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Single atoms transferring between a magneto-optical trap and a far-off-resonance optical dipole trap*

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Based on our work on single cesium atoms trapped in a large-magnetic-gradient vapour-cell magneto-optical trap (MOT), the signal-to-noise ratio (SNR) is remarkably improved. Also a far-off-resonance optical dipole trap (FORT) formed by a strongly-focused 1064 nm single frequency Nd:YVO_4 laser beam is introduced. One cesium atom is prepared in the MOT, and then it can transfer successfully between the MOT and the FORT which is overlapped with the MOT. Utilizing the effective transfer, the lifetime of single atoms trapped in the FORT is measured to be 6.9± 0.3 s. Thus we provide a system where the atomic qubit can be coherently manipulated.

Keywords: single atoms, magneto-optical trap, far-off-resonance optical dipole trap, lifetime of single atoms

PACC: 3280P, 3280, 4250

1. Introduction

Experiments with individual quantum systems make it possible to investigate quantum effects at a fundamental level. One topic which is receiving more and more attention is quantum information processing (QIP). The manipulation of single atoms is to provide us with tools suitable for quantum qubit, entanglement and generation of single photons. In 2000, Frese *et al* [1] stored a small and deterministic number of neutral atoms in an optical dipole trap and they also prepared atoms in a certain hyperfine state and demonstrated the feasibility of state-selective detection. In 2001, Kuhr *et al* [2] loaded one cold cesium atom from a magneto-optical trap into a standing-wave dipole trap, and by controlling the motion of the standing wave, they adiabatically transported the atom with sub-micrometer precision over macroscopic distances on the order of one centimeter. In 2003, Schrader *et al* [3] demonstrated the realization of a quantum register with a string of single neutral atoms trapped in a one-dimensional optical lattice. In 2005, by illuminating an individual rubidium atom stored in a tight optical tweezer with short resonant light pulses, Beugnon *et al* [4] created an efficient triggered-single photon source with a high rate, and measured intensity correlation of the emitted light pulses showing almost perfect anti-bunching. Quantum interference between two single photons emitted by independently trapped atoms was achieved in 2006.[5] The coherent control of a few trapped atoms is a crucial element for a quantum system. It is thus of fundamental importance for future applications in QIP. Tey *et al* [6] have observed experimentally a substantial extinction of a weak coherent light field by a single atom in a tightly focused dipole trap. The result opens a new way of using atoms to process quantum information carried by light, which is important for experiments that require an atom in free space to strongly absorb single photons.[6]

The neutral atom magneto-optical trap (MOT) is a very efficient tool for cooling and trapping atoms.[7,8] Unfortunately, the MOT is a dissipative trap, the interaction of cooling and trapping light with the trapped atoms is nearly resonant, and the sponta-

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neous photon scattering rate is so large that the trap rapidly destroys the coherence of an atomic state. On the other hand, we also cannot know when and how many atoms can be trapped from the background because the trapping is a completely random process. All these further restrict the application of trapped atoms to quantum communication.

The conservative potential of a dipole trap allows trapping with a long coherence time. A far-off-resonance optical dipole trap (FORT) can confine atoms in all ground states for a long time as it is created by the interaction of a far-detuned laser beam with the atomic dipole moment, and the photon scattering rate is quite small.[9−12] In general, there are two kinds of schemes to load single atoms from a MOT into a FORT: one is to load a single atom prepared in a large-magnetic-gradient MOT into a FORT,[2,3] and the other is to a load single atom from many cold atoms in a MOT into a micro-size FORT by making use of the near-resonant light-assisted collisional blockade effect.[13,14]

In the present paper, we give a description of our experimental setup, which traps single atoms in the MOT with a high signal-to-noise ratio (SNR) and then loads a single atom from the MOT into the FORT. We also measure the lifetime of the atoms trapped in the FORT, and it is 6.9±0.3 s. We provide a system where the atomic qubit can be manipulated coherently.

