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Guiding, focusing, and cooling of atoms in a strong dipole potential

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Abstract. We report on the application of holographically generated TEM^*_{01} (doughnut) modes for atomic beam manipulation. A slow atomic beam is guided over up to 0.3 m and focused down to 6.5 μm radius. The doughnut mode is used as a strong mesoscopic dipole potential with vibrational level spacings up to the photon recoil energy. Polarization gradient cooling in this system generates a bimodal momentum distribution with a narrow component momentum width of 4 $\hbar k$.

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Laser manipulation of atoms has a strong impact on fundamental and applied research in atomic physics, quantum optics, and atom optics. Traps for neutral atoms and optical cooling schemes with temperatures close to or even below the recoil limit are state-of-the-art tools to generate and manipulate cold and dense atomic samples [1]. In parallel to the development of trapping and cooling geometries in 3D, advances in laser cooling have opened the way for novel schemes to prepare slow and brilliant atomic beams.

The main interest in slow beams with high brilliance arises from new applications in atom lithography, collisional physics, atom interferometry, and quantum statistics. These critically depend on monochromaticity, high intensity, or high density. Recent techniques for sophisticated beam preparation include magneto-optical funnels [2], isotropic cooling [3], hollow core optical fibers [4], and modified magneto-optical traps [5].

1 Experiment and results

We report on a novel tool for preparing a slow and dense atomic beam with a radius well below 10 μm and a transverse velocity spread of only a few photon recoils. This is achieved by guiding and focusing of atoms in the dark region of a holographically generated TEM^*_{01} laser mode (also called ‘doughnut mode’). For a laser frequency tuned above resonance of an atomic transition the dipole potential repels atoms from regions of high intensity. In the intensity profile of the doughnut mode the atoms are therefore confined near the laser beam axis. We have investigated in detail the guiding efficiency and the lens-like properties of this device for applications in atom optics. As an all-optical device the doughnut mode provides a powerful and extremely flexible tool for the manipulation of atomic samples. In general, higher order Laguerre–Gauss modes (TEM^*_{pl}) offer appealing possibilities of atom trapping [6, 7] and beam focusing [8].

Furthermore, the doughnut mode atom guide as discussed here allows for experimental conditions in which the spacing between the quantized levels of the transverse center of mass motion exceeds the photon recoil energy. In this case the strong dipole potential offers the possibility to trap neutral atoms in the Lamb–Dicke limit as known from ion traps yet without electrostatic repulsion. This regime is interesting, because the population of one vibrational mode with several neutral bosonic atoms by purely optical methods seems feasible [9].

For principle investigations of laser cooling in strong dipole potentials we have combined the doughnut mode guide with additional 2D sub-Doppler cooling. Whereas in earlier experiments with red-detuned strong dipole traps sub-Doppler cooling was severely degraded [10], most recent experiments combining red dipole traps with blue Sisyphus cooling have exhibited efficient sub-Doppler cooling [11]. However, quantum Monte Carlo simulations indicate a degradation of the cooling process for even stronger trapping light shifts [12]. The doughnut mode provides an interesting trapping geometry for additional sub-Doppler cooling, because it confines atoms in the intensity minimum where the perturbation induced by the trapping light is minimal.

Our studies are performed with metastable neon atoms. Apart from intrinsic interest in collisional studies the metastable rare gases are of major interest for lithographic nanostructuring of surfaces [13].

The principal idea of employing the doughnut mode as an atom guide with lens properties [8] is the following: A laser-decelerated and compressed atomic beam is injected into the dark region of a blue-detuned doughnut mode. If in addition the laser beam is focused, the atomic beam is spatially compressed. This system offers the feature of a diffraction-limited atom guide capable of steering atoms over long distances

In more detail, for a two-level atom of resonance frequency ω_0 in a TEM^*_{01} laser field of frequency ω_L propagating along the z axis the dipole potential is given by

$$U(\boldsymbol{r}) = \frac{\hbar\Omega^2(\rho, z)}{4\Delta} = \frac{\hbar\Omega_0^2(z)}{4\Delta}\frac{\rho^2}{w^2(z)}\exp\left(-2\frac{\rho^2}{w^2(z)}\right) \quad . \tag{1}$$

