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RESEARCH ARTICLE

Extending the trapping lifetime of single atom in a microscopic far-off-resonance optical dipole trap

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In our experiment, a single cesium atom prepared in a large-magnetic-gradient magneto–optical trap (MOT) can be efficiently transferred into a 1064-nm far-off-resonance microscopic optical dipole trap (FORT). The efficient transfer of the single atom between the two traps is used to determine the trapping lifetime and the effective temperature of the single atom in FORT. The typical trapping lifetime has been improved from $\sim$ 6.9 s to $\sim$ 130 s by decreasing the background pressure from $\sim 1 \times 10^{-10}$ Torr to $\sim 2 \times 10^{-11}$ Torr and applying one-shot 10-ms laser cooling phase. We also theoretically investigate the dependence of trapping lifetimes of a single atom in a FORT on trap parameters based on the FORT beam's intensity noise induced heating. Numerical simulations show that the heating depends on the FORT beam's waist size and the trap depth. The trapping time can be predicted based on effective temperature measurement of a single atom in the FORT and the intensity noise spectra of the FORT beam. These experimental results are found to be in agreement with the predictions of the heating model.

Keywords magneto–optical trap (MOT), far-off-resonance optical dipole trap (FORT), single atom, trapping lifetime, release-and-recapture method (R&R), effective temperature

PACS numbers 37.10.De, 37.10.Gh, 37.10.Vz

1 Introduction

With the help of the optical field gradient force, an optical dipole trap [1–3] can trap objects with its large restoring force and long trapping lifetimes. In particular, the microscopic far-off-resonance optical dipole trap (FORT) [2] can realize full control of internal and external degrees of freedom of a single neutral atom, which provides a good playground for the research of light–matter interactions at the levels of the single-atom and the single-photon. Using the trapped single atoms in FORTs, a quantum register [4], a triggered single-photon source [5], and atom–photon entanglement [6] have been demonstrated experimentally. In all these applications, a long trapping lifetime and a low trapped-single-atom temperature are of great importance.

Losses from the trap can be caused by the collisional process and heating mechanisms. Contributions to the collisional process arise from background gas collision, light-assisted binary collisions, and hyperfine-change collision [3, 7, 8]. For a few or even single-atom FORT in an ultra-high vacuum (UHV) environment, the losses are dominated by background gas collision and atom heating. Thus, obviously, improving UHV background can be employed to reduce the loss. The primary source of heating is the photon-scattering heating in the trap. Several groups have attempted to obtain a long trapping lifetime by detuning extremely far from resonance to decrease the photon-scattering rate in systems, such as a FORT or even in quasi-electrostatic traps (QUEST) [3]. In addition to photon-scattering heating, the heating resulted from the technical noise of the FORT laser beam [9] is also an important factor. Along this line, an ultra-stable laser system was employed as a trapping laser to form a low-trap-frequency FORT to suppress the heating due to intensity noise in the system [10]. Although the intensity noise of the FORT lasers is the same for a high-trap-frequency FORT with a tightly-focused beam and a low-trap-frequency FORT with a larger beam waist, the heating due to the intensity noise is still quite different in these two cases. The heating rate constant actually strongly depends on other FORT parameters. Using laser cooling, the heating can be effectively countered

[11], and the trapping lifetime can be extended [5, 12]. Furthermore, the application of cooling may contribute to the improvement of the quantum coherence of the trapped atom [13]. For instance, the increased decoherence time and the inhomogeneous dephasing of atomic qubits that arise from large variations in the position of the trapped atom can be reduced [13–18]. In addition, the linewidth of the fluorescence spectrum from the single atom trapped in FORT is broader than the nature linewidth because of the residual Doppler effect of single atom with relatively high temperature [19], and inversely this point can be adopted to get the effective temperature of the single atom, so the linewidth can be narrowed by cooling the single atom down.

In this paper, we achieve a longer trapping lifetime and lower effective temperature for the trapped single atom in a FORT using one-shot laser cooling than that has been achieved with comparable methods. We study the dependence of the trapping lifetime on FORT parameters theoretically and give a qualitative description of our experimental results. In contrast to the periodical pulse cooling [12], we decrease the energy of trapped atom by one-shot laser cooling phase at the initial stage just after the single atom, which was prepared in a large-magnetic-gradient magneto-optical trap (MOT), is transferred into the FORT. Furthermore, because the effects of light-assisted binary collisions and hyperfine-changing collisions can be avoided in this single atom system, we can experimentally distinguish various loss mechanisms, and the theoretical analysis is greatly simplified.

2 Experimental setup

A schematic diagram of the experimental setup is shown in Fig. 1. In our system, a glass ampoule that contains 5 grams of high purity cesium atoms is sealed in an oxygen-free copper tube as the source of atoms (not shown), which can be released into MOT area by an ultra-high vacuum (UHV) mechanic valve. We control the cesium atom number in the working area through this valve. The background pressure is maintained by a combination pump consisting of an ion pump and a titanium sublimation pump, and it is measured by the vacuum ion gauge. After cesium vapor is released from the atomic source, usually the typical background pressure can be maintained at about $\sim 1 \times 10^{-10}$ Torr when only the ion pump is operated, and can further reach $\sim 2 \times 10^{-11}$ Torr with the help of the titanium sublimation pump. In our large-magnetic-gradient MOT system cooling/trapping laser beams and repumping laser beams were provided by two homemade 852-nm grating external-cavity diode lasers (ECDL) in the Littrow configuration. The two pairs of beams in horizontal plane intersected with the glass cell at a 60° angle. The total power of the cooing/trapping beams was 0.6 mW; their $1/e^2$ diameter was 2 mm; the frequency detuning from the $(6S_{1/2}Fg = 4) - (6P_{3/2}Fe = 5)$ cooling cycling transition was -2γ ($\gamma/2\pi = 5.22$ MHz is the natural linewidth for the Fg = 4–Fe= 5 transition). This frequency-offset was stabilized using the modulation-free polarization spectroscopic locking scheme. The repumping laser, which had a power of 0.1 mW, was locked to the $(6S_{1/2}Fg = 3) - (6P_{3/2}Fe = 4)$ hyperfine transition using the radio-frequency modulation spectroscopic locking scheme. The magnetic field of the MOT was produced by a pair of water-cooled anti-Helmholtz coils. The supplied 20-A current that yielded a field gradient of 30 mT/cm (∼300 Gauss/cm) in the axial direction of the coils, could be switched off completely within 3.9 ms using our control electronic circuits. The fluorescence photons of the cold atoms in the MOT were collected by a lens assembly with a numerical aperture of 0.29, and were then coupled into a multi-mode-fiber-coupled avalanche photo-diode (APD) that was working in the photon-counting mode.

