Cold-atom accumulation using an optical trap door

H. J. Davies, K. Szymaniec, and C. S. Adams
Department of Physics, Durham University, South Road, Durham DH1 3LE, United Kingdom
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Experiments are performed on loading cold atoms into a far-off resonance optical dipole trap that is spatially separated from the laser-cooling region. The atoms are delivered using a far-off resonant optical dipole guide and enter the trap through a switchable blue-detuned light sheet or ''trap door.'' This scheme provides a means to transfer atoms from a dissipative to a non-dissipative trap without a significant loss of phase-space density. We study the dynamics of atoms within the trap and measure their lifetime. Preliminary results on multiple loading are presented. As the technique does not rely on near-resonant light, the atom number limit characteristic of laser-cooling experiments can, in principle, be exceeded.

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I. INTRODUCTION

The field of laser cooling and trapping of neutral atoms has achieved staggering progress during the last two decades [1]. The standard building block of laser-cooling experiments is the magneto-optical trap (MOT). However, despite its utility, a possible drawback is that the number of trapped atoms is limited to $\sim 10^{10}$, mainly due to loss mechanisms caused by near-resonant light [2]. In many experiments, e.g., precision measurement or Bose-Einstein condensation, far larger atom numbers would be desirable. To overcome this number limit, a trap-loading mechanism that does not involve near-resonant light is required. One example is ''evaporative'' or ''buffer gas'' loading that has been shown to work effectively using a cryogenically cooled helium buffer gas [3,4]. However, a disadvantage of this technique is that it requires very large numbers of cold buffer gas atoms, consequently, it is not readily adaptable to the lower temperatures characteristic of laser-cooled atomic vapors [5].

Atoms can also be loaded using a time-dependent trapping potential, e.g., magnetic traps are loaded by imposing a magnetic potential around a sample prepared in a MOT. However, exceeding the number limit requires multiple loading of a second trap that is spatially separated from the laser-cooling region. In the standard multiple loading scheme, atoms are transferred from a vapor cell to an UHV MOT in order to overcome the trade-off between loading rate and trap lifetime [6,7]. In this case, the number limit is still $\sim 10^{10}$. However, if the second trap does not involve near-resonant light, much larger atom numbers are possible. For example, if the trap lifetime is 100 s and the loading rate is 10^{10} s^{-1}, then, neglecting the leakage during each reload, one expects to accumulate 10^{12} atoms. However, as the density builds up, the leakage also increases and a steady state is reached when the input flux is equal to the leakage flux. The ability to accumulate large atom numbers depends on minimizing the leakage. The principle of multiple loading has been demonstrated using an ac magnetic trap where final atom numbers nearly five times that of a single load were reported [8].

In this paper, we investigate the potential for multiple loading of a far-off resonant optical dipole trap that is spatially separated from the laser-cooling region. Compared to magnetic traps, optical dipole traps [9] have the advantage of flexible geometry and fast switching, but the disadvantage of limited trap depth. In our experiment, the trap is formed by a far red-detuned laser beam aligned vertically that both guides cold atoms toward the trapping region and forms the walls of the trap. The atoms enter the trap through a blue-detuned light sheet or trap door that may be switched on and off. After they enter the trap region, the trap door is closed, and the atoms subsequently fall under gravity and bounce off the light sheet. This geometry gives the maximum trap volume for a given laser power. We study the bouncing dynamics of the trapped atoms that differ significantly from previous experiments [10–12], and present a simple model of the classical trajectories to explain the observed density distributions. Also, we investigate multiple loading of the trap. After the first guided cloud has been launched, the MOT is switched back on to prepare a second cloud. The second cloud is allowed into the trap by briefly opening the trap door. During this reload, we lose about 15% of the trapped atoms; therefore, ignoring other losses, one could expect to accumulate about seven times the number delivered from each MOT. By using a tall vertical trap, the number of trapped atoms can be further enhanced by a density buildup at the apex where the atoms spend more time [5].

