Continued imaging of the transport of a single neutral atom

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Abstract: We have continuously imaged the controlled motion of a single atom as well as of a small number of distinguishable atoms with observation times exceeding one minute. The Cesium atoms are confined to potential wells of a standing wave optical dipole trap which allows to transport them over macroscopic distances. The atoms are imaged by an intensified CCD camera, and spatial resolution near the diffraction limit is obtained.

OCIS codes: (020.7010) Trapping , (140.7010) Trapping

References and links

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1. Introduction

The first image of an individual atomic particle in a trap was obtained by recording the fluorescence light from a single Barium ion on a photographic plate in 1980 [1]. Initially, the effort to realize experiments at the single particle level was largely motivated by the investigation and demonstration of fundamental quantum processes. Today, in the perspective of quantum information processing, such experiments intend more and more to engineer and to control the quantum state of the trapped atoms or ions. This control is particularly important if one wants

to realize a coherent interaction between two or more particles in order to implement quantum logic operations.

In this context, we demonstrated that a standing wave optical dipole trap allows to control the external degrees of freedom of individual neutral atoms and to transport them over millimeter scale distances [2, 3]. Furthermore, we showed that the electronic states of the atoms in our trap exhibit long coherence times, making them a good candidate for storing and processing quantum information [4]. However, for an efficient and flexible state preparation and detection as well for a controlled interaction the absolute position of the atoms in the trap has to be known and controlled.

This can readily be achieved in ion trapping experiments where the position of the ions is determined by the fixed trapping potential including the Coulomb repulsion of the ions. Furthermore, due to their strong spatial confinement, trapped ions can resonantly scatter light without influencing their motional state. As an impressive example of this observation method, the molecule-like vibrations of a chain of trapped ions have been recorded in [5] using a stroboscopic method. Imaging of single neutral atoms in a stationary dipole trap potential has also been achieved [6].

In this letter, we present a continued observation of the controlled transport of individual neutral atoms in a standing wave dipole trap with an observation time of the order of one minute. Our technique should enable us to control the absolute position of the atoms with submicrometer precision and to address the atoms individually. Our results therefore represent a major step towards the preparation and manipulation of a string of trapped neutral atoms for use as a quantum register.

2. Experimental setup

A specially designed six-beam magneto-optical trap (MOT) [7] serves as a source of cold neutral cesium atoms. A high magnetic field gradient of $340\,\mathrm{G/cm}$ localizes the atoms to a region of $d_{\mathrm{MOT}} = 12\,\mu\mathrm{m}$ in diameter. The diameter of the MOT beams is about $1\,\mathrm{mm}$ and the saturation parameter of each beam is $s = 0.5$. The high magnetic field gradient reduces the loading rate of the MOT, which allows us to work at the level of single atoms. The fluorescence light from the MOT is collected and collimated by a home made diffraction limited objective (NA$= 0.29$) [8] and is evenly split by a beam splitter (Fig. 1). The transmitted light is spatially and spectrally filtered before it is focused onto an avalanche photodiode (APD). The light reflected by the beam splitter is only spectrally filtered and imaged onto the photocathode of an intensified CCD camera (ICCD).
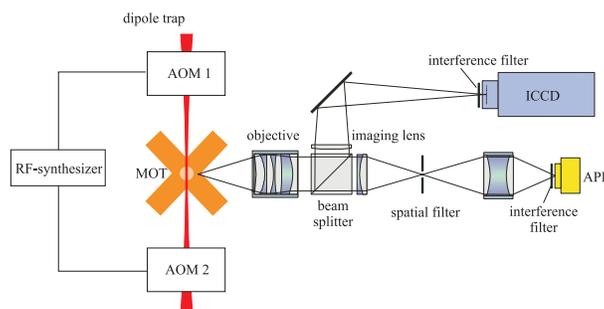

Fig. 1. Scheme of the experimental setup. The fluorescence light from the MOT is collimated and divided into two parts by the beam splitter. One part is sent onto the APD, while the other part is imaged onto the intensified CCD camera.

The APD (SPCM-200, EG&G) has a quantum efficiency of 50% for the fluorescence light at the wavelength of 852 nm. For typical MOT parameters this yields a count rate of 35000/s for each trapped atom at a stray light background of 25000/s. This allows us to determine the exact number of up to 20 atoms trapped in the MOT at any moment in less than 10 ms, limited by shot noise.

