Vol 17 No 10, October 2008
1674-1056/2008/17(10)/3662-06

Chinese Physics B

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Enhanced cooling of a V-type three-level atom in an optical cavity*

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(Received 30 December 2007; revised manuscript received 15 May 2008)

We have studied theoretically and numerically the enhanced cooling of a V-type three-level atom in a high-finesse optical cavity and shown that the cooling rate can be increased by one order of magnitude over that of a two-level atom, and the momentum amplitude tends to a stationary state much smaller than that of a two-level atom. We have further shown that the cooling rate can be significantly improved by using feedback and a time-dependent pump.

Keywords: cavity cooling, three-level atom, enhanced cooling
PACC: 3280, 4250, 3280P, 4250V

1. Introduction

Laser cooling is indispensable for trapping and observing ultracold atoms and molecules. All conventional methods for laser cooling atoms are based on repeated optical pumping cycles followed by spontaneous emission. Such pumping schemes can only be applied to a small number of atomic species, which have closed optical transitions.[1−3] Drawbacks caused by photons spontaneously emitted from atom can be avoided in the strong atom–cavity system. New cavity cooling methods, which use a cavity detuned from resonance to preferentially scatter blue shifted photons out of cavity and extract energy from the atoms within the cavity, have been proposed for a single atom strongly coupled to a high-finesse cavity.[4−6] For a single atom in an optical cavity, the atom moves through the periodic potential created by the atom-field interaction within a cavity. For a red detuned light the frequency shift is a minimum when the field is maximum. In the experiment, the intracavity field is temporally modulated by changing the effective cavity length as the atoms go through the standing wave in the cavity. Cavity cooling of a single rubidium atom stored in an high-finesse cavity was demonstrated,[7] the cooling mechanism resulted in extended storage time and improved localization of the atom. It is shown that the observed cooling rate is at least five times larger than the cooling rate which can be achieved by free-space cooling methods for comparable excitation of the atom.[7] Further improvements were also suggested including introducing a linear feedback,[8] exploiting interference effects[9] and keeping the Rabi frequency invariant but reducing the mode volume.[10] Recently, the addition of a probe laser and an optical cavity leading to a strong cooling force were investigated experimentally and theoretically.[11,12] The cooling of atoms and molecules in a bistable cavity has also been proposed.[13,14] In fact, the ultracold atom–cavity systems are becoming a framework for investigating the foundation of quantum mechanics and their application to ultracold atoms and molecules. Application of such cooling schemes would improve the performance of atom–cavity systems for quantum information processing,[15−18] and cavity Bose-Einstein condensation.[19]

Usually, a two-level system is used to analyse the cavity cooling of atoms and molecules. Nevertheless the practical experiments are carried out on multilevel atoms. The nature of multilevel atom–cavity field interaction is quantitatively different from that of a two-level atom. In general, the involvement of multiple levels enhances the atom–cavity field coupling

*Project supported by the National Natural Science Foundation of China (Grant No 10704031), the National Science Foundation for Fostering Talents in Basic Research of the National Natural Science Foundation of China (Grant No J0630313), the Fundamental Research Fund for Physics and Mathematics of Lanzhou University (Grant No Lzu05001), and the Natural Science Foundation of Gansu Province, China (Grant No 3ZS061-A25-035).
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strength, which leads to a large momentum change between the atom and the cavity field. The extended level structure provides flexibility, a three-level atom can be cooled down to lower temperature than a two-level atom.[20] Furthermore, there are more parameters capable to control the cavity cooling, namely, two scattering losses, two frequency shifts and two initial positions of the displacement from the equilibrium for excited states. On account of above aspects, it is interesting to study the cavity cooling of a three-level atom. The present work provides several important findings beyond the scope of previous investigation on cavity cooling using the two-level atom model. We find that the cooling rate can be increased 10 times and the enhanced cooling can be obtained by exporting a pump field.

