Chapter 2

Experimental background

In this chapter, an overview of our experiment to realize an ultracold optically trapped mixture of $^{87}$Rb and metastable $^4$He is presented. The laser systems implemented for laser cooling and optical trapping, and the microwave and radiofrequency sources used for the evaporative cooling and preparation of the different spin-states are described. General descriptions about the trap configurations used are given while details regarding their implementation for specific experiments are discussed in the succeeding chapters. The detection schemes to measure atom number and temperature are also explained.
2.1 Overview of experimental approach

Experiments with ultracold ($T < 1$ mK) neutral atoms rely mostly on laser cooling and subsequent evaporative cooling. In laser cooling, atoms are slowed down or cooled by repeated absorption and emission of photons from a red-detuned laser beam propagating opposite to the direction where the atoms are moving [93]. When performed with six laser beams for all directions and combined with a magnetic field, the atoms can be confined with temperatures close to absolute zero. An example of this scheme is a three-dimensional magneto-optical trap (3D-MOT) [8]. Typical configuration consists of three retro-reflected red-detuned laser beams combined with a magnetic field gradient from a pair of coils in anti-Helmholtz configuration. In the 3D-MOT, atoms are laser-cooled and trapped to temperatures in the order of mK down to a hundred μK.

To achieve even colder samples, trapping in a pure magnetic potential (magnetic trap) is usually implemented in which evaporative cooling can be performed on the sample. Here, the magnetic potential is truncated in a controlled way, with microwave (MW) or radiofrequency (RF) radiation that couples trappable states to non-trappable states, such that the more energetic atoms can escape from the trap while the remaining atoms rethermalize to a much lower temperature. Magnetic traps, however, can only confine atoms in low-field seeking magnetic substates. There are various magnetic trap configurations and the simplest is the quadrupole magnetic trap (QMT) [94]. One major drawback of a QMT is the existence of a zero magnetic field at the trap center in which the atoms can undergo so called Majorana spin-flips, leading to transition to non-trappable spin-sates and therefore trap loss. This also limits the temperature that can be achieved in a QMT, because colder atoms spend more time at the center of the trap, and are more likely to undergo these spin-flips. Their rate scales inversely with mass and is therefore more pronounced for light atomic species [9, 95].

Another possibility to confine atoms is optical trapping [16, 96]. In its simplest form, an optical trap is a high power far off-resonant Gaussian laser beam focused to a waist of a few tens to hundreds of micrometers. The atom in the vicinity of the focus experiences a force due to the huge intensity gradient. This creates a dipole potential for the atom, and thus the commonly used term optical dipole trap (ODT). In contrast to magnetic traps, a far off-resonant ODT can provide confinement that is independent of the spin-state. Mostly, crossed-beam ODT’s in which focused laser beams are crossed and atoms are trapped in the intersection region are utilized, offering tighter confinement as compared to single-beam ODT’s.

Recently, a technique based on combining a single-beam ODT and a weak QMT, i.e. a hybrid trap, was introduced [97]. The addition of the weak QMT provides extra confinement along the axial direction of the single-beam ODT. In here, the QMT gradient is chosen to be slightly below the
2.1. Overview of experimental approach

Figure 2.1: Overview of the experimental scheme to realize an ultracold mixture of Rb and He* in an optical trap (see text). The typical temperature $T$ for the different trapping stages are also indicated.

gradient at which the magnetic force balances gravity, i.e. the levitation gradient, to ensure that atoms are confined in the hybrid trap and not by the QMT. In addition, the single-beam ODT is aligned slightly away from the QMT center to avoid Majorana spin-flips.

Our experiment utilizes standard laser cooling techniques, and the optical and magnetic trapping configurations mentioned above. In this chapter, a general description of the various traps and cooling scheme will be given only in the context as they are used in the experiment. A detailed discussion about laser cooling and the magneto-optical trap can be found in the book by Metcalf and van der Straten [98]. A comprehensive review about magnetic trapping and evaporative cooling can be found in the paper by Ketterle and van Druten [99]. Optical dipole traps are explained in the review paper by Grimm et al. [100].

Our goal is to realize an ultracold mixture of $^{87}$Rb and metastable $^4$He in an optical dipole trap. For this, a few trap configurations are implemented and sequentially applied (see Fig. 2.1). First, the two species are loaded and laser cooled in a 3D-MOT. He* atoms are loaded from a Zeeman slower in which they are slowed down to velocities in the order of a few 10 m/s. A detailed description of our Zeeman slower can be found in the thesis by Stas [101]. Rb atoms are loaded from a two-dimensional magneto-optical trap (2D-MOT), which is added on top of the main chamber of an existing He* setup [102]. In the 2D-MOT, laser cooling is performed only in two directions forming a cold beam of atoms along the other direction. Afterward, the sample is transferred into a QMT in which forced evaporative cooling of Rb and He* is performed using MW and RF, respectively. Lastly, the mixture is loaded into a single-beam ODT using the hybrid trap as an intermediate stage.
Figure 2.2: (Left) Hyperfine structure splittings of $^{87}\text{Rb}$ and (right) fine structure splittings of $^4\text{He}$ showing the different optical transitions used in the experiment. The metastable state of $^4\text{He}$ is accessed using a dc discharge.

