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Efficient fluorescence detection of a single neutral atom with low background in a microscopic optical dipole trap

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A single cesium atom is trapped in a far-off-resonance optical dipole trap (FORT) from the magneto-optical trap (MOT) and directly imaged by using a charge-coupled device (CCD) camera. The binary single-atom steps and photon anti-bunching are observed by a photon-counting-based HBT system using fluorescence light. The average atom dwelling time in the FORT is about 9 s. To reduce the background noise in the detection procedure we employ a weak probe laser tuned to the D_1 line to illuminate the single atom from the direction perpendicular to the large-numerical-aperture collimation system. The second order degree of coherence $g^{(2)}(\tau)=0.12\pm0.02$ is obtained directly from the fluorescence light of the single atom without deducting the background. The background light has been suppressed to 10 counts per 50 ms, which is much lower compared with the reported results. The measured $g^{(2)}(\tau)$ is in good agreement with theoretical analysis. The system provides a simple and efficient method to manipulate and measure single neutral atoms, and opens a way to create an efficient controlled single-photon source.

magneto-optical trap (MOT), far-off-resonance optical dipole trap (FORT), single atom, collisional blockade, second-order correlation function

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1 Introduction

Quantum information processing [1] is currently attracting intense interest and is fueled by the promise of many applications [2]. Controlled neutral atoms are one of the ideal candidates for demonstrating deterministically the processing of quantum information [3–5], quantum computation [6,7], quantum simulation [8–10] and quantum metrology [11,12]. Deterministic manipulation and detection of single neutral atoms is necessary for all these applications and exciting perspectives. In the past decade, laser cooling and trapping techniques [13] allow people to control individual neutral atoms either in free space with an optical dipole trap [14] or inside an optical cavity [4]. Single atom detection with high sensitivity (low background) and high resolution is an important issue for internal state manipulation and further demonstration of quantum information processing. The ability to manipulate and detect individual atoms represents a milestone to encoding and processing information at the quantum level [15,16] and it enables a neutral-atom-based quantum logic device [17–19]. There are usually two approaches to trap and address individual atoms with high sensitivity and spatial resolution. The first one is the cavity quantum electrodynamics (CQED) system, which provides a route for quantum control of an atom in-

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side a high-finesse optical cavity. Due to the large Purcell effect, the emitting rate can be enhanced in the cavity mode and photons can be regulated and collected without much losses and a single atom can thus be detected with very high distinction ratio [20–23]. The high sensitivity measurement of single atoms [24] allows the possibility to determine the parameters of the atoms, such as the single atom trajectory [25] or the temperature of the cold atomic ensemble [26]. The second approach is to employ an objective with a high numerical aperture to collect the fluorescence emitted from an atom trapped in a far-off-resonance optical dipole trap (FORT). The FORT provides conservative potentials and excellent isolation from the environment. Single atoms can be obtained by a micro-size optical trap with the effect of light-assisted collisions [14,27,28]. The fluorescence signal of a single atom is so weak that many research groups devote themselves to improving the signal-to-noise ratio. The background photon counting rate is crucial in the experiment for internal state detection and control and people hope to keep it as low as possible. Usually the background is higher than 1000 counts per 50 ms [29–31]. In recent years, multiple traps were demonstrated with various arrays of atoms, where each atom can be individually addressed [32,33] and these 2D, or even 3D, traps provide feasible systems to demonstrate quantum information processing and quantum simulation. Several experiments have demonstrated trapping and arranging single atoms in red [17,34] or blue [35–37] detuned dipole traps. Based on the red detuned FORT [38], we have achieved the trapping and controlling of a single cesium atom, either in the mini-magneto-optical trap (MOT) with large magnetic gradient [39] or a microscopic optical tweezer [40]. The temperature of the single atom trapped in the FORT is further reduced by polarization gradient cooling and the effective temperature is evaluated by the release-and-recapture technique [41,42]. The signal-to-noise ratio is high but the background is also high (700 counts per 50 ms).

In order to reduce the background of single atom detection, we demonstrate a method of loading and detecting an individual cesium atom in a red detuned micro-size FORT. Single atoms are confined in a micro-trap with average lifetime up to 9 s without additional cooling before loading to the FORT. Due to the collisional blockade [43] in small size, the possibility of two atoms in the trap is extremely low. So the statistical distribution of atoms in the FORT is sub-Poissonian. In an attempt to avoid the background noise and combat inevitable losses and finite efficiencies, we use a very weak probe laser, which is close to resonance on the hyperfine transition $6^2S_{1/2}F=4\rightarrow 6^2P_{1/2}F'=4$ of the D_1 line of the cesium atom and the background is suppressed to a very low level. To prove the nonclassical photon statistics of a single atom, we have measured the second-order coherence of the single atom fluorescence with a Hanbury Brown-Twiss (HBT) setup [44], which exhibits strong anti-bunching without deducting the background.