In this paper, we will explore how cavity cooling rate can be enhanced using a V-type three-level atom. The paper is organized as follows: In section 2 we first set up the dynamic equations for a V-type three-level atom in a single-mode cavity, following the cavity cooling optical method with the potential for cooling species in the mK regime. Section 3 is devoted to the investigation of the enhanced cavity cooling of a V-type three-level atom using a numerical and graphical method. We verify that our results agree well with the existing experimental results. A summary is included in section 4.

2. General model

Let us start with a schematic sketch as shown in Fig.1. We consider a V-type three-level atom (with internal levels $|0\rangle$, $|1\rangle$ and $|2\rangle$, with increasing energies 0, $\hbar\omega_1$, $\hbar\omega_2$, where $|1\rangle$ ($|2\rangle$) decays radiatively into $|0\rangle$ at rate Γ_1 (Γ_2)) strongly coupled to a single mode of a high-finesse cavity. In general, the system is driven by a monochromatic field of frequency ω_p and effective amplitude η. The cavity photons decay at a rate κ.

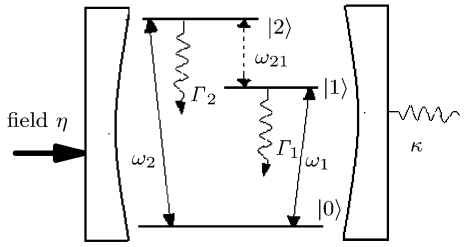


Fig.1. Schematic diagram of a V-type three-level atom coupled to a single-mode cavity and driven by a laser field.

The cavity field induces a dipole moment of the V-type three-level atom, which in turn contributes to the electric field as a driving term in the wave equation[21]

$$\begin{aligned}&\left(-\Delta+\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\boldsymbol{E}(\boldsymbol{x},t)+\mu_0\sigma\frac{\partial}{\partial t}\boldsymbol{E}(\boldsymbol{x},t)\\&=-\mu_0\frac{\partial^2}{\partial t^2}\boldsymbol{P}(\boldsymbol{x},t)+\mu_0\sigma\frac{\partial}{\partial t}\boldsymbol{E}^{\rm ext}(\boldsymbol{x},t),\\&\boldsymbol{P}(\boldsymbol{x},t)=\boldsymbol{P}_1(\boldsymbol{x},t)+\boldsymbol{P}_2(\boldsymbol{x},t)+\boldsymbol{P}_{\rm inter}(\boldsymbol{x},t),\end{aligned}\tag{1}$$

where σ is the conductivity of the cavity mirrors; the damping term was modelled as $\mu_0\sigma\frac{\partial}{\partial t}\boldsymbol{E}(\boldsymbol{x},t)$ and the external pump was taken into account by this term. $\boldsymbol{P}_1$ and $\boldsymbol{P}_2$ are the dipole moments resulting from the transitions between $|1\rangle\leftrightarrow|0\rangle$ and $|2\rangle\leftrightarrow|0\rangle$, respectively. The term $\boldsymbol{P}_{\rm inter}$ results from the cross coupling between the transitions $|1\rangle\leftrightarrow|0\rangle$ and $|2\rangle\leftrightarrow|0\rangle$. For simplicity, we neglect the coupling term $\boldsymbol{P}_{\rm inter}$,[22] and the optical field in the cavity is considered as a single-mode plane wave in the x direction, which leads to

$$\begin{aligned}&\frac{\partial^2}{\partial t^2}E(x,t)+\frac{\sigma}{\epsilon_0}\frac{\partial}{\partial t}E(x,t)-c^2\frac{\partial^2}{\partial x^2}E(x,t)\\&=-\frac{1}{\epsilon_0}\frac{\partial^2}{\partial t^2}P_1(x,t)-\frac{1}{\epsilon_0}\frac{\partial^2}{\partial t^2}P_2(x,t)\\&\quad+\frac{\sigma}{\epsilon_0}\frac{\partial}{\partial t}E^{\rm ext}(x,t).\end{aligned}\tag{2}$$