The photocathode of the camera intensifier (Gen III HQ, Roper Scientific) is connected to an intensifying microchannel plate. For each photoelectron the microchannel plate together with the fluorescence screen of the intensifier produces a photon burst which is recorded by the CCD camera (PI-MAX:1K,HQ,RB, Princeton Instruments). On average this photon burst results in 350 counts on the 1024×1024 pixel CCD chip. The counts are concentrated in a 3×3 pixel area with 50% in the central pixel. The quantum efficiency of the intensified camera is approximately 10% at 852 nm. Since our imaging optics has a magnification of $13.99(\pm 0.06)$, one CCD pixel of $13 \times 13\,\mu\text{m}^2$ corresponds to $0.929(\pm 0.004)\,\mu\text{m}$ at the position of the atom. The expected full width at half maximum (FWHM) of the point spread function of our imaging optics is $w_{\text{PSF}} = 1.4\,\mu\text{m}$ (all further widths in this letter are FWHM).

We use a red-detuned standing wave dipole trap (DT) in order to trap and move the atoms. The DT consists of two counter-propagating Gaussian beams ($\lambda = 1064$ nm) in lin∥lin polarization configuration (Fig. 1). Each beam is focused to a waist of $2w_0 = 32\,\mu\text{m}$ at the position of the MOT and has 1.3 W of optical power. The resulting interference pattern yields a chain of traps, $\lambda/2$ apart, each with a potential depth of $U/k_{\text{B}} = 2.9$ mK and a radial FWHM of $b = 19\,\mu\text{m}$. The atoms are transferred from the MOT into the DT with an efficiency close to 100%. Acousto-optic modulators (AOMs) control the frequencies of both beams of the DT. They are driven by a digital dual-frequency synthesizer (DFD100, APE) with two phase synchronized RF outputs. This allows us to phase-continuously detune the frequencies of each of the beams, causing the standing wave pattern to move in a controlled way along the dipole trap axis. The direction of the transport depends on the sign of the relative detuning between the two beams. Using this "optical conveyor belt" the atoms can be transported over macroscopic distances of up to 1 cm with submicrometer precision on a millisecond timescale [2, 3].

3. Experimental results

3.1. Imaging of an atom in the MOT

Under continuous illumination the fluorescence light of a single atom in the MOT generates $n_{\text{MOT}} = 6400$ photoelectrons/s on the photocathode. Figure 2(a) shows an image of a single atom trapped in the MOT with an exposure time of 1 s. The size and the position of the MOT are determined by binning the pixels of the picture in the vertical and horizontal directions and by fitting the resulting histogram with a Gaussian. Here, the MOT has a size of $11\,\mu\text{m}$ in the vertical and of $13\,\mu\text{m}$ in the horizontal direction.

A trajectory of an atom in the MOT corresponds to a trace of sequentially recorded single photon events. In order to reconstruct the atomic trajectory with a spatial resolution at the diffraction limit of our optics, the mean spacing between consecutive photons should not exceed the diffraction limited spot size w_{PSF}. This results in the upper limit of the atomic velocity of $v_{\text{max}}^{\text{d}} = w_{\text{PSF}} \cdot n_{\text{MOT}} = 9$ mm/s. This number is much smaller than the Doppler velocity of $v_{\text{D}} = 9$ cm/s for a Cs atom in a MOT. At the Doppler velocity v_{D} and with the current count rate n_{MOT}, the information available from the recorded photon trace is therefore insufficient for a reconstruction of atomic trajectories at full spatial resolution. To detect only a global motion of an atom from one to another side of the MOT, the upper limit for the atomic velocity is $v_{\text{max}}^{\text{g}} = d_{\text{MOT}} \cdot n_{\text{MOT}} = 8$ cm/s. This number is close to the Doppler velocity of 9 cm/s, and it seems feasible to resolve such motion in future experiments.
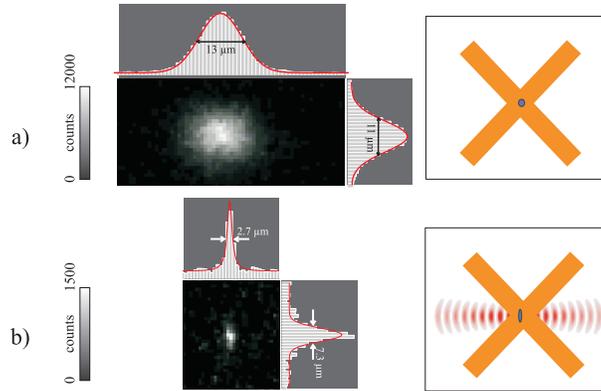
Fig. 2. a) CCD image of one atom stored in the MOT (exposure time 1 s). The counts are binned in the vertical and horizontal directions and fitted with Gaussians to determine the size and the absolute position of the trap. b) One atom in a potential well of the DT illuminated by an optical molasses (Exposure time 0.5 s).

