Evaporative cooling of cesium atoms in the gravito-optical surface trap

M. Hammes, D. Rychtarik, and R. Grimm
Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria
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We report on cooling of an atomic cesium gas closely above an evanescent-wave atom mirror. Our first evaporation experiments show a temperature reduction from 10 µK down to 300 nK along with a gain in phase-space density of almost two orders of magnitude. In a series of measurements of heating and spin depolarization an incoherent background of resonant photons in the evanescent-wave diode laser light was found to be the limiting factor at this stage.

I. INTRODUCTION

Optical dipole traps based on far-detuned laser light have become very popular as versatile tools for experiments on ultracold atomic gases in an almost dissipation-free environment \cite{1}. In our experiments, we use the \textit{gravito-optical surface trap} (GOST) \cite{2} to produce an ultracold sample of cesium atoms on an evanescent-wave atom mirror with the prospect to study a two-dimensional atomic gas at high phase-space densities.

Atomic cesium is a candidate of particular interest because of its resonant scattering properties. In the lowest Zeeman-substate, a low-field Feshbach resonance \cite{3} facilitates convenient magnetic tuning of the \textit{s}-wave scattering length from zero to very large positive or negative values. For low-dimensional atomic systems, a scattering length exceeding the extension of the ground-state wavefunction in one or more dimensions constitutes an intriguing system \cite{4, 5}.

Here, after summarizing the basic properties of the trap (Sec.II), we report our first experiments demonstrating evaporative cooling of atoms in the GOST (Sec.III). This important step to attain a two-dimensional gas at high phase-space densities is achieved by ramping down the optical trapping potentials. The current limitations imposed by heating in the GOST are investigated (Sec.IV), and the prospects of future experiments are discussed (Sec.V).

II. GRAVITO-OPTICAL SURFACE TRAP

A schematic overview of the geometry of the trap is given in figure \[\text{fig:1}\]. The GOST is an “optical mug”, whose bottom consists of an evanescent-wave (EW) atom mirror generated by total internal reflection of a blue-detuned laser beam from the surface of a prism, while the walls are formed by an intense hollow beam (HB) which passes vertically through the prism surface.

The steep exponential decay of the EW intensity along the vertical direction and the sharp focussing of the hollow beam lead to large intensity gradients and thus in combination with the blue detuning of both light fields to a strong repulsive dipole force. We exploit this fact to efficiently keep the atoms in the dark inner region of the trap where the unwanted effect of heating through scattering of trapping light photons is suppressed. In addition to that, the concept also features a large trapping volume which allows for a transfer of a large number of atoms into the GOST. Due to the accurate focussing of the hollow laser beam into a ring-shaped intensity profile \[\text{fig:2}\], the shape of the potential is box-like along the horizontal directions whereas the combination of gravity and the repulsive wall of the EW leads to a wedge-shaped potential vertically.

The experimental constituents of the GOST are the EW diode laser (SDL-5712-H1, distributed Bragg reflector), a titanium:sapphire laser to create the hollow beam and an additional diode laser to provide the light for the repumping beam. The EW laser is reflected from the prism surface at an angle of $\theta = 45.6^\circ$ (2° above the critical angle), has a power of 45 mW, a 1/e$^2$-radius of 540 µm and initially a detuning of $\delta_{ew}/2\pi = 3$ GHz with respect to the D$_2$-line. This leads to a 1/e$^2$-decay length of $\Lambda \approx 500$ nm and a repulsive optical potential barrier with a height of $\sim 1$ mK. This is further reduced to about half of this value by the attractive van-der-Waals interaction between the atoms and the dielectric surface \[\text{fig:3}\].
The hollow beam is generated using an axicon optics to create a ring-shaped focus of an inner and outer 1/e-radius of $r_{HB} = 260 \mu m$ and $r_{HB} + \Delta r_{HB} = 290 \mu m$, respectively. It has a power of 350 mW and its detuning is in the range between $-0.3$ nm and $-2$ nm. The HB provides a potential barrier on the order of 100 $\mu$K height.

The weak repumping beam needed for the optical Sisyphus cooling is resonant with the $F = 4 \rightarrow F' = 4$ hyperfine transition of the $D_2$-line and has an intensity on the order of 1 $\mu$W/cm$^2$. It is shown on the trapping region from above.

About $2 \times 10^7$ atoms are loaded into the GOST from a standard magneto-optical trap in a scheme which includes compression and precooling to $\sim 10 \mu$K. Details on loading and other experimental procedures can be found in [9].

### III. EVAPORATIVE COOLING

The GOST offers favorable conditions to implement forced evaporative cooling. In contrast to red-detuned dipole traps used for evaporation experiments [3, 6], the spatial compression of the cold sample essentially results from gravity and is thus not affected when the optical potentials are ramped down. Moreover, many more atoms are initially loaded into the GOST as compared to typical red-detuned traps. Here we describe our first experiments demonstrating the feasibility of efficient evaporation in the GOST.

