



Ultra-cold Li and Rb atoms in a Magneto-Optical Trap

Diploma Thesis

by

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July 2007 © Bastian Schuster 2007 I hereby confirm that the following thesis has been composed only by myself. All the sources of information that I used are mentioned in this thesis.

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(Bastian Schuster)

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Chapter 1

Introduction

Although a student of the Universität Konstanz, I decided to do my Diplomarbeit at the University of British Columbia. The research project I was participating in, creating ultra-cold ensembles of LiRb molecules via photoassociation, is a cooperative project between the Laboratory of Ultrastable Femtosecond Lasers, lead by Dr. David Jones, and the Laboratory of Quantum Degenerate Gases (QDG), lead by Dr. Kirk Madison.

In this chapter motivation for the work on cold LiRb molecules is covered. Following this discussion, an overview of this thesis is given.

1.1 Motivation

Various research groups around the world are currently performing research on dense samples of ultra-cold atoms and molecules. In the ultra-cold regime, meaning temperatures below 1 mK, many new physical and chemical properties of atoms and molecules are expected. What happens with chemical reactions at such low temperatures? Are there new collisional phenomena? Several different cooling techniques have been developed. The reason is, that by studying atoms and molecules of low thermal energy, new observations can be easily made. A prominent way is laser cooling, which reaches temperatures of around 1 mK. The idea to cool atoms with photons was first proposed by Hänsch and Schawlow in 1975 [31]. In using other techniques, like evaporative cooling, atoms can be cooled down even further to about 1 nK. At this temperature, atoms can form a so-called "Bose-Einstein-Condensate" (BEC) [3], a phenomenon which was predicted by Einstein and Bose in 1925. It is clear that Bosons and Fermions, due to quantum effects, start to behave differently when they are cooled down into the ultra-cold regime. An interesting idea is, therefore, to cool down both species simultaneously in the same space. The study of cold atomic collisions also involves the formation of two-species molecules. They offer new properties, such as high body-fixed electric dipole moments. One of these "polar" molecules is LiRb, which is of interest for the QDG lab, has a dipole moment of 4.2 Debye [17]. This results in a long-ranged intermolecular interaction, which alters its behaviour fundamentally at low temperatures [2].

The isotopes used to create LiRb are ⁶Li (a Fermion), and ⁸⁵Rb or ⁸⁷Rb (both Bosons). The first step is to trap an ensemble of Li and Rb atoms. From this dual species magneto-optical trap (MOT), a sample of ultra-cold LiRb molecules can be created. The first trapping of a polar molecule in a magnetic field, CaH, was done by Weinstein et al. in 1998 [12]. Now, the field of ultra-cold molecules is growing very fast, and ultra-cold chemistry is of high interest for various scientific disciplines. A possible application of ultra-cold polar molecules might be in quantum computation [22]. Due to their high dipole moment, they could serve as qbits in quantum computers by holding them, for example, in an optical lattice.

1.2 Overview of this thesis

The following thesis is divided into 6 chapters. Chapter 2 provides the theoretical background. Some atom cooling techniques and their temperature limits are discussed, followed by a description of producing cold molecules using the techniques of Feshbach resonances and photoassociation. Some properties of ⁶Li and Rb are explained as well, since they are critical for understanding the experimental setup.

Chapter 3 describes all the items that are used to build the experimental setup, as well as how they were prepared or aligned. The chapter is divided into a description of the optical sources, and the hardware around the MOT structure. It is followed by a brief description about the electronic control system.

Chapter 4 gives a description of how the cooling and repump light for the Rb and Li MOTs is created. It talks about how the "master" lasers provide the light and how the "slave" lasers amplify it in order to run the experiment. This amplification technique, optical injection, was studied and characterized in more detail.

Chapter 5 shows some first experimental results. Loading rates for a Rb and a Li MOT have been studied under different conditions, like magnetical field gradients and optical detunings. The results show loading times and numbers of Rb and Li atoms in the MOT, as well as an estimated background pressure in the vacuum cell. Some other general observations have been made as well. The thesis closes with a conclusion and an outlook to the next experimental steps for the photoassociation experiment, that might be taken in the near future. At the very end, the idea for a possible application of ultra-cold molecules is mentioned.

Chapter 2

Theoretical background

This chapter will provide the theoretical background for the photoassociation experiment and will discuss some aspects of the interaction of light and matter. When examining this topic, questions arise such as why are atoms sometimes cooled and not heated by shining light on them? How can light create molecules and therefore trigger a chemical reaction? The first section of this chapter shows how atoms can be brought into the ultra-cold regime (T < mK) with different cooling techniques. The second section explaines how ultra-cold atoms can be used to form hetero-nuclear molecules. In particular, focus will be put on the photoassociation technique as this is the method employed in the photoassociation experiment.

2.1 Production of cold atoms

This section describes how ultra-cold atoms can be produced. For that purpose different techniques are used such as laser cooling, evaporative cooling, and sympathetic cooling. The techniques will be introduced and the limits in temperature that can be attained will be discussed.

2.1.1 Laser cooling

For simplification let us first assume a two-level system for the atoms. Atoms excited by a photon to the higher energy level, will always de-excite to the ground level. The principle idea of laser cooling is based on the fact, that a photon with a certain wavelength λ carries the momentum $p_{ph} = h/\lambda$. A hot atom, meaning an atom in a highly excited translational state, absorbing this photon can be decelerated if the momentum of the photon points in the opposite direction of the atom momentum $\vec{p_a} = m\vec{v}$. Of course, p_a is huge compared to p_{ph} , therefore many photons are needed to slow down an atom. In fact, about 100,000 hits are necessary to classically "stop" an atom with a velocity of 1000 m/s, each photon contributing a velocity change of roughly 1 cm/s. A similar picture in comparison to the photon-atom slowing is trying to slow down a rolling car with tennis balls. Enough balls thrown against the car will eventually stop it.

Two effects, the Doppler effect and optical pumping, however, complicate the deceleration of the atoms.

Doppler effect

The picture in which a car is slowed down with tennis balls does not entirely work for atoms. It is clear, that "enough balls" necessitates the use of a laser. One issue is that an atom with a velocity component $v \neq 0$ parallel to the traveling direction of the light absorbs light with a Doppler-shifted frequency, f', which is given by

$$f' = f_0 \pm \frac{f_0 v}{c} \tag{2.1}$$

where f_0 is the light frequency observed by non-moving objects. Atoms moving towards the light source will "see" the frequency shifted up. Therefore, the light needs to be red-shifted to f_0 , meaning shifted to lower frequencies, in order to be used as cooling light. The atoms then absorb photons with f' and emit photons with f''. Since $f'' \geq f'$, the atom loses energy almost every time it absorbs a red-shifted photon. In momentum space the atom loses momentum almost every time this occurs. Statistically it is possible, but very unlikely, that this momentum kick accelerates the atom in the same direction where the photon came from. The atom mostly releases a photon in a random direction and therefore gets a momentum kick in the opposite direction.

The velocity distribution of an ensemble of atoms is given by the Maxwell-Boltzmann distribution. Light which is red-shifted to resonance (f_0) can only be absorbed effectively by that velocity-class of atoms which are in resonance

with the light. After several slowing processes, however, the Doppler-shift of the atoms is too low to still absorb the cooling light, which is now too reddetuned. To cool these atoms down even further, there are two possibilities: either the frequency of the cooling light is constantly adjusted to resonance by chirping the laser, or the magnetic field gradient is adjusted. Adjusting the magnetic field would change the energy levels of the atoms due to the Zeeman effect. This cooling process is called Zeeman-slowing.

Optical molasses

If light is shone on the atoms from all 6 room directions, every velocity component of the atom will be decelerated. A setup of cooling beams in such a way therefore creates a volume where the atom will be slowed down in any direction. This region is called "optical molasses".

The average force that causes the atoms to decelerate is called the scattering force, F_{scat} . It is the product of the photon momentum, p_{ph} , and the scattering rate of the atom, γ . From [19] the scattering force is given by

$$\vec{F}_{scat} = \hbar \vec{k} \gamma = \hbar \vec{k} \frac{\Gamma}{2} \cdot \frac{I/I_o}{1 + I/I_o + [2(\delta - \vec{k}\vec{v})/\Gamma]^2}$$
(2.2)

where I is the light intensity, I_o the saturation intensity of the atoms, $k = 2\pi/\lambda$ the wave-vector, δ the detuning in frequency, and Γ the natural linewidth of the excited state of the atom.

In one dimension the scattering force due to the radiation is

$$F_{\pm} = \hbar k \frac{\Gamma}{2} \cdot \frac{I/I_o}{1 + I/I_o + [2(\delta \mp kv)/\Gamma]^2}$$
(2.3)

where F_+ is the force on the atom with the photons moving in the same direction, and F_- is the force if they move in opposite directions. For small velocities v and low cooling light intensities I, it can be assumed that $|kv| << \Gamma$ and $I/I_o << 1$. The total optical force on an atom, obtained by adding F_+ and F_- , is then given by

$$F_{tot} = 4\hbar k^2 \frac{I}{I_o} \cdot \frac{2\delta\Gamma v}{[1 + (2\delta/\Gamma)^2]^2}$$
(2.4)

Eq. 2.4 shows, that for red-detuned light, $\delta < 0$, F_{tot} is negative and therefore the atom is slowed down due to a force opposite to the propagating direction of the atom. For cooling beams in all 6 room directions, this force can be seen as a viscous damping of the motion of the atom. This is why it is called "optical molasses".

Optical pumping

Besides the Doppler effect, the second reason for not being able to mechanically decelerate an atom, as with balls and a car, is optical pumping. In reality the energy level system of an atom contains more than just two levels. Both, the ground state and the excited state of the atoms, are split into hyperfine levels. These levels might have a distance which is bigger than the linewidth of the laser. That means if an atom de-excites from an excited state into one of the lower ground states, it can not absorb the laser light any more because the energy difference between that level and the next excited level is bigger than the photon energy. Therefore this atoms sits in a "dark" state and cannot be cooled further. A solution to this problem is the use of a second laser with a frequency high enough to bring this atom back in an excited state. That laser is usually called the "repump" laser.

2.1.2 Trapping of cold atoms: The MOT

Atoms can be cooled by an optical molasses as described above. Without an additional spatial confinement they would leave the molasses by diffusion. Confinement can be achieved using a magneto-optical trap (MOT). The MOT was first demonstrated in 1987 [4] by the successful cooling and trapping of sodium atoms. In addition to optical molasses, a magnetic quadrupole field combined with circularly polarized light provides the spatial confinement for the atoms. A magnetic quadrupole field is produced by a pair of coils that are run in anti-Helmholtz configuration, which means the current in the coils is run in opposite directions. It is important to have light with the correct polarization: for a given direction of the current in the coils, the light in the X/Y plane needs to be left-circularly polarized (LCP), the light in the Z-axis then has to be right-circularly polarized (RCP) (Fig.2.1). The quadrupole magnetic field provides a field-free region in the center between the coils. Atoms outside this center experience a force, which always pushes them towards the center.



Figure 2.1: Schematic of a MOT, formed by three orthogonal pairs of circular polarized cooling beams and a quadrupole magnetic field [6].

This trapping force can be understood by an atomic two energy-level system, where J=0 is the ground state and J=1 the excited state. In the presence of a magnetic field, the excited state is split into 3 magnetic sub-levels, $M_J = 0, \pm 1$, due to the Zeeman-effect (Fig.2.2). Beams propagating along the $\pm z$ -axis are σ^{\pm} polarized, which means they drive the $M_J = \pm 1$ transition, respectively. Since the light is red-detuned in frequency by δ in order to cool the atoms, σ^- light is only absorbed by atoms traveling in +z direction, and σ^+ light only by those atoms traveling in the -z direction. It follows then that all atoms are pushed towards the center.

For the X and Y direction, the principle works exactly the same, but the light has to be LCP. Altogether this leads to a 3-dimensional confinement of the atoms in a MOT and creates a cloud of cold atoms in the zero-center of the magnetic field.

2.1.3 The Doppler cooling limit

As described above, the Doppler cooling technique makes use of light that is red-detuned in frequency by several linewidths, Γ , of the cooling transition of



Figure 2.2: Mechanism of a MOT. Atoms traveling on the +z side only absorb σ^- light, atoms on the -z side only absorb σ^+ light in order to be in resonance with the $M_J = \pm 1$ levels. In this way the atoms will always get pushed towards the center of the magnetic field.

the atom. The cooling light creates an optical molasses for the atoms, which can be described by a damping force, F_{tot} , given by Eq. 2.4. The frequency detuning of the cooling is negative, and Eq. 2.4 can also be written as

$$F_{tot} = -\alpha v \tag{2.5}$$

with $\alpha > 0$. The cooling power of the optical molasses is given by $P_{cool} = F_{tot} \cdot v$. The cooling light, however, heats the atoms every time they scatter a photon. This heating power is described by $P_{heat} = 2\hbar\omega_r\Gamma$, where Γ is the natural linewidth of the light emitted by the atoms, and $\omega_r = \omega_{abs} - \omega_{em}$ is the frequency difference between the absorbed and the emitted photon. The minimum temperature of the atoms is reached, when the cooling power becomes equal to the heating power of the light. The steady-state kinetic energy of the atoms is therefore given by

$$\frac{1}{2}Mv^2 = \frac{\hbar\Gamma}{8} \cdot \frac{1 + (2\delta/\Gamma)^2}{-2\delta/\Gamma} = \frac{1}{2}k_BT$$
(2.6)

The minimum of this kinetic energy occurs at a red-detuning of the cooling light equal to half of the natural linewidth, $\delta = -\Gamma/2$. This corresponds to

a minimum temperature of the atoms which is given by

$$k_B T_D = \frac{\hbar \Gamma}{2} \tag{2.7}$$

The so-called Doppler temperature, T_D , is the lowest temperature which is expected for molasses cooling of atoms with a two level energy system [6]. The Doppler limit for ⁸⁷Rb is 146 μ K [30], and for Li is approximately 140 μ K [34].