$E(x,t)$ can be expanded into normal modes

$$E(x,t)=\sum_{n=0}^{\infty}\tilde{E}_n(t)\cos(K_nx),\tag{3}$$

with eigenfrequencies $\omega_n{=}cK_n{=}n\pi c/d$, where d denotes the cavity length. After some straightforward manipulations, the following ansatz for the electric field and the polarization, the equation for the dynamics of the cavity mode with eigenfrequency ω_c can be obtained.

$$\dot{\varepsilon}+(\kappa-{\rm i}\Delta_c)\varepsilon\approx\frac{{\rm i}\omega_p(P_1+P_2)}{2\epsilon_0}+\kappa\varepsilon^{\rm ext},\tag{4}$$

where $\Delta_c=\omega_p-\omega_c$ and $\kappa=\sigma/(2\epsilon_0)$. Here we have assumed that the amplitudes vary slowly as compared to the rapidly oscillating exponential functions. As a next step we have to introduce the dynamics of the atomic dipoles, which are modelled as two elastically bound electrons.[23,24] Thus their elongations are governed by the equation of a damped harmonic oscillator driven by an electric field at the atomic position x_i (i=1, 2):

$$\begin{aligned}&\ddot{y_1}(t)+2\Gamma_1\dot{y_1}(t)+\omega_1^2y_1(t)=\frac{e}{m}E(x_1,t),\\&\ddot{y_2}(t)+2\Gamma_2\dot{y_2}(t)+\omega_2^2y_2(t)=\frac{e}{m}E(x_2,t),\end{aligned}\tag{5}$$

where $x_i = x + x_{0i}$ (i=1, 2), with x being the position of the centre-of-atom; x_{0i} are the initial positions of the displacement from the equilibrium for excited states.

Using the slowly varying complex amplitude $Y(t)$ via the ansatz, we have

$$\begin{aligned} y_1(t) =& Y_1(t)\mathrm{e}^{-\mathrm{i}\omega_p t} + Y_1(t)^*\mathrm{e}^{\mathrm{i}\omega_p t}, \\ y_2(t) =& Y_2(t)\mathrm{e}^{-\mathrm{i}\omega_p t} + Y_2(t)^*\mathrm{e}^{\mathrm{i}\omega_p t}. \end{aligned} \tag{6}$$

Upon inserting Eq.(6) into Eq.(5) and solving for the steady states, we obtain

$$\begin{aligned} Y_1(t) =& \frac{e\varepsilon(t)/m}{2\omega_p(-\mathrm{i}\Gamma_1 + (\omega_1^2-\omega_p^2)/2\omega_p)}\cos(Kx_1), \\ Y_2(t) =& \frac{e\varepsilon(t)/m}{2\omega_p(-\mathrm{i}\Gamma_2 + (\omega_2^2-\omega_p^2)/2\omega_p)}\cos(Kx_2). \end{aligned} \tag{7}$$

For a point-like particle the polarization density can be defined as $P_i(x_i,t) = ey_i(t)\delta(x-x_i)/A$, where A is the cavity cross section and V is the cavity volume, which yields the following expressions for the slowly varying amplitudes:

$$\begin{aligned} p_1(t) =& \mathrm{i}\frac{e^2}{m\omega_p V}\frac{\cos^2(Kx_1)}{\Gamma_1 + \mathrm{i}(\Delta-\omega_{21})}\varepsilon_{(t)}, \\ p_2(t) =& \mathrm{i}\frac{e^2}{m\omega_p V}\frac{\cos^2(Kx_2)}{\Gamma_2 + \mathrm{i}\Delta}\varepsilon_{(t)}. \end{aligned} \tag{8}$$

