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Characterizing optical dipole trap via fluorescence of trapped cesium atoms

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Abstract Optical dipole trap (ODT) is becoming an important tool of manipulating neutral atoms. In this paper ODT is realized with a far-off resonant laser beam strongly focused in the magneto-optical trap (MOT) of cesium atoms. The light shift is measured by simply monitoring the fluorescence of the atoms in the magneto-optical trap and the optical dipole trap simultaneously. The advantages of our experimental scheme are discussed, and the effect of the beam waist and power on the potential of dipole trap as well as heating rate is analyzed.

Keywords: magneto-optical trap, optical dipole trap, cold atom, light shift.

Since it was first proposed in 1962, optical dipole force (ODF) has been used in trapping various particles from cells, molecules to neutral atoms[1]. With the landmarks by Chu in 1986, ODT has become a great tool of atom cooling and trapping[2]. Based on the extremely low optical heating rates of atoms, the trapping independence of the particular sub-level of the electric state and a great variety of trap geometry of the far-off resonant beam, ODT provides a perfect solution for the investigations on dynamics of atomic internal states[3]. Single atoms can even be trapped with the novel designed schemes, and the interest of ODT increases very rapidly due to the progress of atom manipulations[4,5]. Obviously the optical dipole trap will be the most important method to control the individual particles eventually.

For the final aim of realizing the optical trapping of single atoms in a micro-cavity, we first build a single beam dipole trap loading from a MOT continuously in free space. Although this type of trap has no novel structure compared with other standing wave traps, and comprehensive operation between multiple traps cannot be applied, a single focused beam dipole trap has still wide applications in many fields for its simpleness of operation, such as atom confinement of Bose-Einstein-Condensation of atoms and molecules[6−9] and quantum degeneration of Fermi atoms[10].

Generally, the properties of cold atoms, such as temperature, atom number and volume, instead of those characters of trap itself were studied widely in early papers. Although the measurement of trap frequency is a common method to determine the trap potential, a relatively complex system for measurement of low-frequency oscillation of atoms moving inside a trap is needed[11−13].

In this paper, we report the experimental results of optical dipole trap by utilizing a far-off resonance trap (FORT) beam detuned on either D_1 or D_2 line of cesium atoms and focused on the conventional magneto-optical trap (MOT) from vapor chamber[12,13]. The light shift of the atoms in ODT is measured directly by recording the 2D fluorescence spectrum of Cs atom D_1 line at 894 nm from the atoms located in MOT and ODT simultaneously. This is a novel and simple method for determining the potential depth especially for those relatively shallow wells.

When an atom is placed in the laser field, the atomic energy level can be shifted due to the interaction between the light field and the induced dipole moment, also called AC Stark shift or light shift. The atom undergoes the optical dipole force, which varies directly to the intensity gradient of light field.

Considering the usual practical condition, the potential depth can be simplified as

$$U_{\mathrm{dip}}(r) = -\frac{3\pi c^2}{2\omega_a^3}\frac{\Gamma}{\Delta}I(r), \tag{1}$$

where $\Delta = \omega_0 - \omega_a$, is the detuning; ω_0 is the laser frequency; ω_a the atomic resonance frequency; Γ the atomic natural decay rate; $I(r)$ the light intensity.

Depending on the sign of detuning, there are two kinds of dipole traps: red-detuned trap and blue-detuned trap. For the red-detuned trap, the potential minimum appears when the laser intensity reaches its maximum. Therefore, atoms are pushed towards the focus of laser beam. In experiment, the laser beam is focused in order to get deeper dipole potential and localize the atoms with relatively intense laser beam.

Although the excitation is kept low in the dipole trap, the atoms still have the chance to absorb the photons from the light field and reemit them as dipole radiation. This is one of the factors that determine the heating effect on the trapped atoms. The scattering rate is

$$\Gamma_{\mathrm{sc}}(r) = \frac{3\pi c^2}{2\hbar\omega_a^3}\left(\frac{\Gamma}{\Delta}\right)^2 I(r). \tag{2}$$

Scattering rate is proportional to $\frac{I}{\Delta^2}$. Therefore, the optical dipole trap usually employs a large detuning and high intensity beam to keep the scattering rate as low as possible while maintaining a certain potential depth.