Here, $\Omega_0(z)/\sqrt{2e}$ is the maximum Rabi frequency attained at the radial position $\rho = w/\sqrt{2}$, $w(z) = w_0\sqrt{1+z^2/z_\mathrm{R}^2}$ is the beam radius, z_R is the Rayleigh range, and $\Delta = \omega_\mathrm{L} - \omega_0$ is the laser detuning from resonance. Equation (1) is valid in the limit $\Delta \gg \Gamma, \Omega$, with Γ the natural linewidth of the upper level. Note that in this regime the light-induced torque on the atoms [14] can be neglected. In paraxial approximation ($\rho \ll w$) the dipole potential is harmonic with a vibrational frequency given by $\omega^2_\mathrm{vib}(z) = \hbar\Omega_0^2(z)/(2\Delta m w^2(z))$ (m is the atomic mass).

In the following we will concentrate on configurations where atoms inside the doughnut mode are guided and simultaneously focused. When the atomic beam is injected into the doughnut mode in the far field ($|z| \gg z_\mathrm{R}$), as is shown in Fig. 1, it is confined by a comparatively weak potential. Moving towards the focus the potential increases as z^{-2}. As a consequence the atomic beam is spatially compressed and the transverse momentum increases.

The experimental setup starts with a laser-decelerated, deflected, and compressed slow atomic beam with a high brilliance of $5\times 10^{12}/(\mathrm{sr\ s})$ [15, 16]. The longitudinal velocity is 28 m/s with a rms width of 4 m/s. The atoms are injected into the doughnut mode through a 30-μm-radius hole in a dielectric mirror at 45° (Fig. 1). Behind the mirror the flux is 1.4×10^6 atoms per second with a transverse Gaussian velocity distribution where $\sigma_v = 7.8\,\mathrm{cm/s} = 2.5\ v_\mathrm{rec}$, with $v_\mathrm{rec} = \hbar k/m$ the photon recoil velocity.

The beam of metastable neon atoms is guided and focused over distances between 10 and 30 cm, limited by the size of the vacuum chamber. The doughnut mode is generated by passing the single-frequency Gaussian beam of a commercial ring dye laser through a computer-designed blazed phase hologram which has been produced by direct laser writing techniques [17]. Note that the single hologram does not produce a pure doughnut mode but rather a superposition of modes, where the doughnut mode has a contribution of 93%. For the atom guiding, the hologram is positioned such that the light field remains dark on axis in the guiding region. With a filter cavity it is possible to separate the doughnut mode from the mode mixture [18].

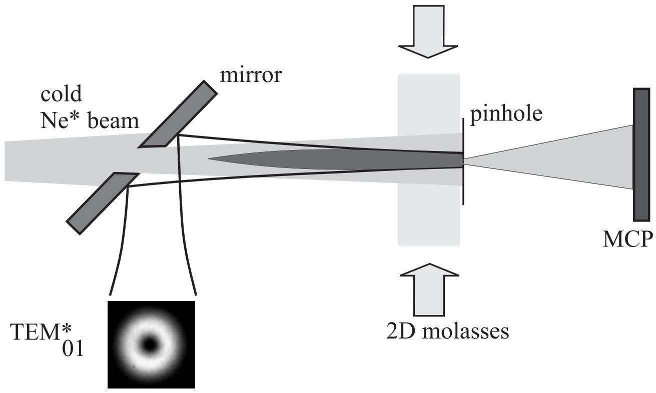

Fig. 1. Experimental setup for guiding and focusing of metastable neon atoms. Optionally an additional 2D molasses cools the transverse motion. The atoms are detected with a microchannel plate (MCP)

The laser frequency is tuned to the blue side of the cooling transition $3s[3/2]_2 \to 3p[5/2]_3$ at 640 nm. The linearly polarized doughnut mode is focused as sketched in Fig. 1. A blackened pinhole (radius 8 μm), which can be moved in the transverse direction, is positioned in the focal plane for measurement of the spatial atomic beam profile inside the doughnut mode. The velocity distribution is determined from the 2D atomic intensity profile detected on a microchannel plate (MCP) 20 cm downstream. The spatial resolution results in a transverse time-of-flight velocity resolution of 0.5 v_rec.