Here $\omega_{21} = \omega_2 - \omega_1$, $\Delta = \omega_2 - \omega_p$, and approximations $(\omega_1^2-\omega_p^2)/(2\omega_p) = (\omega_1-\omega_p)(\omega_1+\omega_p)/(2\omega_p) \approx \Delta-\omega_{21}$, $(\omega_2^2-\omega_p^2)/(2\omega_p) = (\omega_2-\omega_p)(\omega_2+\omega_p)/(2\omega_p) \approx \Delta$ have been made. Putting everything together and splitting the polarization into a real and an imaginary parts, Eq.(4) leads to the following equation for the slowly varying field amplitude,

$$\begin{aligned} \dot{\varepsilon}(t) =& [-\kappa + \mathrm{i}\Delta_c - \gamma(x_1) + \mathrm{i}U(x_1) \\ & - \gamma(x_2) + \mathrm{i}U(x_2)]\varepsilon(t) + \kappa\varepsilon^{\mathrm{ext}}, \end{aligned} \tag{9}$$

where

$$\begin{aligned} U(x_1) =& \frac{\Delta-\omega_{21}}{\Gamma_1^2 + (\Delta-\omega_{21})^2}g_0^2\cos^2(Kx_1), \\ \gamma(x_1) =& \frac{\Gamma_1}{\Gamma_1^2 + (\Delta-\omega_{21})^2}g_0^2\cos^2(Kx_1), \\ U(x_2) =& \frac{\Delta}{\Gamma_2^2 + \Delta^2}g_0^2\cos^2(Kx_2), \\ \gamma(x_2) =& \frac{\Gamma_2}{\Gamma_2^2 + \Delta^2}g_0^2\cos^2(Kx_2). \end{aligned} \tag{10}$$

Here $g_0^2 = e^2/(2V\epsilon_0 m)$ is a measure for the cavity-atom coupling strength, $\gamma(x_1)$ and $\gamma(x_2)$ are the scattering losses, and $U(x_1)$ and $U(x_2)$ are the frequency shifts of the cavity due to the interaction with the particle.

The force on the atom is then given by

$$\begin{aligned} f(x) =& \nabla[ey(x_1,t)E(x_1,t)] + \nabla[ey(x_2,t)E(x_2,t)] \\ =& -\nabla\left[\frac{e^2}{2\omega_p m}\frac{\Delta-\omega_{21}}{\Gamma_1^2+(\Delta-\omega_{21})^2}\right]\varepsilon^2\cos^2(Kx_1) \\ & -\nabla\left[\frac{e^2}{2\omega_p m}\frac{\Delta}{\Gamma_2^2+\Delta^2}\right]\varepsilon^2\cos^2(Kx_2). \end{aligned} \tag{11}$$

For simplicity, we define a dimensionless parameter $|\alpha|^2 = \epsilon_0|\varepsilon^2|V/\hbar\omega_p$, which is associated with the average cavity photon number. We obtain the following coupled equations for the cavity field, the momentum of the V-type three-level atom , and its position,

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \frac{p}{m}, \tag{12a}$$

$$\frac{\mathrm{d}p}{\mathrm{d}t} = -|\alpha|^2\frac{\mathrm{d}U(x_1)}{\mathrm{d}x} - |\alpha|^2\frac{\mathrm{d}U(x_2)}{\mathrm{d}x}, \tag{12b}$$

$$\begin{aligned} \frac{\mathrm{d}\alpha}{\mathrm{d}t} =& [-\kappa + \mathrm{i}\Delta_c - \gamma(x_1) + \mathrm{i}U(x_1) \\ & - \gamma(x_2) + \mathrm{i}U(x_2)]\alpha + \kappa\eta. \end{aligned} \tag{12c}$$

Equation (12a) describes the position of the V-type three-level atom in the cavity. Equation (12b) corresponds to the dipole force. Instead of one term as in the case of monochromatic two-level model, the dipole force now has two contributions involving the frequency shifts of the cavity from the two excited states, yielding two periodic potentials with a period of half of the wavelength. Equation (12c) describes the pumping of the cavity mode: the frequency detuning from the pump laser shifted according to the coupling to the atom, and the mode damping due to cavity decay and photon scattering by the V-type three-level atom. The atomic action as a position-dependent frequency shift and the loss term for the mode is clearly manifested. In the following, Eqs.(12) will be used to study the cooling of a V-type three-level atom in a high-finesse cavity.