The effects of laser waist and laser power on the dipole potential and scattering rate are given in Fig. 1, where we use $\Gamma/2\pi$ = 5.3 MHz and the detuning Δ = 120 GHz. The light intensity is directly determined by the power and the size of the beam. For Gaussian beam, we have

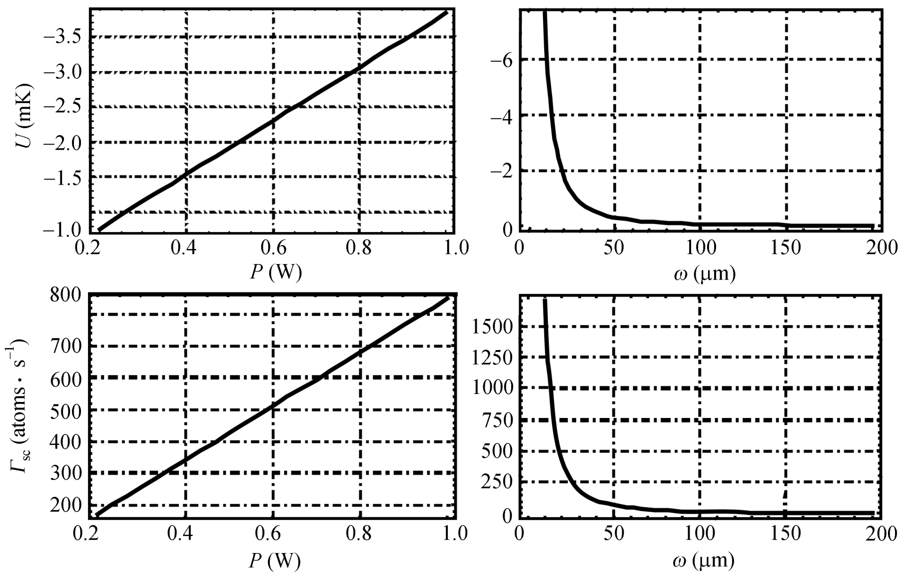

Fig. 1. The relationship between dipole potential (U), scattering rate (Γ_{sc}) and the laser power (P) and the waist radius (ω) of the beam.

$$I(r,z)=\frac{2P}{\pi\omega^2(z)}\exp\left[-\frac{2r^2}{\omega^2(z)}\right], \tag{3}$$

where $\omega(z)$ is the radius of the beam at z. Dipole potential increases with the laser power increasing, and the scattering, i.e. the heating rate shows the same tendency. Therefore, the proper laser power should be chosen to avoid excessive heating. In addition, the trap potential decreases fast with the increase in the laser waist. In order to reach deeper dipole potential and control more localized atoms, the laser beam should be strongly focused. Since the depth of the potential here in our experiment is not so high, we do not systematically measure the potential as a function of the above parameters based on the method discussed below.

Cesium cold atoms are prepared from a vapor chamber by a conventional magneto-optical trap[13−15]. The magneto-optical trap is composed of three pairs of counter-propagating σ^+-σ^- laser beams intersecting at the zero-magnetic field point of the spherical quadruple magnetic field. The cooling laser is frequency locked and biased to the Cs atom hyperfine transition F_g = 4–>F_e = 5 with the light power of each beam about 8 mW and the diameter about 15 mm. The repumping laser is locked to hyperfine transition F_g = 3–>F_e = 4 with the laser power about 10 mW and the diameter about 15 mm. The magnetic field gradient is 10 G/cm along the axial direction. The vacuum pressure is about 5×10^{-7} Pa. Typical parameters of cold atoms after the loading of 5 s are as followings: the diameter is approximately 1 mm, the atom number is about 1×10^7 and the average density is about 10^{10} atoms/cm^3.

