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Efficient extension of the trapping lifetime of single atoms in an optical tweezer by laser cooling

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Abstract
Optical tweezers have become powerful tools for the confinement and manipulation of neutral atoms, molecules, mesoscopic biological molecules and living cells. In our experiment, a single caesium atom was prepared in a large-magnetic-gradient magneto-optical trap (MOT). It was then efficiently transferred back and forth between the MOT and a 1064 nm microscopic optical tweezer. The atomic transfer between the MOT and the tweezer can be employed to measure the trapping lifetime and the energy distribution of the single atom in the tweezer. In order to extend the trapping lifetime, laser cooling is used to decrease the atom's kinetic energy. The trapping lifetime was extended from ∼75 to ∼130 s by applying a 10 ms laser cooling phase just after the single atom is transferred into the tweezer.

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(Some figures in this article are in colour only in the electronic version.)

1. Introduction

Using the optical-field gradient force, optical tweezers can confine and manipulate particles ranging in size from neutral atoms and molecules to mesoscopic biological molecules and living cells [1–4]. Therefore, optical tweezers have become widely used tools for research in the fields of atomic and molecular physics, biology and colloidal chemistry. Here, we focus on the case of neutral atoms, especially the single neutral atom. A far-off-resonance microscopic optical tweezer can realize full control of the internal and external degrees of freedom of a single neutral atom. This provides a good test bed for research on light–matter interactions at single-atom and single-photon levels.

Several groups have successfully prepared single atoms in magneto-optical traps (MOT) [5–12] and optical tweezers [13–18]. Longer trapping lifetimes and lower average energy for single atom trapped in optical tweezers are preferable for many experiments. The trapping lifetime is primarily limited by atomic collisional processes [1, 2] (such as background gas collisions, light-assisted binary collisions and hyperfine-change collisions) and atom heating [1, 2, 19] (such as photon scattering heating and parametric excitation heating caused by the noise of the tweezers' laser beam). For far-off-resonance optical tweezers, the photon scattering heating is negligible, because of their low photon scattering rate. The heating due to the intensity noise and the beam-pointing noise of the tweezers laser beam [19] is another limiting factor in the extension of the trapping lifetime. An ultra-stable CO_2 laser system can be employed as a tweezer to suppress atom heating [20]. Therefore, the trapping lifetime can be extended. Alternatively, the trapping lifetime can be increased by decreasing the kinetic energy of the atoms with effective cooling techniques (e.g. cavity cooling [21], laser cooling [22] and adiabatic cooling [17, 23]). Moreover, effective cooling of a trapped single atom can be employed to narrow the fluorescence spectrum of the emitted single photons [16]. And the neutral alkali-metal atoms with two long lifetime hyperfine folds in the ground state can be used to encode quantum bits (qubits) [24–25]. The inhomogeneous dephasing time of the quantum state depends on the energy of the trapped atom [24–26]. Therefore, the effective cooling of trapped atoms can also be used to extend the dephasing time of atomic qubits.