2.1.4 Sub-Doppler cooling

For the Doppler-limit in temperature the atoms were assumed to have a simple two-level system. It has been demonstrated, however, that the Dopplerlimit is not the absolute temperature limit for laser cooling and therefore the energy system has to be different. W. Phillips et. al [23] discovered in 1988 that sodium atoms can be cooled down even further until they reach the so-called **recoil limit**, T_R , which is given by

$$k_B T_R = \frac{\hbar^2 k^2}{2M} \tag{2.8}$$

where M is the atom mass. This limit is given by the momentum kick $\hbar k$ of the last cooling photon that, in this case, heats it up by a small amount when emitted. For ⁸⁷Rb this limit is 362nK [30] and approximately 6μ K for Li [34].

Since this limit in temperature is induced by light, to reach temperatures that are even lower than the temperature given by Eq.2.8, the light needs to be switched off after T_R is reached. One popular technique to cool down atoms further from this point is to slowly decrease the depth of the trap potential. This technique is called **Evaporative Cooling**. By lowering the potential walls of the trap, the hottest atoms, meaning atoms with a velocity higher than the average velocity \bar{v} of all the trapped atoms, will evaporatively leave the trap. This results in a decrease of the average velocity and with

$$\frac{1}{2}m\bar{v}^2 = \frac{1}{2}k_B T_{evap}$$
(2.9)

the temperature of the entire cloud will be lowered. With evaporative cooling of bosons a Bose-Einstein Condensation (BEC) of the atom cloud can be achieved. For alkali metals T_{evap} is of the order 1nK [19].

Another effect is observed when two different types of atoms are cooled down simultaneously. In the case of Li and Rb, Rb has a recoil limit which is much lower than that of Li. If cold Rb and Li atoms are located in the same cloud, Rb will cool the Li atoms even lower via elastic collisions. This effect has been shown with ⁶Li and ⁸⁷Rb in [2], and is called **Sympathetic cooling**. This technique also works for different isotopes of a certain atom, which was demonstrated in cooling ⁸⁵Rb with ⁸⁷Rb in a MOT [10].

2.2 Production of ultra-cold molecules

The production of ultra-cold molecules can be done using direct or indirect methods [11]. Molecules cannot easily be cooled with light directly because they are complex multi-level systems. Direct methods, for example, include buffer-gas cooling [12], or beam skimming via stark deceleration [5]. Buffer-gas cooling uses He atoms as a buffer, which cool the molecules via elastic collisions. Beam skimming removes the mean translational energy from a supersonic beam of molecules via Stark shift in the use of an array of electrodes.

Indirect methods of creating cold molecules are via Feshbach resonances or photoassociation (PA) of pre-cooled atoms. The QDG-lab will use both of these methods in order to create ultra-cold LiRb molecules.

In the following sections, some important properties of the alkali metals Li and Rb will be introduced. Furthermore, the creation of molecules via photoassociation will be discussed.

2.2.1 Li and Rb

The choice to take Li and Rb for the experiment was made because of several reasons. First, the energy distance between the ground and excited states of Li and Rb atoms is on the order of 1.5 eV. That makes it very convenient to build a MOT, since laser light with wavelengths in the visible range or near infrared (IR) can be used and is commercially available. Second, both elements are alkali metals and have only one valence electron. This makes the energy structure relatively simple. Third, alkali metals in general have a vapor pressure which increases by several orders of magnitude when they are

heated up by a hundred degrees. Therefore it makes the atom source very easy to build - the metal basically needs to be heated up by several hundred degrees in order to achieve a sufficient metal vapor density.

Lithium

Since Li has an atom number of 3, it is a very light element and, therefore, its fine and hyperfine splittings are quite small. The hyperfine splitting of the ground state into F=1/2 and F=3/2 is separated by 128 MHz (Fig 2.3). A de-pumping of the atom from the excited state into the lower (F=1/2) state therefore happens very quickly. The difference of 128 MHz is still much



Figure 2.3: Schematic of the energy levels of ⁶Li [29].

bigger than the linewidth of a frequency-stabilized laser running single-mode, which is in the order of several MHz. Hence, a repump laser is required which pumps the atoms from the dark state back into the cooling cycle. Without a repump laser all atoms eventually drop into the F=1/2 state and are not decelerated by the cooling light any more. Li atoms that absorb the cooling light are brought from the F=3/2 into the F'=5/2 state. The splitting of the excited state is around 4 MHz, hence the F=1/2, 3/2, and 5/2 levels can be considered as one level because the splitting is in the order of the natural linewidth of the laser. The small splitting of the ground state results in a high de-pumping rate. This necessitates a repump laser, whose output power is as high as the power of the cooling laser.

The energy difference between ground state and excited state is equal to the photon energy with a light wavelength of 670.776 nm. This makes the alignment of the laser quite convenient, since the wavelength is in the visible range.

Rubidium

With an atom number of 37, the element Rb is quite heavy compared to Li. The hyperfine splittings of the ground state, therefore, are much bigger than for Li. For ⁸⁵Rb the splitting is 3.03 GHz, and for ⁸⁷Rb it is 6.83 GHz. Unlike Li, the hyperfine splitting of the excited state is quite large as well. Hence, the probability for a Rb atom to be de-pumped into the lower ground state is very low. However, all atoms still drop into the lower ground state F=1 (Fig 2.4) if no repump laser is used. The repump laser is tuned resonant to the repump transition, which is F=1 to F'=2 for ⁸⁷Rb and F=2 to F'=3 for ⁸⁵Rb. Due to the small probability of de-pumping, the repump light can be very low in power and does not need to hit the atoms from all three directions.

2.2.2 Photoassociation

As previously mentioned, ultra-cold molecules can be indirectly created from a sample of pre-cooled atoms. The setup for our experiment allows the creation of LiRb molecules via Feshbach resonances or via photoassociation. The Feshbach technique uses a strong homogeneous magnetic field, which causes a shift of the unbound atomic energy levels due to the Zeeman effect. If the magnetic field is strong enough, the shifted levels become resonant



Figure 2.4: Schematic of the energy levels of ⁸⁵Rb and ⁸⁷Rb. For the best trapping efficiency, the repump light is resonant with the ground state and the excited state. The cooling light is red-detuned in order to decelerate the atoms [29].

with the levels of the bound LiRb molecule. Li atoms that collide with Rb atoms can then form a molecule.

In the photoassociation experiment, the only purpose of the magnetic field is to trap the Li and Rb atoms. The association of cold colliding Li and Rb atoms is done by a laser. If the light frequency, ω_{PA} , corresponds to the energy difference between the ground state level and one of the vibrational levels in the excited state of the molecule, a LiRb molecule is formed (Fig 2.5). This molecule is electronically excited and decays very quickly. Since it is highly vibrationally excited as well, the decay rate into an unbound Rb-Li pair is much higher than the rate of decaying to the molecular ground



Figure 2.5: The principle of photoassociating Li and Rb. A photon with the frequency ω_{PA} puts the unbound Li and Rb atoms in an electronically excited, bound state (a). From there the molecule either decays into two atoms (b) or into the electronic ground state of the molecule (c) by emitting a photon [24].

state. This rate, however, can be increased by a second laser that drives the molecule from its electronically excited state into the electronically ground state. The light of that laser needs to be in resonance with the vibrational levels.

Due to the fact that the molecules do not absorb the trapping light, they diffuse out of the MOT. Hence the photoassociation of Li and Rb can be observed by measuring the MOT fluorescence while tuning the frequency of the photoassociation laser. A decreasing fluorescence indicates that the photoassociation laser is resonant to one of the vibrational molecular levels. The creation of cold molecules via photoassociation was first proposed by [7]. Some examples of hetero-nuclear molecules that already have been formed by photoassociating alkali atoms, are RbCs [13] and KRb [20].

Further informations about the photoassociation process of LiRb are found in chapter 6.

Chapter 3

Experimental setup

The QDG lab is currently developing several different experiments simultaneously: the miniature atom trap (MAT) experiment, the Feshbach resonance (FR) experiment, and the photoassociation (PA) experiment. The idea of the MAT experiment is to develop a MOT in a portable glass cell which can be run without vacuum pumps. The FR experiment has its goal in measuring Feshbach resonances between ${}^{85}\text{Rb}/{}^{87}\text{Rb}$ and ${}^{6}\text{Li}$. The attempt of the PA experiment is to create molecules from an ultra-cold ensemble of ${}^{87}\text{Rb}$ and ${}^{6}\text{Li}$ atoms by using PA lasers.

Most of my work has been done on building and aligning the optics for the photoassociation table, therefore the focus is put on details pertaining to that setup. This chapter will describe most of the items that are necessary to run the PA experiment and its setup. It begins with the semiconductor lasers that provide the cooling and repump light, then proceeds to the mechanical structure of the MOT, the optical components, the photoassociation and ionization lasers and finally the electronic control system.

3.1 Overview: The amplification system

All of the experiments mentioned above involve the cooling and trapping of ⁸⁵Rb/⁸⁷Rb and ⁶Li atoms. In principle it is possible to run all these experiments at the same time. This is achieved by generating frequency selected and stabilized light on the "Master table" (Fig 3.1). Since every experiment is located on different tables, the light generated on the master table needs to be split and somehow brought to each experimental setup.



Figure 3.1: Scheme of the amplification system. The red lines correspond to light in free-space, the green lines are the single-mode fibers. For simplification, the Li light going to the Feshbach table is not shown.

This is done by using fiber coupler arrays that split the light in order to share it amongst all experiments. Single mode fibers, purchased from Ozoptics, are strung to the other experiments and provide them with light. The total optical output of a frequency stabilized master laser is only around 10 mW for Li and 50 mW for Rb. Since that light is split and sent to all experiments it needs to be amplified. The amplification is done by using optically injected "Slave-Lasers", which are locked to the master light. An exact description of this amplification technique is given in the next chapter.

3.2 Li and Rb semiconductor laser

The QDG lab uses temperature-controlled semiconductor laser diodes to provide light for cooling and trapping of the atoms. To better understand the properties of the laser diodes it is worthwhile to review some general basics

of semiconductors.

A semiconductor, by name, is a material whose conducting properties are in between those of metals (conductors) and insulators. More precisely, the Fermi-energy is between the valence band (VB) maximum, E_v , and the conduction band (CB) minimum, E_c . Its bandgap, $E_g = E_c - E_v$, is smaller than that of an insulator. The electrical conductivity of semiconductors can be increased by doping, increasing the temperature, applying electrical fields or by illuminating with light of a certain wavelength. One of the mechanically simplest semiconductor devices is a diode. The central unit of a diode is a p-n



Figure 3.2: p-n junction without (left side) and with applied voltage. The equalization of E_v and E_c narrows the depletion region and allows carriers to overcome the barrier [38].

junction. The p and n side are often made of the same material, for example silicon, and doped positive or negative. When the two sides are brought together, a thermal equilibrium of the electronic distribution is created by electrons traveling to the p-side and holes traveling to the n-side leaving a so-called depletion region. The Fermi level is therefore uniform on both sides and the VB and CB are bent (Fig. 3.2). By applying a forward bias to the diode the thermal equilibrium is disturbed in a way that allows carriers to overcome the depletion region.

The forward biased structure just described normally operates as a diode. The carriers diffuse very quickly to the + or - pole and almost no radiative electron-hole-recombination is observed. By fabricating a heterojunction

structure (Fig. 3.3), potential wells are created in which carriers are confined when a voltage is applied. This is the active layer of the light-emitting diode (LED). The recombination of electrons and holes in this region produces photons with $\hbar \cdot \omega = E_g$.

In general LEDs emit incoherent and unpolarized light in a broad spectrum. To run a LED as a laser the following conditions need to be satisfied:

- population inversion of the energy levels
- stimulated emission rate exceeds spontaneous emission rate

For heterojunction structures the first condition can be fulfilled by applying a small forward bias current which injects electrons into the CB and holes into the VB -potential well. It was found that the carrier density inside the potential well needs to be higher than 10^{18} cm⁻³ [38] for a semiconductor to lase. For that reason a simple p-n junction does not work because carriers



Figure 3.3: Principle of a double-heterojunction structure. From [38]

too quickly diffuse away from the junction and the carrier density mentioned above is not reached.

To satisfy the second condition the photon density inside the active region of the laser medium has to exceed the so-called laser threshold. This is usually achieved by building a cavity with two parallel mirrors that reflect the spontaneously emitted light inside the active medium back and forth. In the case of a semiconductor laser this cavity is the active layer $(l \approx 10^{-3}m)$ with parallel and polished end facets. The reflectivity of the facets, r, is around 0.55 arising from the high refractive index, n, which is typically around n = 3.4[38]. Compared to gas lasers, r seems to be quite small. Due to the high charge carrier density inside a semiconductor, however, the gain factor for stimulated radiation still easily outnumbers the internal photon loss rate even at comparably small voltages.

By running current through a laser diode a typical behavior is observed (Fig. 3.4): for low currents the laser diode acts exactly like a LED until thresholdcurrent is reached. At the threshold, the stimulated emission rate of photons inside the gain medium is equal to the photon loss rate. At this point the



Figure 3.4: Characteristic plot of a Rb laser MLD 780-100, used as a slave laser for the experiment. At the threshold current of 34 mA the stimulated emission starts to exceed the spontaneous emission.

stimulated radiation causes the power output to rise much faster than in LED-mode and the output power goes linear with the current.