Fig. 2 shows the hyperfine transitions of D_1 and D_2 line of cesium. The wavelengths of MOT lasers are both around 852 nm. As the dipole beam, two configurations can be chosen. The dipole laser is red detuned either from D_2 line (852 nm)(Fig. 2(a)) or from

D_1 line (894 nm)(Fig. 2(b)). The dipole trap has no much difference between the two configurations, but the measurement of the fluorescence is different in experiment. For the latter choice, no matter what wavelength of the probe laser is, there is obviously strong background either from cooling beam or from FORT beam, which may cause the reduction of signal-to-noise ratio of the fluorescence signal from ODT atoms.

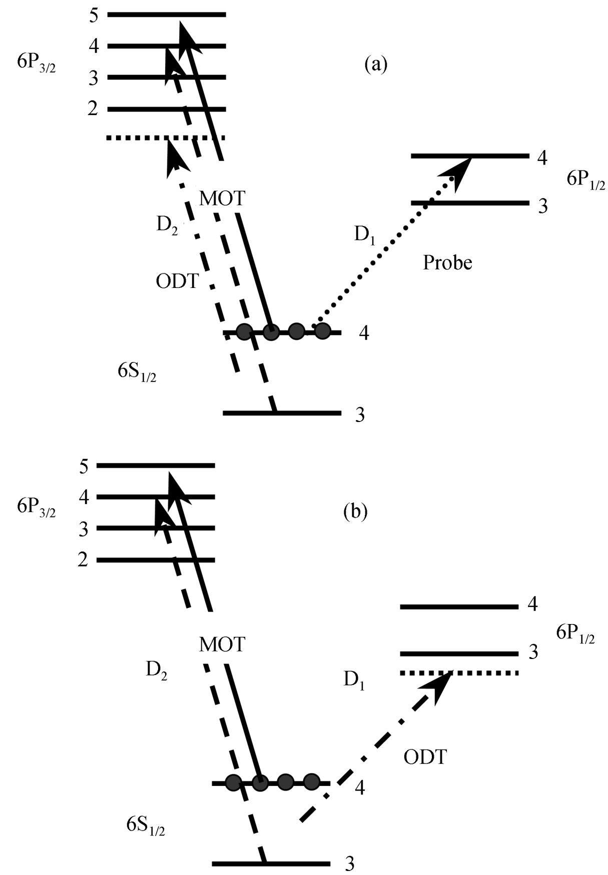

Fig. 2. Relevant hyperfine energy levels of cesium atom. The solid arrow line and the dash arrow line are cooling light and repumping light of MOT; the solid-dot arrow line is the dipole laser named ODT in figure; the dot arrow line is probe laser. (a) and (b) correspond to the two configurations in the experiment.

The experimental scheme of dipole trap is shown in Fig. 3. A single mode, linear polarization Ti:Sapphire laser is red detuned about 120 GHz to the Cs atom D_2 line and serves as a dipole trap beam. This detuning is measured by a reference Fabry-Perot cavity. The linewidth of the laser is about 200 kHz near 852 nm. At the MOT center, the dipole laser beam is focused with a waist size of approximately ω_0 = 50 μm, which is measured from the diameter of cloud of cold atoms. When the laser power is 300 mW just in front of the window of the chamber, the average intensity at the waist is about 900 W/cm^2, the potential depth is supposed to be 1.9 mK, and the lightshift is 40 MHz with the photon scattering rate of 11000 atoms per second. The corresponding trap frequency in the radial direction ω_r is about 2π×7 kHz, and in the axial direction ω_z is about 2π×13 Hz.