We have studied atomic flux, atomic beam diameter, and atomic density in the focal plane of the doughnut mode as a function of the doughnut mode well depth. For this purpose the frequency detuning was varied between 10 and 1000 GHz at fixed laser power. Figure 2 shows the normalized atomic intensity in the focal plane as a function of the doughnut mode well depth for a waist w_0 of 50 μm and a power of 300 mW. The distance between the mirror and the pinhole was 14 cm.

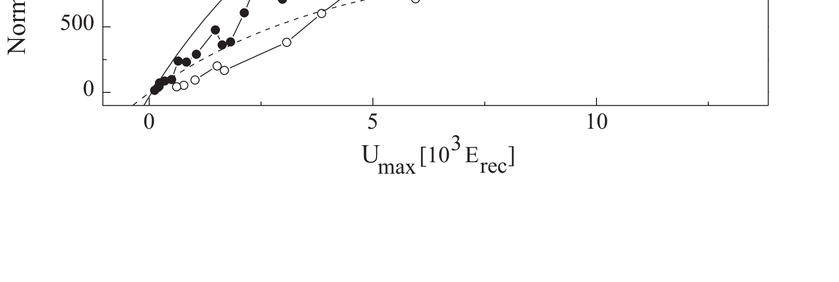

Fig. 2. Measured atomic intensity enhancement as a function of maximum light shift for atom guiding in a blue-detuned doughnut mode (•) and in a red-detuned Gaussian mode (○). The *dashed* and *solid curve* show the results of a numerical simulation, plotted for a wider range in the inset

The atomic flux through the pinhole is normalized to the flux of atoms detected without doughnut mode. In this way the normalized intensity might be regarded as an intensity enhancement factor at a given position along the atomic beam.

For a shallow potential only a minor part of the atomic beam is captured by the guiding potential when entering the doughnut mode (Fig. 2). For increasing potential height a growing number of atoms is trapped and guided. A semi-classical Monte Carlo simulation shows good agreement with the experimental data as indicated by the solid curve in Fig. 2. The simulation accounts for Zeeman substructure, spontaneous emission, and photon recoil. Typically, for $U_{\max} \equiv U(z=0, \rho = w/\sqrt{2}) < 1500\ E_{\text{rec}}$ the atoms scatter less than one photon during the guiding process. The scattering rate increases as Δ^{-2}. Therefore, for higher $U_{\max}$ a growing fraction of atoms is heated due to spontaneous scattering. As a consequence the atomic beam diameter expands and the peak intensity as a function of $U_{\max}$ flattens (Fig. 2 inset).

The experimental curve in Fig. 2 gives slightly lower guiding efficiency compared to the result of the simulation. We attribute the additional losses to a 25% azimuthal intensity variation of the doughnut mode near the focus. This intensity variation is due to residual astigmatism in the laser beam. In the far field ($|z| > z_{\text{R}}$) this effect is much less pronounced and the azimuthal intensity variation is less than 10%.

For $U_{\max} = 8500\ E_{\text{rec}}$ the intensity enhancement is a factor of 1600. In this case $(60 \pm 10)\%$ of all atoms injected into the doughnut mode are captured and guided. The inset of Fig. 2 shows that for high $U_{\max}$ the enhancement factor is expected to reach values well above 3000. In principle, 98% of all atoms injected into the guiding laser can be captured for such high potentials. For $U_{\max} = 2000\ E_{\text{rec}}$ we inferred a Gaussian atomic beam radius of $\sigma_x = 6.5\ (\pm 1.5)\ \mu\text{m}$ $(1/\sqrt{e})$ after de-convolution of the measurement with the finite-size pinhole. The corresponding flux is 8×10^5 atoms per second, the density is $2 \times 10^8\ \text{cm}^{-3}$ and the intensity is $6 \times 10^{11}/(\text{cm}^2\text{s})$. These values can be increased by a modified injection geometry [19] and with higher order Laguerre–Gaussian beams. So far we have achieved a factor of 10 improvement in atomic flux when using the doughnut mode and a factor of 80 with a TEM^*_{05} mode.