The paper is organized as follows. In sect. 2 we briefly describe our experimental setup and give the details of the FORT. In sect. 3 we present the measurements of single atom signals and dwelling time. In the mean time, we record images of the single atom in the FORT and extract the anti-bunching effect by photon-counting the fluorescence. The second order degree of coherence is measured as a function of delay time, which is in accordance with the theory. Sect. 4 is the conclusion.

2 Experimental setup

Figure 1 shows a schematic diagram of our experimental setup. The FORT is formed by a linearly polarized single-frequency Gaussian beam of a diode pumped solid state laser at wavelength of 1064 nm, which is steered by a single mode polarization-maintaining (PM) fiber to aplanatic and achromatic lenses (Melles Griot Triplets, MGP) that expands the beam diameter to about 20 mm. The beam is then focused by a high numerical aperture objective (Alt lens NA=0.29 and f=36 mm) [45–47] to a waist of (2.0±0.2) μm. The whole objective, including its mount, is located outside the vacuum chamber. For a FORT power of 48 mW, the trap depth is 1.8 mK with the photon scattering rate of 17.6 s^{-1}. In order to load atoms into the FORT, we first trapped and cooled cesium atoms to sub-millikelvin temperatures inside a vacuum chamber with the usual MOT techniques (red detuned about 10–20 MHz to the cesium D2 line for the cooling laser and resonant on the $6^2S_{1/2}F=3\rightarrow 6^2P_{3/2}F'=4$ hyperfine transition for the repumping laser, the waists of both beams are 4 mm). A single atom is trapped by the micro-size optical dipole trap and the fluo-

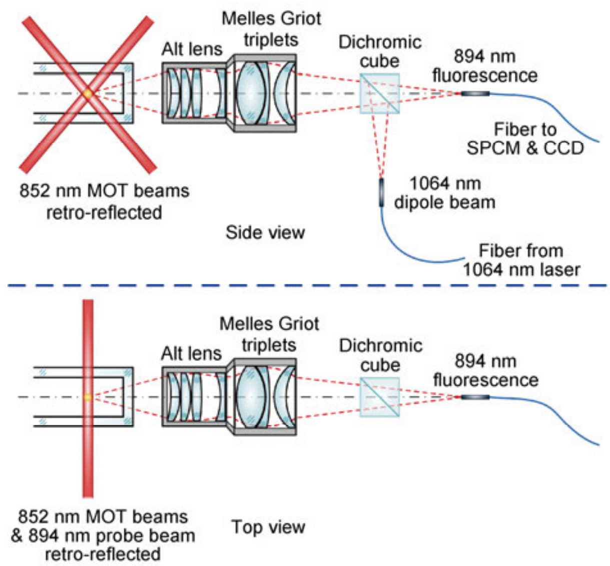

Figure 1 Schematic diagram of the experimental setup. MOT: magneto-optical trap; CCD: charge-coupled device; SPCM: single photon counting module.

rescence light scattered by the atom is collected with the same objective. The fluorescence light is separated from the FORT beam with a dichromic mirror. To image the atom, we illuminate the atom with a weak probe beam at 894 nm, which is nearly resonant to the hyperfine transition $6^2S_{1/2}F=4\rightarrow 6^2P_{1/2}F'=4$ of the D_1 line. This probe beam is perpendicular to the FORT beam. The fluorescence light is coupled into a single mode optical fiber and divided into two parts. One part goes to a charge-coupled device (CCD) camera, and another part goes to the single photon detectors. This configuration can suppress effectively suppress the background to a very low level.

