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# Creation of ultra cold rubidium atoms for sympathetic cooling of ytterbium

Diploma thesis

March 2003

## University of Stuttgart

5th Institute of Physics Chair of Professor Tilman Pfau



Fluorescence picture of  $1.2\cdot 10^9$  rubidium atoms in a magneto-optical trap.

Bernd Kaltenhäuser  $\cdot$  Creation of ultra cold rubidium atoms for sympathetic cooling of ytterbium  $\cdot$  Diploma thesis  $\cdot$  5th Institute of Physics  $\cdot$  Chair of Professor Tilman Pfau  $\cdot$  University of Stuttgart  $\cdot$  Final edition  $\cdot$  March 2003

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## Abstract

Within the scope of this work an experiment to cool ytterbium and rubidium atoms down to temperatures in the  $\mu K$ -region has been set up. The main parts of this experiment are a vacuum system and two laser systems.

The vacuum system consists of the ovens, where the atoms are evaporated, the Zeeman slowers, where they are decelerated and the main chamber where they are first trapped magneto-optically and afterwards magnetically (Rb) and optically (Yb). Subsequently the rubidium atoms will be cooled down by evaporative cooling and thus the ytterbium atoms will be cooled down sympathetically.

The laser system to decelerate and trap the rubidium atoms consists of four diode lasers while the laser system for ytterbium consists of a Verdi-pumped, frequency-doubled titanium-sapphire-laser. Furthermore, there is a dye laser operated with rhodamin 110 to cool ytterbium on its 556 nm transition. For trapping the ytterbium atoms there will be a bichromatic dipole trap, consisting of light, split off from the Verdi V10 solid state laser and a ytterbium fiber laser (type PYL-20 M).

In this work a description of the setup of the ovens, the Zeeman slowers, the main chamber and the magnetic coils will be given. Furthermore, measurements on the Zeeman slower for rubidium, the loading and decay dynamics of the rubidium MOT and on the magnetic trap for rubidium will be shown. The Zeeman slower provides a flux of  $10^8$  slow atoms per second, which can be loaded into the magneto-optical trap, which currently loads up to  $1.2 \cdot 10^9$  atoms. Presently, the atomic cloud reaches a temperature of  $1.9 \,\mathrm{mK}$  and a density of  $1.8 \cdot 10^{10}/\mathrm{cm}^3$ .

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## 1. Introduction

## 1.1 A brief history of atom optics

It was not until the 1990s when the breakthrough of atom optics took place: long predicted quantum effects were realized experimentally and fascinated the whole world of science. But the roots of atom optics date back to the turn of the century:

Because all classical attempts to explain the black body radiation failed in the 19th century, the physicist Max Planck realized that a completely new theory had to be developed and in 1901 he introduced his quantum hypothesis, which was honored with the Nobel Prize in 1918. With his theory he was the first to derive a formula that completely described the radiative behavior of black bodies.

In 1905, Albert Einstein followed up on Planck's particle model of light and put forth his theory about the photoelectric effect which was honored with the Nobel Prize as well in 1921.

In 1923, Louis de Broglie came up with the idea that atoms, which at this time were understood to be solid particles, could be treated as matter waves and introduced - in analogy to light - a wavelength for atoms (Nobel Prize 1929).

Until 1924 several ways to derive Planck's radiation formula were shown but all of them used classical assumptions. Satyendra Nath Bose was unsatisfied with this shortcoming of the formula and showed a new derivative which was free of classical assumptions [Bos24]. Einstein, who translated Bose's article, saw that this approach could be used on massive particles as well and gave a description of the behavior of an ideal gas [Ein24]. After a few months he found out that his theory resulted in a macroscopic occupation of the ground state of an ideal gas that is cooled below a critical temperature which is depending on the particle density [Ein25a]. Although this phenomenon, that was later called Bose-Einstein-Condensation (BEC), had already been widely accepted, he published more arguments to confirm his theory within the next month [Ein25b].

In 1938 F. London used the theory of BEC to describe the superfluidity of helium [Lon38a, Lon38b] which had just been discovered by P. L. Kapitza [Kap38] (Nobel Prize 1978). The difference between liquid helium and dilute gases lies in the stronger interaction in helium that limits the number of atoms in the ground state.

First attempts to create a gaseous BEC with spin-polarized hydrogen by cryogenic cooling failed in 1984 because of the high realized densities which leaded to great particle losses due to three-body collisions [Hes84]. Nevertheless these experiments continued for more than ten years.

Although dating back to the 1970s, when A. Ashkin [Ash70], and T. W. Hänsch and A. Schawlow [Hae75] proposed that atoms could be cooled and trapped with laser light, this completely different approach was not realized before 1982 when William J. Phillips slowed an atomic beam with lasers for the first time [Phi82].

In 1985 much progress in the field of cooling and trapping was made in various ways: Steven Chu was able to cool atoms in optical molasses, but he was not able to trap them because of the lack of magnetic fields [Chu85].

In the same year W. J. Phillips chose a completely different way when he built the first magnetic trap: instead of light he used only magnetic fields and was able to trap but not to cool the atoms [Mig85].

It didn't take long before Harald F. Hess proposed to cool these magnetically trapped atoms by evaporation, that means to use radio frequencies to remove always the hottest atoms out of trap [Hes86].

In 1986 a completely different trap was build by Steven Chu. In his dipole trap the atoms were trapped using far off-resonant light whose dipole forces pulled the atoms into the center of the trap [Chu86].

Just a year later he built the first magneto-optical trap (MOT) which used lasers as well as magnetic fields. In this trap the atoms could be cooled and trapped but the minimum temperatures were still limited [Raa87].

In the following years Claude Cohen-Tannoudji showed theoretical ways for further decreasing the temperature in optical traps [Dal89] and in cooperation with W. J. Phillips he was able to cool atoms below the Doppler limit [Nob]. In 1997 Steven Chu, Claude Cohen-Tannoudji and William J. Phillips were honored with the Nobel Prize [Chu98, Coh98, Phi98].

After realizing Hess' idea of evaporation with hydrogen atoms, in 1994 sodium [Dav95a] and rubidium atoms were evaporated as well.

Right after this final step towards the realization of a BEC, nearly at the same time the group of Carl Wieman and Eric Cornell [And95] and the group of Wolfgang Ketterle [Dav95b] condensed dilute gases of rubidium and sodium atoms, respectively. They were honored with the Nobel Prize in 2001.

The first realization of BEC was a breakthrough in atom optics: several groups started to produce BECs and most of them were successful. But the main interests moved forward: 'simple' condensates were no longer interesting. The groups started to investigate the properties and applications of Bose-Einstein-Condensates:

One of the applications was the so-called atom laser which was realized in several ways [Mew97, And98, Blo99, Hag99]. Here a bunch of coherent atoms is extracted from the condensate and moves due to gravity. These atom bunches can e.g. be used to examine surfaces. One of the most interesting properties of condensates is their ability to amplify matter waves: a bunch of atoms that is being shot on a condensate becomes amplified, similar to photons in a laser [Ino99].

Another effect showed up when quantized vortices were created in twocomponent condensates [Mat99].

At the temperatures where BEC occurs, the atoms have to be treated as waves instead of particles. Hence, also nonlinear effects were found: in fourwave-mixing experiments three bunches (matter waves) of sodium atoms with different momenta were brought together and produced a fourth bunch (matter wave) with new momentum [Den99].

An interesting aspect is also the possibility to slow light that travels through a BEC: in the group of Lene V. Hau a BEC of sodium atoms was used to bring light to a full stop. Here, the annihilated light produces an interference in the atomic level scheme and so the information of the light becomes stored for several milliseconds until the stored information is converted into light again [Hau01a]. This effect can also be used to create quantum shock waves [Hau01b].

Although atoms in a BEC usually behave like a fluid, this property can be modified. The atoms can be arranged in an optical lattice, created by the standing light wave of a laser. There the atoms experience another phase transition to the so called Mott insulator [Gre02].

Very important for the realization of a BEC are the collisional properties of the atoms. In 1998 the collisional properties of the atoms were altered using varying magnetic fields [Ino98]. The magnetic field dependence of the collisional properties occurs due to so-called Feshbach resonances.

These Feshbach resonances can also be used to generate coherent coupling between the atoms in a BEC and molecules, which are created of the atoms in the BEC. This has been demonstrated for Rb<sub>2</sub>-molecules of <sup>85</sup>Rb [Don02]. A similar experiment using Raman transitions has been performed for Rb<sub>2</sub>-molecules of <sup>87</sup>Rb [Wyn00].

But molecules are also being investigated independent from BECs: because of the complex level schemes molecules cannot be cooled using laser cooling but in the group of Gerard Meijer ammonia molecules are being cooled and trapped using electric fields [Mei00, Mei01].

And there are still other interesting experiments in atom optics without connection to BEC, where thermal molecule beams are used. For example, in the group of Anton Zeilinger thermal beams of <sup>60</sup>C- and <sup>70</sup>C-molecules are used to demonstrate the wave nature of molecules [Bre02].

Bose-Einstein-Condensates can - as the name says - only be achieved with bosons because fermions show a completely different low-temperature behavior. But with fermions degenerate Fermi-gases have been realized [DeM99]. But the fermions do not necessarily have to be cooled directly. For example, fermionic <sup>6</sup>Li has been sympathetically cooled by bosonic <sup>7</sup>Li [Sch01] and fermionic <sup>40</sup>K has been sympathetically cooled by bosonic <sup>87</sup>Rb [Roa02].

The technique of sympathetic cooling can be used to cool atoms which cannot be cooled directly, e.g. because it is not possible to trap them magnetically. And this is the point where this experiments puts on.

## **1.2** About this experiment

Due to its level scheme ytterbium can be laser-cooled and magneto-optically trapped easily with two different wavelengths, which has already been done by other groups [Kuw99, Lof00, Rap02]. One of the transitions has the advantage of trapping even relatively fast atoms while the other has the advantage of low possible temperatures. Furthermore, with 399 and 556 nm they are both in the suitable frequency region and they don't need a repumping laser. But due to a diamagnetic ground state, ytterbium cannot be trapped magnetically<sup>1</sup>. But it can be trapped in a dipole trap which is suitable for trapping but not for  $cooling^2$ . So it is far more suitable to cool the ytterbium atoms sympathetically by rubidium atoms. Rubidium has many advantages for cooling: it is easy to handle as simple technologies like diode lasers can be used for cooling and many condensates have been realized, including some with large atom numbers. So there is already a lot of knowledge available on single component gases and research efforts can be put in the study of ytterbium and the collisional properties between the ytterbium and rubidium atoms. For this reason both atomic species are loaded into a double-species MOT. After cooling in the MOT the ytterbium atoms will be loaded into a bichromatic dipole trap and the rubidium atoms into a magnetic trap. The ytterbium atoms do not feel the magnetic trap due to their diamagnetic ground state and the rubidium atoms will not feel the dipole trap. Both wavelengths of the bichromic dipole trap pull the ytterbium atoms into the center of the trap. But due to the different atomic transitions in rubidium one of them pushes the rubidium atoms out of the trap while the intensity of the other laser can be chosen to compensate this effect. By evaporating the rubidium atoms they will be cooled down and cool the ytterbium atoms as well.

Once the ytterbium atoms are cooled down they provide a huge range of experiments to study physical phenomena:

The collisions between Yb atoms of the same isotope, Yb atoms of different isotopes and between Rb and Yb atoms can be investigated. Furthermore, it is possible to search for a BCS-transition in fermionic ytterbium, which will probably show up at very low temperatures.

As two of the seven stable ytterbium isotopes are fermionic (see section 2.10), Fermi gases can be realized and fermions can be arrayed in optical lattices.

But not only atoms can be studied: homo-nuclear  $Yb_2$  and hetero-nuclear YbRb molecules can be created and their low-temperature behavior determined.

Ytterbium is also an interesting element for precision measurements: for example one atomic transition can be used to build an atomic clock, more precise than the current cesium atomic clocks.

<sup>&</sup>lt;sup>1</sup> It may be trapped magnetically in an excited state

 $<sup>^{2}</sup>$  It may be cooled in a dipole trap directly but it is difficult to produce high densities

Furthermore, signs of parity violations can be found in atomic transitions and ytterbium is also a candidate for the search for an electric dipole moment. With such measurements the standard model or the supersymmetric theory can be tested. For further information on precision measurements see appendix A.

## 1.3 About this work

At the beginning of this work the lab was nearly empty but many preparations were made: the vacuum chamber was designed and ordered, the calculations for the Zeeman slowers were mostly done, the magnetic coils were designed and first parts of the lasers were set up. The main work of this thesis concentrated on setting up the laser system for rubidium, winding the Zeeman slower for rubidium and the magnetic coils, putting up the vacuum system and carrying out measurements on the rubidium- and the doublespecies magneto-optical trap.

## 2. Theoretical basics

## 2.1 Bose-Einstein-Condensation

Although atom optics consists of far more than Bose-Einstein-Condensates (BEC), this condensation plays an important role: some physical effects become visible only in a BEC and for various precession experiments the accuracy increases with decreasing temperature. The theory of Bose-Einstein-Condensation describes the low-temperature behavior of dilute gases. Because this experiment aims at BEC a brief derivative is given here.

The energy of a free particle can be expressed by its momentum  $\varepsilon_p = p^2/2m$ . For each of these momentum states has the occupation probability  $n(\varepsilon_p)$  the total number of atoms N must be the summation over all states

$$N = \sum_{p} n(\varepsilon_p) \,. \tag{2.1}$$

For bosons (any integer spin, but for simplicity treated here with s = 0) the occupation probability is given by the Bose-Distribution

$$n(\varepsilon_p) = \frac{1}{e^{\beta(\varepsilon_p - \mu)} - 1}, \qquad (2.2)$$

where  $\beta = 1/k_B T$ ,  $k_B$  denotes Boltzmann's constant, T the temperature and  $\mu$  the chemical potential. Obviously  $n(\varepsilon_p)$  must be positive for all p. This forces  $\mu$  to be smaller than the lowest possible energy which is zero for p = 0, that means

$$\mu < 0 . \tag{2.3}$$

This defines the range for the fugacity z:

$$0 < z = e^{\beta\mu} \le 1 \tag{2.4}$$

Because the ground state shows a completely different behavior for  $T \rightarrow 0$  (compared to all other states as shown in [Hua87]), it must be treated separately by taking the p = 0-term out of the sum in equation 2.2

$$N = n(\varepsilon_{p=0}) + \sum_{p \neq 0} n(\varepsilon_p)$$
  
=  $N_0 + N'$ , (2.5)

where  $N_0$  denotes the number of atoms in the ground state and N' the number of atoms in all other states.

In the limit of  $V \to \infty$  (while N/V is held constant) the possible values of p form a continuum. Therefore, the sum can be replaced by a normalized integral

$$N = n(\varepsilon_{p=0}) + \frac{V}{(2\pi\hbar)^3} \int d^3p \ n(\varepsilon_p)$$
  
=  $n(\varepsilon_{p=0}) + \frac{V}{2\pi^2\hbar^3} \int_0^\infty dp \ p^2 n(\varepsilon_p)$   
=  $\frac{z}{1-z} + \frac{V}{\lambda^3} \frac{2}{\sqrt{\pi}} \int_0^\infty dx \frac{x^{(1/2)}}{e^x z^{-1} - 1} ,$  (2.6)

where the integration variable  $x = \beta \varepsilon_p = \beta p^2/2m$  and the thermal wavelength  $\lambda = (2\pi\hbar^2/mk_BT)^{1/2}$  have been introduced. Using the generalized Riemann- $\zeta$ -function

$$g_{\nu}(z) \equiv \frac{1}{\Gamma(\nu)} \int_{0}^{\infty} dx \frac{x^{\nu-1}}{e^{x}z^{-1}-1}$$
$$\equiv \sum_{l=1}^{\infty} \frac{z^{l}}{l^{\nu}}, \qquad (2.7)$$

where  $\Gamma(\nu)$  denotes the Gamma-function (see appendix C), equation 2.6 can be written as

$$\frac{N}{V} = \frac{N_0}{V} + \frac{N'}{V} = \frac{1}{V}\frac{z}{1-z} + \frac{1}{\lambda^3}g_{3/2}(z) .$$
(2.8)

Using N/V instead of N is convenient because N/V is held constant in the thermodynamical limit.



Fig. 2.1: Graph (a) shows the particle density of atoms in all excited states (in dimensions of a constant  $1/\lambda^3$ )  $N'/(V/\lambda^3) = g_{3/2}(z)$  vs. z while the graphs (b), (c) and (d) show the particle density of atoms in the ground state  $N_0/V$  vs. z with V increasing from (b) to (d).

Figure 2.1 shows a plot of the particle density of atoms in the ground state  $N_0/V$  versus z (as mentioned before the values of z must be between 0 and 1) for several values of V. Here the two cases z < 1 and z = 1 must be examined:

#### $\underline{z < 1}$

While z < 1 the number of atoms in the ground state becomes smaller for an increasing volume V. This can also be seen by regarding the population of a single state: because it scales like  $n(\varepsilon_p) \sim N/V^2$ , it becomes zero in the thermodynamical limit (that is  $V \to \infty$  while N/V is held constant).

 $\underline{z=1}$ 

An examination of the power series for  $g_{3/2}(z)$  (equation 2.7) shows that the derivative of that function diverges at z = 1, but it yields a finite value of  $g_{3/2}(1) = 2.612$  as shown in figure 2.1.



Fig. 2.2: Graph (a) shows the temperature dependence of z for a finite atom number, while graph (b) shows the same in the thermodynamical limit. The difference at  $T = T_C$  is of the order  $\Delta z \sim 1/V$ .

Because of the temperature dependence of  $\mu$  the value of z increases with decreasing temperature, but the temperature at which z = 1 is reached does not have to be zero (see figure 2.2). This temperature can be calculated by examining

$$\lim_{\delta \to 0} \left( z - \delta \right) \Big|_{z=1} \tag{2.9}$$

with  $\delta > 0$ . This yields the behavior of  $N_0/V$  and  $g_{3/2}(z)$  for  $\delta \to 0$  but this can also be seen in figure 2.1: when  $\delta$  is infinitely small the value of  $g_{3/2}(z-\delta)|_{z=1}$  approaches its maximum value of

$$\lim_{\delta \to 0} |g_{3/2}(z-\delta)|_{z=1} = g_{3/2}(1) = 2.612 , \qquad (2.10)$$

while  $N_0$  is still zero (because in the thermodynamical limit holds  $V \to \infty$ ). In this limit ( $\delta \to 0$ ) equation 2.8 can be written as

$$\frac{\lambda^3}{V}N = g_{3/2}(z) \tag{2.11}$$

or

$$\left(\frac{2\pi\hbar^2}{mk_B}\right)^{3/2} \frac{N}{V} T^{-3/2} = 2.612 . \qquad (2.12)$$

This shows that the temperature cannot be decreased below a critical temperature  $T_C$ , except by a macroscopic occupation of the ground state, given by the above relation for a fixed ratio n = N/V

$$T_C = \frac{2\pi\hbar^2}{mk_B} \left(\frac{N}{2.612\,V}\right)^{2/3} \,. \tag{2.13}$$

The effect that occurs for  $T < T_C$  can be seen by replacing  $g_{3/2}(z) = 2.612$  in equation 2.8 with equation 2.13:

$$N = N_0 + N \left(\frac{T}{T_C}\right)^{3/2} \tag{2.14}$$

Solving this equation towards  $N_0/N$  yields

$$\frac{N_0}{N} = \begin{cases} 1 - \left(\frac{T}{T_C}\right)^{3/2} & ; \ n\lambda^3 \ge 2.612 \\ 0 & ; \ n\lambda^3 < 2.612 \end{cases} .$$
(2.15)



Fig. 2.3: Graph (a) shows the relative occupation level of the ground state  $(N_0/N)$  vs. T for a dilute gas in the thermodynamical limit while graph (b) shows the same for a finite atom number. This plot is guided to the eye, as the thermodynamical limit occurs already for  $N > 10^3$ .

