Feshbach resonances in ultracold mixtures of the fermionic quantum gases $^6$Li and $^{40}$K
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Citation for published version (APA):
Tiecke, T. G. (2009). Feshbach resonances in ultracold mixtures of the fermionic quantum gases $^6$Li and $^{40}$K

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Download date: 29 Dec 2018
Chapter 3
Experimental Setup

3.1 Introduction

This chapter describes the experimental setup developed for this thesis. A brief discussion of the design considerations will be made followed by an extensive description of all techniques required to achieve the ultracold mixture of $^6\text{Li}-^40\text{K}$. At the time of the start of this thesis no experiment regarding mass-imbalanced Fermi-Fermi mixtures existed. However, next to our experiment two others were started, one by F. Schreck and R. Grimm in Innsbruck and another one in Munich by K. Dieckmann. Interestingly, all three experiments took the $^6\text{Li}-^40\text{K}$ system, but different technical approaches were chosen to achieve the ultracold Fermi-Fermi mixture. In all three experiments collisions between different species provide the rethermalization of the ultracold mixture required for efficient evaporative cooling. The Innsbruck group took an all-optical approach [94], trapping a large amount of lithium in two hyperfine states and a small amount of potassium in a pure hyperfine state. Rethermalizing collisions occur by intra-species collisions of the two lithium hyperfine states where the collision cross-section is enhanced by the broad $^6\text{Li}$ Feshbach resonance [95]. Inter-species collisions between the potassium and any of the two lithium hyperfine states yields the rethermalization of the potassium. At the start of this experiment the s-wave scattering lengths between $^6\text{Li}-^40\text{K}$ were not known and yielded an uncertainty in the possibility to succeed in cooling the mixture. It was unclear which approach would be the best: using a large amount of both spin-polarized $^6\text{Li}$ and $^40\text{K}$ and only relying on inter-species collisions or sympathetic cooling of a small amount of spin-polarized $^6\text{Li}$ with a large spin mixture of $^40\text{K}$ or vice-versa. The Munich group took a different approach to circumvent this uncertainty, namely by adding a third element, the bosonic $^87\text{Rb}$, as a coolant. A large amount of $^87\text{Rb}$ is evaporatively cooled relying on intra-species collisions and small amounts of the $^6\text{Li}$ and $^40\text{K}$ are sympathetically cooled along relying on inter-species collisions of $^6\text{Li}-^87\text{Rb}$ and $^40\text{K}-^87\text{Rb}$. The choice of $^87\text{Rb}$ as a third species was obvious since both the scattering lengths of $^6\text{Li}-^87\text{Rb}$ [71] and $^40\text{K}-^87\text{Rb}$ [96, 97] were known and sympathetic cooling of both fermions to quantum degeneracy by sympathetic cooling with $^87\text{Rb}$ had been achieved [71, 72].

Our approach is somewhat in between the two other approaches. We use only the two fermionic species, and use a combination of magnetic and optical traps. A big advantage of magnetic traps is the large trapping volume yielding large atom numbers and in the case of a linear quadrupole trap also the tight confinement. The largest quantum-degenerate atomic gases have been obtained in magnetic traps [98, 99]. The initial design was to prepare both the $^6\text{Li}$ and the $^40\text{K}$ atoms in the fully stretched hyperfine states which are stable against spin-exchange losses. Rethermalization only occurs due to inter-species collisions and forced evaporative cooling is performed on both species simultaneously. To be able to perform this approach two high flux cold atom sources have been developed, capable of loading $2 \times 10^9$ $^40\text{K}$ atoms simultaneous with $3 \times 10^9$ $^6\text{Li}$ atoms. During the course of the experiment we discovered in a collaboration with the Innsbruck group [17]...
that the singlet and triplet scattering lengths of $^6\text{Li}-^{40}\text{K}$ collisions are nearly identical, $a_s = 52.1(3)\ a_0$ and $a_t = 63.5(1)\ a_0$, yielding a suppression of the spin exchange losses. Therefore, we found that sympathetic cooling of a small amount of $^6\text{Li}$ in a large bath of three hyperfine states of $^{40}\text{K}$ is more efficient than the initial approach of using a large amount of both atoms in their doubly polarized states.

Additionally, two design considerations have been made which are emphasized here. First, we have used an optically plugged magnetic quadrupole trap rather than the commonly used Ioffe-Pritchard type of magnetic traps. This trap was originally used at MIT to achieve BEC, but was abandoned because of the non-harmonic confinement in the trap bottom which complicates analysis of the trapped clouds. However, since most research on ultracold fermions is performed in optical dipole traps the optically plugged quadrupole trap is an excellent option for pre-cooling close to quantum degeneracy. The combination of simple coil design, good optical access, large trapping volume and tight confinement provides a fast manner to achieve large ultracold atomic samples.

Second, the design incorporates an optical transport of the ultracold sample to an appendix of the vacuum system, which will be referred to as the science cell. The choice of transporting a sample close to degeneracy rather than a relatively hot cloud, as it is done by using a magnetic transport [100], was made to have no equipment around the science cell required to cool the sample and only equipment to perform experiments on the degenerate cloud. This allows a very small science cell with superb optical access to the sample, for example high-resolution imaging can be performed with standard microscope objectives as will be discussed in section 3.5.3.

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The chapter is ordered as follows. Sect. 3.2 describes the vacuum system, followed by the description of the laser systems for both species in Sect. 3.3. Subsequently, the various trapping and pre-cooling methods are discussed in Sect. 3.4 and in Sect. 3.5 the methods used for manipulating and diagnosing the samples are explained. The chapter concludes in Sect. 3.6 with the experimental results on the ultracold $^6\text{Li}-^{40}\text{K}$ mixture and the quantum degenerate spin mixture of $^{40}\text{K}-^{40}\text{K}$.

### 3.2 Vacuum

The vacuum system consists of four chambers, a source chamber for a two-dimensional magneto-optical trap (2D MOT) for each atomic species, a main trapping and cooling chamber and a science cell as depicted in figure 3.1 and 3.2. The potassium 2D MOT chamber is a glass cell (Technical Glass Inc.) as depicted in figure 3.1, 3.3 and 3.9. It consists of a four way cross of optical quality windows ($\phi = 30\ mm$) to provide access for two pairs of 2D MOT beams. Along the long side of the cell there is on one side a glass to metal seal connecting to a CF40 flange. This flange connects the chamber to the main vacuum system through a differential pumping tube of 23 mm length and 2 mm diameter. A gold mirror with in its center a 2 mm diameter orifice is mounted in front of the differential pumping tube, keeping a 1 mm distance between the mirror and the differential pumping tube to facilitate pumping between the surfaces. This mirror can be used for a 1D optical molasses or for reflecting a probe beam. On the other side there is an optical quality window for an axial cooling beam or push beam. On the side of the cell a 13 mm glass tube is connected by a T-piece to a break-seal ampule containing enriched potassium-40 and a glass to metal seal connecting through a
bellows to a CF16 flange. This flange is connected to a valve for pumping of the source chamber. During the coarse of the research performed for this thesis the valve has never been opened for pumping. The source cell has been baked while mounted on the main vacuum without the differential pumping section. Subsequently, the differential pumping tube was mounted under a protective atmosphere of Argon. Finally, the source cell has been evacuated through the differential pumping tube by the main vacuum pumps. As a source for $^{40}$K we use KCl enriched to an abundance of 6% $^{40}$K purchased from Trace Science International and distilled into a break-seal ampule by Technical Glass Inc. This break-seal ampule circumvents the use of home-built potassium dispensers [101]. The required vapor pressure for efficient operation of the 2D MOT is achieved by heating the source chamber. During the baking the temperature of the ampule has been kept below 100 °C to avoid the potassium reacting and avoid pressure building up in the ampule which could potentially break the seal.

The lithium 2D MOT chamber is described in detail in Chapter 4. We will briefly resume the design of the vacuum chamber here. It has a configuration similar to the potassium 2D MOT chamber, consisting of stainless steel rather than glass. Lithium is chemically reactive with glass, therefore the design is such that there is no direct line of sight from the oven to any window. The lithium source chamber is connected to the main vacuum by a differential pumping tube of 23 mm length and 2 mm diameter. A gold mirror with a 2 mm diameter orifice, identical to the one in the potassium setup, is mounted in front of the differential pumping tube. The source is connected to a four way cross which connects to a titanium sublimation pump (Leybold V150) and a 40 l/s ion pump (Vacion Plus 40 Starcell). The ion pump is valved off by an all-metal valve (VAT MAV-150-V). The titanium sublimation pump is only used once after closing the vacuum. As a source for lithium we use a combination of 6 g of enriched $^6$Li (95% purity from Sigma Aldrich) with 2 g of bosonic $^7$Li from natural abundance lithium for possible future use. The lithium is shipped as chunks in oil to protect reaction with water vapor in the air, additionally, the lithium contains a large amount of LiH. To clean out the lithium and obtain an oven with pure metallic lithium we degassed the lithium oven for about 2 h at a temperature of 670 °C on a separate vacuum system. During this procedure the oven was connected through a liquid nitrogen cold trap to a turbo pump. About 25% of the lithium was lost during this process. Subsequently, the oven was mounted under a protective atmosphere of argon onto the main vacuum chamber. When the oven is operated, no gas load is observed on the 40 l/s ion pump, indicating that the lithium is properly degassed. Additionally, during the coarse of the experiment the lithium sticking on the vacuum system acts as a getter itself. The lithium oven is connected with a nickel gasket (Caburn MDC) to the source chamber.

The main chamber is built around a spherical octagon (Kimball Physics Inc. MCF800-SO2000800-A). The lithium source is connected by a gate-valve (Leybold UHV 28699) and a close-coupler (Kimball Physics Inc. MCF275-CC200-700-A) to port no. 1 of the CF-40 ports (numbered clockwise from the top as in figure 3.1). The potassium source is connected without a gate valve directly to the opposing port (no. 5). On the port next to the potassium source (no. 6) a four way cross connects a titanium sublimation pump (Leybold V150) and a 55 l/s ion pump (Vacion Plus 55 Starcell) by a 60 cm long 2 1/2" tube. The ion pump is valved off by an all-metal valve (Varian 951-5027). On the top

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1At the time of writing this thesis enriched potassium dispensers have become commercially available from Alvatec.
Figure 3.1: A schematic top view of the vacuum system. The following parts are shown:
a) potassium 2D MOT source chamber, b) lithium 2D MOT source chamber, c) main
UHV chamber, d) science cell, e) to 55 l/s ion pump, f) to 40 l/s ion pump, g/h) titanium
sublimation pumps (mounted upwards), i) viewing direction of figure 3.10, j) gate valve

and bottom of the octagon two re-entry flanges provides space for magnetic field coils
to be mounted close to the atomic sample. Each re-entry flange consists of an uncoated
quartz window (\(\phi = 113\) mm) connected to a CF-150 re-entry flange with a non-magnetic
glass-to-metal seal (VACOM). The port numbers 2, 4, 6, 7 and 8 have uncoated optical
quality vacuum windows. Port no. 3 connects the science cell. The science cell consists
of a \(12.7 \times 12.7 \times 42\) mm square cell of uncoated quartz (Technical Glass Inc.) which is
connected by a glass to metal seal to a CF40 flange. The end facet of the science cell
extends to 23 cm out of the center of the main vacuum.

The vacuum is baked to a temperature of \(180^\circ\) C (limited by the glass-to-metal seals)
for four days. The potassium cell is baked out separately before mounting the differential
pumping tube. The vacuum operates at a pressure below the reading of the 55 l/s ion
pump (< 0.1 \(\mu\)A = \(5 \times 10^{-10}\) mbar) and the complete system is leak tested to a level
of \(10^{-10}\) mbar \(\times \) l/s. The system is continuously pumped by the two ion pumps. About
twice a year the 55 l/s ion pump has to be regenerated due to saturation, most likely by
argon leaking from the potassium 2D MOT chamber. At these events the ion pump is
baked to a temperature of 350 °C for a few hours, followed by running a current of 50 A
for 1 minute through one of the titanium sublimation filaments. The gas load generated
by the ion pump bake and the titanium sublimation pulse is dumped on a turbo pump
connected to the back end of the ion pump. The saturation of the ion-pump within a few
months suggests a pump with a larger pumping speed would elongate the time between
the regeneration events and might elongate the lifetime of the ultracold sample.
3.2 Vacuum

Figure 3.2: Photograph of the vacuum system, the parts indicated with a) to j) are explained in the caption of Figure 3.1.

