Optical Trapping of Cold Neutral Atoms Using a Two-Color Evanescent Light Field Around a Carbon Nanotube

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Optical Trapping of Cold Neutral Atoms Using a Two-Color Evanescent Light Field Around a Carbon Nanotube

Do Thi Nga[1], Nguyen Ai Viet[1], Dao Thi Thuy Nga[2] and Nguyen Thi Phuong Lan[3]

[1]Institute of Physics, Vietnam Academy of Science and Technology, 10 Dao Tan, Ba Dinh, Ha Noi, Vietnam

[2]Han Thuyen High School, Bac Ninh City, Bac Ninh Province, Vietnam

[3]Hanoi Pedagogical University 2, Nguyen Van Linh Street, Xuan Hoa Ward, Phuc Yen Town, Vinh Phuc Province, Vietnam

E-mail: daothuyngaht@gmail.com

Abstract. We suggest a new schema of trapping cold atoms using a two-color evanescent light field around a carbon nanotube. The two light fields circularly polarized sending through a carbon nanotube generates an evanescent wave around this nanotube. By evanescent effect, the wave decays away from the nanotube producing a set of trapping minima of the total potential in the transverse plane as a ring around the nanotube. This schema allows capture of atoms to a cylindrical shell around the nanotube. We consider some possible boundary conditions leading to the non-trivial bound state solution. Our result will be compared to some recent trapping models and our previous trapping models.

1. Introduction

Recently, study properties of cold neutral trapped atoms have attracted much interest because of their significance in both fundamental research and potential technological applications. Cold and trapped radioactive atoms can be used in the fundamental symmetry experiments, including the experiments on nuclear β-decay, atomic parity non conservation and the search for parity and time-reversal violating electric dipole moment [1]. Trapping of ultracold atoms also gives an opportunity to study the collisional processes in cold atomic samples [2]. Trapped cold atoms can be used in the formation of cold molecules [3] and in studies of quantum statistical effects in atomic ensembles at low temperatures, such as the Bose-Einstein condensation (BEC). Since a cold molecules trap lifetime was approximately half a second, so the production of cold molecules opens up new ways of research in molecular spectroscopy.

There are different schemes for trapping and storing cold atoms [4], [5] such as optical trapping using the forces of electric dipole interaction between atoms and laser fields, magnetic trapping based on the use of the forces of magnetic dipole interaction, mixed magneto-optical trapping using simultaneous interaction between atoms and magnetic and laser fields, and also mixed gravito-optical and gravito-magnetic trapping. It has been shown experimentally that neutral atoms can be captured by an optical trap [6], based on the use of an evanescent wave around a thin silica fiber. The attractive potential created by the light is inversely proportional to the

radius of the optical fiber. The condition for the existence of the trap is that the fiber diameter is about two times smaller than the light wavelength. Recently, a cold atom trap model using a charged single wall carbon nanotube (SWCNT) has been presented [7].
Based on these models, in the previous works, we have proposed a new trapping schema for the cold atoms using a single wall carbon nanotube [8]. In that model, for the existence of a stable bound state of cold atom, a strong electromagnetic field has been sent through the carbon nanotube. This field generates an evanescent wave around the carbon nanotube and creates an effective attractive potential. The consideration of some possible boundary conditions leads to this nontrivial bound state solution. There also is a comparison our result to the two most recent models concerning trapping of cold atoms by using a charged carbon nanotube and an optical fiber. It has been shown that the smaller the radius is, the stronger potential is created. The bound state in our model is more stable and resonalbe. New technology of nano materials is developed to optimize the trapping effect.
In this paper, a new design of optical trapping cold atom using a single wall carbon nanotube injected by two strong electromagnetic waves is proposed. This scheme gives strong effect on cold neutral atom, which need to be shown experimentally.

2. Two evanescent light field trap for cold neutral atom moving around a carbon nanotube

Consider an atom moving in a potential around the single wall carbon nanotube (SWCNT). If this potetial has a local minimum at a point outside the SWCNT, the atom can be trapped in the vicinity of this point. Our task is to create a potential with a trapping minimum sufficiently far from the SWCNT surface to make the effects of surface interaction and heating negligible. For this purpose, we use two light fields in the fundamental modes 1 and 2 with differing wavelengths λ_1 and λ_2, respectively. A schematic of our design is shown in Fig. 1.

