Hot recoils from cold atoms
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5 The Magneto Optical Trap

In this section we introduce the basic principles of laser cooling and trapping. Also discussed in this section are the laser set-up, frequency stabilization and frequency manipulation schemes which use optically non-linear crystals.
5.1 Introduction

One of the most important breakthroughs in atomic physics since the development of the laser was the realization of laser cooling. Laser cooling gave atomic physics unprecedented control over free atoms, culminating eventually in Bose-Einstein condensation\(^{111}\). The concepts of laser cooling were introduced in the 1970’s by Letokhov\(^{112,113}\)(1968) and Ashkin\(^{114,115}\)(1970) and (independently from each other) by Hänisch and Schawlow\(^{116}\) and Wineland and Dehmelt\(^{117}\)(1975). All these concepts make use of the fact that light carries a momentum (Einstein\(^{118}\)(1917)) and that atoms can be deflected by resonant light (Lebedev\(^{119}\)(1910) and Frisch\(^{120}\)(1933)). Laser cooling of ions confined in a Paul rf trap was demonstrated by Neuhauser et al.\(^{121}\) in 1978 and laser cooling of neutral atoms in one dimension was performed by Andreev et al.\(^{122}\) in 1981. Laser cooling in two dimensions was experimentally demonstrated in 1984 by Balykin et al.\(^{123}\) and in 1985, three dimensional cooling (but still no trapping) was demonstrated by Chu et al.\(^{124}\). In 1987 Raab\(^{125}\) et al. added an inhomogeneous magnetic field to the laser beams and created the Magneto-Optical Trap (MOT). The MOT was then still loaded from an atomic beam but in 1990 Monroe\(^{126}\) et al. demonstrated that the MOT could also be loaded from a background gas. The vapour cell MOT was born and it soon became an important workhorse in atomic physics by collecting millions of atoms (atoms like Li, Na,...,Fr, Mg, Ca,...,Ra, He*, Ne*,... \((*=\text{metastable})\)) per second, cooling them to sub-mK temperatures and supplying them for other experiments. For our work the MOT supplies us with a small, ultra-cold Na sample which serves as the target for projectile ions.

5.2 Laser cooling and trapping

The principle of laser cooling makes use of the facts that i) resonant light can exert an enormous force \((>50,000\ \text{times gravity})\) on atoms and ii) this force depends on the atoms’ velocity, both its magnitude and direction.
5.2 Laser cooling and trapping

Figure 5.1: The light forces on an atom depending on its velocity (laser light detuned by \( \delta \) from the resonance frequency \( \nu \)). (a, b): Illustration of the light force \( F \) of one laser beam depending on the atom velocity \( v \). (c) Illustration of the light force \( F \) of two counterpropagating light beams depending on the atom’s velocity \( v \). (d) Calculation of the typical light forces for counterpropagating laser beams (solid line) and the individual laser beams (dashed line) for Na.

Figure 5.1a illustrates the latter point: an atom moves into a laser beam which is tuned at a frequency slightly below the atom’s resonance frequency (”red detuning”). However the Doppler shift due to the atom’s velocity (both magnitude and direction) makes that the atom experiences the laser light again as resonant. The atom absorbs photons from the laser beam and emits them again in all directions. Each absorbed photon delivers a small momentum kick to the atom in the laser beam direction i.e. opposite the atoms direction of motion. The emitted photons however deliver momentum kicks in all directions and these effectively cancel each other. The net result is that the atoms motion in the direction of the laser beam is reduced (provided that this velocity was not too large in the first place). Figure 5.1a,b illustrate that when the atoms velocity in the laser beam direction becomes smaller, the Doppler shift becomes smaller and the induced laser force gets smaller. Figure 5.1c shows an atom moving in between two laser beams and the force indicated in figure 5.1c is now slightly smaller than the force shown in figure 5.1a. This because the laser beam in the direction of the atoms motion (i.e. ”light from the back”) also exerts a small force. Figure 5.1d sums up the information of figure 5.1a-c in a typical acceleration curve of an atom between two counter propagating laser beams. The acceleration (solid curve) is opposite to the atom’s motion but decreases in magnitude as the atom’s velocity becomes too high. The dashed
curves show the light force of the individual beams and one can see that the acceleration can exceed $5 \times 10^5 \text{ m/s}^2$. The force of two red detuned counterpropagating laser beams results in a one dimensional damping of an atom’s motion and is also known as optical molasses i.e. "an atom moving through syrup".

