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Long lifetime of single atom in optical tweezer with laser cooling

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ABSTRACT

Single cesium atom prepared in a large-magnetic-gradient magneto-optical trap (MOT) has been efficiently loaded into a microscopic far-off-resonance optical trap (FORT, or optical tweezer), and the atom can be transferred back and forth between two traps with high efficiency. The intensity noise spectra of tweezer laser are measured and the heating mechanisms in optical tweezer are analyzed. To prolong the lifetime of single atom trapped in optical tweezer, laser cooling technique is utilized to decrease atom's kinetic energy, and the effective temperature of single atom in tweezer is estimated by the release-and-recapture (R&R) method. Thanks to laser cooling, typical lifetime of ~ 130.6 ± 1.8 s for single atom in tweezer is obtained. These works provides a good starting point for coherent manipulation of single atom.

Keywords: laser cooling, optical tweezer, single atom, lifetime, release and recapture

1. INTRODUCTION

Optical tweezer is a nearly conservative potential which can confine atoms with extremely low spontaneous scattering rate and long coherence time. Thus optical tweezers become a standard tool being used for trapping and manipulating cold atoms. With the development of laser cooling and trapping technology of neutral atoms, several groups have successfully trapped and manipulated single atom in magneto-optical trap (MOT) or optical tweezer [1-8]. Single atom provides a good playground for light-mater interaction research at single-atom and single-photon levels. Based on single atom system, quantum register [9], single photon source [10], and atom-photon entanglement [11] have been demonstrated experimentally

The lifetime of atoms trapped in optical tweezer is an important parameter. Although optical tweezer have extremely low spontaneous scattering rate and negligible photon recoil heating, the lifetime of trapped atoms is affected by the intensity noise and the pointing fluctuation of tweezer laser beam [12]. In addition, detection and manipulation schemes of single atom normally employ near-resonance laser that drives a cycling transition. Heating of atoms in optical tweezer can also come from the photon absorption and the spontaneous emission due to near-resonance laser. In fact, many experiments have shown that too high temperature limits relative experimental investigations. In the experiment of triggered single photon source [10] based on single atom in optical tweezer, the lifetime of single atom in tweezer is only ~ 34 ms for heating from resonant excitation during the periods of π pulse sequence, which limited the productive rate of single photons. By applying periodic laser cooling pulses to reduce the effective temperature of trapped atoms, a dramatic increase in the lifetime has been demonstrated [13]. In the experiments of coherent manipulation of single atom trapped in optical tweezer [14], when the effective temperature of trapped atom is too high, the Rabi oscillation signals damp quickly maybe due to large spatial motion of atom. Besides, the Doppler effect due to the motion of atom trapped in optical tweezer will cause line broadening in emitted fluorescence spectrum [15-16]. If the trapped atom could be cooled sufficiently down, s the spread in frequencies of emitted photons can be effectively suppressed.

Several groups employed ultra-stable laser system to suppress the heating from the noise of tweezer laser [12, 17]. We show that using cooling techniques to decrease the kinetic energy of single atom trapped in optical tweezer is also an effective way to achieve longer lifetime and lower effective temperature of single atom. In this paper, we present our experiments in detail, in which we can prepare single atom in a large-magnetic-gradient MOT and transfer single atom between MOT and optical tweezer back and forth efficiently. We measured the intensity noise spectrum of tweezer laser and analyzed the heating mechanisms of single atom trapped in tweezer. Based on the analysis, long lifetime of single atom in optical tweezer can be achieved by reducing the kinetic energy by laser cooling. In addition, the effective temperature of single atom in tweezer has been measured via release-and-recapture (R&R) method under different cooling parameters.

