Extending a release-and-recapture scheme to single atom optical tweezer for effective temperature evaluation*

He Jun(何 军), Yang Bao-Dong(杨保东),
Zhang Tian-Cai(张天才), and Wang Jun-Min(王军民)†

State Key Laboratory of Quantum Optics and Quantum Optics Devices, and Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, *China*

(Received 8 December 2010; revised manuscript received 22 February 2011)

By recording the fluorescence fraction of the cold atoms remaining in the magneto-optical trap (MOT) as a function of the release time, the release-and-recapture (R&R) method is utilized to evaluate the effective temperature of the cold atomic ensemble. We prepare a single atom in a large-magnetic-gradient MOT and then transfer the trapped single atom into a 1064-nm microscopic optical tweezer. The energy of the single atom trapped in the tweezer is further reduced by polarization gradient cooling (PGC) and the effective temperature is evaluated by extending the R&R technique to a single atom tweezer. The typical effective temperature of a single atom in the tweezer is improved from about 105 μK to about 17 μK by applying the optimum PGC phase.

Keywords: single atom, optical tweezer, effective temperature, release-and-recapture technique

PACS: 37.10.De, 37.10.Gh, 87.80.Cc, 42.50.–p **DOI:** 10.1088/1674-1056/20/7/073701

1. Introduction

The single atom is a nearly perfect quantum system. It allows us to demonstrate many non-classical properties and verify some quantum theories based on a trapped single atom. In all the applications of a single atom in quantum computer and quantum information processing, the control of all degrees of freedom is required. This is obvious in that the demonstrations of many of the experiments rely on the ability not only to manipulate the internal states, in which the quantum information is encoded, but also to control the external states, such as spatial locality, temperature and trapping lifetime.[1−3]

With the help of the optical field gradient force, an optical tweezer[4−7] can trap objects with its large restoring force and long coherence time. In particular, the far-off-resonance microscopic optical trap (tweezer) can realize the 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.[1−3,8−10] However, high-temperature atoms in the tweezer lead to an inhomogeneous broadening of the transition frequency and a short trapping lifetime. These have been shown to be able to limit the further applications in many experiments. For instance, the inhomogeneous dephasing of atomic qubits arises because of the large spatial variation of the trapped atom.[11−13] When the two-photon stimulated Raman adiabatic passage is used to prepare the trapped atom in a coherent superposition quantum bit (qubit) state, the Rabi oscillation signals damp quickly. The trapped atoms have different light shifts, thereby yielding very short decoherence time for atomic qubits.[14−16] Using laser cooling, the temperature of the trapped atoms can be decreased.[2,17] Furthermore, the application of cooling may contribute to the improvement of the quantum coherence of the trapped atoms. For the above-mentioned applications, lower-energy trapped atoms may extend the dephasing time or the decoherence time. In addition, cooling can reduce the energy of the trapped atoms and keep trapped atoms at the bottom of the tweezer. Therefore, the linewidth of the fluorescence spectrum of the emitted single photons from the single atom trapped in the tweezer is narrowed.[11]

The effective temperature of a single atom in the optical tweezer is an important parameter in many atom-photon experiments. Therefore, the implementation and the evaluation of the cooling efforts are

*Project supported by the National Natural Science Foundation of China (Grant Nos. 60978017, 61078051 and 10974125), the Science Fund for Creative Research Groups of the National Natural Science Foundation of China (Grant No. 60821004) and the Program for New Century Excellent Talents of Ministry of Education of China (Grant No. NCET-07-0524).