2.2 Laser systems

In Fig. 2.2, the hyperfine structure splittings of $^{87}\text{Rb}$ (left) and fine structure splittings of $^4\text{He}$ (right) are shown, indicating the different optical transitions used in the experiment. For laser cooling of $^{87}\text{Rb}$, we use a Toptica diode laser with tapered amplifier (TA pro) operating at 780 nm. The 2 W output power is distributed over the MOT, optical pumping (OP), pushing and absorption imaging beams (see Fig. 2.3(a)). Due to the hyperfine structure of Rb, repumper beams are also needed in order to keep the atoms in the laser cooling cycle. We use a Toptica (DL 100) diode laser at 780 nm for the repumping with an output of 100 mW. For $^4\text{He}^*$, the 1083 nm light is derived from a 2 W Nufern fiber amplifier seeded with a narrowband fiber laser (NKT Koheras Adjustik). The output power is distributed to the 3D-MOT, optical pumping/imaging, Zeeman slowing and collimation beams (see Fig. 2.3(b)). No repumper is needed for $^4\text{He}^*$ due to the absence of hyperfine structure. The laser beams pass through an acousto-optic modulator (AOM) either in a single- or double-pass configuration in order to allow for fast switching and precise control of the power and detuning. The double-pass configuration is necessary in order to avoid misalignment of beam output when tuning over a considerable range of frequencies [103]. The beams are delivered to the setup using polarization maintaining (PM) fibers. Although we typically lose around 30% of the optical power, the gain is in terms of flexibility in alignment and mechanical stability.

The single-beam ODT light at a wavelength of 1557 nm is derived from a 10 W Nufern fiber amplifier seeded with a narrowband fiber laser (NP
2.2. Laser systems

(a) Rb (780 nm)

(b) He* (1083 nm)

(c) ODT (1557 nm)

Figure 2.3: Overview of the laser system used for (a) Rb and (b) He*. The light is distributed over the MOT, optical pumping (OP), pushing, collimation and absorption imaging beams using a half waveplate (\(\lambda/2\)) and polarizing beam splitter (PBS) combination. (c) Laser system for the optical dipole trap (ODT). ZS: Zeeman slower, s-AOM: single-pass configuration and d-AOM: double-pass configuration.
Photonics Scorpio). The output of the amplifier passes through an AOM to allow for fast switching and control of the power when performing evaporative cooling in the HT or ODT. In here, it is not necessary to tune the AOM frequency, so we use a single-pass configuration to keep most of the optical power (see Fig. 2.3(c)). Typically, we have around 60 to 70% AOM coupling efficiency. Finally, the ODT light is delivered to the setup using a PM fiber with a typical coupling efficiency of also around 75%. After passing through the AOM, fiber and collimating and focusing lenses, the total available power for optical trapping is around 4 W.

### 2.3 Two-species magneto-optical trap

Our 3D-MOT consists of three retro-reflected beams and a quadrupole magnetic field derived from a pair of coils in anti-Helmholtz configuration. The laser beam for the 3D-MOT of each species passes through an AOM in a double-pass configuration. The typical total 3D-MOT power used is between 20 to 50 mW for both species. For Rb, the beam is detuned by around -15 MHz with respect to the $f = 2$ to $f' = 3$ transition. For He*, a large detuning of around -33 MHz is used in order to minimize light-assisted intraspecies Penning ionization [79, 80, 104]. To make the alignment easier and save optical access around the main chamber, we couple the 3D-MOT beams for the two species in the same fiber using dichroic mirrors (see Fig. 2.4). With this, the 3D-MOT of both species are automatically overlapped. Lastly, a 920 nm quarter waveplate is used to create the necessary circular polarization. The coils are water-cooled and can provide a magnetic

![Diagram](image.png)

**Figure 2.4:** Rb and He* 3D-MOT beams coupled in the same fibers using dichroic mirrors (DM). The 3D-MOT beam powers (for the three directions) are distributed using half waveplate ($\lambda/2$) and polarizing beam splitter (PBS) combinations. Also shown are the separate $\lambda/2$ plates for aligning the input polarization of the light with respect to the input polarization of the PM fiber.
field gradient of 0.6 (G/cm)/A along the weak axis. In the MOT stage, we typically apply between 10 to 20 A to the coils.

