Surface Trap for Cs atoms based on Evanescent-Wave Cooling

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(Received 20 June 1997)

We demonstrate a gravito-optical surface trap for Cs atoms which exploits cooling in an evanescent light wave. About 10^5 atoms were cooled down to 3 μK and formed a sample with a mean height of $\sim$20 μm above the surface of a dielectric prism. The trap does not use a magnetic field and leads to very small atomic level perturbations. The excited-state population of the stored atoms is $\sim 1.5 \times 10^{-6}$ and collisional losses are strongly suppressed. [S0031-9007(97)04024-6]

PACS numbers: 32.80.Pj, 42.50.Vk

The specular reflection of atoms from an evanescent light wave (EW), originally suggested by Cook and Hill in 1982 [1] and first observed in 1987 [2], has attracted great interest to realize mirrors, resonators, and waveguides for atoms [3].

Efforts to confine the motion of atoms with the help of EW mirrors have so far focused on the conservative, i.e., *nondissipative* or coherent case, motivated by the possibility to construct matter-wave resonators [4,5]. Important experimental steps have been made with the observation of cold atoms bouncing in the field of gravity on a flat EW mirror [6] and with the demonstration of the confinement of atoms in a gravito-optical cavity based on a curved EW [7].

Recent work has shown that the reflection of atoms from an EW can also act in a *dissipative* way [8–12]: Inelastic reflection processes can efficiently extract energy from the atomic motion which opens a way to cool atoms in novel gravito-optical traps with the prospect to obtain very dense samples [9,10]. Experimentally, single cooling EW reflection processes were studied with a thermal Na atomic beam at grazing incidence [11] and with a cold ensemble of Cs atoms dropped onto the EW at normal incidence [12].

In this Letter, we present a novel gravito-optical surface trap (GOST) in which we use EW cooling to store an ensemble of Cs atoms closely above a flat dielectric surface. In our trap, schematically shown in Fig. 1, horizontal confinement is provided by the conservative optical dipole potential of a hollow, cylindrical laser beam, far blue detuned from the atomic resonance.

The EW cooling mechanism in the GOST is based on the splitting of the $^2S_{1/2}$ ground state of Cs into two hyperfine sublevels with $F = 3, 4$. Because of the much smaller hyperfine splitting of the excited $^2P_{3/2}$ state, we can model the atom as a three-level scheme [10] with two ground states separated by $\delta_{\mathrm{hfs}}/2\pi = 9.2$ GHz and one excited state. The EW is linearly polarized and tuned to the blue side of both transitions with corresponding frequency detunings $\delta_F = \delta_{\mathrm{ew}}$ (for $F = 3$) and $\delta_F = \delta_{\mathrm{ew}} + \delta_{\mathrm{hfs}}$ (for $F = 4$). The interaction with the EW leads to light shifts of the atomic levels and thus results in repulsive ground-state potentials for the atomic motion

$$U_F(z) = \frac{\Gamma}{\delta_F} \frac{\lambda^3}{8\pi^2 c} I_0 \exp(-2z/\Lambda), \qquad (1)$$

which depend on the distance z from the surface and the hyperfine state F, but not on the particular magnetic substate [10]. Here $\Gamma = 2\pi \times 5.3$ MHz and $\lambda = 852$ nm denote the natural linewidth and the wavelength of the optical transition, and I_0 and Λ represent the maximum intensity and the decay length of the EW.

As inelastic reflection takes place when the atom enters the EW in the $F = 3$ state and, by scattering an EW photon during the reflection process, is pumped into the less repulsive $F = 4$ state. In such a spontaneous transition the potential energy is reduced according to the ratio of the detunings by $\delta_{\mathrm{ew}}/(\delta_{\mathrm{ew}} + \delta_{\mathrm{hfs}})$ and the atom loses energy in an elementary "Sisyphus" process [9–12]. The mean energy loss $\Delta E_\perp$ from the motion perpendicular to the surface per inelastic reflection is found to be $\Delta E_\perp / E_\perp = -\frac{2}{3}\delta_{\mathrm{hfs}}/(\delta_{\mathrm{ew}} + \delta_{\mathrm{hfs}})$, where $E_\perp = m v_\perp^2/2$ is the kinetic energy of the incoming atom. The probability for spontaneously scattering an EW photon during the reflection is given by $p_{\mathrm{sp}} = m\Lambda\Gamma v_\perp/\hbar\delta_{\mathrm{ew}}$ as far as $p_{\mathrm{sp}} \ll 1$; here m denotes the atomic mass. With the branching ratio $q = 0.25$ of the excited state to the $F = 4$ ground state, the probability for

