Development of reflection-type atom optical elements

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Atom optics aims at developing optical components for the use with neutral atomic waves. Cooled atomic beams display phenomena very similar to photon optics, including reflection, diffraction and interference.

In this thesis, three new atom reflectors are developed and analysed. The theory of reflection and diffraction of atomic waves at these reflectors is presented, together with the experimental setups that have been built to study their properties. Laser cooling and trapping techniques are used to obtain intense and coherent atomic beams [1]. The results are discussed in view of applications in atom lithography [2] and interferometry [3].

A controllable diffraction grating for atoms

The first type of atom reflector is a controllable diffraction grating that allows scanning and coherent splitting of an atomic wave. A new apparatus was built up for this experiment, including the vacuum chamber, the source of an intense and cooled atomic beam, the magneto-optical trap of metastable neon atoms and the setup to diffract the atomic wave. The experimental setup is shown in figure 1.

A time-modulated evanescent wave field above a glass surface was used to diffract the continuous beam of atoms at grazing incidence. In this configuration, the diffraction angles and diffraction efficiencies are determined by the frequency and shape of the light intensity modulation, respectively:

The evanescent wave acts as a mirror for the atoms if the laser frequency is higher than the atomic transition frequency, because the atoms feel a repulsive dipole potential in the exponentially decaying evanescent wave field. A modulation of the laser intensity of the evanescent wave at frequency f corresponds to a vibrating mirror surface and leads to the absorption of energy quanta $n \times hf$ perpendicular to the surface, where h is Plancks constant and $n = 0, \pm1, \pm2, \ldots$ [4]. If an atom of mass M is incident on the mirror with velocity v under a small angle θ_i (measured with respect to the mirror plane), then the diffraction angles $\theta_{o,n}$ are readily calculated:

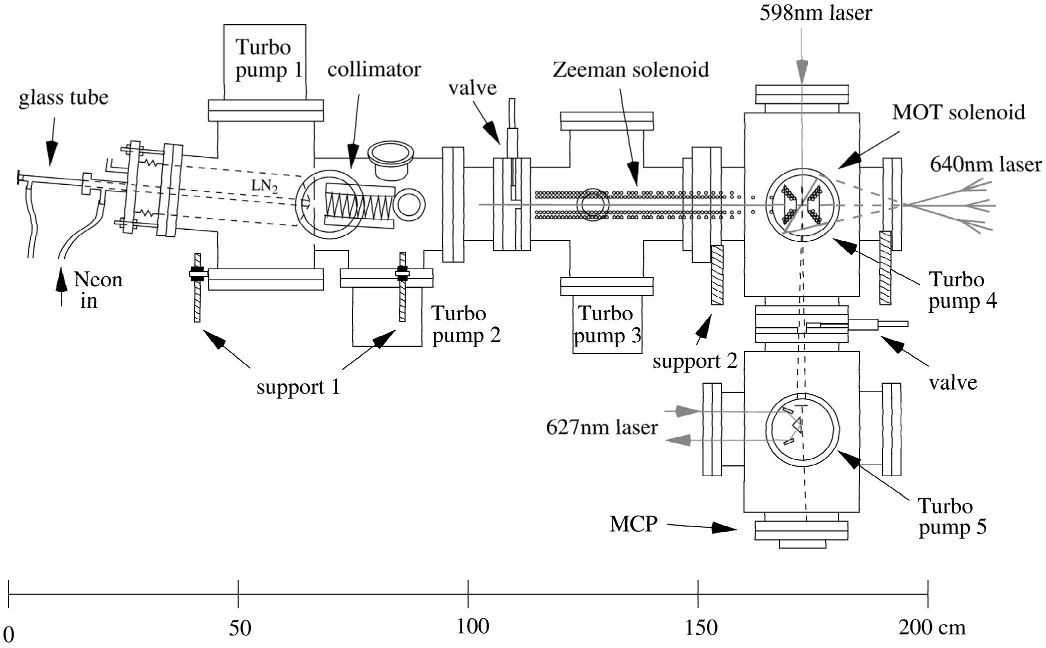

Figure 1: Overview of experimental setup: Neon beam source, magneto-optical trap and reflection at the evansecent wave mirror.

