Experiments on two-component quantum gases on an atom chip

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Chapter 6

Extension to Bose-Fermi mixtures

6.1 Introduction

All results presented in this work were obtained with the CELSIUS apparatus described in chapter 3. Even though the existing setup has proven very fruitful and reliable, there are a number of improvements on our wish list for a next generation setup. First and foremost, we intend to extend our studies of one-dimensional (1D) systems to Bose-Fermi and Fermi-Fermi mixtures. Atom chips offer many advantages in this regard: rapid sympathetic cooling of the fermion $^{40}$K by the boson $^{87}$Rb on an atom chip has already been demonstrated [133], atom chips enable the study of individual realizations of 1D quantum gases [11, 124], and finally they make possible the use of versatile radio-frequency dressed potentials [124, 128] that can be both state- and species-selective [134]. The latter allows tuning the interaction parameters, which enables comparison to exactly solvable models in our experiments (see chapter 5). Our interest is in dynamics, coherence, relative phase, phase separation [135] and coupling between components of a Bose-Fermi mixture in one dimension. Apart from an added species, an improved general performance is desirable. A new apparatus should provide a longer vacuum lifetime, shorter experimental cycle times, better optical access and increased flexibility in the use of on-chip traps.

In this chapter, we present our design of the KELVIN (K15, Experiment for Low-dimensional, Variable-Interaction systems, Next generation) apparatus to investigate quantum degenerate mixtures of Rb and K. It includes a double chamber vacuum setup and a two-species mirror-MOT powered by a system of amplified diode lasers. The setup can be subdivided into three parts: the diode laser system, the vacuum system and the atom chip.

6.2 Laser system

Coherent light for cooling, repumping, optical pumping and imaging of $^{87}$Rb (780 nm) and $^{40}$K (767 nm) is provided by a system of diode lasers, acousto-optical modulators (AOMs) and tapered amplifiers (TAs) (see figure 6.1). Three grating-stabilized external cavity diode lasers (ECDLs) serve as master lasers for the cooling light for Rb and K and the repumping light for K. The lasers are frequency-stabilized by means of FM-spectroscopy. Whereas standard laser diodes in home-built mounts are used for the Rb lasers, an anti-reflection coated diode with a broad gain spectrum (Eagleyard, EYP-RWE-0790) [136] is employed as K master laser. Repumping light for K is generated by frequency-shifting part of the 767 nm light by 1.2 GHz with an AOM in four-pass configuration and subsequent amplification by injection into a high-power slave laser. Amplification by three
TAs (Eagleyard, EYP-TPA-0780 for Rb and EYPTPA-0765 for K) in home-built, highly temperature-stable mounts, yields a total power of maximally 2 W per amplifier. A splitting and frequency shifting stage consisting of ten doubly passed AOMs allows independent control over the individual frequencies. After recombination according to time and location of its application, all light is coupled into six single-mode optical fibers, guiding it towards outcouplers mounted around the vacuum chamber. In this manner the laser light arriving at the chamber has perfect gaussian mode profiles and stray light from the laser system can easily be shielded.
Figure 6.1: Laser system for cooling, optical pumping and probing a mixture of $^{87}$Rb and $^{40}$K. Laser beams for application with rubidium are colored red, those for potassium blue and combined beams are colored purple.
6.3 Vacuum system

We chose a two-chamber approach, illustrated in figure 6.2, to separate the low vacuum \((10^{-7}\text{ mbar})\) volume of the 2D-MOT source from the high vacuum \((10^{-11}\text{ mbar})\) of the main chamber containing the atom chip. This is necessary because potassium will have a higher vapor pressure than rubidium under the planned operating conditions, which would cause increased collisions of the trapped gas with the background gas. The 2D-MOT part is formed by a quartz glass cuvette mounted under a four-way cross piece. The latter provides optical access for atom beam characterization as well as ports for a 5 l/s ion pump and current feedthroughs for powering the dispensers containing \(^{87}\text{Rb}\) and enriched \(^{40}\text{K}\). A gate valve between the 2D-MOT part and the underside of the main chamber allows for rapid exchange of empty dispensers without affecting the high vacuum. The 2D-MOT works such that both species are simultaneously and transversely laser-cooled and pushed through an aperture, thereby forming an intense beam of slow \((10 - 20 \text{ m/s})\) atoms [137, 138, 139, 101]. The aperture between the two chambers has a diameter of 1 mm and a length of 12 mm, resulting in a pumping resistance of 100 s/l. These dimensions ensure that the pressure on the high vacuum side is not limited by differential pumping. Additionally the aperture restricts the opening angle of the atomic beam to 40 mrad, matching the size of the mirror-MOT trapping volume. Close couplers between vacuum components are used to minimize the distance from the 2D-MOT capture region to the mirror-MOT.