The trap is operated at a HB detuning of $-1$ nm. With an EW detuning initially set to a few GHz, Sisyphus cooling provides $N = 10^7$ atoms at a temperature of $T = 10 \mu$K, and a peak density of $n_0 = 6 \times 10^{11}$ cm$^{-3}$ [6]. For the unpolarized sample in the seven-fold degenerate $F = 3$ ground state this corresponds to a peak phase-space density of $D = n_0 \lambda^3_{HB}/7 \approx 10^{-5}$ where $\lambda_{HB} = h/2\pi mk_BT$ is the thermal de-Broglie wavelength. Elastic collisions take place at a rate on the order of 50 s$^{-1}$ and, considering the resonant scattering of cesium [10, 11], lead to a thermalization time of about 200 ms.

To implement forced evaporation we lower the EW potential by ramping up the HB detuning. This simultaneously reduces heating due to photon scattering and suppresses loss through inelastic collisions in the presence of blue-detuned light [6]. Within 4.5 seconds the EW detuning is increased exponentially from initially 7 GHz up to 250 GHz. This is accomplished by rapid mode-hop-free temperature tuning of the EW diode laser. In the last 2.5 seconds of the ramp the evaporation ramp the intensity of the hollow beam is reduced from 350 mW to 11 mW in order to reduce possible heating by residual light in the dark center of the hollow beam. The contribution of the HB potential ramp to the evaporation remains very small.

The experimental results are shown in figure 2.[a] About 1 s after starting the exponential ramp, the temperature begins to drop [filled squares in (a)]. At the end of the ramp, it has reached $T \approx 300 \mu$K. This decrease of $T$ by about 1.5 orders of magnitude is accompanied by a decrease of the particle number $N$ [open triangles in (a)] from $10^7$ down to $\sim 3 \times 10^6$, i.e. about 2.5 orders of magnitude.

Although the number density $n_0 \propto N/T$ [open circles in (b)] decreases by about one order of magnitude, the phase-space density $D \propto n_0 T^{-3/2} \propto N T^{-5/2}$ [filled squares in (b)] shows a substantial increase by 1.5 orders of magnitude. At the end of the ramp, we obtain a phase-space density of $\sim 3 \times 10^{-4}$.

In the regime of resonant elastic scattering ($T \gtrsim 1 \mu$K [11]), the relevant cross section scales $\propto T^{-1}$. In the GOST potential, this leads to a scaling of the elastic scattering rate and the thermal relaxation rate $\propto N T^{-3/2}$. Therefore the elastic scattering rate is almost constant for the conditions of our experiments. However, no runaway regime is reached.

An obvious problem in this evaporation scheme is that, for the applied exponential ramp, it takes about one second until the EW potential barrier becomes low enough to start the evaporation. Up to this point already about 50% of the particles are lost, presumably by the collisional mechanism investigated in reference [6]. After the corresponding initial loss of phase-space density the later
evaporation then leads to a gain of almost two orders of magnitude. This already shows that the potential of evaporative cooling in the GOST is much larger than we could demonstrate in these first experiments.

IV. HEATING

In order to understand the limitations of the evaporation, we have investigated heating in the GOST. To get quantitative results a measurement scheme has to be applied in which the average energy per atom is much smaller than the potential barriers of the trap. That way one can exclude any effects of evaporation which otherwise would influence the measurement. Lowering its power by a factor of eight to 40 nW during the first four seconds after the transfer leads to a strong horizontal energy selection in the sample and thus cooled the remaining $5 \times 10^5$ atoms down to about 3 $\mu$K. To measure heating without any significant energy selection the HB power is then switched back to its original value satisfying the condition $U_{hb} \geq 10k_BT$.

To determine the heating rate, temperature measurements are performed at various times after the HB power is restored. During this stage the EW detuning is constantly kept at $\delta_{ew}/2\pi = 20$ GHz as a compromise to prevent any significant optical cooling effects while still keeping the EW potential high enough for evaporation not to occur. Figure 3 shows a typical temperature evolution measurement and the linear fit curve which yields a heating rate of $\sim 700$ nK/s.

To calculate the expected heating rate, the mean photon scattering rate of an atom bouncing on an EW mirror has to be multiplied with the temperature increase associated with one scattering event. For a two-level atom the mean scattering rate is given by Eq. (1)

$$\Gamma_{sc} = \frac{mg\Delta\Gamma}{2\hbar\delta_{ew}},$$

yielding $\sim 1.2 s^{-1}$ under our experimental conditions. In the geometry of the GOST one scattered photon leads to a heating of $(2/5)\hbar^2 k^2/2m = k_B \times 80$ nK. In combination with the above scattering rate this would lead to a heating rate of about 100 nK/s. However, in the case of cesium atoms with their hyperfine splitting and the repumping laser applied to keep the atoms in the $F = 3$ state, heating by photon scattering is about twice this value, so that we can expect a heating rate of $\sim 200$ nK/s. This falls short of the experimental result by about a factor of three.