†Corresponding author. E-mail: wwjjmm@sxu.edu.cn

© 2011 Chinese Physical Society and IOP Publishing Ltd

important for many purposes. For a single atom trapped in a tweezer, the temperature cannot be measured directly. One usually measures the position, the velocity or the energy distribution of the trapped atom, from which the temperature is then deduced. In recent years, some efforts have been made to achieve the temperature of a single atom in the optical tweezer.[11,17–19] Release-and-recapture (R&R) is a common way to study the properties of trapped cold atoms. It provides a measurement of the velocity distribution. Therefore, the R&R technique[20] can be extended to evaluate the effective temperature of a single atom in a tweezer.[17]

In this paper, we describe an experimental system which can load a single atom from a magneto-optical trap (MOT) into a microscopic tweezer with high efficiency. The effective temperature of the single atom in the microscopic tweezer is decreased by polarization gradient cooling (PGC) and the R&R technique is extended to measure the effective temperature of a single atom. The experimental results are discussed in detail.

2. Experimental setup

A schematic diagram of the experimental setup is shown in Fig. 1. The details have been described elsewhere.[21–23] A glass ampoule containing high purity cesium atoms which can be released into the MOT area by a special ultra-high vacuum (UHV) mechanic shutter was sealed in an oxygen-free copper tube as the cesium atom source. 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 the 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 and 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). The laser frequency was stabilized by 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, which yielded a magnetic field gradient of ∼30 mT/cm (about 300 Gauss/cm) in the axial direction of the coils, could be switched off completely within 3.9 ms by using our control electronic circuits. The laser-induced fluorescence (LIF) 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) working in the photon-counting mode.

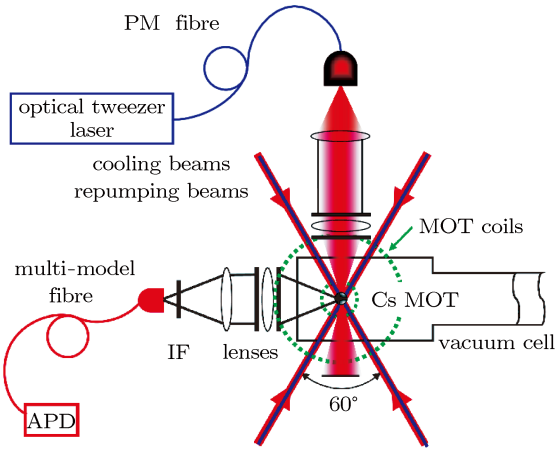


Fig. 1. (colour online) Schematic diagram of the experimental setup. APD: avalanche photodiode working in the photon-counting mode, IF: 852-nm interference filter, PM fibre: polarization-maintaining fiber.

The tweezer 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) fibre to a lens that expands the beam diameter to about 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 background photon-counting rate for the tweezer 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. Loading single atom from an MOT into a microscopic optical tweezer

A tightly-focused red-detuned far-off-resonance TEM_{00}-mode Gaussian laser beam leads to three-dimensional tweezer. In the case of a linearly-polarized laser beam, a large detuning and multiple-level cesium atoms, the trap potential of the tweezer

can be written as[6]

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

where z is the propagation direction of tweezer beam; r is the radial coordinate; $\Gamma_{1/2}$ and $\Gamma_{3/2}$ are the spontaneous decay rates of cesium $6P_{1/2}$ and $6P_{3/2}$ fine excited states to $6S_{1/2}$ ground state, respectively; $\omega_{1/2}$ and $\omega_{3/2}$ are the transition angular frequencies for the D_1 ($6S_{1/2}$–$6P_{1/2}$) and D_2 ($6S_{1/2}$–$6P_{3/2}$) lines, respectively; $\Delta_{3/2}$ and $\Delta_{1/2}$ are the angular frequency detunings related to the D_1 and D_2 lines, respectively; $I(r,z)$ is the intensity of the TEM_{00}-mode Gaussian 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 (P is the laser power of tweezer beam, 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 harmonic trap, the trap potential can be written as

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

where $z_R = 2\pi w_r^2/\lambda$ is the Rayleigh length. The trap frequencies along axial and radial directions are $\omega_{axial} = 2\pi\nu_{axial} = \sqrt{2U_0/mz_R^2}$ and $\omega_{radial} = 2\pi\nu_{radial} = \sqrt{4U_0/mw_r^2}$, respectively. The trap depth is ∼1.5 mK with a laser 1064 nm power of 47 mW, which corresponds to trap frequency along the radial direction (axial direction) $\omega_r = 2\pi \times 41.4$ kHz ($\omega_a = 2\pi \times 4.3$ kHz).