3 Experimental process and results

The experiment starts from the usual MOT, as the red cross beams shown in Figure 1. By very carefully aligning the objective, which is placed on a fine adjustable five dimensional mount with 1 micrometer of alignment resolution, the waist of the FORT beam (ω_0 = (2.0±0.2) μm) is overlapped with the center of the MOT and one can see the fluorescence of the atoms (usually more than 1 atom) from the FORT and background gas in the cooling beams (see Figure 2(a)). By varying the gradient of the magnetic field, the loading rate can be changed. As was discussed before [43], due to the collisional blockade effect, single atoms can be trapped in the micro-trap for a relatively wide range of loading rates. Actually, we reduce the gradient of the magnetic field from 10 Gauss/cm to 2.5 Gauss/cm. The loading rate of atoms to the FORT is changed from 10^5 s^{-1} to 10^3 s^{-1} and in this range we can observe single atoms trapped, which is confirmed by the step signal and the following photon statistical experiment. The fluorescence of the atoms from the dipole trap is measured either by the single photon detectors (single photon counting module, SPCM, PerkinElmer Optoelectronics) or a high sensitivity CCD camera (Princeton MicroMax System: 512BFT). To "see" the image of the single atom clearly, we utilize a CCD with a magnification factor of about 13, which is formed by two lenses with focal lengths of f = 200 mm and f = 80 mm. The CCD provides a 512×512 imaging array and 13 μm×13 μm per pixel covering 6.7 mm×6.7 mm of the available imaging area. A single- atom image is then obtained when the exposure time is 1 s (see Figure 2(b)).

The response of single photon detection is much faster than the CCD. We use the same objective to collect the fluorescence light and couple the weak emission light to the fiber-coupled SPCMs with black cladding. When there is no atom in the trap, a background count rate of about 10 counts per 50 ms is detected due to dark counts of the SPCM and stray light from the surroundings. As an atom enters into the trap, the fluorescence light increases up to 40–80 counts per 50 ms, depending on the intensity and detuning of the probe beam.

Figure 3(a) shows a fraction of the fluorescence measurement with a 50 ms time bin. The single-atom signal inside the FORT can be observed by the occurrence of distinct steps. When the loading rate is properly controlled, other fluorescence jumps of more than 1 atom are rarely observed. In Figure 3(b), a histogram of photon counting for more than 5 h is shown, from which two distinct peaks, corresponding to 0 and 1 atom respectively, are clearly identified. The first peak corresponds to the background count rate of the SPCM (empty FORT) and the second one to the presence of a single atom in the FORT. Events of more than one atom are very rare during our 5 h observation due to the collisional blockade mechanism [14,43]. From the counting rates we have an overall detection efficiency of approximately 0.22%, including collection efficiency, transmission efficiency through the optical components and the quantum efficiency of the SPCM.

According to the fluorescence of single atoms we determine an atom dwelling time in the presence of MOT beams

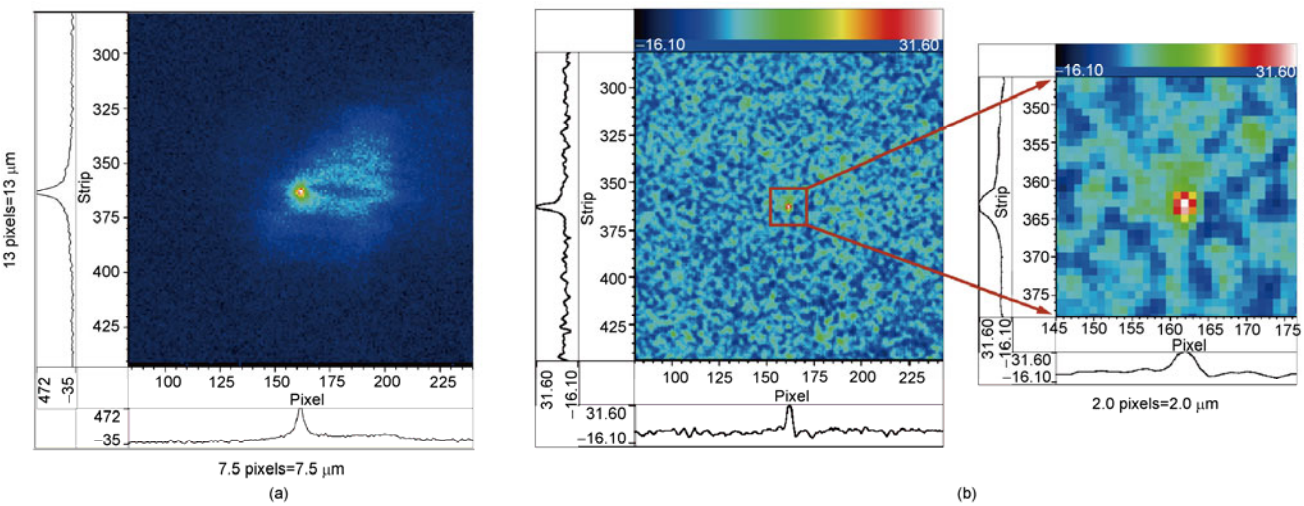

Figure 2 CCD-image of FORT and MOT with the background gas (a) and a single atom only in the FORT (b).