This phenomenon of a macroscopic ground state occupation (see figure 2.3) is called Bose - Einstein - Condensation (BEC) because the atoms 'fall' out of the 'regular' gaseous continuum, similar to particles condensing below the boiling point.

The condition for the phase transition to BEC can also be expressed by the phase-space density  $n\lambda^3$  as indicated in equation 2.15. The phase-space density, which is determined by the temperature and density of the gas, must exceed a value of 2.612.

For a finite atom number the condensation takes place as well, but the transition to the BEC-phase is more continuous than in the thermodynamical limit, as it is also shown in figure 2.3. Another interpretation of BEC is that at these temperatures the thermal wavelength is of the order of the average distance between the atoms. Therefore the atoms have to be treated as waves instead of particles. In the case of BEC these waves start to overlap and thus all the atoms have to be treated as one huge matter wave.

A similar derivative of the BEC can be made for atoms in a harmonic potential, as it is the case in a magnetic trap (see e.g. [Cas01]).

## 2.2 Interaction of light and matter

The interaction of light and matter is extensively discussed in several publications (e.g. [Met99]) and thus only a short summary shall be given here.

#### 2.2.1 The spontaneous force

To understand the interaction of light and matter the atom model is simplified using the so-called Jaynes-Cummings-Paul model: a monochromatic light wave interacts with an electron that can only occupy a ground- and one exited state. When the atom is in the ground state, a photon can be absorbed and re-emitted later. The idealized scattering rate of this statistical process depends on the light parameters and reads for an atom at rest

$$\gamma_{p_0} = \frac{\Gamma}{2} \frac{I/I_0}{1 + I/I_0 + (2\delta/\Gamma)^2} , \qquad (2.16)$$

where I denotes the light intensity,  $I_0$  the saturation intensity of the atom,  $\delta = \omega_l - \omega_a$  the detuning of the light with respect to the atomic transition frequency and  $\Gamma$  the decay rate of the excited state.

If the atom is not at rest, its velocity v results in a Doppler shift  $\omega_D = \vec{k}\vec{v}$  for the absorption and re-emission of the photon and thus in a shift of the detuning  $\delta \to \delta + \omega_D$ . Therefore equation 2.16 reads

$$\gamma_{p_0} = \frac{\Gamma}{2} \frac{I/I_0}{1 + I/I_0 + (2(\delta + \omega_D)/\Gamma)^2} , \qquad (2.17)$$

The absorption and re-emission of a photon leads to a momentum transfer on the atom and thus to a force on the atom, the so-called spontaneous force

$$\vec{F}_{sp} = \hbar \vec{k} \gamma_p = \hbar \vec{k} \gamma_{p_0} \eta_{CG} , \qquad (2.18)$$

where  $\vec{k}$  denotes the wave vector. The scattering rate  $\gamma_p$  is obtained by multiplying the idealized scattering rate  $\gamma_{p_0}$  with the Clebsch-Gordan coefficient  $\eta_{CG}$  [Mey01], which reflects the probability for an atom to absorb a photon, depending on the atoms magnetic quantum numbers before and after the transition and on the polarization of the light.

Descriptive explanation of the spontaneous force: the force on the atom results from the momentum transfer from and to the photon. Due to momentum conservation, the momenta, transferred by the absorption, point always in the direction of the wave vector of the laser while the momenta, transferred by the emission, point in stochastic directions and average themselves away (see figure 2.4).



Thus, the resulting force on the atoms points in the direction of the wave vector.

In the limit of a high saturation ratio  $(I/I_0 \rightarrow \infty)$  equations 2.16 and 2.17 simplify to

$$\gamma_{p_0} = \frac{\Gamma}{2} . \tag{2.19}$$

#### 2.2.2 Doppler cooling (optical molasses)

To demonstrate the effect of this force the so-called one-dimensional optical molasses is used: the moving atoms are hit by two laser beams from opposite directions, resulting in the forces  $\vec{F}_+$  and  $\vec{F}_-$ . Therefore equation 2.18 can be rewritten for each of the two lasers as

$$\vec{F}_{\pm} = \pm \frac{\hbar k \Gamma}{2} \frac{I/I_0}{1 + I/I_0 + [2(\delta \mp |\omega_D|)/\Gamma]^2} , \qquad (2.20)$$

where the first  $\pm$ -sign depends on the direction of the wave vector  $\vec{k}$ . In the case of small velocities  $|\omega_D| \ll \Gamma$  and low light intensities  $I \ll I_0$  the overall force  $\vec{F} = \vec{F}_+ + \vec{F}_-$  can be expanded, yielding

$$\vec{F} = \frac{8\hbar k^2 \delta I / I_0}{\Gamma \left[1 + I / I_0 + (2\delta/\Gamma)^2\right]^2} \, \vec{v} = -\beta \vec{v} \,.$$
(2.21)

Due to  $|\omega_D| \ll \Gamma$  terms of the order of  $O((|\omega_D|/\Gamma)^4)$  are neglected in this equation. For a negative detuning ( $\delta < 0$ ) the force damps the atomic motion with the positive friction coefficient  $\beta$ . The force is therefore slowing down (and hence cooling) the atoms.



Fig. 2.5: Curve (a) shows the force  $\vec{F}_{-}$ , (b) the force  $\vec{F}_{+}$  and (c) the total force  $\vec{F}$  acting on the atom and (d) the linear approximation of  $\vec{F}$  (equation 2.27) vs. the velocity of the atoms. The figure is unscaled, due to the  $\delta$ - and  $\Gamma$ dependence of  $\vec{F}$  and for clearness.

#### 2.2.3 Doppler limit

As mentioned before, the momenta, transferred by the emission of photons, point in stochastic directions and average themselves away. But the emissions create a discrete random walk in momentum space with increment  $p = \hbar k$ . This can be understood as a heating process. The balance of the cooling- and the heating process corresponds to a minimum temperature, the so-called Doppler temperature. It reaches its minimum for  $\delta = -\Gamma/2$  and reads

$$T_D = \frac{\hbar\Gamma}{4k_B} \frac{1 + (2\delta/\Gamma)^2}{2|\delta|/\Gamma} \stackrel{\delta = -\Gamma/2}{=} \frac{\hbar\Gamma}{2k_B} .$$
 (2.22)

## 2.3 Zeeman slower

#### 2.3.1 Zeeman effect

The Zeeman effect can be used for compensating the Doppler shift of fast atoms in a Zeeman slower or for a confinement of the atoms in a magnetooptical trap:

The potential energy of an atom with the magnetic dipole moment  $\vec{\mu}$  in a magnetic field  $\vec{B}$  reads  $E_{pot} = \vec{\mu}\vec{B}$ . In terms of the magnetic substates this can be expressed by

$$E_Z = m_F g_F \mu_B B , \qquad (2.23)$$

where  $m_F$  denotes the magnetic quantum number of the hyperfine state F with respect to the quantization axis,  $g_F$  the Landé-g-factor and  $\mu_B$  the Bohrmagneton.

Hence, the magnetic field determines the energy of the magnetic substates. The Zeeman shift of the atomic transition frequency  $\delta_Z$  is the difference of the shifts of the two involved states  $|g\rangle$  and  $|e\rangle$ :

$$\delta_Z = (g_e m_e - g_g m_g) \frac{\mu_B B}{\hbar} = \frac{\Delta \mu B}{\hbar}$$
(2.24)

This detuning becomes space-dependent in an inhomogeneous magnetic field and thus equation 2.21 becomes space-dependent by adding  $\delta_Z$  to the detuning  $\delta$ .

Electric dipole transitions are possible for  $\Delta m_F = \pm 1$  and  $\Delta m_F = 0$ . Transitions with  $\Delta m_F = +1$  can only be induced by photons with spin  $m_s = +1$  ( $\sigma^+$ -light) and transitions with  $\Delta m_F = -1$  only by photons with  $m_s = -1$  ( $\sigma^-$ -light), while transitions with  $\Delta m_F = 0$  can be driven by  $\pi$ -light (e.g. light that is linearly polarized along the quantization axis).

#### 2.3.2 Operation principle

In the case of a Zeeman slower the atoms fly in one direction and are slowed down by a laser beam that comes from the opposite side. Due to the Doppler shift only the atoms whose velocity is within a narrow range are resonant with the laser. Using a magnetic field, the Doppler shift can be compensated by the Zeeman shift.

As the atoms are slowed down over a fix distance, the velocity can be assigned to a position. Therefore a space-dependent magnetic field creates a velocitydependent shift. This magnetic field must be designed to compensate the Doppler shift along all the way of the atoms for a given detuning  $\delta$ .

The magnetic field can increase or decrease along the slower, where each of the two slower types has its own advantages (see section 3.3). The slower type determines the detuning  $\delta$ :

In an increasing field slower the fast atoms are in resonance with the laser at B = 0 and  $\sigma^-$ -light must be used, while in a decreasing field slower the slow atoms are in resonance with the laser at B = 0 and  $\sigma^+$ -light must be used. These two slower types can be extended in various ways: e.g. an offset field  $B_0$  can be added to the magnetic field. In this case, the atoms, which would

determine the resonance condition for the laser detuning at B = 0, determine the latter one at  $B = B_0$ .

## 2.4 The magneto-optical trap

#### 2.4.1 Operation principle



Fig. 2.6: Figure (a) shows the spatial dependence of the magnetic field for the one-dimensional model of a MOT. Figure (b) shows the Zeeman shift  $\delta_Z$  of the exited state for the transitions with  $\Delta m = +1$  and  $\Delta m = -1$ . The lasers have a frequency  $\omega_l = \omega_0 + \delta$  and are resonant with the transition at the points -R and R, respectively. The  $\sigma^+$ -polarized laser acts only on the transition with  $\Delta m = +1$  and the  $\sigma^{-}$ polarized laser only on the one with  $\Delta m = -1$ .



The MOT uses a magnetic field, that is linearly increasing along the quantization axis z (see figure 2.6 a). This results in spatially dependent Zeeman shifts for the two transitions with  $\Delta m = +1$  and  $\Delta m = -1$  (see figure 2.6 b): the one for the transitions with  $\Delta m = +1$  creates a positve detuning with increasing z and the one with  $\Delta m = -1$  creates a negative detuning with increasing z. The detuning of the  $\sigma^+$ -polarized laser, which can only act on transitions with  $\Delta m = +1$ , is compensated at z = -R and increased at z = +R. Hence, the probability to absorb  $\sigma^+$ -polarized photons increases for decreasing z and the atoms at z < 0 are pushed back into the center of the trap. Because it is the other way round for the  $\sigma^-$ -polarized laser, the resulting force traps the atoms. By increasing this force (by increasing the laser power) more atoms can be trapped. This dependence (atom number vs. force) shows a saturation behavior.

#### 2.4.2 Extension to three dimensions

The principle of the three-dimensional MOT is in effect the same: three pairs of  $\sigma^+$ - and  $\sigma^-$ -beams are used, while the magnetic field is a rotationally symmetric quadrupole field (figure 2.8), usually created by two opposing coils in an Anti-Helmholtz configuration, as shown in figure 2.7.



Fig. 2.7: Three-dimensional model of a MOT. It shows the six polarized laser beams, the magnetic coils and the electric currents which flow through them.



Fig. 2.8: The quadrupole field created by two opposing coils, which are denoted at the bottom and top of the picture. Due to equation 2.26 the field in zdirection is twice as strong as the one in r-direction.

In this quadrupole field the magnetic field strength is linearly increasing in the three spatial directions and zero in the center. Due to the Maxwell equation

$$\mathbf{div}\vec{B} = \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} = 0 \tag{2.25}$$

a gradient in one dimension has to be equal to the negative sum of the other two gradients. In the case of rotational symmetry, x and y point into the r-direction and are therefore equal. This yields

$$2\frac{\partial B_x}{\partial x} + \frac{\partial B_z}{\partial z} = 2\frac{\partial B_r}{\partial r} + \frac{\partial B_z}{\partial z} = 0.$$
 (2.26)

Hence, the gradient along the axis is twice as strong as the gradient in radial direction. This is also indicated by the thickness of the arrows in figure 2.8 (see also section 3.6.2).

For small excursions and velocities, the force on the atoms can be expanded into a power series and leads to

$$\vec{F}(\vec{z},\vec{v}) = -\kappa \vec{z} + \beta \vec{v} , \qquad (2.27)$$

where the spring constant of this harmonic oscillator reads

$$\kappa = \frac{\Delta \mu}{\hbar k} \frac{dB}{dz} \beta \tag{2.28}$$

and  $\beta$  is defined as in equation 2.21.

#### 2.4.3 Capture region

The points where the light is in resonance with the transition of an atom at rest, R and -R in figure 2.6, define the capture region of the MOT. In the three-dimensional case these points do not necessarily have the same distance from the center in each direction. Atoms may be cooled and trapped also outside these points, but the efficiency decreases with increasing distance from the center. If the radius of the laser beams is smaller than R, the capture region is defined by the laser beams.

#### 2.4.4 Capture velocity

To estimate the maximum velocities the MOT can capture, it is assumed that an atom enters the trap at z = R with maximum velocity and is brought to a standstill at z = -R due to the maximum spontaneous force. The maximum velocity is then given by the maximum energy of the particle

$$v_{max} = \sqrt{\frac{2E}{m}} = \sqrt{\frac{4F_{max}R}{m}} . \qquad (2.29)$$

Typical values are  $5m/s \leq v_{max} \leq 40m/s$ . This is the reason why the thermal atoms from the ovens, where most of them have velocities of  $v \approx 50-300 m/s$ , have to be decelerated in a Zeeman slower.

#### 2.4.5 Density distribution

In the limit of low atom numbers  $(N \leq 10^6)$ , the interaction of the atoms can be neglected and the potential energy of an atom depends only on its position in the trap. In thermal equilibrium the density distribution in the MOT reads

$$n(\vec{r}) = n_0 e^{-\frac{E_{pot}(\vec{r})}{k_B T}}.$$
(2.30)

Using the potential energy

$$E_{pot}(\vec{r}) = \frac{1}{2} \sum_{i=1}^{3} \kappa_i x_i^2$$
(2.31)

of the spring constant  $\kappa$  of equation 2.28 the density distribution becomes Gaussian in each direction

$$n_i(x_i) = n_0 e^{-\frac{x_i^2}{2\sigma_i}} . (2.32)$$

The width of the MOT's Gaussian profile

$$\sigma_i = \sqrt{\frac{k_B T}{\kappa_i}} \tag{2.33}$$

depends only on the temperature and the trap parameters.

In the case of high atom numbers  $(N \gtrsim 10^6)$  the atoms interact with photons, which have been scattered by other atoms, resulting in a repulsive force between the atoms. Additionally, due to the high optical density the laser power gets weaker in the center of the trap. Hence, the density distribution depends on these effects as well and is given by

$$n = \frac{3\kappa c}{P_l \sigma_l (\sigma_r - \sigma_l)} , \qquad (2.34)$$

where  $\sigma_l$  denotes the scattering cross section for the laser photons,  $\sigma_r$  the scattering cross section for the re-emitted photons and  $P_l$  the total laser power [Tow95].

#### 2.4.6 Temperature in a MOT

If no Sub-Doppler cooling techniques are used, the minimum temperature in the MOT is given by the Doppler temperature. The temperature can be measured using the time-of-flight method as shown in appendix B.

#### 2.4.7 Loading and decay dynamics of a MOT

To derive an equation that describes the behavior of a MOT, it is assumed that the MOT is loaded continuously at a rate  $R_L$ .

Furthermore, there are several decay mechanisms that have to be considered (see section 2.6):

Due to one-body losses like collisions with the background gas and atoms from the loading beam, the MOT decays proportional to N at a rate  $\Gamma_L$ .

And the MOT also decays proportional to  $N^2$  at a rate  $\beta$  due to two-body collisions like radiative escape- and spin-flip collisions while three-body collisions can be neglected.

Off-resonant excitation can also lead to atom losses but due to a repumping laser this loss mechanism is suppressed and can be neglected as well. Hence, the rate equation reads

$$\frac{dN}{dt} = R_L - \Gamma_L N - \frac{\beta}{V} N^2 . \qquad (2.35)$$

The solution of this equation is rather complicated and only the two special cases of loading and decay of the MOT are needed here: during the initial loading of the MOT the particle Number N can be assumed to be small and the last term can be neglected. Using N(t = 0) = 0 the solution reads

$$N(t) = \frac{R_L}{\Gamma_L} (1 - e^{-\Gamma_L t}) .$$
 (2.36)

During the loading process  $\Gamma_L$  corresponds to collisions with the background gas as well as collisions with atoms from the loading beam. When the trap is loaded, a mechanical shutter cuts off the atomic beam and  $\Gamma_L$  reduces to  $\Gamma_D$ , the rate of collisions with the background gas. Therefore equation 2.35 reads

$$\frac{dN}{dt} = -\Gamma_D N - \frac{\beta}{V} N^2 . \qquad (2.37)$$

Assuming a trap, loaded with  $N_0$  atoms as initial condition, the solution of equation 2.37 reads

$$N(t) = N_0 \frac{e^{-\Gamma_D t}}{1 + \frac{\beta N_0}{V \Gamma_D} (1 - e^{-\Gamma_D t})} .$$
 (2.38)

#### 2.4.8 Sub-Doppler cooling

If the opposing laser beams, acting on the atomic cloud, are linearly polarized under a different angle or  $\sigma^+$ - and  $\sigma^-$ -polarized, the polarization of the total light field varies along the axis. Each position along this polarization gradient corresponds to a potential energy, depending on the magnetic sub-state. In the most simple picture, the potential- and kinetic energy of an atom, that moves through this sinusoidal potential, transform into each other along the way. Due to the  $m_F$ -dependence of the potential, the potential can be adjusted so that a photon will preferably be absorbed by an atom with high potential- and low kinetic energy. The re-emission of the photon will bring the atom in a state of low potential energy while the kinetic energy is already low. Hence, the atoms are slowed down.

The temperature limitation of this process is the recoil temperature and corresponds to the recoil energy of an atom after the emission of a photon. It reads

$$T_r = \frac{(\hbar k)^2}{2mk_B} \,. \tag{2.39}$$

A discussion of cooling below the recoil temperature can be found in [Asp88] and especially with Raman transitions in [Kas92].

## 2.5 The magnetic trap

#### 2.5.1 Operation principle



Fig. 2.9: Potential lines for the magnetic moments being parallel (blue), antiparallel (red) and orthogonal (green) to the magnetic field: the atoms with antiparallel magnetic moments ( $g_f m_F > 0$ ) are caught in the center of the trap, the ones with orthogonal magnetic moments ( $g_f m_F =$ 0) don't feel the trap and the ones with parallel magnetic moments are pushed out of the trap.

The spin of the electron is aligned with its magnetic dipole moment. Therefore the total spin of an atom can result in an atomic magnetic dipole moment  $\vec{\mu}$ as well (see section 2.3.1). The energy of this dipole moment in a magnetic field depends on the magnetic field strength and the relative orientation of the dipole moment with respect to the magnetic field

$$E_Z = -\vec{\mu}\vec{B} = m_F g_F \mu_B B . \qquad (2.40)$$

Here,  $m_F$  denotes the magnetic quantum number of the hyperfine state F with respect to the quantization axis,  $g_F$  the Landé-g-factor and  $\mu_B$  the Bohrmagneton.

As seen in figure 2.9 the energy increases, decreases or stays constant with increasing field for  $m_F g_F$  being positive, negative and zero, respectively. As all particles try to minimize their energy, the ones with positive  $m_F g_F$  move to regions with low magnetic fields (weak-field-seekers) while the ones with negative  $m_F g_F$  move to regions with high magnetic fields (high-field-seekers) and the ones with  $m_F g_F = 0$  do not interact with the field. As in three dimensions only local minima in a static magnetic field can be generated, only weak-field-seekers can be trapped magnetically.

