Inelastic bouncing and optical trapping of cold atoms
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Link to publication

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

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Chapter 1

Introduction

1.1 Cold atoms

Cold atom physics is a rapidly growing field in experimental physics. A breakthrough was the realization of the magneto-optical trap (MOT) by Chu and coworkers in 1987 [1], which was proposed by Dalibard. It has become a standard source of cold atoms for a large number of experiments because it is robust, reliable and fairly easy to build. The ability to confine atomic samples by laser light and magnetic fields without environmental contact provides excellent control over the atoms, necessary for high-resolution experiments. For example, cold atoms are nowadays used in time-metrology: the application of cold atom fountains [2] increased the accuracy of atomic clocks by two orders of magnitude [3].

Aside from these practical applications, ultracold samples are of interest because of their quantum mechanical properties. This led to the observation of Bose-Einstein condensation (BEC) in 1995 in cold dilute samples of alkali-metal vapors [4] which was recently rewarded with the Nobel prize. The standard route to BEC is to trap atoms in a MOT and subsequently in a magnetic field gradient. By using evaporative cooling techniques the phase-space density is further increased.

However, it is important and interesting to explore also other ways to create a BEC, in particular by optical means, i.e. to use laser fields. This is the interest of the experiments we perform in our group [5]. We aim to create a low-dimensional quantum degenerate gas in an optical standing wave potential. This trap is to be loaded by an optical Raman transition, driven by an evanescent wave. The first step was the realization of an evanescent-wave atomic mirror, and to characterize its behaviour.

Optical potentials can be used as attractive or repulsive potentials depending on the detuning, the difference between the frequency of the light and the atomic transition frequency. In this way one can construct light fields which act like atom gratings [6], lenses [7], and mirrors [8]. Already in 1982 Cook and Hill proposed the use of a blue detuned evanescent wave (EW) as an atomic mirror, or atomic “trampoline” [9]. Due to the short extension (on the order of the wavelength of the light), the duration of the
reflection is very short, which keeps the number of scattered photons small. In 1987 Balykin et al. experimentally realized an EW mirror for atoms at grazing incidence [10], and in 1990 atoms dropped normal to the surface (from a MOT) were reflected [11]. The turning point of the atomic trajectory inside the EW is very close to the surface, and the van der Waals force was measured by careful analysis of the fraction of bouncing atoms [12]. Our group has built an atomic trampoline for rubidium atoms and in 2000 we reported on radiation pressure exerted by an EW mirror by measuring the deflection angle of reflected atoms [13].

An EW can also be used to cool atoms by making use of photon scattering, which leads to transitions between different internal states of the atom. Such an inelastic reflection, or elementary Sisyphus process was reported in 1996 [14] and investigated in detail by the group of Grimm [15, 16]. By multiple inelastic reflections they extracted almost all energy from the atoms, while simultaneously the atomic density was increased. The low dimension of this Gravito-Optical Surface Trap reduces photon re-absorption [17]. The atoms reach a temperature of 300 nK and almost two orders of magnitude gain of phase-space density was achieved [18]. We also constructed and characterized such an inelastic atom mirror because it is a crucial step in loading our standing-wave optical trap. Our experiments provided high resolution measurements on the density profile of the reflected atom cloud. From these data we are able to obtain detailed information about the reflection process, and it revealed an unexpected and novel physical process: a stochastic rainbow [19].

We pursue a low-dimensional quantum gas in a standing wave trap. Atoms are trapped in the nodes (anti-nodes) of the interference pattern of a blue (red) detuned laser beam, interfering with its reflection. To obtain high phase space density, the atoms have to be loaded preferentially into a single potential minimum. To address a single anti-node one needs a highly spatially selective light field which transfers atoms from a free state, to a trapped state. A promising tool to do this is an evanescent wave [5]. When atoms are dropped on the EW, they are slowed down and reflected. Raman scattering by the EW around the turning point transfers the atom into a (single) potential minimum of the SW.