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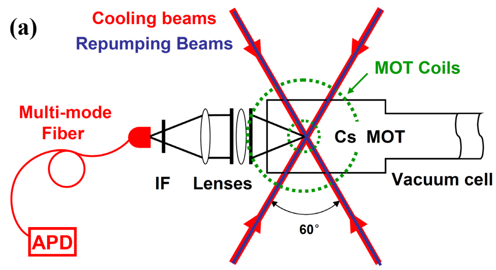
2. EXPERIMENTAL SETUP AND SINGLE ATOM LOADING AND TRANSFERRING

2.1 Single atom MOT

By increasing the MOT magnetic field gradient to decrease the loading rate, we can trap very few atoms even single atom in MOT and have a good spatial localization [5-7]. Our experimental setup is depicted in Fig 1(a) schematically. An 852nm-anti-reflection-coated glass cell with size of 30×30×120 mm^3 is evacuated by vacuum pump system to keep the pressure. The high-purity cesium atoms are sealed in an oxygen-free copper tube as the source of atoms.



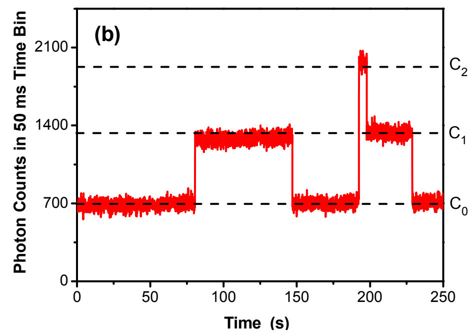
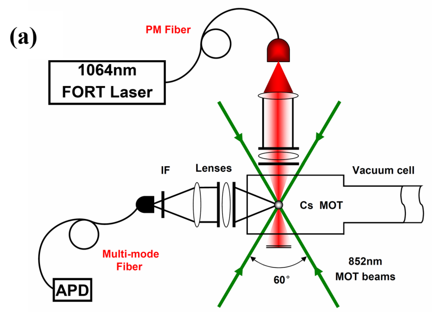


Fig. 1 (a) Schematic diagram of the single atom MOT. A glass cell is evacuated by vacuum pump system (not shown) to keep the pressure at ~ 2×10 $^{-11}$ Torr with cesium atoms released from ampoule. The four of MOT beams in horizontal plane are shown, and the other two beams which are perpendicular to horizontal plane are not indicated. The dot circles show the position of quadrupole magnetic coils which are mounted outside the vacuum cell. A single-photon counting avalanche photodiode (APD) is used to detect the collected fluorescence photons scattered by trapped atoms in MOT. IF: interference filter. (b) Typical fluorescence photon counting signal of single atom MOT. The number of trapped atoms can be determined from photon counting signal. C_0 indicates the photon counts level due to background for no atom in MOT. C_1 and C_2 indicate the photon counts level for one atom and two atoms trapped in MOT, respectively. The MOT parameters: laser beam diameter ~ 2 mm, total power of cooling and trapping laser beams ~ 0.7 mW, frequency detuning Δ~ -2π × 12.9 MHz (~ -2.5Γ), repumping laser power ~ 0.1 mW, and magnetic field gradient along axial direction dB/dz ~ 18.2 mT/cm.

Both cooling/trapping and repumping lasers are home-made external-cavity diode lasers (ECDL) with blazing gratings in the Littrow configuration. The beams are combined and coupled into a polarization-maintaining (PM) fiber by polarization beam splitter (PBS) cube for transmission and special filter. Two pairs of cooling/trapping beams in horizontal plane intersect into the glass cell with an angle of 60 degree. This configuration can suppress stray light efficiently and obtain a larger fluorescence-collection solid angle when MOT area is close to the detection system. Another pair of cooling/trapping beams along the axis of MOT magnetic coils is perpendicular to horizontal plane (not shown in Fig. 1(a)). The MOT magnetic field is produced by a pair of water-cooled anti-Helmholtz coils which are mounted outside of glass cell. Typically 20 Amps of current yielding ~ 30 mT/cm of magnetic field gradient along axis can be switched to zero within ~ 3.9 ms by electronic circuit and can be switched back on within ~ 40 ms which is limited by eddy current. The fluorescence photons of cold trapped atoms in MOT are collected by a lens assembly with numerical aperture of 0.29, and counted by a multi-mode-fiber-coupled single-photon counting avalanche photodiode (APD) worked at the Geiger mode. The counting time bin is set to 50 ms, which is much shorter than the lifetime of trapped atoms and is much longer than the spontaneous radiation decay time. Typical fluorescence photon counting signal of single atom MOT versus record time is shown in Fig. 1(b), in which the typical photon counting step for each atom is about 600 counts/50ms.

