lab manual in form of a wikipedia was established by Christoph Hofmann and Marc Repp. Then it was updated by Vladislav Gavryusev. This pdf version is the full mirror of the contents of the wiki.

In order to comply with the social distancing rules imposed due to the worldwide coronavirus pandemic (2020), the experiment was completely made remote-controllable and the pdf manual was duly updated by Jonas Tauch, Saba Zia Hassan and Manuel Gerken. The parameters for the MOT could be tuned remotely and thus making the process of data acquisition possible from a remotely connected PC.

Since 2022/02 this document is on overleaf and is mend to be optimized permanently.

Part II Introduction



Figure 1 Temperature scale. (Taken from [1])

The idea of cooling particles to lower temperatures has always been of great interest to physicists. This is perfectly encapsulated in the Nobel Lecture by Prof. Wolfgang Ketterle [11], "The lure of lower temperatures has attracted physicists for the past century, and with each advance towards absolute zero, new and rich physics has emerged. Laypeople may wonder why "freezing cold" is not cold enough. But imagine how many aspects of nature we would miss if we lived on the surface of the sun. Without inventing refrigerators, we would only know gaseous matter and never observe liquids or solids, and miss the beauty of snowflakes. Cooling to normal earthly temperatures reveals these dramatically different states of matter, but this is only the beginning: many more states appear with further cooling. The approach into the kelvin range was rewarded with the discovery of superconductivity in 1911 and of superfluidity in helium-4 in 1938. Cooling into the millikelyin regime revealed the superfluidity of helium-3 in 1972. The advent of laser cooling in the 1980s opened up a new approach to ultralow-temperature physics. Microkelvin samples of dilute atom clouds were generated and used for precision measurements and studies of ultracold collisions. Nanokelvin temperatures were necessary to explore quantum-degenerate gases, such as Bose-Einstein condensates first realized in 1995. Each of these achievements in cooling has been a major advance, and recognized with a Nobel prize."

Using laser radiation to cool and trap atoms was first suggested by Wineland and Dehmelt [2]

and independently by Hänsch and Schawlow [3]. Since photons carry momentum, the momentum exchange between the laser radiation and the atoms in an absorption process can be used to apply a force on the atoms. Since the absorption depends on the difference between frequency of the laser radiation and the absorption frequency of the atoms, the absorption process can be made velocity-selective due to the Doppler effect, which shifts the atoms absorption frequency depending on its velocity. It is this simple notion that forms the basis for the research that has been carried out in the last 30 years in the field of laser cooling and trapping. Especially the velocity dependence of the process, leading to the fact that the forces are no longer conservative but can instead dissipate kinetic energy of the atoms, allows the experimentalists to cool atoms down to extremely low temperatures bridging more than more than nine orders of magnitude on the temperature scale!

During the course of this experiment you will lower the temperature of hot Rubidium atoms of several 100 K down to at least several 100 μ K, thereby crossing as many as seven orders of magnitude. In the same time you will learn how to realize one of the most important laser cooling experiments carried out in modern Atomic Physics. As you might know, a magneto-optical trap (MOT) is the first step towards the formation of ultracold quantum gases. And it is a technique which is used on a daily basis also here in Heidelberg, where a whole variety of alkali atoms are trapped in the groups of Prof. Matthias Weidemuller (Lithium, Rubidium, Caesium), Prof. Selim Jochim (Lithium) and Prof. Markus Oberthaler (Lithium, Sodium, Rubidium, Argon). Before you can get started, you have to acquaint yourself with the topics listed below:

- Of course no lab course can be successfully carried out without Theory
- But for an experimentalist, Theory is only part of the story. The theory must be verified or falsified by doing experiments. Therefore he needs an Experimental setup.
- Before you can enter the lab you need to familiarize yourself with several Safety issues, which we will also discuss during our colloquium at the beginning of the lab course.
- After having read all the above pages and after having passed the small colloquium, you need to carry out the experiment. To do so, please read the Work instructions carefully .
- Last, but not least you should analyse the acquired data and report your results. The Data Analysis instructions int he manual will guide you for the same.

Part III Theory: Spectroscopy

Saturated absorption experiments were awarded the 1981 Nobel prize in physics (Nicolaas Bloembergen and Arthur L. Schawlow) and related techniques have been used in laser cooling and trapping experiments, leading to the 1997 Nobel prize (Steven Chu, Claude Cohen-Tannoudji, and William D. Phillips), and then the achievement of Bose-Einstein condensation was recognized with the 2001 Nobel prize (Eric A. Cornell, Wolfgang Ketterle, and Carl E. Wieman). Although the basic principles are straightforward, you will only be able to unleash the full power of saturated absorption spectroscopy by carefully considering many details that will be discussed in this first theory section.

1 Basic laser absorption spectroscopy



Figure 2 Schematic sketch of a spectroscopy path allowing for Doppler spectroscopy: PBS = polarizing beam splitter, GT = Galilean Telescope, H = half waveplate.

The basic arrangement for ordinary laser absorption (not saturated absorption spectroscopy) through a gaseous sample is shown in Fig. 2. A laser beam passes through the vapor cell and its intensity is measured by a photo diode detector as the laser frequency ν is scanned through the natural resonance frequency. When a laser beam propagates through a gaseous sample, the two stimulated transition processes change the intensity of the laser beam and affect the density of atoms (number per unit of volume) in the ground and excited states. Additionally, Doppler shifts associated with the random thermal motion of the absorbing atoms must be taken into account. There is an interplay among these effects which is critical to understanding saturated absorption spectroscopy. We begin with the basic equation describing how the laser intensity changes as it propagates through the sample and then we'll continue with the effects of Doppler shifts and population changes.

Because of stimulated emission and absorption, the laser intensity I(x) varies as it propagates from x to x + dx in the medium. This gives rise to the well known Lambert-Beer absorption law

$$\frac{dI}{dx} = -\kappa I \tag{1.1}$$

with the absorption coefficient (fractional absorption per unit length)

$$\kappa = h\nu n_0 \alpha \left(P_0 - P_1 \right) \tag{1.2}$$

Here

$$\alpha = \alpha_0 \mathcal{L}(\nu, \nu_0) \tag{1.3}$$

$$\mathcal{L}(\nu,\nu_0) = \frac{1}{1 + 4(\nu - \nu_0)^2 / \Gamma^2}$$
(1.4)

give the Lorentzian (or natural resonance) frequency dependence.

The proportionality to $P_0 - P_1$ arises from the competition between stimulated emission and absorption and it is important to appreciate the consequences. If there are equal numbers of atoms in the ground and excited state ($P_0 - P_1 = 0$), laser photons are as likely to be emitted by an atom in the excited state as they are to be absorbed by an atom in the ground state and there will be no attenuation of the incident beam. The attenuation is maximized when all atoms are in the ground state ($P_0 - P_1 = 1$) because only absorption would be possible. And the attenuation can even reverse sign (becoming an amplification as it does in laser gain media) if there are more atoms in the excited state ($P_1 > P_0$).

In the absence of a laser field, the ratio of the atomic populations in the two energy states will thermally equilibrate at the Boltzmann factor $P_1/P_0 = exp\{-\Delta E/k_BT\} = exp\{-h\nu_0/k_BT\}$. At room temperature, $k_BT \approx 1/40$ eV is much smaller than the energy difference between the levels involved in this experiment $h\nu_0 \approx 1.6$ eV and nearly all atoms will be in the ground state, i.e., $P_0 - P_1 = 1$. While you will see shortly how the presence of a strong laser field can significantly perturb these thermal equilibrium probabilities, for now we will only treat the case where the laser field is weak enough that $P_0 - P_1 = 1$ remains a good approximation throughout the absorption cell.

2 Doppler shifts

Atoms in a vapor cell move randomly in all directions with each velocity component having a distribution of values. Only the velocity component parallel to the laser beam direction will be important when taking into account Doppler shifts and it is this component that we refer to with the symbol v. The density of atoms dn in the velocity group between v and v + dv is given by the Boltzmann velocity distribution:

$$dn = n_0 \sqrt{\frac{m}{2\pi k_B T}} e^{-mv^2/2k_B T} dv$$
(2.1)

With a standard deviation (proportional to the width of the distribution) given by:

$$\sigma_v = \sqrt{\frac{k_B T}{m}} \tag{2.2}$$

this is just a standard Gaussian distribution

$$dn = n_0 \frac{1}{\sqrt{2\pi\sigma_v}} e^{-v^2/2\sigma_v^2} dv \tag{2.3}$$

with a mean of zero-indicating that the atoms are equally likely to be going in either direction. Note that the distribution's variance σ_v^2 increases linearly with temperature and decreases inversely with atomic mass.

Atoms moving with a velocity v see the laser beam Doppler shifted by the amount v(v/c). We will take an equivalent, alternate view that atoms moving with a velocity v have a Doppler shifted resonance frequency

$$\nu_0' = \nu_0 \left(1 + \frac{v}{c} \right) \tag{2.4}$$

in the lab frame. The sign has been chosen to be correct for a laser beam propagating in the positive direction, so that the resonance frequency is blue shifted to higher frequencies if the velocity is positive and red shifted if the velocity is negative.

The absorption coefficient $d\kappa$ from a velocity group dn at a laser frequency ν is then obtained from Eq. 1.2 by substituting dn for n_0 and by adjusting the Lorentzian dependence of α (Eq. 1.3) so that it is centered on the Doppler shifted resonance frequency ν'_0 (keeping its dependence on ν in mind through Eq. 2.4):

$$d\kappa = h\nu\alpha_0 \left(P_0 - P_1 \right) \mathcal{L}(\nu, \nu'_0) dn \tag{2.5}$$

Introducing the velocity dependence of dn (Eq. 2.1) and accounting for the weak laser field case ($P_0 - P_1 = 1$) yields:

$$d\kappa = n_0 h \nu \alpha_0 \sqrt{\frac{m}{2\pi k_B T}} \mathcal{L}(\nu, \nu_0') e^{-mv^2/2k_B T} dv$$
(2.6)

The absorption coefficient from all atoms is then found by integrating over all velocity groups:

$$\kappa = \kappa_0 e^{-(\nu - \nu_0)^2 / 2\sigma_\nu^2}$$
(2.7)

with the width parameter given by

$$\sigma_v = \nu_0 \sqrt{\frac{k_B T}{mc^2}} \tag{2.8}$$

and

$$\kappa_0 = n_0 h \nu \alpha_0 \sqrt{\frac{m}{2\pi k_B T}} \frac{c}{\nu_0} \frac{\pi \Gamma}{2}$$
(2.9)

The frequency dependence of the absorption coefficient is shown in Fig.3.



Figure 3 Doppler profile. The absorption coefficient vs. the laser frequency offset from resonance has a Gaussian lineshape.

3 Populations

Now we would like to take into account the changes to the ground and excited state populations arising from a laser beam propagating through the cell. The rate equations for the ground and excited state probabilities become:

$$\frac{dP_0}{dt} = \gamma P_1 - \alpha I \left(P_0 - P_1 \right) \tag{3.1}$$

$$\frac{dP_1}{dt} = -\gamma P_1 + \alpha I \left(P_0 - P_1 \right) \tag{3.2}$$

where the first term on the right in each equation arises from spontaneous emission with rate γ and the second term arises from stimulated absorption and emission. The steady state of the above two level system then obeys:

$$P_0 - P_1 = \frac{1}{1 + 2\alpha I/\gamma}$$
(3.3)

which is now dependent of the laser power. This fact of course also influences the absorptive behavior of the sample and results in an intensity dependent absorption coefficient:

$$\kappa = \kappa_0' e^{-(\nu - \nu_0)^2 / 2\sigma_\nu^2} \tag{3.4}$$

where the width parameter, σ_{ν}) is the same as before (see Eq. 2.8), but compared to the weak-field absorption coefficient derived in Eq. 2.9, the strong-field coefficient decreases to

$$\kappa_0' = \frac{\kappa_0}{\sqrt{1 + 2I/I_{sat}}} \tag{3.5}$$

Here *I*_{sat} is called the **saturation intensity**

$$I_{sat} = \frac{\gamma}{\alpha} \tag{3.6}$$

and is about 1.6 mW/cm^2 for our Rubidium transitions.

4 Saturated absorption and Doppler free spectroscopy

Up to now, we have considered only a single laser beam propagating through the cell. Now we would like to understand what happens if a second laser propagates through the cell in the opposite direction. This is the basic arrangement for saturated absorption spectroscopy shown in Fig. 4. The laser beam traveling to the right is called the pump beam. The second, retro-reflected laser beam propagating in the opposite direction is called the probe beam.

With only a single weak laser propagating through the sample, $P_0 - P_1 = 1$ would be a good approximation throughout the cell. To do saturated absorption spectroscopy the probe beam will still be kept weak enough to neglect its effect on the populations. However, the pump beam will be made strong - strong enough to significantly affect the populations and thus change the



Figure 4 Schematic sketch of a spectroscopy path allowing for Doppler free saturated absorption spectroscopy. PBS = polarizing beam splitter, GT = Galilean Telescope, H = half waveplate, Q = quarter waveplate, M = mirror

measured absorption of the probe beam. To understand how this comes about, we will again have to consider Doppler shifts.

