5. Neutralization and Trapping of a Na Ion Beam

For precision measurements of parameters describing nuclear $\beta$-decay one would like to collect atoms in a trap for a time on the order of the lifetime of the investigated radionuclide. An ideal method is to trap neutral atoms in a Magneto Optical Trap (MOT). This allows for manipulating atoms such that they can be studied, e.g. to observe the full kinematics of the recoiling daughter nucleus in a nuclear $\beta$-decay. However, in the TRIUMF facility the thermal ionizer delivers a beam of singly charged ions. In order to be able to feed this ion beam efficiently into a MOT we investigate in this chapter the principles of neutralization of these ions and their subsequent trapping. This will be followed by a discussion of the design and the measured properties of a MOT setup for accumulation of Na atoms.

5.1 Theory of Laser Cooling and Trapping of Atoms

Laser cooling was one of the important breakthroughs in modern (atomic) physics. This technique results from groundbreaking developments in laser technology and atomic spectroscopy. The concept was introduced in the late 1960-s and early 1970-s. It is based on the fact that photons carry a momentum which can be transferred to atoms (see for example [Ashk 70]). The first success on 3-dimensional cooling was reported by [Chu 85] and is known as an optical molasses. Raab [Raab 87] added an inhomogeneous magnetic field to the laser beams and created the first Magneto Optical Trap, which rapidly became a very powerful tool in atomic physics [Adam 97]. A MOT is the most efficient atom trap invented until now and it became a central and essential tool in most experiments which work with cold atoms. In this section we discuss the principles of laser cooling and trapping.

5.1.1 Photon Atom Interaction

Laser cooling is based on the interaction between light and atoms \(^1\). Let us first consider an atomic two-level system. For an atom of mass \(m\) absorbing a
photon, the energy $h\nu$ of the latter is almost entirely converted into internal energy i.e., populating the excited state. The momentum of the absorbed photon $\hbar \mathbf{k}$, where the absolute value of the wavevector is $|\mathbf{k}| = 2\pi/\lambda$, causes the atom to recoil in the direction of incoming light and the atoms velocity is changed by

$$\Delta \mathbf{v} = \frac{\hbar \mathbf{k}}{m}.$$

Between subsequent absorptions of photons the atom returns to the ground state by spontaneous emission. The emitted photon again will change the momentum of the atom, but isotropic emission results in an average of zero momentum transfer after a large number of such events (Fig. 5.1). Therefore the resulting net change in the atoms momentum is directed along the laser beam.

Spontaneous emission is central for laser cooling, since it introduces a dissipation mechanism which is required in any cooling scheme. An absorption can also be followed by a stimulated emission into the driving laser field. In these two processes then no momentum is transferred to the atom, since the momentum transfer in stimulated emission is exactly in the opposite direction of absorption (Fig. 5.1). The acceleration depends on light intensities. Even at arbitrary high light intensity the spontaneous emission rate can not exceed

\footnote{In this chapter we are mainly following the description given in large detail in \cite{Metc99}.}
\[ \dot{\mathbf{a}}_{\text{max}} = \frac{\Delta \mathbf{v}}{2\tau} = \frac{\hbar k \gamma}{m \frac{2}{\tau}} \]

where \( \gamma \) is the spontaneous decay rate which is related to the natural linewidth through \( \gamma = \frac{2}{\linewidth} \).

In this work we are concerned with the Na atom which offers the \( D_2 \) line for optical cooling and trapping. This atom technically realizes a complication-free two-level system. The parameters for the relevant \( ^2S_{1/2} \rightarrow ^2P_{3/2} \) transition are: a wavelength of \( \lambda = 589.16 \) nm corresponding to a transition energy of \( \hbar \omega_a = 2.104 \) eV and a spontaneous decay rate of \( \gamma = 1/\tau = 6.29 \cdot 10^7 \text{s}^{-1} \).

The saturation intensity is \( I_s = \pi hc/3\lambda^3 \tau = 6.4 \) mW/cm\(^2\) for the Na \( D_2 \) line. The atom has a mass of \( m_{Na} = 22.99 \) u. For Na the maximum possible deceleration by laser light is \( 9 \cdot 10^5 \) m/s\(^2\) or \( 10^5 \) g. Therefore, even though a single photon recoil is relatively small, the radiation force can be enormous, since the atom can scatter on resonance up to 30 million photons per second.

The photon scattering rate \( \gamma_p \) depends on the detuning \( \delta_L = \omega_L - \omega_a \), where \( \omega_L \) is the laser frequency and \( \omega_a \) is the atomic resonance frequency. The Doppler-shifted laser frequency, as it is seen by the atoms, must match the atomic transition to maximize the scattering rate, which is given by a Lorentzian

\[ \gamma_p = \gamma \frac{s_0}{1 + s_0 + \left| 2(\delta_L + \omega_D)/\gamma \right|^2}, \]

where \( s_0 = I/I_s \) is the saturation parameter defined as the ratio of the light intensity \( I \) to the saturation intensity. The Doppler shift seen by the atom is \( \omega_D = -\mathbf{k} \cdot \mathbf{v} \). The absorption of (directed) laser light results in a force

\[ \mathbf{F} = \mathbf{a} \cdot m = \hbar k \gamma_p. \]

To decelerate moving atoms the laser beam must be detuned to compensate for the Doppler shift. Let us consider a one-dimensional case. For two laser beams of identical frequency directed opposite to each other the total force is determined by adding the forces exerted by each beam (Eq. 5.4). Atoms moving along the laser beams experience a force which depends on the frequency of the laser light. One single atom will interact in general mostly with only one of the laser beams (unless the velocity is very small). So the net force will be directed against the propagation of the atoms. This damping mechanism is called ‘optical molasses’ (OM). For three orthogonal intersecting laser beam pairs it is possible to achieve significant three-dimensional velocity.
damping of the atoms in the intersection region. This leads to cooling and accumulation of atoms in the region where all laser beams overlap. From equations 5.3 and 5.4 one can calculate the force on atoms in a one-dimensional optical molasses $F_{OM} = F_+ + F_-$, where

$$
F_\pm = \pm \hbar k \frac{\gamma}{2} \frac{s_0}{1 + s_0 + [2(\delta_L \mp |\omega_D|)/\gamma]^2}
$$

This includes stimulated emission as well. For the negative $\delta_L$ the applied force leads to a deceleration of the atoms (see Fig. 5.2). It is maximal close

**Figure 5.2:** Dependence of the acceleration due to the two counter-propagating red detuned laser beams on the Na atom velocity. For the calculation a detuning of $\delta_L = -\gamma$ is taken. The laser power in each beam is 20 mW/cm$^2$. The dotted lines indicate the force from the individual laser beams. The solid line is the total force from (both) counter-propagating laser beams.
to \( v_c \approx \pm \gamma/k \). Since the force is directed against the direction of motion this leads to a damping of the velocity of the atoms. For Na this maximum is at 6 m/s. Experimentally the optical molasses requires balancing of the intensities of the counter-propagating laser beams to about 1%. In an optical molasses the atomic motion is damped and the average velocity is reduced to less than 1 m/s. However, there is no force which would confine atoms in the laser beams. This shortcoming can be overcome by a magneto-optical trap, which will be discussed in the next section.