When the doughnut mode is focused to $w_0 \approx 15\ \mu\text{m}$ the simulation predicts an atomic beam size below $1\ \mu\text{m}$ (rms) for a power of 300 mW and a detuning of 10 GHz at the expense of increased loss. Only 10% of all atoms are expected to be captured for such a tight focus. In this regime, other diagnostic tools, such as atom lithography [13], have to be implemented in order to measure the atomic spot size.

We have also performed the guiding experiment with a red-detuned Gaussian mode [20] of the same waist size and power as the doughnut mode. Diffraction of the Gaussian beam at the hole in the mirror is negligible because the beam radius at the mirror is much larger than the hole radius. In contrast to the doughnut mode atom guide, now the atoms with the lowest transverse temperatures experience the highest scattering rates because they are guided in the maximum intensity. Due to the strong heating for large $U_{\max}$ the measured atomic intensity remains much smaller in the Gaussian beam atom guide (see Fig. 2).

We now turn to a discussion of experiments on transverse sub-Doppler cooling inside the doughnut mode atom guide. The vibrational ground state energy inside the atom guide can be made equal to or even larger than one photon recoil energy, i.e. close to the cooling limit of optical molasses. The main objective here is to investigate the feasability of cooling to low vibrational states in a strong dipole potential with the continuous cooling scheme of optical molasses.

A 2D molasses is inserted in the focal plane of the doughnut mode. The molasses is generated from two crossed standing waves, perpendicular to the doughnut mode axis, polarized either linearly in the plane of the k-vectors ($\pi_x\pi_y$) or in $\sigma^+\sigma^-$ configuration. The wings of the intensity profile are clipped to avoid adiabatic processes when the atoms enter and exit the cooling light. The transit time through the cooling beams is 0.3 ms.

The sub-Doppler cooling process was studied by measuring transverse velocity distributions as a function of the cooling light intensity for different values of $U_{\max}$ and different cooling light polarizations. We observe a qualitative difference in the cooling behavior for comparatively weak doughnut mode potentials as compared to a strong doughnut mode.

In the weak doughnut mode regime, i.e. $\omega_{\text{vib}} < 0.5\ \omega_{\text{rec}}$, the measured velocity distributions consist of two Gaussian components. One component has the velocity width of the initial (uncooled) ensemble ($\sigma_v \approx 7-9\ v_{\text{rec}}$) and the other has a sub-Doppler width of $\sigma_v \approx 4\ v_{\text{rec}}$ (see Fig. 3), well below the Doppler limit ($10\ \hbar k$). Bimodal velocity distributions have been discussed in the context of cooling with limited interaction time [21]. For initial velocities larger than the capture range of the sub-Doppler molasses, only the atoms within the capture range are cooled to sub-Doppler velocity widths. With the remaining atoms in the wings of the distribution, they form a non-Gaussian distribution.

The width of the sub-Doppler component is essentially independent of cooling light intensity for single-beam saturation parameters s between 0.015 and 0.09, where $s = I\big/\left(I_{\text{sat}}\left(1+4(\Delta/\Gamma)^2\right)\right)$. This behavior is shown in Fig. 3a (lowest two curves) for the case of $\pi_x\pi_y$ polarization of the cooling light. With increasing cooling light intensity a larger number of atoms are cooled into the sub-Doppler component, thus the overall ‘temperature’ decreases. As is shown in