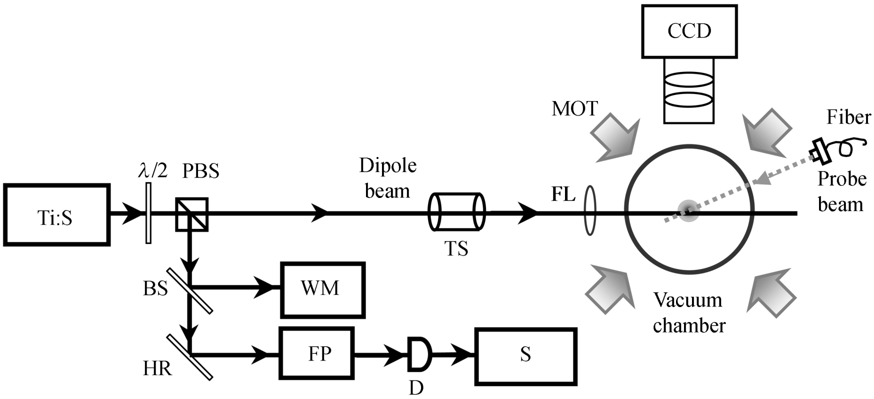

Fig. 3. Experiment scheme. Ti:S, Ti:Sapphire laser; $\lambda/2$, half wave plate; PBS, polarization beam splitter; TS, telescope; FL, focus lens; CCD, CCD image system; BS, 50% beam splitter; HR, high reflector; WM, wavelength meter; FP, Fabry-Perot cavity; D, detector; S, oscilloscope; MOT, laser beam of MOT.

Fig. 4 shows the 2D and 3D fluorescence images of MOT and ODT recorded at 852 nm and 894 nm respectively. The size and intensity of MOT are larger than ODT obviously. The diameters of MOT and ODT are approximately 1 mm and 100 μm, respectively. The great difference of diameters between the two axes of ODT is due to the spatial distribution of the focused Gaussian beam.

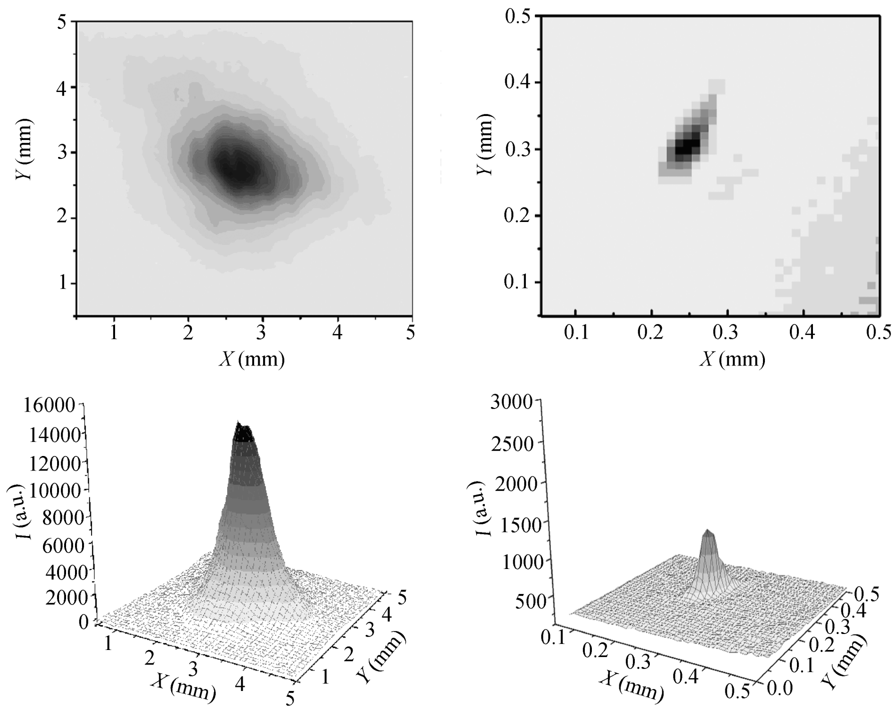

Fig. 4. 2D and 3D fluorescence image of MOT (left side) and ODT (right side).

The effective temperature of cold atoms in MOT is measured by the short distance time-of-flight (TOF) with a probe beam a few millimeters beneath MOT[16]. The measured effective temperature is about 70 μK, showing that the atoms can be loaded into ODT.