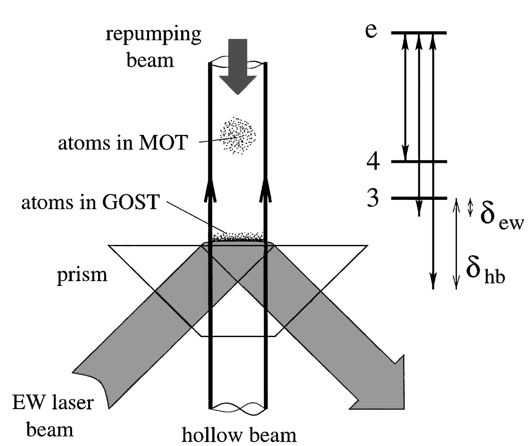

FIG. 1. Illustration of the gravito-optical surface trap.

a cooling reflection is $p_{\mathrm{cool}} = q p_{\mathrm{sp}}$. The cooling cycle can be closed by repumping the atom into the $F = 3$ state shortly after the reflection. An atom repeatedly bouncing in the field of gravity on a horizontal surface with a time $t_{\mathrm{r}} = 2v_{\perp}/g$ between two successive reflections then loses its vertical kinetic energy with an average rate

$$\beta = p_{\mathrm{cool}} \frac{\Delta E_{\perp}}{E_{\perp}} t_{\mathrm{r}}^{-1} = \frac{q}{3} \frac{\delta_{\mathrm{hfs}}}{\delta_{\mathrm{ew}}} \frac{mg\Lambda}{\hbar(\delta_{\mathrm{ew}} + \delta_{\mathrm{hfs}})} \Gamma . \quad (2)$$

An additional cooling is caused by the average momentum transfer of $1.5\hbar k$ in the repumping process, if the repumping beam is directed downward [10]. The final temperature attainable with EW cooling is recoil limited to a value of the order of $10\hbar^2 k^2/mk_B \approx 2\ \mu\mathrm{K}$ [10], similar to an optical molasses [13].

The EW that forms the bottom of the GOST (see Fig. 1) is produced on the flat horizontal surface of a fused-silica prism by total internal reflection of the 60-mW beam delivered by a laser diode (SDL-5712-H1). The diameter of the nearly round, Gaussian-shaped EW spot on the surface is 950 μm ($1/e$ intensity drop); the EW polarization is linear and perpendicular to the plane of incidence. For the angle of incidence of $\theta = 49.2°$ and the refractive index of $n = 1.45$, we calculate an EW decay length of $\Lambda = \lambda/2\pi[n^2 \sin^2(\theta) - 1]^{-1/2} = 0.30\ \mu\mathrm{m}$ and a peak intensity of $I_0 = 2.9 \times 10^4\ \mathrm{mW/cm^2}$. We set the detuning to $\delta_{\mathrm{ew}}/2\pi = (1.0 \pm 0.1)$ GHz, which leads to optical potentials in the center of the EW spot with $U_3(0)/k_B \simeq 2.9$ mK and $U_4(0)/k_B \simeq 280\ \mu\mathrm{K}$. The influence of the van-der-Waals attraction [12,14] reduces the potential barriers to about 1.8 mK and 110 μK, respectively, but has only a minor effect on the cooling dynamics.

The upward directed hollow beam (HB) used for horizontal confinement in the GOST is produced by imaging the 300-mW output of a Ti:Sapph laser with a spherical lens (achromatic-doublett, focal length 100 mm) in combination with an *axicon* lens [15] (conical glass substrate, base angle 10 mrad). By this means we obtain a ring-shaped focus with an inner and outer $1/e$ diameter of 700 and 750 μm, respectively. In order to clean the inner region of the HB from scattered and diffracted light, we place a 650 μm "dark spot" right into the center of the ring-shaped focus, which we then image with a 150-mm achromatic doublett one to one onto the prism surface. The HB contains a total power of 120 mW and is far detuned by about 0.3 nm, corresponding to $\delta_{\mathrm{hb}}/2\pi \approx 100$ GHz. In the whole central region imaging the dark spot, the HB contains far less than 1 mW. The potential barrier provided by the HB amounts to $U_{\mathrm{hb}}/k_B \approx 100\ \mu\mathrm{K}$.