2. Principles

We consider an atom as a simple classical oscillator in deriving the main equations for the optical dipole interaction.[12] When an atom interacts with a laser beam, the electric field $\boldsymbol{E}$ induces an atomic dipole moment $\boldsymbol{P} = \alpha\boldsymbol{E}$, where α is the polarizability, which oscillates at the driving frequency ω. The interaction potential of the induced dipole moment $\boldsymbol{P}$ in the driving field $\boldsymbol{E}$ is given by[12]

$$U_{\rm dip} = -\frac{1}{2}\left\langle \boldsymbol{p}\cdot\boldsymbol{E}\right\rangle = -\frac{1}{2\varepsilon_0 c}\mathrm{Re}(\alpha)I, \qquad (1)$$

where I is the laser beam intensity, c is the speed of light in vacuum, and ε_0 is the permittivity constant of vacuum. For the practical case of a detuning much larger than the natural linewidth ($\varDelta = \omega - \omega_0 \gg \varGamma$, where ω_0 is the atomic angular frequency, and $\varGamma$ is the natural linewidth of the atomic transition), we can derive the expressions for the trap depth $U_{\rm dip}$ and the scattering rate $R_{\rm sc}$ in the rotating wave approximation as follows:[12]

$$U_{\rm dip}(r) = \frac{3\pi c^2}{2\omega_0^3}\cdot\frac{\varGamma}{\omega-\omega_0}\cdot I(r), \qquad (2)$$

and

$$R_{\rm SC}(r) = \frac{3\pi c^2}{2\hbar\omega_0^3}\cdot\frac{\varGamma^2}{(\omega-\omega_0)^2}\cdot I(r). \qquad (3)$$

A quantum-mechanical description can also give the same results. Because of the interaction, the atomic ground state and excited state are shifted downwards, or upwards in the case of negative detuning ($\varDelta = \omega - \omega_0 < 0$). In other words, the dipole trap potential for an atomic level is thus its light shift (AC Stark shift). Actually, the atom is a multi-level system, and we can construct the total Hamiltonian including all interactions. But the two-level approximation is appropriate in our case.

The use of a FORT leads to nearly non-dissipative potentials with very low spontaneous emission rates, in which pre-cooled atoms can be trapped. We can combine the convenience of the MOT for trapping and cooling atoms with the advantages for quantum manipulation offered by the nearly conservative potential of a FORT.

3. Experiments

In the first step, we have one atom trapped in the MOT; the experiment setup and its details have been described in Ref.[15]. Compared with the earlier experiment,[15] we have greatly enhanced the SNR. From the scattering formula $\varGamma_{\rm s} = \frac{\varGamma}{2}\frac{I/I_{\rm s}}{1+I/I_{\rm s}+4\varDelta^2/\varGamma^2}$ (where I is the total intensity of the laser beams, the saturation intensity $I_{\rm s}$ = 1.12 mW/cm^2 for cesium atoms, $\varDelta = \omega - \omega_0$ is the frequency detuning), one can know that the observed photon count rate is governed by the laser beam intensity and the frequency detuning. To enhance the scattering rate of trapped atoms, we decrease the cooling laser red detuning of the MOT to one natural linewidth, and appropriately increase the power of the cooling beam. In order to suppress noise we make the laser frequency very stable by the modulation-free polarization spectroscopy locking scheme.[16] Furthermore, the optimal feedback has a very positive effect on the piezoelectric transducer (PZT) modulation port (frequency response range DC $\sim$ 2 kHz) and the current modulation port of the laser diode driver (bandwidth DC $\sim$ 200 kHz).[16] Besides, part of the noise may originate from the system: the quadrupole magnetic coils are cooled by circulating water because they work at a large current (15∼20 A); mechanical vibration noise from the circulating water refrigerator as well as the water stream may cross the optical bench, thereby introducing noise into the signal of the trapped atoms. In order to reduce the above-mentioned noise as much as possible, the optical bench can be floated with nitrogen gas. Of course, we also improve the alignment accuracy of the detection system. As shown in Fig.1, under the optimal conditions the photon counting signal of trapped atoms has a distinct step-like shape, because the trapped atom makes an identical contribution to the total fluorescence signal. This allows us to infer the exact number of atoms trapped in the MOT.

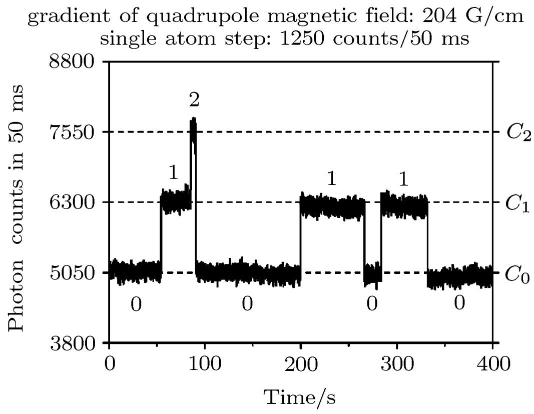

Fig.1. Photon counts of the avalanche photodiode (APD) detecting the fluorescence of the MOT. Each trapped atom contributes the same amount of fluorescence to the signal. When an atom enters or leaves the MOT, the counts rate suddenly increases or decreases. The number of trapped atoms can thus be determined from the fluorescence count rate. For this data set, the MOT parameters are as follows: cooling and trapping laser power $P \sim 250\ \mu$W, beam diameter ~ 2 mm, frequency detuning $\Delta \sim -\Gamma$.