5.1.2 The Magneto Optical Trap

By combining an optical molasses with a spherical quadrupole magnetic field a trapping potential can be created. Such a trap is called a Magneto-Optical Trap. The inhomogeneous magnetic field creates a position dependent Zeeman splitting of the resonant transition frequencies as shown in Fig. 5.3. The atom is placed between counter-propagating laser beams with opposite circular polarizations (\(|R\) and \(|L|\). The frequency of the laser light itself is red detuned to compensate for the Doppler shift. For simplicity it is assumed that the magnetic field varies linearly with the distance from the center and is equal to zero in the center. Due to the splitting of the atomic magnetic sublevels in the magnetic field the scattering rate \( \gamma_p \) varies with the magnitude of the magnetic field. In this way exited states with \( M_J = +1 \) are shifted upward for positive magnetic fields and the state with \( M_J = -1 \) is shifted downward by the same magnetic field. Selection rules for dipole transitions with \( \sigma^+ \) and \( \sigma^- \) light are \( \Delta M_J = +1 \) and \( \Delta M_J = -1 \), respectively. For an atom at position \( z_0 \) (Fig. 5.3) the detuning \( \delta^- \) is smaller than \( \delta^+ \) and hence it will interact more likely with the \( \sigma^- \) beam than with the \( \sigma^+ \) beam and consequently will be pushed towards the center. The same reasoning can be applied to the atoms at other positions on the \( z \) axis. All atoms are therefore pushed towards and collected in the center (\( z = 0 \)). This picture can be extended to three dimensions (Fig. 5.4) by using (instead of one beam) three mutually orthogonal pairs of counter-propagating laser beams. The magnetic coils are in anti-Helmholtz configuration which gives a zero magnetic field in the center, where all laser beams overlap.

Similarly as for the optical molasses (Eq. 5.5) the total force \( \vec{F} = \vec{F}_- + \vec{F}_+ \) on the atoms is given by

\[
\vec{F}_\pm = \pm \hbar \frac{\gamma}{2} \frac{s_0}{1 + s_0 + [2\delta_\pm/\gamma]^2},
\]  

(5.6)
Figure 5.3: Principle of a one-dimensional MOT for an atom with ground state $J$ and excited state $J+1$. a) Applied magnetic field as a function of distance to the trap center. b) Selection rules for various polarizations of the laser light. c) Schematic illustration of the interaction of an atom with laser light in a MOT.

where we include the Zeeman shift in the detuning for each laser beam

$$\delta_{\pm} = \delta_L \mp \bar{k} \cdot \bar{v} \pm \mu' B/\hbar.$$  \hspace{1cm} (5.7)

Here $\mu' \equiv (g_e M_e - g_g M_g) \mu_B$ is the effective magnetic moment of the transition and $B(r)$ is the position dependent strength of the magnetic field. The
5.1. Theory of Laser Cooling and Trapping of Atoms

![MOT Diagram](image)

**Figure 5.4:** MOT in three dimensions. Three pairs of circular polarized counter-propagating laser beams are combined with a magnetic field generated by two coils carrying a current \( I \) in an anti-Helmholtz configuration. The direction of the electric current (\( I \)) is indicated with arrows. Right and left circular polarization of the laser beams are indicated by \( | R > \) and \( | L > \).

Subscripts \( g \) and \( e \) refer to the ground and excited states, \( g_{(e)} \) is the Landé \( g \)-factor, \( \mu_B \) is the Bohr magneton, and \( M_{g(e)} \) is the magnetic quantum number. In a MOT the atomic density is limited because trapped atoms absorb photons scattered by other trapped atoms, which leads to a repulsive force between the atoms. Owing to these factors the maximal atomic density in the MOT is limited to \( \sim 10^{11}/cm^3 \) [Metc 99].

For Na the level scheme differs from the idealized one (Fig. 5.3), where also \( J \) is the only relevant angular momentum. There is hyperfine splitting of the atomic levels in \( ^{23}\text{Na} \) caused by the nuclear spin of \( 3/2 \). The hyperfine splittings of the \( ^2S_{1/2} \) ground state and \( ^2P_{3/2} \) excited state are shown in Fig. 5.5. When the laser drives the \( F_g = 2 \rightarrow F_e = 3 \) transition, the \( F_e = 2 \) excited state is also accidentally excited due to Doppler and Zeeman shifts, the line-widths of the states involved, non-perfect circular polarization of the laser beams etc. The \( F_e = 2 \) excited state can decay then into the \( F_g = 1 \) ground state, where eventually all atoms would end up, because of this unwanted optical pumping effect. To get atoms back to the cooling cycle a ‘re-pumping’ transition \( F_g = 1 \rightarrow F_e = 2 \) is used. The highest velocity of an atom at which it still can be trapped is called the capture velocity. It depends on the trap parameters: magnetic field gradient, the size of the laser beams and the
Figure 5.5: Left side: Schematic view of the hyperfine splittings of the $^3\!S_{1/2}$ and $^3\!P_{3/2}$ states of Na. $F$ is the total atomic angular momentum and $M_F$ is the projection of the total angular momentum of the atom on the magnetic field axis. Right side: Possible schemes for laser trapping. Thicker arrows indicate possible trapping transitions and thinner arrows show 're-pumping' transitions.

Laser intensity. It can be determined through a simulation of the scattering process. We have (Eq. 5.6)

$$\overrightarrow{a}(\delta, \overrightarrow{r}, s_0) = \frac{\overrightarrow{F}_+ + \overrightarrow{F}_-}{m},$$

(5.8)

for $r$ smaller than the radius of laser beams $r_{\text{laser}}$. The acceleration $\overrightarrow{a}(\delta, \overrightarrow{r}, s_0)$ is a function of the trap parameters: the detuning $\delta$, the position $r$ and the laser saturation intensity $s_0$. The dependence on the velocity $v$ of the atom enters through the detuning $\delta$ (Eq. 5.7). Numerical integration of the equation of motion

$$d\overrightarrow{v} = \overrightarrow{a} \cdot dt = \frac{\overrightarrow{F}_+ + \overrightarrow{F}_-}{m} dt,$$

(5.9)

$$d\overrightarrow{r} = \overrightarrow{v} \cdot dt,$$

(5.10)
5.2 Laser Setup

A dye laser is shared with the Atomic Physics group at KVI. The laser system was originally set up by [Turk 01] and improved subsequently [Knoo 06]. In particular for the requirements of our experiment we improved the stabilization of the dye laser frequency using saturated absorption spectroscopy.

The schematic layout of the laser setup is shown in Fig 5.7. The main laser is the Spectra Physics (Model 380) dye laser (2) which is operated with Rhodamine 6G dye. This laser is pumped by a solid state Millenia laser 532

Figure 5.6: One-dimensional simulation of capture velocity $v_c$ versus laser detuning in units of $\gamma$ ($\gamma = 10$ MHz for Na). The sets correspond to saturation parameters of $s_0 = 0.4, 1.1, 2.1,$ and 3.1. The simulations were made for a magnetic field of 10 G/cm (0.1 T/m) and a trap radius of 1 cm.

have been performed, where the atom starts at the distance $r_l$ for different initial velocities. We determine the maximal velocity $v_c$ for which the atom is still trapped in the trap center. In Fig. 5.6 the result of such a calculation is shown for parameters which are used in our experiment. The maximum capture velocity $v_c$ is shown as a function of laser detuning and saturation parameter $s_0$. For Na $v_c$ is around 30-60 m/s for typical experimental parameters. Since the capture rate is proportional to $v_c^4$ (see Eq. 5.26) it is very important to maximize the capture velocity to obtain the highest trapping efficiency.
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Figure 5.7: Laser setup used for the experiments. (1) Millenia solid state pump laser (3.6 W), (2) Spectra Physics dye laser (≈360 mW), (3) Spectra Physics Stabilock, (4) New Focus resonant EOM (1720 MHz), (5) saturation absorption spectroscopy setup, (6) Photodiode for detection of saturated absorption signal, PID module, (7) fiber launcher and (8) interferometer. (9) Lock-in amplifier to derive saturation spectrum. The signal is fed into a PID controller which allows us to stabilize the laser to the side of the saturated absorption spectrum.

The dye laser needs to be frequency stabilized. This is achieved in two stages. Fast frequency changes are corrected by the Stabilock system (3) (Spectra Physics Model 388). However, slow frequency changes cannot be corrected by the Stabilock system. For trapping of Na atoms the laser fre-
5.2. Laser Setup

Figure 5.8: The intensity distribution of a laser beam after passing through an electro optical modulator at the frequency of 1720 MHz. The intensity of the sidebands is determined by the rf-power to the EOM. For efficient re-pumping of Na atoms the intensity ratio of the carrier to the first order sideband at the higher frequency should be 5:1. The situation indicated in the figure is also acceptable.

