MOTRIMS investigations of electron removal from Na by highly charged ions
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CHAPTER THREE

Experimental setup

3.1 Introduction

In this chapter an overview of the experimental setup is given. The necessity of measuring very small recoil momenta demands two major conditions to be fulfilled. Firstly, a high resolution spectrometer that precisely images the recoil momentum vector of the target particle on a detector is needed. Secondly, the target atoms must have a velocity spread much lower than the velocity resolution needed to resolve different channels, thus a very cold target obtained by laser cooling is used in our experiments.

The target issue is addressed first, starting with a short explanation of the principles of laser cooling and trapping followed by the description of the laser system with its frequency stabilization and the magneto-optical trap. Then the recoil-ion spectrometer is treated including the production of the projectile ions (ion source and beam transport). Finally, the methods used to extract the spectra and to analyze the data are presented.

The construction of the first version of the setup started in 1998 becoming operational in the second half of 2000. A complete overview of the setup is given here with emphasis on the changes compared to previous versions described in the theses of Turkstra [65] and Knoop [36].

3.2 Laser cooling and trapping of Na atoms

In this section we introduce first the principles of laser cooling and trapping followed by the detailed description of our magneto-optical trap for Na together with some
properties relevant to the MOTRIMS technique.

### 3.2.1 Theory of Magneto-Optical Trapping

Laser cooling and trapping are based on the interaction between light and atoms. Let us consider a two-level atom interacting with a laser beam. The atom can absorb a photon, the energy of the latter being almost entirely converted into internal energy exciting the atom from the ground to an excited state. The momentum of the absorbed photon causes the atom to recoil in the direction of the incoming light. Due to the finite lifetime of the excited state, the atom will decay to the ground state between subsequent absorptions by spontaneous emission of a photon. Because the direction in which the photons are emitted is random, the net momentum after a large number of events is on average zero, thus the net force exerted on the atom is in the direction of the laser beam.

![Figure 3.1](image_url)

*Figure 3.1: The light forces on a Na atom depending on its velocity, calculated for two counterpropagating laser beams (—) and the individual laser beams (– –). The laser frequency is one linewidth red-detuned from the resonance frequency and the power in each beam is 20 mW/cm². Note that the acceleration is ∼ 50,000 times the gravitational one (≈ 10 m/s²).*

The Doppler shift associated with the atom’s motion makes this force dependent on the velocity of the atoms. When the component of the atomic velocity in the laser beam directions becomes smaller, the Doppler shift becomes also smaller and the induced laser force decreases.

Fig. 3.1 shows a typical acceleration curve of an atom between two counterpropagating red-detuned laser beams. The acceleration (solid curve) is opposite to the
3.2 Laser cooling and trapping of Na atoms

Figure 3.2: Principle of a one-dimensional MOT for an atom with ground state $j_g$ and excited state $j_e$. a) Applied magnetic field as a function of distance to the trap center and the selection rules for various polarizations of the laser light. b) Schematic illustration of the interaction of an atom with laser light in a MOT.

atom motion resulting in a deceleration of the atom but the acceleration decreases in magnitude if the atom velocity is too high. The dashed curves show the light force of the individual laser beams and one can see that the deceleration can exceed $5 \times 10^5$ m/s$^2$. The force of two red-detuned counter-propagating laser beams results in a one-dimensional damping of an atom’s motion and is known as optical molasses, i.e., “an atom moving through syrup” [66].

By extension, using three pairs of orthogonal laser beams one can cool the motion of an atom in all directions but one cannot trap the atom. This is due to the fact that the effective laser force approaches zero when the atom velocity goes to zero, because of the Doppler shift. Therefore the atom can leak out of the laser beams.

To create a trap the light forces must depend not only on velocity, but also on its position in the trap. This can be achieved by adding a magnetic field produced by two coils in anti-Helmholtz configuration. In such an arrangement the magnetic field is zero in the center but increases in all directions. By combining the magnetic field with the optical molasses produced by the six red-detuned laser beams of proper polarization a trap can be obtained, called Magneto-Optical Trap (MOT) (Fig. 3.3).

The inhomogeneous magnetic field creates a position-dependent Zeeman splitting of the resonant transition frequencies as shown in Fig. 3.2.

The atom is placed between counter-propagating laser beams with opposite circular polarizations ($\sigma^+$ and $\sigma^-$). The frequency of the laser light itself is red detuned
Experimental setup

Figure 3.3: The scheme for a magneto-optical trap as introduced by Raab et al. [67] and used in this work. Six red-detuned circular polarized laser beams are arranged along all six spatial directions. Two coils carrying equal currents in opposite direction create an anti-Helmholtz magnetic field.