By extension to three pairs of laser beams one can cool the motion of an atom in all directions but one cannot trap an atom. This because the effective laser force approaches zero when the atom velocity goes to zero. The atom can effectively creep out of the laser beam. To create a real trap, the light forces must also be dependent on the atom’s position with respect to the trap center. This can be achieved with the installation of an anti-Helmholz magnetic field (like the Helmholz configuration but with the current through one coil reversed). The magnetic field of such a configuration is zero in the center but increases in all directions. Atoms outside the center will find themselves in a magnetic field and the Zeeman effect will then change the resonance frequency of the atomic transition because the ground and excited states are affected differently by the magnetic field. The Zeeman effect will shift the atom into resonance with the laser beam into the direction of which the atom has moved and the atom is pushed back to the center again. The inhomogeneous magnetic field together with the six red-detuned laser beams of proper polarization (see figure 5.2) make the Magneto-Optical Trap (MOT).

Figure 5.2: The scheme for a Magneto Optical trap as introduced by Raab et al.\textsuperscript{125} and used in this work.
5.3 Theory: trapping and cooling atoms

For a more analytical description of the MOT we will look at the six light forces $F_{i,j}$ where $i$ indicates the three dimensions $(x,y,z)$ and $j=1,2$ the two counterpropagating beams per dimension. When we work out the balance between stimulated absorption and emission per light force $F_{i,j}$ (see van der Straten\textsuperscript{127,128} and Molenaar\textsuperscript{129}) we obtain eq. 5.1 and the force of two counterpropagating laser beams $F_i$ is given in eq. 5.2.

$$F_{i,j} = \frac{h \kappa \Gamma}{2} \frac{s_0}{1 + s_0 + (\frac{2 \delta_{i,j}}{\Gamma})^2}$$  \hspace{1cm} (5.1)

We see that the light forces depend on the the saturation parameter $s_0$ ($= I_0 / I_0$ the light intensity normalized to $I_0$ the saturation intensity of Na), the spontaneous emission rate $\Gamma$, and the detuning $\delta_{i,j}$ (note: $\delta_i < 0$). The detuning $\delta_{i,j} = \delta_l - (kv)_{i,j} - (\frac{\Delta E_e(B) - \Delta E_g(B)}{\hbar})$ consists of the main laser de-tuning $\delta_l$, the Doppler shift $(kv)_{i,j}$ caused by the velocity of the atom and the Zeeman shift $(\frac{\Delta E_e(B) - \Delta E_g(B)}{\hbar})$ caused by the position of the atom will be discussed in more detail later. In first order approximation (small Doppler and Zeeman shifts), $F_i$ (eq. 5.2) depends linearly on the atom’s position $x$ and the atom’s velocity $v$.

$$F_i \approx \frac{8hks_0\delta_l}{2\Gamma} \frac{kv + \alpha x}{(1 + (\frac{2\delta_l}{\Gamma})^2)^2}$$  \hspace{1cm} (5.2)