Frequency of $5 \times 10^{14}$ Hz needs to be kept in a range of $\pm 15$ MHz absolute. This is achieved by exploiting a saturated absorption signal (Fig. 5.9). In particular for our experimental conditions the high frequency side of the unresolved peak for the $3^2S_{1/2}, F = 2 - 3^2P_{3/2}, F = 1, 2, 3$ transitions is used for stabilization.

A photodiode detects the signal from saturated absorption spectroscopy (Ch. 7 in [Demt 96]). The pump beam is amplitude modulated by a mechanical chopper wheel revolving at around 300 Hz. The photodiode signal is fed into a lock-in amplifier to derive the signal depicted in Fig. 5.9. The error signal for the locking electronics is generated by subtracting an offset voltage. The offset voltage can be varied to scan the laser over a range of about 100 MHz. Shortest scan periods of 100 ms were possible. The light which comes out of the EOM is coupled into an optical fiber of 100 m length via a fiber launcher (7) and transported to the experiment located in a different room. For the experiment we have 70-100 mW laser power available. Although this power is enough for a MOT for Na atoms, optimal performance of the setup requires some 500 mW of laser power. This is due to the fact that for higher capture velocities of the atoms a larger detuning (Fig. 5.6) is needed, which makes more laser power necessary.
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Figure 5.9: Saturation absorption spectroscopy signal recorded with amplitude modulation of the pump beam and lock-in detection. The laser is locked to the high frequency side of the low frequency maximum (indicated with arrow). Cross over resonances within peaks are not resolved. The negative signal is due to cross over resonances. Below the spectrum the position and strength of the Saturated absorption signal (a) and the crossover signals (b) are indicated. The frequency is given relative to the $F = 2 \rightarrow F = 3$ transition.

5.2.1 Design of Efficient Accumulation MOT

The primary goal of this work is to establish an experimental method for efficient loading of Na from an ion beam into a Magneto Optical Trap (MOT). This accumulation MOT has to be optimized concerning neutralization and capture efficiencies. On the other hand the main goal of the $\beta$-decay MOT is to hold trapped atoms as long as possible for the $\beta$-decay measurement. The requirements for the accumulation MOT differ strongly from those for a setup...
Figure 5.10: The grey (red) spectrum shows the number of trapped atoms as a function of the laser frequency relative to the $F = 2 \rightarrow F = 3$ transition. The black (blue) spectrum is a zoom of the spectrum shown in Fig. 5.9. The dotted line represents the resonant transition ($\gamma/2\pi=10$ MHz). We have two different regions in the laser frequency, where we observed trapped atoms. The frequency difference (59 MHz) between these signals was used to calibrate the frequency axis (assuming the trapping transitions indicated in Fig. 5.5).

for $\beta$-decay. The most significant difference is that in the accumulation MOT area a large number of not trapped Na atoms will exist, which also $\beta$-decay and would contribute to a large background in a precision $\beta$-decay experiment in such an environment. Thus we split these two tasks and construct two different MOT setups. Here we focus on the accumulation MOT. The $\beta$-decay experiment itself is carried out in the second MOT, which is loaded with atoms from the first one.

The Na level structure allows for several possible trapping schemes. The first one (type I MOT) is based on the $F_g = 2 \rightarrow F_e = 3$ transition with re-pumping through $F = 1 \rightarrow F = (2, 1)$. Another scheme (type II MOT) is based on the $F_g = 2 \rightarrow F_e = 2$ transition. Here the cooling laser has to be detuned by the splitting of the $F = 2$ and $F = 3$ hyperfine component of the excited state (Fig. 5.5). By scanning the laser frequency we can observe both types in our setup (Fig. 5.10). In our setup the type II MOT is much weaker than the type I MOT, because cooling and re-pumping laser frequencies are
Chapter 5: Neutralization and Trapping of a Na Ion Beam

Table 5.1: Ionization potential $E_{IP}$ and work function $E_{WF}$ for relevant materials. The work functions are taken from [Skri 92].

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_{IP}$(Na)</th>
<th>$E_{WF}$(Y)</th>
<th>$E_{WF}$(Zr)</th>
<th>$E_{WF}$(W)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.139 eV</td>
<td>3.1 eV</td>
<td>4.05 eV</td>
<td>4.55 eV</td>
</tr>
</tbody>
</table>

optimized for the type I MOT. For our experiments we choose the first type because of its larger collection efficiency and higher density of atoms inside the MOT cloud.

5.3 Neutralization Technique

The radioactive $^{20}$Na and $^{21}$Na isotopes are extracted as an ion beam from the thermal ionizer (see Ch. 4.4). They are transported to the accumulator MOT region by an electrostatic transport system and are captured on a thin metal foil. The material for this foil must fulfill several conditions:

- Low work function to extract a large neutral fraction of the evaporated radio-nuclides. This means that there should be a low chemical binding for Na to the material of the foil.
- Large diffusion constant of Na in the foil material.
- Easy to heat to a temperature (low desorption energy) at which Na is released from the surface.
- Low vapor pressure at the high temperatures needed for operation.

In experiments with other alkali elements, K [Gore 00], [Melc 05] and Fr [Aubi 03], [Lips 04], these issues were already addressed. Y and Zr were identified as good candidates for a neutralizer material.

5.3.1 The Neutral Fraction

The Na ions shot into the foil must diffuse rapidly to the front surface and desorb from the foil. The ion to atom ratio evaporated from the surface is determined by three parameters: the work function $E_{EF}$, the temperature T
of the neutralizer material and the ionization potential $E_{IP}$ of Na (5.139 eV). The atom to ion ratio is given by the Langmuir-Saha equation

$$\frac{n_+}{n_0} = \frac{w_+}{w_0} \exp\left(\frac{E_{WF} - E_{IP}}{k_B T}\right),$$

(5.11)

where $w_+$ and $w_0$ are the statistical weights of the ionic and atomic states, respectively, corresponding to the total angular momentum of the states. The ratio of the statistical weights $w_+/w_0 = 1/2$ for all alkali elements [Dinn 96]. We investigated yttrium, zirconium and tungsten foils of 25 μm thickness. The work functions for the materials that we have used are listed in Tab. 5.1. Because $E_{IP} - E_{WF} > 0.5$ eV for all cases the foil can be heated to 1000 K while the fraction of ions remains negligible.

**The Diffusion Time**

The typical kinetic energy of ions impinging upon the neutralizer foil is 1-10 keV. This corresponds to stopping these ions in the neutralizer within a surface layer of thickness 13 nm according to available range tables [Zieg 85]. We want to determine a range of parameters for which the release from the foil is faster than the time scale given by the lifetime of the isotopes of interest.

The distribution of particles inside the foil was calculated with the program SRIM, which determines the stopping and the range of ions in matter based on a quantum mechanical treatment of ion-atom collisions [Zieg 85]. We obtained the depth distribution of ions at various energies from 1 to 6 keV. The results of the simulations are plotted in Fig. 5.11. In the upper part of Fig. 5.11 the implantation depth distribution is shown. The distribution resembles to first order a truncated normal distribution. In the lower part of the figure the ionization density of the particles as a function of implantation depth is shown. Most of the energy is deposited at the surface of the material, regardless of the energy.

We used the simulation package RIBO [Leit 06] to study the dependence of the release time of the neutralizer as a function of the diffusion coefficient $D$. This program allows to solve the diffusion equation in a bulk material from a given starting distribution of particles and a known diffusion constant $D$. For this simulation we used a Gaussian distribution of particles inside the foil given by the straggling range of Na, which itself was obtained with the SRIM program. The fast release of the Na atoms from the surface of the neutralizer is guaranteed, because of the elevated temperature ($\approx 1000$ K).

Values for the diffusion coefficient $D$ which can be found in the TARGISOL databases are listed in Tab. 5.2. The TARGISOL database is the most com-
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Figure 5.11: Implantation of 1 and 6 keV Na ions into a Zr foil. Data taken from SRIM package calculations. In the upper picture the fraction per nm of implanted particles is plotted versus the implantation depth. In the lower part the ionization density of the incident particles versus the implantation depth is plotted.