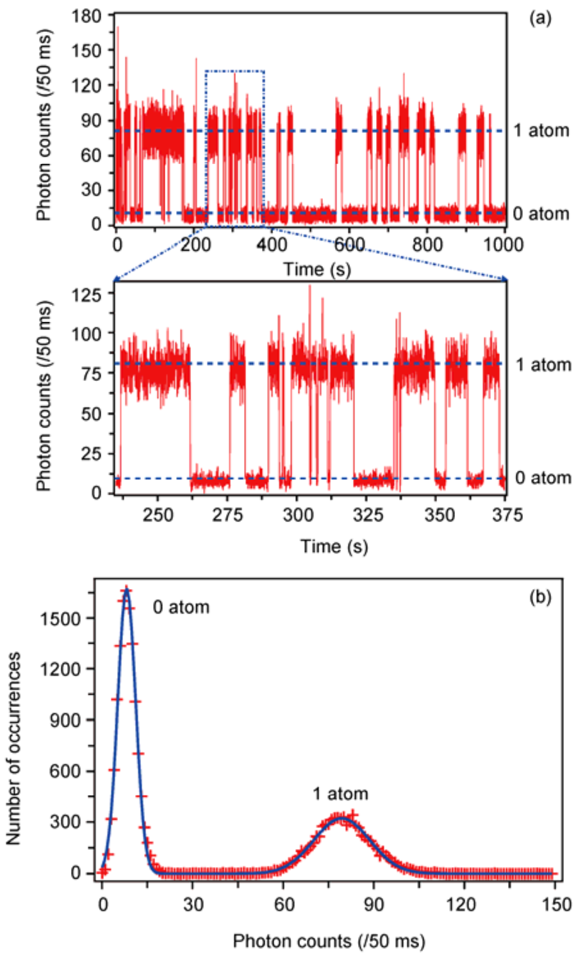

Figure 3 Single atom signal. (a) Fluorescence photon counts per 50 ms observed from the FORT region. The steps correspond to either zero or one atom in the trap. (b) Histogram of the photon counts per 50 ms. The red crosses correspond to the measured number of events. The blue curve is a theoretical fit to the two peaks.

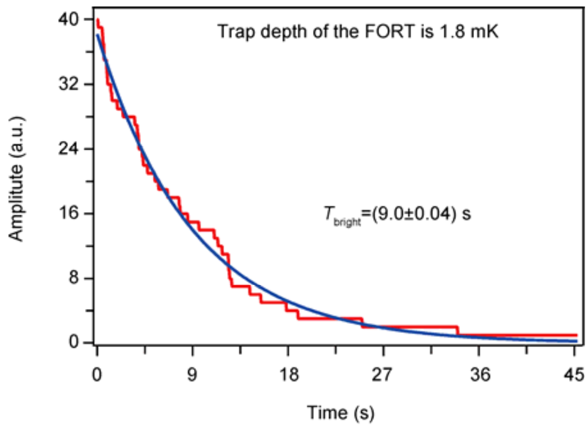

Figure 4 Atom dwelling time of a single atom inside the FORT in the presence of trapping beams (bright trap, red curve). The blue solid curve is an exponential fit to the experimental data yielding a 1/*e* lifetime of (9.00±0.04) s.

(bright trap), as shown in Figure 4. The 1/*e* lifetime of a single atom is (9.00±0.04) s by the exponential fit. Here the lifetime is extracted directly by sampling the length of fluorescence steps. Since the MOT beams are present during the loading stage of the dipole trap, light-induced inelastic collisions occur and an additional loss channel is created, thus we expect the true lifetime of an atom in our FORT will be longer than this dwelling time when the MOT beams are turned off as one atom is loaded in it.

To further confirm the single atom captured in the FORT, we analyze the nonclassical statistical properties of the atomic fluorescence. The nonclassical features of the photon statistics can be obtained by extracting the second order correlation function $g^{(2)}(\tau)$ [48]. Photon anti-bunching [49,50] indicates the radiating character from a single particle. We have performed a HBT experiment [51–53] based on the above mentioned light collection system, a beam splitter, and two single photon detectors. Figure 5 shows the results. The measured second order degree of coherence $g^{(2)}(\tau)$ exhibits strong photon anti-bunching. We get $g^{(2)}(0)$ = 0.12±0.02, indicating the presence of a single atom in the FORT. The time delay between the two detectors is 48 ns and the time resolution is 1 ns, which is limited by the bandwidth of our time-control system. It should be mentioned that the result in Figure 5 is obtained directly from all the counts, including the background. The cross talk in the HBT setup, which is caused by the breakdown flash of silicon avalanche photodiodes that follows the detection of a photon, should be carefully avoided [54]. The signature of Rabi oscillation [21] is not observed due to the weak excitation of the probe beam at 894 nm. In our experiment, the probe beam is overlapped with one of the cooling beams with a power of 24 μW and a waist of 2 mm.