The GOST is loaded from a standard magneto-optical trap (MOT), which is placed right into the center of the HB about 800 μm above the prism surface. The MOT is operated with two diode lasers generating the two frequencies needed for cooling and trapping ($F = 4 \rightarrow F' = 5$) and repumping ($F = 3 \rightarrow F' = 4$). The MOT beams have a diameter of $\sim$1 cm and a central intensity of $\sim$7 mW/cm^2. One pair of the MOT beams is aligned parallel to the surface, the two other mutually orthogonal pairs pass through the surface under an angle of $\pm 45°$. The MOT is loaded from the low-velocity tail of an effusive Cs atomic beam. In accordance with [16] we observe that, under stationary conditions, the proximity of the surface leads to an about four times reduced number of trapped atoms.

After capturing $\sim 3 \times 10^5$ atoms within 1.5 s, we switch the MOT detuning from -2Γ to -10Γ to cool the atoms down to $\sim$12 μK. After further 20 ms we mechanically shutter the MOT beams and switch off the magnetic field and thus release the atoms into the GOST, for which all the necessary three laser beams are switched on by means of acousto-optical modulators. The downward directed GOST repumping beam (diameter 2 mm, power 50 μW) is derived from the main MOT laser field through a -240 MHz acousto-optical frequency shift and is thus tuned about 7 Γ below the $F = 4 \rightarrow F' = 4$ transition.

In a first, qualitative experiment we detected the atoms in the GOST by fluorescence imaging with a slow-scan CCD camera. As the fluorescence induced by this trap itself is extremely weak, we turned on the MOT beams (without magnetic field) for a short 5-ms interval after the GOST was active for 1 s. Figure 2 shows a combined picture of atoms in the GOST (central spot) together with a MOT image (upper spot) taken before the transfer into the GOST. The mirror image of the MOT from the dielectric surface (lower spot) allows us to determine the relevant location of the surface (dashed line). One clearly sees that the atoms cooled in the GOST are collected in close vicinity of the surface.

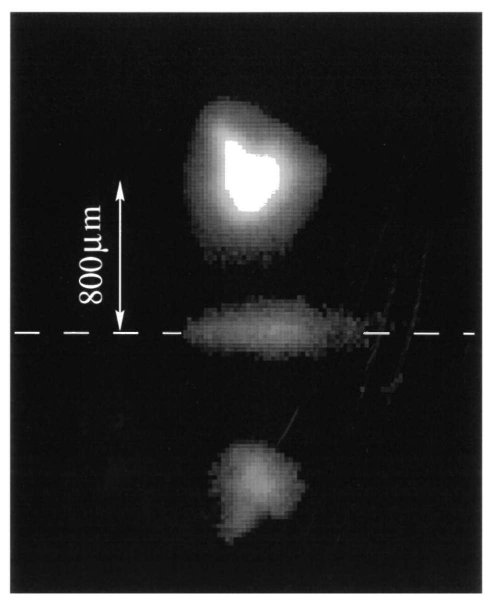

FIG. 2. Combined fluorescence images of atoms in the GOST and in the MOT taken by a CCD camera with its optical axis at a small angle of $\sim 5°$ with respect to the surface. Upper spot, MOT; middle spot, GOST; lower spot, mirror image of the MOT. The dashed line indicates the surface.

We measured the lifetime of atoms in the GOST by recapturing them into the MOT after a variable time. As the atomic beam is blocked and loading from the Cs background gas in our vacuum chamber is negligible, no atoms other than the ones from the GOST are recaptured. Therefore the integrated MOT fluorescence after recapture normalized to the one before release into the GOST is a precise measure for the number N of atoms in the GOST relative to the initial number $N_0 \approx 3 \times 10^5$ released into it. Figure 3 shows the results that we obtained in this way for two different values of the rest gas pressure in our apparatus ($p = 4.2 \times 10^{-10}$ mbar and 7.6×10^{-10} mbar). After $\sim 1s$ the decay is found to be exponential with $1/e$ lifetimes of (6.0 ± 0.1) s and (3.2 ± 0.1) s respectively. These results suggest that, besides small transfer losses of ~30% observed in the first second, losses from the GOST are essentially due to rest gas collisions.