$$\theta_{o,n} = \sqrt{\theta_i^2 + n\,\frac{hf}{Mv^2/2}}\,. \tag{1}$$

In order to calculate the diffraction efficiencies, we numerically solved the one-dimensional, time-dependent Schrödinger equation, describing the reflection of a Gaussian wavepacket at the modulated potential. In this calculation we also included the van der Waals surface potential, taking the result from [5]:

$$V(t,z) = V_0(t)\,e^{-2\kappa z} - \frac{C_4}{(z+\lambda/2\pi)z^3} \tag{2}$$

with $C_4 = 7.3 \times 10^{-56}\,Jm^4$ and $\lambda = 5.0\,\mu m$.

The method was then applied to realize an atomic beam scanner [6]: We optimized the shape of the light intensity modulation in order to transfer a maximum amount of atoms into one of the first order beams. The arbitrary shape of modulation of the optical light potential was described by a Fourier series

$$V_0(t) = V_0\left[1 + \epsilon \sum_{n=1}^{N} c_n \sin(n\,2\pi f t + \phi_n)\right], \tag{3}$$

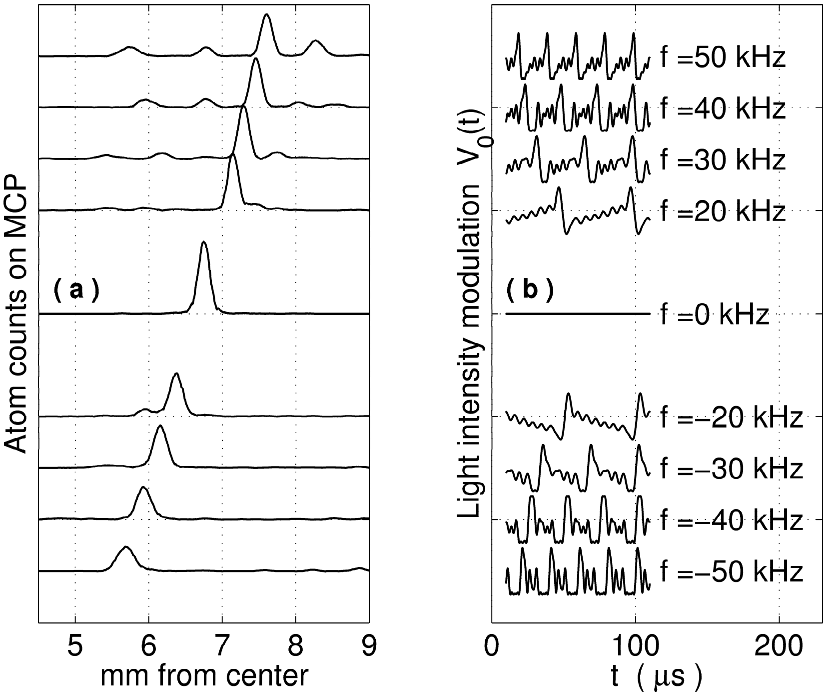

Figure 2: (a) The measured diffraction pattern on the MCP detector when the waveform is optimized to concentrate atoms into a single diffraction order. The strong peak is the first diffraction order. (b) The waveform for each modulation frequency in (a).

and eight harmonics were included in the simulation (N=8). The optimum amplitudes c_n, phases ϕ_n and modulation depth ϵ were then determined by fitting the calculated diffraction efficiencies to the chosen ideal distribution: $|a_1|^2 = 1$ or $|a_{-1}|^2 = 1$ and all other $|a_k|^2$ zero, where $|a_k|^2$ is the relative intensity of the k^{th} diffraction order.

With the calculated optimized shapes, diffraction efficiencies into a single order of more than 60% were achieved, which is exceptionally high for matter wave diffraction. The calculated optimized shapes of the light intensity modulation and the observed distribution of atom counts on the micro-channel plate detector are shown in figure 2.

