Optics and molecules on atom chips

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Abstract. In this paper we will report on four experiments which have been carried out in the last year in our group. All of these experiments are necessary steps towards the trapping and probing of ultracold molecules on a chip surface.

1. Introduction
In recent years, various techniques to cool and trap atoms have been established. One particular interesting example is the atom chip, where atoms are captured by the magnetic fields created from current carrying wires close to a mirror surface. By tailoring the wire structure, a number of different trap geometries can be created, allowing controlled manipulation of the atoms. So far, this technique has only been used in the context of cold atoms. It is tempting to extend this technique to trap molecules on a chip surface. Especially, polar molecules are an interesting candidate, as they might offer one way of implementing quantum computation. For this, it is necessary to localize and manipulate the molecules with magnetic or optical fields.

In this paper, we present the first steps towards such a molecule chip. In the first section, we characterize our experimental apparatus. The second section will describe our studies of the interaction between cesium and the two isotopes of rubidium. The third section will focus on the production of molecules - Cs$_2$ in a mirror magneto-optical trap and NaCs in a regular six-beam trap. In order to effectively manipulate and detect atoms and molecules close to the chip surface, we have also investigated the possibilities of implementing optics onto the surface, which will be described in section four.

2. The experimental apparatus
All of the experiments were carried out in a mirror magneto-optical trap (MMOT) except the production of polar molecules, which was done in a regular six-beam MOT. Both apparatuses have been described in detail elsewhere [1, 2, 3, 4] (for limited space please also refer to the references therein). Extended cavity stabilized laser diodes provided the trapping and repumping light for cesium and rubidium, while for sodium a dye laser was used. External anti-Helmholtz coils produced gradients of typically 20 to 30 G/cm. The vacuum was kept below 10$^{-8}$ Torr. A channeletron was also included in the vacuum chamber to allow the detection of ions. The Cs$_2$ molecules were ionized with a Nd:YAG pumped pulsed dye laser at 706 nm, whereas the NaCs molecules were ionized at 589 nm.
3. The two-species mirror magneto-optical trap - isotopic difference in the heteronuclear loss rate

We have studied the difference in the collision rates of the two Rb isotopes with Cs. Typically, $10^7$ atoms were trapped 3-5 mm below the mirror surface. The overlap between the two clouds was optimized using two CCD cameras which were monitoring the fluorescence of the atoms from two orthogonal directions. During all experiments, the overlap was better than 95% by volume. The fluorescence was additionally observed by two photodiodes. Interference filters were used to look at both species independently.

The Rb MOT was loaded in the absence of Cs. After it reached its steady-state, the Cs MOT was superimposed, leading to a strong decrease in the rubidium atom number (up to 75% losses).

Figure 1 shows a typical data set. By fitting these loading curves (in the presence and absence of Cs), the loss rates due to collisions of trapped atoms with the background gas can be obtained (see Figure 3). Note that the loss rates for both isotopes are equal in the absence of Cs, whereas they differ in the presence of Cs and decrease with Rb trapping intensity. In this intensity regime, hyperfine changing collisions dominate the loss rate. As these collisions release an energy that corresponds to the hyperfine splitting, the energy released per $^{87}$Rb atom is larger than the one for a $^{85}$Rb atom, leading to a higher loss rate for $^{87}$Rb.

