Inelastic bouncing and optical trapping of cold atoms
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Chapter 3

Experimental apparatus and methods

3.1 Introduction

In this chapter we discuss the various parts of the experimental apparatus and methods we used. The most important elements of the apparatus are the vacuum system, several laser systems and the optical imaging system. A more detailed overview of our apparatus can be found in the thesis of D. Voigt [29]. Many of the used techniques are standard in this field of physics and are well documented in the literature.

All our experiments are done in a glass vacuum cell, in order to provide optimum optical access. The experiments follow approximately the following sequence of events. First we create a magneto-optical trap (MOT) by creating a magnetic field gradient at the crossing point of six counterpropagating laser beams. A few million atoms are collected from the background gas in this MOT, and are subsequently cooled to ~ 5 μK by optical molasses. By shutting off the molasses beams, we let the atom cloud fall due to gravity while it expands ballistically. With the use of a 100 mW laser beam, we guide the atoms toward a BK7 glass prism, mounted 6 mm below the MOT. By total internal reflection of a moderate power laser beam (< 80 mW) we create an evanescent wave (EW) potential just above the prism surface. This wave is used to reflect the atoms. For the latter two laser beams we use tapered-amplifiers systems. For the standing wave trapping experiments presented in Chapter 6 we use a Ti:Sapphire laser providing 1 W of optical power. At any given time during the experimental sequence we can image the atomic cloud on a CCD camera using resonant absorption imaging. The whole experiment is controlled by a PC, equipped with an analogue output board, a digital output board and an analogue input board for data acquisition. The interface is based on LabView software, and was developed by H. Alberda (AMOLF Institute, Amsterdam). In the next sections we will discuss some of these elements in more detail.
3.2 Experimental apparatus

3.2.1 Vacuum cell

The experiments are done in a 42 x 42 x 130 mm$^3$ (outside dimensions) glass vacuum cell, with a wall thickness of 4 mm. The glass is uncoated standard “Optical glass” (B 270-Superwite glass). This configuration provides us with excellent optical access to the numerous laser beams. The glass cell is glued with low-vapor pressure epoxy resin (TorrSeal, Varian) on a stainless steel rectangular platform. This platform is mounted on a UHV stainless steel chamber, with a rubidium reservoir. The reservoir is a flexible short spacer tube containing Rb, which can be closed from the UHV by a valve. To increase the Rb pressure in the glass cell, we open this valve and heat the reservoir for a few minutes. The vacuum is maintained by an ion pump, continuously pumping with 15 l/s. We placed a 1.5 mm diameter pinhole between the ion-pump and the glass cell to reduce the pumping speed. Without differential pumping, all rubidium was pumped away within 5 minutes, which manifests itself by a low number of atoms in the magneto-optical trap. With the pinhole inserted, we maintain a nearly constant atom number in the MOT for a few hours. The background vapor pressure below the pinhole is about 10$^{-9}$ mbar, measured by an ionization gauge (UHV-24p, Varian).

Inside the cell, we have mounted a BK7 glass prism, with sizes 10 x 10 x 4 mm$^3$ (01PRB009, Melles Griot, cut in half). The surface quality was specified as better than λ/8 at 632.8 nm, surface quality 20-10 scratch and dig. No surface of this prism was coated.

3.2.2 Lasers

The lasers used to build the magneto-optical trap (MOT), are 50 mW semi conductor diode lasers, producing light around 780 nm (HL7851G, Hitachi) and 795 nm (ML64114R, Mitsubishi).

The starting point is an external grating-stabilized diode laser, in Littrow configuration [30, 31]. The grating feedback enables us to stabilize the laser frequency within an atomic linewidth. The frequency was adjusted by changing the laser current, and by changing the voltage over the piezo-stack on which the grating is mounted. This laser system provides 22 mW of optical power.