2.2 Single atom transferring between MOT and optical tweezer

We set up optical tweezer being perpendicular to fluorescence collecting direction [6], as depicted in Fig. 2(a), which can effectively avoid the background scattering photons entering collection system. The tweezer laser is a home-made laser-diode-pumped Nd:YVO_4 single-frequency laser. The tweezer beam is focused to a waist of ~ 2.3 μm using a lens assembly, which produces a trap depth of ~ 1.5 mK with power of ~ 46.6 mW and corresponding trap frequency along radial and axial directions are ω_r = 2π×41.4 kHz and ω_a = 2π×4.3 kHz respectively. The background photon counts for optical tweezer (without cooling and trapping laser) are ~ 30 s^{-1} (including the APD dark counts of 25 s^{-1}) in 1.46 mK of trap depth with help of 852nm interference filter (IF).Our experiments rely on examining that whether or not there is an atom in MOT after manipulation in optical tweezer. Thus the highly efficient loading and transferring rate are crucial. We adjust the overlap of two traps by light-shift to obtain high efficient loading rate.



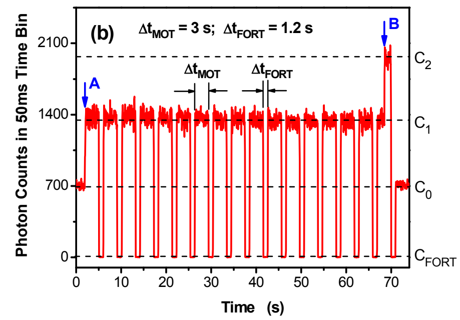


Fig. 2 (a) 1064 nm tweezer beam is guided by a polarization-maintaining (PM) fiber, expanded to ~ 23.5 mm of beam diameter, then is tightly-focused into the vacuum cell with a waist radius of ~ 2.3 μm. (b) Typical photon counting signal for transferring single atom between MOT and tweezer back and forth. Arrows A and B indicate that one more atom is captured into MOT from background cesium atoms occasionally. C_{FORT} denotes photon counts level due to 1064 nm optical tweezer laser (without cooling/trapping laser and repumping laser). C_0, C_1, and C_2 denote photon counts level due to no atom, one atom, and two atoms confined in MOT (without 1064 nm tweezer beam). The overlap time for switching between MOT and optical tweezer is 25 ms.

3. LIFETIME EXTENSION OF SINGLE ATOM TRAPPED IN OPTICAL TWEEZER

For cold atoms ensemble trapped in red detuning optical tweezer, many groups have attempted to achieve long lifetime and long coherence time by employing larger detuning and decreasing background gas collisions. The 1/e lifetime of ensemble cold atoms in tweezer can be obtained by monitoring atom number evolution as a function of time. For single atom trapped in optical tweezer, efficient transferring of trapped atom between two traps provides a simple procedure to obtain the lifetime. The 1/e lifetime can be determined by measuring the survival probability P(t) in the MOT- tweezer - MOT transfer cycling as a function of Δt_{FORT}. Each experimental data point is the accumulation of at least 100 sequences. Our experiments sequence is as follow: Firstly, we confirm that there is only one atom trapped in MOT by photon counting signal, then transfer atom into optical tweezer for time Δt_{FORT} and transfer back into MOT to determine if it is survival [6-7] (see Fig. 2(b)). Fitting the experimental date by exponential decay, the 1/e lifetime of single atom confined in optical tweezer is obtained as ~ 6.9 ± 0.3 s for background pressure ~ 2×10^{-10} Torr [6-7]. When the background pressure has been improved by one order of magnitude, the lifetime also increased roughly one order of magnitude. The measured lifetime is ~ 75.3 ± 5.3 s for background pressures of ~ 2×10^{-11} Torr [7], however it is much shorter than the value dominated by background collisions. It is limited by tweezer laser's intensity noise and beam-pointing fluctuation [12].