Figure 3.3: Photographs of the 2D MOT source chambers. The lithium 2D MOT (left) is described in detail in Chapter 4. Due to the perspective are the dimensions only a rough indication. The flanges on the lithium source chamber are CF40-flanges ($\phi = 70 \text{ mm}$), the glass cross on the potassium source chamber has windows with $\phi = 38 \text{ mm}$. 
3.3 Laser Systems

3.3.1 Potassium

We use the D2-line transitions for trapping and cooling of potassium-40, where we will refer to the $^2S_{1/2}|F = 9/2\rangle \rightarrow ^2P_{3/2}|F' = 11/2\rangle$ transition as the trap transition and to the $^2S_{1/2}|F = 7/2\rangle \rightarrow ^2P_{3/2}|F' = 9/2\rangle$ transition as the repump transition (see figure 3.4). The potassium-40 isotope has a hyperfine splitting of the $^2S_{1/2}$ level of 1285.79 MHz (see Appendix A), therefore it is possible to derive the repump light from the trap light by making use of an acousto-optical modulator (AOM). Figure 3.5 depicts the potassium laser setup. One master laser is used as a stable frequency reference and two tapered-amplifier (TA) chips as amplification stages, a number of AOMs are used to shift the laser frequencies. For low frequencies (< 300 MHz) ISOMET AOMs are used, and for the hyperfine frequency of 1.3 GHz a Brimrose AOM (GPF-1240-200-.766) is used. Optical fibers are employed to distribute the light and to provide an accurate reference point for the beam alignment between certain parts of the experiment. The fibers used are the Schäfter + Kirchhoff PMC-630 models and homebuilt Thorlabs PM630-HP fibers. Schäfter + Kirchhoff fiber couplers (60FC-4-A6,2S-02) are used for in- and out-coupling of the fiber.

Master Laser and locking A Toptica DLX 110 is employed as a stable frequency source (see figure 3.5). The laser is operated at an output power of 350 mW which is distributed over five beams. Two beams are used for injecting the tapered amplifiers, one beam is used for low-field absorption imaging, one beam as a push beam for the 2D MOT and one for high-field absorption imaging. The laser is locked based on polarization Zeeman spectroscopy. Here we briefly describe the configuration. A linear polarized beam
is passed through a natural abundance potassium vapor cell heated to \( \sim 40^\circ C \). Ten percent of the beam is retro-reflected as a probe beam, detecting a doppler-free saturated absorption spectrum. A quarter waveplate combined with a cube splits the beam in its \( \sigma^+ \) and \( \sigma^- \) components. A homogeneous magnetic field of a few Gauss effectively shifts both signals in opposite directions due to the difference in Clebsch-Gordan coefficients for the \( m_F + q \) and \( m_F - q \) transitions, where \( q = \pm 1 \) for \( \sigma^{\pm} \) polarized light. The intensity of these beams are measured by two OPT-101 photodiodes. The two signals are electronically subtracted to create a dispersive signal used for locking. The laser is locked by two separate feedback loops: one slow integrator stage (\( \sim 1 \) Hz) to the piezo and one fast (\( \sim 4 \) kHz) integrator feedback to the laser current. The former tunes the piezo over a range of \( \pm 15 \) V to compensate slow thermal drifts. The latter provides short term stability, additionally it is limited in amplitude by the frequency span of the locking feature. This combination of amplitude-limited fast-feedback and large-range slow feedback eliminates the possibility of 'hopping' to another line due to electrical or acoustical noise spikes, common reasons for 'breaking lock'. The long term stability of this spectroscopic method was characterized by spectroscopy on the MOT and found to fluctuate over less than 1 MHz over the course of a few years. The lockpoint chosen is the spectral line of the \( ^{39}K \ ^2S_{1/2}^F = 1 \) to the unresolved \(^2P_{3/2}\) transitions (see Fig. 3.8).

**Tapered Amplifiers** We use two Eagleyard (EYP-TPA-0765-01500-3006-CMT03-0000) Tapered Amplifier chips as optical amplification stages. The chips are mounted in a homebuilt housing designed for optimum position stability of the chip, the mount is described in detail in Ref. [103]. The chip is mounted on a copper cross which temperature is actively stabilized by two Peltier elements (Eureca Messtechnik GmbH TEC 1H-30-30-44/80-BS). The cross itself is mounted by four spring loads and PEEK mounting studs to an aluminium base. The PEEK mounting studs provide electrical isolation of the diode and the spring loads keep the cross in place but allow it to marginally rotate around the diode laser center. Thermal expansion of the copper will therefore result in a rotation of the diode rather than a displacement. The collimation lenses are mounted in a PEEK holder, machined slightly too big for the aluminium housing such that longitudinal alignment can be done very accurately. During the operation period of a year we did not see any decay in the output power of both Tapered Amplifier chips, nor did the in- or out-coupling need any realignment.

The trap TA is operated by a Sacher Pilot 2000 temperature and current controller and is run at a temperature of \( 25^\circ C \) and a current of 2.0 A. Its typical input (output) powers are 46(766) mW. The repumper TA is temperature stabilized by a Thorlabs TED 200C temperature controller at a temperature of \( 31^\circ C \) and it runs a current of 1.7 A, provided by a homebuilt power supply around a Thorlabs LD3000 module. Its typical input (output) powers are 8(200) mW.

### 3.3.2 Lithium

The D-lines of lithium have a wavelength of 671 nm (see figure 3.6). For a long time high power narrow band laser light at 671 nm has been an issue for experiments on ultracold lithium. At the time of the writing of this thesis, various options are commercially available, these include tapered amplifiers from Toptica, dye lasers (see e.g. Radiant Dyes Laser), diode lasers (Mitsubishi ML101J27) and broad area diode lasers from Eagleyard.
Figure 3.5: Optical setup of the potassium laser system. The Toptica DLX 110 provides a narrowband frequency which is actively stabilized on the spectral line of the $^{39}\text{K} \, ^2S_{1/2}$ $F = 1$ to the unresolved $^2P_{3/2}$ transitions. The laser beam is split in total into five beams which are independently frequency shifted (see text), the typical frequencies used are indicated at each AOM. Two beams are amplified by Tapered Amplifiers (TA). Additional mirrors, beam shaping telescopes and shutters have been left out of the drawing.
When this project was started neither the tapered amplifiers, nor the high power diode lasers were available. Therefore we started with a Coherent 699 dye laser pumped with 5W at 532nm from a Verdi V10, using LD688 laser dye dissolved in Dowanol EPH. However due to its lack of stability we developed an injection locked dye laser, where an external low power diode laser was made narrowband by optical feedback from the dye cavity. The dye cavity itself was a compact bow-tie cavity consisting of four mirrors and the dye jet as optical elements. The concept of placing the bandwidth narrowing parts out of the cavity greatly improved the power output and stability of the system. At that time however the high power diode lasers had become available and to characterize the lithium 2D MOT behavior we needed independent control of the four frequencies for the 2D and 3D MOT beams. Therefore the ease of use of diode lasers and remaining instabilities due to the dye jet made us switch to the diode laser system as it is used now in the experiment. Two master lasers and four slave lasers provide ample power for the conducted experiments (see figure 3.7).

Master Lasers As stable frequency sources we operate two external cavity diode lasers (ECDL), similar to Ref. [105], operating a 120 mW wavelength selected diode (Mitsubishi ML101J27). One laser is locked on the D1-line and used for optical pumping, the other laser is locked on the D2-line and used for imaging beams, the push beam and injection locking of the slave lasers. The grating-mount and diode are temperature stabilized to $T = 70^\circ$C (Thorlabs TED 200C temperature controller) to tune the free running wavelength close to 671 nm. By tuning the grating, the laser can be tuned mode-hop free over a spectral range of 3 GHz. The current of the laser is provided by homebuilt power supplies based on the design of Libbrecht, et al. [106], providing a current stability on the timescale of hours of $\sim 10^{-5}$ on a current of up to 300 mA. Frequency stabilization of the master
Figure 3.7: Schematic of the lithium laser setup. For a legend see figure 3.5. The ECDL is locked to a saturated absorption spectroscopy and distributed over 5 beams which can independently be shifted in frequency. Four beams are used for injecting slave lasers. The push beam is derived from the 3D-repump. The intensity of the 3D-trap light can be controlled by the EOM and the intensity of the 3D repump by an AOM. Additional mirrors, beam shaping telescopes and shutters are not shown.

The actual buffer gas pressure in the heat-pipe oven is likely to be higher due to the presence of hydrogen outgassing from the lithium.
3.4 Trapping and Cooling

This section describes the various techniques used for trapping and cooling of both species. As sources for lithium and potassium we use two 2D MOTs. The lithium 2D MOT is described in detail in Chapter 4. In Sect. 3.4.1 the potassium 2D MOT is described followed by the double 3D MOT in Sect. 3.4.2. In Sect. 3.4.3 the optically plugged magnetic trap is described. This is the first realization of such a trap for lithium. The chapter concludes in Sect. 3.4.4 with a description of the optical trap and the optical transport.

3.4.1 2D MOTs

Two-dimensional magneto-optical traps have become a widely used method to obtain a high flux cold atom source. Although the largest fluxes up to date have been achieved with designs incorporating Zeeman slowers, alternative sources like the 2D MOT are very popular due to their compactness, the absence of hot flux in the main vacuum chamber and the little engineering required to set them up. The 2D MOT is formed by a combination of a 2D quadrupole magnetic field and two pairs of orthogonal trapping laser beams (see Fig. 3.9b), detuned to the red of the atomic resonance line. As in a standard 3D MOT [55], counter-propagating lasers have $\sigma^+ / \sigma^-$ polarization, so that the Zeeman shift relative to the two opposing lasers is opposite. As a result, a cold atom that moves toward one side of the trap finds that the Zeeman shift places it closer to resonance with the laser whose propagation direction points toward the trap center. Thus cold atoms will tend to be pushed toward a line that coincides with the zero of the quadrupole magnetic field. Since there is no confinement in the axial direction, atoms are free to leave the trapping region along this axis, and cooled, trapped atoms stream out of the trapping region along this line. Furthermore, due to the negative detuning of the trapping lasers, the atoms are cooled in the radial directions, producing a well collimated beam. We distinguish two types

![Figure 3.8: Spectroscopic signals obtained from the difference of the two photodiodes detecting the $\sigma^+$ and $\sigma^-$ saturated absorption signal. The spectroscopic features are labeled by the quantum number of the hyperfine groundstate. For both species the excited states are unresolved. Positive frequency refers to blue detuning. The current locking range is limited to $\pm 50$ MHz for the potassium and $\pm 25$ MHz for the lithium (see text). The potassium is locked to the $^{39}K_F=1$ line and the lithium to the crossover feature.](image)
of two-dimensional cooling. First, axially-loaded 2D MOTs like, for example, the original atom funnel [108] to which we will refer as beam brighteners since a beam source is needed to load this type of 2D MOT. Second, isotropically or radially-loaded 2D MOTs operated as a beam source, to which we shall refer as 2D MOTs. Isotropically loaded 2D MOTs are widely used for rubidium [109, 110, 111], cesium [112, 113] and also potassium [114, 115]. Our setup employs two 2D MOTs, for lithium and potassium. The lithium 2D MOT is the first 2D MOT for a light species like lithium, additionally it is the first 2D MOT radially loaded from an effusive source, therefore the setup and requires an extensive description to which we refer the reader to Chapter 4. The isotropically loaded potassium 2D MOT is described below. For both species a separate source chamber is used to have fully independent control over the vapor pressures and optical setup of the sources. Lithium is chemically reactive with glass and various groups working with potassium MOTs reported the potassium adsorbing on the stainless steel vacuum chamber. To avoid these problems we developed a stainless steel chamber for the lithium and a separate glass vacuum cell for the potassium.

**Potassium 2D MOT**  Figure 3.9 depicts the setup of the potassium 2D MOT. A break-seal ampule containing enriched potassium (Technical Glass Inc.) is connected to the vacuum cell. A glass-encapsulated magnet is placed in the tube of the break-seal, and after the bake the magnet is hit against the break-seal to open the enriched potassium ampule. The complete vacuum cell is heated to a temperature of \( T \approx 50^\circ\) C to achieve a vapor pressure optimal for the 2D MOT operation. Two circularly polarized beams are retro-reflected with additional quarter-waveplates to obtain two pairs of counter-propagating cooling and trapping beams. The magnetic quadrupole field required for the trapping is provided by two sets of \( \text{Nd}_2\text{Fe}_{14}\text{B} \) magnets (Eclipse magnets N750-RB) with a measured magnetization of \( 8.8(1) \times 10^5 \) A/m. Each set consists of two \( 25 \times 10 \times 3 \) mm magnet bars separated by 12 mm to make an effective dipole bar of 62 mm total length. The magnets are displaced from the symmetry axis by 35 mm, resulting in a two-dimensional quadrupole field with a gradient of 20 G/cm along the optical axes. The 2D MOT is operated at the parameters as shown in Table 3.1. For these parameters a 3D MOT loading rate of \( 3 \times 10^8 \) s\(^{-1} \) is obtained, nearly two orders of magnitude more than the previously reported \( ^{40}\text{K} \) 2D MOT [113, 116]. During the writing of this thesis a 2D+ MOT for \(^{40}\text{K}\), employing additional axial cooling, has been realized at the ENS in Paris yielding a 3D MOT loading rate of up to \( 2 \times 10^9 \) s\(^{-1} \) [117].