If a weak-field-seeker would simply flip the spin, the atom would gain energy by leaving the field, but in this case the angular momentum would not be conserved. This is the same principle that keeps a gyroscope upright: the gyroscope would gain potential energy by stopping its rotation and toppling down, but due to angular momentum conservation it keeps on turning.

A case where the atomic spins can flip is at a vanishing magnetic field (see Majorana flips in section 2.6).

The atomic spins can also flip when they move so fast that the magnetic dipoles cannot follow the magnetic field any more. To avoid these flips the change of the angle  $\phi$  between the dipole moment and the magnetic field must be smaller than the Larmor frequency  $\omega_L$ , that is the precession of the magnetic moment around the direction of the local magnetic field:

$$\frac{d\phi}{dt} = \omega_t < \omega_{Larmor} = \frac{g\mu_B}{\hbar}B \tag{2.41}$$

In summary, the important conditions for the magnetic field are: it must increase in every direction and must have a small but non-vanishing offset field in the trap center. Furthermore, a very high gradient respectively curvature are recommended for a strong confinement. These conditions are satisfied by several coil configurations. One of them, the so-called clover leaf trap (see figure 2.10), which is used in this experiment, will be discussed here: twelve coils, arranged in two x-y-planes with the same distance from the center of the trap, create a three-dimensional confinement. Furthermore, the optical access to the chamber is relatively high because all the coils are in two planes.



Fig. 2.10: The figure illustrates a clover leaf trap: the pinch coils (green), being connected in a Helmholtz configuration create a strong curvature along the z-axis and hence a confinement in this direction; the offset coils (red), being operated in the 'opposite' direction, leave the curvature of the pinch coils nearly unchanged but lower the offset field close to zero. The clover leaves (blue),

where always the two opposing leaves are operated in an Anti-Helmholtz configuration and always two adjacent leaves are flown through in opposite directions, create a strong confinement in the radial direction (see figure 2.11).



Fig. 2.11: Understanding the clover leaf trap: the current through a leaf can be seen as an inner current and an outer current flowing in opposite direction, as indicated in figure 2.10. This figure shows only the inner currents (blue), because they are mainly responsible for the magnetic field in the relevant area of the trap, due to the proximity of the trap center and the inner parts of the leaves. The currents 1 and 2 in two opposing leaves create the magnetic field 1 (green) that is orthogonal to the currents and points into the center of the trap (right-hand-rule). The other pairs of opposing currents act the same way. The complete field in the trap center is shown in figure 2.12.

The magnetic field along the z-axis is created by the so-called pinch coils: in the center of each coil the magnetic field reaches its maximum and decreases towards the middle of the trap. For a strong confinement a strong field curvature is needed, but this also results in unwanted high offset fields. The strong curvature is created by the pinch coils and the offset coils lower the offset of the field, while their nearly homogeneous field leaves the curvature nearly unchanged. Thus a weak but still positive offset field can be realized. For the confinement in the x-y-plane the clover leaves are used: they create a linear quadrupole field, whose field strength increases linearly in the radial plane, being zero in the center (figure 2.12).

Hence, the magnetic field is increasing in every direction with a strong gradient respectively curvature and thus strong confinement and also a low but non-vanishing offset field.

The magnetic field in this kind of trap can be approximated by [Pri83]

$$\vec{B} = B_0 \begin{pmatrix} 0\\0\\1 \end{pmatrix} + B' \begin{pmatrix} x\\-y\\0 \end{pmatrix} + \frac{B''}{2} \begin{pmatrix} -xz\\-yz\\z^2 - \frac{1}{2}(x^2 + y^2) \end{pmatrix} , \qquad (2.42)$$

where  $B_0$  denotes the field offset, B' the gradient in radial direction and B'' the field curvature. Expanding  $B = |\vec{B}|$  into a three-dimensional power series and putting terms up to the second order into equation 2.23 yields a harmonic approximation of the potential of the trap

$$U = E_Z = \frac{g_F m_F \mu_B}{2} \left[ \left( \frac{B'^2}{B_0} - \frac{B''}{2} \right) (x^2 + y^2) + B'' z^2 + B_0 \right] .$$
(2.43)

The strength of the confinement can be expressed using the trap frequencies of the anisotropic harmonic potential

$$\nu_{\rho} = \frac{1}{2\pi} \sqrt{\frac{g_F m_F \mu_B}{m}} \left(\frac{B'^2}{B_0} - \frac{B''}{2}\right)$$
(2.44)

$$\nu_z = \frac{1}{2\pi} \sqrt{\frac{g_F m_F \mu_B}{m} B''} , \qquad (2.45)$$

where  $\nu_{\rho}$  and  $\nu_z$  denote the trap frequencies in radial and axial direction, respectively.



Fig. 2.12: The quadrupole field that is created by the cloves leaves. The field in y-direction points into the trap center while the one in x-direction points out of it, but the absolute values are equal at the same distance from the center.

#### 2.5.2 Mode matching and compression

In a first approximation, the shape of the MOT is spherical while the shape of the magnetic trap is ellipsoidal. For transferring the atoms from the MOT into the magnetic trap, the shape of the magnetic trap can be altered to be spherical as well and changed 'back' after the transfer. Furthermore, the potential in the two traps should be equal: if the magnetic potential is too shallow too many atoms will be lost while the temperature increases for a too deep trap. By performing this 'mode matching' the transfer can be optimized. There exist two possibilities for changing the shape of the magnetic trap:

One possibility is to lower the currents through the clover leaves but in this case the atoms will be lost due to the instability points: the instability points are hyperbolic points in the magnetic field. If atoms reach these points they can leave the trap on the other side of them. These points are usually outside the trap but in the case of low clover leaf currents they move towards the trap center and the atoms will leave the trap there.



Fig. 2.13: The magnetic field in axial and radial direction: when the field offset in axial direction reaches zero, the harmonic part of the field in radial direction decreases and thus the field gradient in radial direction becomes steeper.

The other possibility for mode matching is to raise the offset field of the magnetic trap (see. figure 2.13). The potential in axial direction does not change remarkably but in radial direction it changes from linearly increasing to harmonic and becomes shallower. Assuming a Gaussian shape, the density distribution in the magnetic trap can in analogy to the MOT-equations 2.30, 2.32 and 2.33 expressed by its widths

$$\sigma_i = \sqrt{\frac{k_B T}{8\pi^2 m \nu_i^2}} , \qquad (2.46)$$

where  $\nu_i$  denotes the trap frequency in the respective direction *i*.

To derive the Gaussian shape of the density distribution in the magnetic trap, the potential in the relevant region must be harmonic. For an optimized mode matching, the atomic cloud usually fits into the the harmonic part of the potential, which yields  $\sigma_{\rho} \approx B_0/B'$ . Putting this condition into equation 2.46 and using the equation for the trap frequency (equation 2.44) and the valid approximation  $B''/2 \ll B'^2/B_0$  yields the relation between the temperature and the field offset:

$$B_0 \approx \frac{k_B T}{g_F m_F \mu_B} \tag{2.47}$$

All other magnetic field parameters for an atomic cloud at the temperature T and the widths  $\sigma_i$  can be calculated using equations 2.44, 2.45 and 2.46:

$$B'' = \frac{k_B T}{g_F m_F \mu_B \sigma_z^2} \tag{2.48}$$

$$B' = \frac{k_B T}{g_F m_F \mu_B} \sqrt{\frac{1}{\sigma_{\rho}^2} + \frac{1}{2\sigma_z^2}}$$
(2.49)

$$B_{\rho}'' = \frac{B'^2}{B_0} - \frac{B''}{2} = \frac{k_B T}{g_F m_F \mu_B \sigma_{\rho}^2}$$
(2.50)

Once the atoms are trapped, the field offset has to be lowered again to increase the phase space density. An additional effect that occurs during this compression is that the field in radial direction becomes linear (see figure 2.13). It has been shown that this effect leads to an additional increase in the phase space density of a factor  $e \approx 2.718$  because of a different density of states in the two potential types [Sue98].

#### 2.5.3 Evaporative cooling

The most efficient way to cool the atoms in a magnetic trap is to evaporate them (figure 2.14): atoms, exceeding a given energy, are taken out of an ensemble in thermodynamical equilibrium. The remaining sample is not in equilibrium any more, but will thermalize after 3 - 5 elastic collisions [Sno89]. Then, the temperature and the phase-space density of this ensemble have decreased.



Fig. 2.14: Cooling an atomic ensemble evaporatively: plot (a) shows the distribution function of a thermodynamically balanced atomic ensemble. In plot (b) the atoms with energies higher than  $E_{cut}$  are taken out of this ensemble. The remaining atoms are initially not in thermodynamical equilibrium but they thermalize after 3-5 elastic collisions and the temperature has decreased (plot (c)).

Due to the removal of the atoms with high energy there occurs a loss in the number of atoms in the ensemble. But it has been shown, that the loss of only few atoms can result in a considerable increase of the phase space density [And95].



Fig. 2.15: An atomic ensemble in a magnetic trap with decreasing potential depth: the atoms with an energy  $E > E_{cut}$  can 'jump' over the rim. The temperature T yields the average energy of the atoms  $E_A = k_B T$  Figure 2.15 shows the potential, felt by the atoms during the evaporation. The potential follows the (usually) harmonic curve until it reaches the energy  $E_{cut}$  and becomes then zero.  $E_{cut}$  is then equivalent to the potential depth. Obviously, atoms, whose total energy is higher than the potential depth, can leave the trap. The energy  $E_{cut}$  must always be higher than the average energy in the atomic ensemble, given by its temperature via  $E_A = k_B T$  or too many atoms would be lost at once.

When the ensemble has thermalized, the potential depth must be lowered (again) to continue the cooling mechanism.  $E_{cut}$  is usually defined in terms of the temperature

$$E_{cut} = \eta k_B T , \qquad (2.51)$$

where  $\eta$  denotes a cutting parameter.

The steps of lowering the potential depth and thermalization can be discrete but usually the potential depth is lowered continuously, until the desired temperature is reached.

For  $\eta$  being relatively small (e.g. ~ 1), the potential is lowered fast and the atoms are cooled down fast. But in this case also slow atoms, being at the trap border, can leave the trap, leading to great atom losses.

For  $\eta$  being relatively high (e.g. ~ 10), the potential is lowered relatively slow and the atoms are cooled down slow. The atom losses in this case are relatively low, but due to the slowly decreasing potential, there is a long time for the atoms to collide with the background gas (see section 2.6).



2.16:Evaporation Fig. using radio frequencies. At the positions  $r_{cut}$  and transitions into  $-r_{cut}$ lower magnetic substates are induced. The states with  $m_F \leq 1$  are not trapped any more. The plot on top of the figure shows  $_{\mathrm{the}}$ probability distribution of finding an atom along the axis. For  $|x| > r_{cut}$  this probability is zero.

In magnetic traps, the evaporation is done easiest using radio frequency waves (see figure 2.16). Equation 2.23 yields the transition frequency between two atomic substates with  $\Delta m_F = \pm 1$  in the magnetic field  $\vec{B}(\vec{r}_{cut})$ 

$$h\nu_{rf} = \Delta E_Z = g_F \mu_B |\vec{B}(\vec{r}_{cut})| . \qquad (2.52)$$

Only the atoms having at least the Zeeman energy  $E_Z(\vec{r}_{cut})$  can perform this atomic transition and leave the trap.

## 2.6 Cold collisions

In a MOT the collisions of cold atoms with other cold atoms are not necessary for cooling while in a magnetic trap they are necessary for evaporative cooling. But collisions also involve loss mechanisms for the atoms. These collisions can be treated quantum mechanically as a scattering problem [Bur02].

#### Elastic collisions

Elastic collisions can occur between two trapped atoms. In effect they lead to a thermalization of the atomic cloud which is very important for the evaporative cooling, which uses the effect of thermalization. These collisions are called good collisions because they don't involve a loss of atoms.

The wave functions of the scattered atoms can be expanded into partialwaves with the angular momentum l. The angular momentum conservation leads to an angular momentum barrier that can't be overcome by atoms at low temperatures (due to their low energy) and therefore only collisions with l = 0 are possible. The cross-section for these collisions is given by

$$\sigma = 8\pi a_s^2 \,, \tag{2.53}$$

where  $a_s$  denotes the scattering length. The scattering length is used because it reflects the collisional properties of the atomic species (see e.g. [Bur02]). The rate of the elastic collisions is given by

$$\Gamma_{el} = n\sigma v \propto n\sqrt{V} \,, \tag{2.54}$$

where n denotes the particle density, v the thermal velocity and V the volume of the atomic cloud. The elastic collision rate decreases with decreasing temperature.

#### **Spin-Flip** collisions

During the collision of two atoms dipolar relaxation can occur: one flips its spin, and the energy, that is set free, becomes transformed into kinetic energy, which can throw the atom out of the trap [Ses89].

Similar is the effect that occurs when two atoms with  $m_F = 1$  hit each other: one can change its magnetic quantum number to  $m_F = 0$  while the other one changes its to  $m_F = 2$ . If this spin relaxation occurs in a magnetic trap, the atom with  $m_F = 0$  will leave the trap.

#### Hyperfine state changing collisions

Not only the magnetic quantum number  $m_F$  can change in a collision: the quantum number of the hyperfine state F can change as well. For example during the collision of two atoms with F = 2 and  $m_F = 1$  one of them can change its hyperfine state to F = 1 while  $m_F$  and the quantum numbers of the other atom do not change. The collision rate of spin- and hyperfine state changing collisions is proportional to the particle density n

$$\Gamma_{2b} = \beta n , \qquad (2.55)$$

where  $\beta$  denotes a constant that depends on the magnetic field and the magnetic quantum numbers of the involved atoms. Its value has been theoretically determined to be in the region of  $3 - 9 \cdot 10^{-15} \text{cm}^3/\text{s}$  [Boe96].

#### Three-body losses

Due to momentum- and energy conservation, no molecules can be formed by a collision of two atoms but when three atoms hit each other at the same time, they can form molecules which will gain enough kinetic energy to leave the trap.

The collision rate for this process reads

$$\Gamma_{3b} = Ln^2 \tag{2.56}$$

and is proportional to the square of the particle density. The value of the constant L has been determined to  $L = 4 \cdot 10^{-29} \text{cm}^6/\text{s}$  [Bur97].

#### Majorana flips

The magnetic dipoles of the atoms in the magnetic trap follow the potential adiabatically but when the potential changes too rapidly they can't follow any more. This effect can also occur when the magnetic field becomes zero but is usually suppressed by a non-vanishing offset field. During these Majorana flips the magnetic quantum number changes and the atoms are lost (see e.g. [Bin02]).

#### Background gas collisions

Although the traps are operated in ultra high vacuum (UHV) there are still hot atoms in the chamber, the so-called background gas. These atoms have temperatures of  $\approx 300 \text{ K}$  and if one of the trapped atoms is hit by a background gas atom it will be thrown out of the trap. This effect limits the lifetime in the trap. The lifetime can be calculated by

$$\tau_D / [s] \approx 8 \cdot 10^{-9} \frac{1}{p / [\text{mbar}]},$$
 (2.57)

where p denotes the pressure in the chamber [Met99]. The collision rate is given by  $\Gamma_D = 1/\tau_D$ .

#### Collisions with the atomic beam

Collisions between the atoms of the Zeeman slower beam and the trapped atoms are only possible during the loading of the MOT because the atomic beam is shut off mechanically when the MOT is loaded. Most atoms from the atomic beam are so fast that atoms in the MOT gain enough energy to leave the trapping area by such a collision.

#### Radiative collisions

During a collision of two atoms, the atoms experience molecular potentials. If a photon is absorbed during this collision, the atoms can gain energy due to a change in the molecular potential. This potential energy can be transformed into kinetic energy. If a photon is emitted after gaining this kinetic energy, the kinetic energy becomes further increased and the atoms can leave the trap, although the emitted photon has less energy than the absorbed one [Ses89]. Because radiative collisions occur only in the presence of light, they are only relevant in the MOT and limit the achievable density.

#### Imperfect cooling cycles

Imperfect cooling cycles have not much to do with collisions but they are a loss mechanism and so they are mentioned here.

Although the atoms are treated as two-level atoms they have more atomic levels which have to be taken into account. The probability for the excitation into another level depends on the atomic level scheme and the laser tuning. It is usually far less than into the desired one but it is not zero. Once being in another excited state the atom can decay into another state for which the probability of absorbing another cooling photon can go to zero. The atom can reach such a state also when the probability to decay from the desired excited state into this state is not zero.

Losses due to imperfect cooling cycles can in general always be suppressed by using appropriate repumping lasers, which pump the atoms back into the desired state. Atoms which are not pumped back must be treated as lost.

#### 2.6.1 Effective evaporation

All the collisions mentioned in section 2.6 (except the elastic ones) are called 'bad collisions' because they lead to atom losses. For achieving a BEC by evaporative cooling there are about 500 elastic collisions needed, depending on  $\eta$  (2.5.3) and the initial conditions [Ket96]. Hence the ratio of good ( $\Gamma_{el}$ ) and bad collisions that must be considered in the magnetic trap ( $\Gamma_D$ ,  $\Gamma_{2b}$  and  $\Gamma_{3b}$ ) must be higher than 500:

$$R(n,T) = \frac{\Gamma_{el}}{\Gamma_D + \Gamma_{2b} + \Gamma_{3b}} \ge 500 \tag{2.58}$$

More information on R(n,T) and how the atom number in the condensate can be maximized can be found in [Hei02].
## 2.7 The dipole trap

### 2.7.1 The dipole force

When the light forces acting on an atom are derived properly, it can be shown that the spontaneous force is not the only force acting on the atoms. The other force is based on the interaction of the dipole moments, induced by the light field, and the intensity gradient of the light field. This force is therefore called dipole force. For a non-vanishing intensity gradient the dipole force reads [Mey01]

$$F_{dip} = -\hbar \delta \frac{I/I_0}{1 + I/I_0 + (2\delta/\Gamma)^2} \frac{\nabla \omega_R}{\omega_R} , \qquad (2.59)$$

where  $\omega_r$  denotes the Rabi-frequency, which describes the coupling of the light field and the atom, depending on the strength of the light field.

For  $\delta < 0$  (red detuning) the force pulls the atoms into the field while for  $\delta > 0$  it pushes the atoms out of the field.

In contrast to the spontaneous force, the dipole force is not limited by the saturation. For a more detailed description of the dipole force see e.g. [Kro02].

### 2.7.2 Operation principle



Fig. 2.17: The figure shows a focussed Gaussian beam and the potential  $U_{pot}$  of the dipole force, that is created by this beam.

To create a dipole trap a strong red-detuned laser is focussed on an atomic ensemble. The dipole force of this beam pulls the atoms into the center of the beam. As shown in figure 2.17 the potential of this force is very anisotropic. This can be avoided by overlapping two orthogonal beams at the same position, creating a strong confinement in all spatial directions.

This effect occurs also in a MOT: the MOT lasers act on the atoms also due to the dipole force and therefore a stronger detuning pulls the atoms additionally (to the spontaneous force) into the trap. Hence, the atom number in the MOT can be increased but the temperature increases as well (equation 2.22).

## 2.8 Sympathetic cooling

Sympathetic cooling means that two atomic species are trapped at the same position where one species is cooled down directly (e.g. by evaporative cooling) and the other one is being cooled by elastic collisions with the cold species. The great advantage of this technique is that there is no loss in the atom number of the cooled species and hence an initial condition of a low atom number can nevertheless lead to a sufficient number of cold atoms. The disadvantage lies in the fact that the cooling efficiency is very sensible to the collisional properties between the two species. In the case of rubidium and ytterbium these properties are yet completely unknown. But this also opens the field of studying diatomic collisional properties.