II. EXPERIMENT

The experimental geometry is shown in Fig. 1. The key feature of the setup is that the optical dipole trap is spatially separated from the laser cooling region. In the lower chamber, ^{85}Rb atoms are cooled from the vapor and collected in a MOT formed by a magnetic-field gradient of 10 Gcm^{-1} and three orthogonal counterpropagating molasses beam pairs, one horizontal and two at $\pm 45°$ to the vertical, with a diameter of 1.5 cm ($1/e^2$) and peak intensity of 10 mW cm^{-2}. The optical molasses beams are produced by a tapered amplifier diode injected by an extended cavity diode laser (ECDL) that is offset locked to a rubidium resonance line. A repumper beam, resonant with the $5S_{1/2}(F=2)$ to $5P_{3/2}(F=3)$ transition, is produced by a second frequency-stabilized ECDL and overlapped with the horizontal molasses beams.

A Nd:YAG (yttrium aluminum garnet) laser beam with wavelength 1064 nm is aligned along the vertical axis of the

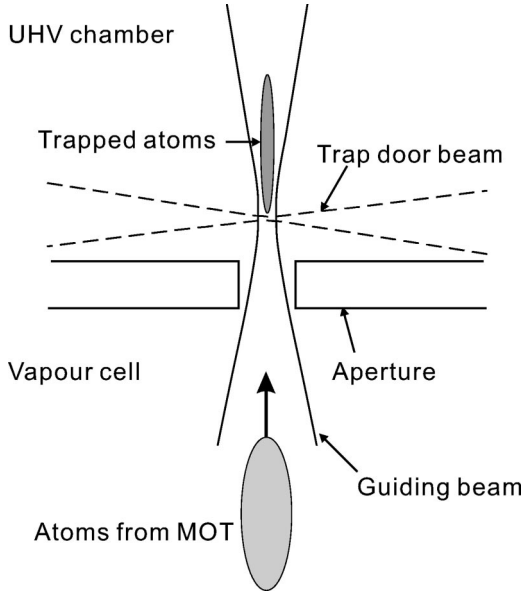

FIG. 1. Schematic diagram illustrating cold-atom accumulation using an optical trap door. Laser-cooled atoms are prepared in a MOT and launched toward the trapping region (8 cm above the MOT) using moving molasses. They are guided by a far-off resonant laser beam through a 1-mm aperture leading to a differentially pumped UHV chamber. They are prevented from leaving by switching on a blue-detuned trap door beam.

vapor cell MOT and left on throughout the experiment. This laser is focused to a waist of 100 μm$(1/e^2)$ located 7 cm above the MOT (see Fig. 1), producing a two-dimensional guiding potential with a depth equivalent to 100 μK at the focus. About 10^7 or 20% of the MOT atoms are loaded into the guide with an initial density of $\sim 6\times 10^{11}$ cm^{-3}. The atoms are launched vertically with a velocity of 1.25 ms^{-1} by shifting the frequency of the upper and lower molasses beams. The temperature in the moving frame is 20 μK [13]. Note that the initial phase-space density in the guide ($n\lambda_{\mathrm{dB}}^3 \sim 4\times 10^{-5}$) is considerably higher than in the MOT (where $n\sim 3\times 10^{11}$ cm^{-3} and $T\sim 60$ μK, giving $n\lambda_{\mathrm{dB}}^3 \sim 3\times 10^{-6}$). The guide laser directs the atomic fountain through a 1-mm hole in a quartz plate located 7 cm above the MOT that separates the vapor cell from a differentially pumped UHV chamber (background pressure 10^{-10} Torr). The atoms turn around between 0.5 and 1.5 cm above the aperture.

An optical trap door is produced by a 40-mW diode laser focused to provide a horizontal light sheet with thickness 10 μm and width 200 μm positioned about 1 cm below the apex of the fountain. The frequency of the trap door beam may be switched by injecting light from a master laser (an ECDL with a linewidth of a few hundred kHz and stable to a few MHz). The master output is passed through an acousto-optic modulator (AOM) with the first order injected into the slave. When the AOM is ''off,'' the slave is free running and has a detuning of $\sim$5 nm from resonance. In this case, the light shift experienced by atoms in the guide is negligible, i.e., the trap door is ''open.'' When the AOM is ''on,'' the slave is locked to the master that is blue-detuned by a variable amount Δ from resonance. To minimize spontaneous scattering, Δ is chosen as large as possible while still providing sufficient light shift to reflect all the atoms. During the flight to the apex of the fountain (duration $\sim$110 ms), a 20-μK atomic cloud (along the guide axis, $v_{\mathrm{rms}}=\sqrt{k_{\mathrm{B}}T/m}\sim 4.4$ cm s^{-1}) with initial vertical size 2 mm expands to 1.2 cm. Atoms falling from this height have a potential energy equivalent to 1.2 mK, which limits the detuning to $\sim$100 GHz. In practice, the optimum performance was obtained with a detuning of 20 GHz. At this detuning, one still expects a significant probability of photon scattering on each bounce that leads to loss through the trap door (about 2% per bounce). If a higher laser power were available, one could achieve the same trap depth at a larger detuning and thereby reduce this loss mechanism.

