Evanescent-wave mirrors for cold atoms
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Inelastic bouncing of cold (10 \( \mu \)K) rubidium atoms from an evanescent-wave mirror was observed by tuning the evanescent-wave laser close to an open optical transition. The number of photons that were off-resonantly scattered by a bouncing atom was \( \geq 1 \). The resulting optical hyperfine pumping by the evanescent wave causes dissipation. Atoms that undergo a change in hyperfine ground state jump off the mirror with reduced kinetic energy. Inelastic mirrors for \(^{87}\)Rb were realised on both fine structure lines, \( D1 \) and \( D2 \). Cold atom clouds were released from 6 mm above the mirror and both elastically and inelastically bouncing atoms were detected by absorption imaging. The observed inelastic bouncing height ranged between 0.5 – 1.1 mm. The optical pumping efficiency was adjusted between 30 – 100 % by varying the laser detuning. Using absorption imaging also the velocity distribution of inelastically bouncing atoms was investigated.
7.1 Introduction

Evanescent-wave mirrors for atoms [3-5] are usually designed to preserve the coherence and to provide specular reflection of atomic matter waves [194,195]. This requires the amount of photons scattered by the bouncing atoms to be low within the typical bouncing time scale of $3-10 \mu s$, i.e. the scattering rate should be $\ll 10^6 s^{-1}$. Since this rate varies as $\propto 1/\delta$ with the detuning, evanescent-wave mirrors are commonly realised with large blue detuning.

In experiments that allow for a few scattered photons, evanescent waves are preferentially tuned to optical cycling ("closed") transitions. This avoids atom loss by change of hyperfine state. To observe radiation pressure by several scattered photons, we therefore used the closed $F_g = 2 \rightarrow F_e = 3$ transition on the D2 line of rubidium, see Chap. 6. On the other hand, in various applications photon scattering by bouncing atoms on an open transition is an essential part of the physical process under investigation. Examples are:

(i) loading schemes for a low-dimensional optical trap [82-84,86,87], as discussed in Chap. 2. A spontaneous optical Raman transition provides a dissipative, phase-space compressing mechanism to transfer atoms into the trap. This results in an accumulation of atoms that are decoupled from the mirror potential in a layer close to the surface. Also a two-dimensional magnetic waveguide for cold atoms using an optical loading mechanism has been proposed [85].

(ii) Spontaneous Raman transitions are essential for reflection cooling of atoms by an evanescent-wave [16,17,106]. A single inelastic bounce can be considered as a fundamental "Sisyphus" process [106], in analogy with polarisation gradient cooling [70]. Net cooling is achieved by multiple inelastic bouncing. Reflection cooling is not restricted to evanescent-wave mirrors. It has also been demonstrated in a gravito-optical trap, where cooling occurred by reflections at a hollow, conically shaped dipole trapping potential [198].

(iii) Diffraction of cold atoms by an evanescent-wave grating should also be mentioned at this place. It represents an atom-optical tool, e.g. as beam splitting mechanism for atom interferometers. It was first demonstrated using atomic beams at grazing incidence [199] and later with cold atoms at normal incidence [200]. Stimulated Raman transitions between magnetic or hyperfine sublevels are inherent to the diffraction process [201].

We have realised inelastic mirrors on both the D1 (795 nm) and D2 (780 nm) rubidium fine structure lines, see Fig. 3.7. Our particular interest is in the D1 line, since the hyperfine structure, $F_g = F_e = \{1,2\}$, allows to prepare dark, far off-resonance optical trapping potentials, see Chap. 2. Note that there is no hyperfine cycling transition on the D1 line, so that (purely) elastic bouncing was not possible using this line with our moderate evanescent-wave detunings.

We observed bouncing atoms directly with an absorption imaging technique that allowed us to trace the evolution of the atomic density after the bounce. We thus observed the inelastic bouncing height, in contrast to the time-of-flight detection that was employed in earlier experiments by Desbiolles et al. [106]. The bouncing height, velocity distribution and inelastic transfer efficiency are discussed qualitatively.
7.2 Principle of inelastic evanescent-wave mirrors

Inelastic bouncing from an evanescent-wave mirror occurs when bouncing atoms dissipate potential energy, which they have acquired from their kinetic energy by climbing the mirror potential. The spontaneous process involved, is optical pumping either by the evanescent wave of the mirror or by an additional near-resonance evanescent pumping field [86]. If no additional light is provided, optical pumping can only occur when the mirror laser is tuned to an open optical transition. Working with $^{87}$Rb, this is realised with atoms falling down in the $F_g = 1$ ground state. Using a mirror on the D1 line, the evanescent wave is applied with a detuning $\delta_1$ above the $F_g = 1 \rightarrow F_e = 2$ transition. Atoms are off-resonantly excited to $F_e = \{1, 2\}$ by the evanescent wave and decay into $F_g = 2$. The laser detuning relative to the $F_g = 2 \rightarrow F_e = 2$ transition will be denoted as $\delta_2$ in the following. The same notation holds for an inelastic mirror on the D2 line, since there is no dipole-allowed transition from $F_g = 1$ to the $F_e = 3$ excited state.