## 2.9 Properties of rubidium



Fig. 2.18: An overview of the periodic table of the elements where the positions of rubidium and ytterbium are marked.

Figure 2.18 shows the periodic table of the elements and where rubidium can be found: it is one of the alkali metals. Its melting point is  $39.3 \,^{\circ}$ C at 1 bar ambient pressure, the boiling point  $688^{\circ}$ C. The relative isotopic abundance of <sup>85</sup>Rb is 72.2% while the one of the only other natural occurring stable isotope <sup>87</sup>Rb is 27.8%. Both isotopes are bosons and the nuclear spins of them are I = 5/2 (<sup>85</sup>Rb) and I = 3/2 (<sup>87</sup>Rb). Hence, both of them have a magnetic hyperfine structure. <sup>87</sup>Rb is used in this experiment because it has better collisional properties.



Fig. 2.19: The level scheme of <sup>87</sup>Rb showing the MOT- and the repumper transition and information on the MOT transition [Gol02]. As shown in figure 2.19 the transition at 780.247 nm between the states  $5S_{1/2}$ , F = 2 and  $5P_{3/2}$ , F = 3 is used for the MOT. Once the atoms are in the state  $5P_{3/2}$ , F = 3 they can only decay into the state  $5S_{1/2}$ , F = 2. But due to the distance between the  $5P_{3/2}$  states F = 2 and F = 3 of only 267 MHz, the atoms in the state  $5S_{1/2}$ , F = 2 can also become excited into the state  $5P_{3/2}$ , F = 2. Once they are in this state, they can decay into the  $5S_{1/2}$  states F = 1 and F = 2. Due to the distance of 6.835 GHz between the  $5S_{1/2}$  states F = 1 and F = 2 the atoms in the  $5S_{1/2}$ , F = 1 cannot be excited by the MOT laser anymore and are lost if no repumper is used. A repumper pumps these atoms back into the state  $5P_{3/2}$ , F = 2 (F = 3 is not possible due to angular momentum conservation) and thus the atoms are brought back into the cooling cycle.

Because of their paramagnetic ground state the rubidium atoms can be trapped magnetically.

### 2.10 Properties of ytterbium

Figure 2.18 shows the periodic table of the elements and where ytterbium can be found: it is one of the rare earths and has a level scheme that resembles the one of the alkaline earth metals. It has five stable bosonic and two stable fermionic isotopes. Their relative natural occurrence is shown in table 2.1.

Isotope	Relative natural abundance / %	Nuclear spin	Type	
168	0.1	0	bosonic	
170	3.1	0	bosonic	
171	14.3	1/2	fermionic	
172	21.9	0	bosonic	
173	16.1	5/2	fermionic	
174	31.8	0	bosonic	
176	12.7	0	bosonic	

Tab. 2.1: Relative natural abundance, nuclear spin and quantum statistical type of the seven stable ytterbium isotopes.

Only the two fermionic isotopes have a non-vanishing nuclear spin and hence a magnetic hyperfine structure (in the excited state).

As shown in figure 2.20 the transitions at 398.9 and 555.8 nm between the ground state  $6s^{2}{}^{3}S_{0}$  and the excited states  $6s6p{}^{1}P_{1}$  and  $6s6p{}^{3}P_{0}$ , respectively, can be used as a MOT transition. The blue transition at 398.9 nm has the advantage of being very broad, resulting in a strong spontaneous force. Therefore the atoms can be decelerated very effectively and relatively high velocities can be trapped in the MOT (23 m/s). The other transition at 555.8 nm is very narrow, resulting in a very low Doppler temperature of only  $4.4 \,\mu$ K.

This combination can e.g. be used to slow and trap the atoms using the blue transition, while they can be transferred into the green MOT later, where they can be cooled further down. Once the atoms are in the excited state



 $6s6p {}^{1}P_{1}$  they decay into the states  $6s5d {}^{3}D_{0}$  and  $6s5d {}^{3}D_{1}$  which decay into the states  $6s6p {}^{3}P_{0}$ ,  $6s6p {}^{3}P_{1}$  and  $6s6p {}^{3}P_{2}$ . Once they end up in the state  $6s6p {}^{3}P_{1}$  they decay back into the ground state. But if they end up in one of the states  $6s6p {}^{3}P_{0}$  or  $6s6p {}^{3}P_{2}$ , the transition probability into another state is low enough to treat them as lost. But the chance of ending up in one of these states is only  $1 : 10^{-7}$  and thus no repumper is needed.

As the ground state of ytterbium is diamagnetic the atoms in this state cannot be trapped magnetically but it is possible to trap them magnetically in the metastable state  $6s6p^{3}P_{2}$ .

# 3. Experimental setup

## 3.1 Main chamber



Fig. 3.1: A model of the main chamber showing all relevant parts. A picture of this can be seen in figure 3.3.

A vacuum chamber must always be designed to fit the magnetic coils. Because the clover leaf trap is used in this experiment (see section 3.6.1) the chamber has two buckets, where the coils fit into, as shown in figure 3.1. Each of these two buckets has a little window ( $\emptyset 2.54 \text{ mm}$ ) in its center where the axial lasers can enter the chamber.

The extraordinary feature of this chamber are the twelve flanges in radial direction, where 2 of them are used to attach the Zeeman slowers and ten are

covered with un-coated windows. Two of them are on the opposite side of the slowers to shoot the lasers against the atoms flying towards the chamber. The angle between the two slowers is 90° to leave enough space for two other 90° flange crosses, each existing of four flanges. The four main flanges, having inner diameters of 6.8 cm, are aligned orthogonal to the table and are currently used for the imaging system and the cameras observing the MOT. The other four, having inner diameters of 3.8 cm, fit into the space between the slowers (and the opposite flanges) and the main flanges. The angle between them is also 90° and they are turned 34° counterclockwise with regard to the main flanges from the point of view in figure 3.2. They are mainly used to operate both MOTs. The slowers and their opponent flanges are turned 30° clockwise with regard to the main flanges.





The long tube below the main area is connecting the main chamber to the pumps. In the foreground of figure 3.1 is a valve where a turbo and a roughing pump can be attached. These pumps create a vacuum in the order of  $10^{-7}$  mbar. Once this vacuum is created, the ion getter pump in the right foreground of figure 3.1 is turned on and creates a vacuum in the order of  $10^{-9}$  mbar. This pump ionizes the atoms in the trap with high voltages and pulls them on spiral paths out of the chamber, using magnetic fields. It keeps running all the time while the titanium-sublimation pump is turned on only every few months. The latter one emits titanium into the chamber which gets stuck at the inside of the walls. Once an atom hits the wall it becomes 'glued' to the titanium atoms and thus an ultra high vacuum of roughly  $10^{-11}$  mbar is created.

The tube and the connection to the main part of the chamber have an inner diameter of about 15.2 cm to allow a sufficient flux of atoms towards the pumps [Ede85].

The cooling shield is used to 'collect' the fast rubidium atoms of the Zeeman slower, which don't become trapped in the MOT and end up on the window on the opposite side of the slower. Due to the colder temperature of the shield the atoms condense on it. The cooling shield can also be heated to evaporate the atoms into the chamber where they can be pumped away. During this procedure the pressure in the chamber will increase and so this has to be done in the downtime between experiments. At the moment this procedure does not have to be performed because no rubidium can be seen on the window beside the cooling shield.



Fig. 3.3: A picture of the main chamber. Most of the chamber cannot be seen due to the framework holding the slowers, ovens and opto-mechanics.

## 3.2 Rubidium oven

The rubidium atoms are in a glass cuvette in the nipple at the end of the oven (see figure 3.4). At at temperature of 20 °C the vapor pressure is  $p(20^{\circ}\text{C}) = 3.4 \cdot 10^{-7}$  mbar [Lid01], which is not high enough to produce a sufficient flux of atoms to load the MOT in the desired time of 1-10 seconds (see section 3.3). Hence the atoms have to be heated and in the experiment a temperature of  $\approx 200^{\circ}\text{C}$  showed to be sufficient.



Fig. 3.4: A model of the rubidium oven showing all relevant parts.

Once the atoms are evaporated they move through a nozzle which has to be heated as well to avoid a blockage of the pinhole. To the following four- and six-way crosses an ion getter pump, a valve for the turbo and the roughing pump, a mechanical shutter and a cooling shield are connected. The shutter is connected to a step motor outside the oven by a rotary motion feedthrough. It can cut off the atomic beam when the MOT is fully loaded.

The cooling shield is cooled down to temperatures around  $7 \,^{\circ}$ C. The rubidium atoms, which are not leaving the oven directly towards the slower, condensate on the shield to prevent a fast filling of the ion getter pump.

There is also a window with an attached camera to see if the laser of the Zeeman slower makes its way all up the slower.

Finally there is a differential pumping tube that allows a pressure difference of a factor  $10^4$  between the main chamber and the oven. Because the atoms leave the oven through this pumping tube it has to be adjusted to point into the middle of the chamber.

For the calculation of the differential pumping tube the formula for the conductance C of a molecular current through the tube was used. For long tubes (length  $\gg$  radius) it reads [Ede85]

$$C = \frac{4}{3} \frac{r^3}{l} \left(\frac{2\pi k_B T}{m}\right)^{1/2} , \qquad (3.1)$$

where r denotes the inner radius of the tube and l its length. A pump with a suction S = Q/p pulls a molecular current Q = V/t through the tube. The equation for this current through the tube, where  $p_1$  and  $p_2$  are the pressure on either side of the tube reads

$$Q = C(p_1 - p_2). (3.2)$$

Substituting these equations into each other yields the pressure difference which can be maintained by the tube:

$$\frac{p_1}{p_2} = 1 + \frac{S}{C} \tag{3.3}$$

Using this equation, the desired pressure ratio of  $\approx 10^{-4}$  leads to values of l = 120 mm and r = 5 mm. A similar pressure ratio was achieved in the experiment.

Additionally there is a gate valve between the oven and the slower that can be closed to open either the main chamber or the oven (e.g. for refilling the rubidium), while maintaining the vacuum in the other part.

### 3.3 Rubidium slower

There exist several ways to load a magneto-optical trap. An overview of these possibilities is given in [Bat01]. In this experiment Zeeman slowers are used because they produce a sufficient flux of cold atoms and are relatively easy to build and handle. The functional principle of a Zeeman slower is shown in section 2.3.

#### Magnetic field considerations

The maximum deceleration of the atoms is given by

$$a = \frac{\vec{F}_{sp}}{m} , \qquad (3.4)$$

where m denotes the mass of the atom and  $\vec{F}_{sp}$  is defined as in equation 2.18. This results in a maximum increase of the magnetic field. If that becomes too steep, the atoms cannot be decelerated fast enough to stay in resonance with the field and would leave the slower at a velocity, too high to become trapped in the MOT. Depending on the length of the slower, the maximum magnetic field steepness yields a maximum magnetic field. This field has to compensate the difference in the Doppler shift of the slow and the fast atoms. Therefore, the length of the slower determines the maximum velocity of the atoms which can be slowed. A slower length of 85 cm showed to be long enough to slow a sufficient amount of atoms (see also the following calculations).

#### Temperature dependence of the atomic flux

The pressure of the atoms in the oven is the vapor pressure of rubidium, which depends on the temperature [Lid01]:

$$p(T) = 10^{5.006 + 4.312 - \frac{4040}{T/K}} \,\mathrm{pa} \tag{3.5}$$

The atoms are leaving the oven into a cone (which is rotationally symmetric around the nozzle), whose beam spread angle  $\Theta$  is given by [Wut92]

$$\frac{N_{Rb87}}{t} = 0.278 \sqrt{\frac{2}{\pi m_{Rb} k_B T}} \ p(T) A \int_{0}^{\Theta} \sin \theta \, d\theta , \qquad (3.6)$$

where  $m_{Rb}$  denotes the mass of rubidium in its natural abundance and A the area of the nozzle. The equation must be multiplied by 0.278, the relative natural abundance of <sup>87</sup>Rb because only this isotope is of interest here. The beam spread angle  $\Theta$  is given by the geometry, shown in figure 3.5.



Fig. 3.5: The shape of the atomic beam from the oven to the MOT (not to scale). The beam expands along all its way but the spread increases towards the MOT because of the lower longitudinal velocity.

The atoms flying inside the shape of the atomic beam in figure 3.5 will directly reach the main chamber while the others will hit the slower, the cooling shield or another part of the vacuum system and must be treated as lost.

The velocities inside the relevant beam are Maxwell-distributed. Multiplying the Maxwell-distribution with the velocity v yields the velocity-distribution of the flux [Wut92]

$$f(v) = \left(\frac{m}{k_B T}\right) v^3 e^{-mv^2/2k_B T} , \qquad (3.7)$$

where v denotes the velocity in longitudinal direction. Assuming a Gaussian shaped beam that expands during the flight of the atoms, especially because of the decreasing longitudinal velocity in the slower and the low longitudinal velocity on the way from the slower to the MOT, the width of the Gaussian beam is given by [Kro02]

$$\sigma_{MOT\,i} = \left\{ \left[ \frac{1}{2\sqrt{2}} \left( \varnothing_{source} + 2\Theta \left( d_{source} + L + \frac{(v_i - v_{end})^2}{2a_{eff}} \right) \right) \right]^2 + \left[ \frac{2}{3a_{eff}} \sqrt{\frac{\hbar k}{m_{Rb87}}} (v_i - v_{end})^{3/2} \right]^2 + \left[ \left( \Theta v_i + \frac{\hbar k}{m_{Rb87}} \sqrt{\frac{m(v_i - v_{end})}{\hbar k}} \right) \frac{d_{MOT}}{v_{end}} \right]^2 \right\}^{1/2}, \quad (3.8)$$

where  $\emptyset_{source}$  denotes the diameter of the nozzle, k the magnitude of the wave vector,  $m_{Rb87}$  the mass of the <sup>87</sup>Rb atoms (because only these ones are of interest),  $v_i$  the respective velocity,  $v_{end}$  the velocity at which the atoms leave the slower and  $a_{eff}$  the deceleration of the atoms, given by

$$a_{eff} = \frac{F_{sp}}{m_{Rb87}} = \frac{\hbar k \gamma_p}{m_{Rb87}} . \tag{3.9}$$

The scattering rate  $\gamma_p$  is defined as in equation 2.18.

By a two-dimensional integral over the transverse Gaussian profile of the atomic beam the ratio of atoms ending up in the MOT can be calculated. This ratio must be calculated for each initial velocity up to the maximum velocity that can be slowed, depending on the slower detuning (404 m/s). This ratio must be weighted with the probability for an atom to leave the oven at this velocity (equation 3.7).

Assuming resonant laser light ( $\delta = 0$ ) respective a perfectly compensating slower field ( $\omega_D = 0$ ), a capture region (diameter) of 1.86 cm (see section 4.1.6), a saturation ratio of  $I/I_0 = 20$ , a final velocity of  $v_{end} = 20$  m/s and the values shown in figure 3.5 yields a ratio of  $\approx 14$  %. Increasing the oven temperature by 20°C decreases the ratio by  $\approx 12$  % (respective the 14%). The theoretical flux of atoms is shown in figure 3.6.



Fig. 3.6: Temperature dependence of the atomic flux of slow atoms into the MOT.

It can be seen that increasing the oven temperature results in an increased flux of slow atoms but in this ideal case already a temperature of  $100^{\circ}$ C is sufficient.

#### Setup

Because the excited rubidium state  $5P_{3/2}$  splits off into four hyperfine substates (see section 2.9), the atoms in the MOT can be excited by the red detuned beam of the slower laser as well. Therefore the detuning of the slower laser must be as far as possible or otherwise it would 'blow' the atoms out of the MOT. This is given in the case of an increasing field geometry, while the disadvantage is that the magnetic field is due to the slower coils still relatively high at the MOT-position. But this field can be mostly compensated by compensation coils, which are coiled around the flanges of the main chamber. For clearness of the picture they are not shown in figure 3.1 but they can be seen in figure 3.3: there is a coil around each of the two buckets to compensate the field in axial direction (I = 84.5 mA), one coil around the connection between the main chamber and the pumping tube acting in gravity direction (I = 7.1 A) and one around the three flanges on the right side of the chamber (I = 0 A), because the magnetic fields of the two slowers nearly compensate each other in this direction in the center of the trap) to compensate the field in the left-right radial direction (according to figure 3.1). Each coil consists of 40 windings.

Figure 3.7 shows a model and a picture of the rubidium slower used in this experiment. The increasing field geometry (increasing diameter of the slower coil with increasing distance from the oven) can be easily seen and also some broad parts at constant distances. Here some spacers were used for an easier winding of the slower. A field measurement using a Hall probe (type 634SS2) showed an insufficient field at these positions and additional coils were used to compensate this insufficiency. For the coils a copper wire with an outer diameter of 3 mm was used. The wire is hollow inside (inner diameter 1.5 mm) and flown through by water to cool the slower. Outside it was wrapped with an insulating band (Kapton) to avoid shortcuts.



Fig. 3.7: A model and a picture of the rubidium slower. The increasing field geometry and the compensation coils (broad parts) can be seen.

The outer diameter of the wire became then  $3.3 \,\mathrm{mm}$ . The calculations used an outer diameter of  $3.5 \,\mathrm{mm}$ , but this was easily compensated by winding the slower not as tight as possible.

The wire was glued together using 'UHU endfest' epoxy adhesive. The temperature of the slower can be monitored by LM35DZ temperature sensors, which have been glued on the outside of the slower and are connected to temperature displays.

#### Calculations

For the slower calculations a computer program was written in Matlab [Kro02]. First an increasing field, being zero at the oven and compensating the Doppler shift of the slowed atoms, was designed (see figure 3.8). This field was tested in a 'flight simulator' program, calculating the behavior of atoms leaving the oven at different velocities and for different laser detunings (see figure 3.9). This simulation yielded an optimal detuning of 442 MHz.

When an optimal field was found the winding pattern of the slower was designed by a computer simulation using Biot-Savart's law. The field, generated by this coil, was plotted and compared with the desired theoretical field.

Figure 3.8 shows a plot of the theoretical magnetic field and the field estimated by the winding plan. All windings had to carry a current of 15 or 100 A because only two power supplies should be used for this slower. Additionally it should be possible to wind the coil easily.



Fig. 3.8: The theoretically ideal field (dashed line), the field created by the ideal coil (scale on the left side), the difference between them (scale on the right side) and the winding plan to create this field are shown. The blue dots show the positions of 15 A windings and the red dots the ones of the 100 A coils.

When a satisfying agreement between the theoretical field and the one using the simulated coil was found, the field was tested in the flight simulator program as well (see figure 3.9).



Fig. 3.9: The plot shows the behavior of atoms leaving the oven at velocities of 50, 100, 150, 200, 250, 300 and  $350 \,\mathrm{m/s}$  for a given detuning. The atoms leaving the oven at low velocities do not immediately interact with the laser field. Due to the increasing field they into resonance come with the laser after a certain time and are then decelerated.

This simulation showed an optimal detuning of 442 Mhz as well.

The coil configuration that showed to be optimal in the flight simulation was wound and the field of the slower was measured using a Hall probe (type 634SS2). This showed the insufficient points. Then the compensation windings were simulated by 'adding' them to the measured field and testing them in the flight simulator. Then they were put on the slower and the field was probed again. Figure 3.10 shows the final Hall-probed field and the simulated compensation windings.



Fig. 3.10: The theoretically ideal field (dashed line), the field measured with the Hall-probe (scale on the left side), the difference between them (scale on the right side) and the coiling plan that created this field are shown. The blue dots show the positions of 15 A windings, the red dots of the 100 A windings and the green dots of the compensation windings.

Using the flight simulator program on this measured field yielded no definitive results because the limits of the numerical calculation were reached. But it indicated that the slower would likely work with an optimal detuning of 447 MHz with slightly reduced currents (due to the increased number of windings). In all calculations a saturation ratio of  $I/I_0 = 10$  was used.