Table 5.2: Diffusion coefficient calculated by $D = D_0 e^{-E_0 / RT}$, where $R$ is the universal gas constant and $E_0$ is the activation energy. [T]: data are taken from TARGISOL database [TARG 07], [K]: diffusion coefficient scaled from KVI Thermal Ionizer performance [Tray 06b].
5.3. Neutralization Technique

plete database, which combines the data from various sources. Data from this
compilation have been used for developing ISOL targets. Some data in the
database for the very same parameter are not compatible with each other and
depend on the original sources. They must be applied with great caution. For
Na in Y and Zr there are no data available. To get an estimate we used the
data for Na in Ti [TARG 07]. For W the reported $D$ varies by several orders
of magnitude. We take the $D$ values derived from the KVI Thermal Ionizer
performance [Tray 06b]. The approximated $D$ value for W was scaled to 1000
K temperature, which is the typical operation temperature for the neutralizer
foils [Melc 05].

The result of the simulations is presented in Fig. 5.12. For $D > 10^{-13}$ m$^2$/s,
which corresponds to temperatures $> 1200$ K for Na in Ti (see Tab. 5.2), the
release time is less than 100 ms. According to the simulation it is possible to
release $> 90\%$ (for $D > 10^{-14}$ m$^2$/s) of the particles implanted into the foil
in less than 100 ms. The release time scales with $1/D$. For a very small dif-
fusion coefficient ($D \approx 10^{-20}$ m$^2$/s) the main fraction of implanted particles
remains inside the foil for much longer time (longer than the typical lifetime of
particles of interests). In the accumulation MOT setup we have chosen 25 $\mu$m
thick 10x5 mm$^2$ Y and Zr foils at temperatures of about 1000 K (Sec. 5.4.6).

Sticking Time

Although a detailed description of desorption is complicated, for the purpose
of this study we can describe it with a simplified model. The Na atoms are
trapped in a Van der Waals potential close to the surface of the foil. The depth
of the potential is $E_{des}$. The desorption of the Na atom from the neutralizer
is to first order governed by

$$\frac{dN_n}{dt} = -\kappa N_n,$$

where $N_n$ is the number of atoms in the neutralizer and the desorption rate
$\kappa$ is given by

$$\kappa = \nu_0 e^{-\frac{E_{des}}{kT}}.$$  \hspace{1cm} (5.13)

Here $\nu_0$ is the frequency of the vibrating bond between atom and surface. A
typical value for $\nu_0$ is $10^{13}$ s$^{-1}$. For Na on a Zr surface we have $E_{des} = 0.97$
eV. The average sticking time $\tau_s = 1/\kappa$ therefore depends exponentially on
temperature. For Zr we get $\tau_s \approx 10^3$ s at room temperature and 1 $\mu$s at
700 K. Fast desorption requires therefore a heated neutralizer, but still lower
temperatures are required than for fast diffusion, which means that $\tau_s$ is in
our experiment always much smaller than the lifetime of the radionuclide.
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Figure 5.12: Result of RIBO simulations. Differential release in %/s as a function of time for a number of foils. Panels a-c show diffusion out of the titanium foil at 900 K, 1200 K and 1500 K. Panel d shows diffusion out of a tungsten foil at 1300 K. For the simulation we used the stopping range profile for 2-10 keV Na ions (see Fig. 5.11).

Since neutral atom trapping requires Ultra High Vacuum (UHV) conditions the vapor pressure of the heated metal neutralizer foils is important. For Y it is $10^{-11}$ mbar and for Zr and W $< 10^{-15}$ mbar at a temperature of 1200 K.

We performed measurements for a number of neutralizer materials and temperature combinations to find the optimal conditions for neutralization and trapping.

5.3.2 Glass-cell Design for Na Trapping

The accumulation MOT is made of glass because it is UHV compatible and it allows for a very compact design of the MOT. In addition, it can be coated with dryfilm to reduce the sticking of Na atoms to the surface of the vacuum
5.3. Neutralization Technique

vessel. The effective capture volume of the MOT can be a large fraction of the total volume of the cell. The neutralization foil is inside of the glass cell.

In the past two decades many schemes were developed for loading of an atom trap. Since short-lived radioactive atoms can only be obtained in limited quantities, improving the collection efficiency plays a central role in the field and was studied in a number of experiments [Rosa 03], [Aubi 03], [Gore 00], [Lu 97] with K, Na, Rb, Cs, Fr. High efficiency MOT’s for radioactive atoms were reported in [Corw 97] for Rb [Aubi 03] and [Step 94b] for Cs. According to these articles the material and the shape of the MOT chamber is very important for high efficiency performance. The vacuum conditions inside the MOT chamber play also an important role. The vacuum should be better than $10^{-8}$ mbar for a storage time in the trap of larger than 1 s. In the design of the vacuum cell for the trap we considered the trapping efficiency in some detail. In an Appendix to this work we give detailed equations for a determination of trapping efficiencies and the dependence on the geometry and surface properties of the cell.

For modelling the trapping efficiency we assume that the atoms have a velocity distribution of a three-dimensional thermal gas. The normalized distribution is

$$ f(v) \cdot dv = \frac{v^2}{\bar{v}^3} \cdot \sqrt{\frac{2}{\pi}} \cdot e^{-\frac{v^2}{2\bar{v}^2}} \cdot dv, $$

with

$$ \bar{v} = \frac{v_{rms}}{\sqrt{3}} = \sqrt{\frac{k_B T}{m}} $$

where $m$ is the mass of the atom. An estimate of the probability to catch an atom in a single pass through the laser beams is given by (see also [Metc 99])

$$ P_1 = \int_{0}^{v_c} f(v)dv \approx \frac{1}{3} \sqrt{\frac{2}{\pi}} \left( \frac{v_c}{\bar{v}} \right)^3, $$

where $v_c$ is the capture velocity. This shows that for a high capture efficiency a large capture velocity $v_c$ is a prerequisite. The capture velocity can be found by solving the equation of motion using Eq. 5.6 and 5.9 specifying the MOT parameters. For Na and realistic total laser power of 200 mW the capture velocity $v_c$ can be as high as 60 m/s as shown in Fig. 5.6. As the MOT capture rate depends strongly on $v_c$ also the available laser power is highly important. In Fig. 5.13 $P_1$ is shown as a function of temperature for various $v_c$. At room temperature one has $P_1$(Na) $\approx 8 \cdot 10^{-4}$ (Fig. 5.13). The volume from which an atom can be collected is given by the volume which is illuminated by all
six laser beams, if we assume a flat top intensity profile of the laser beams. This volume we call $V_{\text{capture}}$ and it has a surface area of $A_{\text{capture}}$.

The probability to trap an atom increases with the number of passes of the atom through the trapping region and with decreasing velocity of the atoms. Wall collisions allow not only repeated crossing of the trapping region but also thermalize the atoms to the wall temperature of the glass cell of 300 K. Since the wall temperature is lower than the foil temperature these collisions will lower the average velocity of the particles and hence increase the capture probability (Fig. 5.13).

There are two factors, which are important for optimizing the number of passes: the sticking of the atoms to the wall and the escape of atoms through the exit ports of the cell. Both of them must be minimized for optimal performance of the MOT. In general, alkali metals like Na easily share their valence electron with other materials; in other words they stick to them. The dominant attracting force of atoms to the wall is the Van der Waals force.

![Figure 5.13: Single pass capture probability for neutral atoms in a MOT (see Eq. 5.16) as a function of temperature for a number of capture velocities $v_c$ from the thermal gas in three dimensions.](image)
Choosing a coating that minimizes this force will shorten the sticking time of the atoms. We used a dry film coating SC-77 which is based on paraffin (silane based compound) [Step 94a]. This kind of coating is transparent for the laser light. A detailed description of the coating mechanism and instruction on the coating procedure can be found in [Fedc 97].