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 exited states with $M_J = +1$ are shifted upward for positive magnetic fields and the states with $M_J = -1$ are 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 $z'$ (Fig. 3.2) 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. 3.3) 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.

Na is the target atom in the ion-atom collisions studied in this thesis. Na is one of the most common atomic species in laser cooling and trapping. There is a nuclear spin of $I = 3/2$ in the only stable isotope $^{23}$Na causing a hyperfine splitting of the levels. The energy differences between the hyperfine levels of the Na 3s $^2S_{1/2}$ ground state and the 3p $^2P_{3/2}$ excited state are shown in Fig. 3.4. Our MOT is a Type
3.2 Laser cooling and trapping of Na atoms

Figure 3.4: Hyperfine splitting of the $3s^2 S_{1/2}$ ground state and $3p^2 P_{3/2}$ excited state of Na. The pump frequency is resonant with the $3s^2 S_{1/2}(F=2) - 3p^2 P_{3/2}(F=3)$ transition, while the repump frequency is resonant with $3s^2 S_{1/2}(F=1) - 3p^2 P_{3/2}(F=2)$.

I MOT and operates at the $F_g = 2 \rightarrow F_e = 3$ transition frequency. Due to the linewidth of the transition and the small Doppler and Zeeman shifts present in the MOT, some atoms can be excited accidently to the $F_e = 2$ state and this excited state can also radiate to the $F_e = 1$ ground state, a state not coupled to the laser light. In this way the atoms are leaking out of the cooling cycle. To get these “lost” atoms back into the cooling cycle, a second frequency is used, resonant with the $F_g = 1 \rightarrow F_e = 2$ transition, called the “repumping” laser beam. Note that initially the two ground states are populated statistically, i.e., 3/8 in $F_g = 1$. The repumping laser beam also brings these atoms into the cooling cycle.

Adding an inhomogeneous magnetic field to the optical molasses Chu [66] Raab et al. [67] created the first operational MOT in 1987. The MOT was loaded from an atomic beam and in 1990 Monroe et al. [68] demonstrated for the first time a background loaded MOT. The latter type of MOT is the most common nowadays. Laser cooling and trapping has been described extensively in literature and will not be discussed further here. Details about the principles of laser cooling and trapping of Na within the context of MOTRIMS can be found in [36, 65, 69].
3.2.2 The laser system

The laser used in our experiment is a single-frequency dye laser Spectra Physics model 380D operating with Rhodamine 6G dye [70].

![Beam path in the Model 380D cavity (top view). The spherical folding mirrors M1, M2 and M3 and the flat output coupler M4 fold the beam in a figure-eight path, which is traversed in the direction shown by arrows. The direction is dictated by a unidirectional device. The dye jet intersects the beam perpendicular. 1. astigmatism compensator, 2. dual galvoplates, 3. unidirectional device, 4. thin etalon, 5. scanning etalon and 6. birefringent filter.](image)

The dye laser is pumped by a solid state CW laser (Millennia Vs, Spectra-Physics) with an output wavelength of 532 nm and a maximum power of 5 W. The gain medium in the dye laser is an organic dye dissolved usually in ethylene glycol. Dyes being complex molecules with diffuse energy bands makes possible to continually tune the laser over a broad range (∼ 50 nm). By using different dyes the whole visible wavelength can be spanned with the constraining condition that the photons emitted by the dyes have a lower energy than the ones absorbed. A detailed overview of the working principles of dye lasers can be found in [71].

A schematic of the Spectra Physics 380D dye laser is shown in Fig. 3.5. The ring dye laser resonator is formed by 4 mirrors M1 to M4 which fold the laser beam into a "figure 8" type cavity. The M2 mirror which is mounted on a high-voltage piezoelectric translator (PZT) is used for active stabilization by adjusting the cavity-length.

To scan the frequency of the laser two quartz galvoplates are used which are inserted into the cavity at Brewster’s angle. By rotating the plates consisting of quartz the optical length of the cavity changes because quartz has a significantly higher index of refraction than air. By changing the optical path length in the cavity the laser is scanned in frequency. Two plates are used and by counter-rotating them beam steering of the laser output is eliminated during the scan.
3.2 Laser cooling and trapping of Na atoms

![Diagram of laser system]

**Figure 3.6:** Schematic of the laser system with emphasis on the saturated absorption spectroscopy setup. The main laser beam is split by beamsplitters (BS) into a pump beam and a probe beam. The intensity of the probe beam is measured by a photodiode (PD), and after passing a lock-in amplifier sent to a PID control, used to lock the laser frequency. Also shown are the EOM and the input of the fibre.