3.2. Imaging of atoms in the dipole trap

An exactly known number of atoms is prepared in the MOT and transferred into the conservative potential of the DT. For continuous observation, we illuminate the atoms in the DT by a 3-D optical molasses. We use the MOT beams for this purpose, however, we red-detune them by $13.5\,\Gamma$ from the light-shifted transition of the trapped atom and reduce the saturation parameter to 0.004 for each beam ($\Gamma = 2\pi \times 5.2\,\mathrm{MHz}$ is the linewidth of the excited state). Figure 2(b) shows an image of one atom trapped in a potential well of the DT recorded with an exposure time of 0.5 s. The observed fluorescence spot corresponds to about 70 detected photons ($n_{DT} = 140$ photoelectrons/s). The trapping region has a size of $a_{rad} = 7.3\,\mu\mathrm{m}$ in the vertical direction, which is a few times smaller than the radial width $b = 19\,\mu\mathrm{m}$ of the trap. This shows that the atom is trapped close to the minimum of the DT potential and remains cold during the illumination. From the standing wave geometry we know that the axial width of the trapping region is smaller than $\lambda/2 = 532\,\mathrm{nm}$. However, the observed width of the fluorescence spot is $a_{ax} = 2.7\,\mu\mathrm{m}$. Therefore, two atoms are optically resolved if they are separated by more than a_{ax}, which corresponds to 6 or more potential wells. The deviation of a_{ax} from the expected diffraction limited spot size of $w_{PSF} = 1.4\,\mu m$ is mainly due to the fact that one photon detected by the camera produces a spot on the CCD chip with a width that corresponds to $w_{Det} = 2.50(\pm 0.03)\,\mu\mathrm{m}$ at the position of the atoms. The width of the observed fluorescence spot a_{ax}, in combination with the current count rate in the dipole trap n_{DT}, results in a lower limit of the precision of the detection of the axial atomic position of $a_{ax}/\sqrt{n_{DT}} = 230\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$.

The radial distribution a_{rad} of the imaged atom depends on its temperature T. Using a Fokker-Planck equation model [9] we find that $T = (U/2k_B)(a/b)^2$. Here, the width a is extracted from the radial extent of the fluorescence spot corrected for the point spread function of the camera, $a = (a_{rad}^2 - a_{ax}^2)^{1/2}$. This results in a temperature of $188(\pm 40)\,\mu\mathrm{K}$, which is of the same order as the Cs Doppler temperature of $125\,\mu\mathrm{K}$.

3.3. Controlled motion of trapped atoms

We use the above method for continued observation of an atom during its controlled transport. The image sequence is recorded according to the following procedure. First, we check the presence of one atom in the MOT from the APD signal, and record a fluorescence image with an exposure time of 1 s. Then, the atom is transferred into the DT, the optical molasses is

switched on and the second picture is taken, again with 1 s exposure time. We then displace the atom by $2\,\mu$m within 2 ms and the next picture with 1 s exposure time is recorded. The sequence of displacement and imaging is repeated and yields a series of pictures of the same atom.

The movie corresponding to the screenshot in Fig. 3 shows a transport of a single atom over a distance of $60\,\mu$m within about one minute. The transport ends with the loss of the atom from the DT.
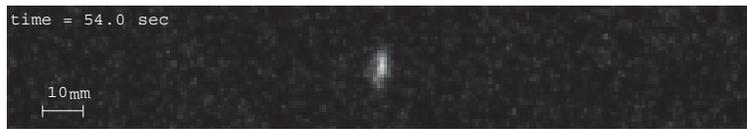

Fig. 3. (89 KB) Controlled transport of one neutral atom over a distance of $60\,\mu$m during some tens of seconds.

In the second movie, see Fig. 4, we show the synchronous transport of three spatially resolved atoms. The reversal of the transport direction was initiated by manually changing the sign of the relative detuning between the dipole trap laser beams. The stochastic nature of the loss mechanism results in random departure times of the atoms. The mean observation time before atom loss is of the order of 30 s. This time is close to the limit expected for loss due to background gas collisions [9, 10].

Fig. 4. (316 KB) Transport of three neutral atoms.

4. Summary

We have spatially resolved and continuously observed individual neutral atoms stored in a standing wave dipole trap. Our optical conveyor belt transports them over macroscopic distances with submicrometer precision. The combination of these two techniques allows us to continuously observe the controlled motion of the same atoms trapped in the dipole trap during several tens of seconds.

In future experiments we now aim at the control of the absolute position of the atoms in our dipole trap. This could be achieved by measuring the position of the atom using a CCD image and by then actively transporting the atom to a predetermined position. Such an absolute position control is essential for deterministically and reproducibly coupling one or more atoms to the mode of an optical high finesse resonator in order to realize elementary quantum logic operations in the framework of optical cavity quantum electrodynamics.