For the escape of the atoms through the exit ports all cell openings must be small to minimize the escape probability from the cell. The number of passes through the laser volume can be estimated (see Appendix A.1) as

\[ N_{\text{pass}} \approx \frac{A_{\text{capture}}}{A_e + A_s P_s} < \frac{A_{\text{capture}}}{A_e}, \]  

(5.17)

where \( A_{\text{capture}} \) is the surface of the volume where the laser beams overlap, \( A_s \) and \( A_e \) are the surfaces of the cell and the exits, respectively. \( P_s \) is the sticking probability.

The best shape of the cell would be a sphere because in this configuration the whole volume of the cell can be illuminated by the MOT beams. However, in such a design the laser light would suffer because the curvature of the glass acts as a lens and external correction lenses would be required. Another option is to use a cubic cell. Assuming 5 cm sides and two exit holes of 10 and 5 mm diameter, which are necessary for the entrance aperture of the atom and the exit aperture for the transport to the \( \beta \)-decay MOT setup. In this case it is possible to get around 80 passes of the atoms inside the overlap region of the laser beams. The manufacturing of cubes with optical-quality glass surface is difficult. Glueing the glass plates together is not an option because the cleaning and coating procedure includes exposure of the cell to chemically active substances that dissolve the glue. A commercially available solution [Inc 06] keeps all essential features of a cube and it is shown in Fig. 5.14.

The cell has 3 ports with standard CF16 flanges. The widest opening of 16 mm inner diameter is for the incoming ions and pumping of the cell. The opposite flange of 11 mm inner diameter is used for inserting the neutralizer. From the various neutralizers we chose Y and Zr as the most promising ones (see Ch. 5.3.1). The third flange in the glass cell has 11 mm inner diameter and is intended for transferring trapped atoms to the \( \beta \)-decay MOT. The diameter of the six windows for the laser beam is 25 mm each. The cell itself is made of Pyrex glass. Fig. 5.15 shows a close up view. The central spot is a cloud of trapped Na. For our glass cell we have \( A_s \approx 100 \text{ cm}^2 \), \( A_{\text{capture}} \approx 20 \text{ cm}^2 \) and \( A_e \approx 4 \text{ cm}^2 \) which were technical compromises accommodating the possibilities of the technical support available at the time of setup. Nevertheless, it allows to study the main features of such a device. The maximum number of passes (Eq. 5.17) is five and it is determined by
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Figure 5.14: Glass vacuum cell for the accumulator MOT. (1) the direction of incoming ions, (2) the direction for particle transfer to the second trap. Location (3) is used for the neutralizer. Opposite to the port (2) is a window for a laser pushing beam, to transport the atoms from the accumulator MOT to the $\beta$-decay -MOT.

Figure 5.15: Atomic $^{23}\text{Na}$ cloud loaded from background gas into the accumulator MOT. The trapped atoms are visible in the center of the glass cell. The vapor pressure of $^{23}\text{Na}$ in the experiment was increased by heating an attached reservoir containing Na metal to about 330 K.
the size of the exit holes. For a large amount of atoms, as they can be made available from a $^{23}$Na heated sample, the single passage efficiency still is sufficient to make a MOT-trapped cloud of atoms visible to the human eye. For radioactive species it will be important to optimize the capture efficiency in particular by increasing the number of passes.

5.4 Commissioning of the Na Accumulator MOT

A schematic drawing of the experimental setup to study the accumulator MOT is shown in Fig. 5.16. Singly charged ions are extracted from a HeatWave Labs (Model HWIG-250) ion gun (1) which delivers ion beams with energies up to several keV and currents up to several 10 nA. After the ion gun, the beam is focused by two Einzel lenses (2) and steered to the neutralizer (4) by two pairs of steering plates (3). The neutralizer can be heated by a direct current supplied via two electrodes spot welded to the neutralizer foil.

The laser light is transported from the dye laser setup to the optics table with a 100 m optical single-mode fiber. It is coupled to the setup by a fiber launcher (5). To define the polarization the laser beam passes a linear polarizer (6). After a beam expander (7) the laser beam is split in three beams of about the same intensity and routed through the MOT glass cell. Circular polarization is produced by quarter wave plates. A magnetic field gradient of up to 0.15 T/m was produced by two 5 cm diameter coils in anti-Helmholtz configuration. The MOT cloud is more confined for a higher magnetic field gradient, but the gradient has only a weak influence on the number of trapped atoms.

To understand the system we performed a number of measurements.

- In the first experiment we exposed the cold (T≈300 K) neutralizer to Na ions from the ion gun for different time intervals. Next the neutralizer was rapidly heated to T ≈ 1000 K by a 2.0 A current, thereby releasing the Na atoms deposited. The time dependence and magnitude of the signal were recorded and the number of trapped atoms was estimated. These measurements were performed in a collect and release cycle. All other measurements were done with the neutralizer at a fixed temperature of T ≈ 1000 K and the ion beam was chopped instead.

- To investigate the influence of the incoming ion energy, a measurement of the number of trapped atoms for different energies and intensities of incoming ions was performed.
Figure 5.16: Accumulator MOT setup scheme. A singly charged Na ion beam from an ion gun (1) is transported through two Einzel lenses (2) and a set of steering plates (3) onto the neutralizer foil (4). The laser light is transported with a single-mode optical fiber from the laser room and coupled to the optical setup by a fiber launcher (4). The beam is linear polarized (5) and expanded (6). To split a laser beam into three retroreflective beams for the MOT operation, two beam splitters (8a, 8b) of 70%:30% and 50%:50% splitting ratio are used.
5.4. Commissioning of the Na Accumulator MOT

An avalanche photodiode S2382 from Hamamatsu with 0.5 mm active area is the heart of the detection system.

![Fluorescent light detection scheme for the accumulator MOT setup.](image)

- To quantify the effect of the dry film coating we compared the number of trapped atoms for coated and uncoated cells.

5.4.1 Detecting the MOT Population

An avalanche photodiode S2382 from Hamamatsu (0.5 mm active diameter) with a built-in preamplifier built at KVI [Damm 06] serves as light detector for the scattered light from the atom cloud in the MOT. The sensitivity is $R_p = 0.2 \text{ V/nW}$ in a 100 Hz bandwidth. The signal is further amplified in a Stanford Research System low noise preamplifier Model 560. The time dependence of the signal is recorded on a storage oscilloscope. For imaging the MOT cloud onto the photodiode we used apertures and a single lens (see Fig. 5.17).

The aperture is necessary to reduce scattered laser light from the surfaces of the glass cell. Furthermore, the imaging system is shielded from other light sources: To reduce the light intensity from the hot neutralizer, we have a narrow band interference filter around 590 nm which has a transmission of $C_f = 50\%$ and a filter width of 10 nm. The interference filter allows to suppress light coming from sources other than Na atoms or the laser including the light from the neutralizer. The sensitivity of this detection system allows to observe the light emitted by as few as about 100 atoms in the MOT cloud.

In order to establish the detection limit we have pursued a dedicated measurement, based on an estimate of scattered light intensity. For a two-level system the power of scattered light of one atom $P_\Omega$ is

$$P_\Omega = \frac{\Omega}{4\pi} \hbar \omega e \gamma_p = \frac{\Omega}{4\pi} \hbar \omega e \gamma \frac{s_0}{2 + s_0 + 4(\delta_L/\gamma)^2},$$

(5.18)
where $e$ is the charge of the electron needed for converting transition energy $\hbar \omega$ from eV to $W \cdot s$. $\Omega$ is the solid angle covered by the optical system. The fluorescence signal $S_F$ detected by the photodiode is related to the number of atoms in the MOT ($N_{MOT}$) by

$$N_{MOT} = \frac{S_F}{C_f \cdot R_p \cdot \Omega},$$

(5.19)

We neglect the light attenuation due to the glass surfaces of the cell, because it is much smaller than the uncertainty in $P_m$. The laser beam of the accumulator MOT with 20 mW per beam ($5.3 \text{ mW/cm}^2$) of laser power remains below the saturation intensity of 6.4 mW/cm$^2$. For scattered light of the MOT the total light intensity from all 6 beams is $\approx 30 \text{ mW/cm}^2$ or $s_0=4.7$. For the current setup the estimated maximal detuning $\delta_L \approx 20 \pm 10 \text{ MHz}$. In this case $\frac{s_0}{1+s_0+4(\delta_L/\gamma)^2} = 0.3 \pm 0.2$. For example, for these parameters the calculated photodiode sensitivity is $(9 \pm 3)10^6 \text{ atoms/V}$. For our measurements we had a noise limit of 10 $\mu$V.