### Table 3.1: The optimal parameters for operating the potassium 2D MOT. Note that the 2D MOT is operated in a retro-reflected configuration.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<td>trap laser detuning</td>
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</tr>
<tr>
<td>repump laser detuning</td>
<td>(-2\Gamma)</td>
</tr>
<tr>
<td>beam waist</td>
<td>15 mm</td>
</tr>
<tr>
<td>trap power per beam</td>
<td>120 mW</td>
</tr>
<tr>
<td>repump power per beam</td>
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</tr>
<tr>
<td>field gradient</td>
<td>20 G/cm</td>
</tr>
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</table>


3.4.2 3D MOTs

Setup

Single species three-dimensional Magneto Optical Traps (3D MOTs) for lithium \([118, 119]\) and potassium \([120, 121, 122]\) have been extensively described elsewhere. This section describes the double-species 3D MOT and for which conditions it operates optimally. In contrast to other groups, the largest atom numbers for the potassium 3D MOT have been obtained by applying a very low power dark MOT operating close to resonance.

The trapping and cooling beams of the 3D MOT are formed by three orthogonal pairs of counter-propagating beams (see figure 3.10). Each beam consists of four colors: trap and repump light for the lithium, trap light for the potassium and (optional) bright repump light for the potassium. The six beams are clipped at roughly the 1/e diameter of \(d = 18\) mm, and are derived from one single beam by making use of polarization cubes and dichroic waveplates. We use \(d = 18\) mm dichroic quarter waveplates (Casix custom 670 + 767 nm) for the circularly polarized light of the MOT beams. The lithium trap (repump) light has a power of \(P = 10\) mW (11 mW) per beam corresponding to a peak-intensity of \(I = 1.8I_s (2.0I_s)\). The trapping light is red-detuned from the \(F = 3/2 \rightarrow F' = 5/2\) D2 transition by \(\delta_t = -6\Gamma\), and the repump light by \(\delta_r = -4.5\Gamma\) from the \(F = 1/2 \rightarrow F' = 3/2\). The potassium trapping (bright repumper) beams have \(P = 10\) mW (1.5 mW) per beam corresponding to \(I = 2.7I_s (0.4I_s)\). The trapping light is red-detuned from the \(F = 9/2 \rightarrow F' = 11/2\) D2 transition by \(\delta_t = -3\Gamma\), and both the bright and dark repump beams are detuned by \(\delta_r = -2\Gamma\) from the \(F = 7/2 \rightarrow F' = 9/2\) transition, significantly closer to resonance compared to other \(^{40}\)K 3D MOTs \([123, 115]\). We use a separate dark repumper beam for the MOT loading stage to achieve a high atom number and corresponding density. The dark repumper beams consist of two counter-propagating beams with both the same dark spot imaged on the MOT position. At the position of the MOT the dark spot has a diameter of 3 mm and an extinction ratio of 1 : 50 corresponding to the surrounding repump light. Both beams have 1.4 mW per beam (\(\simeq 0.4I_s\)). The magnetic quadrupole field for the MOT is formed by the magnetic trap coils and operates at a gradient of 14 G/cm. The double species 3D MOT is loaded simultaneously from the two 2D MOT sources in a continuous (non-pulsed) manner. The potassium MOT is typically loaded for 20 s, and the lithium MOT is loaded for the first few seconds of the potassium loading time. Depending on the experiment which is performed the atom number in the lithium MOT can be well controlled by means of the oven temperature and loading time. During the loading of the 3D MOTs the three trim coils apply a field of a few Gauss at the trap center to optimize the trapped atom number. We load simultaneously up to \(2 \times 10^9\) \(^{40}\)K atoms with \(3 \times 10^9\) \(^6\)Li atoms, where the MOT field gradient and beam alignment is optimized for maximum potassium atom number. The potassium MOT temperature is 190 µK, colder MOTs have been achieved for different MOT parameters resulting in a smaller number of trapped atoms. The lithium MOT temperature is 1.6 mK. In an optimized single species lithium MOT we can load up to \(10^{10}\) \(^6\)Li atoms (see chapter 4).

Compressed MOT and Optical Pumping

After loading of the double species MOT we apply a short modification of the MOT parameters to increase the phase-space density of both clouds before loading the mixture...
Experimental Setup

Figure 3.9: Schematic of the potassium 2D MOT system. The glass cell is filled with enriched potassium, distilled out of the break seal ampule after baking the vacuum. The vapor pressure of the cell is kept at a temperature of $T \sim 50^\circ C$ to achieve a vapor pressure optimal for operating the 2D MOT. Two beams are retroreflected to perform two-dimensional cooling on the vapor. The magnetic quadrupole field is applied by two bars of permanent magnets.

Figure 3.10: Schematic side view of the MOT optics and coils. The viewing direction is under 45° with the $x$ and $y$ axes (see figure 3.1). The dark repumper is not shown and propagates along the viewing axis. The parts shown in the figure are: a) optical table, b) main vacuum chamber, c) optical beams towards the MOT axis along the viewing direction, d) MOT/MT coils, e) vertical trim coils, f) horizontal trim coil, g) RF/MW antenna’s (see Sect. 3.5.2), h) potassium optical pumping beam, i) lithium optical pumping, j) imaging fiber with $f = 25\text{mm}$ lens making a collimated beam with $\phi = 20\text{mm}$, k) mirror for retro-reflecting lithium optical pumping beam, l) imaging lens $f = 160\text{mm}$ forms 1 : 1 telescopes with m) to collimate MOT beams and n) to image the ultracold sample, o) Sony X710 camera.
into the magnetic trap. During this compressed MOT stage the magnetic field gradient is linearly increased to \( B' = 44 \text{ G/cm} \) in 25 ms and the position of the field zero is shifted to optimize the transfer to the magnetic trap. During the last 3 ms of the compression the lithium 3D trap(repump) laser intensity is reduced to 1\% (2\%) of the original power and the trap(repump) detuning is decreased to \(-1.5\Gamma(-2\Gamma)\). This reduces the lithium temperature to \( T_{Li} = 0.6 \text{ mK} \), increases the density to \( n_{0,Li} = 3 \times 10^{10} \text{ cm}^{-3} \) and increases the degeneracy parameter by almost a factor 40 to \( D = n_{0}\Lambda^3 \simeq 7 \times 10^{-7} \), where \( \Lambda = \sqrt{2\pi\hbar^2/mk_B T} \) is the thermal de Broglie wavelength.

After the compression and cooling the mixture is optically pumped towards low field seeking states in the \( F = 9/2 \) and \( F = 3/2 \) manifolds for the potassium and lithium respectively. The potassium is optically pumped by a 60 \( \mu \text{s} \) flash of intensity \( 1.4I_{sat} \) resonant with the \( F = 9/2 \rightarrow F' = 9/2 \) transition, simultaneously the bright repumper is switched on to avoid leaking to the \( F = 7/2 \) manifold. The transfer efficiency of total atom number is \( \sim 60\% \) optimized for a spin mixture in the \( F = 9/2, m_F = +5/2, +7/2, \) and \( +9/2 \) states. Transfer efficiencies of up to 80\% can be achieved, however this results in an excess of atoms in the fully stretched state which is unfavorable for rethermalization in the magnetic trap. The lithium is optically pumped by a 150 \( \mu \text{s} \) flash on the D1-line. The pulse consists of two colors with intensities \( I = 1.0I_{sat} \) resonant with the \( F = 3/2 \rightarrow F' = 3/2 \) transition and \( I = 2.4I_{sat} \) resonant with the \( F = 1/2 \rightarrow F' = 3/2 \) transition. These parameters are optimized to achieve a maximum number of lithium atoms in the fully stretched state. We obtain a transfer efficiency of \( \sim 80\% \) in magnetically trapped states. A 3.6 G homogeneous field is pulsed on during the optical pumping pulses to provide a quantization field for the hyperfine states.

### Light induced collisions

Figure 3.11 a) and b) show the fluorescence decay curves of the single species lithium and potassium dark-spot MOT’s respectively. The curves are fitted to a decay model

\[
\frac{dN}{dt} = -\frac{1}{\tau} N - \beta \int n^2 dV \tag{3.1}
\]

where \( \tau \) is the background lifetime of the MOT and \( \beta \) is the loss coefficient due to homonuclear light induced collisions. The density distributions \( n \) of the lithium and potassium clouds are obtained by absorption imaging. The lithium has an optimal fit for \( \tau_{Li} = 65 \text{ s} \) and \( \beta_{Li,Li} = 5 \times 10^{-13} \text{ cm}^3\text{s}^{-1} \). For the potassium the optimal fit values yield \( \tau_K = 166 \text{ s} \) and \( \beta_{K,K} = 2 \times 10^{-12} \text{ cm}^3\text{s}^{-1} \), for a bright MOT we obtain a loss coefficient of \( \beta_{K,K} = 7 \times 10^{-12} \text{ cm}^3\text{s}^{-1} \). The discrepancy of the background lifetimes of the lithium and potassium MOTs is most likely due to an imbalance of the lithium MOT beams since these measurements are performed in a MOT optimized for the potassium. The low value of \( \beta_{Li,Li} \) is attributed due to the trap depth of the lithium MOT being larger than the fine structure splitting of lithium [124]. The large trap depth allows atoms to stay trapped after having undergone a fine-structure changing collision from the \( ^2P_{3/2} \) to the \( ^2P_{1/2} \) excited state, picking up a kinetic energy of \( E = k_B \times 0.48 \text{ K} \). Our obtained value for the \( ^6\text{Li} \) loss parameter agrees the values from Ref. [124] and [119] for \( ^7\text{Li} \).

Figure 3.11 c) shows the fluorescence of the single MOTs and of the double MOT. We observe very low losses in the double MOT due to the interspecies light induced collisions, this can be attributed to the dark spot of the potassium. To obtain the heteronuclear loss
**Experimental Setup**

**a.**

![Graph](image1.png)

**b.**

![Graph](image2.png)

**c.**

![Graph](image3.png)

Figure 3.11: a) decay curve of a single $^6$Li MOT and b) decay curve of a single $^{40}$K MOT, the lithium MOT is less lossy due to the small fine structure splitting [124]. The black lines are the fluorescence signals of the MOTs and the red lines are fits to Eq. 3.1.

c) loading curves of the double MOT of $^6$Li and $^{40}$K, the losses for the double MOT are suppressed due to the dark spot in the repump light (see text).

The coefficient $\beta_{Li,K}$ we use the following rate equation

$$\frac{dN_{Li}}{dt} = L_{Li} - \frac{1}{\tau} N_{Li} - \beta_{Li,La} \int n_{Li}^2 dV - \beta_{Li,K} \int n_{Li} n_{K} dV$$

(3.2)

In the case of the steady state, $dN_{Li}/dt = 0$, we can obtain the heteronuclear loss coefficient from Eq. [3.2]. We obtain a value of $\beta_{Li,K} = 4 \times 10^{-12}$ cm$^3$s$^{-1}$. Similarly we obtain a value of $\beta_{K,Li} = 5 \times 10^{-12}$ cm$^3$s$^{-1}$. We attribute these low losses due to the suppression of light-induced collisions by the potassium dark-spot. Due to the dark spot in the repump light most of the $^{40}$K atoms in the high density region are in the $F = 7/2$ manifold. Since the trap light is blue detuned with respect to the $^2S_{1/2}|F = 7/2\rangle \rightarrow ^2P_{3/2}$ levels it will not couple to any molecular bound states in the K(4p)+Li(2s) excited state potentials which could lead to photo-association losses. Molecular bound states in the K(4s)+Li(2p) excited state potentials extend to a maximum of $15.5\,\text{a}_0$ [125], much smaller than the interparticle spacing of atoms in a MOT. These properties suppress light induced collisions resulting in the relatively low values of $\beta_{K,Li}$ and $\beta_{Li,K}$.