Fig. 2.5 shows a schematic diagram of the experimental setup illustrating the preparation and loading of the atomic species into the 3D-MOT. Rb atoms, that are initially laser cooled in the 2D-MOT, are transferred to the 3D-MOT using two distinct pushing beams [105]. One pushing beam is red-detuned to redirect the atoms that are initially going in the opposite direction while the other pushing beam is blue-detuned to guide the atoms toward the 3D-MOT. He* atoms are loaded from a zero-crossing Zeeman slower where the atoms are initially slowed down. We use a dc-discharge to access the metastable state (typical metastable fraction of $10^{-4}$ [106]). The source is cooled with liquid nitrogen and the beam of metastable atoms is collimated after exiting through a skimmer before entering the 2.5-m Zeeman slower. We first load the Rb atoms followed by He* loading. To minimize the continuous flux of ground state He towards the 3D-MOT, two in-vacuo shutters are introduced between the source and the Zeeman slower (before and after a differential pump tube), which are only opened during the He* loading. We typically load at least $10^9$ Rb and $10^8$ He* atoms. After loading the two atomic species, we compress the sample by increasing the 3D-MOT gradient (cMOT stage). Afterward, the gradient is switched off to start the optical molasses (OM) stage for further cooling. After the OM stage, we apply simultaneous optical pumping (OP) on both species in order to prepare the sample in the desired low-field seeking doubly spin-stretched spin-state ($|m_s = +1\rangle_s^{\text{He}^*} + |f = 2, m_f = +2\rangle_s^{\text{Rb}}$) before transferring to the QMT for evaporative cooling. The two OP beams are also coupled in the same fiber using a dichroic mirror (see Fig. 2.13(a)).
2.4 Evaporative cooling in the quadrupole magnetic trap

For magnetic trapping, we have used the same coils as for the 3D-MOT to create the quadrupole magnetic trap. In the QMT, the current applied to the coils is typically 200 A, corresponding to a magnetic field gradient of 120 G/cm. To perform forced evaporative cooling on Rb, we drive MW transitions between the trappable and non-trappable hyperfine states. The choice of using MW instead of RF is to allow for simultaneous evaporative cooling of both species in the QMT, as He* atoms are not affected by the MW radiation. For He*, we use RF to drive transitions between the Zeeman states. A feature that is generally true for any He* + alkali mixture is that the Zeeman splitting in He* is larger than in the alkali atoms. In the case of He* and Rb, these are $2\mu_B B$ and $\mu_B B/2$ respectively. For Rb in the $|f = 2, m_f = \pm 2\rangle$ state, the trap depth given by the RF is a factor of two larger than that for He*, and therefore RF can be selectively used for He*. The condition that the MW-truncated trap depth of Rb is lower than the RF-truncated one is given by: $\nu_{\text{MW}} - \nu_{\text{HFS}} < 3\nu_{\text{RF}}$, where $\nu_{\text{RF}}$ and $\nu_{\text{MW}}$ are the RF and MW frequencies respectively, and $\nu_{\text{HFS}}$ is the hyperfine splitting of Rb. For the two species to have equal trap depths in which the Rb is governed by MW and He* by RF, the condition is $\nu_{\text{MW}} - \nu_{\text{HFS}} = 3\nu_{\text{RF}}/2$. The duration and frequencies used in the evaporative cooling are mentioned in the next chapters for each specific experiment that is performed. In here, we only describe the technical details of the RF and MW sources used for the evaporative cooling of each species.

2.4.1 Radio-frequency source

The RF radiation used for the evaporative cooling of He* is derived from the output of an 80 MHz tunable signal generator (Agilent 33250A) which is sent to a frequency doubler (Mini-Circuit MK-3) (see Fig. 2.6(a)). The principal signal is suppressed by at least 25 dBm with respect to the frequency doubled signal and is negligible. The 4th and higher harmonic signals are suppressed by only around 10 to 20 dBm with respect to the frequency doubled signal. However, these harmonic signals in principle will not be in resonance with the remaining He* atoms in the QMT during the evaporation process. Afterward, the signal is pre-amplified (Mini-Circuit ZFL-500LN+) to reach the desired input threshold of the next amplification stage. We observe that the overall output power of the RF system changes noticeably within the frequency range used for the evaporative cooling (see Fig. 2.6(b), red squares). To compensate for this non-uniformity in the power, we initially fix the output power at a relatively high value and use a variable attenuator (Mini-Circuit ZAS-3+) to regulate the power throughout the frequency range for the evaporative cooling (see Fig. 2.6(b), blue circles). Finally, the
2.4. Evaporative cooling in the quadrupole magnetic trap

Figure 2.6: (a) Schematic diagram of the RF radiation source used for the evaporative cooling of He$^*$ showing the frequency doubling scheme in combination with the variable attenuator to regulate the RF output power. (b) Comparison of the RF output power with (blue circles) and without (red squares) using the variable attenuator (see text).

signal is sent to a 30 W linear amplifier (Mini-Circuits LZY-22+) from which the output is used to drive the RF coil that is positioned inside the main vacuum chamber. During the evaporative cooling in the QMT, we typically send around 5 W to the RF coil with a frequency range up to 160 MHz.