In order to investigate the possibility that a background of resonant photons in the EW light causes this discrepancy between calculation and measurement, we have used a cesium vapor cell heated to 50°C to filter resonant light out of the EW beam. The open circles in figure 3 indicate the resulting temperature evolution with a slope of 240 nK/s, which is now indeed consistent with the expected heating rate. This strongly supports our assumption that the problem of heating is mainly due to an incoherent background of resonant photons. In contrast to the case without a filtering cell, we now also find the residual heating rate to strongly depend on HB and EW detunings. By tuning the evanescent wave to 40 GHz and the hollow beam to 1 nm heating rates as low as 130 nK/s were observed.

To further investigate the consequences of photon scattering, we removed the filtering cesium cell and measured the depolarization of the ground-state hyperfine population as a function of time. As long as the repumping beam of the GOST is switched on essentially all atoms remain in the $F = 3$ ground state. Without the repumping beam the sample gradually depolarizes and atoms are transferred into the $F = 4$ state due to spontaneous Raman scattering.

To get information on the time constant of the depolarization we use the same procedure as before to prepare the sample at a temperature of 3 $\mu$K and then switch off the repumping beam. After various time intervals a 30 ms lasting light pulse of resonant $F = 4 \rightarrow F' = 5$ light illuminates the sample and pushes all atoms in the $F = 4$ state out of the trap. Measuring the number of remaining atoms then yields the population of the $F = 3$ ground state. Figure 4 shows the ground state population normalized to the case without a resonant pulse as a function of time.

A photon scattering rate of $\sim 5 s^{-1}$ can be deduced from the depolarization rate of the ground-state hyperfine population. With the repumper present this corresponds to a heating of about 800 nK/s. This again supports our assumption that the observed heating can essentially be attributed to photon scattering from a very small, but detrimental fraction of resonant photons present in the EW light.

To investigate the origin of the resonant photons, we measured the steady-state ground state population after three seconds of depolarization time as a function of the EW detuning $\delta_{ew}$. Figure 5 shows the striking result of...
FIG. 4: Relative population of the $F=3$ state versus time. From the decay time of 0.47 seconds and the branching ratios for optical hyperfine pumping we infer a photon scattering rate of 4.8 photons/s.

this experiment. The $F = 3$ state population exhibits a resonance-like behavior and takes a value close to 100% at an EW detuning of $\delta_{ew}/2\pi = 27$ GHz and vanishes at $\delta_{ew}/2\pi \approx 36$ GHz. We interpret this as the effect of amplified spontaneous emission of photons into non-lasing side modes of the diode laser cavity (mode spacing $\sim 36$ GHz). As the side mode is tuned in resonance with the optical transition from the upper state this leads to an efficient repumping into the $F = 3$ ground state and thus to a relative population of almost one whereas in the opposite case of a resonance with the optical transition from the $F = 3$ state is depleted by the resonant photons.

FIG. 5: Measured population of the $F = 3$ ground state after three seconds depolarization time as a function of the detuning of diode laser that provides the evanescent-wave light. The surprising dependence is explained by a amplified spontaneous photons in a non-lasing side mode of the diode laser leading to hyperfine pumping.

The presence of the side modes obviously constitutes a severe problem for evaporation by ramping up the EW detuning. If a periodic comb of side modes with a spacing of 36 GHz is present during the EW detuning ramp over 250 GHz, this leads to several successive coincidences between side modes and the atomic transition and thus repeatedly to strong heating. This behavior easily explains the limited efficiency of evaporation as reported in the preceding section.

V. CONCLUSIONS AND OUTLOOK

Our experiments demonstrate evaporative cooling in the gravito-optical surface trap. A gain in phase-space density of almost a factor of 100 was achieved by ramping up the evanescent-wave detuning. The maximum phase-space density obtained in these experiments was $\sim 3 \times 10^{-4}$ at a temperature of about 300 nK.

As the limiting factor we have identified heating by scattering of resonant photons contained in the diode-laser light used for the evanescent wave. Even though the lasing mode of the diode laser is detuned far enough, amplified spontaneous emission in non-lasing side modes lead to significant heating. An easy remedy to this problem is the use of a cesium absorption cell to filter out these photons. First experiments have indeed shown a substantial reduction of heating with such a cell.

In other experiments not reported here we have also found strong indications that at low EW potentials the lifetime of the trapped sample is severely limited by surface defects of our prism. The performance of the GOST then strongly depends on the exact position on the prism surface. Therefore we are now preparing a new set-up featuring a superpolished high-quality fused-silica prism.

At the lowest temperatures that we have obtained the atoms bounce on the prism surface with a mean height as low as $\sim 2 \mu$m. In this case, the mean quantum number of the vertical motion is already quite small (about five to ten). Thus the cold surface gas is not far from conditions under which the vertical motion will freeze out and the system will acquire two-dimensional character. With optimized evaporative cooling, the above improvements, and the further option to enhance the anisotropic character of the trap by using a second evanescent wave \cite{[14]}, a two-dimensional quantum gas in the GOST with tunable interactions seems to be in experimental reach.

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