Both output power and wavelength, λ , of a semiconductor laser strongly depend on conditions like temperature, current and optical injection of photons with slightly different λ . These factors will be discussed later in more detail. One thing to note now is that the output of a semiconductor laser therefore can be tuned by varying these conditions.

The observed behaviour of a semiconductor laser diode (Fig. 3.5) shows that only certain modes are amplified by the cavity. The distance between these modes in frequency space is called the free spectral range (FSR) and is given by

$$\Delta \nu = \frac{c}{2nL} \tag{3.1}$$

with cavity length L and the index of refraction, n. For a semiconductor laser with a typical cavity length of about 0.3 mm, and n = 3.4, the FSR is approximately 150 GHz. For the slave lasers in the experiments the HL 6535



Figure 3.5: Spectrum of a semiconductor laser, generated with MatLab. By Eq. 3.1, only those modes are amplified that fit into the cavity, therefore the output spectrum of a freerunning semiconductor laser is not continuous. The envelope function is given by the inverse recombination time of the carriers in the gain medium.

MG from Opnext are used for creating the Li light and the MLD 780-100 from Intelite for the Rb light. At room temperature the output wavelength of the Rb diodes is at $\lambda = 780$ nm, and for the Li lasers it is around $\lambda = 651$ nm. In order for the Li diodes to lase at 671 nm, they have to be heated up to T=64°C. The increasing wavelength due to heating is explained by the fact, that an increase in temperature causes an increase in the average distance of the atoms in the gain medium of the laser, which results in a decreasing interaction of these atoms. The bandstructure, therefore, changes in such way, that the bandgap between valence band and conduction band decreases. However, due to the growing effect of the photons scattering on phonons, the output power of the laser drops as the temperature increases.

3.3 The optics setup

The current version of the optical setup on the photoassociation (PA) table, including some of the MOT-optics, can be seen in 3.6. The principle idea is as follows:

For Lithium there is light from two master fibers injecting two Li slaves (MOT+repump), respectively. The light from the slaves is mixed in a polarizing beam splitter (PBS) using halfwaveplates (HWP). The HWP angle defines the fraction of light going to the MOT or to the diagnostic fiber. The mirror reflecting the light into the diagnostic is mounted magnetically. When the magnetic mount is removed, the light hits a periscope and can be used as a probe beam. The probe beam is used to measure the temperature of the cold atom cloud. Chapter 5.2.2 describes, how this is done at our experiment. The MOT light is split by a PBS. Since MOT and repump light have perpendicular polarizations this PBS ideally does a 1:1 split. One part goes to the X-axis of MOT beams after passing through the spatial filter. The other part undergoes another 50:50 split and reaches the MOT Y- and Z-axis. For the Li-MOT the intensity balance therefore is 2:1:1 in the X:Y:Z dimensions.

For Rubidium, there is light from the Rb-master injecting the first Rb-slave (Rb1). The slave output is split into the pump beam and a beam going to a double-pass acousto-optical modulator (AOM). The double-pass AOM shifts the slave light by approx. 2x80MHz and then injects the second slave (Rb2). Part of that light is coupled out and is used for the Rb-probe beam. For diagnostic purposes, the undiffracted beam of Rb1 is picked off by a mirror and sent into the diagnostics fiber. Slave Rb2 provides the cooling light for the Rb MOT. It hits a PBS, which both splits it by 2:1 and mixes it with the Li light. The 33% are added to the X-axis Li light and the other 66% undergo a 1:1 split for the Y- and Z-axis. The Rb repump light is not amplified. It double passes an AOM and is mixed into the Y-axis. For Rb therefore the intensity balance of the beams in all 3 dimensions is 1:1:1.

The idea of generating the MOT light using two Li slaves, two Rb slaves, Rb repump light and AOMs for double-passes came from the qdg-lab. My task was to design the assembly of the optics for the PA table using VectorWorks¹. A list of parts with some of their specific properties can be found in table 3.1. Since the Rb and the Li light is mixed, most optics have to work for both

¹VectorWorks is a program for 2D- and 3D-designing



Figure 3.6: Scheme of the optical setup on the photoassociation table.

colors, Li and Rb. However, it turned out that the HWPs, the quarterwaveplates (QWP) and PBSs will not work perfectly for each frequency. This means there are small power losses or imbalances after a split on a PBS. In the following, a description of the AOMs, the mirrors, and the spatial filters is given, and an alignment technique is introduced.

3.3.1 AOM double pass

As mentioned previously, for cooling and trapping atoms the cooling light needs to be red-detuned from the atomic resonance by several MHz. Furthermore, this detuning needs to be adjustable in order to determine the frequency-dependent properties of the cold atoms in a MOT. For that pur-

Item	Company and type	$\mathbf{Properties}$
lenses	Thorlabs	BK7, ARC f. λ =650-1050 nm
mirrors	Tower Opt.Corp. M0750	dielectric HR $665-785 \text{ nm}$
parabolic mirrors	VLOC	ARC f. λ =650-900 nm
$\mathrm{HWP}/\mathrm{QWP}$	Casix	for 670 and 780 nm
PBS	Casix	for 670 and 780 nm
AOM	IntraAction ATD 801-A2	$\Delta f = 6090 \text{ MHz}$
Optical isolator Li	Isowave I-67T-5H	$30 \mathrm{dB}$ isolation for 670 nm
Optical isolator Rb	Isowave I-80T-4H	30 dB isolation for $800 nm$

Table 3.1: Table of items used for the photoassociation setup.

pose AOMs are in use which can be variably shifted in frequency. An AOM is generally used as a beam deflector and a frequency shifter. For this experiment only the frequency shift is significant. An AOM, however, also deflects transmitting light depending on the AOM frequency. This problem can be solved with a double-pass configuration, shown in 3.7. Horizontally polarized



Figure 3.7: Scheme of an AOM double-pass. The green arrows indicate light which is shifted by Δf , the red arrows correspond to light with $2\Delta f$.

light passes the PBS and is then focused into the center of the AOM by a lens with focal length f_1 . The First-order shifted beam hits a spherical mirror and is backreflected through the AOM, where it undergoes a second frequencyshift. The Zero-order beam is blocked by an iris or coupled into a diagnostic fiber (compare to Fig 3.6). The distances lens - AOM and AOM - spherical mirror are the same, therefore the radius of curvature of the spherical mirror is equal to f_1 . This mirror has two purposes: First, it refocuses the light into the AOM, and second, it compensates the changing beam-deflection caused by changing the AOM frequency.

The double-passed QWP turns the horizontal polarization into a vertical one in order to reflect the double-passed light at the PBS. It is important to put the QWP between AOM and spherical mirror to make sure that only "pure" (meaning horizontal or vertical) polarizations enter the AOM. By putting the QWP between lens and AOM the intensity of the second-order beam shows a strange oscillating behaviour with a long time scale of several minutes. This



Figure 3.8: Measured intensity of the double-passed light (blue trace) while ramping the frequency of the AOM (red trace) after optimizing.

is explained by the fact, that the AOM crystal is naturally birefringent. If the polarization of the light that transmits the crystal is a mixture of horizontal and vertical polarization, the phase of these two components will vary with temperature variations in the crystal. This causes the polarization to drift and therefore the amount of the double-passed light which is reflected at the PBS, drifts as well.

Furthermore, it was discovered that the way the AOM is mounted also has an influence on its performance. Since the double-passed light is used for injecting Rb2 it is critically important to get constant injection power without any deflection of the beam while changing the AOM frequency. If the AOM is mounted the way shown in Fig 3.7 then the double-pass efficiency seems to be more stable than in a position rotated by 180°. The AOM manual from Intraaction also showed, that this is the proper mounting direction for the AOM. Even mounted the right way the distance between spherical mirror and AOM needs to be optimized as well as the angle of that mirror. Figure 3.8 shows the result of optimizing distance and angle of the spherical mirror for the MOT-light AOM. The intensity changes when ramping the AOM-frequency are less than 10% which is fine for injecting Rb2. The actual double-pass efficiency was around 45% which gives still way more optical power than needed for injecting Rb2 (see Chapter 4: Optical injection). The corresponding values for the repump AOM were a bit lower. Since the repump light does not need to have much power to enable a MOT, not much effort was put into improving its performance.

3.3.2 Mirrors

One of the optical items used the most are mirrors. For the experiment the dielectric mirrors M0750 from Tower Opt.Corp. were chosen, which are highly reflective (99%) for light between 665 and 785 nm. It turned out that their properties can change significantly for different batches, meaning ordered at different times. The batch used for the PA experiment for example showed birefringent properties, that means reflecting linear polarized light which is not s- or p-polarized will be turned into elliptical polarized light by the mirror. However, not every single mirror behaves the same way and the birefringence is temperature dependent as well. For the experiment it therefore means to have power losses when mixing or reflecting this light with a PBS. This is particularly important for the mirrors between the slave lasers and optical isolators; these reflect light with a polarization-axis 45° to the table plane. Because of that, almost all of the approximately 50 mirrors on the photoassociation table were tested on that problem using a Glan-Thomson polarizer to analyze the reflected light. In the test, linear polarized light with a polarization axis 45° to the table plane was reflected The polarization after the reflection was tested with the on the mirors. Glan-Thomson. The result is a list with a certain polarization ratio a/bfor each mirror, where a and b are the longest and the shortest axis of the polarization-ellipse, respectively. 30% of all tested mirrors had an $a/b \le 15$, and 30% had a/b > 100. The mirrors with the highest a/b were chosen to be used for the 45° polarized light.

3.3.3 Spatial filters

By observing the beam profile of a diode laser it is found, that it is not a perfect Gaussian beam. First, it clearly has an elliptical shape caused by the flat active layer inside the diode. Usually that is not a problem, it could be fixed with an anamorphic prism pair. Second, especially after several reflections and transmitting HWPs the beam is spatially noisy which might be a problem for the Li-MOT. At least this is claimed by Florian Schreck [27] from the Institute of Quantum Optics and Quantum Information of the Austrian Academy of Sciences, who reported, that the Li-MOT would not work well if the Li-light is not spatially filtered near the MOT. It was



Figure 3.9: Beam profile unfocused (a) and and in the focus (b) [36]. To remove noise the beam is suggested to be cut at " $1.57\hat{a}$ " using a pinhole which is put at the focus of the beam.

decided to spatially filter the light with a microscope objective and a pinhole which can be adjusted by a 3-D translation-stage from Newport. A lens with 125mm focusing length collimates the filtered light to a beam of about 18mm diameter.

To find the right combination of pinhole and objective the following formula is suggested by [36]:

$$D_{opt} = \frac{\lambda F}{a} \tag{3.2}$$

where D_{opt} is the optimum pinhole diameter, F is the focal length of the objective, and a is the beam radius before hitting the objective. By using an objective with a numerical aperture (NA) of 0.1, which corresponds to a focal length of F = 15mm, $\lambda = 670$ nm, and estimated beam radius a = 1.5mm, the optimum pinhole size is calculated to be $D_{opt} = 6.7\mu m$. However after testing different pinhole/objective combinations the optimal combination turned out to be NA=0.1 and $D = 25\mu m$, despite the calculated result using Eq. 3.2. Pinholes smaller than $25\mu m$ or lenses with F > 15mm produced fringes. These "Airy fringes" result from the minima in the Airy function and are expected to occur, when light passes through a circular aperture. The reason for the difference are explained by the fact, that the beam profile has an elliptical shape. The two dimensions of the ellipse cannot be treated independently by the circular pinhole. Furthermore, for the Li-MOT it is necessary to have trap light with a high intensity. A smaller pinhole creates a more circular beam, but results in an intensity loss.

By the end of April the first Rb-MOT was achieved. In running the experiment without the pinholes, the Rb-MOT was still there, and the cloud seemed to be much more stable and more circular than with inserted pinholes. A possible explanation could be, that small air circulations move the center of the beam focus in respect to the (fixed) center of the pinhole, which causes beam deflections and intensity variations.

Similar tests with Li showed, that the Li-MOT worked with and without filters. After removing the pinholes the MOT just seems to be a bit smaller, and is located in a slightly different position than before.

Considering these facts, it is still unclear, whether the light needs to be spatially filtered at all in order to run the experiment.

3.3.4 Aligning technique

To run the experiment it is important to have all beams perfectly overlapped. Without doing so it is not possible to reach one of the primary goals, to overlap the cold cloud of Rb atoms with the cold Li cloud. Since the optical setup on the photoassociation table includes many mirrors and PBSs which can be used for aligning and overlapping the beams, this system has quite a lot of degrees of freedom. In this section an alignment technique will be described that seems to work well.

When two beams A and B are to be overlapped, meaning one beam is
mixed with another one, often a PBS and two HWPs are used. With the HWPs the polarization of one beam A, for example, is set vertical, beam B is then set horizontal. Therefore B is transmitted and A is reflected by the PBS. To overlap both beams, A and B need to overlap at two points: first, inside the PBS and second, far away from it. Once A and B hit the same spot inside the PBS the light then is sent further away to better improve the overlap. Now only the position of beam A can be changed which is done by adjusting the PBS. Here the spatial filters turn out to be a very precise tool for checking the overlap of two beams. Since the beam focus needs to be centered to the pinhole, the spatial filter is very sensitive to slightly misaligned beams. With beam A blocked the spatial filter is optimized for beam B. Then beam A can be optimized by adjusting the PBS until it hits



Figure 3.10: Schematic for the principle alignment of the X-, Y-, and Z-axis of the MOTbeams. An intensity balance of the beams hitting the cell from both sides is achieved by rotating the HWP.

the same spot behind the spatial filter as beam B.

The overlapping is started with both Li-beams (compare to Fig 3.6), then the Rb-MOT light is added, and finally Rb-repump is mixed in.

