Increasing the trapping lifetime of lithium-7 atoms in optical dipole trap

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Abstract. We have developed far-off resonance single beam dipole trap for optically cooled
lithium-7 atoms. In the present paper we discuss some preliminary results. In order to improve
performance of the trap we optimized the trapping time and increased the atoms number. The
lifetime was increased by improving the vacuum from \( \approx 3 \times 10^{-10} \) Torr to \( \approx 10^{-11} \) Torr and
preparing all the atoms in the selected atomic state (the lower ground state level). After vacuum
improvement the single particle losses in the magneto-optical trap was reduced by 100 times
and as the result the lifetime in the dipole trap reached 25 s.

1. Introduction
Optic traps and optic tweezers are the most useful tools for capturing and manipulating neutral
particles, atoms and small biological objects. In a resonant trap, such as a magneto-optical trap
(MOT), which operates with near-resonant light, confined atoms scatter light, and achievable
density is limited by radiation trapping and light-assisted inelastic collisions \([1, 2]\). In far-off resonance optical dipole traps (FORT) the photon scattering rate is negligible. Typical
trap depth is relatively small, comparing to the other type of traps such as magnetic traps or
electrostatic traps for charged particles. To load atoms into the FORT, it is necessary to cool
them using a MOT.

The storage time (or lifetime) of atoms in a FORT is usually limited by residual background
gas collisions \([3]\), interatomic cold collisions \([2]\), photon scattering and laser intensity noise
induced heating \([4]\).

In this work, we describe the improvement of our single beam far-off resonance dipole trap.
By decreasing residual gas pressure and preparing the atoms in the selected quantum state we
were able to significantly increase the trapped atoms number and lifetime.

2. Experimental setup and procedure
Our experiments start with cooling of lithium-7 atoms in the MOT. For cooling and trapping
lithium atoms we used two external cavity diode lasers (Toptica TA 671 nm and VitaWave
ECDL 671 nm). Both lasers were frequency locked near the transitions \( 2S_{1/2}(F = 2) \rightarrow 2P_{3/2} \)
and \( 2S_{1/2}(F = 1) \rightarrow 2P_{3/2} \) with variable red detuning.
Figure 1. The magneto-optical trap atom number decay curves for different vacuum values: (a) before TSP activation, residual gas pressure $3 \times 10^{-10}$ Torr; (b) after TSP activation, residual gas pressure approximately $10^{-11}$ Torr. Solid line is the best fit with equation (1) with $\beta = 0$ and lifetime $1/\gamma = 20$ (a) and 175 s (b); dashed line is the best fit with taking into account two-particle interaction induced losses and $1/\gamma = 1800$ s.

We captured $10^9$ lithium-7 atoms at density $6 \times 10^{10}$ cm$^{-3}$. Initial temperature of atomic cloud at this stage was approximately 0.7 mK. Detailed description of our MOT is presented elsewhere [5, 6].

In our previous works [6], the cold atomic cloud lifetime in the MOT was limited by vacuum quality in the vacuum chamber which was not better than $3 \times 10^{-10}$ Torr. For lifetime measurement we turned off the Zeeman slower beam and recorded decay of the MOT fluorescence [6]. Recorded fluorescence signal is proportional to the number of atoms $N$ in the trap. To describe the total atom number evolution in the trap we used the following rate equation:

$$\frac{dN}{dt} = -\gamma N - \beta N^2,$$

where $\gamma$ s$^{-1}$ is single-particle loss coefficient due to collisions with the residual gas atoms and $\beta$ s$^{-1}$ is two-particle loss coefficient, which correspond for trap losses due collisions between the trapped atoms.