The difference between the  $5P_{3/2}$  states F = 1 and F = 3 is 424 MHz (the state F = 0 cannot be reached in a single transition from the  $5S_{1/2}$ , F = 2 state). To suppress the interaction of the slower laser and the trapped atoms on this transition the detuning of the slower laser must be far more than 424 Mhz. First calculations didn't consider this condition and yielded optimal detunings of 442 respectively 447 MHz.

Due to this interaction the slower 'blew' the atoms out of the MOT and the detuning had to be changed to  $\approx 530$  Mhz, depending on the currents through the slower coils.

The strong current was set to 92 A because this was the optimal current for the ytterbium slower that uses the same power supply. The maximum flux of slow atoms was then found for a weak current of 17 A and a detuning of 518 MHz. The frequency could only be shifted that far because for the theoretical slower calculations a deceleration of 50% of the maximum possible deceleration was assumed.

A theoretical simulation, using these parameters, showed still a not significantly reduced flux of slow atoms leaving the slower. But due to the new field geometry (because of the changed currents) the position, at which the atoms leave the slower at a velocity of  $\approx 20 \text{ m/s}$ , is situated about 1 cm 'before' the planned position (at the end the field becomes too steep and the atoms cannot stay in resonance). Thus a bigger part of the atoms spreads away and misses the MOT (due to the relatively higher transversal velocity compared to the longitudinal one). But where the fast atoms leave the oven, the laser is resonant with faster atoms and so a larger part of the velocity spectrum of the atoms is being slowed down. In the experiment a lower than expected, but still sufficient flux of slow atoms could be realized (see section 4.1.2).

### 3.4 Ytterbium oven

The ytterbium oven setup is similar to the rubidium oven setup. The main difference occurs from the vapor pressure of only  $p(20^{\circ}\text{C}) = 2.5 \cdot 10^{-18}$  mbar: the nipple, where the solid ytterbium is put in, has to be heated up to  $\approx 400^{\circ}\text{C}$ (and thus the nozzle to  $450^{\circ}\text{C}$ ).

In spite of the higher temperature there are fewer atoms in the oven region and the cooling shield could be build more simple and only a 6-way cross was needed. Further information on the ytterbium oven can be found in [Kro02].

### 3.5 Ytterbium slower

The ytterbium slower is very similar to the rubidium slower, but it is only 55 cm long. Because only a maximum of  $10^8$  ytterbium atoms need to be trapped in the MOT, the flux of slow atoms does not have to be very high. Like the rubidium slower it is built in increasing field geometry and some compensation windings had to be added due to an insufficient field at the positions of the spacers.

Due to different parameters like  $\Gamma$  and  $\lambda$  the results of the simulation were different. They are summarized in [Kro02].

## **3.6** Magnetic coils

There are several coil configurations to create a magnetic quadrupole field with non-vanishing offset [Cou02]. For this experiment the clover leaf trap was chosen because here all coils are set up in two planes, providing a very good optical access to the chamber (see figure 3.1). Furthermore, sufficient fields can be created by currents of 'only' 250 A, which can be 'easily' handed.

### 3.6.1 Design of the coils

A Matlab program was written to simulate the magnetic fields [Gri02]. For currents of 250 A and a magnetic offset field  $B_0 = 1$  G, the calculation yielded the values shown in table 3.1.

Туре	Symbol	Value
Radial field gradient	$B'_r$	$165.4\mathrm{G/cm}$
Axial field curvature	$B_z''$	$253{ m G/cm^2}$
Radial trap frequency	$\nu_r$	$209.9\mathrm{Hz}$
Axial trap frequency	$\nu_z$	$20.2\mathrm{Hz}$

Tab. 3.1: Estimated specifications of the magnetic coils.

For the magnetic coils the same copper wire as for the slowers was used, except for the offset coils. Here an insulated copper wire with a nearly quadratic cross section (side length 4.2 mm) was used. It is also hollow inside and flown through by water.

A pinch coil consists of 8 windings, always 2 from inside to outside and 4 'upward' (see figure 2.10). The diameter of the inner coils is 32.5 mm while the one of the outer coils is 39 mm.

An offset coil consists of 12 windings, always 3 from inside to outside and 4 'upward'. The diameter of the coils increases from 108.6 mm (inner coils) to 125.4 mm (inner coils).

A clover leaf consists of 16 windings, always 4 from inside to outside and 4 'upward'. The 'diameter' of the long axis of the elliptic coils increases from 49.4 mm (inner coils) to 70.4 mm (outer coils) and of the short axis from 17.8 mm to 38.8 mm.

The coils were glued together using Araldite 2012 epoxy adhesive and finally sealed with Lord 310 epoxy adhesive because these epoxy adhesives are ideal for gluing metal and plastic and have a low thermal expansion coefficient. The temperature can be achieved by LM35DZ temperature sensors, which have been poured into the epoxy adhesive as well and are connected to temperature displays. The coils are shown in figure 3.11.





Fig. 3.11: A model and a picture of the magnetic coils. In the picture's top view an aluminium ring can be seen. Some retaining screws will push towards this ring to hold the coils at a fixed position in the buckets. The coil model also shows the movable coils: these copper rings will be connected in series to the pinch and offset coils. By moving them along the axis the offset field in the middle of the chamber can be raised or lowered by about 14.8 G (depending on the direction of the current).

### 3.6.2 Connection scheme for the MOT

The most intuitive way to connect the coils for a MOT is described in section 2.4.2. In this experiment another connection scheme is used because it has more in common with the connection scheme for the magnetic trap and changing the currents from MOT to magnetic trap is more simple: one pinch coil and the offset coil on the same side are flown through by currents in opposing directions (like in the magnetic trap, but only one side). This creates a quadrupole field as as well (see figure 3.12).



Fig. 3.12: The quadrupole field, created by the MOT configuration of this experiment. As in figure 2.26, the field in axial direction is stronger than the one in radial direction. The main difference lies in the relatively weaker fields for z > 0. The pinch coil, the offset coil and the directions of the currents through them are shown at the bottom of the figure.

The offset coils are designed to compensate the field of the pinch coils in the middle of the chamber, due to the desired low offset field. Therefore, one offset coil compensates the field of one pinch coil in the middle of the chamber as well. The main difference is that the axial gradient is not linear. In the zero-crossing area the gradient becomes shallower with increasing distance from the coils (see figure 3.13).



Fig. 3.13: The magnetic field in axial (z) and radial (r) direction. The zerocrossing is moved about 1.2 mm in axial direction, due to the non-vanishing offset field in the middle of the chamber, but this can be varied using the movable coils.

For a determination of the field in the MOT configuration the fields were first calculated numerically by the Bio-Savart-Law for the MOT- and the clover leaf configuration. Then the coils were measured in the clover leaf configuration (see section 3.6.3) and the parameters of the simulation were

slightly modified to fit into the measured data points. Finally the field of the MOT configuration was simulated by using the modified parameters. These field simulations are shown in figure 3.13. For currents of 40 A the calculation yielded values of

$$\frac{\partial B}{\partial z} \approx 17.5 \frac{G}{cm} \bigg|_{B=0G}$$
 (3.10)

and

$$\frac{\partial B}{\partial r} \approx 8.75 \left. \frac{G}{cm} \right|_{B=0G} \,. \tag{3.11}$$

The value in axial direction is twice the one in radial direction (see section 2.4.2).

#### 3.6.3 Measurement of the magnetic trap fields

For the coil measurement the same Hall probe was used as for the measurement of the Zeeman slowers (type 634SS2) and the coils were connected in the clover leaf configuration (see section 2.5.1). The center of the trap could not be determined exactly by the eye. Thus, the field was probed in axial direction along several radial lines and in radial direction along several axial lines. Then the trap center could be determined relative to the data points and the data points were shifted into the trap center. The main plots are shown in figure 3.14.



Fig. 3.14: The probed field along the radial (r) and axial (z) axis at a current of 250 A. The one in axial direction also includes the plots with the movable coils directly attached to the offset coils, once lifting and once downcasting the offset field.

Type	Symbol	Value	Relative deviation from table 3.1
Radial field gradient	$B'_r$	$149.5\mathrm{G/cm}$	9.6%
Axial field curvature	$B_z''$	$236\mathrm{G/cm^2}$	6.7%
Offset field	$B_0$	$3.21\mathrm{G}$	—
Radial trap frequency	$\nu_r$	$105.5\mathrm{Hz}$	_
Axial trap frequency	$\nu_z$	$19.7\mathrm{Hz}$	2.8%
Radial trap frequency for $B_0 = 1 G$	$ u_r$	$190.2\mathrm{Hz}$	9.4%

The field specifications obtained by this measurement are summarized in table 3.2.

Tab. 3.2: Measured specifications of the magnetic coils.

The radial trap frequency can be easily increased by lowering the offset field with the movable coils. The axial one cannot be increased without increasing the current but the value of  $\nu_z = 13.85$  Hz should be sufficient.

## 3.7 Laser system for rubidium

The rubidium laser system (see figure 3.15) consists of four self-made diode lasers using Rohm RLD78-PZW2 diodes. The laser system at the MOT transition operates using the master-slave principle: one laser (the master) splits off into several spectral orders at a holographic grating. The zeroth order is coupled out while the first order is feedback into the laser (Lithrow setup). This stabilizes the laser by moving the grating with a piezoelectric element, controlled by a spectroscopy signal (see section 3.7.1). The feedback limits the maximum output power to  $\approx 70$  %. The stabilized signal is then detuned by one respectively two acousto-optical modulators (AOMs) to inject two freewheeling lasers (slaves), one for the MOT and one for the Zeeman slower. Due to the injection the slaves have to emit exactly the same wavelength as the master and are thus stabilized, but their output power is not limited by the stabilization.

For the repumping transition only one master laser is used. Although the output power is limited and the power has to be split off between the slower and the MOT, it is sufficient.

The output power of the freewheeling diodes is  $\approx 80 \,\mathrm{mW}$  at a current of 110 mA and of the feedback diodes  $\approx 47 \,\mathrm{mW}$  at 100 mA.

The master laser for Rb first passes through a Faraday rotator to avoid any feedback from surface reflexes (e.g. at the AOMs) as well as from light emitted by the slaves. Then the light for the stabilization spectroscopy (see section 3.7.1) is separated from the beam by a glass plate (with anti-reflex coating on one side) and right after that the light for injecting the MOT slave using a  $\lambda/2$ -plate and a polarizing beam splitter (PBS) to control the injecting power. This beam passes through an AOM in double-pass configuration



Fig. 3.15: The laser system for rubidium. Shown are the beams emitted by the repumping laser (R), the master (M) for injecting the slaves, the slave for the Zeeman slower (S1) and the slave for the MOT (S2). The AOMs with blue and red numbers are shifting the beams blue and red, respectively. The frequencies are summarized in table 3.4.

(because then the laser can be detuned without moving the beam seriously): the first order is reflected back into the AOM and the first order of this beam, that is still following the way it came from, is separated by the PBS it passed first because it meanwhile passed twice a  $\lambda/4$ -plate, that turned the linear polarization by 90°. The zeroth orders of the beam are blocked by diaphragms and the efficiency of the double-pass AOM is 55%. Hence, the wavelength has been blue shifted by about  $2 \cdot 113 \text{ MHz} = 226 \text{ MHz}$  (the AOM can be detuned) and the light can now inject the slave laser for the MOT by a onesided anti-reflex coated glass plate. The part that is not reflected is used for the imaging system (see section 3.9).

Laser / beam	Lock point / frequency		
Master	(2,3) cross-over transition $\hat{=} (F = 2 \rightarrow F' = 3) - 133.5 \text{ MHz}$		
MOT slave	$(F = 2 \to F' = 3) + 92 \mathrm{MHz}$		
Slower slave	$(F = 2 \rightarrow F' = 3) - 513 \mathrm{MHz}$		
Repumper	(0,1) cross-over transition $\hat{=} (F = 1 \rightarrow F' = 2)$ - 193 MHz		
MOT beam	$(F = 2 \rightarrow F' = 3) - 13 \mathrm{MHz}$		
MOT repumper beam	$(F = 1 \rightarrow F' = 2) - 1 \mathrm{MHz}$		
Slower repumper beam	$(F = 1 \rightarrow F' = 2)$ - 425 MHz		

Tab. 3.3: Frequencies and lock points of the lasers and beams of figure 3.15.

The light that is not separated at the PBS passes through another  $\lambda/2$ -plate and a PBS where it splits off between the part that injects the slave for the slower and the part that is analyzed in a wavemeter and a Fabry-Pérot interferometer.

The part for injecting the slave passes through two AOMs (one tunable and one set to 105 MHz) and  $\lambda/4$ -plate and then all the way back to the PBS where it is separated from the original beam. After every passing through an AOM (four altogether) the zeroth order is blocked by a diaphragm and the light is red shifted by altogether about  $2 \cdot 105 \text{ MHz} + 2 \cdot 85 \text{ MHz} = 380 \text{ MHz}$ . This beam injects now the slave for the Zeeman slower by a onesided anti-reflex coated glass plate as well.

The light from the MOT slave passes through a Faraday rotator to avoid any feedback from the retro-reflecting MOT and all reflecting surfaces (although these can be usually neglected). A part of the beam is split off for analysis in the wavemeter and the Fabry-Pérot interferometer. Then the elliptic shape of the beam is made circular with an anamorphic prism pair and afterwards the beam becomes red shifted 105 MHz in another AOM (efficiency 75%). This AOM can be turned on and off in microseconds to block the beam while the AOMs in the master beam are just for the detuning of the laser. Right after this AOM is a mechanical shutter that can block the beam completely within milliseconds. Then the beam is expanded by lenses and split off into the three directions needed for the MOT. Each of them is retro-reflected behind the MOT and follows the way it comes from.

AOM	Frequency detuning	Frequency	
1	variable	$+113\mathrm{MHz}$	
2	fix	$-105\mathrm{MHz}$	
3	variable	$-85\mathrm{MHz}$	Tab. 3.4: The
4	fix	$-113\mathrm{MHz}$	detunings of the
5	fix	$+95\mathrm{MHz}$	AOMs shown in
6	fix	$-105\mathrm{MHz}$	figure 3.15

In this MOT with retro-reflected beams the laser power is used more efficiently because every beam is used twice. During the first passing of the MOT a part of the beam becomes absorbed and is therefore weaker in the second passing. To compensate this effect the lens before the mirror is moved to focus the beam slightly. Each MOT beam also passes a  $\lambda/4$ -plate before and one behind the MOT to set the polarization of the beam for each direction. The laser power is distributed equally between the three MOT directions.

The slave laser for the Zeeman slower splits off in a PBS for analysis in the wavemeter and the Fabry-Pérot, is made circular with an anamorphic prism pair, can be cut by a mechanical shutter within milliseconds, becomes expanded with lenses and is finally focussed to the rubidium oven, cooling the atoms in the Zeeman slower. A Faraday rotator is not needed for this beam.

The repumping laser, which is set up in Lithrow configuration, passes a Faraday rotator, splits off for analysis in the wavemeter and the Fabry-Pérot and becomes then split off ( $\lambda/2$ -plate and a PBS) into two beams, one for repumping the atoms in the slower and one for repumping the atoms in the MOT. Each beam passes a double-pass AOM and is then combined with the respective beam at the MOT transition in a PBS. The main beams pass the PBS straightforward while the repumpers enter the PBS' orthogonally. Therefore, the polarization of the repumper is rotated by  $90^{\circ}$ compared to the polarization of the main beam and the repumper is not distributed equally between the three MOT directions. But this effect can be neglected. By passing the AOMs the elliptically shaped mode of the beam is deformed and cannot be restored by an anamorphic prism pair. This is not further limiting the experiment because the mode looks nearly circular and is therefore sufficient. In the respective AOMs the repumper for the MOT becomes  $2 \cdot 95 \,\mathrm{MHz} = 190 \,\mathrm{MHz}$  blue shifted while the repumper for the slower becomes 2.116 MHz = 232 MHz red shifted. Both AOMs can be used for cutting off the repumper beams.

### 3.7.1 Spectroscopy for laser stabilization

From each of the two master lasers a part (intensity 4%) is split off using a onesided anti-reflex coated glass plate. This reflex is used to stabilize the laser. In this experiment an absorption spectroscopy is used as shown in figure 3.16.



Using a  $\lambda/2$ -plate and a PBS the beam is split off into a probe- and a pump beam. The probe beam passes through a glass cuvette that is filled with rubidium vapor, a  $\lambda/4$ -plate and a pbs. Due to the  $\lambda/4$ -plate the photons with spin  $m_s = -1$  (with respect to the quantization axis along the beam) leave the PBS towards one detector while the photons with spin  $m_s = +1$  leave the PBS towards the other detector.

Using a piezoelectric element, being attached to the grating inside the laser, the frequency can be tuned. Putting a sinus-function on the piezo 'scans' the spectrum up to a range of about 1 GHz. When the laser scans over one of the absorption lines of rubidium, the beam is absorbed. But due to the temperature of 294 K in the glass cuvette the velocity of the atoms is not zero and a Doppler broadening occurs. The broadening is so wide that no individual absorption lines can be resolved (see figure 3.17).

For resolving the absorption lines the pump beam is used: it pumps the atoms, whose Doppler shift matches the laser detuning, into the excited state.

There is no Doppler shift for atoms at rest, moving slowly or moving orthogonal to the laser beam and therefore the pump- and the probe-beam excite the same (hyperfine) transition in these atoms. Because the pump beam is far stronger than the probe beam it pumps up to the maximum of 50 % of these atoms into the excited state. Additionally many of these excited states decay into the other hyperfine state (F = 1 instead of F = 2 and the other way round) and thus the interaction with the probe beam is much weaker. At these frequencies the probe beam becomes not absorbed any more and this results in the so-called Lamb dips (see figure 3.17).



Fig. 3.17: The Doppler-broadened spectrum and the lamb of dips the  $5S_{1/2} \rightarrow 5P_{3/2}$  transition in gaseous  $^{87}$ Rb. Dips (a) and correspond (b) to the (1,3) and (2,3)cross-over transitions, respectively, and dip (c) to the transition into the F = 3 state.

Lamb dips also occur for atoms moving parallel to the laser beams: when the doppler shift of an atom matches the detuning relative to one transition of the pump beam as well as the detuning relative to another transition of the probe beam, the probe beam becomes not absorbed at this frequency and results in a Lamb dip as well. These lamb dips are called cross-over transitions.

Although a scan of the spectrum shows all lamb dips, the signal is not suitable for stabilizing the laser because locking on an absorption signal is far more complicated than locking on a dispersive signal. To transform the absorption signal into a dispersive signal, a magnetic field is applied parallel to the rubidium cuvette. The Zeeman effect shifts the lamb dips created by photons with  $m_s = -1$  and  $m_s = +1$  into opposite directions (see figure 3.18).



Fig. 3.18: The enlarged lamb dip from figure 3.17, with a positive and a negative Zeeman shift of about 21 MHz.

The magnetic field is chosen to shift the dips in the order of their line width. Subtracting the signals of the two detectors (amplified BPW 34 photo diodes) yields a dispersive signal (see figure 3.19).



Fig. 3.19: The shifted Lamb dips of figure 3.18 and the amplified difference signal of them. The two dips are obtained from different detectors and are slightly different due to an imperfect polarization of the light. The lower figure shows the complete dispersive signal of the  $5S_{1/2} \rightarrow 5P_{3/2}$ transition

The zero-crossing of this signal is insensitive to temperature variations and variations of the laser power and thus the lock is very stable. Figure 3.20 shows the spectroscopy signal of one detector of the repumper transition and the amplified difference signal of the two detectors.



Fig. 3.20: The spectrum obtained by one of the detectors of the  $5S_{1/2} \rightarrow 5P_{3/2}$  transition and the amplified difference signal of the two detectors.