2.4.2 Microwave source

The MW source to be used for the evaporative cooling of Rb should be able to cover the hyperfine splitting of 6.835 GHz. We use a 6.8 GHz phase-locked oscillator (Amplus PLO) mixed (Mini-Circuits ZMX-8GLH) with the output signal of an 80 MHz tunable signal generator (Agilent 33250A), which is also frequency doubled (Mini-Circuits MK-3) (see Fig. 2.7(a)). Due to the presence of several harmonic signals resulting from both frequency doubling and mixing, we also introduce a series of high pass (Mini-Circuits VHF-7150+) and low pass (Mini-Circuits VLF-6000+) filters to allow only signals within the desired frequency range. The frequency response of this filter combination is shown in Fig. 2.7(b). Here we show the insertion loss as
Figure 2.7: (a) Schematic diagram of the MW radiation source used for the evaporative cooling of Rb showing the frequency doubling of the function generator and frequency mixing with the 6.8 GHz phase-locked oscillator signal. Also shown are the added high pass (HPF) and low pass filter (LPF) forming a band pass filter to allow only the frequency range useful for the evaporative cooling. (b) Frequency response of the MW design showing the attenuation of the signals outside the frequencies used for the evaporative cooling. The two vertical dashed-lines indicate the range used for evaporative cooling.

A function of frequency, attenuating most of the signal frequencies outside the range that is useful for the evaporative cooling. We also introduce a series of pre-amplification stages (Mini-Circuits ZJL-7G+). Finally, the signal is sent to a 8 W amplifier (Kuhne KU PA 7000A) from which the output is used to drive the MW horn (LABEM), which is placed outside the vacuum setup and is directed to the center of the main vacuum chamber through a window. However, the amplifier is saturated because it is not possible to completely remove the additional harmonic signals, especially those frequencies that are close to the desired frequency signal. We estimate a total of only around 1 to 2 W sent to the MW horn that corresponds to the actual desired frequency. Nonetheless, these spurious signals that are not significantly suppressed, are either below the hyperfine splitting or higher than the desired frequency signal for the evaporative cooling, and these
signals will also not affect the remaining Rb atoms during the evaporation process. The actual consequence is limited MW power available for the experiment.

2.5 Hybrid trap and optical dipole trap

Our optical dipole trap (ODT) laser beam is delivered to the setup using a polarization maintaining single-mode fiber (OZ optics). After a fiber outcoupler and a telescope, the light is focused into the setup by an achromat doublet 2-inch lens with \( f = 400 \text{ mm} \) (Thorlabs, AC508-400-C) at an angle of 11° with respect to the axial direction of the QMT coils and 22° with respect to the imaging beam (see Fig. 2.8(a)). The lens is on a translation stage to axially align the focus of the ODT beam with the center of the QMT. The kinematic mount of the last mirror (before the lens) is piezo-controlled to allow for precise alignment of the ODT in the radial direction. The Rayleigh length is 3 mm, which is much smaller than the 4 cm distance between the glass windows of the vacuum chamber and the waist \( w_0 \) is \( 39.8 \pm 0.3 \text{ \mu m} \), obtained by measuring the radial trap frequency in a pure ODT [107].

Towards the transfer to a pure ODT, we have used the hybrid trap (HT) as an intermediate stage to facilitate the initial transfer from the QMT. In principle, further evaporative cooling can also be performed in the HT. The HT is basically a single-beam ODT combined with a weak QMT, in which the ODT is aligned slightly away from the QMT center in such a way that the atoms remain at a finite magnetic field and thus avoid Majorana spin-flip loss (see Fig. 2.8(b)). The weak QMT provides an additional confinement along the axial direction giving a higher peak density as compared to the pure single-beam ODT, and is chosen to be slightly below the levitation gradient \( B_{lev} = mg/\mu \) (where \( m \) is the mass, \( \mu \) is the magnetic moment of the atom and \( g \) is the gravitational acceleration), to ensure that atoms are trapped in the HT and not by the QMT.

We first implement the HT to Rb and scan the position of the ODT with respect to QMT using the piezo-controlled mirror. We make use of the fact that if the ODT is located at the QMT center, the atoms will undergo Majorana spin-flips and leave the trap. A typical measurement is shown in Fig. 2.8(c). We first do the horizontal scan (see inset) and observe a symmetric loss feature with a \( 1/e^2 \) half width of 30 \( \mu \text{m} \). At the horizontal piezo voltage position where the signal is minimum, we scan in the vertical direction, again showing a clear minimum with a \( 1/e^2 \) half width of 40 \( \mu \text{m} \). Here the data clearly shows more atoms when the ODT is placed below the QMT center, and that the transfer efficiency is constant over a broad range of offsets from the QMT center. Still, to maximize the axial trap frequency and peak density one preferably chooses the offset as small as possible within
Figure 2.8: Schematic diagram showing (a) the orientation of the ODT beam with respect to the QMT coils and imaging beam, and (b) the hybrid trap configuration (ODT+weak QMT) showing the offset in the $y-z$ plane. (c) Number of atoms loaded in the hybrid trap as function of position of the ODT with respect to the QMT center in the vertical direction (main graph) and horizontal direction (inset).
2.5. Hybrid trap and optical dipole trap

Figure 2.9: Number of atoms loaded in the HT/ODT as function of ODT power, comparing Rb (top) and He* (bottom). For the case of Rb, a clear sign of saturation in the loading is already noticeable at an ODT power of around 2.5 W. In contrast, there is no clear sign of saturation in the loading for He* even at an ODT power close to 4 W. The data shown are typical measurements performed in a single-species preparation.