To frequency lock this laser, a small RF signal is added to the laser current, creating frequency sidebands. We use 1 mW of laser light for Doppler free saturation spectroscopy [32]. A dispersive absorption signal is obtained by mixing the photodiode signal with the local RF oscillator [33]. This dispersive signal is used as feedback to the laser. Fast oscillations of the frequency are fed back to the laser current, whereas slow drift of frequency is adjusted by the grating. This laser is locked to the cross-over of the $F_g = 2 \rightarrow F_e = 1, 3$ transitions of the $D_2$ line.
Figure 3.1: Schematic overview of the laser system. The MOT master laser and the repumper laser are external grating diode lasers (EGDL), locked to a $^{87}\text{Rb}$ transition by means of Doppler-free spectroscopy. This light is used for two injection locked diode lasers (ILDL). Frequencies were shifted by double-pass AOM configurations. Two tapered-amplifier (TA) diode laser are used. All optical beams are spatially filtered, and transported to the vacuum cell by single mode optical fibers, except for the 1 Watt beam, created by a Ti:Sapphire laser (Ti:Sapph).
## Table 3.1: Overview of different lasers and their properties. The guiding, evanescent wave and trapping laser have a detuning much larger than the hyperfine splitting, and therefore not related to a single $F_g \rightarrow F_e$ transition.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Transition</th>
<th>D line</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOT</td>
<td>$F_g = 2 \rightarrow F_e = 3$</td>
<td>$D_2$</td>
<td>17</td>
</tr>
<tr>
<td>Probe/Imaging</td>
<td>$F_g = 2 \rightarrow F_e = 3$</td>
<td>$D_2$</td>
<td>0.1</td>
</tr>
<tr>
<td>Repumper</td>
<td>$F_g = 1 \rightarrow F_e = 2$</td>
<td>$D_1$</td>
<td>8</td>
</tr>
<tr>
<td>Depumper</td>
<td>$F_g = 2 \rightarrow F_e = 1$</td>
<td>$D_2$</td>
<td>0.05</td>
</tr>
<tr>
<td>Guiding</td>
<td>-</td>
<td>$D_1, D_2$</td>
<td>100</td>
</tr>
<tr>
<td>Evanescent wave</td>
<td>-</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>SW Trapping</td>
<td>-</td>
<td>-</td>
<td>1000</td>
</tr>
</tbody>
</table>

This frequency locked laser light is used in an injection lock scheme, or so-called “master-slave configuration”. The light of the master laser is injected into two slave lasers, which then operate at the same wavelength as the injected light. In this way we only have to lock one laser actively to a spectroscopy signal, and have the ability to use almost all power produced by the two injection-locked lasers. The purposes of the two slave lasers are the following:

### MOT slave

The first slave is used to create the three MOT beams. Before the light of the master laser enters the slave, it is frequency shifted by passing a double-pass acousto-optical modulator (AOM) setup. The tunable AOM was operating around 102 MHz, such that the light is close to the $F_g = 2 \rightarrow F_e = 3$ transition. By adjusting the frequency of the AOM, we could shift the frequency up to $-2\pi \times 60$ MHz from resonance while the slave remains injection locked. The light of this slave is used for the MOT beams. To control its intensity, the light passes an electro-optical modulator (EOM) followed by a polarizing beam splitter. By adjusting the EOM voltage we could maximally reduce the intensity by a factor 200. Full extinction is accomplished by a mechanical shutter (LS2T2, Uniblitz). After passing a single mode optical fiber, the available power is 17 mW, distributed in a Gaussian beam profile with $1/e^2$ radius of 4 mm.

### Probe/depumper slave

The output of the second slave laser is divided into two parts which are both frequency shifted by means of a double-pass AOM configuration. The first part of this light is shifted ‘upwards’ such that it is resonant with the closed $F_g = 2 \rightarrow F_e = 3$ transition. It is used to probe the atoms. The intensity could be changed from 0 to 100% within 0.1 μs by the AOM. The probe is transported to the experiment by a single mode fiber, and provides up to 200 μW.
The second part of the light of this laser is frequency shifted downwards, resonant with the $F_g = 2 \rightarrow F_e = 1$ transition. It is used as a depumper: it optically pumps the atoms from the $F_g = 2$ to the $F_g = 1$ state. Behind a single-mode fiber the power is 50 $\mu$W.

**Repumper laser**

Although the MOT laser is tuned close to the $F_g = 2 \rightarrow F_e = 3$ transition, atoms will also scatter on the $F_g = 2 \rightarrow F_e = 2$ transition, and can thus decay into $F_g = 1$. This state is not trapped by the MOT, and thus will be lost. To prevent this loss, a second laser is needed: the "repumper" laser, resonant with the $F_g = 1 \rightarrow F_e = 2$ transition of the $D_1$ line. The repumper laser is also a external grating stabilized diode laser, using Doppler-free spectroscopy.

### 3.2.3 Tapered amplifier systems

The typical power for the optical guidance of the atoms (Chapter 4) is about 100 mW, where the spatial distribution should be preferably Gaussian. Therefore we used a home-built tapered amplifier (TA) diode laser, described in [35]. The master light is provided by an external-grating stabilized 50 mW diode laser which was not actively locked. The passive drift is a few MHz per hour, which is small compared to the large detuning in the range of 30 - 90 GHz. We could not increase this detuning because we were limited

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Figure 3.2: a) The spectral density of the laser light for two currents of the TA chip (TA-100, TUI Optics). The thick curve represents good locking, whereas for a minor difference in amplifier current the amplifier is not properly locked (thin curve). b) Power behaviour of the tapered amplifier as a function of amplifier current.
by the angle of the feedback grating of the master laser. We measured this detuning by means of a wavemeter (Wavestarr, Burleigh), with an absolute accuracy of 100 MHz, and a relative frequency accuracy of 50 MHz. Due to the stable frequency of the laser, continuous monitoring was not necessary. We split off a fraction of 15 mW, which was amplified by the TA chip to 250 mW. We checked the injection quality by measuring the frequency spectrum of the amplified light with a spectrometer (PC2000, Ocean optics). The transmission through a single mode fiber was only 40% due to the low quality of the spatial beam profile.