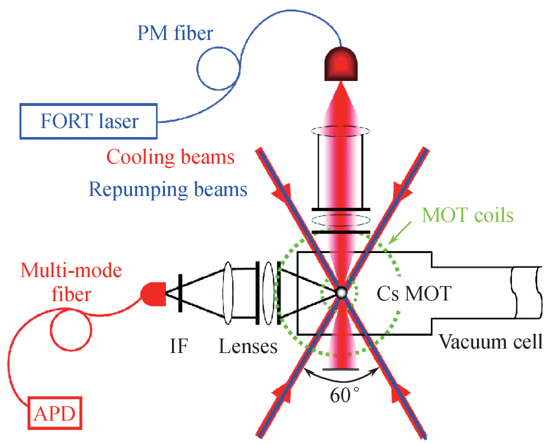

Fig. 1 Schematic diagram of the experimental setup. APD: avalanche photodiode working in the photon-counting mode; IF: 852-nm interference filter; PM fiber: polarization-maintaining fiber.

The FORT beam was provided by a homemade laser-diode-pumped $Nd:YVO_4$ single-frequency 1064-nm laser, which is guided by a polarization-maintaining (PM) fiber to a lens that expands the beam diameter to ∼ 20 mm. Then the beam was tightly-focused into a vacuum cell with a waist radius of 2.3 μm using a lens assembly. The trap depth was 1.5 mK with a laser power of 47 mW. The background photon-counting rate for the FORT laser beam at 47 mW was 30 s^{-1} (including the APD dark counts of 25 s^{-1}). This low background photon counting was achieved with the help of an 852-nm high-transmission (82%) narrow-band (4 nm) interference filter (IF) in combination with the specific arrangement of our system.

3 Characterization of a MOT and a microscopic FORT

3.1 Dependence of loading rate on the magnetic field gradient of MOT

Several groups have successfully trapped a single atom in an MOT by decreasing the loading rate [20–26], or in a microscopic FORT using the collisional blockade effect [5, 19, 27]. We loaded a single atom into an MOT with a large-magnetic-field gradient and then transferred the trapped atom into the microscopic FORT. This process is described in references [23, 24, 28] in details. Allowing the trapping of a few atoms or large quantities of atoms in an MOT or FORT demonstrated the importance of controlling the loading rate of the trap. The control of the loading rate not only permitted the trapping of a single atom [20–24], but also produced a near-deterministic number of atoms [25, 26] that could be delivered on demand in an experiment, which is necessary for various experiments in quantum optics, cold collisions, precision measurement, and quantum information.

Haubrich *et al.* [29] proposed a simplified analytic model for atom loading in a large-magnetic-field gradient MOT, in which the loading rate is very sensitive to the magnetic-field gradient:

$$R_{\mathrm{L}} \propto \left(\frac{\mathrm{d}B}{\mathrm{d}z}\right)^{-14/3} \tag{1}$$

This is helpful for experiments involving the trapping of even a few single atoms in an MOT. In Ref. [29] a few experimental data were also presented, which supported the above scaling law. Nakagawa group [30] also measured the loading rate of an MOT versus the magnetic-field gradient and gave a few experimental data that were consistent with Eq. (1). However, Choi *et al.* [31] measured the loading rates and fit their experimental data by the law of $R_{\mathrm{L}} \propto (\mathrm{d}B/\mathrm{d}z)^{-3.66}$, which was slightly deviated from Eq. (1).

In our experiment, we also measured the loading rate, R_{L}, of the MOT by recording the light-induced fluorescence (LIF) of the atoms trapped in the MOT [32]. R_{L} can be given by $R_{\mathrm{L}} = N_{\mathrm{photon}}/(\tau \cdot \gamma_{\mathrm{scattering}})$, where $\gamma_{\mathrm{scattering}}$ is the photon scattering rate of single atom, τ is the lifetime of atoms in MOT, (where τ can be determined from the loading process), and $N_{\mathrm{photon}} = N_S \cdot \gamma_{\mathrm{scattering}}$ is the LIF photon counts, (where N_S is the steady-state atoms number in the MOT and N_{photon} can be obtained from the APD photon counts). Figure 2 shows the dependence of the loading rate (R_{L}) on the magnetic-field gradient ($\mathrm{d}B/\mathrm{d}z$) of the MOT. For comparison with the theory, Eq. (1) is also plotted in Fig. 2. We give more experimental data points here, and our measurements are found more clearly to be in good agreement with the theoretical prediction of Eq. (1).