$$\approx -\kappa x - \beta v$$

The physical origin of the velocity dependence of the force (eq. 5.2) was already discussed in the introduction (see figure 5.1d) and in figure 5.3 we see the ingredients for the position dependence of the light force. First we look at the magnetic field influence on the excited Na levels (figure 5.3a) and on the ground states (figure 5.3b) (a level scheme of Na is given in figure 5.3c). The energy levels show a linear increase or decrease on $B$ (small $B$) depending on their magnetic sub-state $m_F$ (see figure 5.3b: the $F=1$ ground state splits into its 3 $m_F$ states and each $m_F$ state has a different energy change as a function of $B$. To see what two circularly polarized counterpropagating laser beams will do with this Na atom, we first take a step back and look at an ideal 2 level ($J=0,1$) atom placed in a linearly increasing $B$ field. In figure 5.4a we see the $m_J$ sub-states of an ideal 2 level atom and indicated are the transitions that can be made with $\sigma^-$, $\pi$ and $\sigma^+$ polarized light. We now put our atom (at position $z$) in a linearly increasing magnetic field and apply two counter propagating $\sigma^+$ and $\sigma^-$ laser beams of frequency $\nu_{laser}$: figure 5.4b. The de-tuning with respect to the $\sigma^-$ laser beam ($\delta^-$) is much smaller than to the $\sigma^+$ laser beam ($\delta^+$) and the atom will therefore absorb more photons from the $\sigma^-$ laser beam than from the $\sigma^+$ laser beam. For three pairs of counter
Figure 5.3: (a) the Zeeman splitting of the $3^2P_{\frac{3}{2}}$ hyperfine levels in Na. (b) the Zeeman splitting of the $3^2S_{\frac{1}{2}}$ hyperfine levels. (c) overview of the $3^2P_{\frac{3}{2}}$ and $3^2S_{\frac{1}{2}}$ hyperfine levels

propagating laser beams (with polarizations indicated in figure 5.2) the net result is a force $F_i$ ($i=x,y,z$) driving the atom back to the center. The red detuning (i.e. tuning below resonance) also guarantees a damping of the motion (as discussed in the introduction). The restoring force is in fact not equal in all directions since the magnetic field gradient in the $z$ direction (i.e. through the coils figure 5.2) is twice as large as the gradients in $x$ and $y$ directions (parallel to the coils figure 5.2).

With (5.1) one can calculate the basic MOT trapping and cooling capabilities both analytically and numerically. The simplest analytical procedure is to calculate the light force of two counter-propagating beams in one dimension in case the atom stays close to the center and its velocity is small. This force results effectively in a damped harmonic oscillator motion (eq. 5.2) but it is also reasonably straightforward to plug the forces (eq. 5.1) into a computer code which can then track particles, starting somewhere outside the MOT with an initial velocity random both in magnitude and direction, as they interact with the light forces. From this one can get an impression of the MOT’s capabilities to capture background gas depending on parameters such as laser de-tuning, magnetic field gradient, laser power etc.
5.3 Theory: trapping and cooling atoms

Figure 5.4: light forces as a function of the magnetic field. (a) definition of the magnetic field, circular ($\sigma^+$ and $\sigma^-$), and linear ($\pi$) polarization. (b) The atom at position $z'$ is "pushed back to $z=0$" by the $\sigma^-$ beam

Figure 5.5: (a) The probability of a MOT to capture a free Na atom for a very small (5 Gauss/cm) (○) and a larger (15 Gauss/cm) (▲) magnetic field gradient (computer simulated, with $s_0=2, \delta_I=40MHz$). (b) Maxwell-Boltzmann distribution of a Na gas at 330 K
In figure 5.5a two curves are shown of the capture probability versus the initial particle velocity for two different magnetic field gradients. These curves illustrate that with smaller gradients a larger velocity class can be captured but particles with \( v_i > 30 \text{ m/s} \) can usually not be captured (this is in agreement with more realistic MOT simulations performed by Molenaar\textsuperscript{129}). Comparing the capture probabilities with the Maxwell-Boltzmann velocity distribution of Na gas at 330 K (figure 5.5b) makes clear that only a very small fraction of the background gas can be trapped by a MOT.