After overlapping all beams in the plane of the optical table, the light has to be aligned with respect to the glass cell in which the cold atoms are trapped. A schematic of how this is done for each axis can be seen in Fig 3.10. The Z-axis is aligned first. This helps to align the X- and Y-axis, because they need to hit the Z-axis beam in order to create a volume in the cell, the optical molasses, which gets light from all 6 beams. An adjustable iris is inserted into the center of the beam to overlap the counter-propagating beams. To run the experiment, of course, its aperture is maximized in order not to block any light needed for cooling and trapping. The glass cell needs to be hit perpendicular and in the center of the the coils, where the Zero-center of the magnetic field is expected. It is also important to hit each mirror, waveplate, and PBS in their center, otherwise the full-sized beam would be clipped. Once the beam reflected on the PBS is centered to the coils and glass cells, it is overlapped with the other beam by adjusting M2 and M3. The beam that transmits the PBS is then overlapped with the first beam by adjusting M4. With the HWP the intensities of the beams hitting the cell from both sides can be equalized.

The X- and Y-axis are basically treated the same way, however they hit the glass cell at an angle of about 45° (see Fig 3.14).

For laser cooling it is necessary to have circular polarized light in a way described in Chapter 2. If the light in the X- and Y-axis is chosen to be LCP, then the Z-axis needs to be RCP, or vice versa. The polarizations are adjusted with a polarization-checker which consists of a QWP and a PBS. The polarization-checker is tuned as follows: horizontal polarized light is sent through the PBS and the QWP and backreflected through both with a mirror. The QWP is rotated, until the reflection of the backreflected light on the PBS is maximized. This means, the QWP turns the horizontal polarized light into circular polarized light, which is reflected on the mirror. When the light passes the QWP again, it is turned into vertical polarized light. If the QWP1 (Fig. 3.10) was rotated to achieve maximum transition in the X- and Y- axes, then the QWPs for the Z-axis needs to be adjusted for minimum transmission. Then the the polarization of the Z-axis is orthogonal to the polarizations of the X- and Y-axis.

3.4 The hardware around the MOT

After the optics setup was almost complete and aligned, work was started on the structure that is located close to the MOT. First, this structure and all its including parts were assembled virtually with SolidWorks². This was

²SolidWorks is a 3D-design program.

done to get an overall picture, before the next assembling steps were taken. Several items had to be added or changed in terms of size or design. Some of these items then were designed with SolidWorks and machined on the mill or on the lathe.

This section describes that structure and its parts. In particular, the parts are the vacuum system including the pumps that are used, the magnetic coils, the atom sources, and the time-of-flight spectrometer (TOF).

3.4.1 The vacuum system

To reduce the loss of atoms from the MOT due to collisions with background gases, the experiment is done in high vacuum. For that purpose, a glass cell is in use with a square section made of optical quality (highly polished) Borosilicate glass. The square section is 9.5 cm long, has an inner diameter of 20 mm and an outer diameter of 30 mm. It contains the TOF (Fig. 3.11) and it is connected on both sides to the stainless steel tubes of the vacuum system by glass-to-metal seals purchased from MDC and Larson Electronics. The welding of the square cell on the glass-to-metal seals was done by Ron Bihler from Technical Glass. For the experiment it is necessary to have an ultrahigh vacuum, that means to have a pressure of about 10^{-9} torr. To reach such low pressures it is important to clean all vacuum parts very carefully before assembling them. The cleaning procedure includes different chemical and mechanical methods and is described below.

The vacuum pumps

To reach the ultra-high vacuum there are three different pumps in use, that are a turbo pump, an ion pump and a non-evaporable getter (NEG) pump. The *turbo pump* is used first to reach a pressure of around 10^{-6} torr. In use is the Varian V70 which has a pumping speed of 70 l/s. A turbo pump basically consists of a high speed turbine with angled blades that push atoms out of the system when they collide with these blades.

The *ion pump* can be used when the pressure of the system is lower than 10^{-5} torr already. For the vacuum system in our experiment there is the Varian StarCell in use, which has a pumping speed of 20 l/s. In principle it pumps by ionizating gases which are accelerated by an electric field and hit a highly reactive material. This material usually is metal, mostly titanium,



Figure 3.11: The vacuum system in an oven built with bricks that are wrapped into aluminum foil.

and needs to be replaced once in while. The ions hitting it are deposited near the surface in reaching with it.

The *NEG pump* is basically an absorbing material which is brought into high vacuum and removes some residual atoms and molecules like hydrogen and water. In use is the SAES CapaciTorr which has a pump speed of 100 l/s for H and H₂O when new activated getter material is used. When the getter is heated up for a while the atoms and molecules sticking in it get desorbed. This is done do re-activate the pump .

Chemical cleaning

The chemical cleaning of the vacuum parts prior to pumping involved 4 steps, that are:

- 30 min in the ultrasonic cleaner with Alcanox (detergent) solved in water
- 15 min rinsing, twice, in the ultrasonic cleaner with distilled water

- 15 min ultrasonic cleaning with methanol
- 15 min, twice, ultrasonic cleaner with acethone

All parts are then dried in air and from this point only touched with gloves.

High temperature air bake

All metal parts of the vacuum system, including tubes, components for mounting like screws, are baked in an oven at around 400°C for 3-4 days. For that purpose an oven was built in the lab using bricks that are wrapped into aluminum foil. Ceramic heaters were used in order to reach the desired temperatures. The copper rings for sealing and the glass cell are not included. The baking helps to get a better vacuum, because impurities that are sticking in the surface of the parts can be desorbed by increasing the temperature [35].

Assembling and leak-check

After the high temperature bake, all parts are put together and checked for leaks by connecting to the turbo-pump and monitoring the pressure.

Preliminary bake

The vacuum parts, now assembled, are baked again for 5-10 days at a temperature of 200°C. For that the atomic sources are built in. It is important to turn them on during the bake-out in order for them to degas some impurities they contain. Otherwise they could degas when running them in the experiment, which means to have an unwanted source of hydrogen and other atoms in the vacuum system. This would disturb the experiment and lead to a pressure increase. The turbo-pump is connected to the vacuum system during the bake and pumps out the impurities which now get off the inside surfaces. A residual gas analyzer, which is connected to the turbo pump, shows, that mainly water and hydrogen gets desorbed.

Final bake

For the final bake all vacuum parts are included, the oven is kept at 200° C for about one week. The TOF (described later in this chapter) is taken apart and baked for 1 day at 400° C before it is assembled and installed into the

vacuum system. Now the system is complete and consists of the glass cell, the atomic sources, the TOF, a non-evaporative getter (NEG) pump and the ion pump. After the last bake the ion gauge indicated a pressure of about 10^{-8} torr. Then the NEG pump was activated, the ion pump was switched on, and the entire vacuum system was brought to the photoassociation table. Fig. 3.11 shows the assembled vacuum system.

3.4.2 Magnetic coils

For the photoassociation experiment there are two types of coils in use: a pair of trap coils, which provide the magnetic field for trapping the atoms, and three pairs of compensation coils, which are used to compensate the earth's magnetic field.

The trap coils are made of Kapton-coated copper wires, and each of the coils has a total number of 253 ± 2 windings [16]. They are embedded in plastic



Figure 3.12: Picture of the MOT structure on the photoassociation table. The glass cell is located between the water-cooled trap coils. Three pairs of compensation coils are fixed to the support structure, surrounding the trap coils and the glass cell.

housings connected to two plastic hoses in order to cool them with water. Since the magnetic field for the experiments needs to be a Helmholtz- or an anti-Helmholtz field, the coils are mounted with a distance to each other which is equal to their radius of 8cm. For the photoassociation experiment there is a current of about 4 A in Helmholtz mode needed in order to get a big Li-MOT (see Chapter 5), which causes the coils to warm up due to their heat dissipation. The setup, however, also should allow to run the Feshbach-experiment where a Helmholtz field of about 1 kGauss is necessary. The current in the coils then needs to be around 25A, which produces a lot of heat. The flow rate of the cooling water is estimated to be 6 l/min in order to keep the temperature change of the water smaller than $2^{\circ}C$ [16]. The current is provided by a coil driver, which has a digital input allowing for computer control of the current.

The compensation coils are much bigger in diameter. One pair of the coils has its magnetical field axis pointing along the z-axis. The axes of the other two pairs are perpendicular to each other and to the z-axis, therefore the earth's magnetic field can be compensated in every dimension in space (Fig 3.12). Each coil has about 80 windings of Kapton-coated copper wires. The compensation coils are run at a very low current and therefore no cooling is necessary.

3.4.3 Support structure

To mount the compensation coils and all the optics around the MOT there was a special structure designed. It includes aluminum pillars from 80/20 Inc. which are square in diameter (Fig 3.12). Their special profile allows to easily mount optics by using T-nuts. The Z-axis beam hits the cell perpendicularly from the top and the bottom. The mirrors and PBSs that are needed for the light beams that are horizontal to the table plane (X/Y-plane) are mounted in a way such that light hits the glass cell at an angle of 45° . In that way there is still enough optical access for the photoassociation beam and for the imaging system.

3.4.4 The atomic sources

For the experiment it is important to have an atomic source that can be quickly switched on and off. For alkali metals one popular choice is the use of dispensers because they are cheap and reliable, and their usage as an atomic source also have been studied extensively [25]. A dispenser contains a salt of the alkali metal which it is wrapped in metal. By running a current of about 6 A through the dispenser it is heated up. The salt in the dispenser is then reduced by a strong reducing agent, often another metal, and therefore the alkali atoms are released. The isotopic proportions of a particular alkali metal in the dispenser is determined by its natural occurance.

For Rb we used a dispenser from SAES getters as an atom source. For Li, however, a dispenser would not be very useful because it would mainly emit ⁷Li due to its natural occurance of about 92%. Therefore we use an oven



Figure 3.13: The atomic sources of Li and Rb fixed on 1/4" copper rods that are connected to the electric feedthrough. For Rb there are two dispensers at the top and the bottom, the Li oven is in the center.

which contains an enriched (95%) piece of ⁶Li. The oven basically is a small container with small hole at he top. The container is made of NiCr, because Li reacts very strongly with almost any other materials. This effusive atomic beam source produces a Li-beam when the oven is heated with a current of about 10A.

In using the oven as an atomic source for Li the MOT is loaded directly from a beam of hot atoms. Other than Rb, Li sticks very quickly to the glass surface. Evidence for that is a metallic coating on the inside walls of the glass cell close to the oven, which appeared after running the oven for several hours.

To make the loading of a Li-MOT more efficient, a Zeeman slower is often

used [33]. A Zeeman slower makes use of a laser beam that is red-detuned to resonance and counter-propagating to the direction of the emitted atoms. By absorbing this light the atoms are decelerated. Due to the velocity-dependent Doppler-shift the atoms would not absorb the light any more after their velocity has been decreased. A magnetic field, whose strength varies along the traveling axis of the atoms, adjusts the frequency detuning of the light in such way, that the atoms absorb the light for every velocity they have during their travel through the slower. The implementation of a Zeeman slower, however, was not considered for the photoassociation experiment. The reasons are that the magnetic field might disturb the experiment and the technical demand to build it is quite high.

3.4.5 The time-of-flight spectrometer

The TOF spectrometer is used for detecting the ions generated by the ionization laser hitting the MOT. The demands for a TOF are good optical access to the MOT and time focusing: ions of the same type starting at different locations in the MOT should reach the detector at the same time. The time resolution, furthermore, should be good enough to distinguish between isotopes.

The idea for the time focus is to use 3 electrodes E1, E2 and E3 (Fig.3.14) where E3 is grounded and E2 and E1 are set to certain voltages. Ions starting close to E2 are not as fast as ions starting further away from E2 when they reach E2 because of a shorter acceleration time. The slower ions, however, spend more time between E2 and E3 than the faster ions which gives them more acceleration. In choosing the right combination of distances between electrodes and voltages, these effects compensate each other and a time focus is achieved. The ions then pass E3 and hit a micro channel plate (MCP) after traveling for about 40cm. The time it takes to reach the MCP depends on the ion mass. The electrodes are grids with a fine mesh to allow the ions to reach the detector. A small piece of metal is spot-welded on the center of grid E1 to protect the MOT from fast atoms that are emitted by the source (beam block 1). A second beam block (beam block 2) is put close to the MCP. It can be opened and closed by a rotional feedthrough (see Fig. 3.11) and protects the MCP from coating with Li and Rb when the TOF is not in use. A grounded mesh fixed to E3 provides a field-free region and ensures that the ions hit the detector.



Figure 3.14: Scheme of the TOF spectrometer. The geometry of the electrodes E1-3 achieves a time focus for the ions that are accelerated towards the MCP detector, and allows the trap light to transmit through the glass cell without being clipped.



Figure 3.15: Picture of the rods and the grids of the TOF spectrometer.

The electric field for accelerating the ions is provided by ceramic-covered metal rods that are connected to the grids. The metallic rods, however, would create a quadrupole field and deflect the ions. In order to create a homogeneous field between the centers of the grids, the ceramic rods between the grids are coated with graphite (Fig.3.15). The resistance of the rods between the electrodes is set to around 1 M Ω .

The distances between the electrodes and the voltages have been calculated [24] by using "SimIon". The results show that ions of a certain type will reach the MCP if they do not start too far off the center. The voltages applied to E1, E2, and E3 are +300V, +200V and 0V, respectively. Each grid is square in shape and has a size of 18mm x 18 mm. The distance between E1

and E2 is 56 mm, the distance between E2 and E3 is 26 mm. This geometry allows the trap beams traveling along the MOT X-axis and MOT Y-axis to transmit the cell without being clipped, since they enter the cell in an angle of 45° to the cell surface (Fig 3.14).