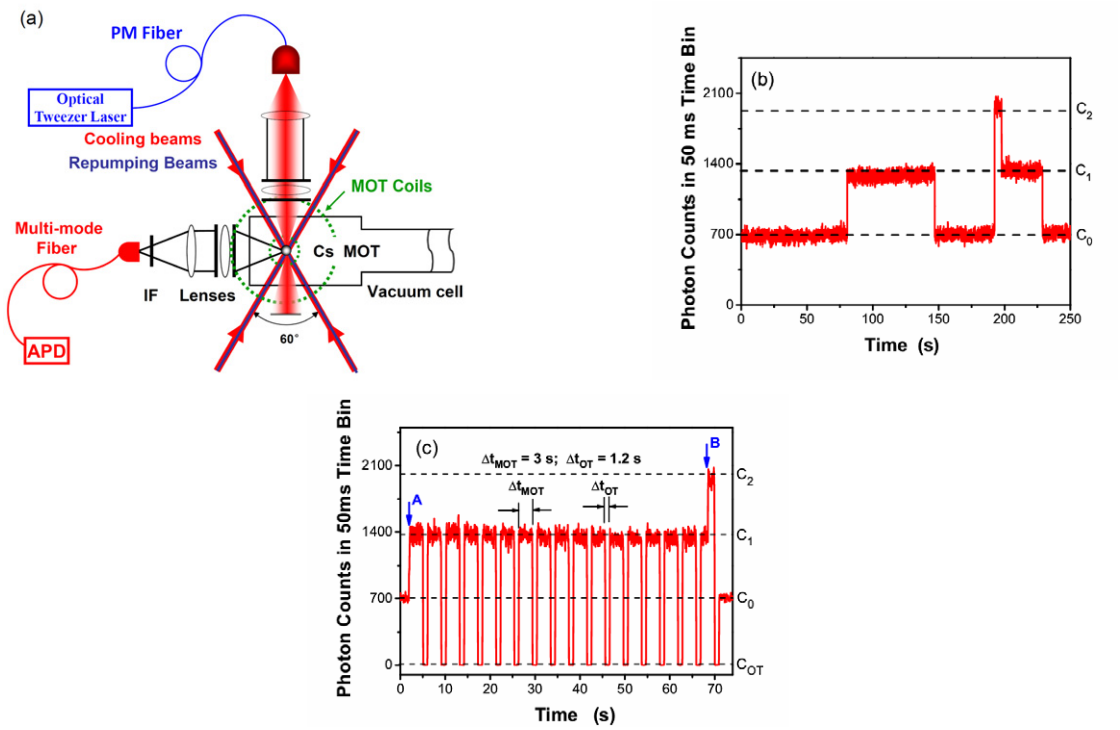

Figure 1. (a) A schematic of the experimental setup. APD, avalanche photodiode working in photon-counting mode; IF, 852 nm interference filter; PM fiber, polarization-maintaining optical fiber. (b) Separated discrete fluorescence photon-counting levels of the MOT. C_0, C_1 and C_2 indicate the photon-counting levels for a 50 ms time bin for no atoms (due to the stray light from the cooling/trapping lasers), one atom, and two atoms trapped in the MOT, respectively. (c) Photon-counting signals for transferring single atoms back and forth between the MOT and the tweezer. Blue arrows A and B indicate events when an additional atom is captured in the MOT from background caesium. C_{OT} denotes the photon-counting level due to the 1064 nm tweezer laser scattering, which is filtered by the 852 nm interference filter.

In the present work, we demonstrate that the one-shot laser cooling phase can be used to extend the trapping lifetime from $\sim$75 to $\sim$130 s for a background pressure of $\sim 2 \times 10^{-11}$ Torr. This is accomplished by decreasing the kinetic energy of the single atom in the microscopic optical tweezer. In [22] periodic pulsed laser cooling was adopted for a few atoms in a one-dimensional optical lattice. Although the 1 s laser cooling phase applied every 19 s can yield very long trapping lifetimes ($\sim$300 s), the 19 s interval limits qubit applications. This is because each 1 s laser cooling will destroy the coherence of the qubit. By contrast, we used a one-shot laser cooling phase just after the single atom was loaded into an optical tweezer. Besides, a one-shot laser cooling phase can be employed to prepare the atom in a specific hyperfine level of ground state by switching the cooling laser prior to the repumping laser (or the reverse) at the end of the laser cooling phase. Furthermore, the system can be used to manipulate an atomic qubit by incorporating two-photon stimulated Raman adiabatic passage just after the one-shot laser cooling phase is done.

2. Single-atom optical tweezer

A schematic of our experimental setup is shown in figure 1(a). In our system, a glass ampoule with 5 g of high purity caesium atoms was sealed in an oxygen-free copper tube to serve as the source of atoms (not shown). These atoms were released into the MOT area via an ultra-high vacuum (UHV) mechanical valve. We controlled the caesium atom number in the working area through this valve. The background pressure was maintained by the combination of an ion pump and a titanium sublimation pump, and was monitored via a vacuum-ion gauge. After the caesium vapor was released from the atomic source, a background pressure of $\sim 1 \times 10^{-10}$ Torr could be maintained when only the ion pump was operated, and could reach $\sim 2 \times 10^{-11}$ Torr with the help of the titanium sublimation pump.