The bouncing process is illustrated in Fig. 7.1. Similar to the experiments discussed in the previous chapters, a sample of cold atoms ($\approx 10 \mu K$) is released in the $F_g = 2$ ground state, 6 mm above the evanescent-wave mirror. A depumping pulse, in resonance with the open $F_g = 2 \rightarrow F_e = 2$ transition, transfers all falling atoms into $F_g = 1$. The potentials, $U_{1,2}$, are shown in the figure [see also Eq. (2.10)]. Close
to the mirror, the figure is scaled in units of the optical wavelength. $\lambda_0 = 780 \text{ nm}$ for the D2 line. The potential in that region is determined by the evanescent-wave dipole potential and the Van der Waals interaction. The broken axis between the potential curves represents the separation by the ground state hyperfine splitting, $\delta_{\text{CHF}} = 1139 \Gamma$. The turning point of the atoms is determined by the initial gravitational potential, here $U_{\text{grav}}(z_0) = Mgyz_0 = 2.1 \hbar \Gamma$. (In Chap. 5, this potential was discussed as the bouncing threshold $U_{\text{th}}$, when varying the mirror parameters.) Optical pumping by the evanescent wave transfers a fraction of the bouncing atoms back into $F_g = 2$. Since $\delta_1 \ll \delta_{\text{CHF}}$, the detuning for atoms in $F_g = 2$ is $\delta_2 = \delta_1 + \delta_{\text{CHF}} \gg \delta_1$. Therefore the potential ratio is $\beta = U_2/U_1 \approx \delta_1/\delta_2 \ll 1$. Pumped atoms end up in a lower potential and bounce inelastically, whereas atoms that remain in $F_g = 1$ can complete the bounce elastically. Atoms in $F_g = 2$ are detected by an absorption probe on the $F_g = 2 \rightarrow F_e = 3$ cycling transition. Elastically bouncing atoms in $F_g = 1$ are detected by first repumping them into $F_g = 2$.

The calculated potentials in the figure are valid for the centre of the mirror ($x = y = 0$) and correspond to the evanescent-wave parameters of the bouncing sequence shown in Fig. 7.3. Note that $U_2$ is below the threshold. Hence, most of the atoms that are pumped while on their way towards the surface hit the glass, are heated and lost.

### 7.3 Configuration of the inelastic mirror

The configuration shown in Fig. 7.2(a) is similar to that of the elastic mirror in Fig. 6.1, with a few modifications. The hypotenuse of the right-angle prism is used to couple in the additional depumping beam from below. Bouncing atoms are now observed by absorption imaging. For investigating low atomic densities this is more sensitive than fluorescence imaging, especially when a relatively strong background is present [151]. In particular, there may be a considerable background illumination in the imaging field-of-view by evanescent light that is diffusely scattered due to roughness of the prism surface. The imaging scheme is illustrated in Fig. 7.2(b). The collimated absorption probe is directed through the sample of falling or bouncing atoms, the shadow of which is imaged on the CCD camera by a relay telescope (L1 and L2, *Melles Griot*, glass doublets, no. 06 LAI101/076, dia. 30 mm). In the present experiments, unity magnification was chosen. Hence, atoms were imaged with a resolution of 15 $\mu\text{m}$, equal to the CCD pixel size. A different magnification is possible by introducing a microscope objective between CCD and lens L2. For more details on this setup, see Ref. [202].

