Cold atom gas at very high densities in an optical surface microtrap

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An optical microtrap is realized on a dielectric surface by crossing a tightly focused laser beam with an horizontal evanescent-wave atom mirror. The nondissipative trap is loaded with \(\sim 10^5\) cesium atoms through elastic collisions from a cold reservoir provided by a large-volume optical surface trap. With an observed 300-fold local increase of the atomic number density approaching \(10^{14}\) cm\(^{-3}\), unprecedented conditions of cold atoms close to a surface are realized.

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The trapping of cold atoms very close to material objects has attracted considerable interest \([1, 2, 3, 4, 5, 6, 7, 8, 9, 10]\) and opens up fascinating perspectives for a great variety of experiments ranging from fundamental studies of surface interactions to the realization of low-dimensional quantum gases to applications in the field of quantum information processing. Material structures that carry currents, produce electric fields, or transport light are the key to realize novel trapping configurations such as microtraps and integrated devices for atom optics. In this context a surface constitutes an interface that connects the atomic quantum system to the environment with the prospect of gaining control and enabling measurements on the quantum level.

For experiments in this research field, various surface trapping and guiding schemes have been devised: Magneto-optical traps near surfaces \([1, 3, 4]\), magnetic surface traps and guides \([1, 3, 4, 7]\), and optical dipole traps and guides \([1, 2]\) represent the three main classes. Very recently magnetic surface traps could be combined with Bose-Einstein condensates (BEC) \([3, 4, 10]\). While in present magnetic surface trapping schemes the atomic samples are still separated from the surface by typically a few ten \(\mu\)m, optical schemes \([1, 2, 11, 12]\) have already trapped atoms much closer to the surface with distances on the order of the optical wavelength and quasi-2D conditions have been attained in low-density samples. Optical surface trapping fields thus offer an intriguing potential for future nanotrap and guides based on integrated optical waveguides \([13]\).

In this Letter, we demonstrate a novel optical surface trap based on an evanescent-wave (EW) atom mirror in combination with a tightly focused red-detuned laser beam; see Fig. 1. This optical dipole trap confines atoms in a very small volume very close to a dielectric surface. Efficient loading through elastic collisions allows us to trap a large number of atoms from an optically precooled reservoir and thus to reach exceptionally high densities even with a classical gas. This scheme also opens up a possible new route for an all-optical production of a Bose-Einstein condensate \([14]\) with prospects for future experiments on quantum-degenerate gases near the surface.

The starting point for our experiments with cesium atoms is the “gravito-optical surface trap” \([1, 3, 4]\). This trap is realized under ultrahigh vacuum conditions \((p < 10^{-11}\) mbar\) by combining the EW atom mirror with a blue-detuned hollow beam (HB). The EW is produced with the 55-mW beam of a diode laser (SDL-5712-H1) in a nearly round spot with a \(1/e^2\)-radius of 0.65 mm on the surface of a fused-silica prism. The angle of incidence is about 2° above the critical angle of total internal reflection and the polarization lies in the plane of incidence. A heated cesium cell is used to filter resonant background light out of this beam \([11]\). The HB for horizontal confinement is derived from a Ti:Sapphire laser (Coherent 899-01/895) at a wavelength of 849 nm, i.e. with a detuning of about \(\sim 3\) nm from the 852-nm Cs resonance line. It is shaped with a special axicon optics \([15]\) to provide a two-dimensional cylindrical box potential. The HB has a total power of 330 mW, a diameter of 820 \(\mu\)m, and a potential height on the order of 100 \(\mu\)K. Typically \(2 \times 10^7\) atoms are initially loaded.
from a magneto-optical trap (MOT) operating a few mm above the surface. First, the optical detuning of the EW is set to 5 GHz to implement Sisyphus cooling by inelastic reflections [1]. After 5 s of optical cooling the EW detuning $\Delta \nu_{\text{EW}}$ is increased in a 2-s linear ramp to a large value in the range between 100 GHz and 200 GHz; this frequency ramp is accomplished by rapid temperature tuning of the laser diode. In this way a conservative trapping potential is realized with negligible photon scattering and heating below 100 nK/s. The large detuning also strongly reduces light-induced collisional loss in the blue-detuned trap light [2].

Our surface reservoir prepared in this way contains $2 \times 10^8$ Cs atoms at a temperature of $T \approx 3 \mu\text{K}$ at $\Delta \nu_{\text{EW}} = 160 \text{GHz}$. The vertical density distribution follows the barometric equation with a $1/e$-height of $\sim 20 \mu\text{m}$ [1] with a peak value close to the EW atom mirror of $2 \times 10^{13}\text{cm}^{-3}$. The peak phase-space density of the unpolarized sample in the $F = 3$ ground state is $\sim 2 \times 10^{-5}$, where we assume that the sample at low magnetic field ($\lesssim 5 \mu\text{T}$) is equally distributed over the seven magnetic substates. The elastic collision rate is of the order of $20 \text{s}^{-1}$, leading to a thermalization time of $\sim 0.5 \text{s}$. At the large EW detuning, the lifetime of the reservoir is limited to typically $1.5 \text{s}$. We believe that this is due to escape through weaker regions of the EW potential barrier in the Gaussian profile and at local surface defects. All measurements reported here are based on recapturing the atoms trapped on the EW atom mirror into the MOT. The number of atoms is determined from the integrated fluorescence detected with a carefully calibrated CCD camera. For the absolute atom number we estimate a calibration error below a factor of 1.5. The temperature is measured with a release-and-recapture method by turning off the EW for a short time interval and measuring the relative loss of atoms [3].