The FORT of cesium atoms in our experiment is formed by a tightly focused Gaussian-mode 1064 nm laser beam, which is generated by a home-made Nd:YVO_4 1064 nm single-frequency laser pumped by a laser diode. The FORT beam is focused on a point by using the diffraction-limited lens assembly, which has a waist of 2.3 μm and a trap depth of ~ 1 mK at a typical optical power of 30 mW as shown in Fig.2. Under these running conditions, we can load a single atom from the MOT into the FORT and have very good localization due to the micro-size FORT.

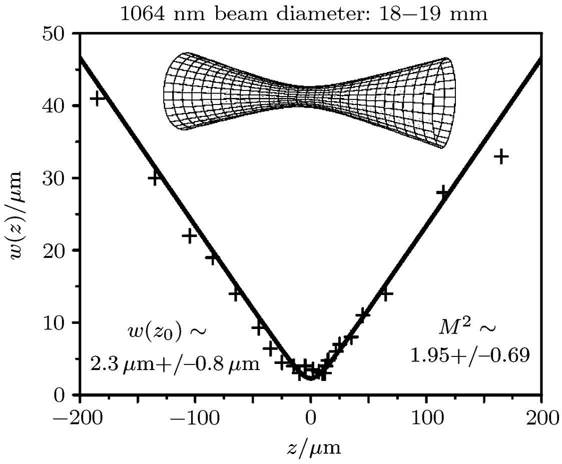

Fig.2. Measurement of the extremely small waist of the 1064 nm laser beam (with a beam diameter of 18∼19 mm), which is strongly focused by a lens assembly. The radius of the waist is 2.3±0.8 μm with an M^2 factor of 1.95.

Then, we introduce a series of operations. The superposition of the MOT and the FORT is crucial for efficient transfer. The light shift of the ground state exactly corresponds to the dipole potential for the two-level atom, therefore the fluorescence intensity of the trapped atoms is then reduced. The optimal geometrical overlap of the waist of the FORT laser with the MOT trapping volume can be achieved by minimizing the fluorescence of the trapped atoms. At the same time, the successful transfer of the trapped atom between the two traps requires suitable timing sequences. As shown in Fig.3, in order to load one cold atom from the MOT into the FORT, both traps are simultaneously operated for some tens of milliseconds before we switch off the MOT. After a period of time in the FORT the atom is transferred back into the MOT, which is switched on for the same length of time before the FORT is switched off. In the transfer process, the overlap time of the two traps is important. If the overlap time is too long, the loss rate during the loading of the FORT will be clearly increased due to light-assisted collision loss of the near-resonant MOT laser beams.[17] If the overlap time is too short, there is not enough time to have a steady FORT to accomplish the entire transfer. In our experiment the optimal overlap time is ~ 20 ms, which has been obtained by varying the overlap time.

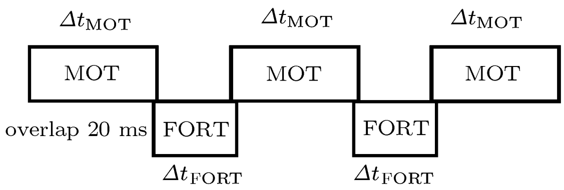

Fig.3. Time sequence of single atoms transferring between the MOT and the FORT with an overlap time of 20 ms. The storage time of a single atom in the FORT is Δt_{FORT}.

Meanwhile, the same atom can be transferred between the two traps repeatedly as shown in Fig.4. The trapped atoms can be transferred many times between the two traps. A survival probability can be introduced to describe the transfer efficiency. This operation is very useful in the follow-up experiment. The atoms in FORT have good coherence because of a much lower excitation rate, so the trapped atoms can be prepared in the particular quantum state with a long decoherence time. And making use of the highly successful transfer, the atom can be transferred back to the MOT to perform state-selective detection. Also, an alkali metal atom trapped in a FORT can serve as a quantum bit (qubit) by using its long-lived clock states in the hyperfine ground state, and it can be coherently manipulated via proper laser fields.