In all experiments the detuning of the laser was chosen such that the MOT fluorescence was maximal. However, the maximum fluorescence does not correspond to the maximum number of particles trapped in the MOT. A model calculation for a 1-dimensional MOT following the approach of [Metc 99] demonstrates this. Simulations were performed for a typical magnetic field gradient of 10 G/cm (0.1 T/m). Figures 5.18 and 5.19 show the dependence of the fluorescence and the number of trapped atoms, respectively, as a function of laser detuning. The detuning is given in units of the linewidth $\gamma$, which is 10 MHz for Na atoms. The maximal number of atoms in the MOT is achieved for $\delta_L = 60 \text{ MHz}$ and the maximum fluorescence is seen at $\delta_L = 20 \text{ MHz}$. This is a combination of two effects: A larger detuning allows for a higher capture velocity of the MOT (Fig. 5.6), which increases the number of trapped atoms (Eq. 5.16). However, a larger detuning $\delta_L$ reduces the power of scattered light of the trapped atoms (Eq. 5.18). There is about a factor of 3 difference in the scattered light intensity for the two optima.

When we are working with stable atoms we tune for maximal fluorescence because this gives the best signal to noise ratio. For radioactive atoms the number of trapped atoms can be determined from the $\beta$-decay rate of stored particles. This means that the MOT capture efficiencies measured in this work can be increased by a factor of three by operating the MOT in a detuning which corresponds to the maximum number of atoms.
Figure 5.18: One-dimensional simulation of the MOT fluorescence versus the laser detuning from resonance in units of $\gamma$. The simulations are performed for saturation parameter of $s_0 = 0.4, 1.1, 2.1$ and $3.1$.

Figure 5.19: One-dimensional simulation for the number of atoms in a MOT versus laser detuning from resonance in units of $\gamma$. The simulations are performed for saturation parameter of $s_0 = 0.4, 1.1, 2.1$ and $3.1$. 
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Figure 5.20: Detection system used for the temperature measurement. \( r_A \) is the radius of the region from which we collect fluorescence on the photodiode and \( r_l \) is the radius of the laser beams.

5.4.2 Temperature of Trapped Particles

The temperature of the atom cloud is important for the design of the transfer system of the atoms to the \( \beta \)-decay MOT. We implemented a method to determine the temperature in a simple way.

Assume we have atoms trapped at a temperature \( T \). The atoms have a velocity distribution according to Eq. 5.14. If the trapping light is switched off for some time \( t_{\text{off}} \) the atoms will fly away with all atoms keeping their individual velocities. The distance \( r \) from the center of the trap changes linearly in time.

\[
    r = v_{\text{avg}} \cdot t. \tag{5.20}
\]

For the average velocity we take \( v_{\text{avg}} = \sqrt{3} \bar{v} \) of Eq 5.15. After some time the atoms have left the region of radius \( r_A \) from which we collect the fluorescence onto the photodiode (Fig. 5.20). Some time later they have left the region of overlap of laser beams. The size of this region is given by the radius \( r_l \) of the laser beams. In the latter case atoms can not be recaptured after the trapping light is switched back on.

In the experiment we collect the fluorescence from the trap center after switching the trapping lasers back on. A fraction of the atoms may still be inside the region of radius \( r_A \), or in the region of laser beams \( r < r_l \), or may have left the trap. If the distance \( r < r_l \) the atoms can be recaptured and they slowly drift to the center of the trap. Thus the fluorescence will increase again as a function of time (Fig 5.21). From a set of such measurements we determine the number of atoms in the trap center by the fluorescence right after the laser was switched back on and the number of atoms that remained still in the full laser covered trapping volume (Fig. 5.22). The
5.4. Commissioning of the Na Accumulator MOT

Figure 5.21: Trap population fraction versus time for a number of time periods $t_{\text{off}}$ in which the trapping laser was switched off.

Figure 5.22: Fraction of atoms inside the imaged volume of the radius $r_A$ (upper plot) and inside of the trapping laser beams (lower plot) versus the time the trapping beams were switched off.

An s-shaped increase of the signal arises from the recapturing of atoms, that remained in the laser-beam overlap region. For a short time of $t_{\text{off}} = 1.2$ ms
a fraction about 40% remains inside the volume imaged on the photodiode. The rise time of this signal is dominated by the response of the photodiode.

The data (Fig. 5.21) show that during the first \(\approx 10\) ms the atoms are recaptured and driven back to the center of the trap. For \(t_{\text{off}} > 10\) ms atoms are lost from the MOT. It takes about 1.5 ms for half of the atoms to travel more than the distance \(r_A\) and \(\approx 20\) ms to move out of the region of trapping beams defined by the radius \(r_l\) (Fig. 5.22).

In the experiment we used a mechanical chopper to block the trapping beams for time ranges from 1.2 ms to 54 ms. We recorded the fluorescence from the center of the trap with a photodiode setup (Fig 5.20). The experimental values are \(r_A = 0.8(2)\) mm and \(r_l = 10(2)\) mm. This together with the times at which 50% of the atoms have left the respective volume (Fig. 5.21) gives an average velocity of 0.8(2) m/s and 0.5(1) m/s, respectively. This corresponds to temperatures of 230(80) \(\mu\)K and 590(240) \(\mu\)K, respectively. The measurement is limited by the accuracy of the radii \(r_A\) and \(r_l\). For a better and more consistent measurement the determination of \(r_A\) and \(r_l\) have to be improved and the Gaussian distribution of the light in a laser beam would have to be taken into account. The extracted temperatures are within the expected range for a Na MOT.

### 5.4.3 Pulsed Release from Neutralizer

In our first measurements we accumulated Na from the ion beam on the neutralizer for a certain period and then released the particles by increasing the neutralizer temperature in a fraction of a second. We observed that the atoms are released in a short time interval from the neutralizer. A typical example of this neutralizer operation is shown in Fig. 5.23. The beam-on time was 60 s at 3 nA of incoming ion beam. The current of implanted ions was measured with a picoampmeter. In this figure the vertical left line indicates the time \(t_{\text{on}}\), when the neutralizer was switched on. The right vertical line indicates, when the ion beam was switched off (\(t_{\text{off}}\)) while the neutralizer remains on. After about another 10 seconds the magnetic field was switched off. This releases all atoms from the MOT and the remaining signal is a measure of the background. The experiment was performed with a non-coated glass cell, which means that we were working in the single path approach where the capture efficiency is determined by \(P_1\) (Eq. 5.16 and A.27).

We recognize three components contributing to the signal:

1. Sudden release of Na atoms in the MOT when the neutralizer is heated.
Figure 5.23: Typical signal of trapped particles as a function of time. Na ions from an ion beam at 0.45 keV were accumulated for 60 s. Then the neutralizer was heated to 1230(50) K. The left vertical line corresponds to the time, when the neutralizer heating is turned on. The right vertical line indicates, when the ion beam is turned off. (a) gives the slow release of the Na from heater support etc. (b) includes the constant ion beam (see Eq. 5.22). (c) is an overall fit of the contributions (a) and (b) plus a contribution from the accumulated particles heated off the neutralizer foil.

