Trapping a single atom in a blue detuned optical bottle beam trap

Peng Xu,[1,2,3] Xiaodong He,[1,2,3] Jin Wang,[1,2] and Mingsheng Zhan[1,2,*]

[1]*State Key Laboratory of Magnetic and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences—Wuhan National Laboratory for Optoelectronics, Wuhan 430071, China*

[2]*Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071, China*

[3]*Graduate University of the Chinese Academy of Sciences, Beijing 100049, China*

**Corresponding author: mszhan@wipm.ac.cn*

Received March 16, 2010; revised May 27, 2010; accepted May 28, 2010; posted June 7, 2010 (Doc. ID 125435); published June 21, 2010

We demonstrate trapping a single rubidium atom in a blue detuned optical bottle beam trap. The trap was formed by a strongly focused blue detuned laser beam, which passes through a computer-generated circular π phase hologram displayed on a spatial light modulator. Single atoms were loaded from a magneto-optical trap and stored in the optical trap for several seconds. © 2010 Optical Society of America

OCIS codes: 020.3320, 020.7010, 270.5585, 090.2890.

Trapped single neutral atoms are good candidate blocks for building a quantum computer besides trapped ions, quantum dots, etc. Among the techniques developed to trap single atoms, using the far off-resonance optical trap (FORT) to confine single atoms is relatively simple, and the quantum states of atoms can be well preserved. Most groups choose to trap single atoms with the red detuned FORT (bright trap) [1–3], in which the laser beam is focused to attract atoms to the region of higher intensity. However, some groups have utilized the blue detuned FORT (dark trap) to capture single atoms [4,5]. The dark trap confines the atoms in a dark volume surrounded by blue detuned laser beams. It has several advantages over the bright trap. As the atoms are trapped in the "dark" place, the photon scattering rate due to the trapping laser can be greatly reduced, while in the bright trap this rate can be reduced only by increasing the detuning of the trapping laser. The coherent time of the atoms in a dark trap can thus be maintained to several seconds [6]. The ac Stark shift of the trapping laser can also be eliminated in the dark trap to make the coherent manipulation of the atoms much more easy. Another important application of the blue detuned trap may lay on equaling the polarizability for the ground and Rydberg state atoms [7].

Several types of dark traps have been proposed and demonstrated in past decade, including traps formed with a hollow beam plus two plugging beams [8], interfering two fundamental Gaussian beams [9], and a single beam passing through diffractive optical elements [10–12]. Dark traps for single atoms have been realized in a cavity [4] or in optical lattices [5]. In this Letter, we choose strongly focusing a blue detuned laser optical bottle beam generated by a spatial light modulator (SLM) to trap a single ^{87}Rb atom. Compared with other blue detuned optical traps for single atoms [4,5], this dark trap possesses advantages of both scalability and addressability; also the trapped atoms can be transported freely in space by well-controlled movement of the optical trap.

The optical bottle beam trap is generated by focusing a laser beam, whose phase is modified by a hologram displayed on an SLM (Holoeye 1080P). This hologram is to take the place of the circular π phase plate in the Ozeri experiment [11]. We calculated the hologram, as shown in Fig. 1(b), with MATLAB software. This hologram contains two parts: (1) a blazed phase grating structure used to separate the first-order light from the zeroth-order and nonmodulated light and (2) a central ellipse with π phase shift to generate destructive interference between the central and outer parts of the laser beam and to ensure a dark region around the focus. The elliptical instead of the circular π phase shift is to compensate for the tilting angle between the incident laser beam and the SLM. We calculated the intensity distribution, as shown in Fig. 1(c), by numerically solving the Fresnel diffraction integral as [13]

