Inelastic bouncing and optical trapping of cold atoms

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Citation for published version (APA):
Wolschrijn, B. T. (2001). Inelastic bouncing and optical trapping of cold atoms

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Summary

Over the last decades the field of atom optics has grown rapidly. Whereas in usual light optics, matter is used to manipulate light fields, in atom optics their roles could also be reversed: light fields can be used to manipulate the motion of matter waves. In this way one is able to build atomic mirrors, lenses, beamsplitters and cavities. Moreover, light fields allow cooling of atoms: the dissipative nature of optical scattering can increase the phase-space density of atomic samples.

This thesis describes three experiments that use optical dipole potentials. The first experiment (Chapter 4) is on optical guiding: $^{87}\text{Rb}$ atoms are released from a magneto-optical trap (MOT), and guided by a red-detuned Gaussian shaped laser beam towards a glass surface. For the second experiment (Chapter 5), we create an evanescent wave (EW) potential that acts as a repulsive potential for the atoms in a region close to the glass surface. This EW reflects the atoms inelastically by inducing a spontaneous Raman transition. Understanding of the scattering during the inelastic reflection is important for the application of the inelastic mirror to load a low-dimensional optical dipole trap. In the third experiment (Chapter 6) we use this inelastic mirror as a mechanism to load an optical standing wave potential close to the glass surface. Dissipation allows the phase-space density to increase, possibly leading to a low-dimensional quantum degenerate gas by purely optical means. Ultimately a continuously operating “atom laser” might be realized, as a bright source of coherent matter waves. Being an open system out of thermal equilibrium, it would be in close analogy to an optical laser.

In Chapter 2 we characterize the evanescent wave. In particular, we describe the polarization properties of this exponentially decaying field, when it is created by a laser field which is TE or TM polarized. We also review the two types of light force: radiation pressure and the dipole force. We start with the approximation of a two-level atom and then extend it, taking the full electronic level structure of rubidium into account.

The experimental apparatus is described in Chapter 3. We briefly review the vacuum system and the grating feedback diode lasers to create a MOT. The MOT collects $10^7$ atoms in 1 mm$^3$, which are subsequently cooled to $T \approx 5\mu$K by optical molasses. We probe the atomic density distribution by imaging the atomic cloud on a CCD camera by resonant absorption imaging. To create optical potentials with a low optical scattering
rate, we use two moderate-power tapered amplifier diode lasers, each producing 100 mW Gaussian shaped laser light after passing a single-mode optical fiber. One of these beams is used to create the atomic mirror, the other is used as the optical guide.

Chapter 4 reports on optical guiding of atoms from the MOT towards the glass prism. The purpose of the guiding beam is to increase the number of atoms, reflected by the EW mirror. This guiding beam is a 100 mW Gaussian shaped beam and is red-detuned with respect to the $D_2$ line. For optimal guiding the beam overlaps the MOT as well as the EW. For detunings around $-12 \times 10^3 \Gamma$ optimal guiding is achieved: 42% of the atoms falling from the MOT are guided towards the prism surface. The use of the guide yields a density increase of a factor 2.8 at the prism surface. We measured the guiding fraction as a function of power and detuning, and showed good agreement with an analytic expression. When the laser is tuned further from resonance, the hottest atoms are no longer guided due to the decreasing guiding potential. For lower detuning (closer to resonance) the fraction of guided atoms increases, but optical scattering by the guide starts to increase. Radiation pressure by the guiding beam then pushes the atoms upwards so that the atoms experience an apparent gravity less than $g$. We also numerically investigated pulsed guiding and concluded that a short pulse could focus a large fraction of the atoms onto the EW. To obtain a density increase comparable to the continuous guide, the large pulse strength can only obtained by lowering the detuning due to limited available laser power. This results in a large number of scattered photons: even larger than in the continuous case. Heating of the cloud is of the order of its initial temperature and radiation pressure pushes the atoms upwards. Therefore pulsed guide is less suitable than a continuous guide.