As mentioned, the stimulated emission and absorption rates are non-zero only when the laser is near the resonance frequency. Thus, we will obtain $P_0 - P_1$ from Eq. 3.3 by giving α a Lorentzian dependence on the Doppler shifted resonance frequency:

$$\alpha = \alpha_0 \mathcal{L}(\nu, \nu_0'') \tag{4.1}$$

with the important feature that for the pump beam, the resonance frequency for atoms moving with a velocity v is

$$\nu_0'' = \nu_0 \left(1 - \frac{v}{c} \right) \tag{4.2}$$

This frequency is Doppler shifted in the opposite direction to that of the probe beam because the pump beam propagates through the vapor cell in the negative direction. That means that the resonant frequency for an atom moving with velocity v is $v_0 (1 + v/c)$ for the probe beam and $v_0 (1 - v/c)$ for the pump beam.

For large detunings $\delta \gg \Gamma$, $P_0 - P_1 = 1$ implying that in this case the atoms are in the ground state. On resonance, i.e., at $\delta = 0$, $P_0 - P_1 = 1/(1 + 2I/I_{sat})$, which approaches zero for large values of *I*. This means that atoms in resonance with a strong pump beam will have equal populations in the ground and excited states ($P_0 - P_1 = 0$). In other words, a strong resonant laser field causes such rapid transitions in both directions that the two populations equilibrate. Such laser beam is then said to "saturate" the transition, which is the origin of the name of the technique.

According to Eq. 4.2, the resonance condition $\delta = 0$ translates to $v = v_{pump}$ where

$$v_{pump} = c \left(1 - \frac{\nu}{\nu_0} \right) \tag{4.3}$$

Consequently, for any frequency ν within the Doppler profile, only atoms near this velocity will be at zero detuning and will have values of $P_0 - P_1$ perturbed from the "pump off" value of unity.

The density of atoms in the ground state $dn_1 = P_1 dn$, plotted as a function of the velocity,

will follow the Maxwell-Boltzmann distribution except very near $v = v_{pump}$ where it will drop off significantly as atoms are promoted to the excited state. This is called "hole burning" as there is a hole (a decrease) in the density of atoms in the ground state near $v = v_{pump}$ (and a corresponding increase in the density of atoms in the excited state) as demonstrated in Fig. 5.



Figure 5 Hole burning by the pump beam. The density of ground state atoms is plotted vs. their velocity and becomes depleted near the velocity that Doppler shifts the laser frequency into resonance with ν_0 .

How does hole burning affect the probe beam absorption? You learned that the absorption at any frequency v arises only from those atoms moving with velocities near v_{vrobe} = $c(\nu/\nu_0-1)$. Also recall that the probe beam absorption is proportional to $P_0 - P_1$, which we have just seen remains constant (≈ 1) except for atoms having nearly the exact opposite velocities near $v_{pump} = c (1 - \nu / \nu_0)$. Therefore, when the laser frequency is far from the natural resonance $(|\nu - \nu_0| \gg \Gamma)$, the probe absorption arises from atoms moving with a particular velocity in one direction while the pump beam is burning a hole for a completely different set of atoms with the opposite velocity. In this case, the presence of the pump beam will not affect the probe beam absorption which would follow the standard Doppler-broadened profile. Only when the laser frequency is very near the resonance frequency ($\nu = \nu_0, v_{probe} = v_{pump} = 0$) the pump beam will burn a hole for atoms with velocities near zero which would then be the same atoms involved in the absorption of the probing beam at this frequency. The absorption coefficient would be obtained by taking $P_0 - P_1$ as given by Eq. 3.3 (with Eqs. 4.1 and 4.2) to be a function of the laser frequency and the velocity, using it in Eq. 2.5 (with Eqs. 2.1 and 2.4), and then integrating over velocity. The result is a Doppler-broadened profile with what's called a saturated absorption dip (or Lamb dip) right at $\nu = \nu_0$. Numerical integration was used to create the profiles shown in Fig. 6 for several values of I/I_{sat} . As one can see, increasing the intensity leads to the so called **power broadening** of the Lamb dip.



Figure 6 Absorption coefficient vs. the laser frequency offset from resonance for a two-level atom at values of $I/I_{sat} = 0.1$; 1; 10; 100; 1000 (from smallest dip to largest). It shows a Gaussian profile with the saturated absorption dip at $\nu = \nu_0$.

5 Multilevel effects

Real atoms have multiple upper and lower energy levels which add complexities to the simple two-level model presented so far. In the spectroscopy cell, transitions between two lower levels and four upper levels can all be reached with our laser and add features called crossover resonances and a process called optical pumping. Crossover resonances are additional narrow absorption dips arising because several upper or lower levels are close enough in energy that their Doppler-broadened profiles overlap. Optical pumping occurs when the excited level can spontaneously decay to more than one lower level. It can significantly deplete certain ground state populations further enhancing or weakening the saturated absorption dips.



Figure 7 Energy levels for two possible three level systems. The V-configuration with two upper levels and the Λ -system with two lower levels.

The basics of crossover resonances can be understood within the three-level atom in either the Λ - or V-configurations shown in Fig. 7 where the arrows represent allowed spontaneous and stimulated transitions. In this experiment, crossover resonances arise from multiple upper levels and so we will illustrate with the V-system. Having two excited energy levels 1 and 2, the resonance frequencies to the ground state 0 are ν_1 and ν_2 , which are assumed to be spaced less than a Doppler width.

Without the pump beam, each excited state would absorb with a Doppler-broadened profile and the net absorption would be the sum of two Gaussian profiles, one centered at v_1 and one

centered at v_2 (as pointed out by the thin lines in fig. 8). If the separation $|v_1 - v_2|$ is small compared to the Doppler width, they would appear as a single broadened absorption profile (thick envelope in fig. 8).



Figure 8 Absorption coefficient vs. the laser frequency for a V-type three-level atom. The three Bell shaped curves are with the pump off and give the Doppler-broadened absorption from the individual resonances at v_1 and v_2 and their sum. The pump on curve shows normal saturated absorption dips at $v = v_1$ and $v = v_2$ and a crossover resonance midway between.

When the pump beam is turned on, two holes are burned in the ground state velocity distribution at velocities that put the atoms in resonance with v_1 and v_2 . These two velocities would depend on the laser frequency v. For example, at $v = v_1$, the probe absorption involving upper state 1 is from zero velocity atoms while the probe absorption involving the higher-energy state 2 arises from some non-zero, negative velocity atoms. At this frequency, the pump beam burns one hole in the ground state for zero velocity atoms due to upper state 1 and another hole for some non-zero, positive-velocity atoms due to upper state 2 (see fig. 9). As with the two-level system, the hole at $v \approx 0$ leads to a decreased absorption to upper state 1 and produces a saturated absorption dip at $v = v_1$. A similar argument predicts a saturated absorption dip at $v = v_2$. Thus at $v = v_1$ and at $v = v_2$ there will be saturated absorption dips similar to those occurring in two-level atoms.

A third dip, the crossover resonance, arises at a frequency midway between at

$$\nu_{12} = (\nu_1 + \nu_2) / 2 \tag{5.1}$$

All three dips are illustrated in Fig. 8 assuming $I/I_{sat} = 10$ and assuming that the excited levels have the same spontaneous transition rate γ and the same stimulated rate constant α_0 . At the crossover frequency, the pump and probe beams are resonant with the same two opposite velocity groups:

$$v = \pm c \left(\nu_2 - \nu_1 \right) / 2\nu_{12}. \tag{5.2}$$

Atoms at one of these two velocities will be resonant with one excited state and atoms at the opposite velocity will be resonant with the other excited state. The pump beam burns a hole in the ground state populations at both velocities and these holes affect the absorption of the probe beam, which is simultaneously also arising from atoms with these two velocities.



Figure 9 Velocity distribution for different laser frequency considering the pump and the probe laser. The transitions of the pump beam is presented by the thick arrow, while the probe beam correspond to the thin arrow. (Figure adapted from [14])

6 Energy levels of Rubidium

The rubidium atom has atomic number 37. In its ground state configuration it has one electron outside an inert gas (Argon) core and is described with the notation [Ar]5s. The Rb ground state configuration is said to have filled shells up to the 4p orbitals and a single valence electron in a 5s orbital. The next higher energy configuration has the 5s valence electron promoted to a 5p orbital with no change to the description of the remaining 36 electrons.

6.1 Fine structure levels

Within a configuration, there can be several fine structure energy levels differing in the energy associated with the coulomb and spin-orbit interactions. The coulomb interaction is associated with the normal electrostatic potential energy kq_1q_2/r_{12} between each pair of electrons and between each electron and the nucleus. The spin-orbit interaction is associated with the orientation energy $-\vec{\mu}\vec{B}$ of the magnetic dipole moment $-\vec{\mu}$ of each electron in the internal magnetic field \vec{B} of the atom. The form and strength of these two interactions in rubidium are such that the energy levels are most accurately described in the L-S or Russell-Saunders coupling scheme. L-S coupling introduces new angular momentum quantum numbers L, S, and J. L is the quantum number describing the magnitude of the total orbital angular momentum \vec{L} and similarly S is the quantum number describing the magnitude of the total electronic spin angular momentum \vec{J} , which is the sum of the total orbital and total spin angular momentum and in the L-S coupling regime can be expressed as:

$$\vec{J} = \vec{L} + \vec{S} \tag{6.1}$$

The values for *L* and *S* and *J* are specified in a notation ${}^{(2S+1)}L_J$ invented by early spectroscopists. The letters *S*, *P*, and *D* are used for *L* and correspond to L = 0, 1, and 2, respectively. The value of (2S + 1) is called the multiplicity and is thus 1 for S = 0 and called a singlet, 2 for S = 1/2 (doublet), 3 for S = 1 (triplet), etc. The value of *J* is annotated as a subscript to the value of *L*.

The sum of $\vec{\ell}_i$ or \vec{s}_i over all electrons in any filled orbital is always zero. Thus for Rb configurations with only one valence electron, there is only one allowed value for L and S: just the value of ℓ_i and s_i for that electron. In its ground state (5s) configuration, Rb is described by L = 0and S = 1/2. The only possible value for *J* is then 1/2 and the fine structure state would be labeled ${}^2S_{1/2}$. Its next higher (5p) configuration is described by L = 1 and S = 1/2. In this configuration there are two allowed values J = 1/2 and 3/2 and these two fine structure states are labeled ${}^2P_{1/2}$ and ${}^2P_{3/2}$.

6.2 Hyperfine structure levels

Within each fine structure level there can be an even finer set of hyperfine levels differing in the orientation energy associated with the nuclear magnetic moment in the magnetic field of the atom. The nuclear magnetic moment is much smaller than the electron magnetic moment and this is why the hyperfine splittings are so small. The nuclear magnetic moment is proportional to the spin angular momentum \vec{I} of the nucleus, whose magnitude is described by the quantum number *I*. Allowed values for *I* depend on nuclear structure and vary with the isotope. The hyperfine energy levels depend on the the total angular momentum \vec{F} of the atom: the sum of the total electron angular momentum \vec{J} and the nuclear spin angular momentum \vec{I} :

$$\vec{F} = \vec{I} + \vec{J} \tag{6.2}$$

The magnitude of \vec{F} is characterized by the quantum number F with allowed values from |J - I| to |J + I|. Each state with a different value of F will have a slightly different energy due to the interaction of the nuclear magnetic moment and the internal field of the atom. There is no special notation for labeling hyperfine states and F is usually written explicitly in energy level diagrams. There are two naturally occurring isotopes of Rb: 72% abundant ⁸⁵*Rb* with I = 5/2 and 28% abundant ⁸⁷*Rb* with I = 3/2. For both isotopes, this leads to two hyperfine levels within the ${}^{2}S_{1/2}$ and ${}^{2}P_{1/2}$ fine structure levels (F = I - 1/2 and F = I + 1/2) and four hyperfine levels within the ${}^{2}P_{3/2}$ fine structure level (F = I - 3/2, F = I - 1/2, F = I + 1/2 and F = I + 3/2).

In Fig. 37 and 38 you can observe the theoretical D2 hyperfine energy level structure for both isotopes, while Fig. 10 shows an experimentally measured hyperfine structure spectrum.

6.3 Allowed transitions

The ${}^{2}S_{1/2}$ to ${}^{2}P_{1/2}$ transitions are all around 795 nm, while the ${}^{2}S_{1/2}$ to ${}^{2}P_{3/2}$ transitions are all around 780 nm. We will only discuss the 780 nm transitions that can be reached with the laser used in this experiment. Dipole transitions follow the selection rule $\Delta F = 0, \pm 1$. Thus, in each isotope, the allowed transitions from the ${}^{2}S_{1/2}$ to ${}^{2}P_{3/2}$ fall into two groups of three. Because the hyperfine splitting between the two ${}^{2}S_{1/2}$ levels is large compared to the hyperfine splittings among the four ${}^{2}P_{3/2}$ levels, the groups will be well separated from each other. Within each group, the three probable transitions can be labeled by the F' of the ${}^{2}P_{3/2}$ state. These three transitions will be more closely spaced in energy.