Our large-magnetic-gradient MOT [12] followed a standard MOT configuration composed of three retroreflected cooling/trapping laser beams and three repumping beams. To properly arrange the detection system, the two pairs of cooling/trapping beams in the horizontal plane intersected into the glass cell at an angle of 60°. This meant that the detection system would be close to the MOT area, and that this configuration would decrease stray light entering the detection system. The total power of the cooling/trapping laser was about 0.6 mW with a $1/e^2$ beam size of 2 mm. The frequency detuning of the cooling/trapping laser from the caesium $6S_{1/2}$ Fg = 4–$6P_{3/2}$ Fe = 5 cooling cycling transition was $\sim -2\gamma$ ($\gamma/2\pi = 5.22$ MHz being the spontaneous linewidth for the caesium Fg = 4–Fe = 5 transition). The cooling/trapping laser was offset stabilized using a modulation-free polarization spectroscopic locking scheme. The repumping laser, which has a power of 0.1 mW was locked to the $6S_{1/2}$ Fg = 3–$6P_{3/2}$ Fe = 4 hyperfine transition using a radio-frequency modulation spectroscopic locking scheme. The MOT magnetic field was produced by a pair of water-cooled anti-Helmholtz coils. With these coils, a current of 20A yielded a magnetic field gradient of $\sim$30 mT cm^{-1} ($\sim$300 Gauss cm^{-1}) along the axial direction.

The current could be switched off completely within ~ 3.9 ms using the electronic circuitry.

Laser induced fluorescence (LIF) photons from cold atoms in the MOT were collected using a lens assembly with a numerical aperture of 0.29. They were then coupled into a multi-mode-fiber-connected single-photon count module (SPCM). The SPCM worked in a photon-counting mode (Geiger mode) and produced TTL pulses when the incident photons arrived. The number of pulses was counted by a multi-channel scaler (MCS) within a typical time bin of 50 ms which should be much shorter than the lifetime of trapped atoms (several tens of seconds in our case) and much longer than the spontaneous lifetime (~ 30 ns for the caesium Fe = 5–Fg = 4 transition). The computer recorded all data as the counts versus time. The typical LIF photon-counting signal, which was optimized based on the dependence of the scattering rate upon all parameters, is shown in figure 1(b).

The loading rate of the MOT was very sensitive to the magnetic-field gradient. With a large magnetic-field gradient, we could cool and trap a few or single atoms in the MOT. We determined the exact number of trapped atoms by detecting the LIF photons from the trapped atoms driven by the cooling transition. The discrete steps indicate the capture or loss of a single atom. When an atom enters (leaves) the trap, the count rate suddenly increases (decreases). Thus the number of trapped atoms can be determined from the fluorescence count rate. The initial value, C_0, corresponds to no atoms in the MOT. It can be calibrated by switching off the magnetic field. The level C_1, which is higher than the background level, is interpreted as the trapping of a single atom. Because each atom provides the same amount of fluorescence, the number of atoms in the trap can be inferred directly from the discrete levels of the count rate. Our optical tweezer beam was provided by a home-made laser-diode-pumped $Nd:YVO_4$ single-frequency 1064 nm laser [18], which was guided by a polarization-maintained fiber and expanded to a beam diameter of $\sim$25 mm. The beam was then tightly focused into the vacuum cell using a lens assembly, and the resulted waist radius was $\sim 2.3\,\mu$m. The trap depth was ~ 1.5 mK when the tweezer laser power was ~ 47 mW, which corresponds to a trap frequency of $\nu_{\text{radial}} = 41.3$ kHz in the radial direction and $\nu_{\text{axial}} = 4.3$ kHz in the axial direction. We achieved a background photon-counting rate of $\sim 30\,\text{s}^{-1}$ with a tweezer beam of ~ 47 mW (see C_{OT} in figure 1(c), which includes the APD dark counts of $25\,\text{s}^{-1}$) with the help of an 852 nm narrow-band interference filter and our system configuration.

Our experiments rely on whether a single atom is still in the trap after optical manipulation. The efficient loading of the optical tweezer and transfer between the MOT and tweezer are crucial. We optimized the overlap of the two traps on the sub-micrometer scale by recording the LIF photon-counting signals, which is dependent on the light shift of the atoms trapped in the far-off-resonance trap (FORT). Apart from the spatial arrangement of the system, the loading rate is governed by the timing overlap of the two traps, the kinetic energy of the atom and the tweezer potential. The typical LIF photon-counting signal for the transfer of a single atom between the MOT and optical tweezer is shown in figure 1(c).