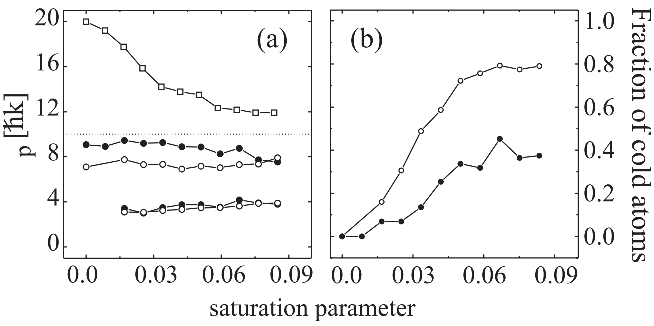

Fig. 3a,b. Measured widths of the transverse momentum distribution (**a**) and fraction of atoms in narrow peak (**b**) as a function of the cooling light saturation parameter (*single beam*). For $\omega_{\text{vib}} = 0.30\ \omega_{\text{rec}}$ (●) and $\omega_{\text{vib}} = 0.26\ \omega_{\text{rec}}$ (○) the same symbols are used for the broad and the narrow width of the double Gaussian momentum distribution. For $\omega_{\text{vib}} = 0.61\ \omega_{\text{rec}}$ (□) the distribution is Gaussian. Cooling light parameters: $\pi_x\pi_y$-polarization, $\Delta_{\text{c}} = -9\ \Gamma$

Fig. 3b, the fraction of cold atoms levels off for a comparatively high saturation parameter, $s > 0.06$. For a dipole potential with $\omega_{vib} = 0.26\,\omega_{rec}$ ($0.3\,\omega_{rec}$) the fraction of cold atoms saturates at 80% (40%). Similar results are obtained for the $\sigma^+\sigma^-$ configuration. The combination of focusing and sub-Doppler cooling increases the transverse phase space density of the atom beam injected into the doughnut mode by about one order of magnitude.

In the free space limit of vanishing guiding dipole potential we find similar bimodal velocity distributions where the width of the cold component is $2.2 - 2.7\,v_{rec}$. As is the case inside the doughnut mode, the width of the cold component is nearly constant over a wide range of the cooling light intensity, whereas the fraction of cold atoms increases with intensity.

The dependencies on cooling light intensity that we observe differ from steady-state results commonly obtained in sub-Doppler molasses in free space [1], where the temperature is found to be proportional to the light intensity. However, our results are characteristic for laser cooling of atomic beams with relatively large cooling light saturation and limited interaction time [22–24].

For strong doughnut mode potentials ($\omega_{vib} > 0.5\,\omega_{rec}$) the initial distribution has a transverse velocity spread of $20\,v_{rec}$ and higher. In this regime the sub-Doppler cooling behaves qualitatively different. The velocity distribution of the cooled sample has a single Gaussian shape. As the upper most curve in Fig. 3a shows, for $\omega_{vib} = 0.61\,\omega_{rec}$ the width of the velocity distribution decreases with increasing cooling light intensity. Note, that the width of $12\,v_{rec}$ obtained for large intensity is far below the limit of Doppler cooling of $42\,v_{rec}$ for the large detuning (-9Γ) of the cooling laser light. Therefore, this cooling is still due to sub-Doppler mechanisms. In either case, strong or weak guiding potentials, there is no significant influence of the doughnut mode polarization on the cooling behavior.

The different cooling behavior in strong doughnut mode potentials shows that the polarization gradient cooling is altered by the additional level shift induced by the external field. For the strong doughnut mode ($\omega_{vib} = 0.61\,\omega_{rec}$) we calculate that for about 60% of the atoms the doughnut mode light shifts exceed those induced by the cooling light. Quantum Monte Carlo simulations confirm a degrading of the sub-Doppler cooling when the additional light shift is on the same order as that induced by the cooling laser [12]. The simulations show that sub-Doppler cooling is retained for high cooling-light intensity as observed in our measurements. In some respect the effect of additional light shifts on the cooling dynamics is similar to the influence of additional magnetic fields [25, 26].

2 Conclusion

We have demonstrated applications of holographically generated Laguerre–Gaussian laser beams for atom optics such as the preparation of strongly focused and dense atomic beams. We have shown that polarization gradient cooling works in dark dipole potentials which makes it a valuable and flexible precooling tool for reaching a macroscopic population of the ground state by purely optical methods. Future prospects include the strong focusing and steering of atomic beams in lithographic applications and the implementation of additional cooling schemes [27].

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