Figure 1(a) displays the time evolution of the total number of atoms in the MOT before our modification of vacuum system [6] with a titanium sublimation pump (TSP). Solid line in figure 1(a) is the best fit of the experimental data by solution of equation (1) with $\beta = 0$. This is a purely exponential decay due to collisions with the background gas. At this condition atoms lifetime in the MOT are $1/\gamma = 20$ s at a pressure of $3 \times 10^{-10}$ Torr. After installation of titanium sublimation pump in the vacuum chamber the trapped atoms lifetime was significantly increased. In figure 1(b) the same MOT decay curve after the TSP activation is shown. The lifetime of atoms no longer depends on collisions with the residual gas and is determined by binary interaction between the trapped atoms. Solid curve in figure 1(b) is the best fit by equation (1) with $\beta = 0$, dash curve is the best fit with taking into account the two-particle losses. From the latter fit we extracted the single-particle loss coefficient $\gamma$ and the corresponding
Figure 2. The evolution of the total number of atoms in the optical dipole trap. Red circles—mixed population between lower ($F = 1$) and upper ($F = 2$) ground state sublevels; black squares—all atoms optically pumped to the lower ground state sublevel $2S_{1/2}(F = 1)$. Solid line is the best fit with solution of equation (1) with $\beta = 0$ and lifetime $1/\gamma = 25$ s for lower ground state and 20 s for mixed population.

The trap lifetime is $1/\gamma = 1800$ s and effective MOT lifetime reached $\approx 200$ s. In order to efficiently load the dipole trap enhancement of the phase-space density is necessary. For this purpose, we implemented compressed MOT (CMOT) procedure for our experimental sequence. Our CMOT procedure was similar to the procedure described in [7].

A commercial infrared cw fiber laser with output power 100 W and wavelength 1074 nm was focused to the center of the vacuum chamber by a lens with focal length $f = 295$ mm to a 50 $\mu$m waist. The value of the dipole trap potential was $U_0 = k_B T_0$, where $T_0 \approx 0.9$ mK. Dipole trap was loaded by overlapping the atomic sample in CMOT stage with focused high-power cw laser beam. Parameters of the trap such as size of the cold atomic cloud, dipole potential depth and trap losses were investigated by using fluorescence and absorption imaging technique. At the end of the CMOT stage approximately $3 \times 10^7$ atoms were loaded in our dipole trap with the temperature 0.55 mK and peak density $5 \times 10^{10}$ cm$^{-3}$ [8]. The atomic cloud temperature was comparable with the trap depth $U_0 = k_B T_0$. By using fluorescence imaging technique, the trap losses induced by modulation of the trap depth were studied. In [8] we observed and studied superharmonics in the trap loss spectrum.

3. Results
Enhancement of the vacuum in the chamber allowed us to gradually reduce collisions between trapped atoms and residual gas and binary ultracold collisional processes became one of the main sources of the trap losses.
Due to the cooling processes in the MOT the populations of the ground state sublevels are equal. In the lithium MOT we used two lasers with comparable output power. Statistical weights of both transitions are very close and cooling and repumping lasers both work as cooling lasers. Cold lithium atoms which loaded in the dipole trap after the CMOT procedure initially have a mixed population between lower \((F = 1)\) and upper \((F = 2)\) ground state sublevels.

In figure 2, the evolution of total number of atoms in dipole trap is presented. For mixture of \(F = 1\) and \(F = 2\) states (red circles in figure 2) we observe a significant trap loss at first few seconds. The binary collision losses can be reduced by preparing the atoms in the lower \(F = 1\) state only [9]. The evolution of total number of atoms prepared in \(2S_{1/2}(F = 1)\) state is presented in figure 2 (black squares). To obtain this dependence, after the CMOT stage was completed, the optical pumping laser was turned off, and all atoms were pumped to the lower ground sublevel \(2S_{1/2}(F = 1)\). Dipole traps with lithium-7 atoms prepared on the upper sublevel of the ground state \(2S_{1/2}(F = 2)\) demonstrated a significantly shorter lifetime [9].

4. Conclusion
We assembled a far-off resonance single beam dipole trap for optically cooled lithium-7 atoms. The trap lifetime was increased by improving the vacuum and preparing atoms in the selected atomic state (the lower ground state level). Lifetime in magneto-optical trap which increased by 100 times and lifetime in the dipole trap was reached 25 s. Trap lifetime was increased by reducing interatomic and background gas collisions. To increase the number and density of atoms in a dipole trap, we plan to implement sub-Doppler cooling methods of lithium atoms at MOT stage [10] and reduce the laser intensity noise [4, 8, 9]. Our optical dipole trap can be applied for preparation and study of an ultra-cold plasma and Rydberg atoms.

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