A spherical octagon with eight CF40 flanges and two CF100 viewports on the outside serves as main chamber. It is extended by a tube to allow for large conductance connection of a 75 l/s ion pump, a turbo-molecular pump and a titanium sublimation pump. The atom chip is mounted from the top on a water-cooled copper block and is positioned 1 cm above the center of the octagon. The other two top flanges are used for a vacuum gauge and current feedthroughs. Three sets of water-cooled coils around the main chamber generate the field for the mirror-MOT and bias fields with arbitrary direction for magnetic traps. The main chamber is surrounded by three sets of coils, generating the magnetic fields for the mirror-MOT, compensation of the earth’s magnetic field and bias fields in arbitrary direction for magnetic trapping. For improved clarity, only two of the pairs of coils are shown in figure 6.2. A third pair is mounted on the front side CF100 flange and around the extended tube.

6.4 Conveyor belt atom chip

The double layer atom chip design, depicted in figure 6.3, is formed by a silver foil with milled wire patterns [140] and a nano-fabricated science chip glued on top. The dimensions of the silver foil are \(62 \times 30 \times 0.25 \text{ mm}\). A 2 mm thick Macor substrate is epoxied between the silver foil and a water-cooled copper block for electric isolation. A “U”- and a “Z”-wire with a 4 mm long central section followed by a meandering conveyor belt pattern are milled into the silver foil, which also acts as the reflective surface of the mirror-MOT. The wires are 500 \(\mu\text{m}\) wide and separated by 150 \(\mu\text{m}\), the minimum groove size. They support a current of up to 20 A. At \(z = 2 \text{ mm}\) distance from the chip surface the “U”-
Figure 6.2: Two views of the double chamber vacuum system. The atom chip is mounted into the spherical octagon vacuum chamber via its top port. A gate valve is connecting the bottom of the chamber to a glass cuvette, which forms part of the 2D-MOT. Two pairs of coils for magnetic field generation are depicted in brown and red. The laser beams of the mirror MOT are colored yellow.

Figure 6.3: Double layer atom chip design. The blue rectangle symbolizes the part of the silver foil which is used as a mirror for the magneto-optical trap. The ellipse therein is the area illuminated by the two laser beams entering the chamber at an angle of 45°. The conveyor belt is located under the science chip.
trap, when operated at 15 A, yields a trap with a magnetic field gradient of 16, 57, 45 G/cm in x,y,z-direction, where the x-axis is parallel to the central wire and the z-axis points in the direction of gravity. For a current of 20 A the “Z”-trap produces a gradient of 1200, 1200, 19 G/cm at z = 0.5 mm with a trap depth of 58 G, or correspondingly 3.8 mK. For calibration purposes, quantum degeneracy can already be achieved in this trap. By multiple rotations of the bias field in the y-z-plane, the trap minimum can be shifted as far as 3 cm along the conveyor belt [73] to a final position below the science chip. In this manner the capture region is separated from the science region, enabling good optical access along the x- and the y-axis. Even in-vacuum lenses for maximum numerical aperture are an option in this setup.

6.5 Experiment cycle time

With background loading replaced by loading from the clean, intense and rapidly switchable atomic beam output from the 2D-MOT, the loading time is reduced to approximately 2 s and the vacuum lifetime in the main chamber will be significantly increased. The large area mirror allows for a bigger capture volume and thereby a higher initial number of trapped atoms. This guarantees an improved robustness against number fluctuations induced by electronic and acoustic noise. After the mirror-MOT and optical pumping stages, we anticipate the atoms can be transferred into the “U”- and the “Z”- trap and finally moved below the science chip within 1 sec. At this position, the atoms are taken over by the “Z”-trap of the science chip, marked as final “Z”-trap in figure 6.3. Another second is needed for the final evaporative cooling of Rb and sympathetic cooling of K, before reaching a degenerate Bose-Fermi mixture. The overall cycle time can be as short as 5 s. Furthermore this design facilitates future science chips which could incorporate multiple, individually addressable trap geometries.

6.6 Concluding remarks

A major guideline to the presented design has been minimizing the time before first experiments can be performed. Where possible, the setup is based on readily available components, reducing the need for home-built parts. In a first step, an already existing compatible atom chip will be glued onto a milled silver substrate to from a double-layer chip. First tests with milling grooves into the silver substrate to create the desired wire pattern were undertaken successfully. The existing CELSIUS setup (see chapter 3) was used for experiments with $^{87}$Rb alone. In comparison, besides the increased experimental possibilities provided through the added second species, the KELVIN setup offers improvements in many regards.

The two-chamber approach separates the atom source from the capture region. This not only speeds up the loading of atoms in the MOT as pointed out in section 6.5, but also avoids contamination of volume the experiments are conducted in. This will greatly enhance the lifetime of trapped atoms. As already mentioned, the time needed to perform
a single experiment will be reduced by approximately a factor of two, leading to a higher
temporal stability during the operation of the experiment. By using a smaller main cham-
ber and bigger windows, the optical access will be improved. Separating the capture region
from the science region below the double layer atom chip serves the same purpose. To-
gether, these two improvements will make possible a higher numerical aperture in the
imaging system, resulting in a better optical resolution.

At the time of writing all components for the optical setup (figure 6.1) and the vacuum
apparatus (figure 6.2) have been either ordered or manufactured. The new atom chip
design is yet to be implemented.