3. Heating from the intensity noise of the tweezer laser

The transfer technique, shown in figure 1(c), provides an effective method for determining the trapping lifetime of a single atom [18] and performing release-and-recapture (R&R) measurements [17, 27] to evaluate the energy distribution of a single trapped atom. For a single atom trapped in the tweezer, the $1/e$ trapping lifetime can be determined by measuring the recapture probability, $P(t)$, of an atom remaining in the tweezer as a function of the release time, ΔT. The trapping lifetime of a single atom confined in optical tweezer was found to be $\sim 6.9 \pm 0.3$ s for a background pressure of $\sim 1 \times 10^{-10}$ Torr [18] and $\sim 75.3 \pm 5.3$ s for $\sim 2 \times 10^{-11}$ Torr (see figure 3). Collisions with background gas in the vacuum glass cell yielded atom loss. Here, the trapping lifetime increased by roughly one order of magnitude when the background pressure was improved by almost one order of magnitude.

This lifetime of 75 s was still shorter than the expected limit for background gas collisions at $\sim 2 \times 10^{-11}$ Torr. Therefore, the trapping lifetime was ultimately limited by heating. The fundamental source of heating is photon-scattering heating from the tweezer laser beam. In this case, the photon-scattering rate caused by the 1064 nm tweezer laser was only $\sim 8\,\text{s}^{-1}$, and the corresponding heating rate was negligible. And only a single caesium atom is trapped in the optical tweezer. Therefore, neither light-assisted binary cold collisions nor hyperfine-changing cold collisions could cause measureable losses. However, the heating induced by the noise of the tweezer laser beam limits the trapping lifetime. The intensity noise and beam-pointing noise of the tweezer laser beam will cause fluctuations in the trap depth and in the position of the tweezer, which leads to parametric excitation heating, especially at the second harmonic of the trap frequency [19]. Heating due to intensity noise causes an exponential increase in the average energy, $\langle E \rangle$, of an atom according to $\langle \dot{E} \rangle = \Gamma_{\text{heating}} \langle E \rangle$ with the inverse of the heating time constant of $\Gamma_{\text{heating}} = \pi^2 \nu^2 S_\varepsilon(2\nu)$. Here, $S_\varepsilon(2\nu)$ is the intensity noise spectrum of the tweezer laser beam, and ν is the trap frequency. We measured $S_\varepsilon(2\nu) \sim 1.23 \times 10^{-12}\,\text{Hz}^{-1}$ at $\nu_{\text{radial}} = 41.3$ kHz, and $S_\varepsilon(2\nu) \sim 3.6 \times 10^{-11}\,\text{Hz}^{-1}$ at $\nu_{\text{axial}} = 4.3$ kHz. For these values, the inverse of the heating time constants are $\Gamma_{\text{heating}} \sim 0.02\,\text{s}^{-1}$ in the radial direction and $\Gamma_{\text{heating}} \sim 0.007\,\text{s}^{-1}$ in the axial direction respectively. 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 neglected the slight heating caused by the beam-pointing noise of the tweezer laser beam.

4. Laser cooling of a single atom in the optical tweezer and the extension of the trapping lifetime

An atom trapped in an optical tweezer can be further cooled via polarization-gradient-cooling (PGC, oppositely circularly polarized σ^+ and σ^- beam pairs). The cooling beam was