Generally the trap frequency of the confined atom is modeled as a harmonic oscillator and is measured to determine the trap potential[11]. In such measurement, the trapping light or the magnetic field is interrupted to drive the trapped atom into oscillation and the oscillation period of cold atoms is recorded by applying a probe light. The potential can then be decided by the oscillation frequency. The potential depth can also be estimated by the frequency shift of the energy level of atom, which is measured by the fluorescence spectrum at 894 nm from the atom in ODT. In our experiment, a diode laser operating at Cs atom D_1 line is applied as a probe to illuminating the cold atoms. When the laser frequency scans between cesium D_1 line hyperfine transition $6S_{1/2}$, $F_g = 4 \rightarrow F_e = 3$ to $6S_{1/2}$, $F_g = 4 \rightarrow F_e = 4$, the fluorescence from atoms in MOT and ODT can be extracted from different pixels on CCD. In Fig. 5, we show the fluorescence spectra of atoms from MOT and ODT extracted from different CCD pixels. The way to do this is to find a pixel A at

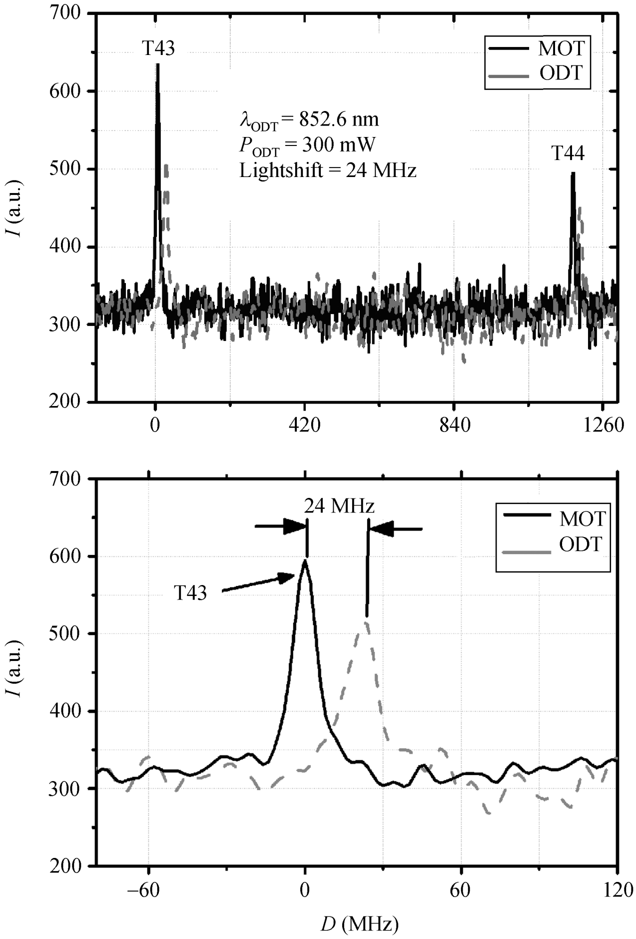

Fig. 5. The fluorescence spectra of MOT and ODT sweeping between Cs D_1 line hyperfine transition $6S_{1/2}$, $F_g = 4 \rightarrow F_e = 4$ (marked T44) and $6S_{1/2}$, $F_g = 4 \rightarrow F_e = 3$ (marked T43). The details of light shift appearing on transition $6S_{1/2}$, $F_g = 4 \rightarrow F_e = 3$ are shown in the lower figure.

the center of ODT on CCD whereas another pixel B that is far from ODT is still in MOT. The distance between A and B is 70 μm and the change of fluorescence can be measured by scanning the frequency of the probe. The whole frequency range between the two peaks of cesium D_1 line hyperfine transition $6S_{1/2}$, $F_g = 4 \rightarrow F_e = 3$ and $6S_{1/2}$, $F_g = 4 \rightarrow F_e = 4$ is 1167.68 MHz. The spontaneous emission peak of ODT (dashed trace) is blue shifted about 24 MHz from the peak of MOT (solid trace). The corresponding dipole potential depth is 1.1 mK. The measured light shift on the transition $6S_{1/2}$, $F_g = 4 \rightarrow F_e = 4$ is the same with $6S_{1/2}$, $F_g = 4 \rightarrow F_e = 3$.