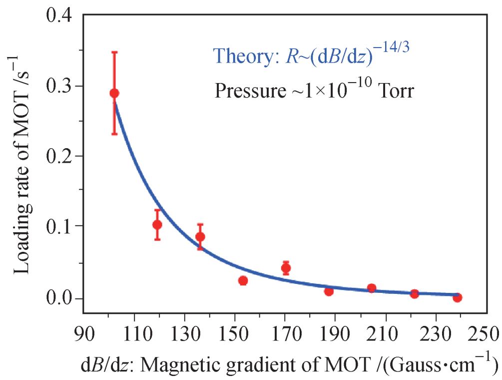

Fig. 2 Atom loading rate versus the magnetic-field gradient of the MOT. The solid circles are experimental data with error bars of ±10%, and the solid line represents the theoretical prediction. The error bars are caused by incomplete and imperfect experimental technique to experimental data.

3.2 Single atom transfer between a MOT and a FORT

A tightly-focused red-detuned far-off-resonance TEM_{00}-mode Gaussian laser beam leads to three-dimensional FORT. In the case of a large detuning and multiple-level atom, the trap potential of the FORT can be written as [3]:

$$U(r,z) = -\frac{\pi c^2}{2}\left(\frac{2\Gamma_{3/2}}{\omega_{3/2}^2\Delta_{3/2}} + \frac{\Gamma_{1/2}}{\omega_{1/2}^2\Delta_{1/2}}\right) I(r,z) \tag{2}$$

where z is the propagation direction of FORT beam and r is the radial coordinate. $\Gamma_{1/2}$ and $\Gamma_{3/2}$ are the spontaneous decay rates of cesium $6\mathrm{P}_{1/2}$ and $6\mathrm{P}_{3/2}$ fine excited states to $6\mathrm{S}_{1/2}$ ground state, respectively; $\omega_{1/2}$ and $\omega_{3/2}$ are the transition angular frequencies for the D_1 ($6\mathrm{S}_{1/2} - 6\mathrm{P}_{1/2}$) and D_2 ($6\mathrm{S}_{1/2} - 6\mathrm{P}_{3/2}$) lines, respectively; $\Delta_{3/2}$ and $\Delta_{1/2}$ are the angular frequency detunings related to the D_1 and D_2 lines, respectively; and $I(r, z)$ is the intensity of the TEM_{00}-mode Gaussian FORT laser beam. At $z = 0$ and $r = 0$, $I(r, z) = I_0 = 2P/(\pi w_r^2)$ is the peak intensity at the beam waist, (where P is the laser power of FORT beam, and w_r is the Gaussian radius at the beam waist), corresponding to the trap depth $U(r = 0, z = 0) = U_0$.

For an atom in the proximity of the harmonic trap, the trap potential can be written as:

$$U(r,z) = U_0\left[1 - 2\left(\frac{r}{w_r}\right)^2 - \left(\frac{z}{z_R}\right)^2\right] \tag{3}$$

where $z_R = 2\pi w_r^2/\lambda$ is the Rayleigh length. The trap frequencies along axial and radial directions were $\omega_{\mathrm{axial}} = 2\pi\nu_{\mathrm{axial}} = \sqrt{2U_0/(mz_R^2)}$ and $\omega_{\mathrm{radial}} = 2\pi\nu_{\mathrm{radial}} = \sqrt{4U_0/(mw_r^2)}$, respectively. The trap depth of our FORT was $U_0 \sim 1.5$ mK for a laser power of 47 mW at 1064 nm and $w_r = 2.3$ μm. This corresponds to a trap frequency along the radial direction (axial direction) of $\nu_{\mathrm{radial}} = 41.4$ kHz ($\nu_{\mathrm{axial}} = 4.3$ kHz).

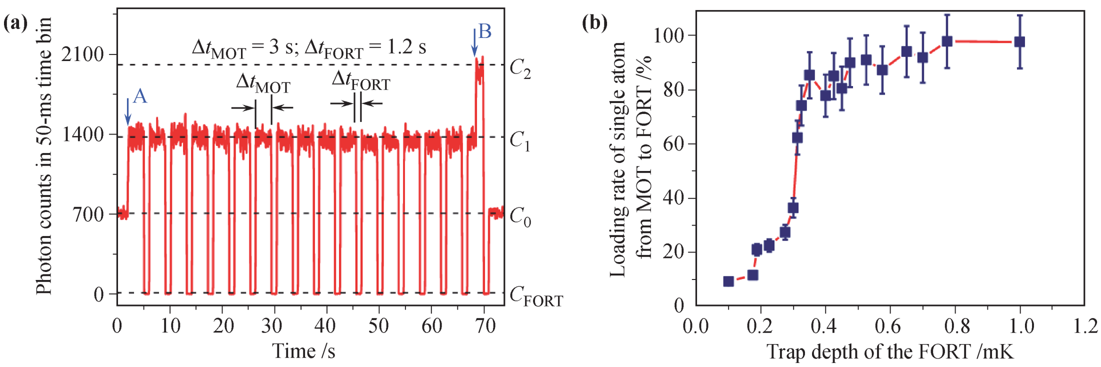

Fig. 3 **(a)** Typical photon-counting signal for transferring single atom between the MOT and the FORT. Blue arrows, A and B, indicate the events in which one more atom is captured in the MOT from the background cesium atoms. $C_{\rm FORT}$ denotes the photon-counting level due to the 1064-nm FORT laser (without the cooling/trapping laser and repumping laser). C_0, C_1, and C_2 denote the photon-counting levels due to no atom, one atom, and two atoms confined in the MOT, respectively (without 1064-nm FORT laser). **(b)** Loading rate of a single atom as a function of the trap depth of the FORT. The error bars are for $\pm5\%$, which is caused partially by imperfect transferring technique and new loading events in transferring process. The solid line is for guiding eyes only.