Deterministic-number atoms in optical tweezer are necessary for many experiments in quantum information processing, cold collisions and precision measurement. Besides, many experiments rely on examining whether there is an atom in MOT after manipulation in tweezer. Therefore, a well-separated discrete LIF photon-counting level and a highly efficient loading and transferring rate are crucial. As shown in Figs. 2(a) and 2(b), we have achieved remarkable improvement on the signal-to-noise ratio of LIF photon-counting signals by optimizing the intensity and the frequency detuning of cooling/trapping laser and using modulation-free polarization spectroscopic technique with feedback to both of the slow channel (piezoelectric transducer channel in the grating extended cavity with a typical bandwidth of ∼ 2 kHz) and the fast channel (current modulation channel in the current driver with a typical bandwidth of ∼ 200 kHz), which has been discussed in details in Ref. [24]. Here, we present a method of transferring a single atom between two microscopic traps,[21−23] which is achieved by controlling and optimizing the parameters of the MOT and the tweezer.

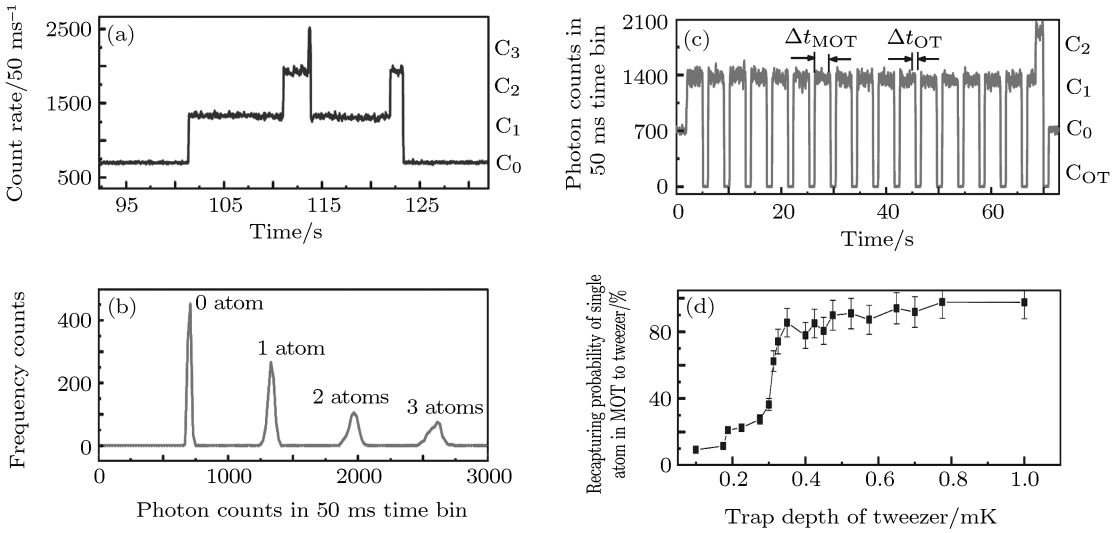


Fig. 2. Typical LIF photon-counting signals of trapped atoms. (a) Separated discrete LIF photon-counting levels, with C_0, C_1 C_2 and C_3 denoting the photon-counting rate levels in a time bin of 50 ms for no atom, one atom, two atoms and three atoms in MOT, respectively; (b) the histogram of the photon counting data, (c) the transferring of the single atom between the MOT and the optical tweezer, with C_{OT} denoting the photon count level due to the 1064-nm tweezer laser (without the cooling/trapping laser and repumping laser), Δt_{MOT} and Δt_{OT} are the trapping time of the single atom in the MOT and in the tweezer, respectively; (d) the recapture probability of a single atom as a function of the trap depth of the tweezer (The error bars are for ±5%, which is caused partially by imperfect transferring and new loading events in transferring process. The solid line is for guiding).