### 3.4.3 Optically Plugged Magnetic Trap

After spin preparation of the laser cooled sample, the mixture is transferred into an optically plugged quadrupole trap [5, 15]. The quadrupole field is formed by a pair of commercially available foil-wound coils (Canatron). The foil has a cross-section of $25 \times 0.25$ mm with on both sides 50 $\mu$m Kapton isolation foil. Each coil has 76 windings yielding a coil with an inner radius of 17.5 mm and an outer radius of 45 mm. The coil is mounted on a copper, water cooled plate, where the largest thermal resistance occurs at the 0.2 mm electrical isolation between the coil and the copper plate. A current of 100 A (corresponding to an axial magnetic field gradient of 180 G/cm) results in a temperature rise of 35$^\circ$C with a time-constant of 2 minutes. During a typical experimental cycle the temperature of the coils varies by about 8$^\circ$C. The current for the coils is provided by a Delta Elektronika power supply (model SM 15-200 D/P104). The current switching electronics is homebuilt inspired by the design of Ref. [126]. Four IGBT’s (Semikron SKM100GB123D) in parallel with $2 \times 15$ transient voltage suppressors (ST Microelectronics SM15T39A) are capable
of switching 100 A off in 100 µs. A high voltage stage can switch the current on from 0 to 100 A in 120 µs. Two industrial relays (Stancor part no. 586-914) can be switched to reverse the current in one coil and provide the possibility of applying a homogeneous field up to 850 G for a current of 200 A.

At the zero point of the magnetic field Majorana spin-flips can occur which lead to heating and a limited lifetime of the sample. To prevent this depolarization we apply an ‘optical plug’ as a repulsive barrier to the atoms approaching the zero in magnetic field \[5\]. As an optical plug we use 532 nm light, which is far detuned from any \( ^2S \rightarrow P \) transition of a lithium or potassium atom.

The optical plug is generated by a Verdi V10 (532 nm), of which 7 W is focused to a waist of \( w_0 = 16 \mu m \). This creates a repulsive barrier for the lithium and potassium both of \( \sim 1 \) mK and a magnetic field in the trap bottom of \( B_0 \approx 260 \) mG (490 mG) along the weak (tight) axis of the quadrupole field. The optical plug can be switched by an Isomet 1205C-2 AOM. The plug position is monitored in real time with a CCD camera (see fig 3.14). From a Gaussian fit to the image we obtain the center position. We find the jitter during the experiment to be \( \sim 0.5 \mu m \) along both transverse directions, well below the beam diameter. We have operated the plug on a daily basis for a month without having to realign it. The plug beam is combined with the optical dipole trap on a dichroic beamsplitter (CVI laser BSR-15-1940), where the dipole trap is reflected and the plug beam is transmitted. This imposes an astigmatism on the plug beam which displaces the focal positions along the \( x \) and \( y \) axes by about 2.2 mm. Majorana losses only occur around the center of the magnetic trap, over an axial distance much smaller than the Rayleigh range of the plug beam. Therefore the astigmatism yields a tunability of the aspect ratio of the plugged volume from \( r_x/r_y \approx 0.3 \) to 3, where \( y \) is the tight axis of the quadrupole field. A slight increase of the aspect ratio to match the magnetic field aspect ratio is found to yield similar results as a circular plug. An aspect ratio in the range of \( 1 \lesssim r_x/r_y \lesssim 2 \) yields comparable results in the performance of the plug. Figure 3.12 shows an image of a potassium cloud with in the optically plugged trap after a time of flight of 1 ms. The plug is kept on during the time of flight to magnify the hole size.

Four of the six spin states of lithium are trapped in an optically plugged quadrupole trap. The \(|3/2, +3/2\rangle \) and \(|3/2, -1/2\rangle \) states are trapped for all magnetic fields, and for an energy \( k_BT \lesssim 310 \) µK the \(|1/2, -1/2\rangle \) and \(|3/2, -1/2\rangle \) states are trapped as well, the former in the trap center and the latter in a hollow pancake around the trap center due to the low hyperfine field of lithium (see Fig. 2.2). For a typical magnetic field gradient of 180 G/cm the \(|3/2, -1/2\rangle \) forms a pancake with a radius of about 1.5 mm along the tight quadrupole axis, additionally the pancake trap forms a stable trap without any field zeroes for \( T \lesssim 310 \) µK. The hyperfine field of the potassium is \( B_{hf,K} = 357 \) G (see appendix A), the potentials for the various spin states are thus well described by the linear Zeeman shift.

**Magnetic field trim coils**

Four magnetic field coils of 80 windings each allow trimming of the magnetic field in the main chamber. Two coils generate a vertical field and two orthogonal coils generate horizontal fields (see figure 3.10), all create a homogeneous field up to \( \sim 10 \) G. The coils are controlled by Delta Elektronica power supplies (model ES030-5) and the current can be quickly switched between a coil and a dummy load by means of a set of MOSFETs.
3.4.4 Optical Trapping and Optical Transport

After pre-cooling in the plugged trap we transfer the mixture in a far-off-resonance dipole trap (FORT) as described in section 2.4.1. The optical trap is formed by focusing up to 2 W of 1070 nm light (IPG Photonics YLD-5-LP) to a waist of \( w_0 = 19 \, \mu m \) yielding a maximum trap depth for the potassium (lithium) of 360 \( \mu K \) (160 \( \mu K \)). The position of the focus is displaced by \( \sim 50 \, \mu m \) from the plug position in the horizontal plane. The harmonic trapping frequencies at maximum laser power are \( \omega_{r,K} = 2\pi \times 4.72 \, kHz \), \( \omega_{z,K} = 2\pi \times 59 \, Hz \) and \( \omega_{r,Li} = 2\pi \times 8.11 \, kHz \), \( \omega_{z,Li} = 2\pi \times 101 \, Hz \). The trap depth can be controlled by modifying the beam power by means of an AOM (Crystal Technology Inc. 3080-197).

The optical trapping beam is focused down to the \( w_0 = 19 \, \mu m \) waist by an achromatic lens (\( f = 100 \, mm \)), mounted on a linear air bearing stage (Leuven Air Bearings LAB-LS). The translation stage is connected to a geared DC motor (Maxon Motor part no. 118751 equipped with a 111:1 gearbox) by means of a rubber belt to minimize vibrations transmitted from the motor to the stage. A motion controller (Maxon Epos 24/5) in combination with an encoder (HEDL 5540 part no. 110512) controls the stage movement. The stage can displace the lens over a distance of 22 cm and after each transport the absolute position of the stage is re-calibrated on a laser beam focused on a razorblade. The focus is translated onto the atoms by a 1 : 1 telescope to maintain the numerical aperture and maintain constant trapping frequencies during the transport. The optical trap light is combined with the optical plug by means of a dichroic beamsplitter (CVI laser BSR-15-1940).

Due to the large Rayleigh range of a typical optical dipole trap the requirements on the longitudinal reproducibility are far less stringent than on the transverse reproducibility. A simple tachometer on the DC motor and an optical switch consisting of a focused laser beam and a razorblade are sufficient to achieve the required longitudinal accuracy. After adiabatic loading of the dipole trap in 250 ms the trap focus is shifted by a sinusoidal profile to its end position in the science cell. The position of the trap focus in the main chamber is monitored by a CCD camera collecting the light transmitted (\( \ll 1% \)) by the beamsplitter. The transverse position reproducibility over 20 transports is \( \sigma_{\perp} = 1 \, \mu m \).
3.5 Manipulation and Diagnostics

3.5.1 Computer Control

The experiment is controlled by one main computer, this computer runs Windows XP as operating system and controls all digital and analog output lines and the cameras. A second Windows XP computer is used for visualizing CCD camera’s to monitor the plug or optical trap beams, magnetic field sensors and to control the optical transport system. The third computer is running a Fedora Core 6 Linux distribution and is used for real-time analysis of the measurements. The experimental system is running on a Windows XP machine because of the vast availability of drivers for any type of hardware and of the Control system described below. The choice to perform the data analysis on a Linux machine and to use open-source software has been made because of the high compatibility and portability for future experiments. Additionally the general properties of the Linux
operating systems simplify batch processing and remote processing of data.

**Hardware**

The hardware used to control the experiment is built around the Control system developed by Todd Meyrath and Florian Schreck [127]. This system uses a 25-bit bus system to program various types of devices. At the moment of writing of this thesis the modules available include: digital outputs, analog outputs, analog inputs, an RF synthesizer and RF amplifier. In our setup only digital output and analog output modules have been implemented. Additionally a module to interface DDS evaluation boards on the bus system has been developed (see section 3.5.2), the design concept is a simple variant of the digital output boards. The bus operates with 16-data bits, 8 address bits and 1 strobe bit, running at a clock speed of 300 kHz. Each analog output is programmed by a 16-bit DA-converter occupying one of the 256 available addresses. The analog output can be programmed from -10 to +10V and is capable of driving a current of 250 mA. For the digital output, one address is occupied by every 16 digital output. The outputs are TTL-compatible and capable of driving 50Ω loads. For our experiment 80 digital output lines and 40 analog output lines have been implemented. The controlling PC is connected to the bus system by means of a 32-bit National Instruments Digital I/O card (NI6533). The system is very cost-effective and has proven to be very reliable.

Additional devices are programmed by the same computer through various protocols, including RS232 (for the fiber laser and the Feshbach coil power supply), USB (for the
AD9956 DDS’s and an Apogee U13 CCD camera), GPIB (for a Fluke PM3394B oscilloscope and a Tulby Thandar Instruments 1906 multimeter) and Firewire (for the Sony X710 and SX90 CCD cameras).

Software

The software controlling the experiment is based on the Control software as developed in combination with the hardware described above, a detailed description can be found in Ref. [127]. The Control software is interfaced by a set of Visual C++ functions in which all outputs can be accessed. Variables can be defined which are accessible by a graphical user interface and which can be automatically scanned to perform measurements. The code is executed once to prepare the order of which digital/analog output lines have to be executed and peripheral devices can be pre-programmed. Subsequently the code is executed for a second time actually switching the digital/analog outputs and synchronized command are sent to peripheral devices. The digital/analog output commands are executed with a timing resolution of 3 $\mu$s. The free availability of this system in combination with its ease of use make it a good choice for ultracold atom experiments. In particular the programming of waveforms on any channel simultaneously can be done without any effort.

Some modifications to the software had to be made to adapt it to our setup. The main modification is that only the Control software is used, and not the data acquisition part Vision. We have developed image acquisition software capable of interfacing with the Control software while running on the same computer. The Firewire cameras are interfaced through a Visual C++ program exploiting the open-source driver 1394Camera [128]. The Apogee U13 Camera is controlled by a Visual C++ program exploiting the Apogee Alta driver, and is permanently running in the background. At the beginning of an experimental sequence the Apogee program is armed and for each Firewire camera an instance of the Firewire program is started. The exact triggers for all cameras are given by hardware triggers from a digital output. Images are acquired and saved in a Portable Gray Map format (PGM) to a local harddrive. All acquired images and experimental parameters are copied to a network drive from where the data analysis software analyses the images. This configuration allows data acquisition to continue when network delays occur. The program to control the Maxon motor controller for the optical transport is written in Visual Basic 6.0 and is running on a separate computer. The program initializes the controller and programs the endpoints and sinusoidal trajectory of the transport. Triggers to start the transport and the homing sequence are provided by digital outputs of the main computer connected to the Maxon controller.

All on-line data analysis software is written in GNU C++ running on the Linux computer. The routines for fitting various 1D and 2D distributions to PGM images are compiled into a dynamic library. This library is accessed from command line programs to perform manual batch fitting to images, or from the graphical user interface. The graphical interface is written in Python 2.5.1 and uses the wxPython library for interfacing to the X-Windows environment and the cTypes library for interfacing the GNU C++ fitting library. The fitting program displays the absorption image, an optical density image, basic fit information like atom number and cloud sizes and an $x$ and $y$-integrated 1D-profile to compare the fit result to the data. An instance of this program is run for each camera separately.
3.5.2 Radio-frequency and microwave sources

Due to the hyperfine structure of the alkali atoms being in the range of MHz-GHz energy scales, many radio-frequency (RF) and microwave (MW) have to be employed in experiments to manipulate the atoms. The RF and MW sources can be divided into two categories: sources used related to optical transitions and sources related to ground state hyperfine transitions. The former are used to shift the frequency of light by means of AOM’s or EOM’s and require frequency stability on the sub-MHz level (smaller than the natural linewidth). For this purpose voltage controlled oscillators (VCO’s) are being used. These oscillators are cheap and easy to setup. The hyperfine states do not experience spontaneous decay and therefore the linewidth of the transition is determined by the coupling strength of the RF or microwave. This requires high frequency and power stability of the sources to drive coherent transitions between the hyperfine levels. For this purpose we employ Direct Digital Synthesis (DDS) technology.