The applied magnetic field has been calculated by the formula for long coils:

$$B = \mu_0 I \frac{n}{l} , \qquad (3.12)$$

where n denotes the number windings and l the length of the coil. Setting this equation into equation 2.23 yields the Zeeman shift:

$$E_Z = m_F g_F \mu_B \mu_0 I \frac{n}{l} \tag{3.13}$$

A sufficient separation of the two shifted absorption lines was found for a shift of  $\approx 3.5$  linewidths of the transition, that is 21 MHz. This separation was realized for atoms in the  $|m_F| = 1$  states with a current of 1 A and 130 windings for a short rubidium cell ( $l \approx 5.4$  cm) and 240 windings for a long rubidium cell ( $l \approx 10$  cm) and applied to the atoms with  $|m_F| = 1$ . The long rubidium cell is shown in figure 3.21.



Fig. 3.21: The rubidium cell for the laser stabilization on the atomic transition.

## **3.8** Laser system for ytterbium

For slowing and cooling the ytterbium atoms, more laser power than for the rubidium atoms is needed. The light for the blue MOT is created in a titanium sapphire laser with an external self-made frequency doubling cavity. It is stabilized on a Fabry-Pérot cavity and spectroscopy cell and it is pumped by a Verdi V10 solid state laser.

The same Verdi pumps a dye laser (filled with rhodamin 110) that creates the light for the green MOT. This laser is not yet set up.

### 3.8.1 Dipole trap

Furthermore, the Verdi is used for the dipole trap. Focussed on the ytterbium MOT it will pull the ytterbium atoms into its center. But due to the different atomic transitions in rubidium it pushes the rubidium atoms out of the trap. To compensate this effect a red (1064 nm) ytterbium fiber laser (type PYL-20 M) will be adjusted to the same position. This one will gain the dipole effect on the ytterbium atoms but the rubidium atoms will only feel the magnetic trap. More information on the laser system for ytterbium can be found in [Kro02].

### 3.9 Imaging system

The imaging system is set up as described in appendix B. The master laser that injects the MOT slave is used for the imaging system as well. The part that passes through the glass plate passes through an AOM and is then transferred to the bottom of the chamber (via a glass fiber), from where it passes through the chamber from the bottom to the top. There two lenses (f = 250 mm and f = 500 mm) are used to project an absorption picture of the atoms onto a CCD camera. The lower one of the two lenses can be moved to focus into the middle of the atomic cloud, depending on the fall time of the atoms after switching of the trap. It projects the picture of the MOT ad infinitum and the other lens projects it onto the CCD camera.

For measurements on the loading and decay dynamics of the MOT a lens (f = 75 mm) projects a picture of the MOT onto a calibrated photo diode.

# 4. Experimental results

### 4.1 Rubidium slower and MOT

Information on the efficiency of the Zeeman slower can be obtained by the determination of the loading and decay dynamics of the MOT. Furthermore, the number of atoms in the MOT can be determined.

The number of photons an atom in the MOT scatters is given by the scattering rate (equation 2.18) via

$$\frac{N_{ph}}{t} = \gamma_p . aga{4.1}$$

Using the energy of a single photon and multiplying the equation with the number of atoms  $N_{at}$ , the power of the scattered MOT light reads

$$P = \hbar \omega N_{at} \gamma_p . \tag{4.2}$$

Due to the detuning of  $\delta \approx 2\Gamma$  and the laser power of 21 mW the atomic transition is not fully saturated. Furthermore, the laser becomes enlarged to a diameter of 22 mm. On the other hand, the intensity in the middle of the beam is larger (due to the Gaussian beam profile), yielding 27 % (measured with a powermeter behind a diaphragm) of the laser power acting on the MOT (estimated  $\emptyset = 8 \text{ mm}$ ). The laser intensity must then be doubled because of the retro-reflecting MOT configuration.

The saturation ratio  $I/I_0$  can be obtained by dividing this intensity by the saturation intensity of 1.6 mW/cm<sup>2</sup>. This yields an idealized scattering rate of  $\gamma_{p_0} = 0.23 \,\Gamma$ . The Clebsch-Gordan coefficient (see section 2.2.1) for the  $F = 2 \rightarrow F' = 3$  MOT transition (circularly polarized light) is  $\eta_{CG} = 7/15$ . A second coefficient is given by the geometrical alignment of the photodiode and the lens: the light is scattered in all spatial directions but only a fraction of it ends up in the photodiode. In this experiment the solid angle ratio is  $\eta_{sa} = 1.7 \cdot 10^{-3}$ .

Using the calibration of the photodiode  $(P/\mu W = 2.27 U/V)$ , equation 4.2 can then be written as

$$N_{at} = \frac{1}{\hbar\omega} \frac{2.27}{\gamma_{p_0} \eta_{CG} \eta_{sa}} \frac{U}{V} \mu W = 1.34 \cdot 10^9 \frac{U}{V} .$$
(4.3)

For some of the quantities an error can be given but for the most error afflicted quantities like the saturation intensity the error can only be estimated. Therefore, no error calculation is made but the error can be estimated to be 'small' for a MOT measurement, that means the real atom number is likely within the range of a factor 2, which is sufficient for the results of these measurements.

The only problem is that the picture of the MOT, which is projected on the photodiode is larger than the initially used photodiode. Replacing this diode with a large photodiode (type IPL 10050) yielded a calibration factor of 2.86 for the fully loaded MOT. For the the determination of the number of atoms in the MOT the obtained number was multiplied with this factor, resulting in an additional measurement uncertainty. But this is not further important as only qualitative statements will be predicted for the measurements involving partially loaded MOTs.

During the initial loading of the MOT no calibration was needed because the MOT was small enough to become projected on the photodiode. The decay dynamics were determined with the large photodiode (calibration factor:  $P/\mu W = 2.10 U/V$ ).

#### 4.1.1 Principle of measurement

The typical dynamics of the MOT during the loading and following decay is shown in figure 4.1. To ensure a complete empty MOT the path of the MOT light is blocked. When the path is opened again the MOT starts to load immediately. During the first few milliseconds the derivative of the atom number is directly proportional to the atomic flux into the MOT as shown by the straight line in figure 4.1. Using the slope of the loading curve at the point where the loading starts yields the flux of slow atoms into the MOT.



Fig. 4.1: A loading curve of the MOT showing the measured data and the fitted exponential function.

After this initial loading the trapped atoms affect the loading sequence and the loading curve becomes shallower. According to equation 2.36 the curve follows a logarithmic behavior

$$N(t) = \frac{R_L}{\Gamma_L} (1 - e^{-\Gamma_L t}) .$$
 (4.4)

By fitting this function into the measured data the loading time of the MOT and the number of atoms in equilibrium of loading and decay can be determined.

For measuring all parameters of the decay dynamics, the MOT must be fully loaded. Then the slower laser and/or the atomic beam will be cut off. The following behavior of the MOT is shown in figure 4.2.



Fig. 4.2: A decay curve of the MOT, showing the measured data and the fitted exponential function.

This behavior is described by equation 2.38:

$$N(t) = N_0 \frac{e^{-\Gamma_D t}}{1 + \frac{\beta N_0}{V \, \Gamma_D} (1 - e^{-\Gamma_D t})}$$
(4.5)

This equation is too complex to fit  $\beta$  as well as  $\Gamma_D$  perfect into the measured data. But the equation can be simplified by recalling that  $\beta$  reflects the twobody collisions, which can only occur in a dense, that means fully loaded, MOT. Thus, at the end of the decay  $(t > t_1)$  the curve can only depend on collisions with the background gas (and the atomic beam if it is not cut off). In this region equation 4.5 can be rewritten as

$$N(t) = N(t_1) \ e^{-\Gamma_D(t-t_1)} , \qquad (4.6)$$

and  $\Gamma_D$  can be obtained by fitting this equation into the measured data. The coefficient  $\beta$  can be obtained by putting the value of  $\Gamma_D$  into equation 4.5 and fitting this function into the 'complete' measured decay data. The time  $t_1$ , from where the curve follows the 'simple' logarithmic behavior, can be determined by displaying the curve in a half logarithmic scale: at the beginning the curve declines faster than exponential, fading into a straight line for  $t > t_1$ .

### 4.1.2 Loading dynamics

Using the method described in section 4.1.1, loading curves of the MOT were taken for oven temperatures of 140, 160, 180, 200 and  $220^{\circ}$ C.

Figure 4.3 shows the temperature dependence of the flux of slow atoms into the MOT as well as the maximum number of atoms in the MOT.



Fig. 4.3: Measured temperature dependence of the atomic flux and the number of atoms in the MOT.

As expected the flux increases with increasing temperature, but the values are about  $10^4$  times smaller than expected (see figure 3.6).

The flux is still sufficient to load up to  $1.2 \cdot 10^9$  atoms into the MOT and is not the limiting factor of the MOT as shown in figure 4.3. But the MOT needs about 20 seconds to load and that is not suitable for running the experiment. Therefore the ratio of  $10^4$  between the calculations and the measurement is a non-trivial shortcoming, whose reasons can be:

- not enough power in the slower laser (see section 4.1.2.1), in the MOT laser (see section 4.1.2.2), in the MOT repumper (see section 4.1.2.3) or in the slower repumper (see section 4.1.2.4)
- a not well optimized slower (see section 4.1.2.5)

- a geometrical misalignment of a part of the vacuum system (see section 4.1.2.6)
- a not well adjusted MOT (see section 4.1.2.7)
- an error in the theoretical calculations (see section 4.1.2.8)
- a not well working oven (see section 4.1.2.9)
- a misaligned slower laser (see section 4.1.2.10)

#### 4.1.2.1 Laser power in the Zeeman slower

The loading measurements were performed for several values of the slower laser power at an oven temperature of 180°C (see figure 4.4).



Fig. 4.4: Measured slower laser power dependence of the atomic flux and the number of atoms in the MOT.

It can be seen that the MOT reaches the saturation limit already at about 35 mW while 64.1 mW are available. The atomic flux shows no clear saturation behavior but the shape of the 'data curve' indicates that the saturation limit is at least close and therefore the laser power in the Zeeman slower is not responsible for the low flux of slow atoms into the MOT.

Furthermore, the flux is also too low at oven temperatures of 140°C and there the laser power is sufficient.

The decreasing number of atoms in the MOT at higher laser powers corresponds likely to measurement inaccuracies. It is also possible that the slower laser 'blows' the atoms out of the MOT (see section 3.3) but this effect seems to play a minor role because the slower laser misses the MOT (see section 4.1.2.10).

#### 4.1.2.2 Laser power in the MOT

The laser power in the MOT limits the maximum number of atoms in the MOT (see section 2.4.1) as well as the ratio of slow atoms leaving the slower that can become trapped (see section 3.3). Therefore it would be very interesting to see if the available laser power of 21 mW is a limiting factor. But increasing the MOT laser power also changes the saturation of the atoms and thus the ratio of atoms and scattered photons. As this conversion factor is already the most error afflicted quantity the MOT laser power dependence cannot reliable be measured with this method. But due to the already relative high saturation ratio it can be assumed that an increase in the MOT laser power could increase the number of atoms just slightly.

#### 4.1.2.3 Laser power in the slower repumper

The loading measurements were also performed for several values of the power in the slower repumper at an oven temperature of 180°C (see figure 4.5). It can be seen that the slower repumper dependence of the atomic flux is in an unsaturated regime. Therefore the atomic flux can be increased by increasing this laser power. Because the AOMs of the repumper laser system are not completely adjusted more power can probably be obtained from the laser system. But this power is also limited and although two repumping lasers could be used (one for the MOT and one for the slower), the maximum gain of the flux is likely lower than 4.

But the number of atoms in the MOT is not limited by this laser power as shown in figure 4.5. The decrease of the atom number for higher laser powers corresponds likely to measurement inaccuracies. It is also possible that the slower repumper interacts with the atoms in the MOT and leads to a loss of atoms in the MOT because it brings an imbalance to the forces in the MOT. But this effect seems to play a minor role because the slower misses the MOT (see section 4.1.2.10).


Fig. 4.5: Measured slower repumper dependence of the atomic flux.

### 4.1.2.4 Laser power in the MOT repumper

The loading measurements were also performed for several values of the power in the MOT repumper at an oven temperature of  $180^{\circ}$ C (see figure 4.6). It can be seen that the MOT repumper dependence of the atomic flux is nearly in the saturated regime. Because the AOMs of the repumper laser system are not completely adjusted more power can probably be obtained from the laser system, but the increase in the flux will be not very high (probably 10-20%).

Although the inaccuracies in the atom number measurement are high, it can be seen that the MOT is already in the saturated regime.



Fig. 4.6: Measured MOT repumper dependence of the atomic flux.

### 4.1.2.5 Slower efficiency

A poorly working Zeeman slower is a very straightforward explanation for an insufficient flux of slow atoms. If the dips in the magnetic field (see section 3.3) are not sufficiently compensated by the compensation coils, only a fraction of the slow-able atoms will be slowed down to the capture velocity. As shown in section 4.1.2, the flux of slow atoms increases for an increasing oven temperature and hence for an increasing flux of atoms at all velocities. This means that the slower works on all (or at least most) atoms up to a maximum velocity, which does not necessarily have to be the calculated maximum velocity of 404 m/s. This velocity cannot be determined but it can be estimated by a determination of the flux of atoms at all velocities, which is determined in section 4.1.5.

The calculation in this section shows that about 16 % of the atoms are being slowed. This value shows that there might be a shortcoming of the slower but it also shows that the total flux is already far too low and that the slower is not responsible for the four magnitudes.

### 4.1.2.6 Geometrical alignment

All atoms that can become trapped in the MOT have to follow a straight line from the nozzle through the differential pumping tube and the Zeeman slower (see figure 3.5). If these components are not exactly aligned, the flux of atoms (at all velocities) can be considerably decreased because many of the atoms will hit e.g. the wall of the differential pumping tube and will be lost. Therefore the differential pumping tube was aligned to point through the Zeeman slower into the middle of the chamber before the vacuum system was closed. The nozzle could not be aligned that way but it is exactly in the middle of the elbow vacuum piece. But it was not tested if the differential pumping tube pointed through the middle of the four-way cross where the elbow piece was attached later. Thus it is possible that the nozzle and the pumping tube are not exactly aligned and this can contribute to the low flux, as a misalignment of just 4 mm can totally stop the atomic flux. Furthermore, it is shown section 4.1.5 that the total atomic flux is far too low.

### 4.1.2.7 MOT adjustment

Due to the many degrees of freedom in the MOT adjustment it is not clear, if the MOT adjustment can be improved further, if no better values have been measured before. By improving the adjustment the total number of atoms as well as the loading rate of the MOT can be increased. Although all the measurements were performed with a very good adjusted MOT, it is possible that the atom number as well as loading rate can be slightly increased, but not by four magnitudes.

#### 4.1.2.8 Theoretical calculations

Although the model of the atomic flux involves many aspects of the atomic motion, the calculation is still error-afflicted. The measurement of the ytterbium slower showed a flux that was one magnitude lower than the calculation yielded [Kro02]. This shows that there is a probability that the calculation for the rubidium slower also yielded a stronger flux. But because there are also some shortcomings with the ytterbium slower, a shortcoming of the calculation can explain only less than one magnitude.

#### 4.1.2.9 Oven efficiency

As shown in section 3.3, the atomic flux is proportional to the vapor pressure of rubidium. If the thermal contact between the heating tape, the oven and the rubidium cuvette is not good it would just need a little bit longer for the vapor pressure to reach its final value (depending on the temperature), but finally the rubidium inside the cuvette will reach the desired temperature. A low atomic flux can only occur when a part of the evaporated rubidium atoms does not contribute to the pressure, e.g. because the atoms get 'stuck' at the walls of the oven. But this can only occur during the initial heating process because the wall will become saturated as well after a short time.

More information on this could probably be obtained with a suitable pressure gauge directly attached to the oven part beyond the nozzle. The ion gauge that is attached to the oven can only measure the pressure that corresponds to an equilibrium of the rubidium pressure beyond the nozzle, the cooling shield and the ion getter pump. Of course this pressure is lower than the rubidium pressure beyond the nozzle but when the equilibrium pressure is reached here, the rubidium cuvette has reached its final temperature and the rubidium pressure in the oven its final value.

Another sign for a low atomic flux out of the nozzle corresponds to the fluorescence of the slower laser that can usually be seen through the window in the oven. In this experiment a broad fluorescence can be seen, indicating a strong flux.

#### 4.1.2.10 Slower laser alignment

It can be easily be shown that the MOT is in the trap center: by increasing the magnetic field the MOT becomes smaller but it also moves into the trap center.

Whether the slower lasers passes through the trap center can be tested by observing the fluorescence signal in the oven. The fluorescence signal in the oven increases when the slower passes through the trap center because the differential pumping tube points directly into it (see section 4.1.2.6).

So it can be seen that the slower laser does not pass through the MOT when it is optimized for the maximum achievable atomic flux. When the laser is shifted into the trap center, the MOT decays within  $\approx 2$  seconds, that is extremely fast, compared to the decay time of 27.7 seconds (see section 4.1.3). This means that the slower laser 'blows' the atoms out of the MOT. Although the laser detuning has been increased further than planned the laser still interacts with the MOT atoms on the  $5S_{1/2}$ ,  $F = 2 \rightarrow 5P_{3/2}$ , F' = 1transition. The detuning of -89 MHz (relative to this transition) is obviously not enough. Due to the high laser intensity  $(I/I_0 \approx 80)$  the scattering rate becomes  $\gamma_{p_0 \, slo} = 0.04\Gamma$  that is just one eighth of the scattering rate of the MOT light ( $\gamma_{p_0} = 0.23\Gamma$ ). Additionally the Clebsch-Gordan coefficient of this transition is just 1/30 and that reduces the effect but nevertheless the imbalance of the forces is too high.

The slower repumper does not mentionable amplify the effect because it is too far off-resonant respective all MOT transitions.

#### 4.1.2.11 Conclusion

Even if all the 'minor reasons' contribute their part to the shortcoming of the loading rate, this would not explain the four magnitudes. Therefore, the low flux of atoms at all velocities and that the slower laser 'blows' the atoms out of the MOT (and has therefore to be moved out of the trap center) are the 'main reasons' for the shortcoming of the loading rate.

### 4.1.3 Decay dynamics

At an oven temperature of  $200^{\circ}$ C (to ensure a fully loaded MOT) the decay of the MOT was measured for three different configurations :

- slower laser and atomic beam cut off
- slower laser on and atomic beam cut off
- slower laser cut off and atomic beam on

As mentioned in section 4.1.1 the decay curve was plotted on a halflogarithmic scale. Instead of the expectations the curve was linear all over. Therefore the one-body decay constant  $\Gamma_D$  (resp.  $\Gamma_L$  if the atomic beam was not cut off) could be easily determined but the two-body decay constant  $\beta$ was always zero.

This means the MOT is either not dense enough for observable two-body collisions or the density is constant. This is calculated in section 4.1.4.

For comparison, the decay was also observed for the slower laser and the atomic beam on, while the laser passes the MOT. The decay constants  $\Gamma$  and the 1/e lifetimes are summarized in table 4.1.

Laser	Atomic beam	τ	$\Gamma_D$ resp. $\Gamma_L$	
off	off	$53.1\mathrm{s}$	$18.8 \cdot 10^{-3}/s$	Tab. 4.1: De-
off	on	$27.7\mathrm{s}$	$36.1 \cdot 10^{-3}/s$	cay constants
on	off	$48.6\mathrm{s}$	$20.6 \cdot 10^{-3}/s$	and lifetimes
on (centered)	on	$\approx 2\mathrm{s}$	$\approx 500 \cdot 10^{-3}/\mathrm{s}$	of the MOT.

The lifetime of 53.1 seconds, which corresponds to collisions with the background gas, should be sufficient to achieve a BEC. This is not astonishing because the pressure in the main chamber is sufficiently low ( $p \le 5 \cdot 10^{-11}$  mbar). When the slower laser is still on, the lifetime decreases only slightly because the laser mainly misses the MOT (see section 4.1.2.10).