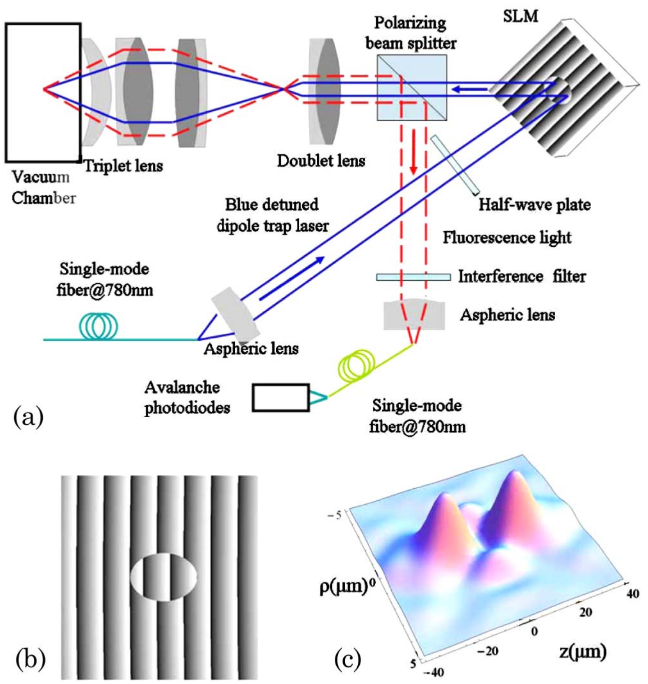

Fig. 1. (Color online) (a) Schematic of the experimental setup. Solid lines with arrows represent the light path of the blue detuned dipole laser, while dashed lines stand for the fluorescence emitted by the trapped atoms. (b) Calculated histogram to be imprinted on the SLM for dark trap (not to scale). (c) Calculated intensity distribution with $a = 0.62$, NA = 0.29, and $\lambda = 772$ nm.

$$E(\rho,\mu)=\frac{2}{1-e^{-1}}\int_0^1 r\exp(-r^2)J_0(\rho r)\times\exp\left(-\frac{1}{2}i\mu r^2\right)\mathrm{d}r-2\frac{2}{1-e^{-1}}\int_0^a r\exp(-r^2)\times J_0(\rho r)\exp\left(-\frac{1}{2}i\mu r^2\right)\mathrm{d}r, \quad (1)$$

and

$$I(\rho,\mu)=|E(\rho,\mu)|^2, \quad (2)$$

where $\rho=\frac{2\pi}{\lambda}(\mathrm{NA})R$ and $\mu=\frac{2\pi}{\lambda}(\mathrm{NA})^2Z$ with a being the normalized radius of the phase shift, λ the wavelength of the dipole laser, R the radial coordinate, and Z the axial coordinate.

The dipole laser is from a Ti:sapphire laser (Coherent MBR-110) with a wavelength of 772 nm, which is blue detuned to the D2 line of ^{87}Rb. To form the dark trap, the dipole laser incident to the SLM is collimated to a waist of 1.36 mm and the elliptical phase shift displayed on the SLM has a 1.90 mm major axis (horizontal) and a 1.84 mm minor axis (vertical). We use a commercial microscope objective (NA = 0.38, LINOS) to strongly focus the dipole laser. The focus status is identified and recorded by an aberration-free objective group to a CCD with 80× magnification. We compare the focus in Fig. 2 with theoretically calculated ones. Good agreement between theory and experiment can be seen from Fig. 2, and the little difference in diameter is due to the imperfect expanding and focusing of the dipole laser. The measured diameter of the surrounded dark region in the focal plane is about 6 μm. The ratio between intensities of the trap center and the trap wall, also called darkness, is measured to be 1:200 by scanning through the focal plane with a pinhole.

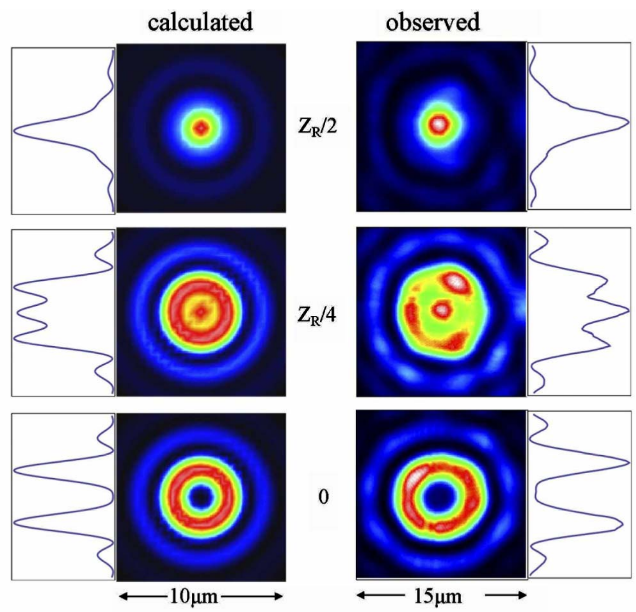

Fig. 2. (Color online) Intensity cross sections and corresponding beam profiles of the dark trap near the beam focus. Images are theoretically calculated (left) and experimentally observed (right) along the optical axis, away from the focus with 0, $Z_R/4$, and $Z_R/2$, where Z_R is the Rayleigh range.