This contribution is given by (Eq. A.20/A.27 in Appendix A)

\[ N_{MOT} \approx A \cdot N_0 \cdot e^{-\gamma_{loss}(t-t_{on})}, \]  

(5.21)

where \( A \) can be different depending on a chosen approximation, \( \gamma_{loss} \) is the MOT loss rate due to collisions of trapped atoms with background gas. \( N_0 = R \Delta t \) is the number of ions implanted on the neutralizer for an accumulation time \( \Delta t \) and incoming rate \( R \).

2. A second smaller contribution is due to the steady state situation, where the Na beam is switched on continuously while the neutralizer is heated
(see Eq. A.22/A.30 and Eq. A.24)

\[
N_{\text{MOT}}^{\text{on}} = \frac{A \cdot R}{\gamma_{\text{loss}}} (1 - e^{-\gamma_{\text{loss}} (t-t_{\text{on}})}), \quad (5.22)
\]

\[
N_{\text{MOT}}^{\text{off}} = \frac{A \cdot R}{\gamma_{\text{loss}}} e^{-\gamma_{\text{loss}} (t-t_{\text{off}})}. \quad (5.23)
\]

Here \( R \) is the number of incoming Na ions per second. It is assumed that the loss rate from the cell volume (Eq. A.2 and A.3) is much faster than the loss rate \( \gamma_{\text{loss}} \) from the MOT.

3. The third component is not associated with the ion beam. It is associated with the Na vapor pressure in the cell. Na is released from heated parts of the neutralizer support etc. To restrict the number of parameters in the fit procedure we assume

\[
N_{\text{MOT}} = B \cdot (1 - e^{-\gamma_{\text{loss}} (t-t_{\text{on}})}). \quad (5.24)
\]

These three components were used to fit the data. A typical example is shown in Fig. 5.23. Four parameters were fitted; they were \( t_{\text{on}}, AN_0, \gamma_{\text{loss}} \) and \( B \). The value for \( t_{\text{on}} \) indicates a delay of about 1 s to heat the neutralizer to the operating temperature. Note that the second component does not require an additional parameter, because its amplitude is related to the first by the fraction \((\Delta t \cdot \gamma_{\text{loss}})^{-1}\).

The deduced lifetime of the atoms in the MOT (\( \tau_{\text{MOT}} = 1/\gamma_{\text{loss}} \)) is found to be \( \tau_{\text{MOT}} = 0.41 \pm 0.03 \) s and does not depend significantly on the accumulation time (Fig. 5.24). The lifetime of the MOT can be estimated for low enough pressure \( P \) roughly to \( 10^{-8}/P \) s, where \( P \) is in mbar [Metc 99]. During the experiment the ion pump gauge (Fig. 5.16) indicated \( P = 10^{-8} \) mbar. Therefore, the measured MOT lifetime \( \tau_{\text{MOT}} \) is consistent with this estimate.

Alternatively, the lifetime can be used to determine the cross section of the trapped atoms with the background gas (see Eq. A.17). In this case we find \( \sigma = 1.3 \cdot 10^{-13} \) cm\(^2\). The uncertainty in this measurement comes from the uncertainty of the pressure in the glass chamber itself. The lifetime is consistent with the typical measured value of \( \sigma_{\text{Na-Na}} = 10 \cdot 10^{-13} \) cm\(^2\) and \( \sigma_{\text{Na-N}_2} = 0.3 \cdot 10^{-13} \) cm\(^2\) (see [Pren 88] and [Cabl 90]).

In Fig. 5.25 we show the dependence of \( AN_0 \) on the accumulation time. A linear dependence \( a_0 + b_0 \Delta t \) is observed. One would expect \( a_0 = 0 \) (no accumulation) but \( a_0 = (9.73 \pm 0.4)10^3 \) is found. We attribute this to the fact that an amount of Na will remain on the surface of the neutralizer and
its support even when the ion beam is switched off. This problem will not arise with radioactive atoms. The fitted value of $b_0 = (2.81 \pm 0.14) \times 10^2 \text{ s}^{-1}$ or approximately $10^2 \text{ s}^{-1}$. A similar type of measurement, but for Cs, is described in [Rosa 03]. For Cs a 20 keV ion beam was used. The reported MOT lifetime was $\tau_{MOT} = 1/\gamma_{\text{loss}} = 4.17 \text{ s}$ for $7 \times 10^{-10} \text{ mbar}$ of background pressure. The estimated foil release constant is 1 s. In our case the release time is also of this order for a neutralizer temperature of 1230(50) K. This is much shorter than the lifetime of radio-nuclides of interest ($^{21}\text{Na}$). We are limited by the diffusion (Sec. 5.3) in the neutralizer and not by the rate at which we increase the neutralizer temperature. We can set a limit $D > 10^{-16} \text{ m}^2\text{s}^{-1}$ for the diffusion constant.

5.4.4 MOT Efficiency as Function of Beam Energy

An alternative way to operate the accumulator trap is to keep the neutralizer at high temperature all the time. Then the atoms will be released continuously into the trapping cell. To increase the signal to noise ratio for measurements

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**Figure 5.24:** The lifetime of particles inside the trap as function of the accumulation time of Na ions on the neutralizer.
of the number of trapped atoms we switch the ion beam on and off. In this case we can distinguish better the signal from the trap from the scattered light. The number of trapped particles in a MOT follows the same pattern as the charging and discharging of a capacitor (App. A.2.1). The characteristic loading and decay rate is determined by the background pressure in the trapping cell. We determine the trap loading rate which is directly connected to the trapping efficiency \( \varepsilon \). It is equal to the ratio of the loading rate of particles into the MOT to the rate of incoming particles (Eq. 5.25).

A typical signal is shown in Fig. 5.26. The left vertical line indicates the time when the beam was switched on and the right line, when the beam was switched off. The fit through the data assumes that the MOT population during the ion beam-on period is proportional to \( R (1 - e^{-\gamma_{\text{loss}} t}) \) and during the ion beam-off times it decays exponentially according to \( e^{-\gamma_{\text{loss}} t} \) (Eqs. A.22 and A.23). From Fig. 5.26 we extract \( \tau_{\text{MOT}} = 1/\gamma_{\text{loss}} = 2.37 \pm 0.06 \) s. This figure is few times larger than the value from the previous experiment.
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Figure 5.26: Typical signal of trapped particles as a function of time for a constantly heated neutralizer and a pulsed ion beam. The vertical lines indicate the time interval, for which the ion beam was switched on. The data are fitted according to the Eqs. A.24 and A.23. At the pressure of $\approx 10^{-8}$ mbar the observed MOT lifetime is $\tau_{MOT} = 2.37(6)$ s. Note that for technical reasons the signal is inverted.

Figure 5.27: A signal of trapped particles as a function of time. The vertical lines indicate the time interval, when the ion beam was switched on. The upper panel gives data and a fit result according to Eqs. A.24 and A.23 with one time constant $\tau_{MOT} = 3.57$ s. The lower panel presents the same spectrum after subtraction of the fitted function. The remaining signal is fitted with the function for pulsed mode operation (see Eq. A.26).
indicating that the vacuum conditions were better for experiments described in this section.

In general it is found that the shape of the signals depends on a number of parameters. The leading signal (after the ion beam is switched on) varies strongly as a function of the temperature of the neutralizer. For example, the signal in Fig. 5.27 (lower panel) shows a loading signal which may be due to the sudden shake-off of atoms from the neutralizer surface when the ion beam is switched on. The ion beam stays on long enough to reach equilibrium. Therefore the value of the signal from trapped atoms just prior to switching the beam off is used to characterize the magneto-optical trap. We study the influence of the incoming beam energy on the number of trapped atoms. Data were obtained for 1, 2, 4 and 6.2 keV of Na beam using a cell that was not coated. The results are shown in Fig. 5.28. The fluorescence signal from the trapped atoms is shown as a function of the neutralizer temperature. A 25 μm thick Zr foil was used as neutralizer. The largest signal is obtained for the lowest energy of the incoming ions. It was not possible to achieve a stable ion beam below 1 keV energy. The data are normalized to 1 nA (6.2 · 10^9 p/s) of incoming beam.