Figure 10 Measured spectra with cross over resonances of both rubidium isotopes.

Part IV Theory: MOT

The combination of laser cooling and atom trapping has produced astounding new tools for atomic physicists. These experiments require the exchange of momentum between atoms and an optical field, usually at frequencies nearly resonant to an atomic transition. The energy of the light $\hbar\omega$ changes the internal energy of the atom, and the angular momentum $\hbar k$ changes the orbital angular momentum l, of the atom, as described by the well-known selection rule $\Delta l = \pm 1$. In contrast, the linear momentum of the light $p = \hbar k$ cannot change the internal atomic degrees of freedom and therefore must change the momentum of the atoms in the laboratory frame. The force resulting from this momentum exchange between the light field and the atoms can be used in many ways to control atomic motion and is the subject of this theory section. If the light is absorbed, the atom makes a transition to an excited state, and the return to the ground state can be either by spontaneous or by stimulated emission. The nature of the optical force that arises from these two processes is quite different and will be described separately.

1 Radiative Optical Forces



Figure 11 Scattering rate γ_p as a function of the detuning δ for several values of the saturation parameter s_0 . Note that for $s_0 > 1$ the line profiles start to broaden substantially due to power broadening (Taken from [1]).

In the simplest case the momentum exchange between a monochromatic light field and the atoms results in a force \rightarrow

$$\overrightarrow{F} = \frac{d\overrightarrow{p}}{dt} = \hbar \overrightarrow{k} \gamma_p \tag{1.1}$$

where γ_p is the excitation rate of the atoms. The absorption leaves the atoms in their excited state and then, if the light intensity is low enough, they are much more likely to return to the ground state by spontaneous emission than by stimulated emission. In this case the resulting emitted light carries off a momentum $\hbar \vec{k}$ in a random direction. In first approximation, the

momentum exchange from the spontaneous emission averages to zero, so that the net total force is given by the above equation.

The scattering rate γ_p depends on the laser detuning from the atomic resonance $\delta = \omega_l - \omega_a$, where ω_l is the laser frequency and ω_a is the atomic resonance frequency (11)). This detuning is measured in the atomic reference frame, and to calculate the absorption and scattering rate it is necessary to consider the Doppler-shifted laser frequency in the moving atom's reference frame.

The excitation rate γ_p for a two-level atom is given by a Lorentzian

$$\gamma_P = \frac{s_0 \gamma / 2}{1 + s_0 + [2(\delta + \omega_D) / \gamma]^2}$$
(1.2)

where $\gamma = 1/\tau$ is an angular frequency corresponding to the decay rate of the excited state. Here $s_0 = I/I_S$ is the ratio of the light intensity *I* to the so-called saturation intensity

$$I_s = \frac{\pi h c}{3\lambda^3 \tau} \tag{1.3}$$

where $\gamma_P(I_s) = \frac{1}{2}\gamma_P(\infty)$. I_s is a few mW/cm² for typical atomic transitions. The Doppler shift seen by the moving atoms is

$$\omega_D = -\vec{k}\,\vec{v} \tag{1.4}$$

(note that \vec{k} opposite to \vec{v} produces a positive Doppler shift). The force is thus velocity dependent and this fact is exploited in laser cooling.

The maximum attainable deceleration is obtained for very high light intensities. High-intensity light can produce faster absorption, but it also causes equally fast stimulated emission; the combination produces neither deceleration nor cooling. The momentum transfer to the atom in stimulated emission is in the opposite direction to what it was in absorption, resulting in a net transfer of zero momentum. Since high intensity causes the atom to divide its time equally between ground and excited states, the force is limited to

$$\vec{F} = \hbar \vec{k} \gamma_p \tag{1.5}$$

so the deceleration saturates at a value

$$a_{max} = \frac{\hbar \vec{k} \gamma}{2M} \tag{1.6}$$

2 Optical molasses

Using Eq. 1.2 it is straightforward to calculate the radiative force on atoms moving in a standing wave produced by two counter-propagating laser beams. In the low-intensity case, where stimulated emission is not important, the forces from the two light beams are simply added to give

$$\overrightarrow{F}_{OM} = \overrightarrow{F}_{+} + \overrightarrow{F}_{-}$$
(2.1)

where \overrightarrow{F}_{\pm} are found from Eqs. 1.1 and 1.2. Then the sum of the two forces is

$$\overrightarrow{F}_{OM} \cong \frac{8\hbar k^2 \delta s_0}{\gamma [1 + s_0 + (2\delta/\gamma)^2]^2} \overrightarrow{v} \equiv -\beta \overrightarrow{v} \propto -\overrightarrow{v}$$
(2.2)



Figure 12 Standard configuration for laser cooling in an optical molasses. By detuning the laser frequency ω below the resonance frequency ω_0 the frequency of the laser opposing the atomic motion is shifted toward resonance, whereas the frequency of the other laser beam is shifted out of resonance.(Taken from [1])

where terms of order $(kv/\gamma)^4$ and higher have been neglected. For small enough velocities, the slowing force is proportional to the velocity. This results in viscous damping [5] and gives this technique the name **Optical Molasses (OM)** [6]. The resulting forces are plotted in Fig. 13. For $\delta < 0$, the sum of the forces opposes the velocity and therefore damps the atomic motion. The force \overrightarrow{F}_{OM} has maxima near

$$v \approx \pm \frac{\gamma \sqrt{s_0 + 1}}{2k} \tag{2.3}$$

and decreases rapidly for larger velocities.



Figure 13 Velocity dependence of the optical damping forces for 1D optical molasses. The two dotted traces show the force from each beam, and the solid curve is their sum. The straight line shows how this force mimics a pure damping force over a restricted velocity range. These are calculated for $s_0 = 2$ and $\delta = -\gamma$, so there is some power broadening evident. (Taken from [4])

2.1 Temperature in laser cooling

If there was no other influence on the atomic motion, all atoms would quickly decelerate to v = 0, and the sample would reach T = 0, a clearly non-physical result. In fact there are two

limits to the obtainable temperature: the first one is related to the absorption or emission of a single photon and it is called **recoil limit** while the second one is related to a statistical effect from spontaneous emission, which gives rise to a heating process and leads to the **doppler temperature limit**. Let's see them more in detail. In the elementary absorption or emission process of a single photon, the atoms obtain a minimum recoil velocity $v_r = \frac{\hbar k}{M}$ and the corresponding energy change can be related to a temperature, the recoil temperature, defined as

$$k_B T_r \equiv \frac{\hbar^2 k^2}{M} \tag{2.4}$$

This limit is generally regarded as the lower limit for optical cooling processes (although there are a few clever schemes that can cool below it) and for most atomic species is on the order of few hundreds of μK .

The other limiting temperature, called doppler temperature, is usually higher than the recoil one and it is due to the fact that as the atoms absorb photons and spontaneously emit them in random directions they will not only have momentum no smaller than that of a laser photon, but they must also scatter one photon momentum in a random direction every natural lifetime of the excited state. If this lifetime is short then the random walk in momentum space (also called brownian motion) occurs at a rate too fast to remain near the origin, leading to an effective heating due to spontaneous emission. You can find an appropriate theoretical treatment of this process in [4], while here we will give a more euristic explanation. At each emission or absorption, the atom momentum is changed by a discrete size steps $\hbar k$, leading to an average kinetic energy change by at least the recoil energy

$$E_r = \frac{\hbar^2 k^2}{M} = \hbar \omega_r \tag{2.5}$$

This means that the average frequency of each absorption is $\omega_{abs} = \omega_a + \omega_r$, and the average frequency of each emission is $\omega_{emit} = \omega_a - \omega_r$. Thus the light field loses an average energy of

$$\hbar \left(\omega_{abs} - \omega_{emit}\right) = 2\hbar\omega_r \tag{2.6}$$

for each scattering. This loss occurs at a rate $2\gamma_p$ (two beams), and the energy is converted to atomic kinetic energy because the atoms recoil from each event. Since these recoils are in random directions the atomic sample is thereby heated. The competition between this heating with the damping force of Eq. 2.2 results in a non-zero kinetic energy and gives rise to a steady state, where the rates of heating and cooling are equal. Equating the cooling rate, $\vec{F}_{OM} \cdot \vec{v}$, to the heating rate, $4\hbar\omega_r\gamma_p$, delivers the steady-state kinetic energy is

$$E_{kin} = \frac{\hbar\gamma}{8} \left(\frac{2|\delta|}{\gamma} + \frac{\gamma}{2|\delta|} \right)$$
(2.7)

This result is dependent on the laser detuning $|\delta|$, and it has a minimum at $2|\delta|/\gamma = 1$, i.e. $\delta = -\gamma/2$. Since in this case it yields $1/2k_BT = E_{kin}$, we get the temperature

$$T_D = \frac{\hbar\gamma}{2k_B} \tag{2.8}$$

where k_B is Boltzmann's constant and T_D is called the **Doppler temperature** or the Doppler cooling limit. For ordinary atomic transitions, T_D is typically below 1 mK. This remarkable result predicts that the final temperature of atoms in optical molasses is independent of the optical wavelength, atomic mass, and laser intensity (as long as it is not too large).

3 Magneto-Optical Trap

The most widely used trap for neutral atoms is a hybrid trap called **magneto-optical trap** (**MOT**) because it employs both optical and magnetic fields. It was first demonstrated in 1987 [7] and its operation depends on both inhomogeneous magnetic fields and radiative selection rules to exploit both optical pumping and the strong radiative force. The radiative interaction provides the cooling that helps in loading the trap, while the inhomogeneous magnetic field exerts a recalling force towards the center of the field, allowing a stable trapping.

The MOT is a robust trap, which does not critically depend on precise balancing of the counterpropagating laser beams or on a very high degree of polarization. The magnetic field gradients are of the order of $10G/cm = 10^{-3}T/cm$ and can readily be achieved with simple coils. The trap can be operated inside a vacuum chamber in which alkali atoms, in our case ⁸⁵*Rb* atoms are captured from a background vapor ejected by so called dispensers. Furthermore, low-cost diode lasers are used to produce the light appropriate for all the alkali (except Na), so the MOT has become an inexpensive ways to produce atomic samples with temperatures below 1 mK.



Figure 14 Arrangement for a MOT in 1D. The horizontal dashed line represents the laser frequency seen by atoms at rest in the center of the trap. Because of the Zeeman shifts of the atomic transition frequencies in the inhomogeneous magnetic field, atoms at $z = z_0$ are closer to resonance with the σ^- laser beam than with the σ^+ beam, and are therefore driven toward the center of the trap. (Taken from [4])

Trapping in a MOT works by optical pumping of slowly moving atoms in a linearly inhomogeneous magnetic field B = B(z) = Az. This quadrupole field is created by a pair coils powered by counter circulating currents, so called Anti-Helmholtz coils. Atomic transitions with the simple scheme of $J_g = 0 \rightarrow J_e = 1$ have three Zeeman components in a magnetic field, each excited by a different polarization π , σ^{\pm} , whose frequencies tune with field (and therefore with position) as shown in Fig. 14 for 1D.

Two counter propagating, circularly polarized laser beams, each detuned below the zero field atomic resonance by δ , are incident as shown in Fig. 14. Because of the Zeeman shift, the excited state $M_e = +1$ is shifted up for B > 0, whereas the state with $M_e = -1$ is shifted down. At position *z* the magnetic field therefore tunes the $\Delta M = 1$ transition closer to resonance and the $\Delta M = +1$ transition further outfrom resonance. If the polarization of the laser beam incident from the right is chosen to be σ^- and correspondingly σ^+ for the other beam, more photons are scattered from the σ^- beam than from the σ^+ beam. Thus the atoms are driven toward the center of the trap where the magnetic field is zero. On the other side of the center of the trap, the roles of the $M_e = \pm 1$ states are reversed and now more light is scattered from the σ^+ beam, again driving the atoms towards the center. The situation is analogous to the velocity damping in an optical molasses from the Doppler effect as discussed above, but here the effect operates in position space, whereas for molasses it operates in velocity space. Since the laser light is detuned below the atomic resonance in both cases, compression and cooling of the atoms is obtained simultaneously in a MOT.



Figure 15 Three pairs of counter propagating laser beams as well as a pair of Anti-Helmholtz coils provide the necessary ingredients for a Magneto-Optical Trap.

So far the discussion has been limited to the motion of atoms in 1D. However, the MOT scheme can easily be extended to 3D by using six instead of two laser beams (Fig. 15). Furthermore, even though very few atomic species have transitions as simple as $J_g = 0 \rightarrow J_e = 1$, the scheme works for any $J_g \rightarrow J_e = J_g + 1$ transition. Atoms that scatter mainly from the σ^+ laser beam will be optically pumped toward the $M_g = +J_g$ substate, which forms a closed system with the $M_e = +J_e$ substate.