The magneto-optical trap (MOT) is the same as in [3]. We used a dipole laser power of 80 mW, corresponding to an optical potential of about 1 mK of the dark trap, according to [14]. To load atoms from the MOT to the dark trap, we adjusted the focus of the dipole laser to overlap with the MOT. Meanwhile, to let an atom overcome the potential barrier and to enter the dark region, we shut off the trapping laser for a while and then turned on the laser again to hold the atom. We took 40 ms as a cycle in the time sequence with the laser off for the starting 1 ms and the laser on for the following 39 ms (the capturing cycle). The fluorescence of the trapped atoms induced by MOT light was collected by the same commercial microscope objective, as shown in Fig. 1(a). A polarizing beam splitter separated the fluorescence from the dipole laser while losing half of the signals. Two interference filters (Semrock LL01-780-12.5) were used to block the stray light of the dipole trap laser. The fluorescence was then coupled to a single-mode fiber with a diameter of 10 μm for spatial filtering and guided to a single-photon counting module [(SPCM), EG&G AQRH-14-FC].

The time sequence is crucial for this experiment. We take the capturing cycle continuously until the counts of fluorescence with a time bin of 40 ms exceed a threshold, then the laser is kept on (the holding cycle) until the count falls below the threshold to repeat the capturing cycle. Figure 3(a) shows the counts recorded following this sequence. The sudden raising and falling of the counts indicate an atom entering and leaving the trap. The two stages of counts represent no atom and one atom in the trap. We believe there is only one atom in the dark trap based on two reasons. First, theoretically, light-assisted collision by the MOT light will eject two or more atoms in a very small trap volume quickly out of a relatively low trap, known as the collisional blockade [15] mechanism. Our dark trap radius is 3 μm in the focal plane, and the optical potential is 1 mK. Under these conditions, when two or more atoms enter the trap, they will collide and quickly leave the trap, so the trap can capture only one atom or no atom. Second, experimentally we get a histogram of the counts recorded in a total time of 2600 s, as shown in Fig. 3(b), and we fit it to a compound Poisson function. From the curve, it is clear that the only two peaks represent events of atom number $N=0$ and $N=1$, with the $N=2$ peak missing. This indicates that

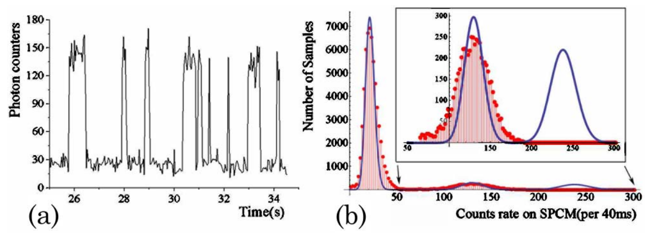

Fig. 3. (Color online) (a) Number of photons counted by the SPCM with 40 ms time bins and (b) histogram of photon counting data lasting for 2600 s (dots) and the fit with a compound Poisson law for the zero-atom, one-atom, and two-atom peaks (solid curve).

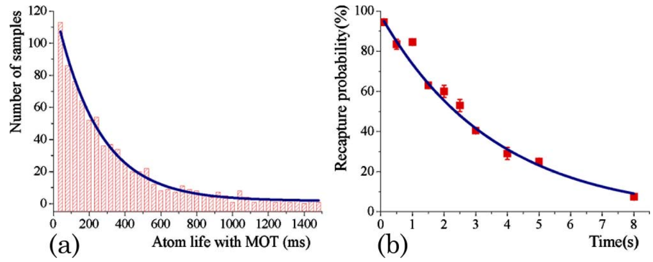

Fig. 4. (Color online) (a) Histogram of 750 single atom events measured by fluorescence induced with the MOT light when the MOT is on and a fit with an exponential decay function and (b) measurement of the atom lifetime in the dipole trap with the MOT off—each point is averaged three times, and each time includes 100 events.

we have actually compressed the trapping volume to the collisional regime, in which more than one atom could not be stably trapped. The photon number distributions of $N=0$ and $N=1$ are approximately Poissonian. The differences mostly come from stray light of the dipole trap laser and the MOT light. We find that the dark trap behaves very similarly to the red detuned dipole trap, as in [1].