### 5.4 Theory: trapping and cooling Na

Up to now we only discussed the trapping and cooling of ideal 2-level atoms but now we will go into the specific features of Na trapping and cooling. In figure 5.3 the level schemes of Na(\( 3^2 S_{\frac{1}{2}} \)) and (\( 3^2 P_{\frac{3}{2}} \)) are shown. Important is the hyperfine splitting of the Na(\( 3^2 S_{\frac{1}{2}} \)) ground state with 1772 MHz. These two ground states are coupled to each other by the laser light via the F\(_g=1\rightarrow F_e=0\) transition then all population of the F\(_g=1\) state would eventually be pumped to the F\(_g=2\) ground state. This is caused by the fact that the F\(_g=1\rightarrow F_e=1\) transition is also accidently excited due to the line-widths of the transition and the small Doppler and Zeeman shifts present in the MOT and this excited state can also radiate to the F\(_g=2\) ground state, a state not coupled to the laser light. Similarly the F\(_g=1\) ground state will eventually become exclusively populated when the laser is tuned to the F\(_g=2\rightarrow F_e=3\) transition. To prevent this so-called optical pumping into dark states, a "re-pumper" should be used i.e. a laser which pumps the dark state population back in to the main trapping transition.

The two ground states F\(_g=1\) and F\(_g=2\) turn out to allow two main frequencies to be used for trapping and cooling, namely the F\(_g=2\rightarrow F_e=3\) + re-pumper resulting in a "type I MOT"\textsuperscript{129,130}) and F\(_g=1\rightarrow F_e=0\) + re-pumper ("type II\textsuperscript{129,131}"). The type I is common for all alkali atoms but type II is unique for Na. Both types of MOT's can be produced in our set-up but only the type (I) was used in this work since it turned out to be much smaller (<0.5 mm) in size than the type (II) (~ 5 mm). An extensive theoretical and experimental study on the various MOT types is given by Atutov\textsuperscript{131} et al. where even a type III is introduced, which involves re-pumping via the D\(_1\) (i.e. Na(\( 3^2 S_{\frac{1}{2}} \)) \rightarrow Na(\( 3^2 P_{\frac{1}{2}} \))) line.
5.5 Experiment: trapping and cooling Na

In *Figure* 5.6a,b the optics used to produce the polarized trapping and cooling laser beams is shown schematically. For clarity the three sets of orthogonal light beams (*figure* 5.6) are shown in one plane.

![Diagram of MOT optics](image.png)

**Figure 5.6:** *Schematics of the MOT optics. The light "starts" at the fiber output and then passes through the AOM, the beam expander, beam dump for the "zero order beam" (see text), a 33% beam splitter (BS), 50% beam splitter, 1/4 polarizers (waveplates).*

The light (~150 mW @589 nm and <1 mm) starts in *figure* 5.6 at the output of the "fiber optic delivery system" (Point Source, 10 m long, 50% transmission). This fiber, especially designed for high power, single frequency light transports the laser light from the laser room to the MOT optical table. After the fiber, the light passes the Acousto Optic Modulator (=AOM, Isomet 1205C-2) a device capable of switching and detuning (approximately 60-100 MHz) the light. The basic principle of an AOM is Bragg scattering of light from an acoustic wave, propagating through an optically non-linear crystal. By rotating the AOM with respect to the incident...
laser beam the angle of incidence is varied and 90% transmission into the first order scattered beam can be obtained. The de-tuned first order beam can be separated from the weak, un-detuned zeroth order beam and guided to the beam expander which makes the $2 \text{ cm}$ trapping beams. The zero order laser beam is guided into a beam dump but could in principle also be used for additional laser preparation of the MOT cloud.

The $2 \text{ cm}$ beam is split in three equally strong trapping beams by first splitting 33% off the main beam and then splitting the remaining beam in two equal parts. Each trapping beam is guided through a $\frac{1}{4}$ waveplate to produce the desired circular polarization. By retro-reflecting the three trapping beams into themselves the six beams needed for a MOT are created.

Our MOT observation scheme is shown in figure 5.7a: Two CCD camera are installed for MOT observations: a ”MOT monitor” to observe the MOT from the laser room and a fast gate-able CCD camera (”Master Camera”) with zoom lens to perform dynamic measurements on the MOT (temperature measurements). With the ”mirrors +50% beamsplitter scheme” shown in figure 5.7a we can actually observe the MOT from two directions by only using one CCD camera. One single CCD image now consists of two orthogonal projections of the MOT next to each other (figure 5.7b, the difference in height between the two MOT images is caused
by a small imbalance between the two light paths and has no "physical" origin).