The MOT and the FORT both had micrometer size scales. Therefore, controlling the geometry of the overlap between the two traps is crucial for transferring the trapped single atom. We optimized the overlap of the two traps on the sub-micrometer scale by minimizing the LIF photon-counting signals, which is dependent on the light shift of the atoms trapped in the FORT. In addition to the geometrical arrangement of the two traps, the loading rate of the FORT is governed by the kinetic energy of the atom, the trap depth of the FORT, and the overlap time of the two traps. A typical LIF photon-counting signal during the transfer of a single atom between the two traps is shown in Fig. 3(a) (typical overlap time of the two traps is 25 ms). After optimization, the trapped single atom can be transferred back and forth between the two traps many times. In the transfer process, we can neglect the loading of the MOT from the background vapor, because the loading rate of the MOT is very low not only because of UHV condition but also for a large-magnetic-field gradient. We also measured the loading rate of a single atom, which depends on the trap depth of the FORT [Fig. 3(b)]. As the trap depth was increased up to $\sim$ 1 mK, the loading rate increased rapidly and then reached saturation slowly.

4 Heating and laser cooling of a single atom in a microscopic FORT

The trapping lifetime of the atoms in the FORT is usually limited by the background collisions. In a UHV environment, the trapping lifetime of atoms is ultimately limited by heating. The primary source of heating is photon-scattering heating. In our case, the scattering rate was $\sim 8\ \mathrm{s}^{-1}$ and the heating rate was only ~ 0.5 μK/s for a 1.5-mK trap depth, which was small enough that the effect of photon-scattering heating could be neglected. The technical noises of the FORT laser beam are the limiting factors of the trapping lifetime.

4.1 The heating dependence of trapped atom in trap on the parameters of FORT

The heating due to the technical noises of the FORT laser beam depends strongly on the parameters of the FORT. Here, following the viewpoint adopted by Thomas *et al.* [9], we use a simple model for the quantitative analysis of the experimental results, in which we treat the FORT as an approximately harmonic trap and the trapped atom as classical mechanical oscillator.

Considering a single atom in a single-beam tightly-focused FORT, the intensity noise and the beam-pointing fluctuation of a FORT laser beam causes fluctuations in the trap depth and the position over time, which leads to heating. In our experiment, the beam pointing noise of the laser source is small, and we used a PM fiber to guide the FORT laser beam to the vacuum cell with very stable laser-to-fiber coupler and fiber-to-laser collimator, so that the beam pointing fluctuation of the laser source is largely transferred into the intensity fluctuation. Here, we neglect the slight heating due to the beam-pointing fluctuation. According to the theoretical analysis the mean energy of the atom trapped in an FORT increases exponentially [9]:

$$\langle E\rangle = E_0 \mathrm{e}^{\varGamma_\varepsilon t} \tag{4}$$

The energy of the atom accumulates over the trapping time, which is determined by the initial energy E_0; and the heating rate constant $\varGamma_\varepsilon = \pi^2\nu^2 S_\varepsilon(2\nu)$, where $S_\varepsilon(2\nu)$ is the one-sided power spectrum of relative intensity noise at a frequency of 2ν, and ν is the trap frequency of the FORT. Figure 4(a) shows the relative intensity noise spectrum S_ε, which can be obtained by measuring the intensity noise spectrum of the FORT laser. Figure 4(b) shows the corresponding heating-rate constant versus the trap frequency.

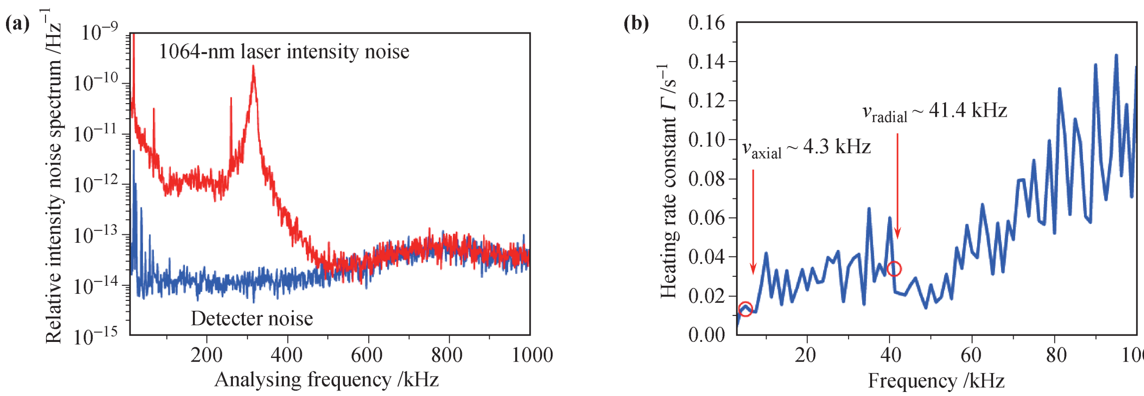

Fig. 4 **(a)** Red line is the relative intensity spectrum, S_ε, for our laser-diode-pumped 1064-nm Nd:YVO_4 laser, and the blue line is the electronic noise of the photodiode and the spectrum analyzer. The intensity noise of our FORT laser beam was measured with an amplified photodiode (bandwidth: DC $\sim$ 5 MHz). By dividing out the DC voltage we can achieve the relative intensity noise. At low frequencies, the pumping noise dominates the intensity noise. The noise peak around 340 kHz is due to relaxation oscillations. **(b)** Calculated heating-rate constant plotted versus the trap frequency.