For a description of the motion of the atoms in a MOT, consider the radiative force in the low-intensity limit (see Eqs. 1.1 and 1.2). The total force on the atoms is given by

$$\overrightarrow{F}_{OM} = \overrightarrow{F}_{+} + \overrightarrow{F}_{-} \tag{3.1}$$

where \overrightarrow{F}_{\pm} are found from Eqs. 1.1 and 1.2 and the detuning δ_{\pm} from the atomic resonance.

$$\delta_{\pm} = \delta \mp \overrightarrow{k} \cdot \overrightarrow{v} \pm \frac{\mu' B}{\hbar}$$
(3.2)

Here $\mu' \equiv (g_e M_e - g_g M_g) \mu_B$ is the effective magnetic moment for the transition used. Note that the Doppler shift $\omega_D = -\overrightarrow{k} \cdot \overrightarrow{v}$ and the Zeeman shift $\omega_Z = \mu' B/\hbar$ both have opposite

signs for opposite beams.

When both the Doppler and Zeeman shifts are small compared with the detuning δ , the denominator of the force can be expanded as for relation 2.2 and the result becomes

$$\overrightarrow{F} = -\beta \, \overrightarrow{v} + \kappa \, \overrightarrow{r} \tag{3.3}$$

where the damping coefficient β is defined in relation (3). The spring constant κ arises from the similar dependence of \vec{F} on the Doppler and Zeeman shifts and is given by

$$\kappa = \frac{\mu'\beta}{\hbar k}A\tag{3.4}$$

where *A* is the magnetic field gradient. The force of Eq. 3.3 leads to damped harmonic motion of the atoms, where the damping rate is given by $\gamma_{MOT} = \beta/M$ and the oscillation frequency by $\omega_{MOT} = \sqrt{\kappa/M}$. For magnetic field gradients $A \approx 10G/cm$, the oscillation frequency is typically a few kilohertz, and this is much smaller than the damping rate that is typically a few hundred kilohertz. Thus the motion is over-damped, with a characteristic restoring time to the center of the trap of $2\gamma_{MOT}/\omega_{MOT}^2$, which is of the order of several milliseconds for typical values of the detuning and intensity of the lasers.

So far, we have considered a two level system, but real atoms have a much more complicated level structure. Which transition to choose for the MOT laser cooling? A first guess would be to select the transition that has the highest excitation rate, leading to the maximum absorption and cooling, but, for any multilevel system, a very important requirement for an efficient MOT is to operate between atomic transitions which form a closed system to avoid losses from the cooling cycle. If the chosen excited level has more than one decay channel, then the most frequent ones have to be addressed by additional laser beams to repump the atoms into the levels used for the cooling transition, thus forming a maximally closed loop of transitions.

4 Comparison of relevant temperature scales in laser cooling

It is convenient to use the label of temperature to describe an atomic sample whose average kinetic energy $\langle E_k \rangle$ in one dimension has been reduced by the laser light, and this is written simply as

$$\langle E_k \rangle = \frac{1}{2} k_B T \tag{4.1}$$

where k_B is Boltzmann's constant. The first characteristic temperature corresponds to the energy associated with atoms whose speed and concomitant Doppler shift puts them just at the boundary of absorption of light. This defines the highest velocity class of atoms that can be efficiently cooled and trapped by a MOT, while the atoms that have higher initial velocities can escape from the trap. So the **capture velocity** is defined as $v_c \equiv \frac{\gamma}{k} \approx 1m/s$, and the corresponding temperature is

$$k_B T_C \equiv \frac{M\gamma^2}{k^2} \tag{4.2}$$

and is typically several mK (for ${}^{85}Rb$, $T_C = 222.12mK$). The next characteristic temperature is the **Doppler temperature** and it is related to the energy associated with the natural width of

atomic transitions. It is given by

$$k_B T_D \equiv \frac{\hbar \gamma}{2} \tag{4.3}$$

Because it corresponds to the limit of certain laser cooling processes, it is often called the Doppler limit, and is typically several hundred μK (for ⁸⁵*Rb*, $T_D = 143.41\mu K$). Associated with this temperature is the one-dimensional velocity $v_D = \sqrt{\frac{k_B T_D}{M}}$ (for ⁸⁵*Rb*, $v_D = 11.85 cm/s$).

The last of these three characteristic temperatures is the **recoil temperature** corresponds to the energy associated with a single photon recoil that we defined as

$$k_B T_r \equiv \frac{\hbar^2 k^2}{M} \tag{4.4}$$

and is generally regarded as the lower limit for optical cooling processes (although there are a few clever schemes that can cool below it). It is typically a few μK , and corresponds to speeds of $v_r \approx 1 cm/s$ (for ⁸⁵*Rb*, $v_r = 0.602 cm/s$, $T_r = 0.370 \mu K$. These three temperatures are related to one another through a single parameter ϵ that is ubiquitous in describing laser cooling. It corresponds to the ratio of the recoil frequency $\omega_r \approx \frac{\hbar k^2}{2M}$ to the natural width γ , and as such embodies most of the important information that characterize laser cooling on a particular atomic transition. Typically $\epsilon \approx 10^{-3} - 10^{-2}$, and is given by

$$\epsilon \equiv \omega_r / \gamma = \frac{\hbar k^2}{2M\gamma} \tag{4.5}$$

From this is clear that $T_r = 4\epsilon T_D = 4\epsilon^2 T_C$.

5 Trap loading and loss processes

The time dependence of the atom number in the trap is given by an interplay of trap loading and different loss processes. As we will see at the end of this subsection, the time dependency of the atomic density can be described by a rate equation. First we will discuss the different terms:

5.1 Loading Rate

The atoms which we trap in our MOT are emitted from a so called dispenser, which is located in the vacuum system. The dispenser produces a vapor with a certain partial pressure of Rb that is related to the current that runs through the dispenser, heating it. Atoms from the background vapor can be captured in the MOT when they loose their kinetic energy by scattering photons from the laser beams until they have nearly zero energy. Depending on the scattering rate and the beam diameters one can determine a capture velocity typically in the order of 10 m/s. This means that only a small fraction of the atoms from the vapor can be trapped in a MOT. The change in the atom number can then be written as:

$$\frac{dN}{dt} = L(I_{\text{Dispenser}};\gamma_{\text{p}}) > 0$$
(5.1)

where *L* is the loading rate, which itself is a function of the dispenser current $I_{\text{Dispenser}}$ and the scattering rate of the atoms γ_{p} . If there were no loss mechanisms in the sample, the atom number in the MOT would diverge to infinity!

5.2 One-body Losses

The trapped atoms in the MOT are lost via collisions. The most dominant loss mechanism for a MOT are collisions between a "hot" atom from the background gas and an atom from the MOT. The gain in kinetic energy is normally much larger as the capture velocity of the MOT and the particle leaves the trapping region. The rate for this process depends on the atom number in the trap and can be written as

$$\frac{dN}{dt} = -\alpha N \tag{5.2}$$

where α corresponds to the one-body loss coefficient.

6 Rate-Equation

The time-dependent change in the atom number can be written by combining the two differential equations for the loading and one-body loss processes:

$$\frac{dN}{dt} = L - \alpha N \tag{6.1}$$

During the preparation of the lab week, you have to solve this differential equation. What is the solution at the beginning of the loading process and what will be the steady state? What is the typical time scale ("loading time") for the loading process of a MOT?

For higher densities one also has to consider density dependent two-body collisions, i.e. fine structure changing collisions, where the fine structure of the atomic pair has changed after the collision and the loss in internal energy leads to an increase of the kinetic energy larger than the capture velocity. This leads to a more complicated differential equation for the atom number:

$$\frac{dN}{dt} = L - \alpha N - \beta N^2 \tag{6.2}$$

with β being the two-body decay coefficient.

7 Temperature measurement via release and recapture

The temperature of a MOT can be measured by the "release and recapture" method, assuming that the velocity distribution of the atoms corresponds to a Maxwell-Boltzmann distribution. The size of the MOT is much smaller than the trapping volume, which is connected to the diameters of the laser beams. When the cooling beams of the MOT are switched off after loading, the atoms don't feel any trapping potential and they start to fly in the direction that is given by their velocity at the time when the MOT is switched off. Due to the low density of the MOT ($\approx 10^9 cm^{-3}$), the mean free path is large and collisions between the atoms can be neglected. After a certain time (typically several ms) the cooling beams are again switched on and the particles with low velocities are still within the crossing of the laser beams and thus are recaptured. Particles with higher velocities have already left the crossing of the beams and so they are not recaptured. When the delay between switch-off and switch-on the MOT is increased, the amount of atoms recaptured in the MOT becomes smaller and smaller. At a fixed delay time, the amount of recaptured atoms is larger the lower the temperature of the sample is.



Figure 16 Velocity distribution for different temperatures in a MOT.

The amount of recaptured atoms at a certain time can be modelled in the following way. The velocity distribution of the atoms is given by a Maxwell-Boltzmann distribution f(v) with

$$f(v) = \frac{4}{\sqrt{\pi}} \frac{v^2}{\alpha^3} e^{[-v^2/\alpha^2]}$$
(7.1)

with $\alpha = \sqrt{2k_BT/M}$. At t = 0, all atoms are assumed to be at the center of the trap i.e. r = 0. After an expansion time t, the velocity distribution is represented by a spatial distribution via v = r/t.

The spatial distribution at a time t is thus given by

$$f(r,t) = \frac{4}{\sqrt{\pi}} \frac{r^2}{t^2 \alpha^3} e^{[-r^2/(\alpha^2 t^2)]}$$
(7.2)

The amount of atoms which are within a sphere with a radius R can be calculated by integrating over this sphere:

$$\frac{N(t)}{N(0)} = \int_{r \le R} d^3 r f(r, t)$$
(7.3)

The analytical solution of this integral is:

$$\frac{N(t)}{N(0)} = erf(\chi) - \frac{2}{\sqrt{\pi}}\chi e^{-\chi^2}$$
(7.4)

where $\chi = \sqrt{\frac{M}{k_BT} \frac{R}{t}}$. The release and recapture measurement in the FP-lab can be done by switching off the MOT beams via a TTL signal that controls the power output of the AOM

driver used to adjust the detuning of the cooling laser. The time delay can be changed by a delay box.

8 Determination of Atom Number

In order to convert the voltage signal measured by the photodiode into the number of atoms captured in the MOT you have to perform few steps.

The atoms absorb light from the laser beams and re-emit this light with a rate given by the **Scattering rate** (pay attention that this rate depends on the detuning of the laser beams!):

$$\gamma_{sc}(\Delta) = \frac{\gamma}{2} \frac{I(r)/I_{sat}}{1 + I(r)/I_{sat} + 4\Delta^2/\gamma^2}$$
(8.1)

where the natural line width is $\gamma({}^{85}Rb) = 2\pi 6.07$ MHz and $I_{sat} = \frac{2\pi^2 \hbar \gamma_c}{3\lambda_c^3} = 4.1$ mW/cm² for randomly polarized light (this gives the best estimation according to [10]). You should approximate I(r) with the intensity in the center of the beam I_0 and consider that the atoms are illuminated by six laser beams. The relationship between I_0 and the six beam total power measured on the power meter is $I_0 = 2P_{powermeter}/\pi w^2$), considering a Gaussian beam profile of the beams with waist w = 2.0 mm.

The next step is to consider that the atoms spontaneously emit isotropically, so the total emitted power by N_{atoms} is:

$$P_{emitted} = \gamma_{sc}(\Delta) E_{\nu}(\lambda) N_{atoms}$$
(8.2)

where $E_{\nu}(\lambda) = \frac{hc}{\lambda}$.

Of this total power we collect only a small fraction with our imaging system because we observe only a small **solid angle**, limited by the distance from the atoms and the radius of the collecting lens (r = 25.4 mm):

$$P_{meas} = \theta_{\Omega} P_{emitted} \tag{8.3}$$

with the solid angle $\theta_{\Omega} = \frac{\pi r^2}{4\pi d^2}$. Our imaging system (see Fig. 17) is made by a simple single lens positioned at a distance of 2 focal lengths away from the MOT in order to form a 1:1 image on the photodiode. Since f = 75 mm, then d = 150 mm.



Figure 17 MOT fluorescence imaging system.

Part V Experimental Setup

The experimental setup comprises of two main parts, the laser table and the vacuum system. These are described in the following sections.

1 Optical Setup

The optical setup comprises of the system comprises of a diode laser which generates coherent laser light. This light is then used for the creation of MOT with the help of different optical components. These components are shown in Fig. 18. The individual components are described in detail in Appendix. 2. The light from the laser passes through beam-shaping prism pair, where a laser light of round beam profile is created. Then the light passes through a beam sampler. Here a part of the light is deflected into the "Spectroscopy" part and another part of the light is directed into the "MOT" section via an electro-optical modulator.



Figure 18 Optical Setup of the laser table in the experiment.