Most AOMs in our setup are being controlled by VCO’s from the ZOS series by Mini-Circuits. The only exception to this scheme is the Brimrose AOM (see figure 3.5), which shifts the light by the frequency corresponding to the potassium hyperfine splitting of about 1.2 GHz. A VCO with sub-MHz drift would require a long term stability of the tuning voltage of the order of 1 mV. To avoid drifts we use a DDS as a frequency source for this AOM.

Analog Devices AD9956 DDS

Three AD9956 DDS’s from Analog Devices are used in our setup. The DDS’s are mounted on standard evaluation boards containing the circuitry for a VCO and a loop filter. These evaluation boards offer USB programming and the possibility of phase-locking a VCO to the DDS. All three boards are mounted with Crystek Microwave VCO’s, two have a CV55BE1000-1500 for frequencies from 0.9 – 1.35 GHz and one has a CV55CL225-425 for frequencies ranging from 200 – 350 MHz. Each evaluation board is equipped with a loop filter adapted for the used frequency range, and configured in a manner as depicted in figure 3.15a. The devices are programmed through USB and to assure time-critical control over the frequencies, the I/O update and Profile Select lines are rewired to digital output ports of the main control system. Reprogramming of all three DDS boards are performed through the USB bus, synchronized with the experimental sequence. Triggers for frequency updating are subsequently given by a digital output line.

Analog Devices AD9858 DDS

During the coarse of the experiment the setup was extended with four additional DDS sources. We chose for an alternative to the AD9956 to have a more flexible control over the frequencies as compared to the USB programmed AD9956’s. Four Analog Devices AD9858 DDS evaluation boards are used in our setup. These DDS’s are parallel programmed through the bus system, facilitating the change of DDS frequency to its full 32-bit frequency accuracy every five clockcycles (15 µs). An interface to the bus system has been developed based on the design of the 16-bit digital output card, with the addition of a demultiplexer stage to allow control over all 18 bits of the evaluation board with a single 16-bit bus module. One of the DDS boards is equipped with a CV55BE1000-1500 VCO to access the 1.0-1.3 GHz frequency range. This VCO is phase-locked to the
3.5 Manipulation and Diagnostics

Figure 3.15: The two DDS setups. a) the setup of the USB programmed AD9956 set up in a fractional divider loop, the divider /R divides by 4 for the 1.0-1.3 GHz boards and is bypassed for the 200-400 MHz board. b) the parallel programmed AD9858 is set up in a direct upconversion scheme. The dotted box in b) is only present for the 1.0-1.3 GHz output.

Table 3.2: The RF and microwave amplifiers used in the setup. The various AOMs are described in Sect. 3.3.1, the potassium and lithium hyperfine manipulation in Sect. 3.5.2 and state preparation on the Zeeman levels for potassium and hyperfine for lithium in Sect. 3.5.3.

<table>
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<td>Zeeman levels</td>
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</table>

DDS according to figure 3.15b. All four boards use a 2 GHz clock provided by an Analog Devices AD9516 clock generator evaluation board.

The clock generator is running with an external 20 MHz clock as a reference. This clock is provided by a temperature compensated voltage controlled crystal oscillator (TXVCXO) from IQD Frequency Products (LF PTX0000006), which has a long term stability of ±1 ppm. Both the AD9956 and AD9858 DDS’s with the phase locked VCO’s have a measured linewidth smaller than 100 Hz, more than sufficient for the experiments performed in this thesis.

RF and MW amplification

The amplitude of the RF and MW from the frequency sources is controlled by various combinations of amplifiers, voltage controlled attenuators and switches. Table 3.2 lists the amplifiers used for the different applications. The power of the RF signals are controlled by MiniCircuits voltage-variable attenuators (ZX73-2500+) and switches (ZASWA-2-500R+).
Experimental Setup

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<td>1</td>
<td>6.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 3.3: The antennas used to manipulate the hyperfine states of the potassium and lithium. The listed properties are the frequency range for operation, the position on the vacuum system, the distance from the sample $z$, the number of windings $n$, the coil radius $r$ and wire diameter $\varnothing$.

RF and MW antennas

The generated RF and MW frequencies used to manipulate the ground state properties of the atoms are amplified and subsequently radiated by means of simple antennas. Four antennas are integrated in the setup (see table 3.3): one at the science cell to perform field calibration of the Feshbach field on the potassium hyperfine splitting ($\sim 1$ GHz) and three in the main chamber: one for the potassium hyperfine splitting (1.0 – 1.3 GHz), one for the lithium hyperfine splitting (200 – 400 MHz) and one for the Zeeman splitting at low field (0 – 10 MHz). The 1.2 GHz coil for the potassium in the main chamber consists of a BNC cable of which the shielding is stripped and the core makes a loop of 19 mm radius ($\approx \lambda/2$ circumference). The coil radiates more than 50% of the power over the frequency range of 1.1 – 1.3 GHz, however, there are strong resonances yielding a non-linear response. The coil is tuned to resonance with a triple-stub tuner to achieve a flat frequency response over the range 1.1 – 1.3 GHz. The field calibration antenna is directly connected to the VCO output of the AD9956 evaluation board. For the field calibration and the Li hyperfine antennas three-port circulators (SIAM CT3.002 and McManus Microwave model 253) are connected to attenuate microwaves reflected from the antenna and protect the VCO and amplifier respectively.

3.5.3 Imaging

Three methods of imaging have been performed for the experiments described in this thesis, low field and high field absorption imaging and fluorescence imaging. In all cases (near)resonant light is scattered by the atomic sample. For absorption imaging light is scattered from a laser beam hitting the camera and the signal consists of the missing scattered photons. For fluorescence imaging the light is scattered from a laser beam not hitting the camera and the signal consists of the scattered photons which are collected by the camera. Fluorescence imaging is used for the lithium-beam measurements as presented in Chapter [4] and for MOT-recapture measurements. An atomic sample trapped in a MOT scatters many photons per atom without changing the number of trapped atoms, therefore the integration time for collecting fluorescent light can be very long yielding a good signal to noise ratio. Absorption images are generally taken on ballistically expanding or ultracold samples. This yields a short interaction time for the imaging pulse with the sample and few photons can be scattered per atom, thus a smaller signal to noise ratio is achieved as compared to fluorescence imaging in a MOT. In our experimental setup fluorescence imaging is only possible in the MOT area, therefore we have used this to characterize the MOT and magnetic trap. Obtaining absolute atom numbers from
fluorescence data is involved, the fluorescence signal of a MOT depends for example on the excited state fraction, ratio’s of trap and repumper light and the solid angle of captured light. Therefore fluorescence imaging was only used to perform relative measurements and absolute atom numbers have always been obtained by absorption imaging.

Near-resonant imaging light for both species is obtained by means of double-pass AOM’s (see figure 3.5 and 3.7). Each color is divided over two beams by half waveplates and polarizing cubes, recombined on bichromatic beamsplitters and coupled into polarization maintaining fibers (Schäfter + Kirchhoff PMC-630-4.5-NA011-3-APC-150-S). With this setup we have two fibers, one for imaging along the horizontal axis and one for the vertical axis, containing both colors controllable by the AOM’s. The fiber for vertical imaging can be connected to either of two collimators for vertical imaging in the main chamber or in the science cell. Imaging along the horizontal axis is performed with linear polarized light and along the vertical axis with circular polarized (σ+) light in both cases. During the imaging pulse a light pulse resonant with the repump transition is also applied to prevent leaking to dark states. These beams are under 45° with the imaging path, where the beams are retro-reflected to avoid a force being exerted on the atoms by the repump light.

During the imaging pulse the atoms absorb photons along the propagation axis of the imaging pulse and re-scatter photons in random directions. The former causes an acceleration which shifts the atoms out of resonance and the latter causes a random walk of the atoms during the imaging pulse which leads to blurring of the image [129, 61]. For a low saturation parameter $s_0 \ll 1$ the number of photons scattered off an on resonance light pulse is given by: $N_p = \left(\frac{s_0}{2}\right)\Gamma \Delta t$, with $\Gamma$ the natural linewidth and $\Delta t$ the duration of the imaging pulse. The longitudinal Doppler shift of an atom due to this pulse is $\omega_D = v_r N_p k$ where $v_r = \frac{\hbar k}{m}$ is the recoil velocity and $k$ the wavevector of the imaging light. The transverse displacement is given by: $r_{rms} = \sqrt{N_p/3v_r \Delta t}$. Typical parameters in our experiment are a saturation parameter of $s_0 = 0.1 \ (0.07)$ and a pulse duration of $\Delta t = 40 \ (100) \ \mu s$ for the lithium(potassium), this results in a blurring of $r_{rms} = 19 \ (9) \ \mu m$ and a shift out of resonance by $\omega_D/\Gamma = 1.8 \ (0.4)$. During the imaging pulses for each species two counter-propagating beams of repump light are applied under 45° with the imaging path. This creates an one-dimensional optical molasses for atoms in the $F = 1/2$ and $F = 7/2$ hyperfine states for lithium and potassium respectively. Due to the unresolved hyperfine structure of the $^2P_{3/2}$ hyperfine state of lithium the lithium atoms spend a significant amount of time in the lower hyperfine state, resulting of a cooling of the atoms due to the counter-propagating repump beams. We have verified that for the lithium cloud the obtained atom number is insensitive to the imaging pulselength $\Delta t$, indicating that the repumper effectively cools the heat imposed by the imaging pulse and suppresses the shift out of resonance $\omega_D$. Concluding, although the lithium imaging suffers strongly from the blurring effects the atom number can be reliably obtained in this manner. For analysis of the lithium density-profiles on the order of the $r_{rms}$ a shorter pulselength or lower intensity should be used. The experiments presented in this thesis on lithium clouds do not require spatial analysis on the order of $r_{rms}$.

Images are analyzed by the conventional method where an absorption image is taken $I_{abs}$, subsequently a reference image $I_{ref}$ of the optical field and a background image $I_{bg}$ are taken without any imaging pulse. The signal is obtained as: $I/I_0 = (I_{abs} - I_{bg})/(I_{ref} - I_{bg})$. For the Sony camera’s $I_{bg}$ was found to be negligible, therefore this image is omitted in the analysis of the Sony data. For low saturation parameters the column-density of the
atomic distribution is obtained by evaluating the Lambert-Beer law:

\[ \frac{I(x,y)}{I_0(x,y)} = e^{-OD}, \]

where \( OD = \sigma n(x,y) \) is the optical density, \( n(x,y) = \int dz \, n(x,y,z) \) is the column density along the propagation axis of the imaging beam and \( \sigma \) is the optical scattering cross section of the imaging pulse with the atoms, given by

\[ \sigma = \kappa \frac{3\lambda^2}{2\pi} \frac{1}{1 + (2\delta/\Gamma)^2}, \]

where \( \kappa \) accounts for the Clebsch-Gordan coefficients of the possible transitions, \( \kappa_{Li} = 1/2 \) and \( \kappa_K = 2/5 \) for linearly polarized light and \( \kappa = 1 \) for circular polarized light, for the lithium \( F = 3/2 \rightarrow F' = 5/2 \) and potassium \( F = 9/2 \rightarrow F' = 11/2 \) transitions. We have cross-checked the absolute atom number calibration by comparing the atom number of vertical imaging with horizontal imaging. The effective pixel-size of the horizontal cameras have been calibrated by measuring the free fall of an ultracold potassium cloud from the optical trap. The resulting vertical position scales according to:

\[ y(t) = \frac{g}{2} t^2 \]

where \( g = 9.8 \, \text{m/s} \) is the gravitational acceleration. The effective pixel sizes of the vertical camera's have been calibrated on a 1951 USAF Resolution Target. For the Sony SX90 camera with a 1 : 1 telescope on the science cell (main chamber) we find an effective pixel size of 3.60 \( \mu \text{m} \) and for the Apogee with a \( \times 4 \) objective we obtain 3.94 \( \mu \text{m} \).

The absorption and reference image are taken within 500 ms with the Sony camera's, limited by readout time. The Apogee U13 camera is used in a fast kinetics mode. This method exposes only part of the CCD array which is shifted to a masked area before the next exposure is performed. This method allows fast consecutive image to be taken before the slow electronic readout is performed. The Apogee U13 camera is capable of shifting CCD-lines at a rate of 45 \( \mu \text{s}/\text{line} \). For a 512-line kinetics image this results in a minimum of 25 ms between the absorption and reference image. For an optically trapped cloud after typical time of flights only 65 pixels are require to to image the complete cloud. This results in 3 ms between the absorption and reference image.

Four cameras are used to perform imaging of the ultracold sample. Two Sony SX90 Firewire cameras are imaging along the optical trap axis, where flippable mirror mounts allow to change between imaging in the main chamber and imaging in the science cell (see figure 3.16). Vertical images are taken in the main chamber by a Sony X710 camera and in the science cell by an Apogee Alta U13 camera.