The loading rate depends on the geometric arrangement and time overlap between the MOT and the tweezer, the kinetic energy of the atom, the trap depth of tweezer, since a single atom can be caught by the optical tweezer only at the place where the trap depth exceeds the atomic kinetic energy. The trap depth is changed by varying the tweezer laser's power, which can be easily controlled to be much larger than the kinetic energy of the single atom precooled in MOT. In our system, the MOT and the tweezer both have micrometer size scales. Therefore, controlling the geometry of overlap between the two traps is important in the first step. We optimized the overlap between the two traps by minimizing the LIF photon counting signal, which is dependent on the light shift of the atoms trapped in the tweezer. For the optimum condition we can control the geometry of overlap on a micrometer scale. The loading rate of the tweezer also depends on the overlap time between the two traps. Obviously, if the overlap time is too short, the loading process will not be finished. On the contrary, if the overlap time is too long, the collision probability will be increased due to the existence of nearly resonant lasers of MOT, which will decrease the loading rate. In our experiment, the optimum overlap time is about 25 ms. In addition to the above factors, we also need to optimize the magnetic field gradient to a suitable value, with which the loading rate of MOT is not so small that we can load a new atom in case of losing one. Furthermore, the current of MOT coils can be turned off within the millisecond scale, which is crucial to the experiment when we transfer a single atom between the MOT and the tweezer. The existence of the magnetic field and fluctuation during the shutting off will not only seriously decrease the loading rate of a single atom in tweezer, but also make the trapped atoms in the typical quantum state tangled and complicated.

A typical LIF photon-counting signal during the transfer of a single atom between the two traps is shown in Fig. 2(c). Under optimal conditions, 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 vapour, because the loading rate of the MOT is very low not only for UHV conditions but also for a large-magnetic-field gradient. This efficient transfer is employed to determine the trapping lifetime and the effective temperature of the single atom in the tweezer. In addition, it is possible to adopt such a technique combined with state-selective detection to detect the quantum coherent superposition state of the trapped atom. We also measure the recapture probability of a single atom as a function of the trap depth of the tweezer. As the trap depth is increased to $\sim$1 mK, the recapture probability increases rapidly and then reaches saturation slowly. This process is shown in Fig. 2(d). Of course, the high loading rate cannot rely on increasing the trap depth of tweezer. If the trap depth is too deep, the light shift will be too large which is not good for detection and manipulation of atoms.

4. Laser cooling and temperature measurement of a single atom in a tweezer

Several techniques were developed to cool the single trapped atom. As the trap size w_0 is much larger than the wavelength λ of the tweezer laser (most cases of the traveling-wave trap), the trapped atom can be cooled by all kinds of cooling techniques in free space.[17,20,25] For the case of $w_0 < \lambda$ (most cases of the standing-wave trap, or called optical lattice), the motion of trapped atoms is strongly localized and the vibration states of atoms must be taken into account especially in the Lamb-Dicke regime. Making use of the participation of the vibration states one can cool the trapped atoms via Raman side-banding cooling[26] and cavity cooling.[27] In addition, there are a variety of cooling mechanisms for atoms trapped in tweezer, such as evaporative cooling,[17,28,29] adiabatic lowering potential (adiabatic cooling),[17,18,30] and selective parametric excitation cooling.[31]