The main function of the relay telescope is to translate the image to a more accessible place. It has the additional advantage that it allows the insertion of a beam stop or a phase plate in the focal plane of the telescope, with the purpose of dark field imaging or phase contrast imaging, respectively [7]. In the present experiments, the atomic density was too low for the use of imaging techniques that are nondestructive to the atomic sample [149, 150]. For a discussion of the various techniques see, e.g., Ref. [47].
7.3 Configuration of the inelastic mirror

Figure 7.2: Configuration of the inelastic mirror. (a) Falling atoms from a MOT are depumped (DP) into \( F_g = 1 \). Inelastically bouncing atoms are detected in \( F_g = 2 \) by an absorption probe (AP). A repumping beam (not shown) optionally transfers elastically bouncing atoms into the detectable \( F_g = 2 \) state. (b) Absorption imaging: A collimated probe beam is directed through the atomic sample (S) onto the CCD detector. The sample is imaged by a relay telescope of unity magnification. The focal length of the achromatic lenses \((L1,L2)\) is 100 mm.

The probe had a waist of approximately 5 mm \((1/e^2\) intensity radius\), with a power of \(\sim 100 \mu W\). The frequency was chosen in resonance with the cycling transition \( F_g = 2 \rightarrow F_e = 3 \) on the D2 line. The saturation parameter was \( s_0 \lesssim 0.2 \). The probe exposure time \(\tau_{\text{ex}}\) was chosen between 20 – 70 \(\mu s\), so that an atom scatters \(\approx 200\) photons. Longer exposure is not useful since \(\sim 400\) photon recoils from the probe are sufficient to Doppler-shift the atom out of resonance \(400k_0v_{\text{rec}} \approx \Gamma/2\). Furthermore the image would be blurred by atomic motion. The maximum velocity in the experiments, \(v_1 \approx 60v_{\text{rec}}\), together with an imaging resolution of 15 \(\mu m\) allows a maximum exposure time of \(\tau_{\text{ex}} \sim 40 \mu s\). In order to achieve quantitatively accurate absorption data, one should keep \(s_0 \ll 1\).
7.4 Observation of inelastically bouncing atoms

7.4.1 Inelastic bouncing height

In the experiments discussed here, an inelastic mirror was first realised with the evanescent field on the open transition $F_g = 1 \rightarrow F_e = 2$ of the D2 line of $^{87}$Rb. The evanescent-wave was TM-polarised with a waist of 0.5 mm ($1/e^2$) and 26 mW power from an injection-locked single-mode diode laser. The angle of incidence was varied between 1.8 mrad and 18 mrad beyond the critical angle and the detuning $\delta_1$ between 70$\Gamma$ and 230$\Gamma$.

A sample of $\sim 10^7$ atoms was loaded within 2 s in the MOT, followed by 5 ms of molasses cooling to a temperature of 10 $\mu$K. A typical image sequence displaying inelastic bounces is shown in Fig. 7.3 for an angle of $\theta_i = \theta_c + 1.8$ mrad (decay length $2.5 \lambda_0$) and a detuning of $\delta_1 = 150 \Gamma$. Due to the destructive character of the probe, each frame was taken in a new realisation of the experiment. The time indicated for each frame is the time elapsed since shuttering the cooling light. Sequence (a) shows the falling and expanding thermal cloud. The irregular shape of the cloud in the first frame, taken immediately after release, may be a consequence of imbalanced molasses cooling forces. Some saturated CCD pixels appear as white spots.

In order to observe inelastic bounces, 4 - 27 ms after releasing the cloud, the depumping laser was switched on for about 2 ms. The upward directed radiation pressure of the depumping beam transfers a few photon recoils to the atoms. This reduces the incident velocity $v_i$ at the mirror by approximately $3\%$. The continued image sequence, (b), with inelastically bouncing atoms starts at 35 ms, when the cloud centre-of-mass hits the mirror. In the following frames, the bouncing cloud leaves the mirror and reaches its maximum height of 0.8 mm at $t \approx 47$ ms. This was 14% of the MOT height $z_0$ and in reasonable agreement with the potential ratio $\beta \approx \delta_1/\delta_2 = 0.12$.

The transfer of atoms into $F_g = 2$ preferentially occurs while atoms are near the turning point, where a relatively long time is spent in a region of a strong optical field. Hence, we can indeed expect a well established peak in the vertical column density of inelastically bouncing atoms, as it is obvious from the sequence shown. In addition, a tail of atoms is visible, stretching out to a height expected for elastically bouncing atoms only. This tail is caused by atoms, that were transferred into $F_g = 2$ either before reaching the turning point or after having partly reaccelerated off the mirror potential. The bouncing dynamics, together with the stochastic nature of optical pumping, thus cause a broad redistribution in atomic velocities. The velocity distribution translates into the imaged spatial distribution after $10 - 20$ ms of free flight.