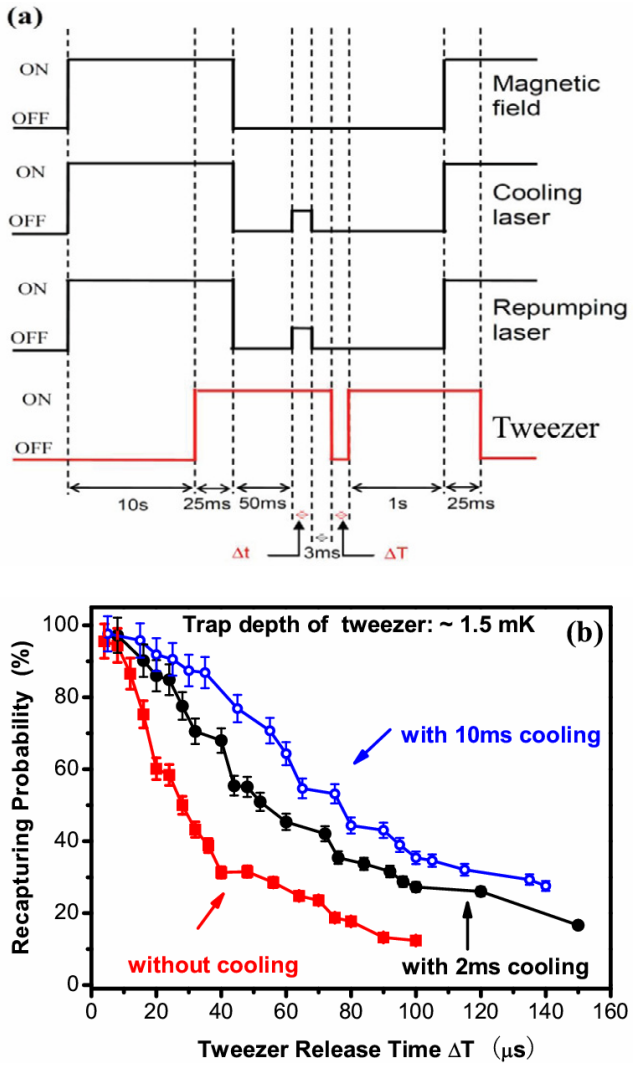

Figure 2. R&R measurement for single atom in the optical tweezer. (a) Schematic of the time sequence. Δt is the laser cooling time, and ΔT is the tweezer release time. (b) Experimental results for the recapture probability of a single atom as a function of ΔT for a 10 ms laser cooling phase (open circles), a 2 ms laser cooling phase (solid circles), and without laser cooling (solid squares). The solid lines are visual presentations only. The error bars represent ±5%. Each experimental data point is the accumulation of at least 100 sequences.

provided by the laser used to form the MOT beams. Here, an atom in the tweezer can be tightly confined, which can effectively decrease the losses caused by spatial diffusion during the cooling phase of optical molasses [28]. Note that the energy distribution of a single atom was calculated by averaging the kinetic energy over many realizations of the experiment under exactly the same conditions. Here, we assumed that the tweezer is an approximately harmonic potential and the velocity distribution of the atoms follows the Maxwell–Boltzmann law. Therefore, the R&R technique [27] can be extended to evaluate the energy distribution of a single atom in an optical tweezer. A schematic of the time sequence of our R&R measurement and the measured R&R data are shown in figure 2. According to the sub-Doppler PGC theory [28], the effective temperature is proportional to the intensity of the cooling laser and inversely proportional to the frequency detuning. During the cooling phase, the

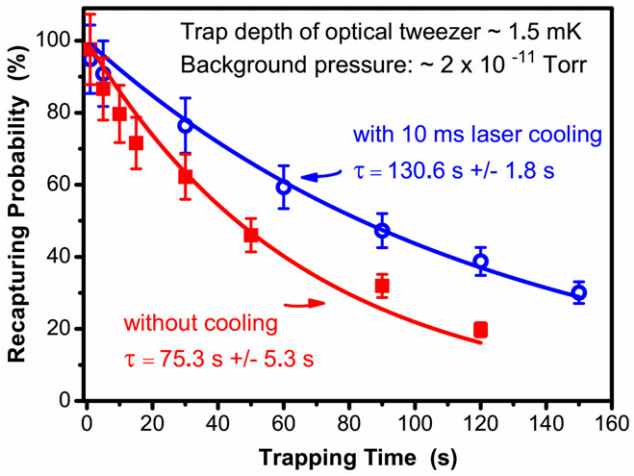

Figure 3. Trapping lifetimes for a single atom in the optical tweezer for a10 ms laser cooling phase just after the atom is transferred into the tweezer (open circles) and without laser cooling (solid squares). The corresponding solid lines were generated through an exponential decay fit ($P(t) = P_0 \times \exp(-t/\tau)$, where τ is the $1/e$ trapping lifetime and P_0 yields the transfer efficiency from the MOT into the tweezer). In the latter case, the relatively fast decay is due to the heating arising from the technical noise of the tweezer laser beam. The error bars represent ±5%. Each data point is the accumulation of at least 100 sequences.

intensities of the cooling laser beams (repumping laser beams) were reduced to 30% (∼25%) of the original values via acousto-optical modulators (AOM). The effective frequency detuning of the cooling laser beam was passively changed from -2.0γ to -6.5γ, in reference to the shifted Fg = 4 – Fe = 5 cycling transition because of the light shift due to the tweezer laser.