For implementing the surface microtrap we use the beam of a Nd:YAG laser at a wavelength of 1064 nm, which is focused right into the center of the cesium ensemble with a power of 330 mW and a waist of $w_0 = 32 \mu\text{m}$. There it produces a Gaussian-shaped horizontally attractive optical potential with a calculated depth of $U/k_B = 48 \mu\text{K}$ [11]. In a harmonic approximation to the trap center the oscillation frequency is $\omega_r = (4U/mw_0^2)^{1/2} = 2\pi \times 540 \text{Hz}$. After turning on the Nd:YAG beam, this additional narrow potential well is filled by thermalizing elastic collisions. Since the narrow well is deep compared with the temperature of the reservoir ($U/k_BT \approx 15$) a very large increase of the local density can be expected. After loading the Nd:YAG beam the reservoir can be removed by shutting down the HB. In this way, a very dense sample of atoms stored in the surface microtrap is realized.

This highly efficient collisional loading scheme plays a crucial role in our experiments as it leads to a drastic local increase of number and phase-space density. The basic idea of a local gain by adiabatically changing the potential shape was first pointed out in [17]. Our scheme is similar to the “dimple trap” described in [15] where an optical dipole trap was combined with a magnetic trap and a 50-fold increase in local phase-space density was reached. We believe that this mechanism also plays an important role for trap loading in the all-optical BEC experiment of Ref. [14], where two tightly focused CO$_2$-laser beams formed sort of a dipole in their crossing region. The efficient “dimple trick” may also find very interesting applications in context with degenerate Fermi gases as suggested in [18].

In order to study the collisional loading process we suddenly turn on the Nd:YAG beam after preparation of the reservoir with $\Delta \nu_{\text{EW}} = 120 \text{GHz}$ and $T \approx 4 \mu\text{K}$. The measured number of atoms loaded into the microtrap with increasing time is displayed in Fig. 2 together with the number of reservoir atoms. The latter is very well described by an exponential decay $N_{\text{res}} = N_{\text{res},0} \exp(-t/\tau_{\text{res}})$ with $N_{\text{res},0} = 3.5 \times 10^6$ and $\tau_{\text{res}} = 1.4 \text{s}$. At zero loading time, a sudden transfer puts an initial number of $4 \times 10^4$ atoms into the phase-space of the microtrap. This transfer of $\sim 1\%$ agrees very well with a calculation of the sudden transfer ratio. Thermalizing elastic collisions then fill the optical microtrap on the timescale of a few 100 ms and the trapped number of atoms reaches a maximum of $\sim 10^5$ after about 500 ms. The atomic ensemble in the microtrap then decays slower than the reservoir, which is due to the high EW potential barrier in the middle of the reservoir.

We can model the loading in a simple way by a differential equation for the number $N(t)$ of atoms in the microtrap,

$$\dot{N} = -\kappa N_{\text{res}}(N - a N_{\text{res}}) - b N^2.$$  

The loading model is based on the experimental facts that the temperature stays constant and that the microtrap does not significantly affect the reservoir. By intro-
ducing the parameter $a \ll 1$ we assume that thermalization tends to load a certain fraction of the reservoir atoms into the microtrap. The loading rate $\kappa N_{\text{res}}$ is assumed to be proportional to the elastic collision rate in the reservoir. For the loss out of the microtrap, we consider two-body collisions as the main mechanism. The loss coefficient is determined independently to $b = 7.2 \times 10^{-6}$ s$^{-1}$ by observing the decay in the absence of a reservoir ($N_{\text{res}} = 0$). A fit of $N(t)$ to the experimental loading data in Fig. 2 then yields $\kappa = 3.3 \times 10^{-7}$ s$^{-1}$ and $a = 0.08$. The resulting initial loading rate $\kappa N_{\text{res,0}} \approx 1$s$^{-1}$ is of the same order as thermalization rate of the reservoir. The parameter $a \approx 8\%$ indicates the thermal equilibrium from the potential assumption of thermal equilibrium from the potential distribution.

The loaded atom number can be maximized by turning on the Nd:YAG beam right after the optical cooling phase at the begin of the 2-s EW detuning ramp. When right after the ramp the HB is turned off and the reservoir atoms completely disappear after 200ms, we observe up to $N = 1.5 \times 10^5$ atoms in the microtrap.