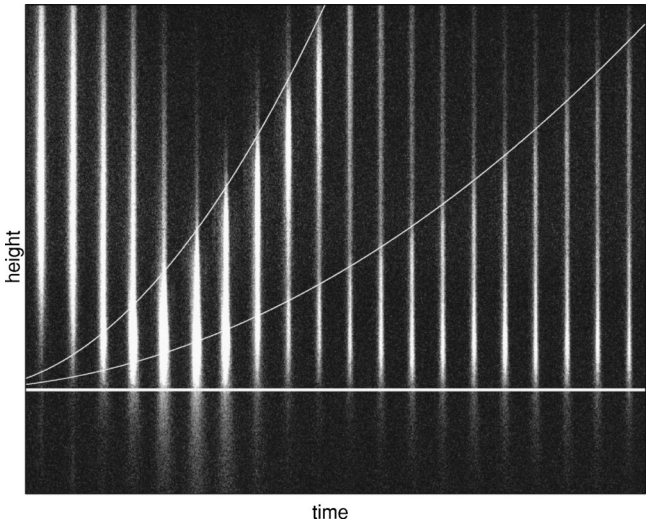

FIG. 2. A sequence of images showing atoms guided by a red-detuned laser beam bouncing off a blue-detuned light sheet. The images (height 17 mm) are recorded at 10-ms intervals. The position of the trap door is indicated by the horizontal white line. Parabolas corresponding to the leading edge of the bounce (see text) are also shown.

A typical experimental time sequence is as follows. After 1 s of MOT loading, the magnetic field is switched off and the atoms are launched using moving molasses. The molasses light is switched off and the atoms travel upward guided by the Nd:YAG laser beam. When they reach the apex of the fountain, the optical trap door is closed. The atoms fall under gravity and bounce off the trap door. After a variable delay, a detection beam is switched on for 0.7 ms and the fluorescence is imaged onto a charge-coupled device camera. The detection beam consists of a counterpropagating beam pair aligned along the vertical axis, and containing molasses and repumper light with peak intensity a few times above saturation.

III. GUIDED ATOM BOUNCING

A typical sequence of images of bouncing atoms taken at 10-ms intervals is shown in Fig. 2. The imaging is destructive; therefore each image is obtained from a different load. As the atoms fall from different heights, they have different bounce periods. In addition, when the trap door is closed,

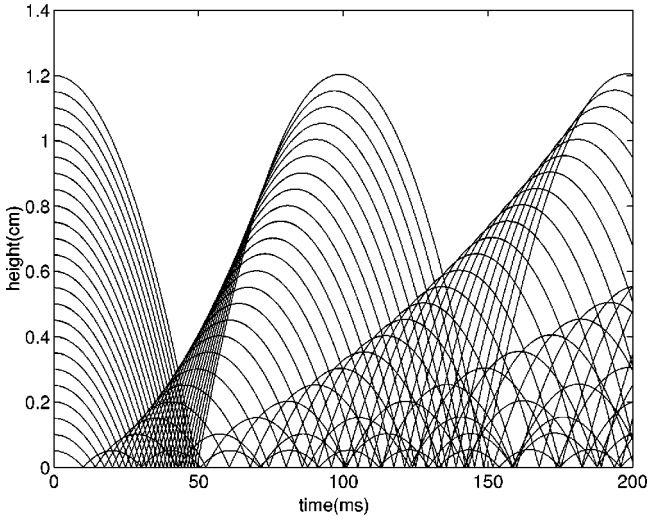

FIG. 3. Parabolic trajectories of particles falling under gravity and bouncing on a hard wall potential. The initial velocity is zero.

some atoms are still traveling upward while others are already falling. This leads to complex dynamics; however, the density profiles can be easily understood in terms of the classical trajectories. Figure 3 shows the classical trajectories of particles bouncing in a gravitational field with a range of initial heights and initial velocity equal to zero. The intersection between parabolas defines the leading edge of the bounce. The leading edge follows a parabola that becomes progressively less steep for successive bounces. Two leading-edge parabolas are superimposed on the atomic images shown in Fig. 2. The agreement indicates that it is reasonable to neglect the initial velocity spread as its effect is small compared to gravity.