**High resolution imaging**

The small dimensions of the science cell allow to image the ultracold sample with a high numerical aperture, resulting in a high optical resolution without the need of special optics. To test the high-resolution possibilities we have mounted a Sony SX90 camera with a standard DIN \( \times 4 \) microscope objective (Edmund Optics NT36-131) directly imaging the ultracold sample in the science cell without any additional optics. Using the \( \times 4 \) magnification the SX90 camera has an effective pixel size of 0.94 \( \mu \text{m} \). Using the USAF test target we clearly resolve (> 40% contrast) the smallest elements, spaced at 4.4 \( \mu \text{m} \). Taking this spacing to be the minimum resolved according to the Rayleigh criterion, we can obtain an upper limit for the imaging resolution. This corresponds to an imaging resolution of \( \sim 3 \, \mu \text{m} \) (1/e^2 radius) of a single point source.
Figure 3.16: Imaging optics for imaging in a) the main chamber and b) the science cell. All $f = 250$mm and $f = 200$mm lenses are mounted on flippable mounts. This allows fast and reproducible switching between the two imaging setups. The vertical imaging in the science cell is done by directly imaging with a standard \( \times 4 \) microscope objective. The position of the vacuum system is shown in light grey.
3.5.4 Spin state preparation and purification

Control and characterization of spin states is an essential tool to perform experiments on ultracold gases. In particular systems involving a species with a high nuclear spin like $^{40}$K require additional care since many spin states can be magnetically trapped. In this section a few methods will be discussed to manipulate the spin mixture of an ultracold potassium cloud.

**Stern-Gerlach analysis**  The composition of spin states is measured by means of a Stern-Gerlach experiment. During the expansion of the ultracold sample a field gradient of $B' = 110$ G/cm is pulsed for the first $4$ ms followed by a free expansion for $3$ ms. The gradient is applied by pulsing on the quadrupole trap and the vertical shim coil generating a homogeneous field of $28$ G. This method yields a gradient of $B' = 110$ G/cm with an absolute value of $B = 28$ G therefore the linear Zeeman effect dominates the separation of the spin states. Figure 3.19 shows typical Stern-Gerlach measurements. To perform a Stern-Gerlach experiment the atomic sample has to expand slower than the separation takes place. Due to the relatively small waist of the optical trap Stern-Gerlach analysis could only be performed on a cloud which was evaporatively cooled in the optical trap and had sufficiently low trapping frequencies. The measurements in figure 3.19 were taken with a radial trapping frequency of $\omega_r = 2\pi \times 560$ Hz and at a temperature of $T = 450$ nK.

**State purification: microwave cleaning in the magnetic trap**  The optical plug induces an effective $B_0$ in the trap along the weak axis of the quadrupole field (see section 3.4.3) of $250$ mG. Evaporation at the plug (inner) side of the cloud can be performed to selectively remove undesired spin states. Figure 3.17a and b show the truncation parameter $\eta = U_0/k_B T$ and the density as a function of the frequency $f_0$ to drive the $|F = 9/2, m_F\rangle$ state to an untrapped $|F = 7/2, m_F - 1\rangle$ state. These curves are calculated for a plug size(height) of $16$ µm($670$ µK) and a cloud of $T = 20$ µK. Evaporating from high frequency down spills spin states with preferably small $m_F$, purely selective spin addressing is only possible for temperatures of $\lesssim 1$ µK.

**State purification: axial spilling**  After pre-cooling the ultracold sample in the magnetic trap it is transferred into the optical trap (see section 3.4.4). This transfer is performed by adiabatically ramping up the optical trap power followed by adiabatically ramping down the magnetic field. For the method considered here we consider the case that the optical trap is ramped on and the magnetic field is still at its full compression. At this moment the confinement of the ultracold cloud is radially determined by the optical trap and axially by the magnetic trap. Applying a homogeneous magnetic field shifts the magnetic trap center away and applies an offset field over the extent of the ultracold cloud. This offset field enables to drive the $|F = 9/2, m_F\rangle$ atoms to a $|F = 7/2, m_F - 1\rangle$ high field seeking state, therefore high field seeking states can be selectively evaporated along the axial dimension of the optical trap. Figure 3.18a shows the axial and radial trap shapes for a shifting field of $10.4$ G and a trap depth of $U_0 = 150$ µK. A microwave sweep for $100$ ms over a frequency span of $200$ kHz is performed to evaporate the magnetically trapped states. Figure 3.18a shows the loss spectrum of a $T = 20$ µK cloud as a function of the starting microwave frequency. The features are well resolved therefore this method
Figure 3.17: Microwave cleaning of the potassium spin states in the optically plugged quadrupole trap. a) The optically plugged quadrupole trap. Due to the plug a minimum magnetic field $B_0$ is experienced by the atoms. b) The calculated $\eta$ parameter of various spin states as function of the microwave frequency for $T = 20\,\mu$K. For finite $T$ the peaks overlap, for $T \to 0$ the peaks become isolated and selective addressing of the spin states is possible. c) Normalized density for each spin state. The spacing between the peaks is determined mainly by the plug parameters and the cloud temperature determines the wings towards the left (lower frequencies). d) A measurement of the atom number left after a microwave sweep from 1285.79 MHz down to a final frequency $f_0$ for a cloud of $T \simeq 20\,\mu$K.
Figure 3.18: Selective axial spilling in a combined optical and magnetic trap. a) loss spectrum of a trapped spin mixture of $^{40}$K, the various loss features are labeled. b) axial (radial) trap shape in the upper (lower) panel, the dash-dotted (dotted) line shows the combined optical and magnetic trapping potential for the $|9/2, +9/2\rangle (|7/2, +7/2\rangle)$ state and the solid line shows the optical potential. The magnetic trap is shifted radially by applying a homogeneous magnetic field, hardly affecting the radial potential but creating an axially anti-trapping potential for high field seeking states.

allows to selectively address each spin state and does not heat the sample, a disadvantage is that the method is only applicable to low field seeking states.

State purification: low field microwave + optical purification In an optically trapped sample with a homogeneous magnetic field the $F = 9/2$ hyperfine states can selectively be transferred to the $F = 7/2$ manifolds by means of an adiabatic microwave sweep. Subsequently the complete $F = 7/2$ manifold can be cleaned by an optical light pulse on the $^2S_{1/2} \rightarrow ^2P_{3/2}$ transition. For this experiment the ultracold sample is evaporatively cooled in the optical trap by ramping down the laser power to 2% of its initial value to enable a Stern-Gerlach analysis. Figure 3.19 shows the various stages of the cleaning process. Figure 3.19a shows the $^{40}$K spin mixture in the optical trap after loading from the magnetic trap and evaporative cooling in the optical trap. Figure 3.19b is after an adiabatic sweep transferring the high $m_F$ values on the low $m_F$ values followed by the optical trap evaporation. The sweep is performed at a magnetic field of $B = 9.4$ G and the frequency is swept linearly from 3.0 MHz to 2.7 MHz in 10 ms. For figure 3.19c the optical trap evaporation is followed by a linear microwave sweep from $f_s = 1302$ MHz to $f_s = 1304$ MHz in 60 ms during which light resonant with the $^2S_{1/2}|F = 7/2\rangle \rightarrow ^2P_{3/2}|F' = 9/2\rangle$ transition is switched on. This method selectively removes the $m_F = -7/2$ state, however due to optical pumping it populates the other $m_F$ states. This optical pumping can be circumvented by applying the optical pulse on the $^2S_{1/2}|F = 7/2\rangle \rightarrow ^2P_{3/2}|F' = 5/2\rangle$ transition since the $F' = 5/2$ excited state can only decay to the $F = 7/2$ groundstate.
3.5 Manipulation and Diagnostics

Figure 3.19: Purification of a spin mixture of $^{40}$K. a) original spin mixture of high $m_F$ states, b) after the adiabatic sweep transferring to the low $m_F$ states, c) after the two-photon removal of the $m_F = -7/2$ state. d) level scheme at a magnetic field of $B = 9.3$G where this state purification is performed.

State purification: high field optical purification For high magnetic fields the Zeeman energy is much larger than the hyperfine energy. For the lithium (potassium) groundstate the hyperfine field corresponds to $B_{hf,Li} = 27$ G ($B_{hf,K} = 357$ G), see Fig. 2.2. For magnetic fields $B \gg B_{hf}$, the nuclear spin decouples from the electronic spin and a good basis to describe the hyperfine states is the $|m_I, m_J\rangle$ basis, where $I$ is the nuclear spin and $J = L + S$ is the total electronic angular momentum; the sum of the orbital angular momentum and the electronic spin. An optical transition can couple a $m_J = +1/2$ groundstate to a $m_J = +3/2$ excited state. This state can only decay back to its originating $m_J = +1/2$ state. Therefore such a transition is a cycling transition and will efficiently exert a force on only one spin state. For intermediate fields the nuclear and electron spin are not completely decoupled, therefore, optical pumping of the potassium to different groundstates will occur. This method is therefore efficient to empty one specific spin state, however it will populate others if the magnetic field is not sufficiently high. We have used this method in the Feshbach width measurement (see chapter 6) to remove possible impurities from the potassium $|9/2, +3/2\rangle$ state, which due to a nearby Feshbach resonance could cause significant losses.

Adiabatic sweep state preparation To manipulate the potassium spin states we apply a homogeneous magnetic field of 9.3 G and sweep an RF frequency from $f_s = 3.0$ MHz downwards in 10 ms to a variable end frequency $2.7 < f_e < 3.0$ MHz. The end frequency determines the final spin composition of the mixture. Figure 3.19b shows the spin mixture after a sweep to $f_e = 2.7$ MHz showing a nearly complete transfer of the spin mixture before the sweep (see figure 3.19a) to the negative $m_F$ values. Lithium state preparation is performed by applying a fixed microwave frequency and sweeping the magnetic field. This method yields a smoother sweep and results in a higher
transfer efficiency as compared to sweeping the frequency for a fixed magnetic field value. Lithium in the state $|F = 3/2, m_F = +3/2\rangle$ is transferred to the $|F = 1/2, m_F = +1/2\rangle$ state with $\sim 50\%$ efficiency.

### 3.5.5 Feshbach Coils

The field of ultracold gases has been tremendously enriched by the ability to tune interactions by means of Feshbach resonances. To be able to control the scattering length accurately one needs to have a good control over the magnetic field applied to the ultracold sample. This requires a high stability, reproducibility, calibration and homogeneity of the magnetic field over the sample size. Since the properties of Feshbach resonances are very diverse in terms of positions and widths magnetic field coils have to be designed according to the needs for a specific system. We have chosen for a design with high field homogeneity and stability.

#### Mechanical Construction

Figures [3.20] and [3.21] show the design of the Feshbach coils as used in our setup. The concept of high field homogeneity and stability is achieved by having a Helmholtz configuration and many windings running a relatively small current to achieve a high and uniform current density with a square cross section. Additionally, the coils are wound anti-symmetrically; i.e., with opposing helicity, around the center. Therefore, the current-density of the coil system is also anti-symmetric around the origin

$$\vec{j}(\vec{r}) = -\vec{j}(-\vec{r})$$

The total magnetic field in the origin is the sum of the magnetic field vectors generated by each coil. Expanding the total magnetic field in the origin in powers of $r$ will only contain even terms due to Eq. 3.3. Any field inhomogeneity occurring from the finite size of wire bends or lead wires is cancelled to first order due to this configuration. The coil mount is chosen to be made from brass for the best compromise of high thermal conductivity and good mechanical properties.\(^3\) The brass housing is cut to avoid creating an inductance loop and the brass volume is impoverished to reduce the volume where eddy-currents can occur.

Each coil contains of 126 windings wound as a continuous helix to avoid strong field inhomogeneities which would be caused by stepwise going to the next winding. The inhomogeneities caused by these types of steps would also be compensated by the second coil due to Eq. 3.3 however, it is very sensitive to the exact placement of the steps, therefore this method is much more sensitive to the winding procedure compared to a helix-wound coil. Additionally, with a helix-wound each layer can be easily filled up with an integer number of windings. To offset the thread at each layer, CNC machined glass-fiber (G10) spacers are included at the start of each layer. The step needed to lift the wire from one layer to the next layer is also performed in a gradual manner: the wire is lifted by its thickness over one complete circumference, this is also aided by including glass-fiber

\(^3\)An interesting alternative are thermally conductive plastics, like the D5506 Thermally Conductive Liquid Crystalline Polymer from CoolPolymers. This polymer is electrically insulating and has a thermal conductivity of $10 \text{ Wm}^{-1}\text{K}^{-1}$. We have performed preliminary tests on using this material for a coil mount, which yield good results.
Figure 3.20: A schematic of the Feshbach coil (left) depicts the various sets of coils. a) main coils, b) trim coils, c) sweep coils, d) ultracold sample and e) thermistor location (see text). The grey indicates the brass, blue indicates the water cooling and red the coils. All coils create a magnetic field along the z-axis. A finite element calculation of the thermal distribution in the coil (right) depicts the maximum equilibrium temperature achieved in the coil while running $I = 28.5\, A$ to obtain a field of $B = 500\, G$.