This type of cavity can support two counter-propagating standing waves, the laser will oscillate in one direction and might switch direction when it gets perturbed. For stable single-frequency operation it is necessary to suppress one of the travelling waves. This can be done by using an unidirectional device which consists of a Faraday rotator and an optically active element. The polarization of the wave which passes through the device in one direction is rotated while the one which passes in the opposite direction is not rotated. Due to the surfaces at Brewster’s angle situated in the cavity the rotated wave suffers multiple reflections being finally extinguished.

The birefringent filter selects the frequency in the cavity by inducing a frequency dependent polarization rotation. The scanning etalon selects a single cavity mode from the modes which are oscillating through the cavity, the thin etalon being used to prevent mode hopping during a large frequency scan.

The pump laser is operating at an output power from 3.5 to 4.2 W which is converted in the dye laser into 450 to 530 mW of laser light at 589 nm (D\(_2\)-line of sodium). To create the re-pumping frequency needed for the MOT we used an electro-optical modulator (EOM) (Fig. 3.6). The EOM is generating RF sidebands using the equiva-
Figure 3.7: Schematic representation of the laser light intensity output of the 1720 MHz EOM used, normalized to the input intensity. The main frequency (0 sideband) is used as pump while the +1 sideband is used as repump.

ference of phase modulation and frequency modulation in a LiTaO$_3$ crystal. The electric field generated in the crystal by an RF generator couples to the incident laser light and induces side bands to the main frequency. The EOM used is a New Focus model 4421 which operates at 1720 MHz. The zero order which contains 60–80% of the incident laser light is used as a pump frequency while the +1 sideband situated at 1720 MHz corresponding to the difference of the ground state hyperfine splitting and the F=3-F=2 hyperfine splitting of the $^2P_{3/2}$ is used as the repump beam (Fig. 3.7). The performance of the EOM is monitored by an interferometer (Fig. 3.6).

3.2.3 Frequency stabilization of the laser

The bandwidth of our laser is less than 1 MHz and the frequency drift can be less than 50 MHz/hour. Typically the linewidth of a dye laser is determined by the stability of the resonance cavity. The stability can be affected by microphonic vibrations, ambient temperature, humidity and pressure fluctuations and instabilities in the dye jet. Slow perturbations as the temperature and humidity changes can cause
a slow drift of the resonance frequency while strong perturbations can cause mode-hops in the cavity. In order to prevent the mode-hops and to achieve a line width a small as possible the Spectra Physics 380D laser uses a so-called Stabilock System (Fig. 3.8) which stabilizes the frequency by locking it to interferences fringes of two Fabry-Perot etalons. The frequency deviations are detected and corrected by sending feedback signals to the piezo driven M$_2$ mirror and to the galvoplates.

The reference interferometer called master has a free spectral range (FSR) of 500 MHz and the second interferometer called slave has a FSR of 10 GHz. The small frequency deviations can be detected by the master but a mode-hop bigger then two cavity modes (cavity spacing is 200 MHz) will make it to lock the frequency to a different fringe. Therefore the second interferometer, the slave, which has a much bigger FSR sees the mode-hop and takes the control returning the frequency to the right fringe of the master.

The Fabry-Perot interferometer converts frequencies changes in to amplitude changes. In the Stabilock the amplitude changes are measured by photodiodes. In order to make the frequency locking insensible to the intensity fluctuations, both signals from the master and slave photodiodes are normalized to the signal from a photodiode which monitors the primary beam entering into the Stabilock (Fig. 3.8).

However the Stabilock can not correct the slow frequency changes thus a fre-
Experimental setup

Figure 3.9: Saturation absorption spectroscopy signal from the lock-in amplifier (left panel). The laser is locked to the right flank of the low frequency maximum. The frequency is given relative to the $F_g = 2 \rightarrow F_e = 3$ transition. The negative signal is due to the cross over resonances. In the right panel a high resolution scan of the low frequency maximum is shown with the resolved saturated absorption signals corresponding to the hyperfine splitting of the $3p^2 P_{3/2}$ level.

A Na atom in the cell moving with a certain velocity $v$ in the pump beam direction is also moving in the same time with a velocity $-v$ in the probe beam direction because the beams are counter-propagating. Due to the Doppler shift, the same atom will see the pump beam at the frequency $\nu_1 = \nu_L \left( 1 + \frac{v}{c} \right)$ and the probe beam at $\nu_2 = \nu_L \left( 1 - \frac{v}{c} \right)$, where $\nu_L$ is the laser frequency. For certain velocities of the atoms the frequencies $\nu_1$ and $\nu_2$ are equal to hyperfine transition frequencies, those atoms can absorb photons from the pump beam as well as from probe beam. If the pump and probe beams are resonant with the transition from the same ground level the pump beam which is more intense brings the population from the ground level to the excited one and from there the population is going back to both ground levels causing a depletion of the ground level from which both beams are operating. This means that less atoms are available for the probe beam causing a smaller absorption for the probe beam which results in a peak in the intensity. Because of the ground frequency drift of $\sim 50$ MHz being obtained. This has to be compensated for in order to be able to run measurements of several hours, since the frequency range in which the atoms can be trapped is only $\sim 20$ MHz wide. To obtain this we use a saturated absorption spectroscopy signal (Fig. 3.6). A strong pump and a weak probe laser beam of equal frequency pass through a Na vapor cell in opposite directions, the absorption of the probe beam being altered by the presence of the pump beam.
level splitting two peaks are observed, spaced by some 1750 MHz (Fig. 3.9). If the pump and probe beams are resonant with the transition from different ground levels, the pump beam brings part of the population from his ground level via the excited state to the probe beam ground state. Thus, more atoms are available for the probe beam increasing the absorption and resulting in a dip in the probe intensity.