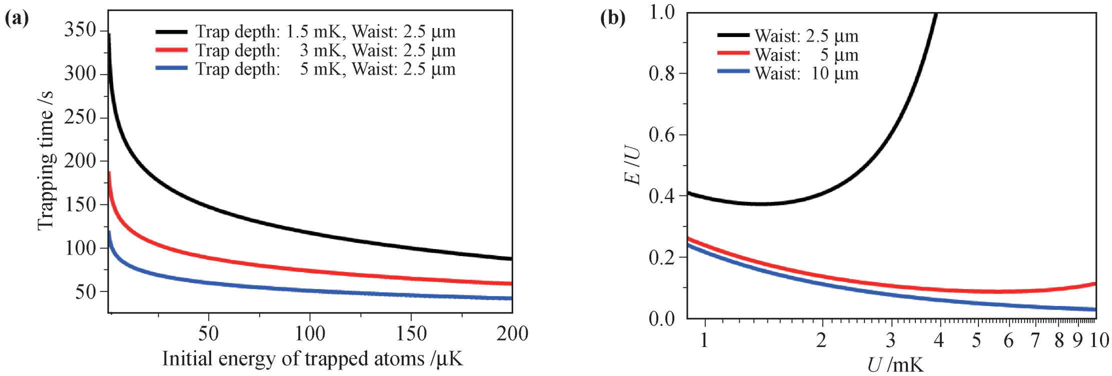

Fig. 5 **(a)** Simulated trapping time as a function of the initial energy of the trapped atom in the FORT. The different color lines represent different trap depths with the same FORT beam's waist 2.5 μm. **(b)** The mean energy of an atom in FORT, E, of the trapped atom due to heating through the intensity noise of the FORT beam versus trap depth, U, for different waist radii. The initial energy of the atom was set to 105 μK. Time scale is $\sim$ 75 s. For different time scale, the heating rate will be different.

The atom will be trapped inside FORT until its accumulated energy allows it to escape ($E_{\max} > U_0$). The time of energy accumulation τ_{heat} can be given by

$$\tau_{\text{heat}} = \frac{m w_r^2}{S_\varepsilon(2\nu) \cdot U_0} \cdot \ln \frac{U_0}{E_0} \tag{5}$$

where w_r is the Gaussian radius at the FORT beam's waist and U_0 is the trap depth. The trapping lifetime depends on the parameters of the FORT. We have determined the relative intensity noise and parameters of the FORT that allow us to simulate the behavior of dependence of τ_{heat} on the parameters of the FORT. Figure 5(a) shows the simulation results of the trapping time versus the initial energy of the trapped atom with typical parameters: $S_\varepsilon(2\nu_r) \approx 1.23\times10^{-12}$ Hz^{-1} at $\nu_{\text{radial}} =$ 41.4 kHz and $S_\varepsilon(2\nu_a) \approx 3.6\times10^{-11}$ Hz^{-1} at $\nu_{\text{axial}} = 4.3$ kHz. The trapping time quickly decreased as the initial energy increased. For different trap depth, the decay behaviors are quite different. Intuitively, the trapping lifetime should increase along with the trap depth. However, the heating rate constant Γ_ε also increases with the trap frequency, especially for a high-trap-frequency FORT with a smaller waist, and Γ_ε increases more quickly than the trap depth. In addition, for different trap waists, the speed of energy accumulation is different. This can be explained using Eq. (5). Figure 5(b) shows the influence of the trap depth and the size of FORT beam waist on the mean energy (E) of an atom in the FORT.

4.2 Laser cooling of single atom in a FORT

The single atom trapped in a FORT can be further laser cooled. Several cooling techniques were developed. Here, we further cooled the tapped single atom via polarization-gradient-cooling (PGC) phase.

A schematic diagram of the time sequence of the laser cooling is shown in Fig. 6(a). According to the sub-Doppler theory of laser cooling [33], the effective temperature after the PGC phase is proportional to the intensity of the cooling laser, and inversely proportional to the frequency detuning. During the PGC cooling phase Δt, the intensities of the cooling laser beams (repumping laser beams) were reduced to 30% ($\sim$25%) of the original values via acousto–optical modulators (AOM), and the effective frequency detuning of the cooling laser beam was passively changed from -2.0γ for MOT to -6.5γ for the PGC phase, in consideration of the shifted $Fg = 4 - Fe = 5$ cycling transition due to the red detuning of the FORT laser.

4.3 The temperature measurement of single atom in FORT

For measuring effective temperature of single atom in optical dipole trap, several works have been done based on different working mechanisms, such as Release-and-recapture (R&R) method [11], spectral analysis of the emitted resonance fluorescence method [19], adiabatic lowering method [34], time-of-flight method [35]. The above mentioned corresponding estimation methods of effective temperature for single atom in FORT are of advantages and disadvantages.