Figure 3.21: CAD drawing (left) and photograph (right) of the Feshbach coils. The monolithic brass mount (beige) ensures exact placing of the coil windings at the Helmholtz distance. The sweep coil is positioned also at the Helmholtz distance by a PEEK holder (light grey). To avoid eddy current the amount of brass is minimized and the mount is cut in two and rejoined with a glass-fiber spacer (green).
spacers. Rectangular $3 \times 2$ mm copper wire (Romal BV) is used to wind the coil, yielding a high copper filling fraction. While winding the coil, Stycast 1266 epoxy is applied to fix the positions of the windings and avoid air-pockets between the windings. Although epoxies with larger thermal conductivity coefficients are available the low viscosity of Stycast 1266 ensures a very thin film between the windings thus the heat conduction in the coil assembly is limited by the electrical isolation layer of the wires. During the winding procedure the wire is kept at a continuous tension of $\sim 20$ MPa to assure compression of the epoxy up to the maximum allowed operation temperature of $\Delta T \approx 30^\circ$ C above room temperature.

Two smaller coils (sweep coils) are mounted inside the large coils to provide the ability to do fast magnetic field sweeps. Figures 3.20 and 3.21 show the placement of the sweep coils with respect to the science cell. The mutual inductance between the coils is minimized to avoid crosstalk between the power supplies of the two pairs of coils. Each sweep coil has a diameter of 21 mm and consists of 10 windings of Laminax B-series foil (Alphacore). This copper foil has dimensions of $3.175 \times 0.254$ mm and a 25.4 $\mu$m thick Kapton isolation layer bonded on one side. The coil is wound on a PEEK holder which is mounted in the main coil mount. Water cooling of the sweep coil is applied from the outside by clamping a water cooled copper strip around the last layer. During the winding procedure Stycast 1266 epoxy is continuously applied to keep the windings in place and facilitate thermal conductivity. Just as the main coil set, this set of coils has an anti-symmetric current density with respect to the origin to cancel out finite size effects of the windings.

Furthermore two simple coils (trim coils) are placed at a spacing larger than the Helmholtz distance to allow trimming of reminiscent magnetic field gradients or curvatures. These coils have a radius of $r = 37$ mm and consist each of 15 windings of copper wire ($\varnothing 1$ mm) fixed in place 5 cm from the field center by Araldite epoxy. No water cooling is applied to these coils since only small currents are required for trimming of the field. The coils yield a gradient of 43 mG/mm/A when running currents in opposite direction.

Field homogeneity

We characterized the magnetic field profile using a XEN-1200 (Xensor Integration) field probe, which has a digital resolution of 3.3 mG up to an absolute field value of 100 G. Figure 3.22a shows the measured axial field of the main coils where the environmental field gradient of 6 mG/cm has been subtracted, the red line indicates the design value without any fit performed. To characterize the remaining inhomogeneities we fit the magnetic field profile to a polynomial in the axial position $z$. An ideal Helmholtz coil would follow the form $B(z) = B_0 - B''''z^4 + O(z^6)$, however to quantify the field inhomogeneities we include the first two orders of correction terms proportional to $z$ and $z^2$: $B(z) = B_0 - B'z - B''z^2 - B''''z^4$. The fitted values of the main coil are $B'/B_0 = 1.5 \times 10^{-6}$ mm$^{-1}$, $B''/B_0 = 6 \times 10^{-6}$ mm$^{-2}$ and $B''''/B_0 = 5 \times 10^{-8}$ mm$^{-4}$. Figure 3.22b shows the same characterization for the sweep coil, here the red line indicates the fitted curve with the fit parameters $B'/B_0 = 4 \times 10^{-4}$ mm$^{-1}$, $B''/B_0 = 9 \times 10^{-6}$ mm$^{-2}$ and $B''''/B_0 = 4 \times 10^{-6}$ mm$^{-4}$. Clearly the magnetic field of the sweep coil is less homogeneous than that of the main coil due to its smaller size and less windings. However, the sweep coil is only used for a magnetic field of a few Gauss around the offset field generated by the main coil, therefore the absolute homogeneity is comparable for the two coils.

At the position of the ultracold sample magnetizable objects from the rest of the setup
generate a small gradient. The main source of this gradient originates from the reminiscence magnetization of the (non-magnetic) optical table, placing it higher above the table significantly reduces the gradient. Using a current density through both trim coils of $j_{tr} = 0.005 \times j_m$, where $j_m$ is the current density through the main coil, the gradient is reduced again to $\sim 10^{-6}$ mm$^{-1}$.

**Thermal properties**

A finite element calculation has been performed by the UvA mechanical design office [131] to quantify the thermal and mechanical aspects of the coil design. The effective thermal conductivity of the wires filled with Stycast and the G10 fillings have been calculated separately. The radial(axial) thermal conductivity coefficient is $\kappa_r = 2.5$ Wm$^{-1}$ K$^{-1}$ ($\kappa_z = 3.7$ Wm$^{-1}$K$^{-1}$) for the Stycast filled windings and $\kappa_r \approx \kappa_z = 1$ Wm$^{-1}$K$^{-1}$ for the first and last winding of each layer filled with the G10-spacer. The thermal conductivity of brass is 109 Wm$^{-1}$K$^{-1}$ therefore it suffices to apply water cooling only at one side of the coil. As can be seen in figure [3.20] the thick mass of the brass is chosen such that the coil is effectively cooled from three sides. The water cooling has a pressure of 2 bar. Figure [3.20] shows the calculated temperature for a current of $I = 28.5$ A, generating a field of $B_0 = 500$ G, at this field the maximum and average temperature of the coil are $T_{\text{max}} = 28^\circ$ C ($T_{\text{av}} = 20^\circ$ C). For a field of 500 G the average temperature of the coil is measured by monitoring the change in resistivity of the copper coil wire, it increases to $23^\circ$ C with an exponential time constant of $\sim 4$ min. During a run of the Feshbach resonance measurements the coil temperature is monitored at its hottest point with a thermistor (see Fig. [3.20]). The maximum temperature is found to be constant to within $0.1^\circ$C for a period of two hours, limited by the temperature drift of the lab cooling water.

**Figure 3.22:** homogeneity measurements of the main coil (a) and of the sweep coils (b). The red curve in a) shows the design value, and the red curve in b) shows a fit (see text). The error bars in b) indicate the probe resolution (negligible in a))
Current source and switching

The use of a brass coil mount with two 126-turn coils raises the question how fast the coil can be switched. Eddy currents which are induced due to switching the magnetic field and the large number of windings could slow down the rate at which the field can be controlled. We have characterized the switching speed of the coil by using the switching electronics of the magnetic trap (see section 3.4.3). The current is measured by means of a Hall probe, and switched off from a typical Feshbach field of 110 G. The current switches off with an initial slope of 849 G/ms. Although our coil design was not optimized for fast switching the coil turns out to be capable of switching at speeds comparable to reported from other Feshbach resonance experiments [44, 132]. A Danfysik Model 858 power supply is used as a high stability current supply for the Feshbach coils. The supply is specified to achieve a current stability of ±1ppm (30 min) and ±3ppm (8 hours). The power supply is programmed through RS232 and regulates the current at a constant speed of 2 A/s (=35 G/s). To allow fast switching of the magnetic field the current can be switched between the coil and a resistance-matched dummy load by means of two BUZ344 MOSFETs, protected with transient voltage suppressors to dissipate the voltage spike induced by the switch off of the MOSFET. The current is programmed to its set value at the beginning of an experimental cycle, running through the dummy load and switched to the coils at the start of the Feshbach experiment. The power supply adjusts to the change of the load to below the $5 \times 10^{-5}$ detection level of the field probe within a few hundred milliseconds. Fast field sweeps or switching is performed by the sweep coil, which is operated by a Delta Elektronica ES075-2 power supply optionally equipped with a homebuilt transistor regulation to achieve linear field sweeps of up to 40 G/ms maintaining a current stability of $<10^{-4}$ and a typical corresponding field stability of better than $10^{-5}$ during the sweep.

Field calibration

We have calibrated the absolute value of the magnetic field by driving transitions between hyperfine states of $^{40}$K atoms. We prepare a spin mixture of potassium containing the $|F = 9/2, m_F = +9/2\rangle$ state in the science and apply a very weak microwave pulse connecting the $|9/2, +9/2\rangle$ and $|7/2, +7/2\rangle$ states for a period of 1 second. Subsequently the field is switched off and the number of atoms with $F = 9/2$ are detected in zero field on the $F = 9/2 \rightarrow F' = 11/2$ transition by absorption imaging. The loss signal has a width of 15 kHz corresponding to field noise or a field inhomogeneity of 6 mG around an offset field of 110 G. The field is calibrated for a few points between 110 and 120 G and found to be linear with respect to the power supply set current within the 6 mG accuracy. In future experiments a crossed dipole trap will be employed resulting in a sample with a much smaller volume. This will easily rule out if the 6 mG width is caused by field noise or field inhomogeneity. The most common source of field noise is low-frequency 50 Hz noise, therefore a higher accuracy can most likely be obtained by triggering the experimental sequence on the 50 Hz line.
3.6 Ultracold Fermionic Mixtures

3.6.1 Quantum degenerate $^{40}$K spin mixture

The first quantum degenerate Fermi gas in the field of ultracold atoms was created in 1999 by the group of D. Jin at JILA [7]. To achieve quantum degeneracy a spin-mixture of two hyperfine states $|9/2, +9/2\rangle$ and $|9/2, +7/2\rangle$ of $^{40}$K was cooled by means of forced evaporation. Interspecies collisions between the $m_F = +9/2$ and $m_F = +7/2$ ensured rethermalization of the atom sample during the process of evaporative cooling. Since the achievement of quantum degeneracy many other groups have achieved quantum degeneracy of $^{40}$K, however always by making use of $^{87}$Rb as a bosonic species to ensure rethermalization. In this section I will describe the achievement of quantum degeneracy of a spin-mixture of $^{40}$K atoms, much like the original approach of the JILA group.

We start our sequence by loading $\sim 10^9$ $^{40}$K atoms in the 3D MOT, subsequently we optically pump the sample such that a mixture of hyperfine states is created. The mixture of spin states is optimized to have a high rethermalization rate in the magnetically trapped sample, this is performed by optimizing the atomic density after an initial stage of evaporative cooling in the magnetic trap. The transfer yields a total efficiency of $\sim 50\%$ yielding a trapped atom number of about $5 \times 10^8$, distributed over the $|9/2, +5/2\rangle$, $|9/2, +7/2\rangle$ and $|9/2, +9/2\rangle$ hyperfine states. The optically pumped sample is captured in the magnetic trap at a gradient of 90 G/cm and compressed to the full gradient of 180 G/cm in 300 ms. The sample is cooled for 23 seconds by forced evaporation on the microwave transitions of K $|9/2, +9/2\rangle \rightarrow |7/2, +7/2\rangle$, $|9/2, +7/2\rangle \rightarrow |7/2, +5/2\rangle$, etc.. Figure 3.23 shows the process of evaporative cooling with and without the optical plug. The cooling procedure is clearly improved by the presence of the optical plug, yielding a lower temperature and a higher phase-space density. For subsequent experiments the evaporative cooling process is stopped at a temperature of the potassium cloud of $T \approx 12 \mu$K.

After pre-cooling in the optically plugged magnetic trap we transfer the spin mixture to the optical dipole trap (see section 3.4.4). The optical dipole trap is linearly ramped on to
a depth of \( U_0/k_B = 140 \, \mu K \) during the last 1 s of evaporative cooling in the magnetic trap. This method transfers \( \sim 10^6 \) atoms into the optical trap at a temperature of \( T \simeq 9 \, \mu K \) \((T/T_F \simeq 1.8)\), corresponding to a peak density of \( n_{0,K} = 6 \times 10^{13} \, \text{cm}^{-3} \). The optical trap has a much tighter confinement than the magnetic trap, however, the temperature after the transfer into the optical trap is comparable to the temperature of the magnetically trapped cloud due to the rethermalizing collisions of the optically trapped atoms with the surrounding magnetically trapped cloud during the last stage of the evaporative cooling. This dimple-loading \cite{133,134} yields a strong increase in phase-space density compared to an adiabatic loading of the dipole trap.