A single atom is prepared in MOT, which is cooled there by the Doppler cooling mechanism and the energy distribution follows that of an ensemble of classic harmonic oscillators at temperature T. When a single atom is loaded into a tweezer, the energy is on the order of Doppler temperature. This is lower than the trap depth so that the trapped atom remains close to the bottom of the trap, and the tweezer can be treated approximately as a harmonic trap. For an atom with Doppler temperature, the mean energy is much larger than the energy of eigenstate of quantum oscillator, which is separated by $\hbar\omega$ (ω is the trap frequency). Therefore, the trapped atom can be treated as a classical harmonic oscillator. For our case, the trapped atom in a tweezer can be further cooled via PGC.[25] Here, it is sufficient to treat the tweezer in the harmonic approximation and the velocity distribution of the atom with the Maxwell–Boltzmann law. Therefore, R&R technique could be extended to evaluating the effective temperature of a single atom in a tweezer. Note that the effective temperature of a single atom is deduced by averaging the energy over many instances

of the experiment under the same conditions. On average, a single atom with a higher kinetic energy is more likely to escape from the tweezer during the tweezer release time, ΔT, than an atom with a lower kinetic energy. Thus, different trends of the recapture probability P versus the tweezer release time ΔT curve show different kinetic energy trends for the trapped atom.

Here we are primarily concerned with the relative values of the effective temperatures with different PGC phases. Therefore, we adopt a simplified method to obtain the effective temperature of the single atom in the tweezer based on the R&R measurement. Based on the statistics of multiple measurements, the velocity distribution for a single atom trapped in a tweezer can be described as

$$f(V) = 4\pi\left(\frac{m}{2\pi k_{\rm B}T_{\rm e}}\right)^{3/2} V^2 \exp\left(\frac{-mV^2}{2k_{\rm B}T_{\rm e}}\right), \quad (3)$$

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

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

Although it was not so easy to solve the integral analytically, the effective temperature ($T_{\rm e}$) of the single atom in tweezer still can be inferred by taking $T_{\rm e}$ as a parameter to fit R&R experimental data. For the simplified approximation, V can be taken to be $2w_{\rm r}/\Delta T$ and ΔT is the independent variable.

5. Experimental results and discussion

A schematic diagram of the time sequence for cooling and temperature measurement is shown in Fig. 3. The cooling light is provided by the laser beams used to form the MOT. According to the sub-Doppler theory of laser cooling,[25] 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, the intensities of the cooling laser beams (repumping laser beams) are reduced to 30%

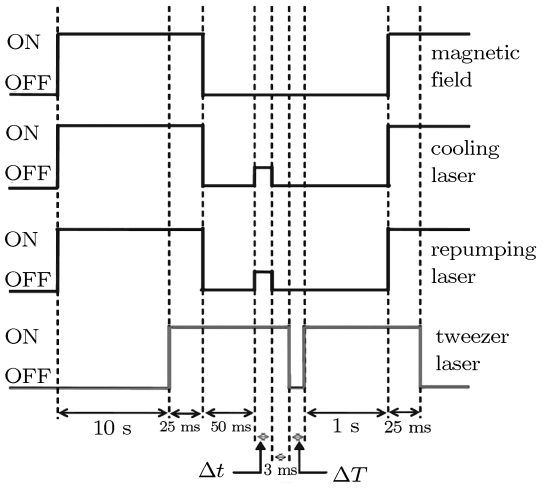


Fig. 3. Schematic diagram of the time sequence of R&R measurement of a single atom in a microscopic optical tweezer, with Δt being the duration of the laser cooling phase.