In the spectroscopy part, the polarization of the light is adjusted before it passes through a PBS1 and then, the light is directed onto an acousto-optic modulator AOM1 via mirror M7, where the frequency of the laser light is shifted. Since in the experiment a double pass AOM is used, the frequency of the light is shifted twice. Before entering the rubidium vapor cell, this light is again split into two parts at PBS2, one being the probe beam and the other being the pump beam. The probe beam goes straight through the Rb vapor cell, consisting of both rubidium 85 and 87 isotopes and is directed onto a photodiode. The pump beam is deflected at PBS2 before Rb cell and is directed into the cell opposite to the probe beam. The probe beam probes the class of atoms which have been excited by the pump beam. This reveals the the lamb dips in the absorption spectrum. The photodiode signal is then finally fed into the locking electronics of the laser to allow frequency stabilization through Frequency Modulation scheme, depicted in Fig. 39.

In the MOT setup part, the light is frequency shifted by the EOM, and directed onto PBS4. A part of this light goes straight onto the imaging setup which is not a part of this experiment. Another part of the light is deflected onto AOM2 where the detuning of the laser light is changed. This is one of the parameters that the students need to change, while carrying out the experiment. Again, as the AOM used is a double pass AOM, the light frequency is shifted twice and the light goes back the same optical path and is directed into a fiber coupler. The other end of the fiber lies on the other table close to the vacuum chamber. The light coupled out of the fiber is then divided into three nearly equal parts and eventually shone into the vacuum chamber in order to create a MOT.

2 Vacuum system



Figure 19 Top view of the ultrahigh vacuum system.

Perfect thermal isolation between a gas sample and the material of walls surrounding it has enabled experiments with ultracold atomic and molecular gases to take place in an apparatus kept at room-temperature. It is remarkable that it is for example even possible to maintain a Bose-Einstein condensate (BEC) for many seconds in a machine that is warmer by a factor of 10^9 than the gas sample. No heating due to the hot walls is detectable unless the atoms ap-

proach a metal surface within microns. Transfer of energy from the walls to the gas sample may take place through two channels:through the room-temperature black body radiation field and through gas molecules. Atomic gases couple extremely weakly to the room-temperature black body radiation field, which leaves most experiments in the rest-gas limited regime. The best condition for any experiment with trapped cold gases is therefore an ultra-high vacuum (UHV) environment (UHV is defined as the region of pressure below 10^{-8} mbar). By relatively simple means, one can now produce a laboratory vacuum which has a pressure of 10^{-11} mbar, comparable to the interplanetary medium. In this regime the "residual gas" normally consists of atoms and molecules which mostly reside on the walls, but that occasionally come off and fly ballistically through the vacuum system with an energy corresponding to the wall temperature. These residual gas particles therefore have an energy that is many orders of magnitude above that of the ultracold gas sample, and even "grazing" collisions will knock particles out of the sample, giving rise to direct loss rather than heating.

The ultra high vacuum (UHV) system you will work with during the next week was machined in the mechanical workshop of the Physics Institute. It has an octagon shape featuring ten viewports, of which nine are optically accessible. The tenth viewport, which is not optically accessible, connects to the Ion pump that is necessary to maintain a certain background pressure. This pressure can be measured through an ion gauge, that is also connected to the UHV system. The vacuum chamber houses inside two Rb-dispensers. When a current > 7 A is sent through them, they emit hot Rb atoms of both stable Rb isotopes. This 700 K background gas will then be cooled by the three mutually orthogonal and counter-propagating cooling beams that form the MOT. Additionally, the vacuum chamber supports a pair of Anti-Helmholtz coils, that provide the required magnetic field gradients which are necessary for successful atom trapping. The entire chamber is mounted on a 50 x 75 cm breadboard on which the optics for the cooling and repumping laser beams are mounted. During the course of your lab work you are only allowed to adjust the optical components in the direct vicinity of the chamber, since the remaining optics are already aligned by the tutors. Each Anti-Helmholtz coil consist of 90 windings, and the coils produce gradients of 1.25 G/A/cm. The coils have a diameter of about 170 mm and have a distance of about 115 mm.

Part VI Lab Work

This section includes the list of tasks to be accomplished by the students, for in-presence Praktikum.

1 Lab safety

This student lab provides an exciting experiment in which you can work with tools that can be found in all the experiments which deal with ultracold atoms. The aim of this experiment is to allow you to learn this techniques from scratch and to play around with atoms, which will be at a temperature of only a few hundred micro kelvin higher than the absolute zero temperature point. But when working with the MOT setup you have to deal with technical devices which can cause dangers to your health, if you don't work carefully and if you don't respect the basic safety rules of a modern optics lab!!! You had to sign that you got the introduction in laboratory and laser security during the "Sicherheitsbelehrung" and you have to take this seriously! Besides some general rules working, the FP20 course has some specific safety issues, in particular lasers and high electrical voltages and currents, which we describe here in detail.

1.1 General rules

- Never work alone in the lab. Make sure that there is always a second person with you, with which you can discuss dangers and working strategies.
- Never work in the lab under the influence of alcohol, drugs or strong medicaments.
- Always contact the lab assistant if you have the slightest doubts about any safety issues or the destruction of any lab equipment.

1.2 Laser safety

To realize a MOT a certain laser power is necessary. The lasers used in the student lab are all classified in the highest laser-protection class ("Laserschutzklasse 4"). This section is intended to introduce you to the very basic rules of working safely with the lasers used in this experiment. Obeying to the rules stated here is absolutely necessary to exclude the risk of severe injury. In this experiment you will be using diode lasers that emit a light power of up to 50 mW. This power is at least ten times higher than the one emitted from a common laser pointer. The fact that the wavelength of the light used here is in the near infrared (NIR), requires even grater caution because the beam path is (almost) invisible to the naked eye. The beams can only be made visible by means of additional equipment such as IR-viewers, viewer cards or CCD-cameras. The laser powers are not high enough to cause injury to exposed skin; they are, however, strong enough to heat up the retina of the human eye very quickly if exposed to the beam. This is particularly dangerous in the case of IR light, because the receptors are insensitive at those wavelengths and none of the automatic protection mechanisms such as eye lid or iris closing works. A heated retina part will very rapidly be irreversibly destroyed which will lead

to blind spots in the vision or even to full blindness of the eye. The above implies the following rules:

- Wear protection glasses (available in the lab) all the time.
- Do not wear jewelery, watches or any other possible reflecting objects on your arms, wrists, hands, and fingers while aligning optics. It is a good practice to take them of during the whole time spent in the laboratory, this way you'll avoid the risk of forgetting to take them of when you'll need to work with the lasers.

In addition to these rules concerning your personal safety, we would like to state an additional set of rules meant to protect the more delicate of the technical equipment used in the experiment. Especially laser diodes are very sensitive instruments that can be damaged easily. If this happens the FP-Mot will not be operational for a long period! Therefore please:

- Always contact a lab assistant when you are not sure about any manipulation of the laser setup.
- Do not change the temperature of the lasers on your own. And please never switch the temperature controllers off!
- Only change the laser current by small amounts when the spectroscopy runs badly. Do so only if you have received a detailed introduction on how to operate the current drivers.
- Do not try to do any mechanical adjustment on the lasers and their housings.

2 Tasks

2.1 Before the Doppler free spectroscopy tasks

- 1. measure the beam power with the power meter at the position A-F shown in fig. 20
- 2. discuss with the tutor if a optimization of the double pass configuration is necessary
- 3. discuss with the tutor if a optimization of the Doppler free spectroscopy setup is necessary

2.2 Before the Laser Cooling tasks

Before measurements on the MOT can be performed, the optical setup need to be prepared

- 1. measure the power in A in fig. 21
- 2. align the double pass configuration by first optimizing the beam path which passes the AOM ones (measure at point B), then align the way back and determine the power in C
- 3. couple light into the fiber and measure the power in D (please note, that a lens is needed in this case due to the large beam size), consider here section 3 and section 4

If all this is aligned one can start to align the MOT beams itself. Start here with one of the horizontal beams and align them one after the other as explained section 5.



Figure 20 Positions for measuring powers in the spectroscopy setup.



Figure 21 Positions for measuring power in the MOT setup.

3 Coupling light into a single mode fiber

To create a first coupling, one connects a test fiber into the fiber coupler. On the other end of the fiber a fiber alignment tool (basically a small laser) need to be connected. Now the main beam and the beam of the fiber alignment laser need to be overlapped by beam walking. When this is done we place a camera behind the fiber and optimize the transmission of the fiber. When enough laser is seen with the camera, the fiber coupling of the test fiber can be optimized as written in section 4 with the help of a power meter. As a final step the test fiber can be replaced by the original fiber and finally optimized.

4 Beam walking-General procedure

Beam walking is a general procedure often used in optical labs. The principle idea is to adjust the angle and the position of a beam on a certain position. This procedure can be realized with two mirrors (or equivalently with one mirror and one adjustable mounting of a fiber-coupler). Step-by-step description to increase the transmission of an optical fiber if you already transmit enough to detect it:

- 1. start with one position of the vertical screw of the mirror
- 2. optimize the vertical screw of the fiber coupler and keep the maximal value in mind
- 3. rotate a small step with the vertical screw of the mirror
- 4. optimize again the vertical screw of the fiber coupler and compare the maximal value
- 5. in case the value increases start with step 3 again turing in the same direction, otherwise in the other direction. Optimize this until the maximum is found.
- 6. then repeat this procedure for the horizontal screw

repeat the whole procedure until you found the global maximum (compare fig. 22).



Figure 22 Fiber beam walking.

5 Alignment of the MOT beams

Now that you have the cooling and repumping beam perfectly overlapped after the fiber, you can proceed by checking and, if required, by adjusting the alignment of the three MOT beams through the vacuum apparatus. First, close the iris which is positioned after the fiber output. This will create a small beam which is much easier to align through the vacuum chamber. Two masks, on which the center of the view-port is marked, will be available for this purpose and have to be placed on the view-ports of the direction you are aligning. You should use the mirror (mirror 1) which is further away from the vacuum chamber to align the beam to the first view-port (iris 1) and the second mirror (mirror 2) for align the beam to the center of the alignment of the initial beam. The alignment of the two mirrors is an iterative procedure commonly called "beam walking". At the end you have to align the retro-reflection with the help of the mask of the first view-port. When you are done open the iris.



Figure 23 MOT beam alignment.

6 Important Values

- MOT coils: start with 9A (never more then 12A)
- **compensation coils:** start with 0.5A (never more then 2A)
- **dispenser:** start with 7A (never more then 12A)

Part VII Working Instructions

The FP20 colloquium is split into two parts. By this we can separate the two main theory sections of this lab course, namely **Doppler free spectroscopy** and **Laser cooling**.

1 Doppler Free Spectroscopy

1.1 Colloquium I

To prepare for the colloquium you need to know details about:

- 1. Basic laser absorption spectroscopy
- 2. Saturated absorption and Doppler free spectroscopy
- 3. Energy levels of Rubidium

1.2 Work Instructions

After having passed the colloquium you will have time to get used to the basic monitoring and controlling units in the optics lab, especially the ones of the laser, digilock and of the spectroscopy. If you feel comfortable with the electronics you have to Record the D2-line spectra of both Rubidium isotopes. To do so you can save the spectroscopy data in the digilock software:

- 1. switch on the scan with the scan button.
- 2. set the scan frequency to 10 Hz (triangle) and go to the "scope" window.
- 3. with "amplitude" you can control the range of your scan (zoom in or out) and shift the scan range with an offset (you might also have to adjust the piezo offset and the current at the laser controller).
- 4. you can save the data as a ".txt" file by right clicking in the spectra and choosing "export data".

Record the D2-line spectra of both Rubidium isotopes. You have to take the following data: All D2-lines in one scan:

- ${}^{87}Rb F = 2 \rightarrow F'$, ${}^{85}Rb F = 3 \rightarrow F'$, ${}^{85}Rb F = 2 \rightarrow F'$, and ${}^{87}Rb F = 1 \rightarrow F'$ transitions with the Doppler free spectroscopy method
- ⁸⁷*Rb* $F = 2 \rightarrow F'$, ⁸⁵*Rb* $F = 3 \rightarrow F'$, ⁸⁵*Rb* $F = 2 \rightarrow F'$, and ⁸⁷*Rb* $F = 1 \rightarrow F'$ transitions without the Doppler free spectroscopy method

From these datasets you use the two Doppler valleys of ${}^{87}Rb$ to calibrate the *x*-axis. With this calibration the frequency of transitions of ${}^{85}Rb$ can be measured. Do separate scans of the:



Figure 24 Locking laser system.

- ${}^{87}Rb \ F = 2 \rightarrow F'$ transitions
- ${}^{85}Rb F = 3 \rightarrow F'$ transitions
- ${}^{85}Rb \ F = 2 \rightarrow F'$ transitions
- ${}^{87}Rb \ F = 1 \rightarrow F'$ transitions

each with and without the Doppler free spectroscopy method (8 spectra in total). Perform those scans with the same scanning amplitude for a better comparison of the different calibrations (keep the scan range rather large to make sure that always all transition are within the scanning range). From these datasets you can measure the natural **line width** of the **hyperfine lines** and the D2 line **hyperfine energy level separation**. For calibrating the *x*-axis, use of each scan the two most significant features with large separation and compare all calibration factors.