Combined with a focusing lens, this scanner can be used in atom lithography to write a pattern onto a surface. The controllable diffraction grating can also be used to make a beamsplitter for atomic waves, and to switch quickly between different diffraction patterns.

Quantum reflection of metastable helium atoms

The second experiment aims at studying the quantum reflection of metastable helium atoms on a silicon surface. Quantum reflection of atomic waves occurs due to the wavevector mismatch at the steep slope of the van der Waals potential close to the surface. It was previously observed for neon atoms reflected at grazing incidence on a silicon plate [5], which is also used in the focusing experiment described below. The reflectivity can be considerably enhanced by using a surface structure with narrow, parallel ridges [7]. In addition, a theoretical analysis shows that quantum reflection is much more effective for atoms with smaller mass. For helium atoms a reasonably high reflectivity is expected even for a normal incident velocity of a few tens of cm/s. The high reflectivity makes it possible to design stable atom reflectors and reflection-type holograms [8] even for perpendicularly incident beams. A new experimental project was started to prepare a coherent beam of helium atoms. A new laser system at 1083 nm and an atomic beam source was built. A magneto-optical trap of metastable helium atoms was realized. The number of trapped atoms is still small, but can be increased by inserting a beam collimator, that has already been prepared, into the apparatus. It is planned to produce a coherent atomic beam by releasing atoms from the magneto-optical trap, which can be achieved with several different techniques.

The current state of the setup is shown in figure 4.

One-dimensional focusing of an atomic beam by a flat reflector

The third experiment demonstrates the focusing of an atomic beam by a flat reflector [9]. The experiment was performed with metastable neon atoms released from a magneto-optical trap and reflected at grazing incidence from a silicon plate, using the enhanced quantum reflection at a surface structure with parallel, narrow ridges. A scheme of the setup is shown in figure 3.

Focusing of the atomic beam and an increase of flux in the reflected beam at the detector plane was observed. Focusing is possible because the momentum transfer perpendicular to the surface depends on the height of the reflecting point due to the gravity acceleration. The quality of the focusing depends on the size of the atomic beam source, the velocity distribution, the flatness and quality of the mirror surface, the size of the reflector and the angle of incidence. The influence of these parameters has been numerically