3. Enhanced cavity cooling of a V-type three-level atom

Using the theory described in the previous section, we have calculated the dipole force and particle momentum in one dimension. Our results are represented in scaled quantities: position of the centre-of-atom is divided by κ, particle momentum by $\hbar\kappa$, time by κ. The other parameters $\Delta_c, \Gamma_1, \Gamma_2, U_1, U_2$ are divided by κ and $\hbar K^2/mk = 1$ is assumed.

The typical dynamical behaviour of this coupled system is shown in Fig.2(a). The cavity cooling of a two-level model has been well studied.[4,5] A brief description is also included in Fig.2(a) for comparison. One can easily observe that enhanced cooling can be attained using a V-type three-level atom in an optical cavity. The cooling rate required to cool the V-type three-level atom can be increased 10 times larger than that of a two-level model system.

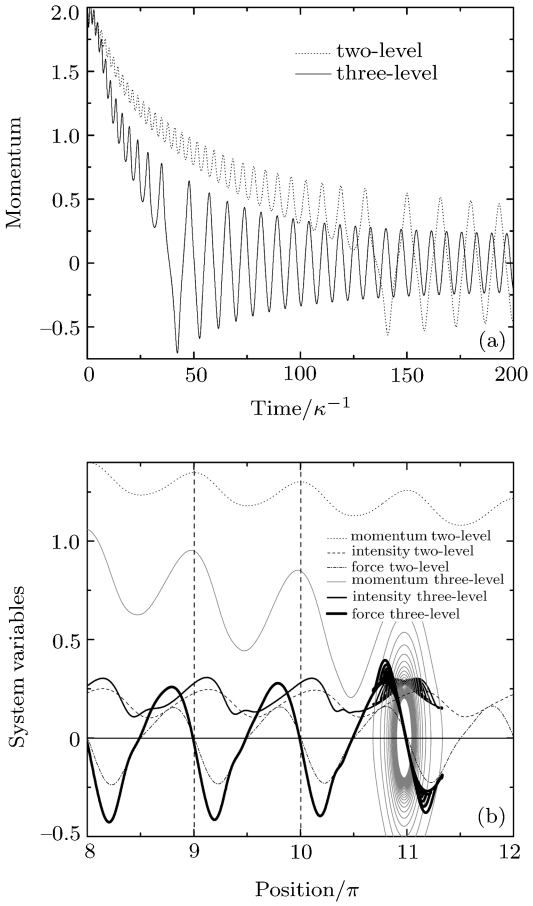


Fig.2. Comparison of cavity cooing between a two-level atom and a V-type three-level atom. (a) Time evolutions of the atomic momentum for a V-type three-level atom, the parameters being set to $\Delta_c = -4.0, U_1 = 0.5, U_2 = 1.0, \eta = 1.5, \gamma_1 = 0.1$, and $\gamma_2 = 0.1$, and for a two-level atom, the parameters are set to $\Delta_c = -4.0, U_0 = -1.0, \eta = 1.5$ and $\gamma_0 = 0.1$. (b) Variations in positions of the cavity field strength, momentum and normalized optical force. Cavity cooling is enhanced in the V-type three-level atom.

The mechanism for enhanced and rapid cooling of a V-type three-level atom in the cavity is shown in Fig.2(b). In a V-type three-level atomic system, the net force is much larger than that of a two-level one. Because of the extended energy level, on average, the V-type three-level atom has to climb steeper hills than that of a two-level atom. Hence, eventually the V-type three-level atom becomes stopped and oscillates in a single well, where the kinetic energy slowly decreases further than that of a two-level one.

The cooling rate may be improved by modulating the frequency shifts $U(x_1)$ and $U(x_2)$. Figure 3(a) shows the time evolutions of the atomic momentum for $U_1 = 0.1, U_2 = 1.0; U_1 = 0.5, U_2 = 1.0; U_1 = 0.5, U_2 = 1.5$, respectively. The other parameters are set to $\Delta_c = -4, \eta = 2.5, \gamma_1 = 0.1$, and $\gamma_2 = 0.1$. It can be found that the atom decelerates faster, and the time required for trapping the atom within a single potential well is shortened, when the frequency shifts $U(x_1)$ and $U(x_2)$ from near resonance to far-off resonance. This can be explained by Fig.3(b), which shows variations of the momentum, normalized optical force in the axis direction. When the frequency