To create the evanescent wave potential, we used a second (commercial) tapered amplifier system (Tui optics, TA-100), which is essentially the same configuration as the home built TA system. We monitored the frequency of this laser by splitting off a small fraction of the amplified light, and measured this with the Burleigh wavemeter. We also checked the locking quality of the TA chip with the PC2000 spectrometer, and observed that only frequency locking was possible for some settings of the amplifier current. At some current settings the lock is good, but a minor change in amplifier current resulted in an increase of spectral background. The spectrum of these two possibilities is shown in Fig. 3.2a. Better spatial alignment and other temperature settings of the chip temperature did not solve this problem. Fig. 3.2b shows the power behaviour of the TA as a function of amplifier current, measured at those current settings where locking was good. Also this laser passed a single mode fiber, and the maximum power at the position of the EW was 70 mW. Both lasers could be shut off and on by means of mechanical shutters.

### 3.2.4 Ti:Sapphire laser

The standing wave trap (presented in Chapter 6) is created by a high-power (> 1 W) cw laser beam which is far-off resonant. This light was created by a commercial Ti:Sapphire laser (Coherent, MBR-110) pumped by a 10 W Verdi-10 laser (Coherent). The MBR is a monolithic block resonator, locked to an external cavity, and has a linewidth below 100 kHz. The available spectrum ranges from 760 to 870 nm (P > 1 W). Directly after the laser its mode profile is TEM\(_{00}\). The experiment is positioned 10 meter away from the laser, where the diameter of the beam is about 3 cm. We pass it through a 10:1 telescope, which makes the 1/e\(^2\) radius 0.6 mm at the position of the prism.

### 3.2.5 Creating the MOT

After passing the optical fiber, the linear polarized light to create the MOT beams is split in three parts, each with 4 mm 1/e\(^2\) radius. Before entering the cell, each beam passes a quarter wave-plate in order to make the polarization circular. Each beam passes the cell and is retro-reflected, while passing another quarter wave-plate twice, in order to obtain the necessary \(\sigma^+ - \sigma^-\) configuration. The repumper beam overlaps two of the MOT beams.
(the one in the horizontal plane, and one diagonal beam). Fig. 3.3a shows a photograph where the beam paths are made visible by reducing their size. Directly outside the vacuum cell, a pair of coils create the magnetic trapping field, also visible in Fig. 3.3a,b. They are placed in anti-Helmholtz configuration, producing a magnetic quadrupole field. The current through these coils is 8 A, and the corresponding field gradient at the center is about 15 G/cm. This current is switched off within 25 µs by a power transistor. It should be noted that ideally the radii of the MOT in the axial and radial direction have an aspect ratio 2 : 1. However by changing the relative intensities of the three MOT lasers, a MOT could be produced with essentially any shape.

The MOT was loaded from the background gas in 3 seconds. After capturing the atoms, they are subsequently cooled in molasses for 8 ms. For this purpose the magnetic field gradient is switched off, and the detuning of the MOT laser beams is increased to -10Γ. Simultaneously the intensity of the beams is reduced by 50%. The whole setup is surrounded by 6 larger Helmholtz-coils to compensate any residual surrounding magnetic fields.

3.3 Analysis

3.3.1 Absorption imaging

We detect the cloud by resonant absorption imaging. The general configuration is schematically depicted in Fig. 3.4. A resonant collimated beam passes the region of interest
Figure 3.4: Schematic picture of absorption imaging. A resonant collimated beam passes the atomic cloud which is imaged on a CCD camera by a relay telescope.

where the atoms are located. The probe beam is Gaussian shaped with a $1/e^2$ radius of approximately 5 mm and is linear polarized. The total power is around 100 $\mu$W, with a corresponding saturation parameter in the center of $s \leq 0.2$. The exposure time was chosen as 20 $\mu$s, such that the atoms scatter maximally 50 photons, which cause no blurring due to heating. The atoms absorb the light, creating a shadow in the beam profile. This shadow is imaged onto a CCD camera by a relay telescope setup, with unity magnification. Both lenses are glass doublets (06LA101/76, Melles Griot). The CCD camera is a thermo-electrically cooled, frame transfer camera (Princeton Instruments). It contains 1024 $\times$ 512 pixels of which half is covered by a mask. After the exposure, the image is shifted within 1.6 ms under the mask to avoid further exposure and is read out. The spatial resolution is 15 $\mu$m, and the field of view is 7.8 $\times$ 7.8 mm (512 $\times$ 512 pixels). The initial position of the MOT is just outside field of view.