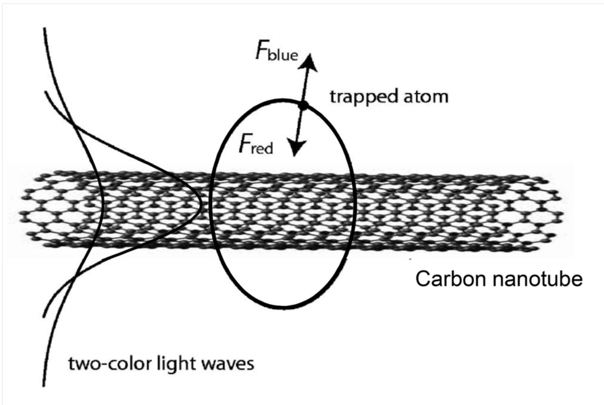

Figure 1. *Design of optical trapping cold atom by sending two electromagnetic waves through a carbon nanotube.*

The schema of our model is an analogy of the optical trap model [9], but the optical fiber is replaced by a SWCNT with radius R. The two electromagnetic waves with wavelengths λ_1 and λ_2 are sent into the SWCNT, the waveguide possibility of carbon nanotube is observed experimentally [10]. By evanescent effect, the wave decays away from the SWCNT surface producing an attractive potential for the neutral atom. The atom needs to be kept away from the SWCNT for a stable trapping. For a clear comparison with the optical trap model using a silica fiber [9] and single wall carbon nanotube, we use the same, red-detuned light λ_1 and blue-detuned light λ_2, as a source of electromagnetic waves.

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We assume that the input light fields are circularly polarized to produce the cylindrically symmetric optical potential. The optical potential of the atom is cylindrically symmetric, that depends on the radial distance r from the atom to the carbon nanotube axis z, but not on two other cylindrical coordinates φ and z. The optical field generates an evanescent wave around the SWCNT to capture cold atoms. Assume that the time scale of atomic motion is much slower than the beating period of the two light fields, that is, the inverse of their frequency difference. Then, the optical potentials of the two fields add up to give the net optical potential

$$U_{\text{opt}}(r) = U_1 + U_2 \tag{1}$$

The sign of the optical potential of each mode is controlled by the sign of the mode detuning. We choose a red detuning (the detuning of the optical frequency from the atomic frequency is negative) for the field in mode 1 and a blue detuning (the detuning of the optical frequency from the atomic frequency is positive) for the field in mode 2. This allows both attractive (red-detuned) and repulsive (blue-detuned) potentials to be created. In the linear-polarization approximation, the net optical potential outside SWCNT can be written as

$$U_{\text{opt}}(r) = G_2 K_0^2(q_2 r) - G_1 K_0^2(q_1 r) \tag{2}$$

where G_1 and G_2 are positive coupling parameters for the interaction between the evanescent waves and the atom. They are proportional to the powers of the corresponding light fields. The parameter $q = 1/\Lambda$ is the inverse of the characteristic decay length Λ of the evanescent-wave field. The modified Bessel function $K_0(qr)$ is used to describe the spatial dependence of the amplitude of the field outside the carbon nanotube in the linear-polarization approximation.
The atom can have a stable bounded state only if $U_{\text{opt}}(r)$ has a local minimum at distance $r = r_m$ outside of the carbon nanotube; that means the potential U_{opt} is attractive. The r_m is the solution of, $U'_{\text{opt}}(r_m) = 0$, from this we find

$$F(r_m) = G \tag{3}$$

where

$$F(r) = \frac{K_0(q_1 r) K_1(q_1 r)}{K_0(q_2 r) K_1(q_2 r)} \tag{4}$$

and

$$G = \frac{G_2 q_2}{G_1 q_1} \tag{5}$$

Since $q_1 < q_2$, the function $F(r)$ is a monotonically increasing function of r. The local minimum point r_m exist only when $G > F(R)$. The requirement $r_m > R$ can be satisfied only when

$$\frac{G_2}{G_1} > \frac{q_1 K_0(q_1 R) K_1(q_1 R)}{q_2 K_0(q_2 R) K_1(q_2 R)} \tag{6}$$