3.1 Heating due to tweezer laser's intensity noise

Tweezer laser's intensity noise and beam-pointing fluctuation can cause parametric heating of trapped atoms [12]. The intensity noise leads an exponential energy growth of the trapped atoms with a time constant T_{heat} ($1/T_{heat} \sim \pi^2 \cdot \omega_{trap}^2 \cdot S_\varepsilon(2\omega_{trap})$, in which ω_{trap} is the trap frequency, $S_\varepsilon(\omega_{trap})$ is the relative intensity noise spectra of tweezer laser). Moreover, for microscopic tweezer size (several microns or less), the heating rate maybe much larger compared to macroscopic tweezer with the same trap depth due to relatively higher trap frequency. As shown in Fig. 3(a), the intensity noise spectrum (red line) of our tweezer laser is measured with amplified photodiode (within bandwidth of DC to 1MHz). By dividing the DC voltage we can achieve the relative intensity noise. At low frequencies, the pumping noises dominate the intensity noise. The noise at intermediate frequencies is probably due to relaxation oscillations. The noise become flat and reaches to shot noise level at high frequencies (broaden peak around ~ 800 kHz is due to a little bit higher gain of the amplified photodiode). There is a peak packet at ~340 kHz due to relaxation oscillations and pumping supply. Fortunately, the trapping frequency of optical tweezer is far away from this peak, so the heating of peak noise maybe weak. The energy of trapped atom grows as s function of e-folding time Γ^{-1} with typical oscillation frequency, as shown in Fig. 3(b). In addition, the tweezer laser beam is coupled into a PM fiber for transmission and mode filter, the tweezer laser's beam-pointing fluctuation can be converted into optical tweezer laser's intensity noise. Intuitively, these heating mechanisms limit the attainable minimum effective temperature of single atom, therefore limit the lifetime of atom in optical tweezer.

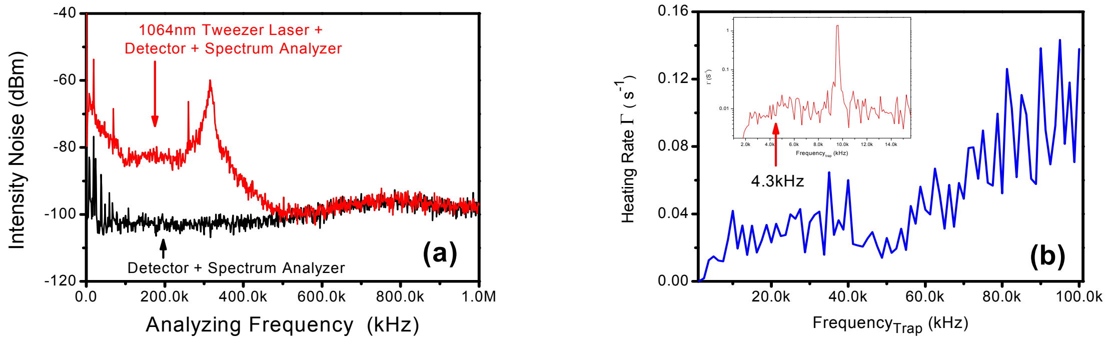


Fig. 3 (a) The black line (lower trace) is noise spectrum for the photodiode plus spectrum analyzer, while the red line (upper trace) is intensity noise spectrum for Nd:YVO_4 laser. There is a peak around ~340 kHz. (b) Heating rate as the function of trapping oscillation frequency. $\omega_a /2\pi$ = 4.3 kHz is the trap frequency of our optical tweezer along axial direction.