We calculated that the phase space density of trapped atoms may increase up to three orders of magnitude compared with the MOT [5]. Another feature is the bosonic nature of the atoms [20]. The probability to occupy the various levels of the SW trap is determined by the quantum statistics of the atoms. Stimulated emission of atoms into a trapped state under emission of a photon should make this scheme to a new type of “atom laser”. Such laser-like behaviour yields non-thermal ensembles, whereas cooling methods usually produces ensembles in thermal equilibrium.

The group of Pfau and Mlynek realized in 1998 loading of a SW by an EW [21]. They proved the predominant loading of Ar* atoms into a single well, and measured the lifetime of the trap. The use of metastable rare-gas atoms provides good detection possibilities but limits the (phase space) density due to Penning ionization. Therefore we believe alkali
atoms are better candidates for reaching quantum degeneracy along this route, although BEC in He\textsuperscript{*} was recently achieved by evaporative cooling [22].

1.2 This thesis

This thesis describes our experiments directed towards, and including the loading of an optical standing wave trap, by an inelastic evanescent-wave mirror. We study in some detail the various individual components. The route that we followed to trap atoms, was to first build and analyze an inelastic evanescent-wave mirror. This turned out to be not only a well suited tool for loading the trap, it also yields surprising physics. To increase the number of reflected atoms we constructed an optical guide, which guides the atoms during their drop from the MOT to the mirror, and thus increases the number of reflected or trapped atoms. Our analysis of the guiding fraction gives excellent agreement with the experimental data. Finally, we used the EW to load an optical standing wave trap, and measured the most important properties, the loading fraction and the lifetime.

We start in Chapter 2 with a summary of the properties of rubidium relevant for light cooling. Also a short overview of atom-light interaction is given. The necessary lasers to manipulate atoms depend on the optical transitions of the used species. For \textsuperscript{87}Rb these are the two D-lines, around 780 and 795 nm.

Chapter 3 gives a short overview of the experimental apparatus. The most important components to create the MOT are discussed: the vacuum system and the various laser systems, most of which are semi-conductor diode lasers. The technique of absorption imaging is described which we used to measure the number of atoms, their temperature and the size of the MOT.

We increase the atomic density of atoms falling from the MOT on the mirror by applying an optical guide. Experiments on optical guiding are presented in Chapter 4. The guiding is simply done by overlapping a red-detuned laser beam with the MOT as well as the EW. This is a direct application of the dipole potential. We show that even with moderate optical power (<100 mW) one can capture efficiently a large fraction of atoms falling from the MOT. We measured that we can guide about 40% of the atoms, in good agreement with the fraction expected on the basis of a calculation. We show that by lowering the detuning of the guiding laser the captured fraction increases, but simultaneously radiation pressure pushes the atoms upwards, along the direction of the guiding laser.

Loading of a standing wave trap could not be done without building an inelastically reflecting mirror first. In Chapter 5 we report on experimental results of such a evanescent-wave mirror. It must fulfill two conditions: first, it must be able to slow down atoms when they fall on it. The second requirement is that it must induce a spontaneous Raman transition, changing the internal state of the atoms. We will show that the combination
of these requirements results in a new type of physical phenomenon: a stochastic rainbow caustic, where a single initial velocity produces a velocity distribution after reflection. This velocity distribution contains a caustic: a classical divergence, just as in an optical rainbow. We do not know of any other physical phenomenon producing a caustic with a stochastic origin. The experimental data corresponds well with our calculations. We measured the degree of dissipation for both D lines as well as the transfer efficiency: the fraction of atoms reflecting inelastically. We also discuss EW cooling in terms of phase space density, and give an outlook to future experiments to observe interference in the inelastic velocity distribution.

In Chapter 6 we present the first measurements we performed on the loading process of a standing wave trap by an inelastic reflection. The high spatial selectivity of the inelastic mirror is able to transfer the atoms very locally into the trapped state of the standing wave. To probe the trapped atoms a few hundred nanometer above the glass surface, we use a resonant beam which is grazing just above the surface and measure the absorption. We measure the loading efficiency as a function of EW parameters. We also estimate the lifetime of the trapped atoms, and compared the results with classical Monte-Carlo calculations. Although the signal to noise ratio has to be increased to provide more accurate absolute numbers, we show that loading and trapping behavior is as we expect on the basis of classical models.