The pump beam is amplitude modulated by means of a mechanical chopper wheel revolving at around 300 Hz. The photodiode signal which is a measure of the intensity of the probe beam is fed into a lock-in amplifier (FEMTO LIA-MV-150) which subtracts the signals with and without the pump beam present deriving the signal depicted in Fig. 3.9. After the lock-in amplifier the signal is sent to a PID (Proportional, Integral and Derivative) controller. A reference voltage from an external stable power supply is fed into the PID and the controller is monitoring the difference between the reference voltage and the signal from the lock-in amplifier. If the frequency changes the signal from the lock-in amplifier is modified, the difference to the reference is changing and thus the PID is sending a feedback to the dye laser to correct the frequency change. In this way stability is obtained over several hours, the frequency drift being $\sim 2$ MHz/hour.

### 3.2.4 Magneto-Optical Trap

The laser system it is placed in a different room in order to protect it from disturbances, the laser light is transported from the laser room to the MOT setup via an optical single mode fibre especially designed for high power single frequency light transport (Point Source, 10 m long, 50% max. transmission).

The laser beam is coupled out of the fibre on the optical table which surrounds the vacuum chamber of the MOT (Fig. 3.10) and passes to the first acusto optical modulator (AOM1, Isomet 1205C-2). The AOM1 is used to switch off the laser beam when the recoil ions are measured, thereby assuring that all the sodium atoms are in the ground state and only collisions with ground state atoms occur. The basic principle of an AOM is Bragg scattering of light from an acoustic wave propagating through an optical 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.

After the first AOM the laser light passes through a $\lambda/2$ plate and a polarization cube, making sure in this way that the light is linearly polarized. The +1 order of the AOM1 which is used as MOT cooling and trapping beam is separated from the zeroth order and guided through a beam expander which expands the beam to a diameter of 2 cm. After being expanded the beam is split into three equally strong beams by first splitting 33% off the main beam and then splitting the remaining beam in two equal parts. Each trapping beam is then passed through a $\lambda/4$ waveplate to produce the desired circular polarization. By retro-reflecting the three orthogonal beams into themselves the six trapping beams needed for the MOT are created.
Figure 3.10: Schematic of the MOT optics.

The zeroth order of the first AOM is sent through a second AOM (AOM2) to create the oven beam which provides longitudinal cooling. This is a way to increase the number of atoms trapped in a MOT by using an additional laser beam directed to the oven to provide longitudinal cooling [72]. This oven beam is further red-detuned than the trapping beams, thus the light decelerates atoms at higher velocities. In this way, by pre-cooling, the number of atoms that can be trapped in the MOT is increased by up to a factor of 5 [73].

The AOM arrangement is shown in Fig. 3.11. When the AOM1 is switched off, all intensity is in the zeroth order and is going into the oven beam. Although the oven beam is far red-detuned and overlaps the MOT-cloud only partially it might excite the atoms in the MOT. In consequence the AOM2 is switched on during the off time of AOM1, such that most of the intensity after AOM2 goes into the first order, not entering the MOT chamber.

The magnetic field necessary for trapping is produced by two parallel anti-Helmholtz coils each of them consisting of 20 water-cooled windings. The coils are provided with a current of 50-80 A this corresponding to a magnetic field gradient of 20-30 Gauss/cm. Also installed are steering coils i.e. three pairs of Helmholtz coils (∼ 30 windings, ∼ 2 A) which produce a small additional magnetic field. With these small fields the position of the zero point in the magnetic field gradient can be
3.3 The Recoil Ion Momentum Spectrometer

The ultracold Na atoms obtained in the MOT are used as a target for recoil-ion momentum spectroscopy investigations on electron dynamics occurring in ion-atom in-
teractions. In this section the other parts of the experimental setup are described. Following a brief introduction of the ion source, our recoil-ion momentum spectrometer is discussed.