3.2 Laser cooling of single atom in optical tweezer

To achieve longer storage time for single atom trapped in tweezer, heating arising from laser's intensity noise and beam-pointing fluctuation should be stringently controlled. Alternative method is to lower the kinetic energy of single atom trapped in tweezer by cooling [13, 18]. The results from experiments and the motion of single atom in deceleration optical field show that the energy (velocity) distribution of single atom in tweezer is very close to Boltzmann distribution corresponding to the time t ($t \gg 1/\Gamma$, $1/\Gamma$ is the spontaneous decay time). One can describe the energy distribution using effective temperature concept under condition of $t \gg 1/\Gamma$, although it is only single atom.[18]

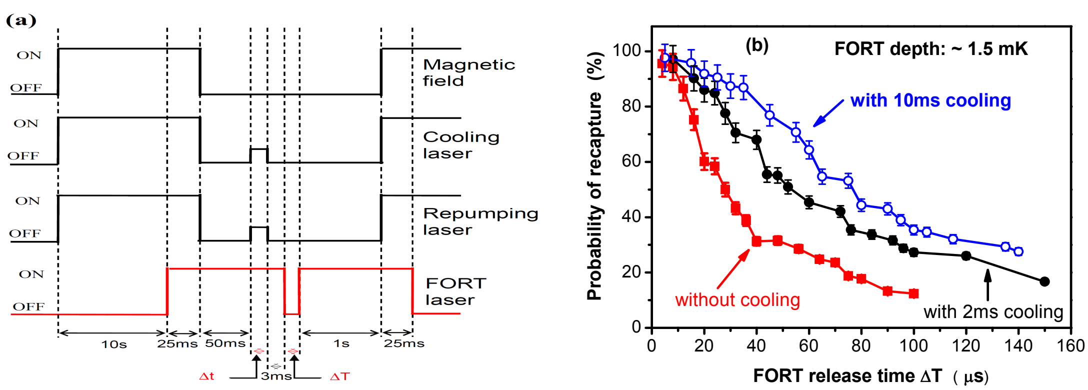


Fig. 4 Release and recapture (R&R) measurement of single atom in optical tweezer. (a) Schematic of time sequence. Δt is the time for laser cooling, and ΔT is the time interval for optical tweezer releasing. (b) Experimental results of the recapturing probability of single atom as a function of tweezer release time ΔT. The open circles, solid dots, and solid squares are experimental data for laser cooling time Δt = 10 ms, 2 ms, and the case without cooling, respectively. Each experimental data point is the accumulation of at least 100 sequences. The error bars are for ±10%. The solid lines are for guiding the eyes. Trap depth of optical tweezer is ~ 1.5 mK. It is clear that the mean energy of trapped single atom is lower after laser cooling compared with the case without cooling.

Single atom in tweezer can be cooled in three dimensions by controlling the parameters of cooling/trapping and repumping laser, which is similar to the polarization gradient cooling (PGC) in optical molasses [13, 18, 19]. As we know that the R&R method [19] can be utilized to measure the temperature of ensemble cold atoms. The R&R technique is also can be extended to determine the effective temperature of single atom trapped in tweezer [18]. On average, single atom with high kinetic energy is much more likely to escape during tweezer release time ΔT than the case of that with lower energy, which shows a smaller recapture probability. Thus it can be recognized that different trends $P(\Delta T)$ show different kinetic energy information of single atom in tweezer.

Based on our transfer technique, we can conveniently accomplish the R&R sequence [7]. During laser cooling phase Δt, the intensity of the cooling and repumping laser beams are reduced to ~ 30% and ~ 25% of the original values during MOT phase, respectively, and the cooling laser's frequency detuning to F=4 – F'=5 cycling hyperfine transition are changed from ~ - 2.5Γ for MOT phase to ~ -6.5Γ for laser cooling phase for single atom trapped in tweezer (after considering the light-shift of tweezer laser). Experimental results of the recapture probability of single atom trapped in ~ 1.5 mK tweezer as a function of tweezer release time ΔT are shown in Fig. 4(b). The effective temperatures obtained from simulation to the experimental data are about 105 ± 12 μK for the case without cooling, 33 ± 3 μK for 2 ms laser cooling case, and 17 ± 1 μK for 10 ms laser cooling case, respectively. It is very clear that the mean energy of trapped single atom is much lower after laser cooling compared with the case without cooling.