In this broad range [107]. In Fig. 2.9, the number of atoms loaded in the HT as a function of the ODT power is shown, comparing Rb and He*. In the case of Rb, a clear sign of saturation in the loading is visible around 2.5 W. In contrast, the He* data suggest that our available ODT power is limited. This observation is not surprising because the temperature at which we load He* into the ODT is much higher as compared to Rb, limiting the transfer efficiency. This is simply constrained by the Majorana heating which is worse for lighter atomic species [9, 95]. Details regarding the application of the HT to He* is presented in Chapter 3 and a comparison with Rb in the mixture experiment is discussed in Chapter 4. Using the HT scheme, we manage to achieve Bose-Einstein condensation (BEC) of Rb [107] and He*
Figure 2.10: RF spectroscopy of He* in the ODT in order to measure and calibrate the small bias magnetic field. He* signal is measured using a microchannel plate (MCP; see section 2.6.2 for detailed discussion). The 80 kHz width is due to the combined effect of temperature (around 5 μK sample) and magnetic field noise (in the order of 10 mG). Solid line is a Gaussian fit.

[108] in our single-species experiments.

An important aspect in our experiment is to investigate different spin-state mixtures. In the HT, due to the presence of the (weak) QMT, the possible spin-state combinations are limited to low field-seeking states, similar as in the QMT. In contrast, a pure (far off-resonant) optical dipole trap allows trapping of all spin-state combinations with a confinement independent of the chosen spin-state. In our experiment with the mixture, we only use the HT to facilitate the initial transfer from the QMT to the pure ODT. For instance, we have used this stage to smoothly introduce and keep a small quantization magnetic field for the atoms. Once in the pure ODT, this small magnetic field is essential to keep the spin-orientation of the atoms. To calibrate and measure this field, we perform RF spectroscopy on the sample in the pure ODT. Fig. 2.10 shows a typical example of such measurement. Here, we use He* atoms as probe and rely on the idea that at resonance, atoms are transferred to the other Zeeman states resulting in a spin-mixture and thus fast Penning ionization loss [109] (additionally, atoms in the $|m_s = -1\rangle$ and $|m_s = 0\rangle$ are not detected on an MCP, see Section 2.6.2). A magnetic field of 2.5 G is obtained from the resonance frequency via the equation $B = h\nu_{RF}/2\mu_B$, where $h$ is the Planck’s constant, $\nu_{RF}$ is the RF frequency and $\mu_B$ is the Bohr magneton.
2.5. Hybrid trap and optical dipole trap

![Graphs showing normalized atom counts over hold time for Rb and He*](image)

Figure 2.11: Lifetimes of the two different hyperfine states of Rb (top) and of the two different Zeeman states of He* (bottom). Solid lines are guide for the eye.

In Fig. 2.11, we show typical single-species lifetimes of the different spin-states used in the experiment, namely the two hyperfine states of Rb ($|f = 2, m_f = +2\rangle$ and $|f = 1, m_f = +1\rangle$) and two Zeeman states of He* ($|m_s = +1\rangle$ and $|m_s = -1\rangle$). These measurements are performed in the ODT at a temperature of $\sim 15$ μK. We find no observable difference between the two Rb hyperfine states and measure a lifetime of $\sim 20$ s. Similarly, for He*, there is also no significant difference between the lifetimes of the two Zeeman states, which is $\sim 35$ s. We have investigated the contribution of the off-resonant scattering at the typical ODT power of up to 4 W and found no direct correlation with the measured lifetimes, which suggest that the lifetimes are mainly governed by background collisions and scattering from
Figure 2.12: (Top) Calculated differential gravitational sag $\Delta z$ (black line) between the clouds of the two species in the ODT as a function of ODT power. This effect is mainly due to huge difference in the masses of Rb and He$. The differential gravitational sag should be compared with the width ($\sigma_z$) of He$^*$ (red line) and Rb (blue line) clouds. (Bottom) Comparison of the peak density by solving the exact potential numerically and using the harmonic approximation, showing a deviation at typical truncation parameter $\eta=10$. Calculation is done for an ODT power of 4 W and waist of 40 $\mu$m.

An important issue which leads to spatial separation of the two clouds is the differential gravitational sag $\Delta z = \delta z^{\text{He}} - \delta z^{\text{Rb}}$, where $\delta z = -g/\omega_z^2$ is the gravitational sag, $\omega_z = \sqrt{4U_0/mw_0^2}$ is the vertical trap frequency and $U_0$ is the trap depth, which scales with ODT power. This is inherent to heteronuclear mixtures due to the difference in the masses and more pronounced with mixtures involving a heavy and a light atomic species like
2.6 Detection scheme

our He*+Rb mixture. Shown in Fig. 2.12 (top panel) is the differential gravitational sag $\Delta z$ as function of ODT powers (for the case of our single-beam ODT), indicating a more pronounced effect towards lower ODT power (lower trap depths). This is very crucial when realizing colder samples, in particular a dual BEC. In our mixture experiments, we stayed at the highest ODT power available (around 4 W) where the effect of differential gravitational sag is negligible.