2 Laser cooling

2.1 Colloquium II

The theory of the MOT will be discussed in detail during a second colloquium. To prepare for the colloquium you need to know details about:

- 1. Radiative optical forces
- 2. Optical molasses

- 3. Magneto-Optical Trap
- 4. Temperature regimes accessible in laser cooling
- 5. Trap loading
- 6. Temperature measurement via release and recapture

The frame of this colloquium will also be used to discuss the characterization measurements of the MOT.

2.1.1 Laser locking



Figure 25 Locking the lasers to the right frequencies.

The laser is locked on the crossover ${}^{85}RbF = 3 \rightarrow X_{34}$ between the F'=3 and F'=4 levels. Therefore you should zoom into the region of the desired transition using scan amplitude and scan offset. The tutor will help you once in the beginning with the laser locking procedure. To lock the lasers, please follow the following steps:

- 1. Switch on the frequency modulation of the laser in the "PDH" tab. The error signal should appear in the scope.
- 2. You might have to adjust the amplidute of the modulation if the error signal is to large or to small.
- 3. Go to the "Autolock" and the "PID2" tabs and fix the scales of the signals
- 4. Drag the cross to the desired absorption peak.
- 5. Right click and choose "LI/PDH: Lock to extremum". In the next scan, the laser will lock to the desired transition.
- 6. If the laser does not lock you might have to adjust the locking parameters of the PID controller. **Note: Do no change these parameters, before consulting the tutor!!**

Note that if you hit the table or any metal part on it, the lasers might unlock and you'll have to lock them again.

Now it is also the right time to switch ON the Rb atoms dispenser, so, on its power supply, increase slowly the current from 0 A up to 12 A. **However, this will be done by the tutor in advance**, since it need some heating up time.

2.1.2 Starting the QD-Control software

- 1. Launch the "QD-Control" LabView program and the window "OD-Control.lvproj" as shown in Fig. 27 appaears. Double click on QD-Control.vi.
- 2. Change the "Delay between the runs" to "500 ms" and the "Auto-Save Interval" to "60 min".
- 3. Click on "Start Run" to run the experimental cycle once. Check the "Continuous" option to continuously run the experimental cycle.
- 4. If you want to stop the runs, click on "Stop Runs."

2.1.3 Magnetic Coils and Laser detuning

- 1. Start the QD-Control.vi project.
- 2. In the FP UI section, go to the Main Section and select Independent Varibales, See Fig. 28.
- 3. You can change the current of the compensation coil by the variable "CurrentCompZ". Choose the value where the MOT is the brightest. (If the experiment is done in-presence the compensation coil power supply is not connected with the PC, but can be adjusted directly. Start with 0 A and do not exceed 3 A (see fig 26.)
- 4. The magnetic field gradient can be changed via the variable "CurrentGradient". This value must be tuned in steps of 0.5 A, 5 data points around the coarsely adjusted maximum. (If the experiment is done in-presence the Feshbach power supply is not connected with the PC, but can be adjusted directly. Start with 0 A and do not exceed 15 A (see fig 26) .)



Figure 26 Power supplies of the coils, just change the red marked adjusting knobs.

5. The detuning of the cooler laser can be changed controlling the signal to the AOM driver via the variable "AOMfrequency". For "AOMfrequency" set to 110, the detuning is calculated as follows:

$$\delta_{\text{cool}} = \nu_{\text{crossover}} - 2(\nu_{\text{AOM1}} - \nu_{\text{AOM2}})$$
(2.1)

$$= -60 \text{MHz} - 2 \times 85 \text{ MHz} + 2 \times 110 \text{ MHz}$$
(2.2)

$$= -10 \text{ MHz}$$
(2.3)

The detuning of the cooling laser must be changed from 4 MHz-16 MHz in steps of 2 MHz.

Every time the detuning of the cooler laser is changed, the detuning of the repumper must be changed accordingly. In order to do so, start the software "ConfigWFNV" as shown in Fig. 29, and follow the steps below:

- 1. Switch on the "RF On" to switch on the RF generator for the EOM.
- 2. Change the "RF Power" to maximum which is 0 dB in this case.
- 3. Now enter the desired RF frequency in MHz. For each cooler laser detuning δ_{cool} , the repumper detuning must be adjusted. For $\delta_{cool} = 10$ MHz, the repumper detuning is calculated as follows:

$$\delta_{\text{repumper}} = \nu_{\text{sep}} - \nu_{\text{crossover}} + |\delta_{\text{cool}}|$$
(2.4)

= 3035 MHz - 120 MHz + 10 MHz (2.5)

= 2925 MHz (2.6)

Here v_{sep} is the separation between the hyperfine levels F = 3 and F = 2 for the ground state ${}^{5}S_{1/2}$.



Figure 27 Launching the experimental control software

With these steps in place, you should be able to trap a cloud of cold rubidium atoms, or in other words, achieve a MOT. The fluorescence of the atoms can be observed with an infrared camera. In order to observe the fluorescence of the atoms as shown in Fig. 30, follow these steps:

- 1. Start the ThorCam application and select the camera.
- 2. Click on the "Settings" and adjust "Peak Clock", "Frame Rate" and "Exposure Time" settings. Ensure the "Dropped Frames" settings is non-zero frames.
- 3. Click on the "Start Capture" button and you should be able to observe the MOT fluorescence on screen.

2.1.4 Acquisition of loading curves

- 1. In Fig. 28, change the time for which the loading occurs via the variable "Loading Time".
- 2. Start the application "Tie Pie Multi Channel".
- 3. Select the pre-programmed settings by clicking on "Load" button. Select the setting "Fp20MOT Settings.tps".

®)			FP UI.Ivli	:FP UI.Ivclass:Actor (Core.vi:5880001 (clone)	
Main LogicBoxes Run	Controller				Start Run (F5)	Continuous
Independent Variables	Dependent Variables	Multiple Me	asurements	Network	Mode Default	
Repeats 1	Shuffle All	Save Set. for Default Run	Total Runs	1		
3 CurrentCompZ	Default Type 2 Default	From 0	To Step	Arb. Steps	^	
4 CurrentGradien	12 Default	0	0 0	÷0 1	Reorder/Sort	1
VoltageGradien	4 Default	x 0	0 0		Set human	1
LoadingTime	10000 Default	0	0 0	() 0 1	(permanent)	
OffTime	500 Default	0	0 0	0 1	Move DOWN	
5 AOMfrequency	110 Default	× 0	0 0		(permanent)	

Figure 28 Tuning the MOT parameters.



Figure 29 Changing the detuning of repumper via the EOM software.

- 4. Click on the "Start (S)" button to acquire the loading curve as shown in the figure. Go to "File>Save Image" and save the file with the desired name as a "png/jpg" file.
- 5. Further right click on the graph area and select "Export data..." option to save the data points of the traces on the screen. Make sure to save the file in ".csv" format. Both the data points and images of the loading curve must be acquired as shown in Fig. 31.

To have a reliable atom number the background need to be subtracted. Perform a background measurement by switching on the MOT lights, but keeping the magnetic fields off. Make sure that you keep for all following measurements the same conditions of light (same room light, closed lids).

2.1.5 Release and recapture measurements

A Release and Recapture measurement is an elegant tool to estimate the temperature of the MOT. Choose the detuning and the magnetic field gradient that gave you the best loading rate. In the FP-UI.vi set the "LoadingTime" to 2000 ms and the "OffTime" to 10 ms. You should start to see your MOT blinking. That's because now you are pulsing off the cooling light for a controlled time by turning off the RF power via a TTL signal on the AOM controller and this allows the atoms to freely expand during that time. When the cooling light is turned back, the



Figure 30 Monitoring the MOT fluoresence via infrared camera.

atoms which weren't fast enough to escape the trapping region are recaptured in the MOT and the loading process starts again.

The frequency and duration of the pulse can be controlled by the QD-control. Now you should set the oscilloscope to trigger on CH1 in mode NORMAL on falling edge, adjust the trigger level and choose an appropriate timescale (100 ms or lower). Don't forget to record a background trace where not MOT is visible with the MOT coils switched off.

You should notice now that the fluorescence signal has three distinct behaviors:

- Initially the pulse is HIGH and you have an initial flat zone where the fluorescence signal is maximum, this is your maximum atom number;
- When the pulse goes LOW the cooling light is turned off and there is no fluorescence from the atoms.
- When the pulse goes back to HIGH, depending on the duration of the previous stage, you see either a sudden jump back to the initial level (i.e. nearly all atoms recaptured), or a smaller jump followed by a rising slope (i.e. less atoms recaptured) or even a rising slope starting from the zero atom level (i.e. no atoms recaptured). The short initial part of this signal represents the amount of atoms which are recaptured after the time of free expansion.

You should acquire 30 traces for various durations of the pulse (i.e. duration of free expansion), taking care to set the pulse delay such that between one pulse and the other you recover your maximum atom level. The 30 traces should be composed as follows:

- 5 traces at such short duration that you don't see a change in the atom number
- 5 at such durations that you loose all the atoms



Figure 31 Acquisition of the MOT loading curve via digital oscilloscope.

• 20 traces at durations in between to sample properly the expansion behavior

From the plot of the relative atom number against the expansion time you can extract the temperature of the atoms inside the MOT through a fit, for more details on the data analysis refer to the Release and Recapture curve analysis.

Part VIII Data Analysis

This is a set of guidelines that should help you to analyze the data and to properly report your results.

1 Spectroscopy

For all these datasets, to perform the frequency measurements you have to calibrate the horizontal axis, by converting it from time to frequency. To do so you should choose a set of two lines as distant as possible (and still well resolved) and equate their time separation to their theoretical frequency separation, then use this linear relationship as your calibration. Compare the calibration factors.

1.1 Multiplet separation

Analyse these datasets by fitting each absorption profile with a Gaussian. Use the ${}^{87}Rb$ lines to calibrate the *x*-axis and measure the frequency of the ${}^{85}Rb$ transition. Compare the distance between the centers with the theoretical multiplet separation. To have a better fit use directly the spectrum with the Doppler broadened transitions. Plot the Doppler-free spectra in the same graph for comparison. Use a relative frequency scale for better readability.

1.2 Natural transition line width and hyperfine splitting

Do for all set of transitions:

- ${}^{87}Rb F = 2 \rightarrow F'$ transitions
- ${}^{85}Rb F = 3 \rightarrow F'$ transitions
- ${}^{85}Rb F = 2 \rightarrow F'$ transitions
- ${}^{87}Rb F = 1 \rightarrow F'$ transitions

the same evaluation. Fit first to the Doppler broadened spectra a Gaussian. Then subtract this form the Doppler-free spectrum. The real absorption peak need to be fitted with a Lorentzian. Determine first, which peak corresponds to which transition and then use two peaks with strong separation and good SNR for calibration. Compare all calibration factors.

Measure the **line width** and the **relative frequency** separation of the **hyperfine lines** and compare them to theory. Use for plotting a relative frequency scale for better readability.

2 Loading Curves

The data that you acquired with the TiePie Multi Channel software is saved as a CSV file that contain the traces are organized in two vertical columns separated by commas ",", the time axis

values are stored in the first column, while the voltages are in the second column, so when importing these files in your data analysis program you should set the comma as the column separator. As a first step of the data analysis, convert the measured voltage into the number of atoms following the conversion guide. Take into account that the initial flat zone corresponds to zero atoms.

From the Loading Process theoretical model, you learned that you have to fit each loading curve (like in Fig. 32) with the solution of the following rate equation:

$$\frac{dN}{dt} = L - \alpha N \tag{2.1}$$

Study the loading rate, the one body loss coefficient and the final atom number as a function of the detuning and as a function of the magnetic field gradient (Examples given for first two in : Fig. 33, 34). Remember that the MOT coils have 90 windings and a diameter of 17 cm. Comment briefly on your results. For instance, are the loss coefficients constant? What would it mean if they were dependent on the atom number? What is the behaviour in detuning?



Figure 32 Example loading curve fit.

3 Release and Recapture

From the acquired traces extract the maximum atom number and the number of atoms recaptured after the free expansion time, paying attention that:

- When initially the CH1 pulse is HIGH you have in CH2 an initial flat zone where the fluorescence signal is maximum, so an average over this part represents your maximum atom number;
- When the pulse goes LOW the cooling light is turned off and there is no fluorescence from the atoms, so this is your zero atom level;



Figure 33 Example loading rate plot.

• When the pulse goes back to HIGH, depending on the duration of the previous stage, you see either a sudden jump back to the initial level, or a smaller jump followed by a rising slope or even a rising slope starting from the zero atom level. The short initial part of this signal, just after the TTL signal on CH1 goes HIGH, represents the amount of atoms which are recaptured after the time of free expansion, so average over it to extract this value.