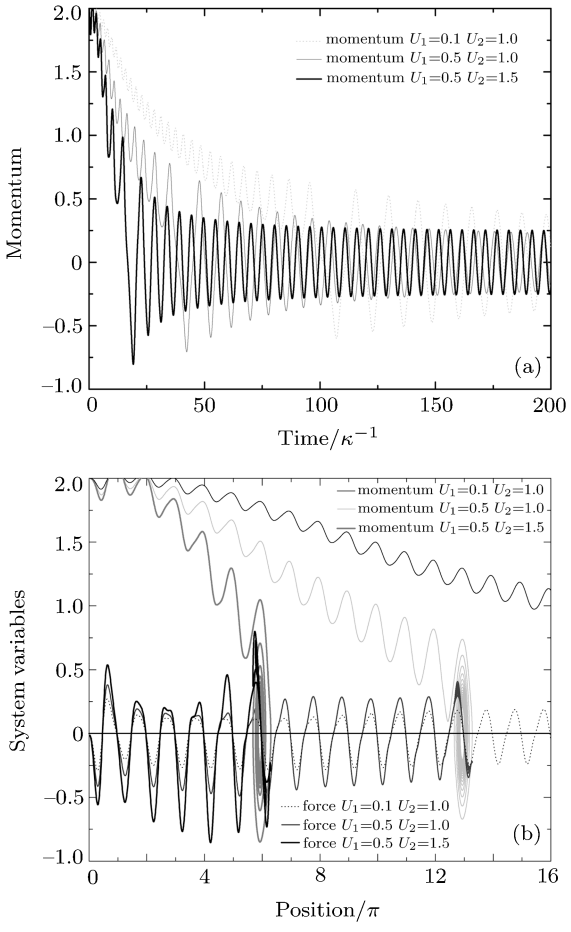


Fig.3. (a) Cooling rate can be further improved using far-off resonance frequency shifts rather than using near resonance frequency shifts. Time evolutions of the atomic momentum for $U_1 = 0.5, U_2 = 1.5$, $U_1 = 0.5, U_2 = 1.0$, $U_1 = 0.1, U_2 = 1.0$. The other parameters are set to $\Delta_c = -4, \eta = 2.5, \gamma_1 = 0.1$, and $\gamma_2 = 0.1$. (b) Variations of the cavity field strength, momentum, and normalized optical force in the axis direction. Cavity cooling of a V-type three-level atom with the frequency shifts $U(x_2)$ from the far-off resonance to near resonance has enhanced cooling rate.

shifts $U(x_1)$ and $U(x_2)$ from near resonance to far-off resonance, the amplitude of the force becomes bigger, and the atom has much larger negative force than positive force, so the net force is larger, which can cool the atom more rapidly, and make the atom oscillate near the initial position.

Moreover, we can improve the cooling rate by modulating the initial position of the displacement from the equilibrium for excited states. Figure 4 shows the time evolutions of the atomic momentum for

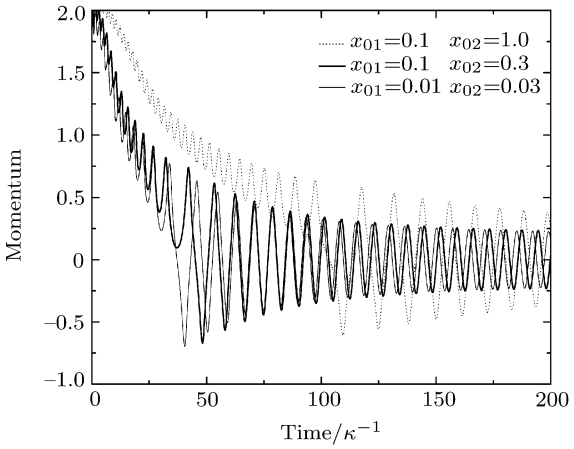


Fig.4. Time evolutions of the atomic momentum for $x_{01} = 0.01, x_{02} = 0.3; x_{01} = 0.01, x_{02} = 0.03; x_{01} = 0.1, x_{02} = 1.0$. The other parameters are set to $\Delta_c = -4, \eta = 1.5, U_1 = 0.5; U_2 = 1.0; \gamma_1 = 0.1$ and $\gamma_2 = 0.1$.