Unfortunately it turned out, that the TOF will not work as it is now. Just recently it was discovered, that the resistance of the graphite-coated grids is around 50Ω and therefore the ions would not reach the TOF due to an inhomogeneous field between the grids. The conductivity probably increased because the rods were coated with Li and Rb. In fact, graphite is often used as a getter for alkali metals. It has been showed, that graphite is able to absorb Cesium by 20% of its weight [21]. Also, for Cs and Li the adsorption energies to graphite have been calculated to be 1.02 eV and 1.21 eV, respectively [15]. This shows, that Li sticks very well to graphite and it probably happened to the graphite-coated rods of the TOF.

3.5 The control system

It is necessary to entirely control and monitor the experiment by electronic means. The final goal is to do this via Internet from anywhere by connecting to the qdg-server and the internal Ethernut which will make research very convenient. Right now, the temperature and the current the lasers can be remotely controlled via Internet already, as well as the mechanical shutters and the magnetic coils. The ultimate goal is a control system, that automatically adjusts parameters like the current of the laser diodes, the diode temperature, and the magnetic field of the MOT in order to get a big cloud of cold atoms.

This Section gives an overview of the flow of informations in the control system and its used components.

The components can be divided into 3 types of devices: base level devices, intermediate level devices and high level devices. A base level device, for example, is the data acquisition card from National Instruments (NI-DAQ). It is programmed with python and C^{++} and interacts with the intermediate level devices. These devices are able to translate and execute orders coming from the NI-DAQ. Examples are the direct digital synthesizer (DDS), and analog/digital output devices (AO/DO). The DDSs are able to generate

a sine wave with a frequency programmed by the user. The AOs are able to give a voltage output which can be almost continuously chosen between +10V and -10V. The output of a DO is either +5V or 0V, therefore it is commonly used for electronically switching the high level devices on and off. In our experiment such high-level devices are AOM drivers, mechanical shutters, cameras, and oscilloscopes. The AOM drivers receive an input from the AO. Depending on the voltage that is sent to their analog input they are able to generate a high amplitude sine wave with a certain frequency. This frequency is sent to the AOMs which frequency-shift the light (see chapter 3.3.1). The AOM drivers also have a digital input and can be switched on and off depending on the signal from the DO device. Other high level devices are mechanical shutters. They are able to block a light beam when they receive a voltage of about 18V and unblock it when 0V is applied.

Chapter 4

The Light

The light obviously is one of the central parts of the experiment. To run the experiment it is crucial to have single-mode light on the desired frequencies over a long time period.

This Chapter provides a description of how the light for the experiment is created on the master table and how it is amplified by the slave lasers via optical injection. The first Section explains the techniques that are used to lock the light to the right frequency and it describes how the light from the master and slave lasers can be diagnosed. The second Section discusses the amplification of the master light by using light-injected slave lasers.

4.1 Master laser system

The purpose of the master table is to provide frequency-locked light and to diagnose it. Since the master table provides light for each experiment it can be considered as the central unit of all the experiments. The work on the master table started in 2005.

In this Section an introduction to the principles of the setup, the diagnostic mechanism and the locking technique is given.

4.1.1 The setup

The scheme in Fig. 3.1 shows that the master table basically consists of the Rb-part and the Li-part including the diagnostics for both. For Rb there are 4 slaves in use that each pre-amplify the light of one particular master. Two

of these master lasers provide the trapping light and the repump light for the ⁸⁵Rb MOT, and the other two provide the repump light and trapping light for the ⁸⁷Rb MOT. To simplify the scheme in Fig. 3.1, only two Rb master lasers and two Rb slave lasers are shown. For Li there is just one master and one slave. The light of that slave is split into two beams, then frequency-shifted by acousto-optical modulators (AOM) and injected into two other slave lasers. The light of these is split and sent to the experiments where it is again amplified by slave lasers.

4.1.2 The diagnostic system

The diagnostic system on the master table is used for two purposes: First, to lock the master lasers to the right frequency, and second, to monitor the light from the slave lasers. To test all slave lasers for single-mode operation some small amount of light from of each slave is sent through a fiber to the diagnostics setup via a fiber switcher. For Rb this setup includes a Fabry-Perot interferometer (FPI) and an absorption cell. The FPI simply consists of two spherical mirrors whose distance can be changed by piezoelectric actuators with the control system. The absorption cell is a simple glass cylinder filled with Rb gas. The Li part has a FPI as well, however to look at the absorption of a slave, a heat-pipe is needed which contains the Li absorption cell. To get the Li atoms desorbed from the walls inside the cell it is heated up to 410° C. At room pressure, Li has a melting point of 180.54° C and a boiling point at 1342° C [37]. At temperatures higher than 180.54°C, Li is fluid and shows an increasing vapor pressure as the temperature is increased. At 410°C, the vapor pressure of Li is high enough to reach a sufficient atom density in the Li absorption cell. The signals from FPI and absorption cell can then be monitored on oscilloscopes with use of photodetectors that are placed behind each FPI and absorption cell. The fiber switcher is used to determine which slave laser is observed with the diagnostic suite.

To obtain an absorption curve for the masters the light from the masters is swept over several GHz. This is done by building an external cavity diode laser (ECDL). The fundamental idea behind an ECDL is the placement of an adjustable grating in the beam path close to the diode and therefore sending light back into the laser diode. This light has a bandwidth of several MHz so



Figure 4.1: Inside a master laser. The piezo moves both the grating and the mirror. Therefore the beam is not deflected while ramping the frequency. For a better protection from disturbing background noise the inside of the metal case is shielded with foam.

that the master in a way injects¹ itself with single-mode light. The angle θ between grating and laser beam can be changed by piezo-electric transducers (see Fig 4.1). With

$$\lambda = 2d\sin\theta \tag{4.1}$$

the resonant wavelength is selected by θ and grating constant d. Fig. 4.1 shows how this idea was realized for our experiment. By periodically moving the mirror and the grating the wavelength can be swept continuously. By sweeping over a frequency range corresponding an absorption signal can be derived.

For more detailed informations about ECDLs please refer to [38].

 $^{^1\}mathrm{A}$ detailed explanation of "optical injection" will be given in chapter 4.2

4.1.3 Saturated absorption

How are the masters locked to the right frequency? One might think that the easiest solution is to lock the laser to the absorption maximum f_{res}^o , which is the resonance frequency for atoms with no velocity-component along the light-axis. To do laser-cooling however the light must be red-detuned to resonance by several MHz. For that purpose the lab makes use of the saturated absorption technique, which was first developed in 2001 with two diagnostics-beams entering an absorption cell from opposite directions [28]. One of the beams, called the probe-beam, transmits through the cell and hits a photodiode. Due to the velocity-distribution of the atoms and the Doppler-effect the absorption curve is a Gaussian profile. The other beam, called the pumpbeam, is up-shifted by $\Delta f = +80 \dots + 120$ MHz and has a higher intensity. Atoms traveling at the right velocity to absorb both the probe and the pump



Figure 4.2: Absorption spectrum with dip, generated with MatLab. Due to the Dopplershift the frequency-distribution is directly correlated to the velocity-distribution of the atoms inside the cell. Therefore the profile follows the Maxwell-Boltzmann distribution.

beam have their absorption saturated. Therefore the absorption signal from the probe beam will decrease for this velocity class since atoms cannot simultaneously absorb from the pump and the probe beam. This decrease in absorption puts a hole in the Gaussian profile (Fig 4.2). The distance between the maximum of the Gaussian profile and the dip depends on Δf ; only a certain velocity class of atoms absorbs the light because it seems Dopplershifted to f^o to them. For a more theoretical explanation please see [28].

4.1.4 Locking technique

To stably lock the master to the dip it is crucial to get a high signal-to-noise ratio in the light signal from the photodetector. A popular method is to use the Lock-in amplifier [1]. The idea basically is to reduce "white" noise $\eta(t)$ by modulating the light frequency ν_o periodically by a small amount $\delta\nu$, multiplying it with the modulating waveform and time-averaging it. With the now time-dependent light frequency $\nu(t) = \nu_o + \delta\nu \sin \omega t$, the absorption signal $I(\nu) = I_o(\nu) + \eta(t)$ looks like

$$I(\nu(t)) \approx I(\nu_o) + \eta(t) + \frac{dI}{d\nu}|_{\nu_o}(\delta\nu\sin\omega t) + \frac{d^2I}{d\nu^2}|_{\nu_o}(\delta\nu\sin\omega t)^2 \qquad (4.2)$$

where ω is the modulation frequency. $I(\nu(t))$ is then sent into the Lock-in amplifier. Its output is of the form

$$A(\nu) = \frac{1}{T} \int_0^T I(\nu) \cdot \sin(\omega t + \phi)$$
(4.3)

$$\propto \frac{dI}{d\nu}|_{\nu_o}\delta\nu \tag{4.4}$$

Because of time-averaging the noise is canceled out. The signal $A(\nu)$ is proportional to the derivative of the original absorption $I(\nu_o)$ and it is displayed as the "error signal". A sample of one of the Rb-masters used for the experiment is shown in Fig.(4.3). The master was swept over about 1.5 GHz in a frequency range where both ⁸⁵Rb and ⁸⁷Rb absorption lines are visible. Even a very small dip in the absorption signal creates a clearly visible error signal which can be used to lock the laser. The zero-voltage of the error signal corresponds to the minimum of the dip in the absorption. The laser is locked by first manually decreasing the ramp amplitude and therefore "zooming" into the graph. Once the ramp is shut off the frequency is stabilized by the proportional and integral feedback mechanisms which constantly adjust the position of the piezo inside the master to the Zero-position of the error signal. There is also a fast feedback which constantly adjusts the laser current to



Figure 4.3: Lock-signal from one of the Rb-masters. The ramp-signal corresponds to the voltage sent to the piezo. Due to its natural occurance of 72% 85 Rb shows a bigger absorption-peak than 87 Rb. "Lock here" indicates the position where the laser is locked to in order to provide cooling light for the 87 Rb MOT.

help to achieve a stable lock.

The Li master laser is locked +140 MHz above the $F=3/2 \rightarrow F'=5/2$ transition (Fig 2.3). Following the scheme in Fig 3.1, the master light is shifted down in frequency by a double-pass AOM. For the cooling light, the downshift Δf_1 depends on the settings of the AOM driver and is usually around 2x -75 MHz. For experiments with the MOT, Δf_1 can be changed in order to vary the optical detuning of the cooling light. This light is amplified by a slave laser via optical injection and sent to the experiments. To generate the Li repump light, part of the Li cooling light is shifted up by $\Delta f_2 = 2x114$ MHz using an AOM double-pass. It is amplified by a slave laser as well and sent to the experiments.

The master laser that generates the cooling light the for the ⁸⁷Rb MOT is locked to -180MHz below the $F=2\rightarrow F'=3$ transition (Fig 2.4). The light is

pre-amplified by a slave laser on the master table and sent to the experiments (Fig 3.1).

The master laser that generates the repump light for the ⁸⁷Rb MOT is locked to -180 MHz below the $F=1\rightarrow F'=2$ transition. This light is sent to the photoasociation table and frequency-shifted by 2x +90 MHz in using a doublepassed AOM. As mentioned in Section 1.2.1, the repump light does not have to amplified for the Rb MOT.

4.2 The slaves: Optical injection of semiconductor lasers

As already mentioned, the master lasers alone cannot be used directly for the MOT of each experiment because their output power is too low. Hence the light needs to be amplified which in our case is done by "optical injection" of slave lasers.

This Chapter explains the principles of optical injecting a semiconductor laser, and it provides a description of the characterization and optimization process of optical injection. The optimization of optical injection is a complicated process because it depends on various conditions such as temperature, laser current, injection power, and alignment. At this stage it is still a critical part of the experimental setup.

4.2.1 Principle: Optical isolator

For injecting the slaves with master light we made use of optical isolators. We used the Isowave I-80T-4H for Rb and Isowave I-67T-5H for Li. Their purpose is first, to block most of the light coming back to the laser, and second, allow some designated light to reach the slave laser and inject it by entering through a side-port of the isolator. An optical isolator basically consists of two Glan-Thompson polarizers GT1 and GT2 (Fig. 4.4) with an orientation such that the transmitting polarization of one differs by 45° to that of the other one. A crystal within a magnetic field rotates transmitting light by 45°. Light going the wrong way is blocked since its polarization after passing GT2 and being rotated in the Faraday medium will be perpendicular to the transmission axis of GT1. About 1% of the output light from the slave is reflected by GT2. That light shows up as two beams A and B leaving the

isolator near its end at an angle of about 40° to the main beam. Beam A is horizontally polarized and beam B vertically polarized. The two beams are



Figure 4.4: Principle of optical injection using an optical isolator. Light leaving the isolator is horizontally polarized. The polarization of beams A is horizontal, beam B is vertical polarized. By overlapping the vertical polarized injection light with beam B it passes the isolator and reaches the slave laser diode. The white arrow on the isolator indicates the designated light direction.

explained by the fact, that the GTs are made of a birefringent material, usually calcite, for which the index of refraction for the different polarizations is different. Therefore their refraction angles to the end facets of the GTs are different.

The isolator is rotated in such way that light leaving the isolator is horizontally polarized. That means incoming light has to have a polarization that is 45° to the table plain in order to have maximum throughput. This is attained by rotating the laser diode and measuring the throughput.