In Chapter 5 we prepare the falling atoms in the $F_g = 1$ ground state and tune the EW near an open $|F_g = 1\rangle \rightarrow |F_g = 2\rangle$ transition which makes the mirror inelastic. While the atom is reflected, the internal hyperfine state of the atom is changed due to photon scattering by the EW. The final state experiences a lower optical potential than the initial state due to the different detuning with respect to the EW. This makes the reflection inelastic: the transferred atoms bounce up less high than their initial position. The position of transfer inside the EW determines the velocity of the atoms after reflection. The spatial selectivity of the transfer causes a diverging probability of transferred atoms around the motional turning point of the atomic trajectory. This manifests itself as a caustic in the velocity distribution of reflected atoms. A caustic of stochastic origin is to our knowledge a new physical phenomenon. Until now all known caustics arise from elastic, deterministic processes. We observed the caustic velocity to be independent on the decay length of the EW.

We measured the caustic velocity and total number of transferred atoms as a function of the detuning of the EW. For detunings between $72 \Gamma$ and $250 \Gamma$ the energy reduction varied between 94% and 82% of the initial energy. The experimental data agrees well with a classical model, describing the atomic trajectory through the EW. We also measured
the fraction of transferred atoms in this range of detuning. This fraction varied between 82 % (δ = 72Γ) and 45 % (δ = 250Γ). The transferred fraction was systematically higher than expected on the basis of a rate-equations model.

With the knowledge of the motional and scattering behaviour, we discuss the inelastic reflection in the context of evanescent-wave cooling, and conclude that although energy is subtracted from the atoms, the phase-space density is not necessarily increased. We end the mirror analysis with an outlook to experiments revealing interference between two possible trajectories in phase space. Such interference is non-trivial since it arises from a spontaneous process, namely the scattering of a photon.

The inelastic EW mirror is used as a loading mechanism for an optical standing wave (SW) trap which is described in Chapter 6. The SW is created by the reflection of a 1 W laser beam at the same position as the EW. The energy of atoms falling on the EW is too high to be trapped by the SW. The EW slows the atoms down and transfers the atom to the less repelled hyperfine state. The transfer occurs most likely around the turning point. In this case the residual energy of the atom is low enough to be trapped by the SW. Due to the small extension of the EW into the vacuum, the atoms are trapped in a region < 1 μm above the surface, in the first three or four anti-nodes of the SW. To measure atoms at such a small distance to the glass surface, we introduced a resonant probe grazing over the surface. The absorption of this beam is only a few % and shows a particular peaked structure in time, which is the result of a combined effect of radiation pressure and Doppler shift. With this probe we measured a maximal transfer efficiency of atoms falling on the EW of 5 ± 3 %. The large error results from the low amount of absorption of the probe beam.

We study the transfer efficiency of the mirror as a function of decay length and detuning. These parameters determine the scattering properties of the reflection. When the scattering rate is too high, the initial hyperfine ground state is already too much depleted when it arrives at the turning point. When the scattering rate is too low, the transfer rate at the turning point is also too low. The measured data correspond well with a classical rate equation model. After being transferred into the SW trap, the atoms heat up due to photon scattering by the high power SW beam, leading to trap loss. We measured lifetimes of 13 ms and 30 ms, for a detuning of the SW laser of -72 GHz and -194 GHz respectively. These values agree with theoretical values, where we have calculated the motion of the atoms in the presence of optical scattering. We end the chapter with an outlook on further improvements on the resolution on the number of trapped atoms by using a resonant EW probe. We also propose a novel configuration where two evanescent waves create a polarization gradient.

The apparatus needs to evolve further to get more insight into the physics of low dimensional optical traps. The measurements presented here are the building blocks for an all-optical quantum degenerate atom gas trapped in a low-dimensional configuration. The ultimate goal is to observe the bosonic enhancement of state occupation, for which
the spontaneous character of the EW photon is necessary. In the future, extension of the experiment may lead to an atom laser, where the emission is stimulated by the atoms, not the photons.