For measuring the vertical and horizontal temperatures T_v and T_h in the GOST, we use a time-of-flight method. We switch off either the EW or the HB for a short time interval Δt_{ew} or Δt_{hb}, respectively, a few 100 ms before the recapture into the MOT takes place. This leads to an additional loss of atoms from the GOST either by hitting the prism surface ($\Delta t_{\mathrm{ew}} \neq 0$) or by escaping horizontally out of the trap ($\Delta t_{\mathrm{hb}} \neq 0$). With the assumption of a Boltzmann distribution in phase space and a free ballistic flight, it is straightforward to calculate the number of remaining atoms as a function of Δt_{ew} or Δt_{hb}. A fit to the experimental data then yields the vertical and horizontal temperature. Figures 4(a) and 4(b) show an example for such a pair of measurements of T_v and T_h, which was made after 4 s of storage and cooling in the GOST. We find that the assumption of a Boltzmann distribution fits always very well to the experimental data points.

The vertical measurement displayed in Fig. 4(a) yields $T_v = (3.0 \pm 0.1)\ \mu$K. At this low temperature the mean time between two bounces is 2.2 ms, corresponding to 450 bounces per second. The mean probability for an incoherent bound is $p_{\mathrm{sp}} = 3.5\%$ and thus for a cooling bounce $p_{\mathrm{cool}} = 0.9\%$. According to the Boltzmann distribution, the vertical dependence of the atomic density obeys the barometric equation $n(z) = n_0 \exp(-mgz/k_B T_v)$ outside of the EW potential ($z \gtrsim \lambda$). In our case the $1/e$ height is as low as $k_B T_v/mg = 19\ \mu$m.

The horizontal measurement shown in Fig. 4(b) yields a temperature $T_h = (3.1 \pm 0.3)\ \mu$K, which is equal to the vertical one within the experimental uncertainty. As the anisotropic EW cooling mechanism is expected to act only upon the vertical motion, this surprising observation of equal temperatures in the GOST indicates the presence of a substantial coupling mechanism between the vertical and horizontal motion.

In order to study the cooling dynamics, we have performed a series of measurements on the temperatures T_v and T_h as a function of the storage time in the GOST; the results are shown in Fig. 5. The initial conditions, $T_h(0) = 12\ \mu$K and $T_v(0) \approx 90\ \mu$K, are set by the temperature and height of the MOT. We observe that the vertical temperature drops rapidly and reaches ~ 5 μK within only 1 s. Then it approaches the steady state of ~3 μK within a few more seconds. The horizontal temperature first shows a slight increase for $t < 500$ ms when T_v still exceeds T_h. Then, within about 2 s, the horizontal motion cools down toward its steady state close to the vertical temperature. These measurements clearly show the influence of a horizontal-vertical coupling.

As a possible cause for this coupling, we could rule out a significant effect of elastic Cs-Cs collisions in additional experiments with about ten times less atoms, which showed essentially the same behavior as in Fig. 5. We believe that the diffusive EW reflection recently observed in [17] is responsible for the coupling. We studied this mechanism in Monte Carlo simulations of the EW cooled atomic motion, in which we assumed each bounce to deviate by a random rms angle ϕ_{diff} from specularity. We obtained satisfying agreement with the experimental observations for a diffusive angle of $\phi_{\mathrm{diff}} = 80$ mrad (see solid line in Fig. 5) which, for the standard $\lambda/10$ polishing of our prism, is consistent with the observations reported in [17].

In our theoretical fit to the experimental data of Fig. 5 we kept the EW cooling rate β and a horizontal and vertical heating rate as free parameters. In agreement with

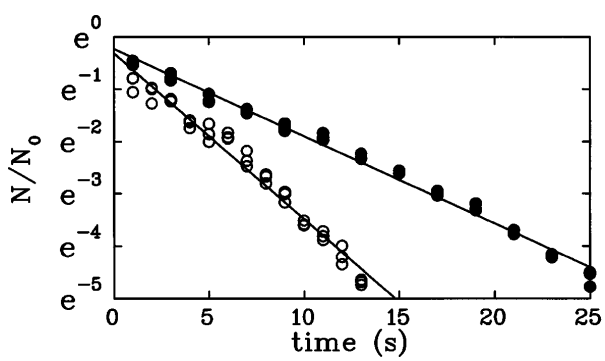

FIG. 3. Number of atoms in the GOST as function of storage time at a rest gas pressure of 4.2×10^{-10} mbar (•) and 7.6×10^{-10} mbar (∘). The solid lines are exponential fits.