In our experiment, we adopted R&R scheme. In the harmonic approximation of the FORT potential, the velocity distribution of the atom trapped in the FORT follows the Maxwell–Boltzmann law. Therefore, the release and recapture (R&R) technique [36], which is normally used to determine the effective temperature of cold atomic ensemble, could be extended to evaluate the effective temperature of a single atom trapped in a FORT [11]. Based on the statistics of multiple measurements, the velocity distribution for a single atom trapped in a FORT can be described as:

$$f(V) = 4\pi \left(\frac{m}{2\pi k_{\mathrm{B}} T_{\mathrm{e}}}\right)^{3/2} \cdot V^2 \cdot \exp\left(\frac{-mV^2}{2k_{\mathrm{B}} T_{\mathrm{e}}}\right) \tag{6}$$

where V is the velocity of a trapped atom and T_{e} is the effective temperature. The recapture probability for velocity larger than V can be expressed as: $P'(V) = \int_V^\infty f(V')\mathrm{d}V'$. Therefore, after different release time ΔT, the recapture probability, $P(V)$, can be written as:

$$P(V) = 1 - P'(V) = 1 - \int_V^\infty 4\pi \left(\frac{m}{2\pi k_{\mathrm{B}} T_{\mathrm{e}}}\right)^{3/2} \cdot V'^2 \cdot \exp\left(\frac{-mV'^2}{2k_{\mathrm{B}} T_{\mathrm{e}}}\right) \mathrm{d}V' \tag{7}$$

The effective temperature (T_{e}) of the single atom in the FORT can be inferred by leaving T_{e} as a parameter to fit R&R experimental data. The effective temperatures obtained from fittings are 105 ± 12 μK for the case without cooling, and 17 ± 1 μK after one-shot 10-ms laser cooling phase, as shown in Fig. 6(b). The results showed that the mean energy of a trapped single atom is much lower after laser cooling than that without cooling. The ratios between the trap depth of our FORT and the effective temperature of a single atom for the above two cases were 14 for the case without cooling and 88 for the case with one-shot 10-ms cooling phase. This indicated that we were approximately in the harmonic regime of the trapping potential. Note that here we just use a simple model to extract the effective temperature of the single atom in the FORT from the experimental data obtained from R&R measurement. In the simple model the following three aspects, the initial position distribution of atom in the FORT, the influence of gravity on R&R processing, the anisotropy of the FORT, are neglected based on experimental parameters, which may yield errors in some mount in the extracted temperature; but it shows clearly the relative differences in mean energy of a single atom in the FORT for the cases with and without cooling phase.

5 Improvement of the trapping lifetime

In this section, we present experimental results showing the dependence of the trapping lifetime on the background pressure and the effective temperature of a single

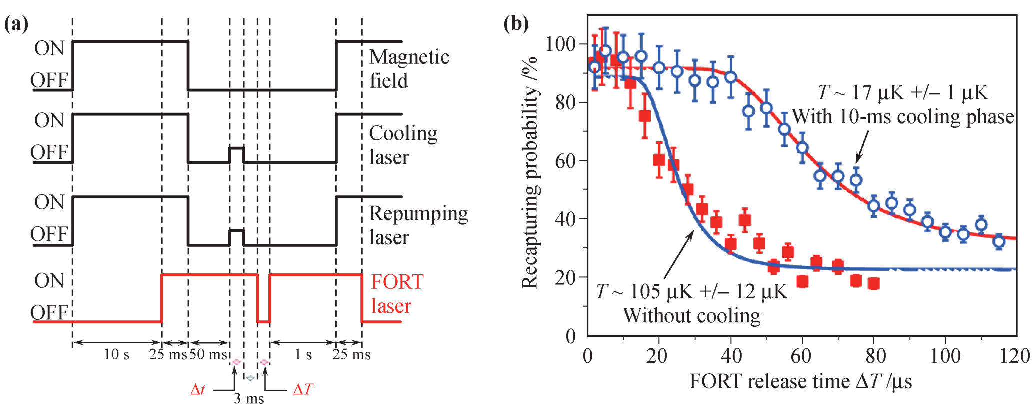

Fig. 6 R&R measurement of a single atom in the FORT. **(a)** Schematic of the time sequence. Δt is the time duration of the laser cooling phase, and ΔT is the FORT release time. **(b)** The recapture probability of a single atom as a function of the FORT release time, ΔT, for the cases with a one-shot 10-ms laser cooling phase (*open circles*) and without laser cooling (*solid squares*). The error bars are for ±5%, which is caused partially by imperfect transferring technique and new loading events in transferring process. Each experimental data point is from the accumulation of at least 100 sequences. The solid lines are theoretical fittings according to Eq. (7). The effective temperatures with statistical errors are extracted from the fittings.

atom trapped in the FORT.

5.1 Extension of the trapping lifetime by improving the background pressure

The trapping lifetime of the atoms in a FORT is usually limited by the background collisions. The trapping life determined [37] by τ_{back} can be written as $\tau_{\text{back}} = (\pi m k_{\text{B}} T_{\text{b}}/8)^{1/2}/(\sigma P_{\text{b}})$, where m is mass of trapped atom, k_{B} is the Boltzmann constant, σ is the cross section of the two-body collision between the cold atoms trapped in the FORT and hot atoms in background, T_{b} is room temperature and P_{b} is the background pressure. Improving the background pressure can prolong the trapping life of trapped atoms. We examined the trapping lifetime of single atom in the FORT for the background pressure condition, 1×10^{-10} Torr and 2×10^{-11} Torr.

Figure 7 shows the measured survival probabilities of a single atom as a function of Δt_{FORT} for two different background pressure values. The trapping lifetime was found to be 6.9 ± 0.3 s for a background pressure of 1×10^{-10} Torr [24], and 75.3 ± 5.3 s for 2×10^{-11} Torr, respectively. Roughly, decease in pressure by one order of magnitude yields an increase in the trapping lifetime by also one order of magnitude.