Condition (6) means that there exists a trapping minimum outside the fiber if the intensity of the blue-detuned light is large enough or if the intensity of the red-detuned light is small enough (but not zero).
The atom can be prevented from coming too close to the SWCNT surface before being loaded into the trap if the net optical potential achieves a non-negative value at the fiber surface, that is, if $U_{\text{opt}}(R) \geq 0$. This requirement will be satisfied if

$$\frac{G_2}{G_1} \geq \frac{K_0^2(q_1 R)}{K_0^2(q_2 R)} \tag{7}$$

When condition (7) is satisfied, condition (6) is also satisfied. To maximize the depth of the trapping minimum, we optimize the powers of the two field in such a way that condition (7) reduces to an equality, namely,

$$\frac{G_2}{G_1} = \frac{K_0^2(q_1 R)}{K_0^2(q_2 R)} \tag{8}$$

Due to the cylindrical symmetry of the total optical potential $U_{\rm opt}$, the component L_z of the angular momentum of the atom is conserved. In the eigenstate problem, we have $L_z = \hbar m$, where m is an integer, called the rotational quantum number. The centrifugal potential of the atom is given by $U_{\rm cf}(r) = \frac{(m^2-1/4)\hbar^2}{2Mr^2}$. The radial motion of the atom can be treated as the one-dimensional motion of a particle in the effective potential

$$U_{\rm eff}(r) = \frac{(m^2-1/4)\hbar^2}{2Mr^2} + G_2 K_0^2(q_2 r) - G_1 K_0^2(q_1 r) \tag{9}$$

In our calculations, we use the SWCNT with (n, m)=(21,0) corresponding to the radius is $R = 0.83$ nm and set the parameters: $\lambda_1 = 1.2\ \mu$m, $\Lambda_1 = 24.8$ nm, $\lambda_2 = 0.7\ \mu$m, and $\Lambda_2 = 4.6$ nm. In the Fig. 3, it is observed that the existence of a deep local minimum of the effective optical potential outside carbon nanotube leads to the existence of captured states of the atom.

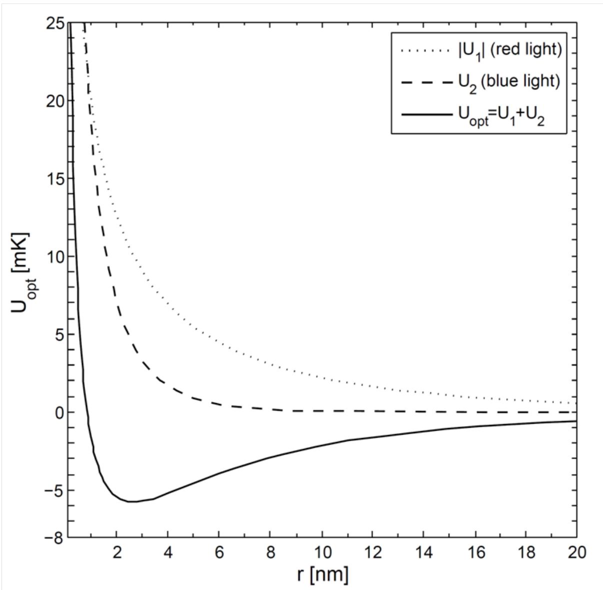

Figure 2. *The net optical potential outside the SWCNT (n, m)=(21,0) with the two evanescent waves $\lambda_1 = 1.2\ \mu m$, $\lambda_2 = 0.7\ \mu m$.*

3. Energy of the neutral cold trapped atoms in the effective potential around the a carbon nanotube

In previous section, we have been shown that the atom can be trapped by injecting two strong electromagnetic waves into a SWCNT. Therefore, the binding energy of the atom will be estimated by solving the Schrodinger equation.