The theoretical light shift is about 40 MHz based on the above mentioned parameters. The deviation between the measured light shift and the supposed result based on the setup is obvious. The main reason for this discrepancy is the inaccurate estimation of the size of the beam waist. Since the potential is very sensitive to the size of the beam (proportional to $1/\omega^2$). Another important factor is the noise of the laser beams, including the intensity, the phase and the beam pointing instabilities of the FORT beam and the laser cooling beams. The noise of the FORT beam will cause the vibration of the potential and randomly change the potential depth, and the atoms cannot be trapped at the real bottom of the shallow optical trap. We are evaluating the effect of this problem but have not got the final results since the phase noise of the laser beams can convert to intensity noise due to the diffusion of optical elements, and we have not figured out how much the conversion it is in our system. The last factor, which may not be the key point but should be mentioned, is the distance between A and B, which is not far enough, and the fluorescence from MOT may be still affected by the dipole beam. Yet, this measurement provides a simple way to test the light shift and it can be used in the usual experiment when we improve the system considering the above factors.

In conclusion, a vapor cell magneto-optical trap is employed in preparing cesium cold atoms, and the optical dipole trap is realized by applying single traveling wave of far-off-resonance laser focused into MOT center. We apply a new method for measuring the light shift of the atoms in ODT by the fluorescence spectrum of the atoms in MOT and ODT simultaneously. This is an easy way to determine the potential depth especially for those relatively shallow wells.

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References

1 Askar'yan G A. Effects of the gradient of a strong electromagnetic beam on electrons and atoms. Sov Phys JETP, 1962, 15: 1088

2 Chu S, Bjorkholm J E, Ashkin A, et al. Experimental observation of optically trapped atoms. Phys Rev Lett, 1986, 57(3): 314－317

3 Grimm R, Weidemüller M, Ovchinnikov Y B. Optical dipole traps for neutral atoms. Adv At Mol Opt Phys, 2000, 42: 95－170

4 Cirac J I, Zoller P A. Scalable quantum computer with ions in an array of microtraps. Nature, 2000, 404: 579－581

5 Protsenko I E, Reymond G, Schlosser N, et al. Operation of a quantum phase gate using neutral atoms in microscopic dipole traps. Phys Rev A, 2002, 65(5): 052301

6 Weber T, Herbig J, Mark M, et al. Bose-Einstein condensation of Cesium. Science, 2003, 299: 232－235

7 Barrett M D, Sauer J A, Chapman M S. All-Optical formation of an atomic Bose-Einstein condensate. Phys Rev Lett, 2001, 87(1): 010404

8 Granade S R, Gehm M E, O'Hara K M, et al. All-Optical production of a degenerate Fermi gas. Phys Rev Lett, 2002, 88(12): 120405

9 Jochim S, Bartenstein M, Altmeyer A, et al. Bose-Einstein condensation of molecules. Science, 2003, 302: 2101－2103

10 Greiner M, Regal C A, Jin D S. Emergence of a molecular Bose-Einstein condensate from a Fermi gas. Nature, 2003, 426: 537－540

11 Boiron D, Michaud A, Fournier J M, et al. Cold and dense Cesium clouds in far-detuned dipole traps. Phys Rev A, 1998, 57(6): R4106－R4109

12 Raab E L, Prentiss M, Cable A, et al. Trapping of neutral Sodium atoms with radiation pressure. Phys Rev Lett, 1987, 59(23): 2631－2634

13 Monroe C, Swann W, Robinson H, et al. Very cold trapped atoms in a vapor cell. Phys Rev Lett, 1990, 65(13): 1571－1574

14 Wang J M, Zhang T C, Yang W D, et al. Cooling and trapping of cesium atoms using the technique of vapour cell magneto-optical trap. Acta Optica Sinica (in Chinese), 1998, 18(12): 1770－1771

15 Wang J M, Zhang T C, Yang W D, et al. Magneto-optical trap loaded from an ultrahigh-vacuum vapor cell of cesium atoms. Acta Sinica Quantum Optics, 1998, 4(4): 229－235

16 Tomasz M B, Maria M, Michal Z et al. Time-of-flight measurement of the temperature of cold atoms for short trap-probe beam distances. J Opt B: Quantum Semiclass Opt, 2002, 4(1): 62－66