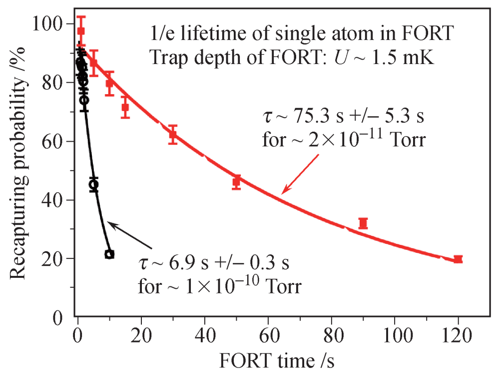

Fig. 7 Trapping lifetime of single atom in the FORT is clearly extended by improving the background pressure. The corresponding solid lines are given by the exponential decay fitting [$P(t) = P_0 \exp(-t/\tau)$, τ is the 1/e trapping lifetime]. The error bars are for ±5%, which is caused partially by imperfect transferring technique and new loading events in transferring process. Each data point is derived from at least 100 sequences.

5.2 Improvement of the trapping lifetime via laser cooling

Based on the theoretical analysis in Section 4, when the initial energy of the trapped atom is decreased, a longer lifetime is expected. In Fig. 8, we compare the trapping lifetime for cases with and without laser cooling phase. For a background pressure of $P_{\text{b}} = 2 \times 10^{-11}$ Torr, the trapping lifetime of the single atom from fittings is 75.3 ± 5.3 s for the case without cooling, and 130.6 ± 1.8 s for the case with one-shot 10-ms laser cooling phase, respectively. The lifetime of a single atom in the FORT is clearly extended through just one-shot laser cooling phase. These results are in good agreement with the theoretical predictions, which gave a trapping lifetime of 96 s for an initial temperature of 105 μK, and 162 s for 17 μK, respectively. The discrepancy between experimental data and theoretical predictions maybe caused by neglecting weak heating due to the FORT beam-pointing fluctuation in our model.

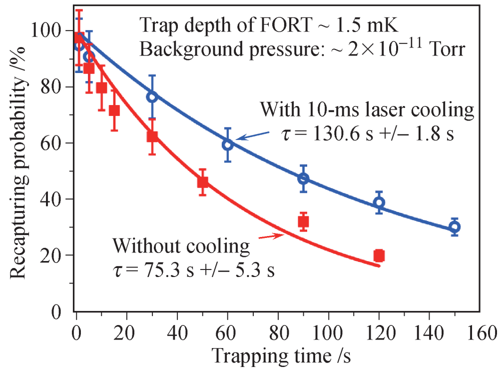

Fig. 8 Trapping lifetimes of single atom in the FORT for the case with one-shot 10-ms laser cooling phase (*open circles*) just after a single atom is transferred from the MOT into the FORT and that without laser cooling (*solid squares*). The corresponding solid lines are given by the exponential decay fitting [$P(t) = P_0 \exp(-t/\tau)$, τ is the 1/e trapping lifetime]. The error bars are for ±5%, which is caused partially by imperfect transferring technique and new loading events in transferring process. Each data point is derived from at least 100 sequences. In the latter case, the relatively fast decay was due to the heating arising from the technical noise of the FORT laser beam.

Achievement of longer trapping lifetime requires a much lower initial energy of trapped atoms and lower heating rate. The heating mechanisms described above are intrinsic to any optical dipole trap, but they play different roles in different kinds of traps. In the experiment of Ref. [34], there is an additional technical noise due to fluctuations of the relative phase between the two laser beams in stand-wave trap, which results in a largely heating rate. Besides, we achieved much lower initial energy of trapped atom. Based on the above reasons, we achieved longer trapping lifetime of single atoms in the FORT. In addition, the relative intensity noise of the trapping laser used in our experiment is two or three orders higher than those used in Refs. [10, 12], and we did not attempt to suppress the intensity noise in current stage of our experiment. To actively suppress the intensity noise of the FORT laser, a noise-eater system can be implemented. In this work we adopted one-shot 10-ms laser cooling phase just after the single atom prepared in the MOT is transferred into the FORT to decrease the effective temperature of single atom. Therefore, the trapping lifetime of 130 s we obtained is useful for coherent manipulation and readout of quantum state of the single atom.

6 Conclusions

In conclusion, we considered a single atom in a tightly-focused single-TEM_{00}-beam FORT, and discussed the dependence of the trapping lifetime on the FORT parameters, which allowed us to differentiate between the various heating mechanisms both theoretically and experimentally. The results showed that controlling the initial energy of the trapped atoms and the parameters of the FORT allow us to improve the trapping lifetime significantly. A single atom prepared in a large-magnetic-gradient MOT can be efficiently loaded into a microscopic FORT. The R&R technique is extended to evaluate the effective temperature of a single atom trapped in the FORT, which yielded similar results to previous studies. We have demonstrated that the trapping lifetime can be extended from 6.9 s to 75 s by improving the background pressure from $\sim 1 \times 10^{-11}$ Torr to $\sim 2 \times 10^{-11}$ Torr, and can be further improved up to 130 s by adopting one-shot 10-ms laser cooling phase just after the single atom prepared in the MOT is transferred into the FORT.

A longer-lived single atom with a lower effective temperature in a FORT is a good candidate to serve as a basis for a triggered single-photon source [5]. In such a system, the longer trapping lifetime would improve the generated photon numbers before the atom escapes, and the lower energy of single atom would narrow the linewidth of the laser-induced-fluorescence spectrum of the emitted photons [19], and therefore would make much less distinguishable single photons. Furthermore, a long-lived single atom in a FORT can also serve as a good qubit system [14, 15], in which lower energy of single atoms would improve the dephasing time. Moreover, long-lived atoms with a lower effective temperature may be significant for applications in precision spectroscopy and optical clocks.