$x_{01} = 0.1, x_{02} = 1.0; x_{01} = 0.1, x_{02} = 0.3; x_{01} = 0.01, x_{02} = 0.03$. The other parameters are set to $\Delta_c = -4, \eta = 1.5, U_1 = 0.5, U_2 = 1.0$. It is shown that the nearer the displacement to equilibrium, the more rapidly the atom can be trapped. To understand this, we plot the position evolutions of the intensity and the optical frequency shifts in Fig.5. When the two initial positions of the displacement from the excited states are both near the equilibrium, the two frequency shifts $U(x_1)$ and $U(x_2)$ coincide with each other at both node and antinode, indicating that the two oscillating dipoles (P_1 and P_2) are travelling uphill and downhill in the frequency shift simultaneously. This leads to a large net cooling force exerted on the V-type three-level atom. So the V-type three-level atom is rapidly cooled and trapped. In the experiment, we can either choose the different energy levels of the same atom, or choose different atoms to modulate the initial position of the displacement from the equilibrium for excited states. We can extend this cavity cooling scheme to a wider range of atomic species, and the direct application for cooling molecules is possible by using this mechanism.

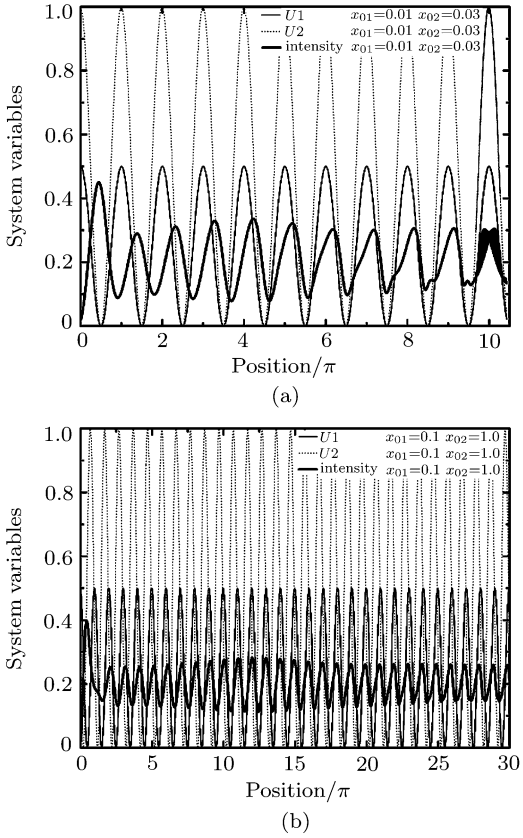


Fig.5. Frequency shifts $U(x_1)$ and $U(x_2)$ and cavity field intensity [x_{01}=0.1, x_{02}=0.03 (a); x_{01}=0.1, x_{02}=1.0 (b)] vs particle position x. The other parameters are set to $\Delta_c = -4, \eta = 1.5, U_1 = 0.5, U_2 = 1.0, \gamma_1 = 0.1$ and $\gamma_2 = 0.1$.

Due to the off-resonant nature of interaction, the effect of population transition can be neglected. This is shown in Fig.6, where we plot the time evolutions of the atomic momentum for $\gamma_1 = 0.8, \gamma_2 = 0.08; \gamma_1 = 0.1, \gamma_2 = 0.1; \gamma_1 = 0.01, \gamma_2 = 0.01$. The other parameters are set to $\Delta_c = -4, \eta = 1.5, U_1 = 0.5, U_2 = 1$. The figure clearly shows that with the change of the scattering losses $\gamma(x_1)$ and $\gamma(x_2)$, the cooling rate can also be improved, but the effect is not pronounced, because the cooling mechanism for an atom in an optical cavity is entirely different from free-space doppler cooling. For a single atom strongly coupled to a high-finesse cavity, the role of spontaneous emission is replaced by the escape of a photon from the cavity. In this situation the pump frequency is far detuned from the atomic transition, the population transition can be neglected, which is consistent with the experimental result.[13]