### 3.3.1 Ion production and transport

The projectile ions used in our experiment are produced by a 14 GHz Electron Cyclotron Resonance Ion Source (ECRIS) [74]. A sketch of the ion source is shown in Fig. 3.12.

![Sketch of the Electron Cyclotron Resonance Ion source (ECRIS). The strength of the magnetic field is overlayed.](image)

In an ECRIS highly charged ions are produced by sequential electron impact ionization. The plasma electrons produced in the trap formed by the radial magnetic field of the hexapole and the longitudinal field from the two magnetic coils (configuration called *minimum – B – structure*), will gyrate inside the trap along the magnetic field lines with the cyclotron frequency \( \omega_c = \frac{eB}{mc} \). If a radiofrequency field (RF field) of the same frequency is injected into that region, the electrons are resonantly accelerated gaining high energies, thus ionizing plasma atoms and ions into high charge states via sequential electron impact ionization.

The key parameters which have to be tuned to optimize the ion output, are the gas pressure, the RF power (0.05-0.5 kW) and the current through the extraction magnet coil (700-1000 A). The current through the injection magnet coil is usually fixed at the maximum value of the current supply (1000 A). For highly charged ions,
the addition of a "support" gas can strongly increase the output of higher charge states [75]. For example, for the production of O\(^6^+\) ions helium is used as support gas and for the production of Xe\(^{18^+}\) and Xe\(^{24^+}\) ions oxygen is used.

The ion source is put on high voltage (up to 25 kV), and the ions produced are extracted using a movable puller lens, which can be put on a negative voltage to improve the extraction of low energy or low charge state ion beams.

After extraction, the ions are charge-over-mass selected by a 110° magnet and guided into one of the experimental setups of the Atomic Physics group by means of a series of magnetic quadrupole triplets and 45° bending magnets. The base pressure in the beamline is \(\leq 10^{-7}\) mbar, which is low enough to prevent significant losses due to charge changing collisions with background gas. After the last bending magnet in front of the MOTRIMS experiment the ions are focussed by a magnetic quadrupole doublet and pass through a series of four diaphragms, the first diaphragm with a diameter of 2 mm and the rest with a diameter of 1 mm. Between the first diaphragm which is located 81 cm from the center of the MOTRIMS chamber and the second diaphragm a chopper system is placed consisting of two condenser plates. By applying a fixed voltage to one of the plates and a higher pulsed voltage on the other plate of the chopper the ion beam is swept over the second diaphragm, resulting in a pulsed beam. After that the ion beam passes two more diaphragms of 1 mm diameter. The last diaphragm is positioned at 20 cm upstream of the collision center. Taking into account the maximum opening angle of the set of diaphragms one estimates that the ion beam has a diameter of 1.8 mm by the time it reaches the MOT-cloud [76].

### 3.3.2 Recoil-ion Momentum Spectrometer

The recoil-ion momentum spectrometer consists of two parts, an extraction region where a weak electrostatic field extracts the ions from the collision region and a field free region (drift region) in which the recoil ions travel to the detector. Time and spatial focussing are crucial for homogeneous extraction.

Using SIMION ion trajectory simulations [77] optimal field shapes for both spatial and time focussing have been calculated. SIMION makes use of potential arrays that define the geometry and potentials of electrodes on which the Laplace equation is solved. In figure 3.13 the electrostatic extraction geometry (cylindrically symmetric) is shown, including equipotential lines calculated by SIMION.

Spatial focussing is achieved by the slight curvature in the equipotential lines (see Fig. 3.13) which cause that the recoil ions starting from different positions in the plane perpendicular to the extraction direction arrive at the same place on the detector. To achieve time focussing we have to use the so-called Wiley-McLaren geometry [78] in which ions after passing the distance L in the homogeneous extraction field are focussed at a drift distance 2L. The resolution depends besides the focussing properties on the time-of-flight of the recoil ions: the longer they travel, the larger their pattern in the focal plane, thus the better the resolution. In consequence we
decided to increase the length of the drift region breaking in this way the Wiley-McLaren criterion. To restore the time focussing three additional lenses had to be placed in front of the drift tube. By applying a positive voltage ($V_+$) to the bottom plate and a negative voltage ($V_-$) to the drift tube, the electric field created accelerates the ions from the extraction region to the drift region. The three lens elements isolated from each other and from the drift tube by ceramic spacers are negatively biased ($V_+$) ($V_1$, $V_2$ and $V_3$) and can be tuned independently.