The background visible in the images is due to imperfections of the detection setup. The observed density of bouncing atoms is significantly lower than that of the falling atoms. (This is partly due to the projection on the image plane.) Therefore the image contrast was enhanced in the sequence (b) by reducing the gray scale display range by an order in magnitude. Hence, the background appeared in these images. The white region at the former location of the MOT is an artifact, possibly
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#### (a) 0 ms  15 ms  19 ms  23 ms  27 ms  31 ms

![Image of time sequence of inelastically bouncing atoms](image)

#### (b) 35 ms  39 ms  43 ms  47 ms  51 ms  55 ms

![Image of time sequence of inelastically bouncing atoms](image)

**Figure 7.3:** Time sequence of inelastically bouncing atoms. (a) Atoms fall from the MOT (in the \( F_g = 1 \) state). Gray scale indicates atomic density. The field of view is 8 mm in height, and the prism surface is indicated by a horizontal dotted line. The first frame was taken immediately after switching off the molasses cooling light. Subsequent frames each represent a new realisation of the experiment. After 35 ms the cloud centre-of-mass hits the prism. (b) Inelastically bouncing atoms were detected in \( F_g = 2 \).

due to a memory-effect of the CCD array, caused by the intense illumination from molasses cooling light, several 10 ms before an image capture. Interference fringes and circular patterns stem from the probe laser and were due to reflections at the uncoated UHV cell and due to diffraction from dust particles. Each absorption image was the result of three image captures, taken shortly after each other. First, the atoms were probed. A second frame was similarly taken without loading the MOT as a zero-absorption reference. From both images the background illumination was subtracted, as captured by the third frame without using the probe pulse. Division of signal and reference image results in the absorption image. The noise level in the atomic signals was reduced by averaging 5 realisations for each image. In principle, no fringes should occur, unless the reflecting optical surfaces move in the time between recording the signal image and the reference image. Accumulating more realisations may be a remedy to average out drifting fringe patterns.
7.4.2 Atom density and transfer efficiency

An inelastic mirror on the D1 line (795 nm) of $^{87}\text{Rb}$ was realised using the tapered amplifier system with the TD387 gain element as a laser source for the evanescent-wave, see Chap. 4. Due to the larger available power of 73 mW, as compared to the injection-locked diode laser, the mirror could be established with a larger laser waist of 0.8 mm ($1/e^2$). The laser was again TM-polarised. The detuning was $70 - 300 \Gamma$ above the $F_g = 1 \rightarrow F_e = 2$ resonance, and the angle was $\theta_\ell = \theta_c + 16.6$ mrad, which resulted in a decay length of $0.82 \lambda_0$ (0.65 $\mu$m). This atom mirror was used to investigate the efficiency of transferring bouncing atoms into $F_g = 2$ as a function of evanescent-wave detuning and decay length. A detailed study including a numerical analysis will be presented elsewhere, see Refs. [202,203]. In this section, the experimental results are discussed.

Density of bouncing atoms.--- In order to quantitatively investigate bouncing atoms, we converted the absorption images into the corresponding atomic column density distributions in the $xz$-plane (see Appendix A.4). The 2D gray-scale density plots of Fig. 7.4 represent column densities. In the left image only inelastically bouncing atoms ($N_2$) were detected. In the right image repumping light was supplied before detection, so that all atoms were detected ($N_1 + N_2$). In these measurements, the evanescent-wave detuning was $\delta_1 = 200 \Gamma$ and the images were averaged over 10 experimental runs. The vertical 1D (linear) density $\rho_z(z)$ was obtained by summing lines of the 2D image for different values of $x$. In Fig. 7.4(a) also the density of elastically bouncing atoms is shown, as derived from the combined signal in Fig. 7.4(b). The linear densities were normalised to the atom numbers, $N_1$ and $N_2$, by integrating the column density distributions and using the resonant rubidium absorption cross section $\sigma_0 = 3\lambda_0^2/2\pi$, see Appendix A.4. Our absorption probe was linearly $\pi$-polarised and we assumed that the atoms were randomly distributed over the $F_g = 2$ ground state magnetic sublevels $m_g = \{0 \ldots \pm 2\}$. The absorption cross section was therefore averaged over these $m_g$-levels using the Clebsch-Gordan coefficients for the $F_g = 2 \rightarrow F_e = 3$ transition and the reduced dipole matrix element, here $d_{2,3} = 1$:

$$\bar{\sigma} = \frac{1}{5} \sigma_0 d_{2,3}^2 \sum_{m_g} \langle 2, m_g, 1, 0 | 3, m_g \rangle^2 = \frac{7}{15} \sigma_0 = 13.5 \times 10^{-10} \text{ cm}^2. \quad (7.1)$$