The on-axis density profile as a function of height is shown in Fig. 4. During the first 100 ms, the cloud develops

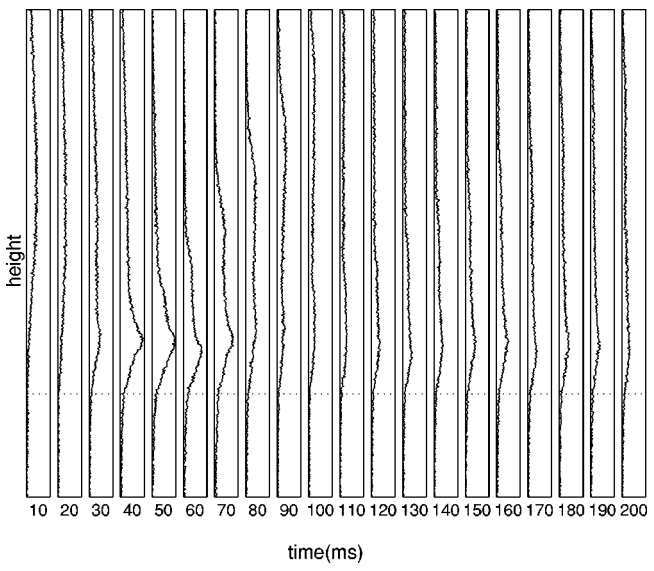

FIG. 4. The on-axis density as a function of height recorded at a sequence of times (in ms) after the trap door is closed. A double maximum is observed between 70 and 100 ms. The *y* scale is the same as in Fig. 2.

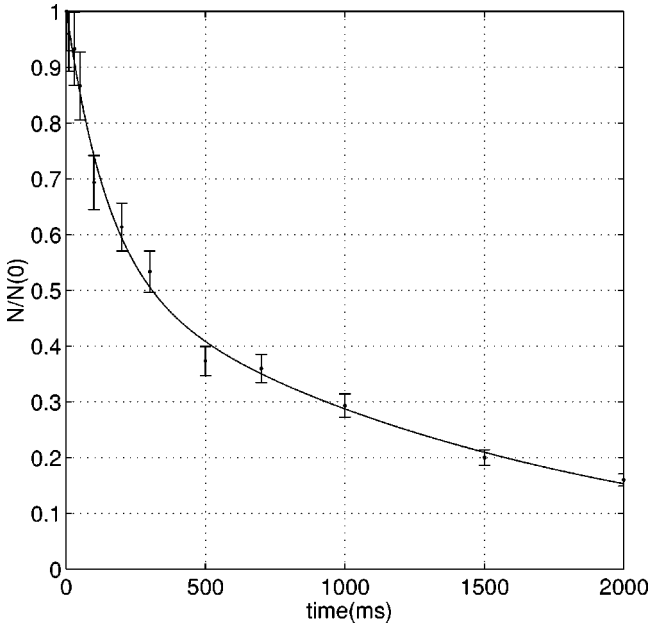

FIG. 5. The number of atoms in the optical dipole trap as a function of time. The data are fitted using a double exponential with fast and slow lifetimes of 0.15 and 1.7 s, respectively.

two distinct maxima. Similar splittings of thermal clouds bouncing on repulsive light sheets has been observed by Bongs *et al.* [12]. However, our experimental parameters differ significantly in that the initial size of the cloud is larger than the mean drop height. In this case, the double maximum arises due to the dephasing of atoms with different initial position (see Fig. 3).