In the ODT, the two atomic species experience different trap depths due to the difference in polarizability, which at $\lambda = 1557$ nm is a factor of 1.4 higher for He* compared to Rb [110, 111]. The main consequence is that the two species have different temperatures because interspecies thermalization is absent for the experimentally relevant time scales due to the small interspecies elastic cross-section [88]. In addition, for the analysis involving peak densities and overlap of the two species, we also consider and solve the exact trapping potential numerically. This is necessary because in our single-beam ODT, at the typical truncation parameter of around $\eta = U_0/k_B T = 10$ (where $k_B$ is the Boltzmann constant and $T$ is the temperature), there is a significant deviation from the typically used analytic expressions derived from the harmonic approximation, see Fig. 2.12 (bottom panel).

2.6 Detection scheme

In our experiment, two important parameters that we need to determine are the atom number and temperature of the sample. Initially, during the optimization and characterization of our system, we have used several schemes such as fluorescence detection (using photodiode and camera) [112], absorption imaging for both Rb and He*, and time-of-flight (TOF) measurement from a microchannel plate (MCP), applicable only to He*. However, for most of the relevant data, we base the analysis from the absorption imaging and MCP TOF detection as these turned out to be the most accurate. In this section, we only describe these two schemes.

2.6.1 Absorption imaging

Standard absorption imaging is used to measure the atom number and temperature for both species. To save optical access around our main chamber, we also couple the imaging lights for the two species in the same fiber using a dichroic mirror together with the OP light for Rb (see Fig. 2.13(a)). For He*, the same OP light can be applied for imaging because the detuning and power can be adjusted accordingly via an AOM. For both species imaging and to avoid heating or pushing the atoms, we send low intensity beams (much lower than the saturation intensities) with 100 to 200 $\mu$W optical power and ~1 inch diameter. To create the proper circular polarization, we implement a 920 nm zero-order quarter waveplate. We send these imaging
Figure 2.13: (a) OP and imaging beams for He* and Rb are coupled in the same fiber using a dichroic mirror (DM). For OP and imaging of He*, the same beam is used while the detuning and power are adjusted accordingly via an AOM. A mechanical shutter (not shown in the figure) is added before the fiber to minimize stray light. (b) Schematic diagram of the dual imaging. To image the cloud, we use a 2:1 (L1 = 30 cm and L2 = 15 cm) telescope to accommodate the size of the cloud on the camera chip. Enclosed in the dashed rectangle is the typical configuration used for delivering the laser beams into the main chamber. The fiber outcoupler, polarizing beam splitter (PBS), quarter waveplate (λ/4) and collimating lenses are mounted on a single stage.
2.6. Detection scheme

Figure 2.14: Absorption images of Rb and He* atoms released from the HT and/or ODT, comparing the difference in the aspect ratio. The difference is particularly noticeable for Rb due to the stronger additional axial confinement provided by the QMT as compared to He*. Note that the axial direction (see also Fig. 2.8(a)) is only viewed from the 22° projection of the imaging beam with respect to the ODT beam. The size of each rectangular image is approximately 1.5×2.0 mm.

beams at an angle of approximately 11° with respect to the axial direction of the QMT coils (see also Fig. 2.8(a)). We use a magnification of 0.5 to accommodate the size of the cloud onto the camera chip particularly during expansion measurements. We also use a dichroic mirror to image the two clouds on two different cameras. For Rb, we use a CCD camera (QImaging Exi-blue) with 6.45 μm pixel size. For He, we use an InGaAs camera (Xenics Xeva 320) with a 30 μm pixel size. In Fig. 2.14, we show and compare typical absorption images of Rb and He* that are released from the HT and ODT. Note that because of the orientation of the imaging beam with respect to the ODT beam, we can only see the projection of the image along the axial direction from the 22° angle (see Fig. 2.8(a)). For Rb in the HT, the cloud is almost circular because of the additional confinement in the axial direction provided by the QMT in contrast to the elliptical shape in the pure ODT. For He*, there is no significant difference between the HT and ODT clouds. This is because of the much weaker additional confinement in the axial direction due to the much lower levitation gradient. In principle, absorption imaging of the two species can be done simultaneously because the light for Rb is far from any transition in He* and vice-versa. Simultaneous imaging of the two species is essential especially during the
optimization process. For instance, we can easily track the positions of the
two clouds when aligning the MOT beams to optimize the OM stage and
the subsequent transfer of the mixture to the QMT.

2.6.2 Microchannel plate detection

Additionally for He\(^\ast\), because of the high internal energy (19.8 eV), we
also use a microchannel plate (MCP) detection that is positioned below
the trap center (at angle 22\(^\circ\) with respect to the direction of gravity, see
Fig. 2.5) to measure time-of-flight (TOF) distributions. In Fig. 2.15(a),
we compare typical TOF distributions for samples released from the 3D-
MOT, QMT and ODT. For the higher temperature samples, where the
average kinetic energy of the atoms is much higher than the potential energy
defined by the distance to the MCP, the TOF clearly exhibits the typical
asymmetric Maxwell-Boltzmann distribution, as seen for the 3D-MOT. For
lower temperature samples (average kinetic energy of the atoms is much
smaller than the potential energy), the TOF becomes symmetric and can be
approximated with a Gaussian distribution, as seen for the ODT. With the
geometry of our MCP detection, the temperature that separates these two
regimes (kinetic energy is equal to the potential energy) is on the order of
\(mgh/k_b \approx 0.5\) mK, where \(m\) is the mass of He, \(h = l \cos 22^\circ\) is the vertical
distance from the center of the trap to the MCP detector and \(l = 10.6\) cm.
Note that the QMT and ODT TOFs are rescaled for clarity.