Whereas the column density represents the measured quantity, the physically interesting quantity is the 3D spatial density, $\rho(x) = \rho_x(x)\rho_y(y)\rho_z(z)$. It is shown as $\rho(0,0,z)$ by an alternative density scaling in Fig. 7.4 and was calculated under the assumption that the horizontal distributions were Gaussians. Due to the aspect ratio, $\chi \approx 1.3$, of the elliptical effective mirror surface, the rms width of the cloud in the $x$-direction is wider by a factor $\chi$ compared to the $y$-direction.

The asymmetrical vertical distribution, $\rho_z(z)$, originates from the distribution of velocities at which atoms leave the surface. It is evident from the peaked structure, that there is a strong preference for atoms to be pumped when they are slow, i.e. close to the turning point on the mirror. For a hypothetic monochromatic sample (without spreading in $v_1$), the distribution would be sharply edged, since the turning
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Figure 7.4: Vertical column density of atoms, 4 ms after bouncing. Evanescent-wave tuned to the D1 line of $^{87}$Rb: (a) Inelastically bouncing atoms detected in $F_g = 2$ ($N_2$, thick curve). (b) All atoms ($N_1 + N_2$) were detected with additional repumping of elastically bouncing atoms. The elastic contribution ($N_1$) is obtained by subtraction [thin curve in (a)]. The absorption images corresponding to the line sums in (a) and (b), are also shown. The prism surface is indicated by a dotted line. (c) Densities obtained with a different evanescent-wave detuning (see Ref. [203]).

point defines the smallest possible inelastic velocity $\approx \sqrt{3} v_i$. Obviously, the tail of fast atoms has also an edge, since the fastest atoms can just reach the MOT height $z_0$. The velocity distribution of inelastically bouncing atoms cannot be described in terms of a thermal Maxwell-Boltzmann distribution, as is the case with elastically bouncing atoms. The large spread in velocities suggests “heating” of the cloud, if one would assign a temperature at all. More useful may be an investigation of atomic phase-space density. Another feature of the bouncing dynamics is revealed by a closer look at the evolution of fast atoms in the sequence of Fig. 7.3(b). From 51 ms on, fast atoms were still rising and separating from slower atoms that fall down again. Indeed, numerical analysis indicates that the larger velocities were slightly more populated than medium velocities, see Ref. [203].

Transfer efficiency.— When investigating radiation pressure on elastically bouncing atoms in Chap.6, a simple analytical model for two-level atoms led to Eq. (2.19) for the number of scattered photons on the cycling transition, $N_{\text{scat}} \propto 1/\delta$. The same result can be used to estimate the transfer efficiency into $F_g = 2$ by inelastic bouncing. For comparison, the elastic and inelastic contributions to the atom density are shown in Fig. 7.4(c) for a smaller detuning of $\delta_1 = 100 \Gamma$. It is obvious
Inelastic mirrors for cold rubidium atoms were realised using evanescent-wave optical potentials tuned near an open optical transitions of the D1 (795 nm) or D2 (780 nm) line of $^{87}$Rb, thus introducing spontaneous Raman transitions between hyperfine ground states. Bouncing atom clouds were directly observed by absorption imaging. The evolution of the peak atomic density reveals the inelasticity of the reflection on the mirror, e.g. loss of kinetic energy ranging between 81 – 92%. The dynamics of the internal state transfer of bouncing atoms causes a broadened non-thermal atomic velocity distribution, that is observed as a tail of fast atoms in absorption images of bouncing atoms. This suggests that, although the observed single inelastic bounce represents a fundamental step of a “Sisyphus” reflection cooling mechanism, it involves heating (and thus a reduction in phase-space density). Only a succession of multiple bounces leads to a net cooling effect and, finally, establishes a thermal barometric density distribution of atoms at a temperature lower than the initial one [17]. Note that in the proposed low-dimensional trapping scheme of Chap.2 the phase-space density already piles up by a single bouncing process. This is due to spatially selective pumping in combination with a trapping potential that accumulates atoms in the vicinity of the surface. Further experimental investigations which are in progress, have to show whether pumping by the evanescent-wave mirror alone, can be used to efficiently optimise a trap loading scheme. For the envisaged very far detuned evanescent waves it may be necessary to introduce an additional near-resonance evanescent-wave contribution in order to adjust optical scattering rates.