The anti-Helmholtz coils consist each of 20 windings, are water-cooled and can handle over 120 A. We however use them in the 50-80 A region and this corresponds to a magnetic field gradients of 25-40 Gauss/cm. Also installed are so called MOT steering coils i.e. two pairs of small Helmholtz coils (~ 30 windings, ~ 2 A) to produce a small additional homogeneous magnetic field. With these small fields the position of the zero point in the magnetic field gradient can be moved and along with it, the MOT cloud. The steering coils can manipulate the MOT’s y and z position in a range of ~2 mm.

Some sofar unmentioned elements needed for a MOT are a Na oven and an UHV vacuum chamber. The Na oven consists of a stainless steel holder containing a few grams of Na placed in an externally heated flange. The Na vapour pressure can be monitored with a vacuum gauge (5·10^{-10} mbar additional pressure when the oven is on) but better still is to use the MOT itself as a Na pressure gauge (more about this in the next section). The UHV vacuum chamber is shown in figure 6.2 in the recoil momentum spectrometer section.

5.6 Temperature, size, density and Na\(^+_2\) ions

Important properties like MOT temperature, size and density were not discussed in the theoretical part. This because the simple trapping and cooling models, like the damped harmonic oscillator described in as resulting from eq. 5.2 and the very similar computer simulation, result in a zero temperature and infinite density. The theory so far did not consider the random walk constantly performed by the trapped particles under influence of all the laser beams. Due to the stochastic nature of the light forces, particles are also continuously heated and an equilibrium between cooling and heating will eventually be reached. A temperature for the MOT can be estimated\(^{127,129,132}\). The so called Doppler limit \(T_D\) is given by eq. 5.3, with \(\tau=16\) ns.

\[
T_D = \frac{h}{2k_b\tau}
\]

(5.3)

We obtain \(T_D=300\) \(\mu K\) in case of Na.

The most common way to measure the MOT temperature is using the release and re-capture method\(^{124,125,129}\) illustrated in figure 5.8a-c.
Figure 5.8: Illustration of the release and re-capture method. (a) A MOT cloud in equilibrium with the light forces is released (b) by switching off the trapping beams. After a certain time $T$ (approx. $100 \mu s < T < 2\,ms$) the beams are switched on again (c) and the prompt fluorescence indicates the fraction of trapped particles left. From this fraction a temperature can be calculated (see text).

With a TTL signal to the AOM, the trapping beams are switched off for a certain time and the prompt fluorescence after the trapping beams are switched back on is a measure for the MOT cloud’s initial velocity distribution. In figure 5.9 a decay curve of the MOT fluorescence is shown. Also shown in figure 5.9 are small

Figure 5.9: Experimental release and re-capture results. The curve shows the decay of the MOT fluorescence as a function of the MOT offtime (see text). Also shown are the CCD images corresponding to the data points at 100, 300, 500 and 700 $\mu s$ and the "fluorescence halflife" $\tau_{1/2}$. 
MOT images (20 μs exposure) of the Na cloud expanding, loosing fluorescence and even slightly falling due to gravity after the trapping switched off for 100, 300, 500 and 700 μs.

The MOT fluorescence is obtained by integrating the central area of the MOT and this central area is defined as the region inside the FWHM of the unperturbed MOT (unperturbed by laser beam switching). After approximately $\tau_{\frac{1}{2}} = 700$ μs the fluorescence from the MOT central area (0.25 mm in radius) has dropped to its half value. This corresponds to a mean velocity of $v = \frac{0.25 \text{(mm)}}{0.7 \text{(ms)}} \approx 0.35$ m/s and a typical temperature of about $300 \pm 100$ μK. The systematical error in this procedure is quite large, but for now we only need an indication of the MOT temperature. The typical temperatures measured agree well with those from Molenaar\textsuperscript{129} which ranged from 200 to 450 μK. The actual temperature depends mainly on the detuning of the trapping laser: the more tuned to the red the lower the temperature.