IV. OPTICAL DIPOLE TRAP DENSITY AND LIFETIME

The average density of atoms delivered to the optical dipole trap is $\sim 10^{11}$ cm^{-3}, so the initial phase space density is $\sim 10^{-5}$ (slightly higher than in the MOT, see Sec. II). However, as the atoms bounce they acquire a nonthermal velocity distribution and the phase-space density becomes ill-defined.

Information on the trap loss is provided by studying the lifetime. The number of atoms in the trap as a function of time is shown in Fig. 5, for a trap-door beam detuning of 20 GHz and power of 40 mW.

The data have been fit to a double exponential $N = N_0[A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2)]$, with $\tau_1 = 0.15$ s, $\tau_2 = 1.7$ s, and $A_1 = 0.47$ and $A_2 = 0.53$, respectively. The long lifetime is roughly consistent with loss due to spontaneous emission and background pressure (10^{-10} Torr). Monte Carlo simulations indicate that the spontaneous loss should be $\sim 2\%$ per bounce, which for a mean bounce time of 70 ms would translate into a lifetime of a few seconds. The fast loss appears to be due to atoms that pass straight through the trap door on their first or second bounce (see Fig. 2). The trap door is theoretically deep enough to reflect all the atoms, so some other effect must be responsible. For example, either stray light reflected from the uncoated quartz windows or polarization gradients (as the guide laser is retroreflected with orthogonal polarization to increase the trap depth) could

introduce weak points in the potential. Further work is required to eliminate these problems. In the limit of high power and large detuning, an optical dipole trap lifetime of a few hundred seconds should be possible [14].

V. MULTIPLE LOADING

A key feature of a trap with a trap door is the possibility of multiple loading. The steady-state number of atoms depends on the MOT loading rate, optical dipole trap loss, and leakage while the trap door is open. To optimize both the MOT loading rate and the trap lifetime, the trap is placed in a differentially pumped chamber (see Fig. 1). To investigate the feasibility of cold-atom accumulation, the following experiment was performed: The MOT is loaded, the atoms are launched within the guide, and then pumped to the lower hyperfine state. They leave the optical molasses region and after a 20-ms delay the MOT is switched back on to collect a second load. Meanwhile, the initial cloud is traveling toward the apex of the fountain and the trap door is opened to allow most of the atoms to enter. The second MOT is loaded for around 70 ms and a second cloud is launched within the guide. By operating at high vapor pressures, we can load $\sim 10^7$ atoms into the optical dipole trap during this period. When the second cloud arrives at the trap, the trap door is opened for 15 ms. This sequence can be repeated an arbitrary number of times.

The MOT loading time and the trap door timing are optimized to maximize the number of trapped atoms. For a trap door opening time of 15 ms, we lose $\sim 15\%$ of the trapped atoms during each refill. The loss between refills is $\sim 20\%$. This means that the steady-state number is only a factor of 2 larger than from a single load. A further serious problem with our existing setup is that the whole chamber is made from uncoated quartz. Consequently, the optical dipole guide is exposed to light reflected from the cell walls. This scattered light reduces the lifetime of the optical dipole trap while the MOT is on. By redesigning the vacuum chamber, it will be possible to eliminate all light paths except for the direct line of sight between the MOT and the optical dipole guide. In this case, only 3×10^{-6} of the photons scattered by the MOT will reach the optical dipole trap. This residual scattered light pumps some atoms into the upper hyperfine state where they can scatter light on the main laser-cooling transition or induce loss by hyperfine changing collisions. However, this loss could be reduced by applying a weak ''depumper'' beam [resonant with the $5S_{1/2}(F=3)$ to $5P_{3/2}(F=2)$ transition] while the MOT is on.

VI. CONCLUSION

We have demonstrated the loading of cold atoms into an all-optical trap that is spatially separated from the laser-cooling region. Atoms are loaded using an optical trap door. The scheme provides a means to transfer atoms from a dissipative to a nondissipative potential without a significant loss of phase-space density. As the technique does not rely on near-resonant light, the usual number limits applying to laser-cooling experiments no longer apply, and therefore by multiple loading, large numbers of cold atoms can be accumulated. In the present setup, the final atom number was limited by losses due to stray light reflected off the cell walls. However, by reducing this loss and increasing the delivered flux, atom numbers in excess of those achieved in a MOT with a phase-space density close to quantum degeneracy may be feasible. The scheme could also be adapted to load a magnetic trap.

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