In Fig. 35 there is an example of such analysis. For these measurement is not important to convert from volts to atom number since you have to perform a relative measurement, just take properly into account the zero atom voltage level.

From the plot of the relative atom number against the expansion time (Fig. 36) you can extract the temperature of the atoms inside the MOT by fitting the following function:

$$\frac{N(t)}{N(0)} = erf(\chi) - \frac{2}{\sqrt{\pi}}\chi e^{-\chi^2}$$
(3.1)

where $\chi = \sqrt{\frac{M}{k_BT} \frac{R}{t}}$ and use as MOT radius R=1.5 mm. The theory behind this fitting function is described in the theory chapter Temperature measurement via release and recapture. Is the calculated temperature compatible with the one that you expected to achieve?







Figure 35 Example raw release and recapture trace.



Figure 36 Example Release and Recapture fit.

Part IX Appendix 1

1 Hyperfine Structure of Rubidium



Figure 37 Rubidium 87 D2 transition hyperfine structure, with frequency splittings between the hyperfine energy levels.



Figure 38 Rubidium 85 D2 transition hyperfine structure, with frequency splittings between the hyperfine energy levels.

2 Frequency modulation (FM) spectroscopy

Frequency modulation spectroscopy is a very sensitive spectroscopy method. It produces a signal which is proportional to the derivative of the atomic resonances. In the spectroscopy part of this student experiment, FM-spectroscopy method will be used to measure the frequency of the Lamb-dips and the cross-overs. For the MOT-part of the experiment, the FM-spectroscopy signal will be also used to create the error-signal for the laser stabilization. This method is schematically illustrated in Fig. 39. The current of the laser is modulated by a small modulation at a fixed frequency ω_M which is produced by a VCO (voltage controlled oscillator). The electrical field of the wave emitted from the diode laser is in this case

$$E(t) = E_0 \times e^{i[\omega_0 t + Msin(\omega_M t)]} + c.c.$$
(2.1)



where ω_0 is the optical frequency, E_0 the amplitude of the light wave and M is the modulation index.

Figure 39 Principle of FM-spectroscopy.

For small modulation indexes ($M \ll 1$) one can make the following approximation:

$$E(t) = E_0 \times e^{i[\omega_0 t]} e^{[iMsin(\omega_M t)]} + c.c.$$

$$\approx E_0 \times e^{i[\omega_0 t]} [1 + iMsin(\omega_M t)] + c.c.$$

$$= E_0 \times [e^{i[\omega_0 t]} - \frac{M}{2} e^{i[(\omega_0 - \omega_M)t]} + \frac{M}{2} e^{i[(\omega_0 + \omega_M)t]}] + c.c.$$
(2.2)

Hence the emitted laser frequencies now consist of a strong carrier with a frequency ω_0 and two weak sidebands at frequencies $\omega_0 \pm \omega_M$. If the modulated beam is sent through the vapor cell, the atoms absorb a part of the beam when the frequency is on resonance with one of the atomic transitions. The carrier frequency and the sideband frequencies have different transmission strengths if they are close to an atomic transition or not. Due to dispersion (the frequency-dependence of the index of refraction) the different components also have a "individual" phase-shift after the transmission through the vapor cell. The electric field of the transmitted wave has now the following form:

$$E(t)_{\rm trans} = E_0 \times [T_0 e^{-i\phi_0} e^{i[\omega_0 t]} - \frac{M}{2} T_- e^{-i\phi_-} e^{i[(\omega_0 - \omega_M)t]} + \frac{M}{2} T_+ e^{-i\phi_+} e^{i[(\omega_0 + \omega_M)t]}] + c.c,$$
(2.3)

where $T_j = e^{-\rho_j} (j = 0, -, +)$ are the transmission coefficients with the frequency depending dampings $\rho_j = \rho_j(\omega)$ and $\phi_j = \phi_j(\omega)$ the frequency dependent phase shifts of the different

frequency components ($\omega_0, \omega_0 - \omega_M, \omega_0 + \omega_M$). The intensity of the transmitted (averaged) signal is measured with a fast photodiode and this device outputs a voltage $U_{\text{PD}} \propto I(t) > = \langle \frac{c}{8\pi} |E(t)|^2 \rangle$.

Due to $M \ll 1$ terms with M^2 can be neglected. All terms with $sin(2\omega_0 t)$ or $cos(2\omega_0 t)$ also cancel because the photodiode is averaging over fast oscillations which are usually out of its bandwidth.



Figure 40 Signal behavior of a modulated laser beam at a resonance on a photodiode.

We can further assume that $|\rho_0 - \rho_{\pm}| \ll 1$ and $|\phi_0 - \phi_{\pm}| \ll 1$. With these approximations the intensity at the photodiode (with the absorption difference $\Delta T = T_+ - T_-$ and relative phase shift difference $\Delta \Phi = \Phi_+ - \Phi_-$) can be written as

$$< I(t) > \propto 2T_0^2 - MT_0T_-(e^{i[\phi_- -\phi_0]}e^{i[\omega_M)t]} + e^{-i[\phi_- -\phi_0]}e^{-i[\omega_M)t]}) + MT_0T_+(e^{i[\phi_0 - \phi_+]}e^{i[\omega_M)t]} + e^{-i[\phi_0 - \phi_+]}e^{-i[\omega_M)t]})$$
(2.4)

A Taylor expansion of $e^{i[\phi_0 - \phi_{\pm}]}$ leads to

$$< I(t) > \propto T_0^2 - MT_0 \Delta T \cos(\omega_M t) - MT_0 \sin(\omega_M t) [T_-(\phi_0 - \phi_-) + T_+(\phi_0 - \phi_+)] \approx T_0^2 - MT_0 \Delta T \cos(\omega_M t) - MT_0 \sin(\omega_M t) [T_0(\phi_0 - \phi_-) + T_0(\phi_0 - \phi_+)]$$
(2.5)
$$= T_0^2 - MT_0 \Delta T \cos(\omega_M t) - MT_0 \sin(\omega_M t) \Delta \phi$$

In order to filter the $sin(\omega_m t)$ and the $cos(\omega_m t)$ dependence, the signal from the photodiode is demodulated by a mixer. The mixer multiplies the signal from the VCO with the amplified signal from the photodiode. The signal from the VCO is additional shifted by a phase ϕ to maximize the phase matching between the two signals. The signal after the mixer is then given (T_0^2 leads only to a constant offset) by:

$$U_{\text{mixer}}(t) \propto U_{\text{PD}}(t) \cdot U_{\text{VCO}}(t) \\ \propto [MT_0 \Delta T_- \cos(\omega_M t) - MT_0 \sin(\omega_M t) \Delta \phi] \cos(\omega_M t + \varphi) \\ = M\{\frac{\Delta T}{2} [\cos(\varphi) + \cos(2\omega_M t + \varphi)] - \frac{\Delta \phi}{2} [\sin(\varphi) + \sin(2\omega_M t + \varphi)]\}$$
(2.6)

The fast oscillating $2\omega t$ parts can be suppressed by a low-pass filter and one gets the final signal (see also Fig. 40):

$$U_{\rm FM} \propto \frac{\Delta T}{2} \cos \varphi - \frac{\Delta \Phi}{2} \sin \varphi$$
 (2.7)

The final signal doesn't depend on the time and by changing the phase shift it is possible to switch between the cos- and the sin-term. By applying a Taylor expansion on ΔT one can show that the cos-term is proportional to the derivative of the atomic resonance (Fig. 41):

$$\Delta T = T_{+} - T_{-} = T(\omega_{0} + \omega_{M}) - T(\omega_{0} - \omega_{M})$$

$$\approx T(\omega_{0}) + \frac{dT}{d\omega}|_{\omega_{0}}\omega_{M} + \frac{1}{2}\frac{d^{2}T}{d\omega^{2}}|_{\omega_{0}}\omega_{M}^{2} - T(\omega_{0}) + \frac{dT}{d\omega}|_{\omega_{0}}\omega_{M} - \frac{1}{2}\frac{d^{2}T}{d\omega^{2}}|_{\omega_{0}}\omega_{M}^{2} \qquad (2.8)$$

$$= \frac{dT}{d\omega}|_{\omega_{0}}2\omega_{M}$$

The positions of atomic resonances can be easily identified by the points where the FM-signal is crossing zero. Here, the mixing frequency is about 21MHz and the modulation index and the phase shift are fixed and should not be changed!



Figure 41 At a certain phase shift, the FM signal is proportional to the derivative of an atomic resonance.

Part X Appendix 2: Setup

1 Laser Diodes





Laser diodes (or diode lasers, unfortunately these names are synonyms) are electrically pumped semiconductor lasers in which the gain is generated by an electrical current flowing through a p-n junction. In such a heterostructure, electrons and holes can recombine, releasing the energy portions as photons. Semiconductor lasers are lasers based on semiconductor gain media, where optical gain is usually achieved by stimulated emission at an interband transition under conditions of a high carrier density in the conduction band. The physical origin of gain in a semiconductor is illustrated in Fig. 42. Without pumping, most of the electrons are in the valence band. A pump beam (or in our case an electrical pumping mechanism) with a photon energy slightly above the band gap energy can excite electrons into a higher state in the conduction band, from where they quickly decay to states near the bottom of the conduction band. At the same time, the holes generated in the valence band move to the top of the valence band. Electrons in the conduction band can then recombine with these holes, emitting photons with an energy near the band gap energy. This process can also be stimulated by incoming photons with suitable energy. Most semiconductor lasers are laser diodes, which are pumped with an electrical current in a region where an n-doped and a p-doped semiconductor material meet.



Figure 43 Simple setup of a diode laser with external cavity. The semiconductor chip is antireflection coated on one side, and the laser resonator extends to the output coupler mirror on the right-hand side.

1.1 External cavity diode lasers (ECDLs)

An external-cavity diode laser is a semiconductor laser based on a laser diode chip which typically has one end anti-reflection coated, and the laser resonator is completed with, e.g., a

collimating lens and an external mirror as shown in Fig. 43.

The external laser resonator introduces various new features and options:

- The longer resonator increases the damping time of the intra-cavity light and thus allows for lower phase noise and a smaller emission linewidth.
- An intra-cavity filter such as the diffraction grating can further reduce the linewidth. Typical linewidths of external-cavity diode lasers are below 1MHz.
- Wavelength tuning is possible by including some adjustable optical filter as tuning element. Most often, a diffraction grating is used for this purpose.





Tunable external-cavity diode lasers usually use a diffraction grating as the wavelength-selective element in the external resonator and because of that they are also called grating-stabilized diode lasers. The common Littrow configuration (see Fig. 44) contains a collimating lens and a diffraction grating as the end mirror. The first-order diffracted beam provides optical feedback to the laser diode chip, which has an anti-reflection coating on the right-hand side. The emission wavelength can be tuned by rotating the diffraction grating. A disadvantage is that this also changes the direction of the output beam, which is inconvenient for many applications. In the Littman–Metcalf configuration (see Fig. 44), the grating orientation is fixed, and an additional mirror is used to reflect the first-order beam back to the laser diode. The wavelength can be tuned by rotating that mirror. This configuration offers a fixed direction of the output beam, and also tends to exhibit a smaller linewidth, as the wavelength selectivity is stronger. (The wavelength-dependent diffraction occurs twice instead of once per resonator round trip.) A disadvantage is that the zero-order reflection of the beam reflected by the tuning mirror is lost, so that the output power is lower than that for a Littrow laser.

1.2 Laser used in the student lab

You will use a commercial laser by Toptica that provides the laser light to address the **cooling transition** $|F = 3, m_F = 3\rangle \rightarrow |F' = 4, m_F = 4\rangle$ of ⁸⁵*Rb*, with an AOM added slight detuning from resonance to fulfill the red detuning condition required for the correct functioning of the MOT. Since the atoms can be off-resonantly excited by this laser to the other allowed transitions from $|F = 3, m_F = 3\rangle$, part of the atoms are lost from the cooling cycle at each absorption, thus leading to a progressive effective atom loss. To prevent this the cooling scheme has to be a closed cycle and this is achieved for alkali atoms by adding just another laser light that addresses the lost atoms, bringing them back into the cooling cycle. Thus the laser light is tuned, via an EOM, to the **repumping transition** $|F = 2, m_F = 2\rangle \rightarrow |F' = 3, m_F = 3\rangle$ of ⁸⁵*Rb*.

2 Laser locking

The laser in the student lab have to run at a constant frequency which is often equal to an atomic transition. Unavoidable thermal fluctuations, acoustic and electronic noise change the frequency of the laser and these changes are undesired, so they have to be corrected by stabilizing the laser to a specific frequency ("Laser locking"). To achieve this the frequency of emission of the laser has to be dynamically adjusted to compensate its drifts and fluctuations by controlling the angle of the external cavity grating via the piezo electric crystal and/or by changing the laser's input current. The amount of correction to be applied to these two control parameters is calculated and generated by an appropriate feed-back circuit (e.g. a PID controller) which requires as input a control variable. This control variable is compared to the set point stored in the feed-back circuit and from this difference is originated the error signal that first will be processed and then applied to the control parameters.