Typical diameters of the MOT cloud (i.e. the fluorescing region) are between 0.3 and 1 mm depending on the magnetic field gradient, and perhaps surprisingly on the Na background vapour pressure. High field gradients will produce a small MOT (as predicted by theory) just as low Na pressures will. The latter because a low Na background pressure results in fewer trapped particles, which can occupy a smaller volume because there is an limiting factor to the compactness of a MOT cloud: light scattered by one trapped atom and effectively emitted in all directions from the center of the MOT can be absorbed by another trapped atom, effectively pushing this atom away from the MOT center. This effect makes that with increasing number of trapped particles the MOT size will increase.

Since we would like to measure the small recoil momenta of charged Na particles we usually keep the field gradients below $\sim 35$ Gauss/cm to minimize its influence and control the MOT size mainly with the vapour pressure, whereby the MOT size and fluorescence can be used as a Na pressure gauge. Very small MOT’s can still be obtained at low field gradients (diameter <0.5 mm) but unfortunately the number of trapped particles will then also be very small ($<10^6$), making some experiments from a point of view of count rates very difficult.

Measuring the density of a MOT from its fluorescence is unfortunately not a straightforward matter. The MOT fluorescence $F$ is related to the number of trapped particles $N_t$ by

$$F = \eta_{eff} N_t \rho_e \Gamma$$

(5.4)

where is the solid angle of the CCD camera and $\eta_{eff}$ its detection efficiency, $\rho_e$ the average excited fraction and $\Gamma$ the spontaneous emission rate. There is quite some uncertainty in $\eta_{eff}$ and especially $\rho_e$ which should be obtained from the exact laser de-tuning together with a good theoretical model.\textsuperscript{129,131} All this easily pushes the uncertainty in $N_t$ beyond a few hundred percent. We found that the usual MOT consists of $N_t = 10^6 \pm 1$ atoms, which is somewhat less than normal\textsuperscript{129} but again, this is because we want small magnetic field gradients and
small MOT sizes. The typical $N_t$'s and MOT sizes result in an approximate target density of $10^{10}$ cm$^{-3}$ and this is actually quite similar again to other Na MOT's. A MOT density of $10^{10}$ cm$^{-3}$ is approximate $10^3$ times the background density ($10^{-9}$ mBar) and the MOT target can still be qualified as a "low - medium density" gas target.

Upto now we did not put in more effort to refine our measurements on $N_t$ up to now for a special reason. The number of particles is only of great importance if we want to determine absolute charge transfer cross sections. But for absolute cross sections we also need the exact overlap between the incident ion beam and the MOT. This will require scanning of the ion beam profile by moving the MOT around and monitoring the Na$^+$ production and this would require re-designing the set-up controls. Absolute cross sections for single electron transfer are however already known within 20% for many collision systems (1-10 keV/u He$^{2+}$, O$^{6+}$, etc. impact$^{133}$), and such a precision would be hard to beat. Normalizing to these known Na$^+$ yields will put all non-single electron capture processes (i.e. multiple electron removal) on a good absolute scale without precisely knowing the MOT density and the target-projectile beam overlap.

In the context of $N_t$ and density measurements we should also mention the Na$^+_2$ MOT-ions. Molecular Na$^+_2$ MOT-ions are produced via associative ionization of excited Na atoms (eq. 5.5):

$$Na(3p) + Na(3p) \rightarrow Na^+_2 + e^-$$ (5.5)

and the production of these ions is quadratically dependent on the MOT density$^{129,132}$. The Na$^+_2$ ions are collected continuously along with the Na$^{q+}$ recoils produced by the incident ion beam. Although we did not use Na$^+_2$ MOT-ions for monitoring the density ($n_t$), they turned out to be very useful for monitoring the exact MOT position (see chapter 6.5) and the spatial focussing properties of the extraction field.

### 5.7 The laser

In Figure 5.10a a schematic of the laser system is shown.
Figure 5.10: The laser set-up: in (a) we see schematically: 1) the Millenia\textsuperscript{Tm} pump laser, 2) the Spectra Physics dye laser, 3) the Spectra Physics Stabilok\textsuperscript{Tm} reference station, 4) the Electro-Optical Modulator (EOM), 5) the fiber in-coupling system, 6) the Saturated Absorption Spectroscopy set-up, 7) the interferometer. (b) illustrates the heart of the EOM: the optically non linear crystal clamped between a folded copper sheet.