When the laser is cut off instead of the atomic beam, the lifetime decreases by a factor of 2. This means that the collisions with the atomic beam are observable and the atomic flux can be calculated using the decay constant. This is done is section 4.1.5.

### 4.1.4 Density

The lack of two-body collisions can correspond to a low or constant density. The latter is not unlikely because MOTs sometimes load (decay) by increasing (decreasing) the volume at a constant density. In this case equation 2.37 can be written as

$$\frac{dN}{dt} = -\Gamma_D N - \beta nN \tag{4.7}$$

$$= -(\Gamma_D + \beta n) N . \qquad (4.8)$$

The solution of this equation reads

$$N(t) = N_0 e^{-(\Gamma_D - \beta n)t} = N_0 e^{-\Gamma_B t} .$$
(4.9)

According to this notation the measurement has yielded  $\Gamma_B$  instead of  $\Gamma_D$ . Assuming (the real)  $\Gamma_D$  to be small, the density can be estimated by

$$\Gamma_B = \beta n + \Gamma_D \ge \beta n . \tag{4.10}$$

Typical values are  $\beta \approx 10^{-12} \text{cm}^3/\text{s}$  [Fen92], yielding

$$n \le 1.88 \cdot 10^{10} \text{cm}^{-3}$$
 (4.11)

If (the real)  $\Gamma_D$  is indeed small, the density is in a sufficient regime, as typical values are in the order of  $1 - 3 \cdot 10^{10} \text{cm}^{-3}$  [Hof93].

### 4.1.5 Atomic flux

In analogy to the procedure in section 3.3 the flux of all atoms into the MOT can be calculated. At an oven temperature of 200°C the flux is  $1.1 \cdot 10^{13}$ /s. The value of this flux can also be measured by an analysis of the decay dynamics: the difference of the decay constants  $\Gamma_D$  and  $\Gamma_L$  reflects the collisions with the atomic beam.

The scattering formula for particle beams reads

$$\frac{\Delta N}{N} = n\sigma \varnothing_{MOT} , \qquad (4.12)$$

where  $\Delta N/N$  denotes the ratio of 'absorbed' and all atoms after their flight through the MOT. Because the light of the MOT increases the collisions ratio, the literature value of  $\sigma = 3 \cdot 10^{-12} \text{ cm}^2$  for the scattering cross-section must be used [Die01].

The total atomic flux can then be calculated by

$$\frac{N}{t} = N_0 \frac{(\Gamma_L - \Gamma_D)}{\Delta N/N} . \tag{4.13}$$

Assuming a density of  $1.88 \cdot 10^{10} \text{cm}^{-3}$  yields an atomic flux of  $6 \cdot 10^8$  atoms per second.

This value is too low but there are there are several unknown magnitudes in the formula and thus the flux can not be exactly determined. But the value should at least be close and this means that the total atomic flux is too low by at least two magnitudes.

### 4.1.6 MOT temperature and capture region

As described in appendix B the time of flight measurement was performed without an absorption imaging system. Figure 4.7 shows a signal obtained by the time of flight measurement.



Fig. 4.7: Capture ratio of the time of flight measurement.

The times of flight were 5, 10, 15, 20, 30, 40, 50, 60, 80 and 100 ms and  $\sigma_{\rho}$  was estimated to be 6 mm. The loading time of the MOT was only 4 seconds because the loaded number of atoms was then more reproducible. Figure 4.8 shows the measured capture ratios and the fitted curve for  $T = 1.86 \,\mathrm{mK} \ (\cong \sigma_v = 0.42 \,\mathrm{m/s})$  and a capture 'radius' of  $r = 9.3 \,\mathrm{mm}$ .



Fig. 4.8: Capture ratio of the time of flight measurement.

The curve does not exactly fit into the measured data. As mentioned in appendix B the agreement between theory and experiment decreases for longer times of flight. The reason for the general poor agreement corresponds to the measurement method and not to the fitting parameters. This can be seen in figure 4.9. Here the theoretical curve is plotted for r being 9.0, 9.3 and 9.6 mm at T = 1.86 mK and it is plotted for T being 1.36, 1.86 and 2.43 mK at r = 9.3 mm.



Fig. 4.9: Capture ratio for different temperatures and capture regions.

It can be seen that altering the temperature by approximately 25% or the capture region by approximately 4% changes the curve in such an order that the agreement with the measured data decreases noticeable. Thus the error of the measurement can be estimated to be in the order of 50%, which is sufficient for this kind of measurement.

The capture region's diameter of 18.6 mm was used to correct the calculations of the atomic flux, which originally used a diameter of 22 mm.

The temperature of 1.86 mK is still high for a MOT, as the temperature in a MOT is usually in the order of  $500 \,\mu$ K. But the temperature can be further lowered by an adjustment of the lasers frequencies, the magnetic fields and the MOT when the temperature can be determined by an absorption imaging system. Additional cooling techniques can be used before and during the transfer into the magnetic trap. The atomic cloud can e.g. be cooled down by a detuned MOT or in an optical molasses. The initial condition of the high number and this temperature will be sufficient for starting an effective cooling sequence in the magnetic trap.

### 4.2 Ytterbium- and double-species MOT

Similar experiments as for rubidium were also performed for ytterbium. The loading rate was between  $3 \cdot 10^6$  and  $16 \cdot 10^6$  atoms per second, depending on the isotope, while the number of atoms in the MOT was between  $4 \cdot 10^6$  and  $18 \cdot 10^6$ . These values are sufficient for running the experiment, as less ytterbium than rubidium atoms are needed and the loading rates are high. These results are extensively discussed in [Kro02].

Also the double-species MOT is working. Just for a 'general test', rubidium as well as ytterbium atoms were loaded into two MOTs, sitting directly beside each other. The MOTs didn't seem to interfere but no measurements were made because the experiment should continue with cooling the rubidium atoms first.

### 4.3 Magnetic trap

Detailed information on the magnetic trap can only be obtained by an absorption image. But the functional efficiency can be tested without the imaging system:

A similar procedure to the time of flight method can be performed. The MOT is loaded and the atoms are directly (without a time of flight) transferred into the magnetic trap. Therefor the lasers are cut off and the currents of the magnetic coils are turned on respectively increased. Then the atoms are 'stored' in the magnetic trap for a variable time, which has to be larger than the times of the time of flight measurement to ensure the functional efficiency of the magnetic trap. Afterwards the magnetic trap is turned off while the MOT is turned on again. The fluorescence signal yields the efficiency of the procedure.

Figure 4.10 shows the fluorescence signal, obtained by this capture-recapture sequence.



Fig. 4.10: Fluorescence signal of the capture-recapture sequence.

The storage time in the magnetic trap was one second and more than 10 % of the atoms have been recaptured. This means that the magnetic trap is working although the recapture rate is not yet well optimized. The reason is that some parameters, e.g. of the mode matching, have not yet been optimized and procedures like pumping all atoms into the  $m_F = 2$  state have not been performed. Therefor an absorption imaging system is needed. But the number of atoms in the magnetic trap is already sufficient for achieving a BEC.

## 5. Discussion and outlook

Although a rubidium MOT with about  $3 \cdot 10^9$  atoms was planned, the  $1.2 \cdot 10^9$  atoms, which can currently be loaded, are sufficient for the experiment. The experiment also works with the flux of  $10^8$  atoms per second and the loading time of 20 seconds but a shorter time would be desirable. The loading rate can probably be further increased by further adjustment of the MOT and the laser systems and by increasing the oven temperature. This can be tested easily and will probably yield an even more satisfactory atomic flux.

Nevertheless a new Zeeman slower has been designed, which works with a further red shifted slower laser. It is designed for a detuning of 640 MHz (at the moment the detuning is 518 MHz) with respect to the  $F = 2 \rightarrow F' = 3$  transition, which yields an idealized scattering rate for the MOT atoms of  $\gamma_{p_0} = 0.008\Gamma$ , which should be low enough for not disturbing the MOT. Additionally the slower has a tunable offset field and thus the detuning can be further shifted if necessary. When the chamber has to be opened anyway the new slower can replace the old one. But this is not the top priority as the experiment works nevertheless.

The lifetime in the MOT is also sufficient, even for achieving a BEC, which is very sensible to the collision rate.

Also the magnetic trap is working, the double species MOT has been realized and the whole experiment can meanwhile be controlled with the computer. The next step is the installation of the CCD camera, the last missing item of the imaging system, which will offer the opportunity of an exact densityand temperature determination, as well as the opportunity to obtain detailed information on the magnetic trap. Then the atoms can be evaporated and the BEC can finally be achieved. This should happen within the next months.

After that the ytterbium can be added step by step to the cooling sequence. First the blue MOT has to be operated again, followed by the installation of the dye laser for the green MOT, as well as the laser system for the dipole trap.

Then the cold collisions of ytterbium can be studied. This will probably take one year and show the way of further experiments.

### Appendix A

## Motivation for ytterbium

As mentioned in the introduction, ytterbium can be laser-cooled easily with two different wavelengths, which has been done by other groups already. One of the transitions has the advantage of trapping even relatively fast atoms while the other has the advantage of low possible temperatures. Furthermore, with 399 and 556 nm they are both in a suitable area and they don't even need a repumping laser. Hence, ytterbium is an ideal candidate for experiments at low temperatures, e.g. studying its collisional properties. But the most interesting experiments that can be performed with ultra cold ytterbium atoms are precision experiments, which will be shown here.

### A.1 Parity nonconservation

Many things in the world that surrounds us exist in two different forms, each being identical to the mirror image of the other, as e.g. hands. These things are called handed or chiral. Their mirror images can be described using the parity operator P which does in effect a space inversion:  $P(\vec{r}) = -\vec{r}$ . In the mirror the images must do the 'opposite' of their originals.

For example, a left-handed molecule that turns the polarization of light clockwise has a right-handed mirror image that turns the polarization counterclockwise. Here, the mirror symmetry is conserved that is identical to parity conservation.

But parity can also be violated: if a cloud of neutral atoms, which are identical to their own mirror images absorb more right- than left-circularly polarized photons, the mirror image of the cloud absorbs more left- than right-polarized photons. Here, the mirror symmetry is broken.

The handedness of the systems treated here arises from interactions preferring one direction in space instead of another. The atomic structure is dominated by the parity conserving electromagnetic interaction but the parity violating weak interaction can play a role as well:

In neutral atoms the valence electrons have a small probability to be found inside the nucleus. There they can interact with the nucleus due to the weak interaction that is transferred in the case of neutral atoms by the neutral vector boson  $Z_0$ . One ideal candidate for the study of this kind of interaction and hence of parity nonconservation (PNC) is the  $(6s^2)^1S_0 \rightarrow (6s5d)^3D_1$  transition in atomic ytterbium (figure A.1): the E<sub>1</sub> amplitude (that is the transition probability due the the electric dipole operator) is strictly forbidden by the parity selection rule and the M<sub>1</sub> amplitude (that is the transition probability due the magnetic dipole operator) is highly suppressed. As the states are eigenstates of the parity operator (even parity) the transition probability given by the dipole operators is zero due to the parity conservation of the dipole operator.



Fig. A.1: Level and decay scheme of the forbidden transitions at 408 nm and 404 nm, where the one at 404 nm is less suitable. The S- and D-levels have an even parity while the P-levels have an odd parity. The decay probabilities from the  ${}^{3}D_{1}$  state into the states  ${}^{3}P_{0}$ ,  ${}^{3}P_{1}$  and  ${}^{3}P_{2}$  are 64%, 35% and 1%, respectively.

But an external electric field can alter the states. In perturbation theory the new states are expressed in the base of the old states and can be understood as mixing even and odd parity states. This results in the Stark-induced transition amplitude  $E_1^{st}$ . If the transition probability is not zero the states are no eigenstates of the parity operator.

The weak interaction can in effect do the same: it alters the states and can also be treated as mixing even and odd states. As the new states are no eigenstates of the parity operator, this results in a PNC-amplitude  $E_1^{PNC}$ .

To determine  $E_1^{PNC}$  the forbidden transition is excited using intense laser light and the interference between  $E_1^{PNC}$  and the far stronger amplitude  $E_1^{st}$ is investigated, measuring the non-forbidden decay rate of the state. Due to a different behavior of the Stark effect and the weak interaction in external electric fields the effects can be 'separated' by measuring the transition probability in varying external electric fields.

Using this technique on single isotopes won't yield satisfying results because in this case the unprecise knowledge of the atomic structure would dominate the uncertainty of the measurement. This knowledge can be obtained from theoretical calculations but the knowledge of the atomic structure of ytterbium is low compared to e.g. cesium. But this disadvantage can be bypassed by measuring the same effect for several isotopes: a measurement depending on number of neutrons can 'replace' the knowledge of the atomic structure because the weak interactions is assumed to be proportional to number of neutrons and therefore ytterbium is an ideal atom with seven stable isotopes (see section 2.10). Measuring the weak interaction means essentially to measure the weak charge  $Q_w$  (in analogy to the electric charge Q) or the weak mixing angle  $\theta_w$ . For a determination of  $\sin^2 \theta_w$  the uncertainty is expected to be in the area of 0.5 - 1% and could top the accuracy of accelerator experiments. To achieve this accuracy a measurement with an accuracy of  $\sim 10^{-4}$  for the six most common isotopes must be achieved.

Furthermore, the so-called anapole moment of the nucleus can be determined: the anapole moment describes the interaction between a chiral nuclearmagnetization component and the valence electrons. Due to its magnetic dependence it can be achieved by the comparison of the PNC-effects on the hyperfine states of <sup>171</sup>Yb and <sup>173</sup>Yb, the only isotopes with a non-vanishing magnetic hyperfine structure.

Further information on PNC can be found in [Bou97b] and on PNC in ytterbium in [DeM95].

### A.2 Permanent electric dipole moment

The Hamiltonian of an atom at rest in an external electric  $(\vec{E})$  and magnetic field  $(\vec{B})$  is given by

$$H \sim \frac{(\vec{d}\vec{E} + \vec{\mu}\vec{B})}{I} \tag{A.1}$$

where  $\vec{d}$  denotes the electric dipole moment,  $\vec{\mu}$  the magnetic dipole moment and I the nuclear spin of the atom. Under the time reversal operation T $(t \to -t)$  the electric field transforms like  $(\vec{E} \to \vec{E})$ , the magnetic field like  $(\vec{B} \to -\vec{B})$  and the nuclear spin like  $I \to -I$ . Hence, for a non-zero EDM the Hamiltonian is not conserved and T is violated.

The PCT-theorem of the standard model of electroweak theory (PCT=1) predicts the PC-operation (parity and charge inversion) to be violated for a violation of T. The standard model predicts the EDM to be  $10^{12}$  times smaller than the current most precise measurements can resolve. But other theories like the supersymmetric theory predict the EDM to be just  $10^2$  times smaller and this region will be available with atom-optical experiments. Hence, measurements on the EDM can help testing the supersymmetric theory.

For a determination of the EDM in atoms, a difference in the Larmor precession frequency, depending on an electric field, being applied parallel and antiparallel to the magnetic field, must be measured. Due to the boson's lack of a magnetic hyperfine structure, only the two fermionic isotopes (which have a nuclear magnetic moment) are suitable for EDM measurements. The second advantage of the heavy ytterbium atom lies in the fact that the EDM is proportional to the electron density at the nucleus and thus proportional to  $Z^2$  [Was02].

# A.3 Optical clock transitions



Fig. A.2: Level and decay scheme of the quasi-forbidden transition at 507.4 nm.

The  $(6s6p)^3D_2 \rightarrow (6s^2)^1S_0$  transition in atomic ytterbium has a lifetime of  $\tau \approx 14.5 \, s$  which is relatively long, compared to most other atomic transitions. This yields a full width at half maximum of  $\Delta \nu = 1/2\pi\tau \approx 11 \,\mathrm{mHz}$ . The relative accuracy of the transition ( $\lambda = 556 \,\mathrm{nm}$ ) is then given by  $\eta = \Delta \nu / \nu = 2.04 \cdot 10^{-17}$  and can top the current most accurate atomic clocks [Was02]. The level scheme is shown in figure A.2.

### Appendix B

# Time of flight temperature measurement

For the time-of-flight temperature measurement (TOF), a probe laser, which is tuned to the atomic transition, is shot on the atomic cloud. If a detector (e.g. a CCD-camera) is placed on the opposite side of the cloud, an absorption image will be obtained. When the magnetic fields are turned off, the cloud starts to fall due to gravity and expands due to the velocities of the atoms. Depending on the temperature of the cloud another falling time is used and therefore it is suitably to position the detector above the cloud. Then only the lenses, which project the cloud onto the detector, must be moved for a different time of flight. Equation 2.34 is too complicated to be used for the analysis of the TOF measurements but therefor a Gaussian approximation is absolutely sufficient. Assuming an elliptical cloud, which is rotationally symmetric around the z-axis, the Gaussian density distribution at t = 0reads

$$n(\vec{r}, v, t = 0) = N \frac{1}{2^3 \pi^3} \frac{\exp\left(-\frac{x^2 + y^2}{2\sigma_{\rho}^2} - \frac{z^2}{2\sigma_z^2} - \frac{v_x^2 + v_y^2 + v_z^2}{2\sigma_v^2}\right)}{\sigma_{\rho}^2 \sigma_z \sigma_v^3} , \qquad (B.1)$$

where the  $\sigma's$  denote the FWHMs for the radial, axial and velocity distribution. After falling for the time t the density distribution reads

$$n(\vec{r},t) = N \frac{1}{2^{3/2} \pi^{3/2}} \frac{\exp\left(-\frac{g^2 t^4/4 + g t^2 y + x^2 + y^2}{2(\sigma_\rho^2 + t^2 \sigma_v^2)} - \frac{z^2}{2(\sigma_z^2 + t^2 \sigma_v^2)}\right)}{(\sigma_\rho^2 + t^2 \sigma_v^2) \cdot (\sigma_z^2 + t^2 \sigma_v^2)^{1/2}} , \qquad (B.2)$$

where g is the acceleration due to gravity in negative y-direction. Setting g = 0 in equation B.2 transforms into the accelerated system. Then the time-dependent behavior of the FWHMs can be determined as:

$$\sigma_{\rho}(t) = \sqrt{\sigma_{\rho}^2(t=0) + t^2 \sigma_v^2}$$
 (B.3)

$$\sigma_z(t) = \sqrt{\sigma_z^2(t=0) + t^2 \sigma_v^2} \tag{B.4}$$

Measuring the density distribution at several times leads hence to  $\sigma_v$  which leads in turn to the temperature.