The collision center situated at 4 cm above the bottom plate is in the middle between the bottom plate and the first lens. The total length of the extraction region including the lenses is 11 cm. The drift tube is 41 cm long. For detecting Na$^+$ recoils the voltages used are $V_+ = +1.02$ V, $V_- = -2.46$ V, $V_1 = -1.7$ V, $V_2 = -1.85$ V, and $V_3 = -0.26$ V, which means that the extraction potential is less than 0.5 V/cm. The whole spectrometer is enclosed in a grounded tube, which contains holes for access of the laser beams, the ion beam and for observation of the MOT cloud.

The detection system situated after the drift region, consists of a pair of chevron-stacked multichannel plates (MCP) in conjunction with a 2D delay line detector.
3.3 The Recoil Ion Momentum Spectrometer

Figure 3.14: The timing scheme of the TDC, showing the inputs of the TDC from the delay-line anode and DLATR6, and the resulting position and time encoding. The black blocks on the X1, Y1 and Y2 wires represent cable delays assuring that the signal of X2 always arrives earlier than the other signals. The external trigger signal is derived from the signal that triggers the ion beam pulse.

The timing scheme of the TDC is shown in Fig. 3.14. If the delayed signal from the ion chopper is used as the start for the TDC this can be blocked or occupied by starts which are not followed by stops in all four channels. In order to avoid this effect the delayed signal from the ion beam chopper signal is used as a stop and one...
Experimental setup

3.3.3 Switching the magnetic field

The presence of the inhomogeneous magnetic field of the MOT is a major disadvantage for the recoil-ion momentum spectroscopy. This is due to the fact that the slow recoil ions, which are extracted in transverse direction, have to cross the magnetic field lines resulting in a disturbance of the image of the detector [69,80].

Figure 3.15: The decay of the MOT-cloud when the magnetic field is switched off (optical molasses).
By switching the magnetic field off during the measurement cycles this disadvantage is completely eliminated. The Release&Recapture measurements show that even after 20 ms from switching off the magnetic field, almost 80% of the MOT-cloud intensity is still left (Fig. 3.15). In order to be able to switch the high current of $\sim 80A$ of the MOT coils we designed a new current supply which is able to run at frequencies up to 8 kHz. Switching such high currents at kHz rate causes eddy currents in the stainless steel of the vacuum chamber which heat up the chamber, whereby the vacuum pressure is increasing by almost two orders of magnitude. As we see from Fig. 3.15 a much lower frequency well below 1 kHz can be used because of the optical molasses.

In order to measure recoils only if the magnetic field is switched off, a start signal is sent to the TDC, only if the current through the MOT coils is off (Fig. 3.16). When the target density drops the magnetic field is switched on again to recover the MOT, the switching frequency used being 100-150 Hz.

### 3.4 Data analysis

In order to clarify the steps taken for data analysis a schematic of the MOTRIMS setup is shown in Fig. 3.17. The collision system possesses cylindrical symmetry

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**Figure 3.16:** Schematic representation of our measurement cycle. The magnetic field is switched at a much lower frequency than the repetition rate of the measurement.
around the beam axis. Therefore the recoil momentum has only two essential components: the longitudinal momentum which is associated with the Q-value (the energy gain in the reaction) and the transverse momentum which is a measure for the impact parameter [81].

The longitudinal component of the Na$^+$ recoil momentum is connected to the energy gain of the reaction (Q-value) via the following relation (in atomic units):

$$p_{\text{long}} = \frac{Q}{v_p} - \frac{1}{2}v_p,$$  \hspace{1cm} (3.1)

where $v_p$ is the velocity of the projectile.

A 2D detector image is depicted in figure 3.18, which shows Na$^+$ recoils resulting from Xe$^{18+}$+Na collisions. Along the $X$-direction (the ion beam direction) lines are observed. The lines arise from capture into different $n$-shells of Xe$^{17+}$. From the projection of the 2D spectrum on the $X$-axis one can obtain the relative intensities of these lines, as shown in figure 3.19 (the $X$-position is converted into Q-value).

The relation between the longitudinal momentum $p_{\text{long}}$ and the $X$-position of the recoil-ion on the detector is given by

Figure 3.17: Schematic view of the experimental setup. The Na recoil ions are extracted in vertical direction by a weak electric field ($< 0.7 \text{ V/cm}$) towards the 2D detector.
in which $X$ is the $X$-position of the recoil-ion on the detector, $M$ is the mass of the recoil-ion, $T$ is the time-of-flight. Because the FWHM of the Na\(^+\) time-of-flight peak is smaller than 0.5 $\mu$s while the total time-of-flight in the normal extraction setting is $T = 63$ $\mu$s we can assume that $T$ is constant. This implies that the longitudinal momentum is simply proportional to the $X$-position on the detector [82], i.e.,

$$p_{\text{long}} \approx \alpha X.$$ 

(3.3)

The constant $\alpha$ takes different values for different extraction potentials and recoil ion charge states, scaling with the time-of-flight. Finally, the Q-value spectra can be obtained from rewriting equation 3.1,

$$Q = v_p(p_{\text{long}} + \frac{1}{2}r v_p).$$ 

(3.4)
Figure 3.19: Q-value spectrum of Na\(^+\) recoils, resulting from 1.67 keV/amu \(^{129}\text{Xe}^{18+}\) + Na collisions, obtained from projecting the XY-distribution shown in figure 3.18 onto the X-axis. The measured X-position is related to the Q-value via equations 3.2 and 3.4.