To inject the slave some vertical polarized injection light is overlapped with beam B. This light is able to pass the isolator and reaches the slave laser diode. Beam A still can be used for diagnostical purposes (see Section 3.3). For the best performance the isolator can be tuned. This is done by finerotating one of the GTs and looking for the minimum throughput of light transmitting through the isolator the wrong way. It is critically important to tune the isolator as best as possible to prevent the laser from self-injecting which would cause stability problems. For the Li isolators a block/transmit ratio of $1 : 10^4$ (40 dB isolation) and a throughput-loss in the forward direction of about 12% was measured. For the Rb isolators we had similar values.

4.2.2 Characterization and optimization

How can one know whether a slave is properly injected? It turns out that optical injection of a semiconductor laser strongly depends on the following conditions:

- 1. Alignment of the master light into the isolator
- 2. Shape and mode matching of the master light with the slave light
- 3. Wavelength of the master light
- 4. Temperature of the slave laser diode
- 5. Current of the slave laser diode
- 6. Power of the injected light

In the following sections I will discuss how each of these items has been dealt with and therefore how optical injection was optimized.

1. Alignment

This condition, of course, is optimized by mechanically adjusting the vertical and horizontal alignment of the frequency-stabilized master light. The injection beam and beam B (isolator) need to overlap at two locations: At the fiber coupler and close to the laser diode. However it turned out that this is just a rough alignment method. The final steps for perfect alignment are taken by running the laser slightly below threshold and comparing its output power with and without injection light. This idea came from James Booth² and has since been called the "Booth-method". The ratio of power with injection light divided by the power without it is called the "Booth-factor", B_f . Maximizing B_f means maximizing the seeding of the slave diode with photons, and this results in the most efficient injection of the slave. Finding the maximum of B_f can sometimes be difficult because the function $B_f(x, y)$ often has multiple local maxima, with x, y = horizontal/vertical position of

 $^{^{2}}$ Dr. James Booth is a collaborating professor from BCIT (British Columbia Institute of Technology) in Vancouver-Burnaby. He is currently working on the MAT-setup.



Figure 4.5: Booth-factor B_f vs. current of one of the Rb slaves. B_f depends on the injection power and has a maximum about 7 mA below threshold.

the injection beam. This problem is solved as follows: The beam needs to be moved horizontally and vertically in such a way that it hits the diode from slightly different angles. Therefore sufficient alignment freedom is needed, so that the horizontal and vertical motion of the beam can be done separately. With one optic the beam is slightly misaligned, with the other the power drop is then corrected. This is to be repeated several times while looking for a power maximum after each correction. An example of B_f -measurements (with alignment optimized) can be seen in Fig. 4.5. By running the Rb-laser at 30 mA, which is near the threshold, B_f reaches its maximum. For the best results in later realignments and to quickly check the injection alignment it is best to do that at 30 mA.

2. Shape and mode matching

Both the alignment and the mode matching have one thing in common: To inject the diode with the maximum amount of master photons given a certain injection power. The closer the injection beam resembles the beam emitted by the diode the better injected the laser can be. The shape of a beam in our case can be described with three features: diameter, collimation and circularity. The injection beam leaving the fiber collimator is usually circular in shape and almost collimated, the very well collimated beam from the laser diode looks elliptical and is somewhat bigger in diameter. To match the beams in terms of collimation and diameter we used a telescope consisting of a concave and a convex lens. By choosing the right combination of focusing lengths and distance, the injection beam can be adjusted in size and collimation. To match the beams in shapes one could use a pair of prisms and extend the circular-shaped injection beam in one dimension to get an ellipse. This manipulation technique was done in one case on the master table because one of the master laser beams had a quite elliptical shape. For the photoassociation table it was not necessary because of the little improvement it would have.

3. and 4. Master frequency and slave temperature

As shown in Fig. 3.5 a semiconductor laser does not have a continuous output spectrum, Fig. 3.1 gives the distance of the modes in frequency space. The envelope function over these modes corresponds to the gain profile of the laser at a certain temperature. To inject the slave the gain profile has to be shifted into a region in wavelength that includes the wavelength of the master. As described in Section 3.2, the gain profile drifts to *higher* wavelengths by *increasing* the temperature. The gain profile of a free-running Rb slave laser at room temperature includes the right wavelength already so the Rb slaves are just kept at around 19°C. The Li slaves however need to be heated up to 68°C. Without doing so the slaves simply would not "see" the injection light, even if it was very intense.

5. Slave current By running a slave laser above threshold and injecting it with light, the laser shows a linear relationship between current, I, and wavelength, λ , when the diode current is changed in a small range. By tuning the current over a larger range there are mode hops occurring which can easily be seen on an optical spectrum analyzer. A mode hop occurs when the laser cavity prefers to lase on another frequency when conditions like laser current or temperature in the diode are changed. The existence of these mode hops can be explained by the frequency spectrum of a semiconductor laser (Fig 3.5). This spectrum consists of modes that are separated by the free spectral range (FSR), which is given in Eq. 3.1. Since the power output of the laser in frequency space is not continuous, the frequency of the injection light needs to match one of these modes in order to lase. By changing the laser current, the FSR changes because the index of refraction of the gain medium in the diode depends on the carrier density of the gain medium. The array of modes in the frequency spectrum of the laser will change their position. when the laser current is changed. That means to run the slave laser as stable

as possible over a long time period, the regions in current have to be found where laser operation is possible. We call them the "windows of opportunity (WO)", referring to the opportunity of being able to inject the laser at that current. Given that all conditions mentioned above are optimized, the WO can be found as follows:

By frequency-ramping the Li master laser over about 10 GHz the signals of master ramp, master absorption, slave absorption and FP are plotted on an oscilloscope. Starting at the laser threshold the current is slowly increased. Between WO's both the FP trace and the absorption signal jump around



Figure 4.6: Signal from the diagnostics system by looking at one of the Li slaves. The height of the FP peaks directly corresponds to the power in a certain mode. It tells how well a certain frequency is amplified by the laser.

wildly and look very noisy. As soon as the current reaches the lower end of a WO, both traces suddenly become calm and show a trace similar to that in Fig. 4.6: the shape of the slave-absorption trace looks similar to the masters absorption and the FP shows an equidistant pattern.

It was found that the optimal current values are close to the lower end of a WO. Turning up the current to the higher end results in a power drop.

Sometimes the absorption trace of the slave looks shifted and the FP peaks are not uniform in height. There are two possible explanations for this: First, it might be that the diagnostic light of that particular slave laser hits the diagnostic fiber at an angle slightly off the ideal axis. Since the diagnostic fibers are multi-mode for Rb- and Li-light they show a birefringent behavior. That means depending on the frequency, the linear polarization of the light is slightly rotated by transmitting through the fiber. Leaving the fiber, the diagnostic light, which is no longer linear polarized, is then split into two parts by a PBS and sent to the absorption cell and FP interferometer. A frequency dependent polarization therefore means sending a frequencydependent amount of light to both which could explain the observation.

However, if optimizing the coupling into the diagnostic fiber does not change this behaviour significantly, that means there is another effect present. In this case the different height in the FPI peaks for different injection frequencies indicates, that the real output power changes for different frequencies. This could mean that the maximum of the slave's gain profile is not close enough to the master's frequency. This problem occurs for most of the Li slave lasers. Since the temperature of 68°C at which the Li slaves are run is already very close to the upper operating limit of the diodes, it is difficult to completely optimize the injection. To go even higher would result in a drop in the output power of the slave laser and would shorten the lifetime of the laser diodes.

6. Injection power

It is clear that the power of the injection light has a big influence on the injection of the laser. For the Rb laser it was found that even 0.2 mW of injection light is sufficient to inject the slave laser running at a current of 80 mA. Its optical output then is 45 mW which is enough to achieve a Rb-MOT. For the Li lasers the lower limit in injection power appears to be at around 0.7 mW. The Li slaves Li1 and Li2 on the photoassociation table are currently injected with 2.1 mW and 2.9 mW, respectively.

It was also found that the position and size of the WO's depend on the injection power. For the Rb slave lasers, a very high injection power of 10 mW produces a very broad WO that spans between I < 20mA and I = 76.5mA (Fig 4.7). This figure also shows, that the WO's shift to lower diode currents when the injection power is increased. As previously mentioned, the FSR depends on the carrier density of the gain medium in the diode. When light is injected into the diode, the carrier density changes because the photons create hole/electron pairs in the gain medium. By changing the power of the injection light, the laser current has to be adapted in order to match the frequency of the injection light with one of the modes in the frequency spectrum of the laser.



Figure 4.7: Windows of opportunity (WO) for Rb slave 2 on the photoassociation table, showing the minimum and the maximum current for each of the four WOs. The WO's slightly shift to lower currents by increasing the amount of injection light. For a high slave current the WO gets narrower.

The Li slave lasers show a lot more WO's than the Rb slaves. Between 70mA and 160mA there are 11 WOs that have an average distance of about 9mA in current to each other.

Using the distance between two WO's, the FSR can be calculated and the cavity length of the laser diode can be estimated. For the Rb slave lasers the change in frequency depending on the laser current has been measured to be 10 GHz/mA. The average distance between two WO's at an injection power of 1 mW (Fig 4.7) is 26 mA. This leads to a FSR of 260 GHz. The corresponding cavity length of the Rb laser, using Eq. 3.1, is 0.17 mm.

Chapter 5

First Measurements and Results

The following chapter describes some basic measurements which have been completed for the Rb- and the Li-MOT. Some loading curves of the MOTs were obtained by unblocking the cooling light and looking at the intensity of the MOT-fluorescence. By changing the detuning of the trapping light from resonance, the number of trapped atoms can be estimated. The background pressure has been estimated using the loading time of the Rb MOT. An estimate of the MOT temperature has also been done.

5.1 Imaging system

To measure the fluorescence of both MOTs simultaneously, a special fluorescence imaging system was built (Fig. 5.1). A dichroic mirror transmits light with a wavelength of 671 nm with an efficiency of 98% and reflects 96% of the light with a wavelength of 780 nm. By using interference filters (IF) the upper photo detector will only measure the Rb fluorescence, and the lower detector only provides a Li fluorescence signal. To provide enough optical access for the photoassociation optics, the detectors have a distance of about 30 cm to the glass cell. A pair of lenses collimates the fluorescence light and focuses it on the detectors.



Figure 5.1: The image system used to measure the fluorescence of both MOTs. A dichroic mirror splits the Rb light from the Li light. Interference Filters (IF) make sure that only the designated light reaches each photodiode (PD).

5.2 Rubidium

On April 6th we observed our first Rb-MOT. The optics was set to the "retroreflecting" mode: the MOT-light was not split by the PBS into two beams, rather it was totally reflected upon itself. The mirror M2 on the other side of the glass cell (see Fig 3.10) was turned vertical to achieve a retro-reflection. First, several problems had to be faced: The AOM-driver was not working properly due to a lose electrical contact. After fixing that, the light was tested for the right frequency and the right polarization. This is done by putting a small glass cell filled with Rb gas in the beam path close to the MOT. If the masters are locked to the right frequency and all slaves are injected properly, a fluorescence in that glass cell is observed, and it disappears, when one of the injection beams going to the slaves is blocked. The polarization is tested as described in Section 3.3.4. It finally turned out that one of the MOT-coils was connected the wrong way and therefore produced a Helmholtz-field.

In the following Section the theoretical model for loading a MOT is introduced and some measurements and its results are presented.

5.2.1 Loading rates

The following model is used to describe the loading of atoms a MOT:

$$\frac{dN}{dt} = R - LN - \alpha N^2 - \beta N^3 \tag{5.1}$$

where N is the number of atoms in the MOT, R is the loading rate, L is the loss rate. α and β are loss rates that occur due to 2-body and 3-body collisions between cold atoms in the MOT. For a small amount of trapped atoms these collisions can be neglected. By doing so, Eq 5.1 can be solved as

$$N(t) = \frac{R}{L}(1 - e^{-Lt})$$
(5.2)

where $R/L = N_s$ defines the steady-state number of the cold atoms in the MOT and $1/L = \tau$ the loading time. τ describes the time it takes until the MOT is filled to a number of cold atoms equal to 1/e of the steady-state number, but also gives the average life-time of an atom in the MOT. The expression "life-time" here corresponds to the average time, an atom can remain in the atom cloud before it is pushed out by fast-moving background atoms. For a certain capture velocity, v_c , which depends on the detuning of the cooling light, δ , the loading rate R can be described as [8]

$$R = \frac{1}{2} n v_c^4 V^{2/3} \left(\frac{m}{2k_B T}\right)^{2/3}$$
(5.3)

where n is the density of atoms in the glass cell, and V the trapping volume created by the the 6 beams crossing each other inside the cell. Eq 5.3 includes the most probable velocity of an atom, \bar{v} , which is given by

$$\bar{v} = \sqrt{\frac{2k_BT}{m}} \tag{5.4}$$

To estimate the number of atoms in the cold atom cloud, the MOT-fluorescence is measured with a photodetector (PD). The following expression gives the relation between the fluorescence power hitting the the PD, P_{PD} , and the number of atoms, N:

$$P_{PD} = \frac{hc}{\lambda} \frac{\Omega}{4\pi} N \gamma_{sc} \tag{5.5}$$

where hc/λ corresponds to the energy of one photon, and γ_{sc} the scattering rate of the atom for a certain detuning δ . The problem, that only a fraction

of the fluorescence light of the MOT hits the PD is solved by using the solid angle of the light. It is given by

$$\frac{\Omega}{4\pi} = \frac{\pi r_L^2}{4\pi d^2} \tag{5.6}$$

where r_L is the radius of the imaging lens close to the MOT, and d the distance between this lens and the atom cloud (see Fig 5.1). The scattering rate γ_{sc} is given by [32]

$$\gamma_{sc} = \frac{\Gamma}{2} \cdot \frac{I/I_o}{1 + I/I_o + (2\delta/\Gamma)^2}$$
(5.7)

where Γ corresponds to the natural line-width of the light scattered by an atom, I the total power of all six cooling laser beams, and I_o the saturation power of the atom.