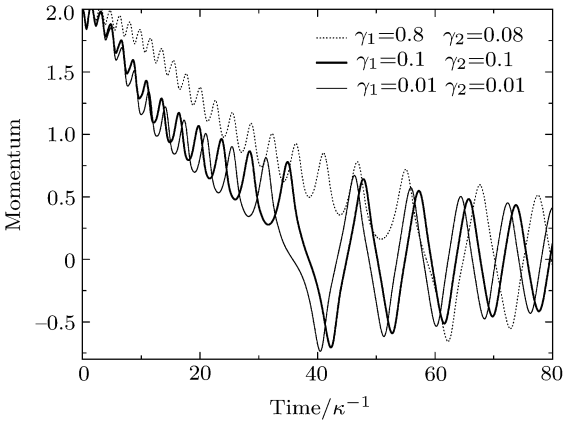


Fig.6. Comparison between cavity coolings of a V-type three-level atom due to different modulation of the scattering loss. Time evolutions of the atomic momentum for $\gamma_1 = 0.8, \gamma_2 = 0.08; \gamma_1 = 0.1, \gamma_2 = 0.1; \gamma_1 = 0.01, \gamma_2 = 0.01$. The other parameters are set to $\Delta_c = -4, \eta = 1.5, U_1 = 0.5$, and $U_2 = 1.0$.

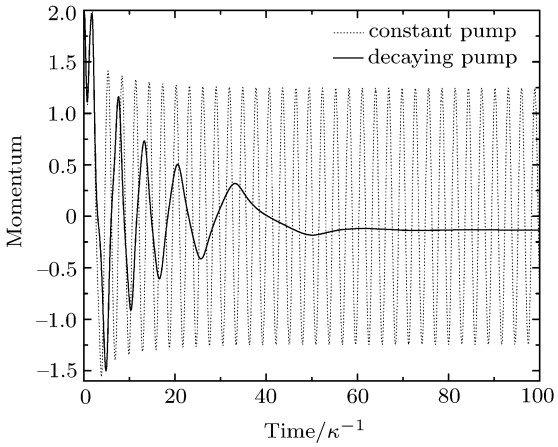


Fig.7. Time evolutions of the atomic momentum for $\eta = 4.0$, and $\eta = 4.0\exp(-t/20)$. The other parameters are set to $\Delta_c = -4, U_1 = 0.5, U_2 = 1.0, \gamma_1 = 0.1$ and $\gamma_2 = 0.1$. By comparison, the exponentially decaying pulse cools the V-type three-level atom much more rapidly than a constant pump.

Cavity cooling of a two-level atom can be enhanced by using a feedback like a time-dependent pump.[8] It is found that this mechanism can also be used to obtain rapid cooling in a V-type three-level atom. Figure 7 shows that the time evolutions of the atomic momentum by using an exponentially decaying pump $\eta = 4\exp(-t/20)$ and using a constant pump $\eta = 4.0$. The other parameters are set to $\Delta_c = -4, U_1 = 0.5, U_2 = 1.0, \gamma_1 = 0.1$ and $\gamma_2 = 0.1$. Even more kinetic energy can be extracted from the atom in each cycle, since enhanced frequency shift changes in each oscillation cycle of the atom in favor of its deceleration.

4. Conclusion

In this paper, using the new cavity cooling mechanism, which is based on the change of the resonance frequency of the cavity induced by the atomic position, we have derived the dynamic equations for laser cooling of a V-type three-level atom in a high-finesse optical cavity. The dependence of the cooling rate on various parameters is shown graphically. It is shown that we can significantly enhance the cooling rate by using a V-type three-level atom. At the same time the cooling rate can be further improved by modulating parameters and using a linear feedback.

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