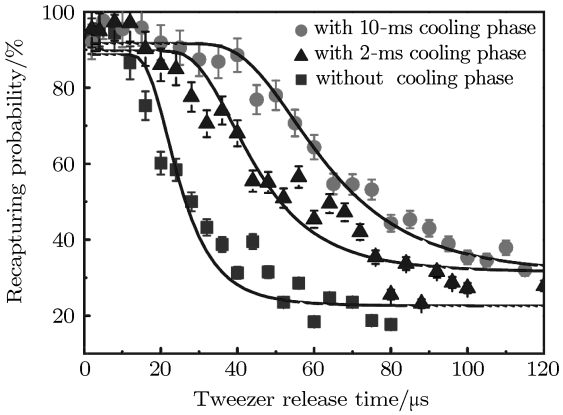


Fig. 4. Measurement of the effective temperature of a single atom in the optical tweezer using the R&R technique. The recapture probability of a single atom as a function of the tweezer release time depends on the cooling time. The error bars are for ±5%, which is caused partially by imperfect transfer and new loading events in the transferring process. Each experimental data point is from the accumulation of at least 100 sequences. The solid lines denote theoretical fittings according to Eq. (4). The effective temperatures are (105 ± 12) μK for the case without cooling, (33 ± 3) μK for the case with a 2-ms laser cooling phase and (17 ± 1) μK for the case with a 10-ms laser cooling phase.

($\sim$ 25%) of the original values via acousto-optical modulators (AOM) and the effective frequency detuning of the cooling laser is passively changed from -2.0γ for MOT to -6.5γ for the PGC phase, with the consideration of the shifted Fg=4–Fe=5 cycling transition due to the red detuning of the trap laser. The effective temperatures obtained from fitting are (105±12) μK for the case without cooling, (33±3) μK

for the case with a 2-ms laser cooling phase and (17±1) μK for the case with a 10-ms laser cooling phase (see Fig. 4). Note that in our experiment the shutoff time of the tweezer is less than 100 ns, which is much less than the oscillation period of tweezer (> 10 μs). It means that the trapped atom could not adiabatically follow the lowering of the trap depth of tweezer during tweezer shutoff, thus there is almost no adiabatic cooling.

The results show that the mean energy of a single trapped atom is much lower after laser cooling than in the case without cooling. The ratios between the trap depth of our tweezer and the effective temperature of a single atom for the 105 μK and 17 μK are 14 for the case without cooling and 88 for a 10-ms cooling phase. This indicates that we are approximately in the harmonic regime of the trapping potential. For the case of 17 μK, the temperature is about 85 times the recoil temperature (the recoil temperature is about 198 nK for cesium atom). The cooling parameters, cooling laser intensity, frequency detuning and cooling time have not been further optimized. After compensation of the geomagnetic field of the trapping area by controlling the currents of the three pairs of Helmholtz coils, the residual magnetic field is estimated to be 2 μT ($\sim$ 20 mGauss), which is detrimental to the effectiveness of the PGC phase. Under optimal conditions, it can yield a lower temperature.

Note that the three aspects in the simple model, i.e., the initial position distribution of the atom in the tweezer, the influence of gravity on R&R process and the anisotropy of the tweezer, are neglected and discussed below:

1) Initial position distribution of the atom in the tweezer. The velocity distribution is given in Eqs. (3) and (4) to help to understand the physics. We can give the energy distribution as well. As the trap depth is far higher than the mean energy of a trapped atom and the mean energy of the atom is far higher than the energy of eigenstate of quantum oscillator, we can consider this trap within a harmonic regime. The atoms are trapped close to the bottom of the tweezer. Therefore, we neglect the initial position distribution of the atom.

2) The influence of gravity on the R&R process. When we adopt the R&R method to infer the energy distribution of the single atom in tweezer, we shut off the tweezer within several tens of nanoseconds. Within this time scale, atom moving infected by gravity will be smaller than the tweezer beam waist. Therefore, we neglect the effect of the gravity.