Measuring loading curves

Some simple loading curves can easily be obtained by unblocking the trapping light and monitoring the fluorescence power of the MOT as a function of time. For estimating the number of atoms in the MOT, some more parameters and calculations are required. The result of loading ⁸⁷Rb atoms into a MOT is shown in Fig 5.2. The exponential fit is of the form given in Eq 5.2. The fit-parameters directly give the loading time τ of 7.5 s. To calculate the steady-state number of ⁸⁷Rb atoms in the MOT, several parameters are needed. For the scattering rate γ_{sc} , the line-width $\Gamma/2\pi$ for ⁸⁷Rb is 6.066 MHz [30], the saturation intensity $I_o=3.58\,\mathrm{mW/cm^2}$ [30], the detuning was set to $\delta = 7.8$ MHz, which corresponds to 1.3 Γ , and the total optical power of the cooling light is $I = 53.1 \,\mathrm{mW/cm^2}$. With Γ and δ the scattering rate is calculated to $1.5 \cdot 10^7$ Hz. The fluorescence power hitting the PD is 122.3 nW. This number is calculated from the measured power in subtracting the background light and including reflection losses of 4% on the glass cell and 2% on the dichroic mirror. The intensity loss of 60% on the interference filter is included in the calibration of the photodiode. With the geometric parameters of $r_L=11.4$ mm and d=75 mm, using Eq 5.6 and Eq 5.5 gives a steady-state number of $N_s = 5.5 \cdot 10^6$ trapped ⁸⁷Rb atoms for this measurement.



Figure 5.2: Loading curve for a 87 Rb MOT. The loading time τ obtained from the exponential fit is 7.5 s. With a detuning of 1.3 Γ , the steady-state number of atoms is calculated to $5.5 \cdot 10^6$.

Optimizing the loading

In order to maximize the steady-state number N_s of Rb atoms in the MOT, the magnetic field and the detuning of the trapping light can be changed. For that purpose, a LabView program was written which controls the frequency of the Rb AOM on the photoassociation table and therefore controls the detuning of the trapping light. A scheme of the timing is shown in Fig 5.3. The program sets the AOM to f_1 , and the MOT is loaded for 8s. Then the frequency is changed to the reference frequency, f_2 . This procedure allows to quickly find the loading frequency, at which the most atoms are loaded into the MOT. The explanation is, that the fluorescence power measured with the detector depends on the number of atoms and on the scattering, γ_{sc} (Eq 5.5). Without changing to f_2 , the number of atoms in the MOT has to be calculated after each loading in order to find the maximum. The program



Figure 5.3: The timing of the absorption measurements. f_0 corresponds to the resonance frequency, f_1 is the loading frequency and f_2 is the reference frequency.

takes a series of 17 measurements. f_2 is always kept the same, and f_1 is changed by +0.5MHz for each measurement, starting with $f_1 = f_2$. Fig 5.4 shows two examples of loading curves, where the timing has been done as described. In plot a) it can be seen, that f_1 is further away from the optimal loading frequency than f_2 , because more atoms are loaded into the MOT after the frequency change. Since f_2 is always kept at a frequency that corresponds to a detuning of 7.8 MHz, the peak height of the jump directly corresponds to the number of atoms loaded into the MOT at f_1 . This jump occurs because the atoms suddenly scatter more light due to the frequency change. Then the amount of cold atoms changes because the different detuning and therefore a different capture velocity, v_c , result in a different loading rate (Eq 5.3) and therefore a different steady-state number N_s.

The result of a series of measurements can be seen in Fig 5.5. The most atoms are loaded at a detuning of 14.4 MHz, which corresponds to 2.4Γ . This result is in very good agreement with previous measurements [14], [32].

The increase of N_s by increasing the detuning can be explained with the v_c^4 dependency of the loading rate (Eq 5.3). As v_c increases even more with increasing δ , the number of photons scattered by the fast atoms during their short stay in the optical molasses eventually becomes to small to entirely slow them down. This causes N_s to decrease from a certain δ_{opt} , which therefore gives the position of the maximum $N_s = 7.5 \cdot 10^6$ atoms.

By keeping f_1 corresponding to $\delta_1 = 13.4$ MHz (=2.24 Γ), the optimal N_s also depends on the magnetic field gradient. The same measurement as



Figure 5.4: Loading curves of ⁸⁷Rb. The MOT is loaded for 8 s with a detuning δ_1 and then probed with a detuning δ_2 of 7.8 MHz. Plot a) shows, that δ_2 first leads to a fluorescence jump due to the different γ_{sc} and then loads more atoms into the MOT. Plot b) shows that jump as well, but here the MOT looses atoms after the frequency change.

before is done again. Instead of changing the frequency, for every measurement the current in the trap coils is changed from a "loading current" to a "reference current". The reference current is always kept at 2.84 A, which corresponds to a magnetic field gradient of 16.8 G/cm. The result of this measurement is displayed in Fig 5.6. Again a maximum in N_s is observed, which is located at a magnetic field gradient of 12 G/cm and yields to $3.8 \cdot 10^6$ atoms. The maximum in atoms can be explained by the Zeeman-shift of the energy levels, which depends on the magnetic field gradient. When the magnetic field is changed, the levels are shifted until they become resonant with the trap light (compare to Fig 2.2). For very small magnetic fields, the potential minimum created by the magnetic field is to shallow for the atoms, and they can escape the trap.

Background pressure

The loading-time, τ , can also be used for an estimation of the background pressure in the cell. Dividing the atoms in the cell into Rb atoms and back-



Figure 5.5: Steady-state number of ⁸⁷Rb atoms in the MOT depending on the detuning of the trapping light.

ground (b) atoms, the loss rate $L = 1/\tau$ can be expressed as [32]:

$$L = n_b \sigma_b \bar{v}_b + n_{Rb} \sigma_{Rb} \bar{v}_{Rb} \tag{5.8}$$

where n the density of scattering particles, σ the collisional cross section, and \bar{v} the average velocity given by Eq 5.4. For simplification, the number of background atoms can be neglected. The neglect is justified by the fact, that the ion pump was already running a long time before the measurements were done. By turning on the Rb dispenser, the amount of Rb atoms in the cell increases by several orders of magnitude. For a Rb gas at room temperature, σ is assumed to be about $6.3 \cdot 10^{-13} \text{cm}^2$ [26]. With T=300 K, this gives a density of $8.7 \cdot 10^6 \text{atoms/cm}^3$. Using the ideal gas law, $pV=nk_BT$, the pressure is calculated to $2.2 \cdot 10^{-10} \text{torr}$.

5.2.2 Attempts at temperature measurements

One goal of the experiments with the MOTs is to measure the temperature of the cold atom cloud. For that purpose, some of the trap light is sent to the



Figure 5.6: Steady-state number of ⁸⁷Rb atoms in the MOT depending on the magnetic field gradient.

glass cell with a periscope. For Rb, part of the double-passed light is coupled out with a PBS (see Fig 3.6), reflected up to a height of about 20cm over the table plane, and from there sent to the glass cell. The beam passes the cell within a distance d, which is a few mm, under the atom cloud (Fig 5.7). For the measurement, the MOT is first loaded with Rb atoms. Then the trap light is electronically switched off with a mechanical shutter, and at the same time the light is tuned to resonance by changing the AOM frequency. The cloud starts to drop and passes through the probe beam. Since its light is resonant with the cold atoms, part of the probe light gets absorbed and the photodetector should measure a drop in the intensity. While the cloud is dropping, it expands due to the kinetic energy of the atoms. The PD signal, therefore, should show a dip whose width depends on the distance, d, between probe beam and original position of the cloud.

However, no such dip has been observed at our setup. The reasons are not entirely clear, but it seems very likely that the mechanical shutter and the way it blocks the light prevents from observing it. The shutter basically consists of a small coil, which moves a piece of aluminum foil into the beam path, when a voltage is applied. Since the motion of the foil into the beam is slow compared to loading processes in the MOT, the shutter distorts the trapping light. This might cause the MOT to fall apart, before it even starts



Figure 5.7: Principle of the probe beam setup for temperature measurements. When the trap light is switched off, the atom cloud drops into the probe beam. The detector signal should show a dip in the intensity, when the cloud passes through the beam.

to drop.

When the probe beam is shone directly on the cloud, an interesting observation is made. After the trap light is switched off with the shutter, the atom cloud is accelerated out of the interaction region since the probe beam hits the atom cloud from one direction. If the frequency of the probe light is blue-detuned with respect to the resonance frequency of the Rb atoms, the detector signal looks similar to Fig 5.8. The intensity minimum in the probe light occurs due to the time-dependent absorption of the atoms. Since they are accelerated by the probe light, their velocity steadily increases. That means, for them the probe light becomes Doppler-shifted to the red and eventually it becomes resonant with the atoms. At that point the photodetector observes a minimum in intensity. The atoms are accelerated further, which results in a decreasing absorption, because the probe light becomes more Doppler-shifted red to resonance.

Another very interesting observation is the presence of fluctuations in the measured transmitted intensity of the probe beam when the Rb atoms are accelerated by the probe light. Fig 5.9 shows the absorption signal measured by the probe-photodetector. The probe light was blue-detuned to resonance by ± 10 MHz, and the oscilloscope that monitored the signal was set to full bandwidth. If the oscilloscope is set to 20 MHz bandwidth, most of the noise in the signal disappears except on the part of the plot which is before the


Figure 5.8: Signal from the probe setup, with a bandwidth of the oscilloscope set to 20 MHz. The probe light is tuned +10MHz to the blue of resonance of the Rb atoms and hits the atom cloud directly. It accelerates the cold atoms, which experience a decreasing Doppler-shift due their increasing velocity, and therefore, eventually become resonant with the probe light. At this point the Rb atoms absorb the light and an intensity minimum on the photodetector is observed.

absorption minimum. These intensity fluctuations could be reproduced and are not noise created by the photodetector. Unfortunately this observation could not be investigated any further.

5.2.3 Other observations

During the experiments, several other observations have been made. Generally, the Rb MOT seems to be very stable against changing conditions, like power balance of the trap light or its alignment. It is still possible to get a Rb MOT, if the power balance of the trapping light for one axis is about 10:1. Even misaligning the beams does not disable the MOT, as long as there is still a small volume in the glass cell that gets illuminated by all 6 beams. An interesting observation is, that the Rb cloud has a strange shape and moves around spatially. As mentioned in Section 3.3.3 already, the Rb cloud suddenly becomes very calm and almost spherical in shape, when the pinholes of the spatial filters are removed and the light is not spatially filtered any more. It was clear beforehand, that the Rb light does not need to be spatially filtered to enable a Rb-MOT. But it was not expected that spatially filtering would result in a worse MOT.



Figure 5.9: Signal from the probe setup, monitored with the full bandwith of the oscilloscope. The probe light is tuned +10MHz to the blue of resonance of the Rb atoms

Another very interesting observation is the fact, that after blocking the repump light, the Rb MOT sometimes does not entirely disappear rather just becomes smaller. This observation is not entirely understood, because there are two possible explanations for it. Either, the trap light is not perfectly single-mode in frequency and has some frequency components, that may serve as repump light. Or, the number of Rb atoms in the glass cell is big enough, to provide a loading rate which is bigger than the rate of atoms getting de-pumped in the lower ground state (see Section 2.2.1). At this point, no further investigations have been made yet to understand that observation.

Some experiments have been done in testing the influence of the Li-oven on the Rb MOT. When the oven is turned up, the Rb MOT seems to get smaller and more elliptical in shape. This happens because fast Li atoms from the oven push some of the Rb atoms out of the Rb cloud. The Rb cloud, however, becomes a lot bigger than it was before, when the oven is switched off. There are several explanations for the increase in size. The Li oven might heat up the Rb dispensers, which are mounted just about 4 mm next to the oven. This might cause the dispensers to emit Rb atoms. A higher Rb density in the cell then results in a bigger cloud. Another idea might be, that the Li atoms bounce against Rb atoms sticking on the glass walls or other items inside the cell, and therefore loosen them from their bonds.



Figure 5.10: A cloud of about 10^6 Rb atoms with a temperature of several hundred μ K, and around 1.8 mm in diameter.

5.3 Lithium

For the Li MOT, the measurement of the loading curves follows a procedure similar to the Rb MOT, the timing used is shown in fig. 5.3. The LabView program, in this case, changed the frequency of the AOM on the master table, which double-passes the master light in order to obtain the Li cooling light. The measurements were done in two ways: first, f_1 was kept at a frequency of 83 MHz, which created a nice big cloud of cold Li atoms, and f_2 was changed between 75 MHz and 68 MHz. By just looking at the fluorescence jump resulting from the frequency change, the resonance frequency, f_0 , was found to be at 72 MHz: f_2 was steadily decreased from 75 MHz, and at the AOM frequency of $f_2 = 72$ MHz the jump in the fluorescence disappeared. At this frequency the atoms cannot absorb the trap light any more, because its frequency is just blue of resonance.

The second part of the measurements was done exactly like the Rb MOT measurements. Since the light on the master table is double-passed by the AOM, δ always corresponds to the double of the difference in frequencies:

$$\delta = 2 \cdot (f_1 - f_2)$$

 f_2 was kept at 76 MHz (δ =8 MHz) and f_1 was steadily increased by 0.5 MHz, starting from 76 MHz and ending at 83 MHz. These series were taken for different magnetic fields, by setting the current in the trap coils to 2.0A, 3.07A, and 4.0A. In Fig. 5.11 the results of the fluorescence measurements



Figure 5.11: Loading rate of ⁶Li into the MOT for different detunings of the trap light and coil currents of 2.0 A, 3.07A, and 4.0A.

for different detunings and coils currents are shown. It can be seen, that the maximum amount of atoms in the MOT not only depends on the detuning, but also on the magnetic field gradient. The explanation is the same as for the Rb MOT: if the trapping light is resonant to the Zeeman-shifted energy-levels of the atoms, a maximum in the MOT fluorescence is observed.

