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PYRAMIDAL-HOLLOW-BEAM DIPOLE TRAP FOR ALKALI ATOMS*

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We propose a dark gravito-optical dipole trap, for alkali atoms, consisting of a blue-detuned, pyramidal-hollow laser beam propagating upward and the gravity field. When cold atoms from a magneto-optical trap are loaded into the pyramidal-hollow beam and bounce inside the pyramidal-hollow beam, they experience efficient Sisyphus cooling and geometric cooling induced by the pyramidal-hollow beam and the weak repumping beam propagating downward. Our study shows that an ultracold and dense atomic sample with an equilibrium 3D momentum of $\sim 3\ \hbar k$ and an atomic density above the point of Bose-Einstein condensation may be obtained in this pure optical trap.

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I. INTRODUCTION

In 1995, Bose-Einstein condensation (BEC) was observed in a ^{87}Rb atomic gas.[1] Since then, other experimental observations of BEC in various atomic gases (such as ^{7}Li, ^{23}Na and ^{87}Rb) have been reported[2−8] and an atom laser has been demonstrated.[9] So far, all of the BECs have been observed in magnetic atom traps, no BEC has been realized in a pure optical atom trap. Recently, a MIT group successfully transferred a Na BEC sample from a magnetic trap to a far-off-resonant, red-detuned optical trap.[10] This work demonstrates the optical confinement of a BEC sample in optical dipole trap and shows that BEC should be achievable in a suitable optical trap. Ketterle *et al.*[10] pointed out that magnetic atom traps impose some limitations on the studies of BEC(such as the optical properties of a BEC and the observation of Feshbach resonance in a BEC, etc.) and atom lasers, whereas optical atom traps may be more advantageous in these studies. It would be interesting and worthwhile to find a suitable optical trap that can be used to directly realize BEC.

Two far-off-resonant, blue-detuned dipole-force traps for cold atoms were proposed and demonstrated by Chu's group[11] and Kuga *et al.*[12] The first trap is composed of two overlapping sheets of focused elliptical laser beams with different wavelengths and the second is a doughnut-beam trap. These traps have advantages over most of the far-off-resonant, red-detuned optical dipole traps that use focused Gaussian beams[13−15], such as a reduced radiation-trapping loss, minimal internal-level light shifts, lower cold-atom collision rates, higher atomic densities, etc. However, there is no cooling mechanism in all of the optical dipole traps mentioned above. In order to load cold atoms from the magneto-optical trap(MOT) into the dipole-force atom traps, an additional sub-Doppler cooling, such as the polarization gradient cooling, has to be introduced to further cool the cold atoms in the MOT down to $\sim 10\,\mu$K.[11−15]

A gravitational laser trap (GOT) for atoms with evanescent-wave Sisyphus cooling was proposed by Ovchinnikov *et al.*[16], which is similar to the Sisyphus effect in standing-wave laser fields[17] and the gravitational Sisyphus cooling in a magnetic trap.[18] Subsequently, the elementary evanescent-wave Sisyphus-cooling process was dmonstrated experimentally by Desbiolles *et al.*[19] Recently, a surface trap for Cs atoms based on 1 D evanescent-wave Sisyphus cooling was reported by Ovchinnikov *et al.*[20] They obtained an ultracold Cs atomic sample with a temperature of $\sim 3\,\mu$K, which is consistent with the prediction of evanescent-wave Sisyphus cooling theory.[16] In both

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Refs.[12] and [20], a far-off-resonant, blue-detuned cylindrical-hollow beam was used to confine the Rb and Cs atoms in the transverse direction, but no dark-hollow-beam(DHB) induced cooling was mentioned and presented. Since the optical potential of the far-off-resonant hollow beam is far lower than the MOT's temperature (100–200 μK), an additional subDoppler cooling has to be applied to cooling cold atoms from 100–200 μK to$\sim$ 10 μK. Then, the ultracold atoms can be loaded into the far-off-resonant, blue-detuned hollow-beam trap.[12,20]

More recently, we proposed a hollow-fiber atomic funnel with DHB induced Sisyphus cooling.[21] Here we propose a dark gravito-optical atom trap using a blue-detuned, pyramidal-hollow laser beam (PHB), and investigate the PHB induced 3-D Sisyphus cooling, and repumping-beam induced geometrical cooling in the trap. In Sec.Ⅱ, we present the scheme of the dark PHB dipole-force atom trap and discuss its working principle. In Sec.Ⅲ, we calculate the optical potential for the atoms loaded and trapped in the dark PHB and study the spontaneous emission, heating and cooling effects for the atoms trapped in the GOT. In Sec.Ⅳ, the trapping loss mechanisms are analyzed and the atomic densities, and BEC densities of the trapped alkali atoms in the GOT are estimated. Possibility of realizing BEC in this dark GOT is briefly discussed. In the last section, we summarize the main results and briefly discuss the potential applications of the dark GOT in the studies of two-species GOT and BEC.

Ⅱ. SCHEME OF PHB DIPOLE TRAP

The 3D-equilibrium temperature of a conical GOT is greater than that of a pyramidal GOT by a factor of 20 because of conservation of the angular momentum Lz along the symmetry axis (in the gravity direction).[16] Similarly, here we propose a novel pyramidal GOT for alkali atoms using a pyramidal-hollow laser beam. The scheme of the pyramidal-hollow-beam GOT is shown in Fig.1.