3) Anisotropy of the tweezer. The tweezer generated by focusing Gaussian TEM_{00}-mode single laser beam in the radial direction and the axial direction is very different. It is not so easy to solve the integral analytically. The effective temperature (T_e) of a single atom in tweezer can be inferred by taking T_e as a parameter to fit R&R experimental data. For the tightly-focused tweezer, the angle of the divergence is quite large. When the longitudinal displacement equals to a half of Rayleigh length, the trap depth is lowered to less than $\sim 8.7\%$ of the trap depth at the beam waist. Possibility of recapturing atoms is small. Therefore, we neglect the anisotropy of the tweezer. The simple model we adopted is rough, thereby possibly yielding errors to some extent in the extracted temperature, but our simple model still can clearly show the difference in effective temperature of a single atom between the cases with and without cooling. In fact, the effective temperature value which is inferred from the simple model we adopted are similar to that extracted from R&R data by the Monte Carlo simulation in Ref. [17] and also are comparable to that extracted from the time-of-flight (TOF) image measurement in Ref. [19].

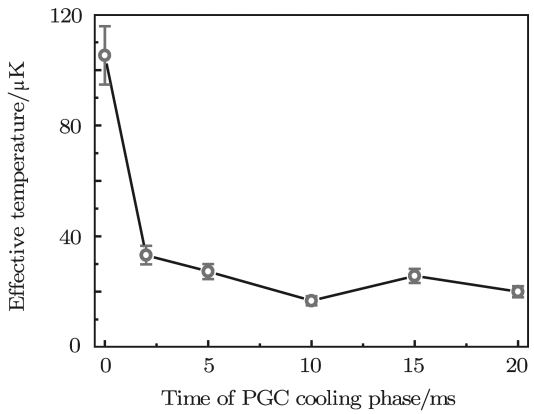


Fig. 5. Dependence of the effective temperature of a single atom in the microscopic optical tweezer on the duration time of the PGC cooling phase. The error bars for ±5% are given in terms of statistical standard deviation. The solid line is only for guiding eyes.

Most of the coherent manipulations of the trapped atom are performed on a millisecond or microsecond scale and the energy increase of the trapped atom due to heating needs to counteract quickly. For example, in the experiment of triggered single photon source,[2] trapped atoms are working only in 115 μs of every working cycle and need to be cooled down in the remaining 885 μs in order to prevent single atoms from escaping out of the tweezer for all kinds of heating. If the parameters of the tweezer and the cooling laser can be further optimized, the generation rate of single photons will be further enhanced by reducing the

cooling phase. Here, we give only the dependence of effective temperature on PGC cooling time as shown in Fig. 5. The results show that the effective temperature can be cooled down on a millisecond scale.

6. Conclusion

We analyse theoretically and experimentally the energy distribution of a single atom in an optical tweezer. The R&R mechanism is extended to evaluating the effective temperature of a single atom in the tweezer and the typical temperature is lowered from ~ 105 μK to ~ 17 μK. All experimental measurements are based on the highly efficient transfer technique of a single atom between two traps. We also discuss and analyse in detail the experimental results associated with our temperature measurements. The measurement of temperature is significant for evaluating the cooling effects which can be used to improve the external state of a single atom in an optical tweezer. With optimum cooling, a single atom in tweezer can be cooled down closed to ground states. A single trapped atom with a lower effective temperature in a microscopic tweezer is a good candidate to serve as a basis for a triggered single-photon source. In such a system, the lower energy would prolong the trapping lifetime and narrow the linewidth of the fluorescence spectrum of the emitted photons.

References

[1] Schrader D, Dotsenko I, Khudaverdyan M, Miroshnychenko Y, Rauschenbeutel A and Meschede D 2004 *Phys. Rev. Lett.* **93** 150501

[2] Darquie B, Jones M P A, Dingjan J, Beugnon J, Bergamini S, Sortais Y, Messin G, Browaeys A and Grangier P 2005 *Science* **309** 454

[3] Volz J, Weber M, Schlenk D, Rosenfeld W, Vrana J, Saucke K, Kurtsiefer C and Weinfurter H 2006 *Phys. Rev. Lett.* **96** 030404

[4] Chu S, Bjorkholm J E, Ashkin A and Cable A 1986 *Phys. Rev. Lett.* **57** 314