#### Recapture method

If no absorption imaging system is available, the temperature can be calculated by the recapture method: the MOT is loaded and then turned off for a variable time in the order of 20 ms. In this time the atomic cloud falls and expands as described in equation B.2. In the case of a spherical MOT  $(\sigma_{\rho} = \sigma_z)$  the equation simplifies to

$$n(\vec{r},t) = N \frac{1}{2^{3/2} \pi^{3/2}} \frac{\exp\left(-\frac{g^2 t^4/4 + g t^2 y + x^2 + y^2 + z^2}{2(\sigma_{\rho}^2 + t^2 \sigma_v^2)}\right)}{(\sigma_{\rho}^2 + t^2 \sigma_v^2)^{3/2}} .$$
(B.5)

Right after this time of flight the MOT is turned on and the atoms within the capture region become trapped again (for the signal, obtained by this method, see figure 4.7). The relative amount can be calculated by

$$\eta = \frac{1}{N} \int_{\substack{\text{Capture}\\\text{region}}} n(\vec{r}, t) \, d\vec{r} \tag{B.6}$$

This might be solved with a spherical capture region as well but the achievable accuracy would not justify the effort and thus the capture region is assumed to be cubic. Therefore the equation reads

$$\eta = \frac{1}{N} \int_{-r-r-r}^{+r+r} \int_{-r}^{+r} n(\vec{r}, t) \, dx \, dy \, dz \tag{B.7}$$

and can be expressed using the error function  $\Phi(x)$  (see appendix C) as

$$\eta = \frac{1}{2} \Phi \left( \frac{\sqrt{2}r}{2\sqrt{\sigma_{\rho}^{2} + t^{2}\sigma_{v}^{2}}} \right)^{2} \Phi \left( \frac{\sqrt{2}(t^{2}g + 2r)}{4\sqrt{\sigma_{\rho}^{2} + t^{2}\sigma_{v}^{2}}} \right) - \frac{1}{2} \Phi \left( \frac{\sqrt{2}r}{2\sqrt{\sigma_{\rho}^{2} + t^{2}\sigma_{v}^{2}}} \right)^{2} \Phi \left( \frac{\sqrt{2}(t^{2}g - 2r)}{4\sqrt{\sigma_{\rho}^{2} + t^{2}\sigma_{v}^{2}}} \right) .$$
(B.8)

This integral is too complicated too be solved analytically but the ratio can be plotted for several values of  $\sigma_v$  and the measured values of t. When a satisfying agreement between the equation and the measured results is found, the temperature can be calculated by [Met99]

$$T = \frac{\sigma_v^2 m}{k_B} \,. \tag{B.9}$$

The accuracy of this measurement method is relatively high for short times of flight because then most of the atoms are within the spherical capture region and the agreement with the theoretical cubic capture region is high. For longer times of flight parts of the cloud first leave the spherical capture region without leaving the cubic one and hence the inaccuracy of the method increases.

#### Another method of temperature measurement

It is also possible to determine the temperature in the magnetic trap without the TOF method. When the specifications of the magnetic trap are known, the temperature in the magnetic trap can be calculated from the density distribution, which can be derived from an absorption image.

# Appendix C

# Nomenclature

### Constants

Symbol	Value [Hak96]	Denotation
$k_B$	$1.380658 \cdot 10^{-23} \mathrm{J/K}$	Boltzmann's constant
$\hbar$	$1.0545887  10^{-34}  \mathrm{Js}$	Planck's constant
С	$2.99792458 \cdot 10^8 \mathrm{m/s}$	Light speed
u	$1.66043 \cdot 10 - 27  \mathrm{kg}$	Atomic mass unit
$\mu_B$	$9.2740154 \cdot 10^{-24} \mathrm{Am^2}$	Bohr magneton
$a_0$	$0.529177249 \cdot 10^{-10} \mathrm{m}$	Bohr radius

# Non-straightforward symbols

Symbol	Definition	Denotation
P	$\vec{r} \rightarrow -\vec{r}$	Parity operator
Т	$t \rightarrow -t$	Time reversal operator
C	$Q \rightarrow -Q$	Charge reversal operator
$Q_w$		Weak charge
$\theta_w$		Weak mixing angle
s		Spin
Ι		Nuclear spin

# Functions

Gamma-function [Gra81]

$$\Gamma(\nu) = \int_{0}^{\infty} e^{-t} t^{\nu-1} dt \quad [\operatorname{Re} \nu > 0]$$
  
=  $\frac{1}{\nu} \prod \frac{\left(1 + \frac{1}{k}\right)^{\nu}}{1 + \frac{\nu}{k}} \quad [\operatorname{Re} \nu > 0]$  (C.1)

## Generalized Riemann- $\zeta$ -function [Sch00]

$$g_{\nu}(z) \equiv \frac{1}{\Gamma(\nu)} \int_{0}^{\infty} dx \frac{x^{\nu-1}}{e^{x} z^{-1} - 1}$$
$$\equiv \sum_{l=1}^{\infty} \frac{z^{l}}{l^{\nu}}$$
(C.2)

Error-function [Gra81]

$$\Phi(x) = \frac{2}{\sqrt{\pi}} \int_{0}^{x} e^{-t^{2}} dt$$
 (C.3)

# Bibliography

- [And95] M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman & E. A. Cornell. Observation of Bose-Einstein Condensation in a Dilute Atomic Vapor. *Science*, **269**:198, July 1995.
- [And98] B. P. Anderson & M. A. Kasevich. Macroscopic Quantum Interference from Atomic Tunnel Arrays. Science, 282:1686 – 1689, November 1998.
- [Ash70] A. Ashkin. Acceleration and trapping of particles by radiation pressure. *Physical Review Letters*, **24**:156, 1970.
- [Asp88] A. Aspect, E. Arimondo, R. Kaiser, N. Vansteenkiste & C. Cohen-Tannoudji. Laser Cooling below the One-Photon Recoil Energy by Velocity-Selective Coherent Population Trapping. *Physical Review Letters*, (7):826 – 829, August 1988.
- [Bat01] Alexander Batär. Effiziente Erzeugung Ultrakalter Rubidiumatome. Diplomarbeit, Universität Stuttgart, 5. Physikalisches Institut, Juli 2001.
- [Bin02] Thomas Binhammer. Verdampfungskühlung ultrakalter Chrom-Atome. Diplomarbeit, Universität Stuttgart, 5. Physikalisches Institut, April 2002.
- [Blo99] Immanuel Bloch, Theodor W. Hänsch & Tilman Esslinger. Atom Laser with a cw Output Coupler. *Physical Review Letters*, 82(15):3008, April 1999.
- [Boe96] H. M. J. M. Boesten, A. J. Moerdijk & B. J. Verhaar. Dipolar decay in two recent Bose-Einstein condensation experiments. *Physical Review A*, 54:R29 – R32, July 1996.
- [Bos24] Satyendranath Nath Bose. Plancks Gesetz und Lichtquantenhypothese. Zur Physik, **26**:178 – 181, Juli 1924.
- [Bou97b] Marie-Anne Bouchiat & Claude Bouchiat. Parity violation in atoms. Rep. Prog. Phys., 60:1352 – 1396, 1997.
- [Bre02] B. Brezger, L. Hackermüller, S. Uttenthaler, J. Petschinka, M. Arndt & A. Zeilinger. Matter-wave interferometer for large molecules. *Physical Review Letters*, 88:100404, 2002.

- [Bur02] Keith Burnett, Paul S. Julienne, Paul D. Lett, Eite Tiesinga & Carl J. Williams. Quantum encouters of the cold kind. *Nature*, 416:225 – 232, March 2002.
- [Bur97] E. A. Burt, R. W. Ghrist, C. J. Myatt, M. J. Holland, E. A. Cornell & C. E. Wieman. Coherence, Correlations, and Collisions: What One Learns about Bose-Einstein Condensates from Their Decay. *Physical Review Letters*, **79**:337 – 340, July 1997.
- [Cas01] Yvan Castin. Bose-Einstein condensates in atomic gases:simple theoretical results. *arXiv: cond-mat*, 0105058:1 146, May 2001.
- [Chu85] S. Chu, L. Hollberg, J. E. Bjorkholm, A. Cable & A. Ashkin. Three-Dimensional Viscous Confinement and Cooling of Atoms by Resonance Radiation Pressure. *Physical Review Letters*, 55(1):48, July 1985.
- [Chu86] Steven Chu, J.E. Bjorkholm, A. Ashkin & A. Cable. Experimental Observation of Optically Trapped Atoms. *Physical Review Letters*, 57(3):314, July 1986.
- [Chu98] Steven Chu. The manipulation of neutral particles. *Review Modern Physics*, **70**:685 – 706, 1998.
- [Coh98] Claude N. Cohen-Tannoudji. Manipulting atoms with photons. Review Modern Physics, **70**:707 – 719, 1998.
- [Cou02] Ph. W. Courteille, V. S. Bagnato & V. I. Yukalov. Bose-Einstein Condensation of Trapped Atomic Gases. arXiv: cond-mat, 0109421:1 – 220, September 2001.
- [Dal89] J. Dalibard and C. Cohen-Tannoudji. Laser cooling below the Doppler limit by polarization gradients: simple theoretical-models. Journal of the Optical Society of America B, 6(11):2023, November 1989.
- [Dav95a] Kendall B. Davis, Marc-Oliver Mewes, Michael A. Joffe, Michael R. Andrews & Wolfgang Ketterle. Evaporative Cooling of Sodium Atoms. *Physical Review Letters*, **74**(26):5202, June 1995.
- [Dav95b] K. B. Davis, M.-O. Mewes, M. R. Andrews, N. J. van Druten, D. S. Durfee, D. M. Kurn & W. Ketterle. Bose-Einstein Condensation in a Gas of Sodium Atoms. *Physical Review Letters*, **75**(22):3969, November 1995.
- [DeM99] B. DeMarco & D. S. Jin. Onset of Fermi Degeneracy in a Trapped Atomic Gas. Science, 285(5434):1703, September 1999.

- [Den99] L. Deng, E. W. Hagley, J. Wen, M. Trippenbach, Y. Band, P. S. Julienne, J. E. Simsarian, K. Helmerson, S. L. Rolston & W. D. Phillips. Four-wave mixing with matter waves. *Nature*, **398**(6724):218, March 1999.
- [Die01] Kai Dieckmann. Bose-Einstein Condensation with High Atom Number in a Deep Magnetic Trap. Academisch proefschrift, Universiteit van Amsterdam, March 2001.
- [Don02] Elisabeth A. Donley, Neil R. Claussen, Sarah T. Thompson & Carl E. Wieman. Atom-molecule coherence in a Bose-Einstein condensate. *Nature*, **417**:529, May 2002.
- [Ede85] Christian Edelmann. Vakuumtechnik. VEB Fachbuchverlag, 1985.
- [Ein24] Albert Einstein. Quantentheorie des einatomigen idealen Gases. Sitzungsbericht der Königlich Preußischen Akademie der Wissenschaften, 261 – 267, September 1924.
- [Ein25a] Albert Einstein. Zur Quantentheorie des idealen Gases · Zweite Abhandlung. Sitzungsbericht der Königlich Preußischen Akademie der Wissenschaften, 3 – 14, Januar 1925.
- [Ein25b] Albert Einstein. Zur Quantentheorie des idealen Gases. Sitzungsbericht der Königlich Preußischen Akademie der Wissenschaften, 18 – 25, Februar 1925.
- [Fen92] Paul Feng, Dominikus Hoffmann & Thad Walker. Comparison of trap-losses collision spectra for <sup>85</sup>Rb and <sup>87</sup>Rb. *Physical Review A*, 47(5):R3495 – R3498, May 1993.
- [Gol02] J. Goldwin, S. B. Papp, B. DeMarco & D. S. Jin. Two-species magneto-optical trap with <sup>40</sup>K and <sup>87</sup>Rb. *Physical Review A*, 65(021402):1 – 4, January 2002.
- [Gra81] I. S. Gradstein & I. M. Ryshik. *Tafeln* · *Tables*. Verlag Harry Deutsch, 5th edition, 1981.
- [Gre02] Markus Greiner, Olaf Mandel, Tilman Esslinger, Theodor W. Hänsch & Immanuel Bloch. Quantum phase transition from a superfluid to a MOTT insulator in a gas of ultracold atoms. *Nature*, 415:39 – 44, January 2002.
- [Gri02] Axel Griesmaier. Aufbau einer kombinierten magneto-optischen Falle für Chrom und Rubidium. Diplomarbeit, Universität Stuttgart, 5. Physikalisches Institut, August 2002.
- [Hae75] Theodor W. Hänsch & Arthur L. Schawlow. Cooling of gases with laser radiation. *Opt. comm.*, **13**:68, 1975.

- [Hag99] E. W. Hagley, L. Deng, M. Kozuma, J. Wen, K. Helmerson, S. L. Rolston & W. D. Phillips. A Well-Collimated Quasi-Continuous Atom Laser. Science, 283:1706 – 1709, March 1999.
- [Hak96] Hermann Haken & Hans C. Wolf. *Atom- und Quantenphysik*. Springer, 6th edition, 1996.
- [Hau01a] Chien Liu, Zachary Dutton, Cyrus H. Behroozi & Lene Vestergard Hau. Observation of coherent optical information storage in an atomic medium using halted light pulses. *Nature*, 409:490 – 493, January 2001.
- [Hau01b] Zachary Dutton, Michael Budde, Christopher Slowe & Lene Vestergaard Hau. Observation of Quantum Shock Waves Created with Ultra- Compressed Slow Light Pulses in a Bose-Einstein Condensate. Science, 293:663 – 668, July 2001.
- [Hei02] Rolf Heidemann. Verdampfungskühlung und Bose-Einstein-Kondensation von Rubidiumatomen. Diplomarbeit, Universität Stuttgart, 5. Physikalisches Institut, Juni 2002.
- [Hes84] Harald F. Hess, David A. Bell, Gregory P. Kochanski, Daniel Kleppner & Thomas J. Greytak. Temperature and Magnetic Field Dependence of Three-Body Recombination in Spin-Polarized Hydrogen. *Physical Review Letters*, **52**:1520 – 1523, April 1984.
- [Hes86] Harald F. Hess. Evaporative cooling of magnetically trapped and compressed spin-polarized hydrogen. *Physical Review B*, 34(5):3476, September 1986.
- [Hof93] D. Hoffmann, P. Feng & T. Walker. Measurements of Rb trap-loss collision spectra. Journal of the Optical Society of America B, 712 – 720, 1994.
- [Hua87] Kerson Huang. *Statistical Mechanics*. John Wiley & Sons, 2nd edition, 1987.
- [Ino98] S. Inouye, M. R. Andrews, J. Stenger, H.-J. Miesner, D. M. Stamper-Kurn & W. Ketterle. Observation of Feshbach resonances in a Bose-Einstein condensate. *Nature*, **392**:151, March 1998.
- [Ino99] S. Inouye, T. Pfau, S. Gupta, A.P. Chikkatur, A. Görlitz, D. E. Pritchard & W. Ketterle. Phase-coherent amplification of atomic matter waves. *Nature*, **402**:641, December 1999.
- [Kap38] P. L. Kapitzka. *Nature*, **141**:141, 1938.
- [Kas92] Mark Kasevich & Steven Chu. Laser cooling below a photon recoil with three-level atoms. *Physical Review Letters*, 69(69):1741 – 1745, September 1992.

- [Ket96] W. Ketterle & N. J. van Druten. Evaporative Cooling of Trapped Atoms. Advances in atomic, molecular and optical physics, 37(0):181, 1996.
- [Kro02] Sven Kroboth. Laserkühlung von Ytterbiumatomen. Diplomarbeit, Universität Stuttgart, 5. Physikalisches Institut, Oktober 2002.
- [Kuw99] T. Kuwamoto, K. Honda, Y. Takahashi & T. Yabuzaki. Magnetooptical trapping oy Yb atoms using an intercombination transition. *Physical Review A*, 60:R745, 1999.
- [Lid01] David R. Lide. *Handbook of Chemistry and Physics*. CRC press, 82nd edition, 2001 2002.
- [Lof00] T. Loftus, J. R. Bochinski, R. Shivitz & T. Mossberg. Powerdependent loss from an ytterbium magneto-optical trap. *Physical Review A*, **61**:51401, 2000.
- [Lof01] T. H. Loftus. Laser Cooling and Trapping Atomic Ytterbium. Phd thesis, University of Oregon, 2001.
- [Lon38a] F. London. Nature, 141:643, 1938.
- [Lon38b] F. London. On the Bose-Einstein Condensation. *Physical Review*, 54:947, December 1938.
- [Mat99] M. R. Matthews, B. P. Anderson, P. C. Haljan, D. S. Hall, C. E. Wieman & E. A. Cornell. Vortices in a Bose-Einstein Condensate. *Physical Review Letters*, 83(13):2498, September 1999.
- [Mei00] Hendrick L. Bethlem, Giel Berden, Floris M. H. Crompvoets, Rienk T. Jongma, André J. A. van Roij & Gerard Meijer. Electrostatic trapping of ammonia molecules. *Nature*, 406:491 – 494, August 2000.
- [Mei01] Floris M. H. Crompvoets, Hendrick L. Bethlem, Rienck T. Jongma & Gerard Meijer. A prototype storage ring for neutral molecules. *Nature*, 411:174 – 176, May 2001.
- [Met99] Harold J. Metcalf & Peter van der Straten. Laser Cooling and Trapping. Springer, 1999.
- [Mew97] M.-O. Mewes, M. R. Andrews, D. M. Kurn, D. S. Durfee, C. G. Townsend & W. Ketterle. Output Coupler for Bose-Einstein Condensed Atoms. *Physical Review Letters*, **78**(4):582, January 1997.
- [Mey01] Pierre Meystre. Atom Optics. Springer, 2001.
- [Mig85] Alan L. Migdall, John V. Prodan, William D. Phillips, Thomas H. Bergeman & Harold J. Metcalf. First Observation of Magnetically Trapped Neutral Atoms. *Physical Review Letters*, 54(24):2596, June 1985.

- [Nob] The Nobel Prize Museum. www.nobel.se.
- [Phi82] William D. Phillips & Harold J. Metcalf. Laser deceleration of an atomic beam. *Physical Review Letters*, 48:596, 1982.
- [Phi98] William D. Phillips. Laser cooling and trapping of neutral atoms. Review Modern Physics, 70:721 – 741, 1998.
- [Pri83] David E. Pritchard. Cooling Neutral Atoms in a Magnetic Trap for Precision Spectroscopy. *Physical Review Letters*, **51**(15):1336, October 1983.
- [Raa87] E. L. Raab, M. Prentiss, A. Cable, S. Chu & D. E. Pritchard. Trapping neutral sodium atoms with radiation pressure. *Physical Review Letters*, 59(23):2631, December 1987.
- [Rap02] U. D. Rapol, A. Krishna, A. Wasan & V. Natarajan. Laser cooling and trapping of Yb from a thermal source. arxiv: physics, 0209021, 2002.
- [Roa02] G. Roati, F. Riboli, G. Modugno & M. Inguscio. Fermi-Bose quantum degenerate <sup>40</sup>K - <sup>87</sup>Rb mixture with attractive interaction. arxiv: cond-mat, 0205015v1, May 2002.
- [Sch00] Franz Schwabl. *Statistische Mechanik*. Springer, 2000.
- [Sch01] F. Schreck, L. Khaykovich, K.L. Corwin, G. Ferrari, T. Bourdel, J. Cubizolles & C. Salomon. Quasipure Bose-Einstein Condensate Immersed in a Fermi Sea. *Physical Review Letters*, 87(8):80403, August 2001.
- [Ses89] D. Sesko, T. Walker, C. Monroe, A. Gallagher & C. Wieman. Collisional Losses from a Light-Force Atom Trap. *Physical Review Letters*, 63(9):961 – 964, August 1989.
- [Sno89] D. W. Snoke & J. W. Wolfe. Population dynamics of a Bose gas near saturation. *Physical Review B*, **39**(7):4030 – 4037, March 1989.
- [Sue98] T. Südmeyer. Präparation atomarer Ensembles für die Bose-Einstein-Kondensation. Diplomarbeit, Universität Hannover, Fachbereich Physik, 1998.
- [Tow95] C. G. Townsend, N. H. Edwards, C. J. Cooper, K. P. Zetie, C. J. Foot, A. M. Steane, P. Szriftgiser, H. Perrin & J. Dalibard. Phase-space density in the magneto-optical trap. *Physical Review A*, 52(2):1423 – 1440, August 1995.
- [Vog95] H. Vogel. Gerthsen Physik. Springer, 18th edition, 1995.
- [Was02] Homepage University of Washington. Physics Department: Time reversal group. www.phys.washington.edu.

- [Wut92] M. Wutz, H. Adam & W. Walcher. Theorie und Praxis der Vakuumtechnik. Vieweg, 5th edition, 1992.
- [Wyn00] Roahn Wynar, R. S. Freeland, D. J. Han, C. Ryu & D. J. Heinzen. Molecules in a Bose-Einstein Condensate. Science, 287:1016, February 2000.

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