The transverse momentum, \(p_{\text{trans}}\), is a two dimensional vector, with components \(p_{\text{trans},y}\) and \(p_{\text{trans},z}\). Its magnitude is given by

\[
p_{\text{trans}} = \sqrt{p_{\text{trans},y}^2 + p_{\text{trans},z}^2}.
\]

Because the \(Y\)-direction is perpendicular to the extraction direction the same argumentation can be made as for the longitudinal momentum,

\[
p_{\text{trans},y} \approx aY.
\]

Because the recoils are accelerated along the \(Z\)-axis, the momentum component \(p_{\text{trans},z}\) is connected to the time-of-flight via the following equation:

\[
T = \frac{-v_{\text{trans},z} + \sqrt{v_{\text{trans},z}^2 + 2zea}}{a} + \frac{z_d}{\sqrt{v_{\text{trans},z}^2 + 2zea}},
\]

in which \(v_{\text{trans},z} = p_{\text{trans},z}/M\), \(z_e\) the distance from the collision center to the entrance of the drift region and \(z_d\) the length of the drift region. The acceleration \(a\) is given by \(a = rE_z/M\), in which \(E_z\) is the electric field. The exact inversion of equation 3.7, needed to calculate \(p_{\text{trans},z}\), is quite complicated [83] and in order to circumvent
this problem we use again the fact that differences in time-of-flight between the recoil ions are small as compared to the average time-of-flight \( T_0 = T(v_{\text{trans},z} = 0) \). Expanding equation 3.7 around \( T_0 \) leads to the relation

\[
\Delta t \equiv T - T_0 = \frac{-v_{\text{trans},z} + \sqrt{v_{\text{trans},z}^2 + 2zea} - \sqrt{2zea}}{a} + \frac{z_d}{\sqrt{v_{\text{trans},z}^2 + 2zea}} = \frac{z_d}{\sqrt{2zea}}. 
\]

(3.8)

If we assume that the initial kinetic energy of the recoil-ion is much smaller than the energy gained in the extraction field (\( MV^2_{\text{trans},z}/2 \ll rE_ze \)) then \( v_{\text{trans},z}^2 \ll 2az_e \) and equation 3.8 becomes

\[
\Delta t \approx -\frac{v_{\text{trans},z}}{a}, 
\]

(3.9)

Only the deviation from \( T_0 \) is needed to obtain the transverse momentum in the \( Z \)-direction, which can be represented as

\[
p_{\text{trans},z} \approx -\beta \Delta t, 
\]

(3.10)

in which \( \beta \) is a constant depending on the extraction potential and geometry.

For the \( \text{Na}^+ \) recoil spectra using the extraction voltages shown in section 3.3.2 a resolution of 0.07 a.u. (corresponding to 3.5 m/s) was achieved in the longitudinal and in one of the transverse directions, i.e. \( p_{\text{long}} \) and \( p_{\text{trans},y} \). This resolution allows us to resolve the main \( n \)-shell capture channels. The resolution is defined by the full width at half maximum (FWHM) of the capture peaks, which are assumed to be Gaussian shaped. Because for a given extraction potential the time-of-flight is inversely proportional to the square root of the charge state, the momentum image on the detector is compressed for more highly charged recoils and thus the resolution is worse. Also higher extraction potentials are usually needed to collect all recoils, because they have larger transverse momenta as compared to the \( \text{Na}^+ \) recoils. This shortens the time-of-flight somewhat and therefore the resolution is reduced.

To conclude, to obtain all the information, i.e. Q-value and scattering angle, only two recoil momentum components are needed, \( p_{\text{long}} \) and \( p_{\text{trans},y} \). As explained above, these components can be determined to a very good approximation independently of the time-of-flight.