To achieve a correct feedback the error signal should be proportional to the difference between the set point (the desired frequency) and the current position (the actual laser frequency). Additionally it has to change sign if the deviation is going in one or the opposite direction. When the difference becomes zero, the error signal is equal to zero and the laser frequency is the same as the atomic transition frequency. A good choice for the control variable is to use the signal obtained from the FM spectroscopy), which represents effectively the derivative of the absorption spectrum. The shape of the FM-spectroscopy signal can be adjusted by varying the phase shift to reproduce as well as possible the derivative of the atomic spectrum. This means that when the value of the FM-spectroscopy signal is zero then the laser frequency is at the middle of the resonance. If the laser frequency is shifted from the atomic resonance, the FM-signal has a positive value at one side of the resonance and a negative value at the other one. The value of the FM-signal is also nearly proportional to the frequency difference for small shifts.



Figure 45 Principle of a PI-Controller.

In the lab, this is done by sending the FM-signal first to a PI (proportional–integral) controller. The PI loop is extensively studied at the FP-E01 Elekronik Grundpraktikum, so we will refer to the instruction and the references therein and give here only a very basic introduction. A PI-controller compares the actual value of a control variable with the set value. If the control variable is not equal to the set value, the (time dependent) error-function is non zero. The error-function is split in two different parts: a proportional part, where the output is proportional to the value of the error function, and a integral part, which integrates the error-function over a certain time. The outputs of the two paths are combined afterwards and the resulting signal is sent as a feedback to the control variable (see Fig. 45). In our case the control variable is the signal obtained from FM spectroscopy. Since we want stabilize the

frequency to an atomic resonance (where the FM-signal is zero) we have to set the set value of the PI loop to zero. If the Laser is not on resonance, the error function is thus non-zero and a P-part and (normally also the I- part) is non-zero and the output of the PI loop differs from zero. The PI-output is sent to the piezo controller, which corrects the laser wavelength by changing the angle of the grating (see Fig. 46).



Figure 46 Principle of locking the laser via FM spectroscopy.

The lasers in the student lab run with an accuracy of the order of one MHz, which is less than the natural linewidth of the atomic transition.

3 Optical Setup

This part describes the different components used in the optical setup.

3.1 Anamorphic Prism Pair

A laser beam emitted from a diode laser has an elliptical beam profile. A round beam profile can be created when one principle axis is magnified by the ratio of the beam diameters of the two principal axises. If a beam of parallel monochromatic light passes through a prism (unless the prism is used in the symmetrical minimum-deviation position) the width of the beam will be increased or decreased in one dimension, as illustrated in Fig. 47. By using two identical prisms in an inverted configuration, compression or expansion can be accomplished without inducing an angular change in the beam direction.



Figure 47 One-dimensional beam expansion without beam deflection using two oppositely oriented anamorphic prisms.

3.2 Wave plates

Wave plates (retardation plates or phase shifters) are made from materials which exhibit birefringence. The velocities of the extraordinary and ordinary rays through the birefringent materials vary inversely with their refractive indexes. The difference in velocities gives rise to a phase difference when the two beams recombine. In the case of an incident linearly polarized beam this is given by $\Delta \phi = \frac{2d(n_e - n_o)}{\lambda}$ (with $\Delta \Phi$ = phase difference; d = thickness of wave plate; n_e , n_o = refractive indexes of respectively extraordinary and ordinary rays λ = wavelength). At any specific wavelength the phase difference is governed by the thickness of the retarder. Note that when a light beam is linearly polarized and the polarization direction is along one of the axes of the wave plate then the polarization remains unchanged.

3.2.1 $\lambda/2$ wave plate

The thickness of a half-wave plate is such that the difference in the optical pathways is 1/2 wavelength or 1/2+n wavelengths (where n is an integer number). This corresponds to a phase difference of π .

A linearly polarized beam incident on a half wave plate emerges as a linearly polarized beam, but rotated such that its angle to the optical axis is twice that of the incident beam. Therefore, half wave plates can be used as continuously adjustable Polarization rotators. Half wave plates are used to rotate the plane of Polarization and as a variable ratio beamsplitter when used in conjunction with a Polarization cube.

3.2.2 $\lambda/4$ wave plates

The thickness of the quarter wave plate is such that the difference in the optical pathways is 1/4 wavelength or 1/4+n wavelengths. The corresponding phase difference is $\pi/2$. If the angle q (between the electric field vector of the incident linearly polarized beam and the retarder principal plane) of the quarter wave plate is 45° , the emergent beam is circularly polarized. When a quarter wave plate is double passed, i.e. by mirror reflection, it acts as a half wave plate and rotates the plane of Polarization to a certain angle. In the setup, quarter wave plates are used for creating circular Polarization of the MOT beams that enter the vacuum chamber. Moreover they find application in the AOM double pass as well as in the spectroscopy path. In these applications they are passed twice, so that they effectively act as a half wave plate.

3.3 Beamsplitter

The ratio of reflectance to transmittance of a beamsplitter depends on the polarization state of the light. The performance is usually specified for light linearly polarized in the plane of incidence (P-polarization) or orthogonal to the plane of incidence (S-polarization). Cube beamsplitters are pairs of identical right-angle prisms cemented together on their hypotenuse faces. Before cementing, a metal or dielectric semi reflecting layer is placed on one of the hypotenuse faces. The operation of a beamsplitter is illustrated in Fig. 48. By placing a wave plate in front of the so called polarizing beamsplitter cube (PBS) the branching ratio between

the transmitted and reflected beam can be easily adjusted. For instance the three retro reflected MOT beams should be split in the ratio 2:1:1 (z:y:x) in this way.



Figure 48 Polarizing beamsplitter cube.

3.4 Laser beam expansion

Laser beams can be expanded and recollimated (or focused and recollimated) with simple or Galilean telescope arrangements, as illustrated in Fig. 49. A Galilean telescope has the advantage that the laser beam is not brought to an intermediate focus inside the beam expander. Since lasers beams are highly monochromatic, beams expanders don't have to be constructed from achromatic lenses. In order to save space mostly Galilean telescopes are used in the laser system.



Figure 49 Laser beam expanders: (a) focusing type with optional optical filter implementation. (b) Galilean Telescope.

Telescopes can also be realized with two positive lenses (Kepler Telescope), producing a true laser focus at the intersection of the two foci. If a small circular aperture is placed at the common intermediate focus of such a simple-telescope beam expander, the device becomes a spatial filter as well.

In order to get a stronger spectroscopy signal a Galilean telescope is used in the spectroscopy path. This way the beam size inside the Rb vapor Cell can be enlarged. Before entering the Vacuum chamber the overlapped cooling and repumping beams are also enlarged by a Kepler Telescope to increase the cooling and trapping region of the MOT. The $1/e^2$ diameter of the MOT beams is 20 mm and the power per beam is circa 2.5-3 mW (you have to measure this power during the experiment).

3.5 Photodiode

The photodiode in the setup is used for measuring the atom number via the fluorescence. This is done in the following way: Depending on the laser detuning in respect to the resonance and on the laser intensity, an atom scatters a certain amount of photons per time unit. The scattering process is isotropic and (depending on the collected solid angle of the emission) a certain amount of photons reaches the photodetector, where the photon power is converted into an electrical voltage. The conversion table (which depends on the resistor, in our case 10 MOHM) can be found in the photodiode manual (Thorlabs PDA36A).

3.6 Acousto-optic modulator (AOM)

An acousto-optic modulator (AOM) is a device which can be used for controlling the power, frequency or spatial direction of a laser beam with an electrically driven signal. It is based on the acousto-optic effect, i.e. the modification of the refractive index by the oscillating mechanical pressure of a sound wave. The key element of an AOM is a transparent crystal through which the light propagates. A piezoelectric transducer attached to the crystal is used to excite a sound wave with a frequency between 60 and 150 MHz. Light can then experience Bragg diffraction at the periodic refractive index grating generated by the sound wave. The scattered beam has a slightly modified optical frequency (increased or decreased by the frequency of the sound wave) and a slightly different direction (Fig. 50).



Figure 50 Schematic setup of an acousto-optic modulator. A transducer generates a sound wave, at which a light beam is partially diffracted. The diffraction angle is exaggerated.

The frequency and direction of the scattered beam can be controlled via the frequency of the sound wave, whereas changing the acoustic power allows to control the optical power. For sufficiently high acoustic power, more than 70% of the optical power can be diffracted. The acoustic wave may be absorbed at the other end of the crystal. Such travelling-wave geometry makes it possible to achieve a broad modulation bandwidth of many Megahertz. Common materials for acousto-optic devices are tellurium dioxide (TeO2), crystalline quartz, and fused silica. In practice we use an AOM to change the frequency of the cooling laser.

3.6.1 Important parameters

Deflection: a diffracted beam emerges at an angle θ that depends on the wavelength of the light λ relative to the wavelength of the sound λ_s

$$\sin\theta = \left(\frac{m\lambda}{2\Lambda}\right) \tag{3.1}$$

in the Bragg regime and

$$\sin\theta = \left(\frac{m\lambda_0}{n\Lambda}\right) \tag{3.2}$$

with the light : normal to the sound waves, where m = ..., 2, 1, 0, 1, 2, ... is the order of diffraction.

Intensity: the amount of light diffracted by the AOM depends on the intensity of the sound wave. Hence, the intensity of the sound can be used to modulate the intensity of the light in the diffracted beam. Typically, the intensity that is diffracted into m = 0 order can be varied between 15% to 99% of the input light intensity. Likewise, the intensity of the m = 1 order can be varied between 0% and 80%. In the FP setup, the modulation strength is optimized such that 80% of the light is diffracted into the +1st order Frequency: one difference from Bragg diffraction is that the light is scattered from moving planes. A consequence of this is that the frequency of the diffracted beam *f* in order *m* will be Doppler-shifted by an amount equal to the frequency of the sound wave *F*.

$$f \to f + mF \tag{3.3}$$

This frequency shift is also required by the fact that energy and momentum (of the photons and phonons) are conserved in the process. A typical frequency shift varies from 50 MHz, for a less-expensive AOM, to 400 MHz, for a state-of-the-art commercial device. In some AOMs, two acoustic waves travel in opposite directions in the material, creating a standing wave. Diffraction from the standing wave does not shift the frequency of the diffracted light.

3.6.2 Double pass configuration

When a laser's frequency is scanned with an AOM, the angle of the first-order diffracted beam shifts as well, since the beam direction angle is a function of modulation frequency. For many applications this beam shift is an unwanted side effect and, when changing the frequency of the AOM, would severely influence the optical alignment of the beam through the following optics. This change in the diffraction angle can be effectively compensated by using the AOM in the double-pass configuration (Fig. 51). Here the output of the m^{th} order of the AOM is retro-reflected for a second pass through the AOM leading to a frequency offset of $2m\Delta f$ on the double passed beam. In this arrangement changing the frequency of the first order output of the second pass. The output of the second pass counter-propagates with the original input beam. While this is desirable, as it allows the frequency to be changed without any steering of the output beam, it poses the problem of how to separate the path of the output beam from that of the input beam. A $\lambda/4$ wave plate is placed just before the mirror and causes the second pass of the AOM to be orthogonally-linearly polarized with respect to the first pass. This allows the beam paths to be separated using a polarizing beam splitter.



Figure 51 AOM alignment for double passed light, PBS = polarizing beam splitter; AP = aperture; AOM = acousto-optic modulator; $\lambda/4$ = quarter wave plate.

3.7 Electro-optical modulator (EOM)

An electro-optical modulator typically makes use of the Pockels effect. This effect describes the change of birefringence of some optical media due to the application of an electric field [12]. If the polarization of the light beam is parallel to a birefringent axis, the light experiences the material with a difference refractive index for different values of the field. Since the phase change of the light which passes an optical media depends on its refractive index, one is able to tune the phase of light beam by tuning the electric field which is applied to the EOM. Consider a time-dependent electric field, *E* at $\vec{r} = 0$ [13]:

$$E(t) = E_0 \exp^{i\omega_c t} \tag{3.4}$$

Let's assume it passes an EOM where the voltage is changed sinusoidal with a frequency ω_m . This will result in an electric field with:

$$E(t) = E_0 \exp^{i\omega_c t + iMsin(\omega_m t)}$$
(3.5)

In case of $M \ll 1$ we can approximate the above equation as:

$$E(t) = E_0 \exp^{i\omega_c t} + E_0 \frac{M}{2} \exp^{i(\omega_c t + \omega_m t)} - E_0 \frac{M}{2} \exp^{i(\omega_c t - \omega_m t)}$$
(3.6)

which means that we created a light beam with two side bands in frequency space. In the FP-20 MOT experiment one of this side bands is used as a repumper beam. The second sideband useless for our purpose, but does not make any significant change due to its large detuning with respect to all transition frequencies.

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