Figure 3.5: Sequence of absorption images, displaying falling atoms. The dotted line indicates the prism surface.
3.3.2 Quantitative analysis

Consider a probe beam which runs in the $x$ direction. When it has an initial intensity distribution $I_0(y, z)$, the intensity distribution $I(y, z)$ of the probe beam after passing through the cloud is described by the Beer-Lambert law

$$I(y, z) = I_0(y, z) \exp^{-\mathcal{D}(y, z)} = I_0(y, z)e^{-\sigma \pi n(y, z)} \quad (3.1)$$

where $\sigma \pi$ is the photon cross-section for linearly polarized light and $n(y, z)$ the two dimensional column density profile of the atoms. Their product $\mathcal{D}(y, z)$ is called the optical density. Because the probe beam projects the atomic density along the line of sight $\langle \hat{x} \rangle$ the two dimensional density is defined as

$$n(y, z) = \int n(x, y, z) \, dx \quad (3.2)$$

where $n(x, y, z)$ is the three dimensional atomic density.

The resonant absorption cross-section for a two-level atom is written as $\sigma_0 = 3\lambda_0^2/2\pi$. For linearly polarized light, this cross section is averaged over the squared Clebsch-Gordan coefficients ($\Delta m = 0$) of the $F_g = 2 \rightarrow F_e = 3$ transition. This average is found to be

$$\sigma_\pi = \frac{7}{15} \sigma_0 = 13.6 \times 10^{-10} \text{cm}^2 \quad (3.3)$$

To extract the density profile from a CCD image it is not necessary to measure the absolute intensity at the CCD camera. Measurements of relative intensities $I(y, z)/I_0(y, z)$ are sufficient for this purpose. These are measured by taking three images in the following way: First, an absorption image $I_{abs}(y, z)$ of the cloud is taken in the manner described above. A second image is taken with no atoms present, called reference field $I_{ref}(y, z)$ with the same exposure. Afterwards, a third image is taken to record the background.
\( I_{bg}(y, z) \) without atomic cloud and without probe beam. The correct intensity ratio is then obtained by first subtracting the background image before normalizing the absorption image to the reference field image as

\[
\frac{I(y, z)}{I_0(y, z)} = \frac{I_{abs}(y, z) - I_{bg}(y, z)}{I_{ref}(y, z) - I_{bg}(y, z)}
\]

(3.4)

From this ratio we can calculate the column density \( n(y, z) \) with Eq. 3.2.

### 3.3.3 MOT characterization

As an example of analysis of an absorption image, the evolution of the atomic cloud is measured by imaging the atoms at different times after releasing the cloud from the molasses. Fig. 3.5 shows such a typical sequence of images of the falling cloud. Note that for each image the MOT has to loaded again, due to the destructive nature of absorption imaging. When we determine the width of the cloud as a function of time, we can deduce the velocity distribution of the atoms, i.e. the temperature. We define \( t = 0 \) as the moment that the atoms are released. The evolution of the one dimensional density distribution \( n(y, t) \) is written as

\[
n(y, t) = \frac{N_y}{\sigma_y(t) \sqrt{2\pi}} e^{-\frac{y^2}{2\sigma_y(t)^2}}
\]

(3.5)

with the time dependent radial width \( \sigma_y(t)^2 = \sigma_y(0)^2 + \sigma_v^2 t^2 \) and the total number of atoms along the line in y-direction \( N_y \). The relation between the temperature of the cloud and the velocity spread is defined as

\[
\sigma_v = \sqrt{\frac{k_B T}{m}}
\]

(3.6)

where \( k_B \) and \( m \) are the Boltzmann constant and the atomic mass respectively. A typical experimental result of the time evolution of the spatial width is shown in Fig. 3.6. We fitted an initial r.m.s. radius of the cloud of 0.5 mm, and a velocity spread of 23 mm/s, i.e. 5.3 \( \mu \)K. The total number of atoms is obtained by integrating the optical density over the whole image. In this example the total number of atoms \( N = 68 \times 10^6 \). It should be noted that this number is exceptionally high: on a day to day basis we obtained a number around \( N = 15 \times 10^6 \). The temperature was always around 5 \( \mu \)K.
Figure 3.6: Measurement of the r.m.s width of the cloud in the horizontal direction. We fit an initial size of $\sigma_y (t=0) = 0.5 \text{ mm}$, and a temperature of $5.3 \mu \text{K}$ ($\sigma_v = 23 \text{ mm/s}$).