4. Ultracold (polar) molecules in the chip environment

Homonuclear molecules are formed continuously in a MOT by photoassociation by the trapping laser light. The rate at which they are produced can be increased by introducing an additional separate photoassociation laser. This allows also the control of the final state of the molecules. We used an argon ion pumped titanium sapphire laser with a power of 50 to 100 mW. The molecules were ionized with a pulsed dye laser and detected via time-of-flight (TOF) measurement by a channeltron. A typical photoassociation spectrum is shown in figure 4 which is centered at the first “giant resonance” at a detuning of $-2.14 \text{ cm}^{-1}$ from the $6S_{1/2}(F=4) + 6P_{3/2}(F'=5)$ dissociation limit.
As the path of the molecular ions, and therefore their TOF, depends critically on the total electric field inside the chamber, it can be altered in a controlled way by applying a dc voltage to the mirror surface. For a positive voltage, the positive ions will be accelerated further, thus decreasing the TOF, whereas a negative voltage will accelerate them towards the mirror, where they will eventually be neutralized. Knowledge of this voltage ("drop-off voltage") and of the geometry inside the chamber allows the determination of the position of the molecular cloud with respect to the mirror surface (we used SimIon to simulate the total electric field inside the chamber). This is intriguing as molecules do not have closed transitions, making it impossible to measure the distance in the standard way of illuminating the cloud with resonant light and detecting either absorption or fluorescence. We found good agreement between the simulated distance of the molecules using the measured drop-off voltage and the measured distance of the atomic cloud. As the molecules are produced from the trapped atoms, their initial position should be the same. For an optimized system (parallel mirror and channeltron, known distances), the resolution of this measurement should only be limited by the width of the ionizing laser, making it possible to map out the two-dimensional density distribution of the molecular cloud.

We have also produced heteronuclear NaCs molecules in a regular six-beam MOT. Figure 4 shows the TOF spectra for only the Na MOT (bottom), only the Cs MOT (middle) and both MOTs together (top). The peak at 13 µs can be attributed to NaCs molecule.

To ensure that those molecules were indeed ultracold and formed during the trapping phase, an additional resonant laser beam was shone into the trap after the trapping light was turned off. This laser removed all Na atoms, but did not influence the NaCs peak, thus showing that the molecules were indeed formed in the trapping phase and are not formed from the background nor photoassociated by the photoionizing light (see Figure 5).

**Figure 3.** Photoassociation spectrum of Cs₂, centered at the first "giant resonance" -2.14 cm⁻¹ from the trapping transition.

**Figure 4.** TOF spectrum of Na, Cs, NaCs and Cs₂. For more details refer to the text.

5. Optical laser fields on the chip
Laser light is commonly used to probe cold atoms. Bringing it close to a reflective surface is not as easy as it sounds as a small angle with respect to the surface creates unwanted stray light from the mirror that heats and perturbs the atoms. One way of bringing the light close to the surface is the use of fibers. We have used a single-mode fiber with an attached spherical lens to produce a tightly focused (31 µm waist) laser beam close to the chip surface. This fiber was glued onto the chip using UHV compatible epoxy. A second multimode fiber was opposing the lensed fiber to transport the light back out of the vacuum chamber, thus reducing stray light...
even further. The transmitted light was detected on a fast photodiode, which was locked to a lock-in amplifier (see figure 6).

![Figure 5](image)

**Figure 5.** The NaCs signal remains unchanged when an additional resonant laser beam is introduced, which removed all Na atoms after the trapping phase.

![Figure 6](image)

**Figure 6.** Experimental setup for detection of atoms close to a surface.

In a first experiment, we moved the atomic cloud through the fiber pair into a beam of resonant light. The intensity decrease due to the presence of atoms was measured as a function of frequency. With this simple setup, we could detect down to about 100 atoms, which were hardly perturbed by this measurement due to the low intensities that were used. An off-resonant dispersion measurement is also possible, reducing the perturbation even further.

### 6. Summary and Outlook

We have studied the interaction of two atomic clouds of different alkalis. An isotopic difference in the heteronuclear loss rate was found. Furthermore, we have shown that homonuclear molecules can be state selectively produced close to a mirror surface. In a second experiment, heteronuclear molecules have also been produced. A fiber pair has been attached to the chip surface, allowing a sensitive detection of atoms.

We are currently improving our apparatus (new vacuum chamber with better known and better suited geometry, better vacuum due to improved pumps) and implementing a third alkali species that will allow us the study of the interaction between trapped bosons and fermions.

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### References

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