The atoms cannot stay long in the dipole trap when the MOT is always on. We show a histogram of 750 single atom trapping events, and fit it with an exponential decay function in Fig. 4(a). The $1/e$ lifetime of the single atom with the MOT on is about 241 ms, which is sufficient for us to judge and execute the time sequence in succession. For long-term storage, the MOT has to be turned off to stop the loading and cooling process after an atom enters the trap, only keeping the atom in the dark trap by the dipole laser. In the experiment, we took the following time sequence: executing the capturing cycle continuously until the counts of fluorescence exceed a threshold, then turning off the MOT for a certain time t while keeping the dipole laser on, after that turning on the MOT light again to see whether the atom is still in the trap by fluorescence counts, then repeat. We scanned the off time t from 0.1 s to 8 s to get the probabilities of atoms still in the trap, then fitted the curve with an exponential decay function in Fig. 4(b). The lifetime is 3.6 s under our experimental conditions, which is of the same order as in the red detuned dipole trap [3]. We believe that by replacing the SLM with a π phase plate to reduce the intensity noise in the present experiment, and by more carefully adjusting the trap parameters to lower the darkness of the dipole trap, the lifetime of the atom in the blue detuned dipole trap can be much longer.

In conclusion, we have shown another way to trap a single atom. By strongly focusing a blue detuned optical bottle beam generated by an SLM, we were able to efficiently capture and store a ^{87}Rb atom. Under typical experimental conditions, the lifetime of the atoms in the trap is as long as several seconds, which is comparable with the bright trap and long enough for the next step of the experimental requirement. Further research is planned to seek the decoherence time of the atom stored in this dark trap. We hope to demonstrate a much longer coherence time of atomic quantum states than in the dominant red detuned dipole trap. We believe it will have more applications in quantum manipulation, quantum simulation, and quantum computation based on laser-trapped single atoms [16].

This work was supported by the National Basic Research Program of China under grant 2006CB921203, by the National Natural Science Foundation of China (NSFC) under grants 10827404 and 10804124, and also by funds from the Chinese Academy of Sciences.

References

1. N. Schlosser, G. Reymond, I. Protsenko, and P. Grangier, Nature **411**, 1024 (2001).
2. J. Volz, M. Weber, D. Schlenk, W. Rosenfeld, C. Kurtsiefer, and H. Weinfurter, Laser Phys. **17**, 1007 (2007).
3. X. D. He, P. Xu, J. Wang, and M. S. Zhan, Opt. Express **17**, 21014 (2009).
4. T. Puppe, I. Schuster, A. Grothe, A. Kubanek, K. Murr, P. W. H. Pinkse, and G. Rempe, Phys. Rev. Lett. **99**, 013002 (2007).
5. K. D. Nelson, X. Li, and D. S. Weiss, Nature Phys. **3**, 556 (2007).
6. N. Davidson, H. J. Lee, C. S. Adams, M. Kasevich, and S. Chu, Phys. Rev. Lett. **74**, 1311 (1995).
7. M. Saffman and T. G. Walker, Phys. Rev. A **72**, 022347 (2005).
8. T. Kuga, Y. Torii, N. Shiokawa, and T. Hirano, Phys. Rev. Lett. **78**, 4713 (1997).
9. L. Isenhower, W. Williams, A. Dally, and M. Saffman, Opt. Lett. **34**, 1159 (2009).
10. J. L. Chaloupka, Y. Fisher, T. J. Kessler, and D. D. Meyerhofer, Opt. Lett. **22**, 1021 (1997).
11. R. Ozeri, L. Khaykovich, and N. Davidson, Phys. Rev. A **59**, R1750 (1999).
12. J. Arlt and M. J. Padgett, Opt. Lett. **25**, 191 (2000).
13. J. P. Yin, W. J. Gao, H. F. Wang, Q. Long, and Y. Z. Wang, Chinese Phys. **11**, 1157 (2002).
14. J. L. Chaloupka, and D. D. Meyerhofer, J. Opt. Soc. Am. B **17**, 713 (2000).
15. N. Schlosser, G. Reymond, and P. Grangier, Phys. Rev. Lett. **89**, 023005 (2002).
16. M. Saffman, T. G. Walker, and K. Mølmer, http://arxiv.org/abs/0909.4777.