The density distribution can be calculated under the assumption of thermal equilibrium from the potential shape and the measured temperature. The trap shape with its cylindrical symmetry is approximately harmonic in the two dimensions of the horizontal $x, y$-plane and has a one-dimensional wedge shape in the vertical $z$-direction. In such a potential the density distribution can be described by

$$n(r) = n_0 \exp(-\rho^2/\rho_0^2) \exp(-z/z_0)$$

where $\rho^2 = x^2 + y^2$. The $1/e$-decrease of the density is characterized by a horizontal radius $\rho_0 = \omega_t^{-1} \sqrt{2kB T/m}$ and a height $z_0 = k_B T/m g$; here $m$ denotes the mass of a Cs atom and $g$ represents the gravitational acceleration. With an effective volume defined as $V_0 = \pi \rho_0^2 z_0$, the peak number density $n_0$ is related to the trapped atom number and the effective volume by $n_0 = N/V_0$. Note that the mean density and the mean quadratic density in this trapping potential are related to the peak density by $\langle n \rangle = n_0/4$ and $\langle n^2 \rangle = n_0^2/9$.

The effective volume $V_0$ occupied in the microtrap depends on the horizontal trap frequency $\omega_t$ and the temperature $T$. Fig. 3 shows measurements of these two quantities. In (a) the calculated value of $\omega_t/2\pi = 540$ Hz is nicely confirmed. In (b) the temperature measurement shows $T = 2.9 \mu$K, obtained at $\Delta T_{\text{res}} = 160$ GHz. These measurements yield a horizontal $1/e$-radius $\rho_0 = 6.1 \mu$m, a 1/e-height $z_0 = 19 \mu$m and an effective volume of $V_0 = 22000 \mu$m$^3$. With $N = 1.5 \times 10^5$ atoms a peak density as high as $7 \times 10^{13}$ cm$^{-3}$ is obtained. This number is about 300 times higher as compared to our reservoir and thus the largest gain realized by loading a “dimple” is $15\%$. The attained density also clearly exceeds the maximum values reported for Cs in previous dipole trapping experiments [21, 22, 23]. The peak phase-space density for a fully unpolarized sample in $F = 3$ is calculated to $7 \times 10^{-3}$. The very high elastic collision rate in the dense sample exceeds 2 kHz and a posteriori justifies the assumption of a thermal equilibrium distribution.

In order to investigate trap loss at these high densities we have measured the number of stored atoms as a function of time. The corresponding experimental data are shown in Fig. 4. Trap loss can be described by $\dot{N}/N = -\alpha - \beta(n) - K_3(n^2)$, where $\alpha$ is a density-independent loss rate and the coefficients $\beta$ and $K_3$ characterize two-body and three-body inelastic trap loss. For our trap the mean density and mean quadratic density can be written as $\langle n \rangle = N/(4V_0)$ and $\langle n^2 \rangle = N^2/(9V_0^2)$, so that the loss equation yields a differential equation for $N(t)$. An attempt to fit the observed decay with $\alpha$, $\beta$, and $K_3$ as free parameters in addition to the initial particle number $N(t = 0)$ gives ambiguous results. We therefore vary $\alpha$ as an external parameter in a reasonable range ($\alpha \leq 0.1$ s$^{-1}$) and obtain good fit results for $\beta$ and $K_3$ (see solid line in Fig. 4). In this way we obtain

![Graph](image-url)
a two-body loss coefficient of \( \sim 5 \times 10^{-14} \text{cm}^3/\text{s} \) together with an upper bound for the three-body coefficient of \( K_3 \lesssim 3 \times 10^{-27} \text{cm}^6/\text{s} \). According to previous experiments [12], the value for \( \beta \) indeed corresponds to an expected loss coefficient for light-induced inelastic collisions in the field of the evanescent wave involving the excitation of repulsive molecular states. The upper bound for three-body loss appears to be surprisingly low regarding the resonant scattering properties of Cs [23].

In another series of experiments, we have tried to further increase the phase-space density by evaporative cooling. For this purpose, we have lowered the intensity of the Nd:YAG beam in an exponential ramp with variable time constants. An optimum result, obtained with a 400-ms ramp down to 10\% of the initial intensity is shown in Fig. 5. After 350\,ms of the ramp, with a potential depth reduced to \( \sim 7 \mu \text{K} \) the temperature reaches values slightly below 1\,\mu K as a result of combined adiabatic and evaporative cooling. With about \( 4 \times 10^4 \) atoms remaining, the phase-space density of the unpolarized gas in its seven magnetic substates reaches values slightly above \( 10^{-2} \). Further reduction of the intensity leads to increased loss, but not to lower temperatures. This indicates that evaporation under our conditions is limited by inelastic loss, which is being studied in more detail in ongoing experiments.

A very interesting further prospect would then be to load the dense gas into a two-dimensional trap formed by two evanescent waves [22] and to study the properties of a two-dimensional surface gas of Cs atoms with their large and tunable interactions.

In summary, by loading an optical surface microtrap through elastic collisions from a reservoir we have locally increased the number and phase-space density by a factor of up to 300. This demonstrates a very efficient and universal loading scheme for nondissipative microtraps or future nanotrapping schemes at surfaces. Moreover it opens up new possibilities to create a degenerate gas of Cs atoms and to create a two-dimensional surface quantum gas with tunable interactions.

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