[5] Miller J D, Cline R A and Heinzen D J 1993 *Phys. Rev.* A **47** R4567

[6] Grimm R, Weidemuller M and Ovchinnikov Y 2000 *Adv. At. Mol. Opt. Phys.* **42** 95

[7] Neuman K C and Block S M 2004 *Rev. Sci. Instrum.* **75** 2787

[8] He X D, Xu P, Wang J and Zhan M S 2009 *Opt. Express* **17** 21007

[9] He X D, Xu P, Wang J and Zhan M S 2009 *Opt. Express* **18** 13586

[10] Xia T, Zhou S Y, Chen P, Li L, Hong T and Wang Y Z 2010 *Chin. Phys. Lett.* **27** 023701

[11] Weber M, Volz J, Saucke K, Kurtsiefer C and Weinfurter H 2006 *Phys. Rev.* A **73** 043406

[12] Kuhr S, Alt W, Schrader D, Dotsenko I, Miroshnychenko Y, Rauschenbeutel A and Meschede D 2006 *Phys. Rev.* A **72** 023406

[13] Jones M P A, Beugnon J, Gaetan A, Zhang J, Messin G, Browaeys A and Grangier P 2007 *Phys. Rev.* A **75** 040301

[14] Urban E, Johnson T A, Henage T, Isenhower L, Yavuz D D, Walker T G and Saffman M 2009 *Nature Phys.* **5** 110

[15] Gaetan A, Miroshnychenko Y, Wilk T, Chotia A, Viteau M, Comparat D, Pillet P, Browaeys A and Grangier P 2009 *Nature Phys.* **5** 115

[16] Zuo Z, Fukusen M, Tamaki Y, Watanabe T, Nakagawa Y and Nakagawa K 2009 *Opt. Express* **17** 22898

[17] Tuchendler C, Lance A M, Browaeys A, Sortais Y R P and Grangier P 2008 *Phys. Rev.* A **78** 033425

[18] Alt W, Schrader D, Kuhr S, Muller M, Gomer V and Meschede D 2003 *Phys. Rev.* A **67** 033403

[19] Fuhrmanek A, Lance A M, Tuchendler C, Grangier P, Sortais Y R P and Browaeys A 2010 *New J. Phys.* **12** 053028

[20] Chu S, Hollberg L, Bjorkholm J E, Cable A and Ashkin A 1985 *Phys. Rev. Lett.* **55** 48

[21] Wang J, He J, Qiu Y, Yang B D, Zhao J Y, Zhang T C and Wang J M 2008 *Chin. Phys.* B **17** 2062

[22] He J, Wang J, Yang B D, Zhang T C and Wang J M 2009 *Chin. Phys.* B **18** 3404

[23] Wang J M, He J, Yang B D, Zhang T C and Peng K C 2010 *Proc. SPIE* **7727** 77270U

[24] He J, Yang B D, Zhang T C and Wang J M 2011 *J. Phys.* D: *Appl. Phys.* **44** 135102

[25] Metcalf H J and van der Straten P 1999 *Laser Cooling and Trapping* (New York: Springer-Verlag)

[26] Kerman A J, Vuletic V, Chin C and Chu S 2000 *Phys. Rev. Lett.* **84** 439

[27] Maunz P, Puppe T, Schuster I, Syassen N, Pinkse P W H and Rempe G 2004 *Nature* **428** 50

[28] Barrett M D, Sauer J A and Chapman M S 2001 *Phys. Rev. Lett.* **87** 010404

[29] Ma H Y, Cheng H D, Wang Y Z and Liu L 2008 *Chin. Phys.* B **17** 4180

[30] Kastberg A, Phillips W D, Rolston S L, Spreeuw R J C and Jessen P S 1995 *Phys. Rev. Lett.* **74** 1542

[31] Poli N, Brecha R J, Roati G and Modugno G 2002 *Phys. Rev.* A **65** 021401