The main laser is a ring dye laser (\textit{figure 5.10a2}) Spectra Physics model 380 operating with Rhodamine 6g dye) pumped by a 532 nm solid state laser (\textit{figure 5.10a1}: a Spectra Physics Millennia \textsuperscript{tm}) at 3 W. The dye laser has an output of approximately 400 mW at 589 nm which implies that there is no laser power limitation for our experiments. Although dye lasers may be almost extinct, a Millennia pumped Rhodamine 6g dye laser system is at the moment an unbeaten combination @ 589 nm. The dye laser light is led through a (1\%) beam splitter to split of the beams needed for the Stabilok\textsuperscript{Tm} (\textit{figure 5.10a3}) and the saturated absorption spectroscopy (\textit{figure 5.10a6}). The main beam is then led through the EOM (Electro-Optic Modulator, \textit{figure 5.10a4}). The EOM creates the extra frequency needed for the re-pumping discussed in section 5.4.
The Magneto Optical Trap

Figure 5.11: Laser related spectra: (a) frequency spectrum of the dye laser before and (b) after the EOM. (c) The MOT fluorescence and (d) the cross-over in the absorption spectroscopy (see text); the laser frequencies are manipulated in such a way that the MOT appears nicely on the slope of the cross-over.

The Electro-Optical Modulator consists of an optically non linear crystal (LiTaO$_3$) clamped between a folded copper sheet, (see figure 5.10b) and this LC circuit is then driven by an rf generator at 860 MHz (approximately the LC resonance frequency). The electric field generated in the crystal couples to the incident laser light and induces side bands to the main frequency $\nu_0$ ($\nu = \nu_0 - 860$ MHz, $\nu = \nu_0 + 860$ MHz, see figure 5.11a,b) are introduced. The first order sidebands, used for the main trapping beam and the re-pumper (section 5.4) have a frequency difference of 1720 MHz, an experimentally found best value\textsuperscript{129} (which is not exactly equal to the Na($3^2 S_\frac{3}{2}$) ground state hyperfine splitting of 1772 MHz, because the trapping laser and re-pumper drive excitations to different ($3^2 P_{\pm \frac{1}{2}}$) hyperfine levels). The performance of the EOM is monitored by an interferometer (figure 5.10a7) in combination with an Spectra Physics model 480 + in house built controller.

The dye laser needs to be stabilized both for fast and slow frequency changes. Fast frequency changes like jitter (mainly acoustic noise) and inter-cavity mode-
hops are dealt with by the Stabilok (figure 5.10a3, Spectra Physics model 388 + controller) system. The Stabilok consists of a reference etalon which can correct for jitter by sending a correction signal to a piezo driven mirror in the dye laser cavity and a slave etalon which detects mode hops and corrects for them by sending a signal to the etalon in the cavity. The result is a line-width of the dye laser of a few kHz which is practically mode hop free.

![Diagram](image)

Figure 5.12: The saturated absorption spectroscopy. Highlighted are the two Lamb dips and the Cross-over (see text). The zero point of the frequency scale is the $F_g=1 \rightarrow F_e=0$ transition.

Slow frequency changes are however not noticed by the Stabilok system but for these we can correct by locking the laser to an absolute frequency standard, an atomic transition of the Na atom. We detect the atomic Na transitions by using so-called saturated absorption spectroscopy (figure 5.10a6). This method is based on two light beams (a pump and a much weaker probe beam) counter propagating through a gas cell. We chop the pump light and detect the probe light in coincidence with the chopper. We thus see the influence of the pump beam on the probe beam resulting in a spectrum as shown in figure 5.12. What happens is that at certain frequencies both pump and probe will excite the same ensemble of atoms and the probe will be absorbed less since the pump beam has depleted (via
optical pumping) the ground state population of those atoms. At these frequencies a dip in the absorption is observed and these dips (approximately) correspond to the frequencies of the \( F_g=1 \) and \( F_g=2 \) ground-states (figure 5.3c).