Because the average kinetic energy scales with temperature as $E \sim k_B T$, using $T(\mu K)$ to indicate the energy makes it easy to compare with the trap depth of the optical tweezer. (Here $k_B = 1.38 \times 10^{-23}\,J\,K^{-1}$ is the Boltzmann constant). The average kinetic energy obtained from the measured R&R data are $\sim 105 \pm 12\,\mu K$ for the case without cooling, $33 \pm 3\,\mu K$ for the 2 ms laser cooling phase and $17 \pm 1\,\mu K$ for the 10 ms laser cooling phase. The values of the energy distribution were derived from theoretical fitting of the R&R data (figure 2(b)) for the above three cases. The errors are statistical. The ratios between the trap depth of our tweezer and average energy of the single atom for the above three cases are 14, 45 and 88, respectively. This indicates that we are approximately in the harmonic regime of the tweezer trapping potential. And these results indicate that the average kinetic energy of a trapped single atom is much lower after the laser cooling phase. Therefore, a trapped atom will stay at the bottom of the tweezer.

The trapping lifetimes for the cases without laser cooling and with a 10 ms laser cooling phase were experimentally measured, and the results are shown in figure 3. For a background pressure of $\sim 2 \times 10^{-11}$ Torr, the trapping lifetime was determined to be 75.3 ± 5.3 s for the case without cooling and 130.6 ± 1.8 s for the case with a 10 ms cooling phase. We demonstrated that the trapping lifetime could be extended using a one-shot laser cooling phase just after the single atom is loaded into the tweezer. These results agree with theoretical predictions based on atom heating

caused by the intensity noise of the tweezer laser, which yield a trapping lifetime of $\sim$96 s for an initial average energy of $\sim$105 μK and $\sim$162 s for $\sim$17 μK. The difference between experimental data and theoretical predictions might be explained by our decision to ignore the weak heating from the beam-pointing noise in the theoretical analysis.

In our experiment, the trapping lifetime is still limited by the initial kinetic energy of the trapped atom and the intensity noise of the tweezer laser after the one-shot laser cooling phase. We made no further attempts to lower the average energy. The atom heating rate also strongly depends on the trap frequency. For the case of a tightly focused microscopic tweezer, the trap frequency is much higher than that of a large waist tweezer. Therefore, this system has a higher heating rate. This partially explains why one can achieve a $\sim$300 s trapping lifetime for a cold atomic ensemble in a low-frequency trap using an ultra-stable CO_2 laser beam [20]. Note that the relative intensity noise of our tweezer laser beam is higher than that of the lasers used in [19, 20, 22]. To achieve a trapping lifetime $\sim$300 s for our trap depth of $\sim$1.5 mK, the relative intensity noise must be below $\sim 9 \times 10^{-4}$. To actively suppress the intensity noise of our tweezer laser, a noise eater system that is based on AOM would be implemented with a feedback control loop, in which the radio-frequency power applied to AOM can be controlled to vary the AOM diffraction efficiency.

5. Conclusion

In conclusion, our experimental results show that a single caesium atom prepared in a large-magnetic-gradient MOT can be efficiently loaded into a 1064 nm microscopic optical tweezer. Moreover, the trapping lifetime of a single atom in the tweezer can be extended from $\sim$6.9 s to $\sim$75 s by improving the background pressure from $\sim 1 \times 10^{-10}$ to $\sim 2 \times 10^{-11}$ Torr and then to $\sim$130 s using a one-shot 10 ms laser cooling phase.

A long-lived single atom with low average energy trapped in an optical tweezer is one of the good candidates for triggered single-photon sources [15]. The cooling can lower the average energy and prolong the lifetime of a trapped single atom, which can increase the generation rate of a single photon in unit time and suppress the linewidth, which is significant for quantum cryptography communication and linear quantum computation. Moreover, a single atom trapped in an optical tweezer could serve as an atomic qubit [24, 25] which can perform single-qubit operations. Qubits can be scaled and implemented by extending the single atom tweezer to form a 1D or 2D tweezer array. Along this line, single-qubit operations are sequentially combined with two-qubit gates (for example, the C-NOT gate) to realize arbitrary logic operations for quantum computation. Furthermore, combining cooling with optical lattices can serve as an excellent basis for atomic clocks.

Acknowledgment

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