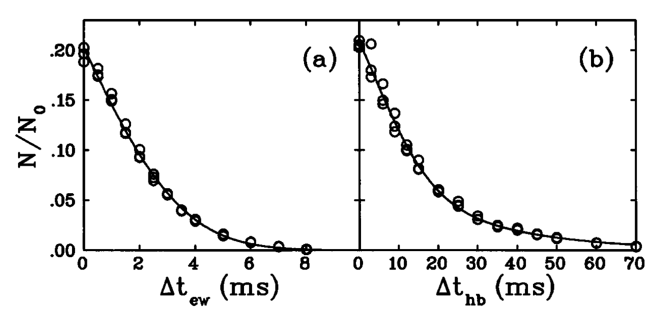

FIG. 4. Time-of-flight measurements of the vertical (a) and horizontal (b) temperature in the GOST after a 4-s storage.

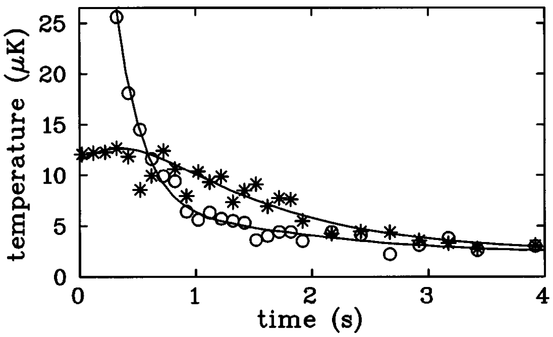

FIG. 5. Temporal evolution of the vertical (∘) and horizontal (∗) temperature in the GOST. The solid line is a fit according to the theoretical model described in text.

Eq. (2) predicting $1/\beta = (400 \pm 40)$ ms, the fit result is $1/\beta = (380 \pm 20)$ ms. For the total heating the fit gives $\sim 6\ \mu\mathrm{K\,s^{-1}}$, which is about a factor of two higher than predicted by EW cooling theory [10]. We found that the scattering of photons from the HB contributes to this additional heating, but there may be also other causes like intensity fluctuations of the laser fields or residual magnetic fields. For the heating rates we can estimate an upper bound for the total photon scattering rate in the GOST, which is $\lesssim 50$ photons per atom and second.

An important quantity for applications of optical traps in high-resolution spectroscopy, as discussed in [18], is the mean light shift experienced by the atoms. In the case of atoms bouncing in a gravito-optical trap, one can derive the simple expression $\delta\nu_s = mg\Lambda/4\pi\hbar$ for the time-averaged shift, which for our conditions in the GOST gives $\delta\nu_s \approx 500$ Hz.

Under our present loading conditions, we obtain number densities n_0 of up to about $2 \times 10^{10}\ \mathrm{cm^{-3}}$ at a temperature of 3 μK corresponding to a mean sample height of 19 μm. This gives a maximum phase-space density of $n_0\,(2\pi\hbar^2/mk_BT)^{3/2} \approx 1.3 \times 10^{-5}$, which is similar to the values obtained in an optimized Cs MOT [19]; the elastic collision rate is estimated to be of the order of $1\ \mathrm{s^{-1}}$. Much higher number and phase-space densities in the GOST can be obtained in a straightforward way by increasing the number of atoms provided by the MOT. Here a factor of 100 or even much more is attainable with a high-flux, laser-decelerated atomic beam [20]. With such an improved loading, the GOST offers an enormous potential for future experiments at much higher densities because losses by hyperfine-changing and excited state collisions are dramatically suppressed as compared to a MOT [10]. From our results we estimate the fraction of atoms in the upper hyperfine state to be in the range of 10^{-4}–10^{-5}, and the fraction in the optically excited state to be as low as $\sim 1.5 \times 10^{-6}$.

In future experiments, we plan to explore the possibility of evaporative cooling [21] in a far-detuned version of the GOST by lowering the optical trap potentials. We furthermore intend to use the GOST as a starting point for loading two-dimensional optical traps [22–24] and to study the collision dynamics in such a system of reduced dimensionality. Moreover, we plan to investigate possible applications of the GOST for high-resolution spectroscopy of optical and radio-frequency transitions.

We wish to thank J. Söding for stimulating discussions and for his contributions in the early stage of the experiments and D. Schwalm for encouragement and support. Yu.B O. gratefully acknowledges a fellowship by the Alexander von Humboldt Stiftung. This work was supported by the Deutsche Forschungsgemeinschaft in the frame of the Gerhard-Hess-Programm.

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