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References

1. S. Chu, J. E. Bjorkholm, A. Ashkin, and A. Cable, Phys. Rev. Lett., 1986, 57: 314
2. J. D. Miller, R. A. Cline, and D. J. Heinzen, Phys. Rev. A, 1993, 47: R4567
3. R. Grimm, M. Weidemuller, and Y. Ovchinnikov, Adv. At. Mol. Opt. Phys., 2000, 42: 95
4. D. Schrader, I. Dotsenko, M. Khudaverdyan, Y. Miroshnychenko, A. Rauschenbeutel, and D. Meschede, Phys. Rev. Lett., 2004, 93: 150501
5. B. Darquie, M. P. A. Jones, J. Dingjan, J. Beugnon, S. Bergamini, Y. Sortais, G. Messin, A. Browaeys, and P. Grangier, Science, 2005, 309: 454
6. J. Volz, M. Weber, D. Schlenk, W. Rosenfeld, J. Vrana, K. Saucke, C. Kurtsiefer, and H. Weinfurter, Phys. Rev. Lett., 2006, 96: 030404
7. S. J. M. Kuppens, K. L. Corwin, K. W. Miller, T. E. Chupp, and C. E. Wieman, Phys. Rev. A, 2000, 62: 013406
8. P. Phoonthong, P. Douglas, A. Wickenbrock, and F. Renzoni, Phys. Rev. A, 2010, 82: 013406
9. T. A. Savard, K. M. O'Hara, and J. E. Thomas, Phys. Rev. A, 1997, 56: R1095
10. K. M. O'Hara, S. R. Granade, M. E. Gehm, T. A. Savard, S. Bali, C. Freed, and J. E. Thomas, Phys. Rev. Lett., 1999, 82: 4204
11. C. Tuchendler, A. M. Lance, A. Browaeys, Y. R. P. Sortais, and P. Grangier, Phys. Rev. A, 2008, 78: 033425
12. M. J. Gibbons, S. Y. Kim, K. M. Fortier, P. Ahmadi, and M. S. Chapman, Phys. Rev. A, 2008, 78: 043418
13. S. Kuhr, W. Alt, D. Schrader, I. Dotsenko, Y. Miroshnychenko, A. Rauschenbeutel, and D. Meschede, Phys. Rev. A, 2005, 72: 023406
14. D. D. Yavuz, P. B. Kulatunga, E. Urban, T. A. Johnson, N. Proite, T. Henage, T. G. Walker, and M. Saffman, Phys. Rev. Lett., 2006, 96: 063001
15. M. P. A. Jones, J. Beugnon, A. Gaetan, J. Zhang, G. Messin, A. Browaeys, and P. Grangier, Phys. Rev. A, 2007, 75: 040301
16. E. Urban, T. A. Johnson, T. Henage, L. Isenhower, D. D. Yavuz, T. G. Walker, M. Saffman, Nat. Phys., 2009, 5: 110
17. A. Gaetan, Y. Miroshnychenko, T. Wilk, A. Chotia, M. Viteau, D. Comparat, P. Pillet, A. Browaeys, and P. Grangier, Nat. Phys., 2009, 5: 115
18. Z. C. Zuo, M. Fukusen, Y. Tamaki, T. Watanabe, Y. Nakagawa, and K. Nakagawa, Opt. Express, 2009, 17: 22898
19. M. Weber, J. Volz, and K. Saucke, C. Kurtsiefer, and H. Weinfurter, Phys. Rev. A, 2006, 73: 043406
20. Z. Hu and H. J. Kimble, Opt. Lett., 1994, 19: 1888
21. F. Ruschewitz, D. Bettermann, J. L. Peng, and W. Ertmer, Europhys. Lett., 1996, 34: 651
22. D. Haubrich, H. Schadwinkel, F. Strauch, B. Ueberholz, R.Wynands, and D. Meschede, Europhys. Lett., 1996, 34: 663
23. J. Wang, J. He, Y. Qiu, B. D. Yang, J. Y. Zhao, T. C. Zhang, and J. M. Wang, Chin. Phys. B, 2008, 17: 2062
24. J. He, J. Wang, B. D. Yang, T. C. Zhang, and J. M. Wang, Chin. Phys. B, 2009, 18: 3404
25. S. B. Hill and J. J. McClelland, Appl. Phys. Lett., 2003, 82: 3128
26. S. Yoon, Y. Choi, S. Park, J. Kim, J. H. Lee, and K. An, Appl. Phys. Lett., 2006, 88: 211104
27. N. Shclosser, G. Reymond, I. Protsenko, and P. Grangier, Nature, 2001, 411: 1024
28. J. M. Wang, J. He, B. D. Yang, T. C. Zhang, and K. C. Peng, Proc. SPIE, 2010, 7727: 77270U

29. D. Haubrich, A. Hope and D. Meschede, Opt. Commun., 1993, 102: 225
30. Y. Nakagawa, Private communication
31. Y. Choi, S. Yoon, S. Kang, W. Kim, J. H. Lee, and K. An, Phys. Rev. A, 2007, 76: 013402
32. J. He, B. D. Yang, T. C. Zhang, and J. M. Wang, J. Phys. D: Appl. Phys., 2011, 44: 135102
33. H. J. Metcalf and P. van der Straten, Laser cooling and trapping, New York: Springer-Verlag, 1999
34. W. Alt, D. Schrader, S. Kuhr, M. Muller, V. Gomer, and D. Meschede, Phys. Rev. A, 2003, 67: 033403
35. A. Fuhrmanek, A. M. Lance, C. Tuchendler, P. Grangier, Y. R. P. Sortais, and A. Browaeys, New J. Phys., 2010, 12: 053028
36. S. Chu, L. Hollberg, J. E. Bjorkholm, A. Cable, and A. Ashkin, Phys. Rev. Lett., 1985, 55: 48
37. A. M. Steane, M. Chowdhury, and C. J. Foot, J. Opt. Soc. Am. B, 1992, 9: 2142