Fig 5.13 shows, that the optimal detuning of the trap light goes linearly with the current in the trapping coils. This is expected, because the Zeemanshift of the energy levels goes linearly with the magnetic field gradient, if the



Figure 5.12: Loading curve of ⁶Li at a current in the trap coils of 2.0A, and δ =15 MHz (=2.55 Γ) with an exponential fit, producing a loading time of 1.7 s.

magnetic field is changed in a small range.

The calculation of the number of ⁶Li atoms in the MOT was done the same way as for the Rb MOT. For a current in the trap coils of 2A, the exponential fit for the loading part with f_1 resulted in a life-time of the ⁶Li atoms in the MOT, τ , of 1.7 s (Fig 5.12). With a total light power in the MOT of 30mW/cm^2 , $I_o = 2.54 \text{ mW/cm}^2$, and $\Gamma/2\pi = 5.87 \text{ MHz}$ [18], detuning $\delta = 15 \text{MHz}$ (= 2.55 Γ), and using Eqs 5.7 and 5.5, the maximum of the steady-state number of ⁶Li atoms in the MOT is calculated to N_s = $2.41 \cdot 10^5$. For a coil current of 3.07A and $\delta = 3.6\Gamma$, the steady-state number N_s= $2.53 \cdot 10^5$ was reached, and at 4.0A and $\delta = 4.1\Gamma$, the steady-state number was N_s = $2.60 \cdot 10^5$.

Fig 5.14 shows the number of ⁶Li atoms in the MOT depending on the current in the trap coils. The trap light was 22 MHz (= 3.7Γ) red-detuned to resonance. The maximum number of atoms is observed at around 4 A and is calculated to N_s = $2.69 \cdot 10^5$.

It can be seen, that the average steady-state number of ⁶Li atoms in the Li MOT is about 10 times lower than the average steady-state number of Rb atoms in a Rb MOT. This can be explained by the different loading mechanisms and the different properties of Li and Rb. Rb is emitted by a dispenser,



Figure 5.13: Position of the maximum N_s depending on the detuning of the trap light and the coil current.

which creates a Rb gas that diffuses to the trap region. The Rb atoms are bouncing several times on the walls of the glass cell and lose most of their kinetic energy. Since fast Rb atoms do not stick to the glass walls, they stay for a long time in the cell and are able to contribute to the cold atom cloud. Evidence for that is the fact, that even several hours after the Rb dispenser is turned off, it is still possible to get a Rb MOT. Li, however, behaves exactly the opposite. It sticks to the walls very quickly, which creates a mirror-like coating on the glass cell near the oven. When the Li oven is turned off, the Li MOT disappears after about 10 minutes. The oven, furthermore, produces a beam of Li atoms whose average velocity is much higher than the average velocity of the Rb atoms. Due to the velocity distribution of the atoms, which follows the Maxwell-Boltzmann distribution, only a small amount of the Li atoms has a velocity which is smaller than the capture velocity, v_c , of the Li MOT. Therefore, the amount of Li atoms in the trap volume which can be captured, is a lot smaller than the amount of Rb atoms. This results in a small loading rate and explains the small cloud of cold Li atoms.



Figure 5.14: Steady-state number of ⁶Li atoms in the MOT depending on the current in the trap coils. The trap light was 22 MHz (= 3.7Γ) red-detuned to resonance.

5.4 Overlapping Li and Rb

In most of our experiments, the Li and the Rb clouds in the cell had a distance of 1-2 mm to each other. Since it is the goal to create LiRb molecules, attempts have been made to overlap the clouds. For the current setup, this seems to be almost impossible since the Rb light is mixed with the Li light before it reaches the spatial filters. After it passes them, the same optics are used for both light colors. Hence, Rb light and Li light cannot be adjusted separately by the optics close to the glass cell. If one color is misaligned with respect to the other in order to overlap the clouds, it can only be done before it passes the spatial filters. Then, one of the colors will be partially blocked by the pinhole of the spatial filter. One idea might be, to remove the spatial filters. This has been tried already and both MOTs could be created. However, the Li MOT then seems to be smaller and further away from the Rb MOT than it was before.



Figure 5.15: A cloud of about 10^5 ultra-cold Li atoms in the MOT. Compared to the Rb cloud (Fig. 5.10) its shape is fuzzier and dim compared to the background light.

Chapter 6

Conclusions and outlook

To finalize this thesis, a summary of my particular work on the project, creating cold LiRb molecules via photoassociations, is given in the following chapter. An outlook of what will come in the near and further future is given as well.

6.1 Conclusions

When I started to work on the project, the table for the experiment was empty. The first task was to design the setup and the alignment of the optics on the photoassociation table using VectorWorks. The result can be seen in Fig 3.6. It clarified, in what quantities the optics had to be ordered.

The first alignment steps were taken in aligning the AOM double-pass for Rb light, and a double-pass efficiency of 44% was achieved. It was also found, that the QWP in the double-pass needs to be placed between AOM and spherical mirror and not between PBS and AOM (Fig 3.7) in order to make the double-pass running properly. Later it turned out, that the double-pass efficiency also depends on the frequency of the AOM, if the distance between spherical mirror and AOM is not optimal. After this distance was optimized, the changes in efficiency where smaller than 10%, when the AOM frequency was changed (Fig 3.8).

Furthermore, a characterization of the AOM drivers was done. Now it is clear, what frequency they will output when a certain voltage is applied The injection of the Rb slaves with master light was the next step. A throughput of 86.4% for the optical isolators was achieved. It was found, that a Rb

slave can be injected with a low injection power of >0.2 mW. The slave then can still be run at around 45 mW optical output power. For the optical isolators of the Li slave laser, a throughput in forward direction of 88% and an isolation of 40dB was reached.

In aligning the light through the isolators, the mirrors showed a birefringent behaviour, if the light is not purely p or s polarized. After testing about 40 mirrors, the less birefringent ones were selected from the other mirrors and put at places, where light with a mixed polarization is reflected. This minimized reflection losses on the PBSs, which are passed by the light later on.

Another task was the spatial filtering of the MOT light. The optimal combination was found after testing several combinations of pinholes and microscopic objectives. With a 25μ m pinhole and an objective with NA=0.1, a clean beam profile with a throughput of about 90% was achieved.

In optimizing the throughput of the diagnostic light through the diagnostic fibers, it was found, that the optimum does not give a nice diagnostic signal, because the fibers are multimode for the light we use. It is rather the angle of the light hitting the fiber, which determines the quality of the signal.

An important task was the characterization of the Li and Rb slave lasers. For the Rb lasers, 4 windows of opportunity in current were found, where the slave lasers are properly injected (see Section 4.2.2). The Li lasers revealed 11 windows of opportunity in current.

For the alignment of the light on the photoassociation table an alignment technique was developed, which can be used as a standard technique for aligning or re-aligning the trap light and repump light.

Of course I participated in many other project-related tasks besides these particular tasks. This was for example the cleaning and baking procedure of the vacuum system, designing and assembling parts of the optics and structure around the glass cell with SolidWorks, running cables and fibers between both labs, and machining items on the lathe and the mill.

Finally, the Li and the Rb MOT have been created and measurements on them have been done, that characterize the behaviour of the cold atom clouds. The results will be a guide for the next steps in research.

6.2 Outlook

To get an idea of what could happen with the experimental setup as it is now, some of the next probable steps are listed below. The goals for the near future could be reached in between about half an year. The further goals, however, still might take a bit longer. At this point it is difficult to make exact predictions.

6.2.1 Goals for the near future

In chapter 5 it was mentioned, that first attempts have been made at measuring the temperature of the cold atom clouds. As discussed previously, the problem appears to be the mechanical shutters. In order to complete this measurement, a new type of optical shutter needs to be designed and built. Furthermore, it has been tried to overlap the cold ⁶Li and ⁸⁷Rb clouds. To achieve the overlap, the only thing that can be done at this point is to slightly misalign the Rb light with respect to the Li light, and to alter with the power balance of the trap light close to the glass cell. In the experimental setup of David deMilles group [9], for example, Rb and Cs atoms are trapped simultaneously. This group solved the problem of overlapping the Rb cloud with the Cs cloud in not mixing Rb light with the Cs light rather in using two sets of optics. In that way the position of the clouds can be adjusted separately. Once the Rb cloud and the Li cloud are overlapped, further experiments in cooling Li and Rb atoms can be done. Due to sympathetic cooling, other loading rates and steady-state numbers of Li and Rb atoms in the MOT are expected when the two atom clouds are overlapped [2].

Another step that needs to be taken is to re-design the TOF. Due to the change in resistance of the graphite-coated rods, the ions would not reach the detector (see Section 3.4.5). Without the TOF, however, the LiRb molecules could still be detected indirectly via optical spectroscopy (see below).

Besides these problems which just concern the photoassociation experiment, some other work still needs to be done simultaneously. This includes the electronic control system, which will synchronize the collection of data, and optimize the loading of atoms in the MOT by adjusting parameters like the coil current, AOM frequency and the current in the laser diodes.

Even after many efforts in optimizing the amplification system, the light still is not reliable enough to just switch it on and run the experiment. One problem is the constant misalignment of the light, probably caused by a creep in the mounts for the optics. Another improvement that should be made is to optimize the locking of the light on the master table. Sometimes the lasers are not locked stable enough to run an experiment over a couple of hours.

6.2.2 Further goals

Once the overlap of the clouds is achieved, attempts at creating LiRb molecules via photoassociation will be made. For that purpose, a Ti:Sapphire laser will be used which is pumped by a 532 nm Nd:YAG laser (10 W) from MilleniaPro. The Ti:Sapphire laser is locked to a fiber comb laser. By changing the repetition rate of the fiber comb, which corresponds to a change in the free-spectral range of its sawtooth-like frequency output, the wavelength of the Ti:Sapphire laser can be tuned around a center wavelength of 790 nm. Its light will be shone on the cold atom clouds. First, the vibrational energy levels of the excited molecular state of LiRb will be mapped out (Fig 2.5) by tuning the photoassociation laser. A decreasing MOT fluorescence for both, Li and Rb, indicates, that the photoassociation laser hits one of these levels. The tuning of the photoassociation laser, therefore, should create a fluorescence spectrum with several dips, where each dip corresponds to a vibrational energy level in the excited molecular state.

The energetic structure of the LiRb molecule is not entirely clear yet, however it is expected to be similar to the energetic structure of RbCs. Therefore, the next steps in research with the ultra-cold LiRb molecules will follow De-Mille's scheme [13], as seen in Fig 6.1. The photoassociation laser is locked to one of the biggest dips, and is then resonant with one of the levels in the excited molecular state. This will provide a reasonable amount of molecules. Then a pulse of a second Ti:Sapphire laser is shone on the cloud and drives the molecules into the molecular ground state. By tuning this laser in frequency, the vibrational levels of the ground state can be mapped out. For that purpose, the MOT fluorescence is monitored while tuning the frequency of the second Ti:Sapphire laser. Every time the photon energy of that laser approaches resonance between the excited molecular state and one of the ground molecular states, both of these energy levels change their distance due to the AC Stark effect. This brings the photoassociation laser slightly out of resonance with the excited molecular state and an increasing MOT fluorescence is observed. By tuning the second laser in frequency, the fluorescence spectrum therefore should show several peaks, where each peak corresponds



Figure 6.1: DeMille's scheme for creating ultra-cold RbCs molecules [13]. Colliding ultracold Rb and Cs atoms are photoassociated (a) and decay into an vibrationally excited, electronical ground state (b). A resonant laser pulse drives these metastable molecules to level i (c), where a second laser pulse resonantly drives them into the vibronic ground state (d).

to an energy level in the molecular ground state. In order to prove that LiRb molecules were created, the photoassociation laser is brought out of resonance and the peaks in the MOT fluorescence should disappear. In this way, molecules can be detected even without using the TOF. By locking the second laser to one of the strong fluorescence peaks and therefore resonantly locking it to one of the molecular ground-state levels, a third laser is used to drive the molecules into one of the lowest levels of the molecular excited state. From there, the molecules again can be driven down into the molecular ground state. The final goal is to reach the lowest vibrational level in the ground state of the LiRb molecule. This entire procedure will yield a big amount of informations about the LiRb molecule for a scientific paper.

As mentioned in Chapter 2, LiRb molecules can also be created via Fesh-

bach resonances. Colliding pairs of ultra-cold Li and Rb atoms would create LiRb molecules in their electronical ground state. From this energy level the LiRb molecules can be driven into the level i (see Fig 6.1) and then into the vibronic ground state.

Once LiRb molecules are created and successfully detected, they somehow need to be hold inside the glass cell for further experiments. Since the molecules do not absorb the trap light any more, they would just diffusively leave the trap region. There are several possibilities to hold them. One of them is the optical tweezer, which makes use of the dipole force. An intense laser beam alters the molecular energy levels due to the AC Stark effect. Therefore, a potential well is created in the focus of a laser beam, and attracts the molecules, which will accumulate there [6]. With two laser beams that cross each other orthogonally in their focus, the molecules are spatially confined in all 3 dimensions.

A very exciting idea is, to bring the ultra-cold molecules in a 2D or 3D optical lattice, produced by counter-propagating beams in 2 or 3 dimensions. Due to their high dipole moment, the molecules could then be polarized by an electrical field, and maybe serve as quits in a quantum computer [22].

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