The Schrodinger equation is written in the cylindrical coordinates (r, φ, z) in the form

$$[-\frac{\hbar^2}{2M}\nabla^2 - U_{\rm eff}(r)]\,\Psi(r,\varphi,z) = E\,\Psi(r,\varphi,z) \tag{10}$$

where E is the energy of atom in the effective potential.
The general form of the wave function is used

$$\Psi(r,\varphi,z) = \frac{1}{\sqrt{r}} R(r)\, e^{im\varphi}\, e^{ikz} \tag{11}$$

substitute $\Psi(r,\varphi,z)$ into Schrodinger equation (10), we obtain the Schrodinger equation for center-of-mass mouvement of the atom in the presence of effective optical potential $U_{\text{eff}}(r)$ is

$$\frac{d^2R}{dr^2} + \frac{2\mu}{\hbar^2}[E - U_{\text{eff}}(r)]R = 0 \tag{12}$$

There is no analytic solution for equation (12), so an approxmation is made for the effective optical potential. Therefore, the potential could be written in the form $\frac{A}{r^2} - \frac{B}{r} + C$ A, B and C are the fitting parameters. The approximated effective potential is made with $A = 25.0$, $B = 19.3$ and $C = -2.1$. The solution of Eq. (12) with the approximated effective potential has the form [11]

$$E_n = C - B^2k^2\{2n + 1 + \sqrt{1 + 4Ak^2}\}^{-2},\ n = 0, 1, 2, ... \tag{13}$$

This expression gives the binding energy of cold neutral atom in the effective optical potential around a SWCNT. The experimental relization of bound states requires the binding energy of

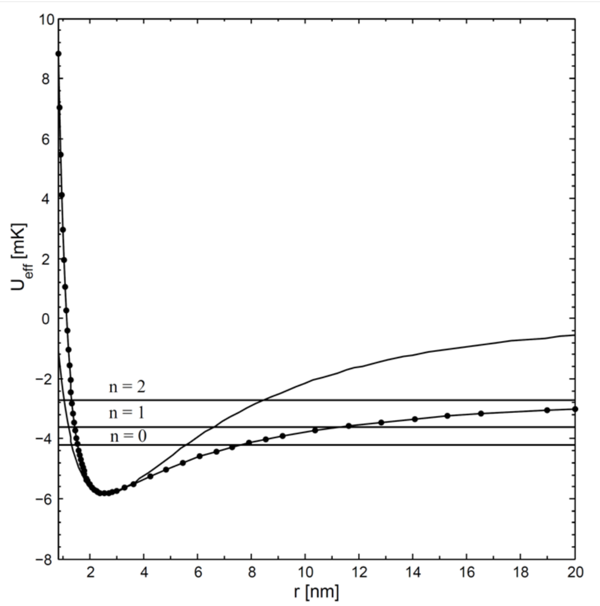

Figure 3. *Theorical effective potential (solid line) and approximate one (dotted line). Bound states for the first three levels (n = 0, 1, 2)of the radial motion of a cesium atom in the effective potential of a single wall carbon nanotube (m,n)=(21,0).*

atoms to be higher than their typical thermal kinetic energy. In Fig. 3, we plot the first three levels of the radial motion of the atom in the effective potential U_{eff} with the rotational quantum number $m = 0$. The energy of the ground state is $E_0 \approx -4.2$ mK. Since the binding energy of an atom in the ground state is $E_b = U_{\text{opt}}(r = \infty) - E_0 \approx 4.2$ mK. Thus our design can trap cesium atoms around the SWCNT at a temperature of less than 4.2 mK.

4. Conclusion

It has been shown that the neutral cold atoms moving near a SWCNT can be captured by sending two evanescent light field through it. It's a new model for trapping cold atoms, based on the ideas of some recent experimental and theoretical model [8]-[9]. In comparing with our previous trapping design [8], the ground state energy is much more smaller, trapping effect is stronger. Cold atom can be trapped and store to be study easily. This is a new design of optical trap which give strong effect on cold neutral atom, which need to be shown experimentally.

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