However because the pump and probe beam interact with a Na gas of 120° C (see figure 5.1b for a velocity distribution of Na at 60°) other correlations between pump and probe can also occur: a Na atom moving with a certain velocity \( v \) in the pump beam direction is also moving with a velocity \(-v\) in the probe beam direction (the beams are counter propagating!). The atom will see the pump light with an \( \nu = \nu_0(1+v/c) \) Doppler shift and the probe light with an \( \nu = \nu_0(1-v/c) \) Doppler shift i.e. two different frequencies which can excite two different atomic transitions. For certain velocities the pump can excite a transition from ground state \( F_g=1 \) and the probe beam a transition from the ground-state \( F_g=2 \). The \( F_g=1 \rightarrow F_e = 1 \) and \( F_g=1 \rightarrow F_e = 2 \) transitions driven by the pump will however also decay to the \( F_g=2 \) ground-state. The resulting increase in \( F_g=2 \) population results in extra absorption of the probe light, corresponding to a peak (“the cross-over”, see Molenaar\(^{129}\) for detail) in the spectrum of figure 5.12. The cross-over is located exactly in between the \( F_g=1 \) and \( F_g=2 \) ground states and it is therefore on the crossover where we want to “frequency lock” our dye laser. The first order sidebands of the EOM (figure 5.11b) will then correspond to the Na \( F_g=2 \rightarrow F_e = 3 \) and \( F_g=1 \rightarrow F_e = 2 \) transitions.

In practice one does not want to lock a laser frequency on the cross-over peak itself but on a slope of the cross-over (on a peak one can not detect small frequency changes, on a slope one can). Here the AOM (figure 5.6a2) comes to rescue by adding a 60-100 MHz de-tuning to the laser frequency allowing us to lock the laser on a slope of the cross-over but still have light (after the AOM) of the right frequency.

In figure 5.11 we can see the MOT fluorescence (5.11c) and the absorption spectroscopy signal (5.11d) as a function of the laser frequency. The MOT fluorescence consists of a large peak caused by the type I MOT, (based on the \( F_g=2 \rightarrow F_e = 3 \) transition + repumper, see section 5.4) and a small bump caused by the type II MOT (the \( F_g=1 \rightarrow F_e = 0 \) transition + repumper). The type II is in our case fainter than the type I since we use only moderate laser powers. Atutow\(^{131}\) et al. showed that the type II fluorescence depends much more strongly on the laser power than the type I MOT and that the type II MOT fluorescence will even overtake the type I fluorescence at approximately twice the laser power used in figure 5.11. An order of magnitude more atoms can be trapped in a type II MOT but the type II is also three to five times hotter and an order of magnitude larger in size than the type I.

The laser frequency can be locked anywhere on the cross-over slope and operate the type I MOT at different detunings. The frequency lock is performed by a computer program (a ”software lock”) which takes the absorption spectroscopy
signal as an input (via an ADC and BitBus) and gives a control voltage as an output (on a DAC). This voltage controls a subtle frequency tuning device (“the dual galvo’s”) in the dye laser cavity.

Last but not least, there is the already briefly mentioned fiber (section 5.5) transporting the laser light from the laser room to the MOT set-up. This system consists of a single mode fiber with a light incoupling system ”welded” permanently to it, which in turn is mounted on a precise XY manipulator. A transmission of 50% is achieved with this fiber system, leaving us with enough laser power to trap and cool Na in a type I MOT.

5.8 Conclusion

In this section we discussed all the important theoretical and experimental aspects of our MOT set-up. The Magnetic Optical Trapping of Na is well understood nowadays (Atutov et al.) but it is still important to realize that the MOT is a dynamic equilibrium of six laser beams continuously heating and cooling the atoms from all directions. Any misalignment of the beams or laser frequency instabilities turns out to result in an odd shaped, moving or vibrating MOT. Aligning the laser beams, tuning the dye laser cavity and the saturated absorption spectroscopy are the parts of the MOT set-up which therefore demand constant attention. However with these items optimized, we are able to create stable MOT operating conditions for many hours.