3.3 Achieving long lifetime of single atom in optical tweezer by laser cooling

The lower effective temperature of trapped atom will provide longer storage [7, 13] time and stronger localization. After transferring the single atom into tweezer, if lowering the effective temperature of trapped atom, long lifetime will be expected. There are some advantages which will not only avoid the various problems from transferring process, but also prepared single atom in certain hyperfine level in ground state by controlling the switching sequence of cooing laser and repumping laser at the end of cooling phase.

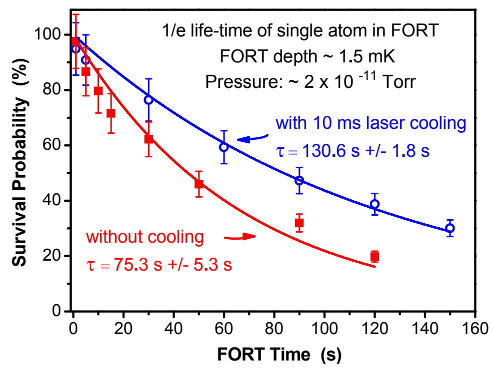


Fig. 5 The lifetime for cases with 10 ms laser cooling phase (open circles) and without laser cooling (solid squares). The error bars are for ±10%. Each data point is the accumulation of at least 100 sequences. Clearly much longer lifetime is obtained by laser cooling.

The lifetimes of single atom are determined to 75.3 ± 5.3 s for the case without cooling and 130.6 ± 1.8 s for the case with 10-ms cooling phase, respectively [7]. We can clearly see that the lifetime of single atom in tweezer with laser cooling is near 2 times of that for without cooling. In the case with 10-ms cooling phase, the lifetime of ~ 130.6 ±1.8 s is still very short compared to the estimated value which is expected only by the background gas collisions. The lifetime is mainly limited by the heating of intensity noise and beam-point fluctuations of tweezer laser beam. Because of the kinetic energy accumulation of trapped atom from heating, the kinetic energy of trapped atom may be rather higher than the potential depth and can escape from tweezer. Thomas group analyzed the heating theoretically [12], and achieved very long lifetime (~ 300 s) of atoms ensemble trapped in an optical tweezer formed by ultra-table CO_2 laser at 10.6 μm experimentally [17]. We can adopt other solutions to lower the intensity noise of tweezer laser. Rough estimations in our system can be made according to references [12]: for our trap depth of ~ 1.5 mK, radial trap frequency is $\omega_r = 2\pi \times 41.5$ kHz, if we want to achieve about ~ 300 s lifetime, the root-mean-square fractional intensity noise must be lower than 9×10^{-4} when the most of the intensity noise distribute over MHz bandwidth. The radio-frequency power applied to acousto-optical modulator (AOM) can be actively feedback controlled to change the diffraction efficiency, therefore the intensity noise of tweezer can be suppressed effectively.

4. CONCLUSION

In conclusion, we have optimized an implementation system for cooling and trapping single atom, with which we can load single atom prepared in a large-magnetic-gradient MOT into a microscopic optical tweezer efficiently, and transfer single atom between two traps back and forth. We have analyzed the various factors effecting the lifetime of single atom trapped in optical tweezer, and achieved lifetime of 75.3 ± 5.3 s by improving the background pressure from ~ 1×10^{-10} Torr to ~ 2×10^{-11} Torr. We have prolonged the lifetime to ~ 130.6 ± 5.3 s by using of 10-ms laser cooling phase. We also have demonstrated R&R technique to determine temperature of single atom trapped in tweezer, and compared the results for the cases with and without laser cooling phase. More generally, the lifetime is limited by heating due to tweezer laser's intensity noise and beam-pointing fluctuations. To achieve longer lifetime, one should decrease the heating by using feedback control of laser intensity noise or periodical pulse cooling [13].

5. ACKNOWLEDGMENT

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