It must be noted that towards lower temperature, the sample will not
hit the MCP because of the 22\(^\circ\) angular displacement from the vertical
axis. Therefore a magnetic gradient pulse (from a single deflection coil, with
approximately 665 windings and 15 cm inner diameter) is applied to direct
the atoms onto the MCP detector [108] for sufficiently low temperature
samples, such as a sample that is released from the ODT. In Fig. 2.15(b), we
compare MCP signals with and without introducing the deflection gradient.
Note that the signal without deflection is also rescaled for clarity. We keep
the pulse duration as short as possible (around 10 ms) to minimize the
disturbance introduced on the cloud during the time-of-flight. We observe
an optimum in the MCP signal at around 6.5 A applied to the deflection coil,
consistent with what we expect from a simple classical mechanics calculation
based on the distance of travel and the force generated from the magnetic
field gradient. TOF measurements of He\(^\ast\) can also be done simultaneously
with the Rb imaging. After the clouds are released from the ODT, we first
capture the images (ballistic expansion typically between 1 ms to 5 ms),
after which the magnetic gradient pulse is applied.

Our experiments involve samples of different spin-states. Distinguishing
between these different spin-states from the detection scheme is essential.
The most common technique employed is Stern-Gerlach imaging, where a
magnetic field gradient is applied during expansion to separate atoms of
Figure 2.15: (a) Typical TOF distributions as measured by the MCP comparing MOT, QMT, and ODT. Notice the change in the shape from the asymmetric Maxwell-Boltzmann distribution (MOT, hotter sample) towards the more symmetric Gaussian shape (ODT, colder sample). For clarity, the QMT and ODT TOF signals are rescaled by a factor of 5 and 10 respectively with respect to the MOT TOF signal. (b) Comparison of the TOF signal for samples released from the ODT (in this example below 10 μK) with and without the deflection gradient. The magnetic gradient pulse duration is around 10 ms. For clarity, the ODT TOF signal without deflection is also rescaled by a factor of 50 with respect to the signal with deflection. The difference in the position of the center of the TOF distributions is due to the small acceleration introduced by the deflection gradient.
different spin-state (due to their distinct magnetic moment). Unfortunately, our deflection coil can only provide a magnetic field gradient (providing a force) along the horizontal direction that coincides with the direction where the absorption images are elongated (see Fig. 2.14), making it difficult to resolve the small shift in the positions between atoms of different spin-state. In addition, it was not feasible to install a different coil around the main chamber that can provide sufficient magnetic field gradient for the purpose due to the limited space. Nonetheless, for Rb, we can use the repumping beam during imaging to distinguish atoms between the two hyperfine states $|f = 2, m_f = +2\rangle$ and $|f = 1, m_f = +1\rangle$. We can only image the atoms in hyperfine state $|f = 1, m_f = +1\rangle$ in the presence of the repumping light. In the case of He$^*$ using the MCP TOF detection, the orientation of the deflection coil and the MCP position will already suffice for the purpose. Note that our deflection coil is designed to give a force that pushes the atoms towards the MCP. Atoms of opposite spins are thus deflected in the opposite direction and not detected. To detect He$^*$ atoms in the $|m_s = -1\rangle$ state, we apply an RF sweep that transfers back the atoms to the $|m_s = +1\rangle$ state (this is discussed in the next section).

2.7 Preparation of different spin-states

For preparation of the ultracold sample, we use the stable mixture in the doubly spin-stretched spin-state $|m_s = +1\rangle_{\text{He}^*} + |f = 2, m_f = +2\rangle_{\text{Rb}}$. However, the study of Feshbach resonances or spin-dependent Penning ionization requires different spin-state combinations. In this section, the preparation of the different spin-state samples using RF and MW frequency sweeps is described.

2.7.1 Rapid adiabatic passage

Consider the case of a two-level atom in a classical oscillating field with frequency $\omega$. In the dressed-states picture (see Fig. 2.16), this constitutes an avoided crossing around a resonance frequency $\omega_0$ where $\Delta = \omega - \omega_0$ is the detuning. The width of the crossing is proportional to the Rabi frequency $\Omega$ (i.e. strength of the field). By applying a linear sweep such that $\Delta(t) = \alpha t$, the probability for a diabatic transition is given by the Landau-Zener formula \cite{113, 114}, $P = \exp \left[ -2\pi \Omega^2 / |\alpha| \right]$, where $\alpha$ corresponds to the constant velocity of the sweep. For a sufficiently slow sweep, the atoms undergo a rapid adiabatic passage between the bare states. Given that initially the atoms are in state $a$, the remaining population $P_a$ after the rapid adiabatic passage, as a function of sweep time $t_{\text{sweep}}$, is given by,

$$P_a = P_0 \exp \left[ -\alpha t_{\text{sweep}} \right], \quad (2.1)$$

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2.7. Preparation of different spin-states