The maximum yield in the MOT is (4.6 ± 0.5)·10^3 atoms/nA. Taking the capture efficiency of the MOT as

\[ \varepsilon_c = \frac{N_{MOT}}{R} \tau_{trap} \]

(5.25)

where \( N_{MOT} \) is the number of particles observed in the MOT and \( R \) is the current of implanted ions on the neutralizer surface. The resulting capture efficiency is \( \varepsilon_c = 3 \cdot 10^{-7} \). The capture efficiency contains the factor \( P_1 \) and the efficiency for releasing the implanted atoms (Eq. A.7).

The fact that at 1 keV one observes the highest number of trapped neutral Na atoms suggests that a smaller implantation depth is of advantage (see Fig. 5.11).

### 5.4.5 Coated Cell Measurements

To investigate the effect of a dry-film coating on the glass the experiment was repeated with a coated and a non-coated MOT cell each. Data for 1 keV incoming Na beam are shown in Fig. 5.29.

In both experiments the total laser light power was 75 mW and was stable within 7 %. For the coated cell the maximum yield of trapped atoms was \((2.9 \pm 0.3) \times 10^4 \) atoms/nA. For the non-coated cell this yield is \((4.6 \pm 0.5) \times 10^3 \) atoms/nA. Thus the number of atoms in the trap is 6 times larger than for
5.4. Commissioning of the Na Accumulator MOT

Figure 5.28: Number of particles inside the accumulator MOT as a function of neutralizer temperature. A Zr foil was used as a neutralizer. The error bars are estimated from the reproducibility of selected points. The lines connect the corresponding points. Low implantation energies give a higher neutralization result, because the diffusion time scales with the square of the implantation depth.

The non-coated cell. From the geometry of the glass cell we can estimate that the enhancement factor should approximately scale with the number of bounces, which is about 5 for the current configuration (see Sec. 5.3.2). The next design of the glass cell should accommodate a much higher number of bounces of particles inside the cell, to exploit the enhancement by the dryfilm coating and to significantly increase the efficiency of the setup.

Assuming that all incoming ions will be available for trapping as a uniform vapor we can estimate the capture velocity using Eqs. A.7 and 5.16

\[
\varepsilon_c = \frac{\gamma_{\text{loss}} \cdot N_{\text{MOT}}}{R} = \sqrt{\frac{2}{\pi}} \left( \frac{v_c}{\bar{v}} \right)^4 \cdot N_{\text{pass}}
\]

(5.26)

where \( N_{\text{MOT}} \) is the number of particles trapped and \( R \) corresponds to the number of incoming particles. Eq. 5.26 results in \( v_c = 10.0 \pm 1.1 \) m/s. This
Figure 5.29: Number of particles trapped inside the accumulator MOT as function of the neutralizer temperature for a coated and an uncoated cell. SC-77 dry film was used for coating (Sec. 5.3.2). Zr foil of 25 μm thickness served as neutralizer. The lines are drawn to group corresponding points.

is well below the estimated 30 m/s (see Sec. 5.1.2) for our laser intensity and detuning and may be related to the specific configuration of the trap and the low laser intensity. Our simulation (Fig. 5.6) shows that for increasing the capture velocity the laser detuning from $F_g = 2 \rightarrow F_e = 3$ must be increased up to 60 MHz together with the laser power (≈500 mW and 2 cm diameter).

5.4.6 Release Efficiency for Different Neutralizer Materials and the Role of the Temperature

Three different neutralizer materials were tested. To see which performed better we measured the MOT signal for Y, Zr and W neutralizer materials. For W we did not observe any significant signal associated with the incoming
Figure 5.30: Number of particles inside the accumulator MOT as function of the neutralizer temperature for a SC-77 dry film (see p. 75 and [Step 94a]) coated cell. Zr and Y foils of 25 μm thickness served here as neutralizers. At high temperature the MOT signal is limited by the high residual gas pressure.

ion beam. The reason is most likely the slow diffusion in the foil. This observation is confirmed by the simulation of diffusion in hot metals (see Sec. 5.3 and Fig. 5.12).

For Y and Zr foils (Fig. 5.30) the maximum yield is approximately the same. Both neutralizers differ only in the temperature where the signal is maximal. The temperature was measured with a pyrometer. The emissivity of the materials ($\varepsilon_Y = 0.368$ and $\varepsilon_{Zr} = 0.436$) was accounted for. The precision of the pyrometer measurement is about ±50 K.

A maximum in the number of trapped atoms is reached at 1180 K for Y and at 1400 K for Zr (Fig. 5.30). Towards higher temperatures the number of trapped atoms decreases in both cases. This effect is associated with a pressure increase in the trapping cell.

One of the contributions to the background gas is the vapor pressure of the neutralizer material. It was found that for the temperature range of
1000-1500 K the vapor pressure of Y is higher than of Zr, which is in good agreement with the observed behavior of these neutralizers. At temperatures above 1400 K the vapor pressure of the Zr neutralizer starts to determine the total pressure.

For Zr and Y the resulting number of trapped atoms is at the maximum
about the same, i.e. some $25 \cdot 10^3$/nA (see Fig. 5.30). The Y neutralizer reaches this value at some 220 K lower temperature. Zirconium is less brittle. Therefore it is considered a better choice.

Since the number of trapped atoms scales with the incoming rate times the MOT lifetime $\tau_{MOT}$ we conclude that the highest loading rates were achieved at the highest achievable temperatures. The capture efficiency we get from this measurement at 1400 K is $\approx 8 \cdot 10^{-7}$ and one could expect that this increases towards higher temperatures. In our experiment we were limited to this temperature range. To go further with these neutralizer materials we have to improve the pumping on the glass cell which counteracts the request for smaller pumping holes. For the accumulator MOT a lifetime as short as 100 ms should be feasible since the atoms can be transferred rapidly to the $\beta$-decay MOT for which a much better vacuum can be maintained ($10^{-9}$ mbar).

## 5.5 Conclusion

In this chapter detailed studies of the accumulation MOT were presented. The experiment confirms that we can successfully neutralize and trap stable $^{23}$Na ions.

We used different materials as neutralizers. It was shown that Y and Zr foils work for our system and that a W foil does not. The main reason, why W does not work, is very slow diffusion of Na from the material (Fig. 5.12). Since the neutralizer efficiency is a combination of different material properties, it is possible that alloys or even insulators might have a better performance.

The optimal temperature range for Y and Zr neutralizers was identified. For Y the optimal temperature is around 1180 K and for Zr around 1400 K. The difference can be understood by the difference in the vapor pressures at the operating temperatures for these materials and by different diffusion constants for Na in these materials as well as their different adsorption energies. At lower than the optimal temperatures the MOT signal is limited by the release from the neutralizer and at high temperatures the increasing vapor pressures contribute to the MOT losses.

Our experiments also confirm that diffusion of the particles inside the neutralizer is of importance. The largest MOT signal was obtained for the lowest energy of the incoming beam where the implantation depth is minimal.

The pressure inside the glass cell of the MOT chamber in general plays an important role for the magnitude of the trapped atoms. For MOT optimization a pressure in the range of $10^{-9}$ mbar is necessary.

The coated and uncoated cells were compared with each other. For a
coated cell 6 times more particles were observed in the MOT for otherwise the same experimental conditions (Fig. 5.29). The enhancement factor for a coated cell is approximately equal to the number of bounces which a particle can have on average before escaping from the cell. For the current glass cell design the number of bounces is about 5 (see Sec. 5.3.2). The enhancement factor for the coated cell is in good agreement with the number of bounces inside the cell, if one assumes that in the uncoated cell every second wall collision results in sticking of the atom. In order to increase the efficiency of the MOT it is important to design a cell which can accommodate as many bounces as possible. That requires a larger ratio of surface to exit port area.

Our model calculations for a one-dimensional capture MOT (Fig. 5.6) show that larger laser intensities result in a larger capture velocity. This has a strong impact on the number of trapped atoms (Fig. 5.19) and increases the capture efficiency.