The dashed blue line in Figure 5 shows the theoretical fitting to the measured $g^{(2)}(\tau)$ function. In our case the predicted correlation function is given by [48,55,56]

$$g^{(2)}(\tau)=1-\mathrm{e}^{-3\Gamma\tau/4}\left[\cos(\Omega_{\mathrm{R}}\tau)+\frac{3\Gamma}{4\Omega_{\mathrm{R}}}\sin(\Omega_{\mathrm{R}}\tau)\right],$$

where $\Omega_{\mathrm{R}}^2=\Omega_0^2+\Delta^2-(\Gamma/4)^2$ with the Rabi frequency Ω_0 at resonance. The natural linewidth Γ is $2\pi\times4.57$ MHz and Δ is the detuning of the excitation laser. For the weak driving field, $\Omega_R/\Gamma<1$ and $g^{(2)}(\tau)$ increases monotonically from 0 to 1 as τ increases. For a strong driving field, $\Omega_R/\Gamma>1$ and $g^{(2)}(\tau)$ shows a damped oscillation depending on how strong the excitation is. In our case $\Omega_R/\Gamma\simeq0.4$, thus the Rabi oscillation is not observed. The total time of measurement is eight hours. We find that the theoretical analysis is in good agreement with the experimental result. Such a single-photon source can be fully controlled by pulses [57] or continuous-wave laser, which has many potential applications for quantum information processing.

4 Conclusion

In summary, we have demonstrated a single atom trap and

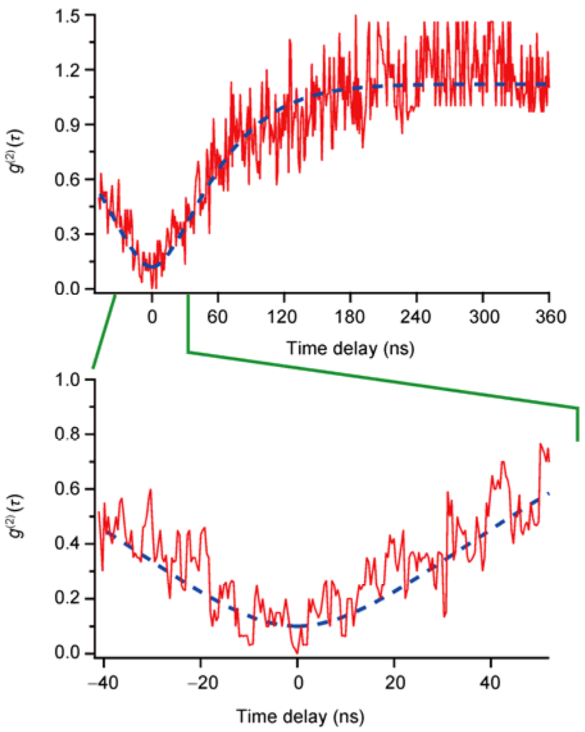

Figure 5 Measured second order correlation function $g^{(2)}(\tau)$ of fluorescence light from single atoms as a function of delay time. The result is obtained by a HBT experiment for an 8 h measurement in total. The dipole trap depth is 1.8 mK and the delay time is 48 ns. For τ=0 the correlation function shows a clear photon anti-bunching ($g^{(2)}(0)$ =0.12±0.02). The blue dashed curve is the theoretical fitting.

detection with low background. A 1064 nm microscopic optical tweezer with the size of 2.1 μm is built up. Due to the collisional blockade effect, single atoms can be loaded in the small FORT and the trap time is approximately 9 s. With the help of a weak 894 nm probe beam, which is perpendicular to the axis of the objective and the wavelength is far away from that of the cooling and FORT beams, the background of detection is suppressed down to an extremely low level: 10 counts per 50 ms. We also obtained the image of the individual trapped atoms and investigate the nonclassical statistical characteristic of its emission. The measured correlation function exhibits strong photon anti-bunching ($g^{(2)}(0)$=0.12±0.02) without deducting the background. Theoretical fitting is in good agreement with the experimental data. This simple single-atom trap system allows for individual atom manipulation and measurement, opening up avenues for quantum memory, quantum bit manipulation and multiple atom control either in free space or inside an optical cavity.

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