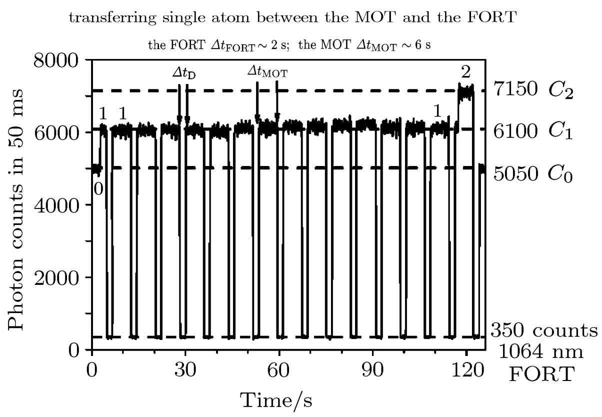

Fig.4. Photon counts detected with the APD in loading atoms from the MOT into the FORT. During the MOT operation single atoms are occasionally loaded into the MOT from background vapour. Discrete signal levels correspond to the empty MOT ($N = 0$) with stray light only, one atom ($N = 1$) and two atoms ($N = 2$), respectively. Transfer between the MOT and the FORT alternately with the fixed cycle is shown. The signal decreases down to the lowest level, which is due to stray laser light from the dipole trap only. After that the atoms are recaptured into the MOT, showing the same fluorescence level as before. If two atoms are transferred into the FORT both are immediately lost.

Furthermore, the efficient transfer of a trapped atom between the MOT and the FORT provides a simple procedure for measuring its lifetime in the FORT. By varying the keeping time of the FORT we can measure the survival probability of the trapped atoms transferring back into the MOT, and the fitting of the survival probability with exponential decay yields a $1/e$-fold lifetime (see Fig.5). The lifetime of single atoms in the FORT is a necessary and important premise for manipulating atoms. In our experiment, the vacuum pressure is about 1.33×10^{-8} Pa ($\sim 1 \times 10^{-10}$ Torr), we can obtain a typical lifetime of 6.9 ± 0.3 s, which is long enough for the subsequent manipulation of a single atom. The lifetime of the trapped atom is limited by background collisions and the heating of the FORT beam. The source of heating is complex, such as laser intensity and frequency fluctuation and laser beam pointing stability. Of course, according to the analysis of heating mechanisms one can further cool the atoms in the FORT. Darquie *et al* [4] utilized optical molasses to cool single atom in the FORT and created an efficient triggered single-photon source with a well-defined polarization and a high repetition rate.

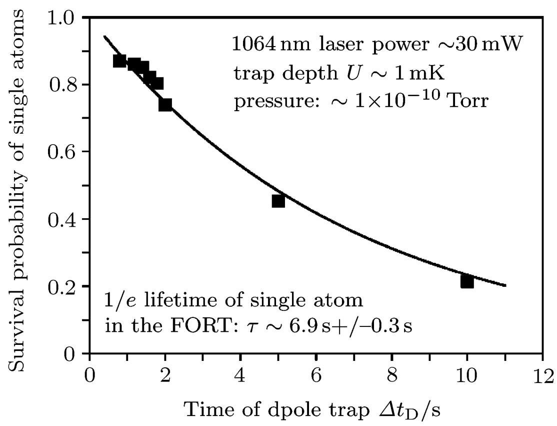

Fig.5. Survival probability of one single atom transferring between the FORT and the MOT as a function of time without cooling light. The fitting of the experimental data with exponential decay yields a $1/e$-fold lifetime of 6.9 ± 0.3 s (1 Torr=133 Pa).

4. Conclusion

We have experimentally demonstrated how to prepare single atoms in the MOT and load one atom from the MOT into the FORT, and have measured the lifetime of single atoms in the FORT based on high transfer efficiency technology. This single-atom trap is a promising tool for the effective generation of narrow-band single photons.[4,5] Furthermore, following the technical line of Ref. [3] a quantum register with more qubits can be demonstrated by using a string of more single atoms trapped in a one-dimentional standing wave FORT. And quantum entanglement between a single atom and a single photon[18] has already been demonstrated with a single atom trapped in a FORT, and this allows people to demonstrate quantum entanglement between two trapped atoms over a macroscopic distance, which is very suitable for a loophole-free test of Bell's inequality.[19]

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