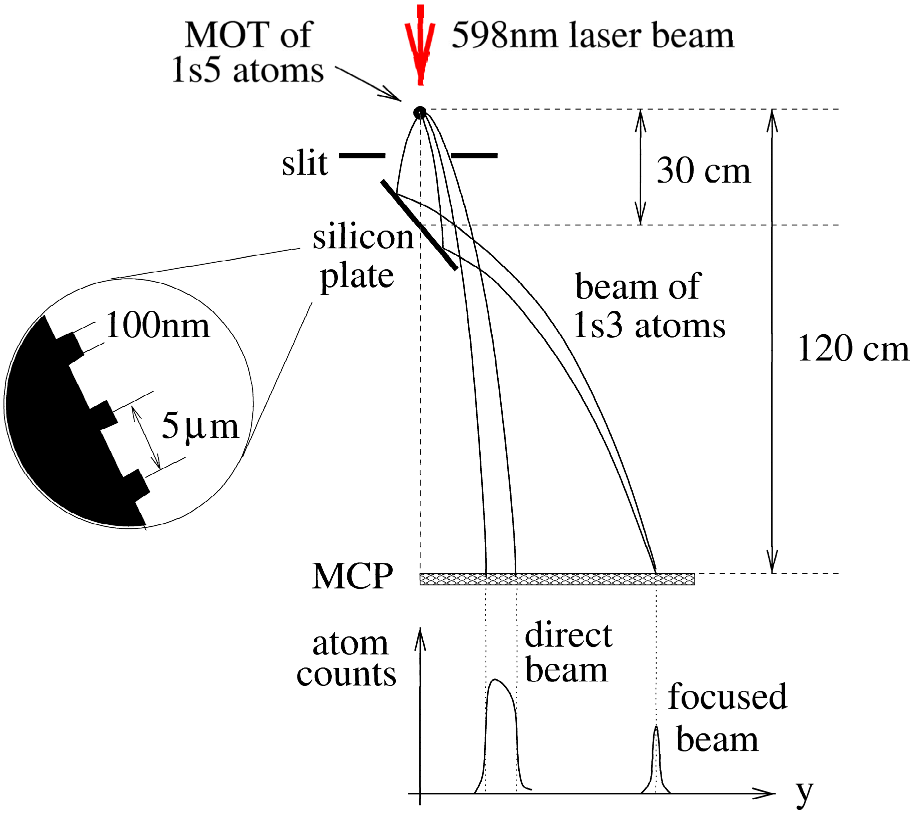

Figure 3: Schematical setup below the magneto-optical trap for the focusing experiment.

analysed. The analysis shows that for a certain parameter range diffraction-limited focusing is possible. In our experiment, the observed beam width at the detector position was reduced from 2.7 mm without focusing to 0.35 mm after reflection on the plate. The observed width was larger than would be expected for a point-like source and a perfectly flat surface: The beam was broadened due to the finite size of the source and probably due to a small curvature of the reflecting surface. At grazing incidence the focusing length is very sensitive to any small curvature of the surface. This effect can be used in a future experiment to adjust the focusing length by deforming the silicon plate with a piezo-actuator. Two-dimensional focusing could be achieved by using a pair of orthogonal mirrors. Such a device provides a simple way to increase the flux of an atomic beam on a specific plane and to analyse the characteristics of the beam source.

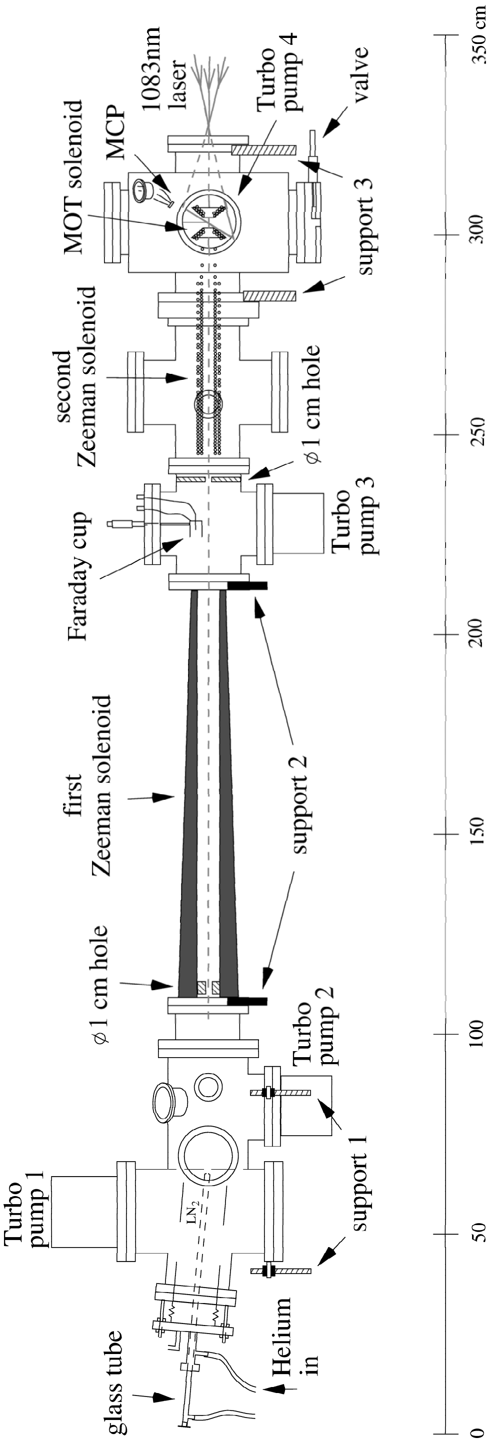

Figure 4: Schematic overview of the helium experiment.

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