Proof of quantum degeneracy is achieved by evaporative cooling in the optical trap. This experiment is performed in the main chamber. The optical trap power is exponentially ramped down in 3 s to a preselected final trap depth. The cloud is imaged along the optical trap axis after a variable time of flight, which is adjusted to achieve an optical density of 0.4 – 0.6 for each image to reduce systematic errors obtained from fitting. The data is analyzed by a two-dimensional fit to the density profile and by a one-dimensional fit over an azimuthal average of the cloud distribution. The fit is performed to Eq. 2.36, where the fugacity, the cloud radius and maximum optical density are the fit parameters. The degeneracy parameter \( T/T_F \) is subsequently obtained from the fugacity by Eq. 2.39. Figure 3.24a shows the degeneracy obtained as a function of the final trap depth. For various points the consistency of the method to obtain the quantum degeneracy is verified by independent imaging along the vertical axis and performing a two-dimensional fit to the anisotropic cloud. Degeneracy parameters obtained from vertical and horizontal imaging are consistent within the scatter of the data. The spin mixture is analyzed by means of a Stern-Gerlach experiment (see section 3.5.4 and found to consist of 43\% |9/2, +9/2\>, 36\% |9/2, +7/2\> and 21\% |9/2, +9/2\>. Due to the comparable atom numbers in the various spin states and the weak dependence of the degeneracy parameter on the number of atoms \((T/T_F \sim N^{1/6})\) fitting the cloud to a single species Fermi distribution is a good approximation. This approximation has been verified by performing the fitting procedure on a numerically generated density profile of a spin mixture.

Figure 3.24b shows a large degenerate cloud after evaporating to a trap depth of \( U_0/k_B = 5 \, \mu K \) and 6 ms of time of flight. This measurement originates from a different dataset than the data in 3.24a. The data of Fig. 3.24b has been taken a few months after the dataset of Fig. 3.24a, with an optimized procedure resulting in a larger atom number and deeper degenerate clouds.

**Prospects for \(^{40}\text{K}\) spin mixtures**

Due to the inverted hyperfine structure of \(^{40}\text{K}\), it exhibits peculiar properties with respect to spin-exchange collisions. Any mixture of two spin components in adjacent hyperfine states \((m_{F,1} - m_{F,2} = 1, \text{ where } m_{F,1} > m_{F,2})\) in the \( F = 9/2 \) manifold will be stable against spin-exchange collisions due to the endothermic nature of the spin-exchange channels: \(|m_{F,1}⟩ + |m_{F,2}⟩ \rightarrow |m_{F,1} + \Delta m⟩ + |m_{F,2} - \Delta m⟩\), for \( \Delta m \geq 1\). Figure 3.25 shows the thermal activation temperature \( T_{ac} \) required to drive the possible spin-exchange transitions for adjacent hyperfine states for \( \Delta m = 1\), for channels with larger \( \Delta m \) the thermal activation temperature is even larger. Ultracold samples with \( T = 1 \, \mu K \) are collisionally stable for magnetic fields of \( B \geq 10 \, \text{G} \). Additionally, spin mixtures of two hyperfine states separated by two angular momenta \((m_{F,1} - m_{F,2} = 2)\) are also collisionally stable because
3.6 Ultracold Fermionic Mixtures

Figure 3.24: Quantum degeneracy of a $^{40}$K spin mixture. (left) Degeneracy parameter $T/T_F$ as a function of the final trap depth after evaporation. Two independent fitting procedures have been performed (see text). (right) Azimuthal average of the optical density of a degenerate cloud for an optimized sequence. This cloud consists of three spin states.

Figure 3.25: Thermal activation temperature $T_{ac}$ required to drive a spin-exchange process for two adjacent states as a function of the magnetic field $B$. The curves correspond to spin exchange transitions involving exchange of one unit of angular momentum.

Pauli blocking suppresses the spin-exchange channel where both outgoing spin states are identical ($m_{F,1} - 1 = m_{F,2} + 1$). A consequence of the above is that spin mixtures of three adjacent hyperfine states in the $F = 9/2$ manifold are also collisionally stable.

An additional feature of $^{40}$K is its relatively large nuclear spin, therefore many Feshbach resonances can occur in these spin mixtures. These properties make $^{40}$K a promising and very rich system to perform studies on three strongly interacting fermions, in contrast to lithium where only one triple spin mixture and corresponding set of resonances is available [135]. In exploring experiments we have observed spin mixtures of three adjacent states to be stable for a period of many seconds (hundreds of collisions). We note that at high densities or near a Feshbach resonance dipolar relaxation may limit the stability of such systems.
3.6.2 Ultracold $^6\text{Li}^{40}\text{K}$ mixture

To achieve an ultracold mixture of $^6\text{Li}$ and $^{40}\text{K}$ various approaches can be taken. One approach is to prepare large atom numbers of both species in their fully-stretched states, namely $^6\text{Li}$ |$F = 3/2, m_F = +3/2$⟩ and $^{40}\text{K}$ |$F = 9/2, m_F = +9/2$⟩. This mixture is the only combination which is stable against spin-exchange collisions. Due to the fermionic nature of both species rethermalizing collisions will occur by inter-species collisions only, therefore evaporative cooling has to be performed on both species simultaneously. Evaporating on one species only will initially cool the sample but will quickly become inefficient since the evaporated species will become a minority. As pointed out in section 2.2 the energy transfer per $^6\text{Li}^{40}\text{K}$ collision is suppressed by a factor $\xi$ and the time to rethermalize will be longer by $1/\xi$ as compared to collisions with equal mass. The $^6\text{Li}^{40}\text{K}$ collisions in the fully stretched state collide through the triplet channel and therefore have a $s$-wave scattering length of $a = 64.41$ a$_0$ [135], and a collision cross-section of $\sigma_{^6\text{Li},^40\text{K}} = 1.5 \times 10^{-10}$ m$^2$. Additionally the temperature of the $^6\text{Li}$ MOT is much higher than that of the $^{40}\text{K}$ MOT, therefore large volumes of $^6\text{Li}$ will pose a significant heat load on the $^{40}\text{K}$ resulting in a heating of the $^{40}\text{K}$.

We have employed a more efficient procedure to achieve an ultracold mixture of $^6\text{Li}$ and $^{40}\text{K}$. This is done by adding more hyperfine states of $^{40}\text{K}$ and load only a small amount of $^6\text{Li}$. In this approach we use a spin mixture as described in section 3.6.1 with the $F = 9/2, m_F = +9/2$, $m_F = +7/2$ and $m_F = +5/2$ hyperfine states and $^6\text{Li}$ prepared in the |$F = 3/2, m_F = +3/2$⟩ hyperfine state. This method has the various advantages over the fully-stretched approach. First the $^{40}\text{K}$ will mainly rethermalize due to inter-species collisions of the various hyperfine states and the $^6\text{Li}$ rethermalizes due to intra-species collisions. For typical magnetic fields in the magnetic trap $^{40}\text{K}$ scattering will mainly occur through the triplet channel. Therefore the scattering length between the various species will be (in the absence of Feshbach resonances) $a \simeq 170$ a$_0$ [137], resulting in an intra-species collision cross section of $\sigma_{^6\text{Li},^40\text{K}} = 1.0 \times 10^{-9}$ m$^2$, almost an order of magnitude larger than the inter-species collision cross section $\sigma_{^6\text{Li},^40\text{K}}$. Additionally the use of a small lithium cloud in combination with the low MOT temperature of the potassium avoids the large heat load as it is present in the fully-stretched method. Rethermalization and cooling of the $^{40}\text{K}$ will fast and efficient. Rethermalizing collisions of the $^6\text{Li}$ with the $^{40}\text{K}$ will sympathetically cool the $^6\text{Li}$.

Spin-exchange collisions

In contrast to the method with both lithium and potassium in the fully stretched states spin-exchange collisions can depolarize the $^6\text{Li}$ sample resulting in lithium atoms in untrapped states. Table 3.3 lists the possible spin-exchange channels with their respective decay rate coefficients $K_2$ obtained from Eq. 2.12. The rate coefficients are low due to the relatively small difference between the singlet $a_s$ and triplet $a_t$ scattering lengths. These collisions polarize the potassium sample, depolarize the lithium sample towards untrapped states and heat the ensemble.

Figure 3.26 depicts the cooling process towards an ultracold mixture of $^6\text{Li}$ and $^{40}\text{K}$, the trajectory was optimized to achieve the maximum phase-space density of the mixture at $T \simeq 10$ µK where the optical dipole trap can be efficiently loaded. The potassium density is kept below $2 \times 10^{12}$ cm$^{-3}$ during the cooling process, yielding a lifetime due to spin-exchange losses of $\tau_{se,^6\text{Li}} \simeq 15 - 35$ s, comparable to the vacuum-limited lifetime. For
higher potassium densities we observe rapid loss of the $^6$Li sample. At truncation energies below $\sim 50 \mu$K the number of atoms in the mixture drops to $< 10^4$, too little to perform reliable measurements on the temperature. The mixture is transferred to the optical trap after evaporating to $\epsilon_t = 64 \mu$K, yielding a mixture of $10^5$ atoms for each species and a temperature of $T = 10 \mu$K. During the adiabatic loading of the optical trap the trap volume for a $T = 10 \mu$K cloud shrinks by nearly two orders of magnitude, corresponding to a strong decrease in the $^6$Li lifetime due to spin exchange. After switch-off of the magnetic trap, the cloud expands axially by about a factor 10, decreasing the spin-exchange losses again, however this still results in a lifetime too short to perform experiments. Figure 3.27 shows an optically trapped sample of $N_{Li} \simeq 10^5$ and $N_K \simeq 10^5$, at a temperature of $T \simeq 20 \mu$K, where the potassium consists of various spin states.

To achieve a heteronuclear mixture stable against spin-exchange collisions, we clean the potassium spin mixture before transferring it into the optical trap. This cleaning is performed by a microwave sweep at the inner (plug) side of the trap (see section 3.5.4). This method results in a loss of about 70% of the total number of $^{40}$K atoms and is not purely state selective, however the lifetime of the mixture in the optical trap is increased to $\tau \simeq 15 \text{ s}$. Removing remaining $^{40}$K spin impurities by driving an optical transition in a high magnetic field (see Sect. 3.5.4) results in a mixture with the lifetime limited by background vapor ($\tau \simeq 25 \text{ s}$ at the time of these experiments).

A strong improvement and simplification to the cooling scheme can be achieved by employing a higher power optical dipole trap. With a proper choice of parameters the ultracold sample can be transferred to a less tight, but as deep optical trap yielding not as strong an increase of the density. Subsequently the spin mixture can be completely purified in the optical trap before compressing it to the final high density sample.

| Li+K initial $|\alpha\beta\rangle$ | Li+K final $|\alpha'\beta'\rangle$ | $K_2$ (cm$^3$/s) |
|---------------------------------|---------------------------------|-----------------|
| $|3/2, +3/2\rangle + |9/2, +7/2\rangle$ | $|3/2, +1/2\rangle + |9/2, +9/2\rangle$ | $1.4 \times 10^{-14}$ |
| $|3/2, +3/2\rangle + |9/2, +5/2\rangle$ | $|3/2, +1/2\rangle + |9/2, +7/2\rangle$ | $2.4 \times 10^{-14}$ |
| $|3/2, +1/2\rangle + |9/2, +7/2\rangle$ | $|3/2, -1/2\rangle + |9/2, +9/2\rangle$ | $1.9 \times 10^{-14}$ |
| $|3/2, +1/2\rangle + |9/2, +5/2\rangle$ | $|3/2, -1/2\rangle + |9/2, +7/2\rangle$ | $3.3 \times 10^{-14}$ |

Table 3.4: Spin-exchange rates for various $^6$Li-$^{40}$K channels calculated at $T = 10 \mu$K and $B = 1 \text{ G}$
Figure 3.26: Sympathetic cooling of $^6$Li by rethermalization with a $^{40}$K spin mixture. The black squares is the potassium and the blue triangles the lithium. The trajectory is experimentally optimized and shows the density of the potassium levelling around $10^{12}\text{cm}^{-3}$ minimizing spin exchange collisions of the $^6\text{Li-}^{40}\text{K}$ sample. As a comparison the red circles are for the same trajectory with potassium only.

Figure 3.27: An optically trapped mixture of $^6$Li in a pure hyperfine state and $^{40}$K in a mixture of spin states. The color scale indicated the optical density of the sample. The temperature of the mixture is $T \simeq 20\mu\text{K} \simeq 2.5T_F$. 