For measuring \( \text{Na}^+ \) recoils we used a continuous ion beam due to the reasonable count rate but for the higher charge state recoils a pulsed ion beam was unavoidable. For the higher charge state recoils the detector was triggered such that the time-of-flight peak of the \( \text{Na}^r+ \) recoils of interest falls inside the 2 \( \mu \)s time window of the TDC. A reasonable \( \text{Na}^+ \) spectrum can be obtained within a few tens of minutes, but for \( \text{Na}^{2+} \) more than 10 hours are needed to obtain good statistics.
3.4.1 Extraction of the recoil spectra

After the projection of the 2D detector image on to the X-axis, the obtained spectra are in XY-channels. A calibration of the zero-point and a conversion from XY-channels to momenta is needed. For one-electron capture in He\(^{2+}\) and O\(^{6+}\) collision with Na the main capture channels are well known, and from the binding energies of these the longitudinal momenta are calculated using equation 4.1. By identifying two capture lines the zero-point can be determined and the conversion from channels to momenta can be made. At the extraction voltages used, a conversion around 88 ch/a.u. was found meaning that for a resolution of 0.07 a.u. the FWHM of the capture peaks covers 6-7 channels.

In the case of one-electron capture in \(^{129}\)Xe\(^{18+}\) and \(^{129}\)Xe\(^{24+}\) collision with Na the capture channels are not so well known. In order to do the conversion from channels to momenta we make use of the fact that the Xe ions are obtained in the ECRIS ion source using oxygen as heating gas. By selecting the O\(^{6+}\) ion from the source and recording a spectrum the calibration can be made, which is valid also for the Xe spectra assuming that the MOT was the same. The zero-point can be found by using the so-called “MOT-ions”, which are Na\(^2+\) molecules produced via associative ionization of excited Na atoms [84, 85],

\[
Na^+(3p) + Na^+(3p) \rightarrow Na^2+ + e^-,
\] (3.11)

the production of these ions depending quadratically on both the MOT density and the excited fraction [86]. Because these ions are produced with almost no kinetic energy, i.e. zero momentum, they can serve to mark the zero position.

3.4.2 Obtaining the cross sections

The relative cross sections of the different processes can be extracted from the Q-value spectra by fitting the spectra, assuming Gaussian peak shapes. This fitting is usually only possible for capture peaks that are sufficiently resolved. In the case of He\(^{2+}\) collisions, separate partial cross sections are only determined up to a certain \(n\)-shell. For higher \(n\)-shells one can obtain only summed cross sections.

The Na\(^+\) recoils are created also by single ionization, this process leading to Q values larger than the ionization potential \(I=5.14\) eV. Taking the experimental resolution into account and assuming that for high subdominant levels the relative contributions are given by the empirical law

\[
\sigma_{np}^{rel} \approx cn^{-p}.
\] (3.12)

the relative contribution of capture into high-\(n\) shells and ionization can be extracted [87, 88].
If \( n_{\text{max}} \) is the highest \( n \)-shell for which separate cross sections can be obtained by the fitting procedure, then the sum contribution of capture into \( n > n_{\text{max}} \), is determined as follows:

\[
\sigma_{n>n_{\text{max}}}^{\text{rel}} \equiv n_{\text{max}}^p \sigma_{n_{\text{max}}}^{\text{rel}} \sum_{n=n_{\text{max}}+1}^{\infty} \frac{1}{n^p},
\]  

(3.13)

where the scaling factor \( p \) can be obtained from:

\[
\frac{\sigma_{n_{\text{max}}}^{\text{rel}}}{\sigma_{n_{\text{max}}}^{\text{rel}}} - 1 = \left( \frac{n_{\text{max}} - 1}{n_{\text{max}}} \right)^p
\]

(3.14)

The ionization cross section can be also obtained in this way

\[
\sigma_{\text{ion}}^{\text{rel}} = \sigma_{\text{tot}}^{\text{rel}} - \sum_{n=1}^{n_{\text{max}}} \sigma_{n}^{\text{rel}} - \sigma_{n>n_{\text{max}}}^{\text{rel}},
\]

(3.15)

in which \( \sigma_{\text{tot}}^{\text{rel}} \) represents the total recoil spectrum and \( \sum_{n=1}^{n_{\text{max}}} \sigma_{n}^{\text{rel}} \) is the contribution of the capture peaks that can be fitted individually.

In order to compare our results directly with theory and other experiments, we have to put the results on an absolute scale. It has turned out that an absolute calibration better than 50\% is not readily feasible to achieve, because we have to control many if not all experimental parameters quite precisely. These parameters are the number of incoming ions, the ion beam profile, the target density and the overlap between the ion beam and the target cloud. The number of ions is easily accessible by measuring the ion beam current in a Faraday cup. The beam profile is difficult to determine but can be estimated from the positions and sizes of the diaphragms. For the target density both the number of trapped atoms and the target profile is needed. The target profile can be obtained from the CCD images which are taken during the experiments, but the number of trapped atoms cannot be obtained very accurately because the fluorescence recorded by the CCD is not a direct measure of the target density. The exact knowledge of the overlap between the ion beam and the target cloud is very difficult to obtain [69]. Therefore, our data are normalized to absolute cross sections available in the literature.