Figure 2.16: Dressed-states picture of a two-level atom in a classical oscillating field with frequency $\omega$ showing the avoided crossing around the resonance frequency $\omega_0$. $a$ and $b$ are the bare states, $\Delta$ is the detuning, and the width of the crossing is proportional to the Rabi frequency $\Omega$.

where $P_0$ is the initial atom number, and $A$ is proportional to the square of the Rabi frequency $\Omega^2 = (\mu_BGfMB_0/\hbar)^2$; $\mu_B$: Bohr magneton, $g_f$: electron g factor, $M = \langle f, m_f | J_z | f + 1, m_f \rangle$: general form of the quantum-mechanical matrix element and $J_z$ is the electron spin, $B_0$: amplitude of the RF or MW field [115]. Population in state $b$ is then given by $P_0(1 - P_a)$.

2.7.2 RF and MW sweeps

Experimentally, there are two ways to perform a transfer sweep on the atoms. The most commonly used is via a magnetic field sweep in the presence of a RF/MW field at a fixed frequency. The second method is by applying a constant magnetic field while sweeping the frequency of the RF/MW field around the resonance. In our case, the frequency sweeps offer better control and stability as compared to magnetic field sweep. We have used the same RF and MW sources described in Section 2.4 for the sweeps, however without using the frequency doubling scheme and thus free from harmonic signals (for the case of RF). However, in the MW source, the harmonic signals due to the frequency mixing are still present. We realize this scheme by using additional signal generators (only used for the sweep) together with a digitally controlled switch (Mini-Circuits ZASWA-2-50DR+) providing two pathways, one path for transfer and another for evaporative cooling as described in Section 2.4.

For He+, we apply RF with typical sweep range of 0.5 to 1 MHz (centered around 6.95 MHz) in less than 50 ms at a magnetic field of 2.5 G to transfer the atoms between the Zeeman states. With an RF power of around 1 W, we transfer all of the atoms from the $|m_s = +1\rangle$ to the $|m_s = -1\rangle$ state (see Fig. 2.17(a)). Also shown is a comparison between three different RF powers, which is in good agreement with what is expected from the
Figure 2.17: (a) $^4\text{He}^*$ atoms in the $|m_s = +1\rangle$ state that remain in the ODT after adiabatic state transfer to $|m_s = -1\rangle$ via an RF frequency sweep as a function of sweep time for three different RF power. $^4\text{He}^*$ atoms in the $|m_s = -1\rangle$ state are not detected because the deflection coil pushes these atoms away from the MCP detector. (b) $^{87}\text{Rb}$ atoms in the $|f = 2, m_f = +2\rangle$ state that remain in the ODT after adiabatic state transfer to $|f = 1, m_f = +1\rangle$ as a function of sweep time of the MW frequency sweep. The imaging is performed without repumping light, which means that $^{87}\text{Rb}$ atoms in the $|f = 1, m_f = +1\rangle$ state are not detected. Solid lines are fit from Eq. 2.1 from which the Rabi frequencies are obtained (see text).
2.7. Preparation of different spin-states

proportionality relation: \( A \propto \Omega^2 \propto P_{RF} \) (see inset of Fig. 2.17(a)). For a three-level system, \( A = \pi \Omega^2 / |\delta \omega_{RF}| \) where \( \delta \omega_{RF} \) is the RF frequency sweep [116]. Rabi frequencies are obtained by fitting Eq. 2.1 to the data, \( \Omega / 2\pi = 3.0 \pm 0.3 \text{ kHz}; \ 2.3 \pm 0.2 \text{ kHz}; \ 1.7 \pm 0.2 \text{ kHz} \) for the three powers respectively, which corresponds to an RF field amplitude \( B_0 \) of a few milliGauss. We confirm the transfer by applying a second sweep that transfers back and recover the atoms to the \( |m_s = +1 \rangle \).

For Rb, we apply MW with typical sweep range of 0.2 to 1 MHz (centered around 5 MHz above the hyperfine splitting) in a few tens to hundreds of milliseconds at a magnetic field of 2.5 G to transfer the atoms from the hyperfine state \( |f = 2, m_f = +2 \rangle \) to \( |f = 1, m_f = +1 \rangle \). However, due to the limited MW power, we only manage to transfer around 50% of the atoms to the \( |f = 2, m_f = +1 \rangle \) (see Fig. 2.17(b)). Nonetheless, to keep only a single spin-state of Rb, we send resonant light to clean the remaining atoms in the \( |f = 2, m_f = +2 \rangle \). For the case of Rb transfer between the hyperfine states, the manifold can be considered as an effective two-level system, and \( A = 2\pi \Omega^2 / |\delta \omega_{MW}| \), where \( \delta \omega_{MW} \) is the MW frequency sweep. Fitting only the first part of the data in Fig. 2.17(b), we extract typical Rabi frequencies \( \Omega / 2\pi \) between 200 to 400 Hz, corresponding to a MW field amplitude of only around a milliGauss.