When the central part of a collimated dark hollow beam[22] or a collimated doughnut-shaped hollow beam[23] propagating upwards is blocked by a black square plate, a dark rectangular-hollow laser beam is produced behind the black square plate. After the rectangular-hollow beam is focused by a lens with a variable focal-length f, a divergent PHB will be generated. A blue-detuned plug beam overlaps with the PHB above its focal point. Then a dark pyramidal-hollow-beam GOT for neutral atoms is formed right above the plug beam, as shown in Fig.1. On the other hand, if the black square plate in Fig.1 is removed, a conical dark-hollow-beam GOT will be formed. The plug beam can be moved up or down such that the GOT's position can be adjusted, this can be used to change the trapped atom density. In order to introduce the efficient Sisyphus cooling and geometrical cooling, a weak, near-resonant repumping laser is propagating down and overlaps with the PHB. Cold atoms are loaded into the PHB from a standard MOT. As the atoms bounce inside the PHB, they experience the efficient Sisyphus cooling and geometric cooling induced by the blue-detuned PHB and the repumping beam (RPB). This is similar to the cooling processes in the evanescent-wave GOT.[16,20]

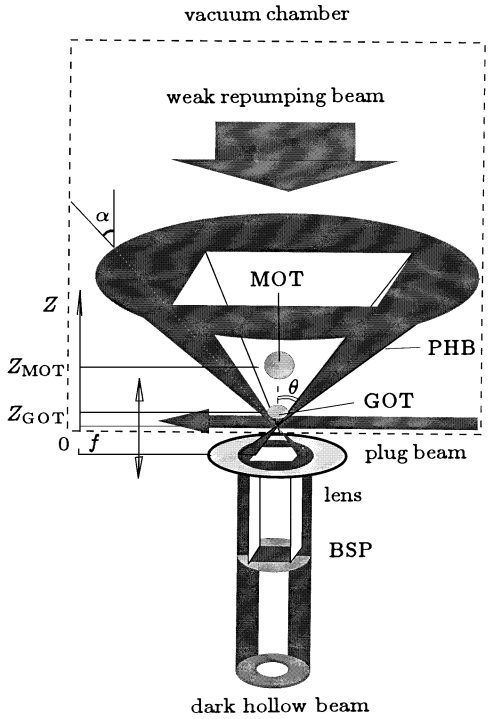


Fig.1. Scheme of the gravito-optical atom trap with a pyramidal dark-hollw laser beam. BSP, PHB, MOT and GOT stand for a black square plate, pyramidal-hollow beam, magneto-optical trap and gravito-optical trap, respectively. $Z_{\rm GOT}$ and $Z_{\rm MOT}$ are the positions of the GOT and the MOT, respectively. And f, the focal length of lens, can be adjusted.

The coupling between a three-level alkali atom (the D_2 or D_1 transition) and the blue-detuned PHB (including the plug beam) leads to the dressed-atom states whose energy-level structures can be found in Ref.[16]. In this pyramidal GOT, the trapping potential is high enough to collect nearly all of the cold atoms from the MOT and the trapped cold atoms are cooled directly from the MOT's temperature (100–200 μK) to near the recoil limit (a few μK). Unlike

the evanescent-wave trap[16,19,20], there is no reflection of the repumping beam and no surface-induced van der Waals attractive potential in the dark PHB GOT. Moreover, the cooling rate, the 3D-equilibrium temperature, the trapping volume and the atomic density in the PHB GOT can be controlled easily by adjusting the divergent angle of the dark-hollow beam(i.e., by changing the focal length f of lens) or moving the plug beam up or down (i.e., by changing the position of the GOT in the PHB).

To efficiently collect the cold atoms dropped from the MOT and obtain a faster Sisyphus cooling rate, we can choose initially a small PHB divergent angle α (for example, $\alpha = 3°$–$5°$) or a small half-apex angle of the pyramid beam, θ (see Fig.1), defined as the trapping angle and having $\theta \leq \alpha$. For the trapped alkali atoms at $Z = Z_{\rm MOT}$, the maxium optical potential can be greater than 1 mK when the power of the PHB $P_0 = 500\,{\rm mW}$, the detuning $\delta = 0.5\,{\rm GHz}$, and the MOT's temperature $T_{\rm MOT} = 100$–$200\,\mu$K.After about 0.5–1 s, we increase the divergent angle α (the trapping angle θ) of the PHB or move the plug beam upward from the focal point to a suitable position (for example, to $Z = Z_{\rm MOT}/2$) such that the geometric cooling can be optimized (see Eq.(5)).This will increase the trap volume and result in a decrease of the atomic density, which will reduce various trapping losses associated with a high atomic density. Finally, before the trapped atoms reach their 3D-equilibrium temperature, we decrease the divergent angle of the PHB to a few degrees or move the plug beam down to the focal point. This will efficiently compress the ultracold atomic smple and obtain a high atomic density. Such manipulation and control of ultracold atomic sample in the dark GOT is quite simple, convenient and flexible.

Ⅲ. TRAPPING AND COOLING OF ATOMS IN PHB

We consider a Λ-type three-level alkali atom interacting with the blue-detuned PHB (including the plug beam) and the repumping beam in the dressed-atom picture. The two lower states($|1\rangle$ and $|2\rangle$) are the two hyperfine ground states and the upper state $|3\rangle$ is the excited state. The spontaneous emission of the trapped atoms in the dark PHB trap is similar to that in a DHB atomic funnel.[21]. If the blue detuning δ of the PHB is far larger than the atomic linewidth $\Gamma(\delta \gg \Gamma)$, the saturation parameter S is small, i.e., $S = \dfrac{\omega_{\rm R}^2}{2\delta^2} \ll 1$ ($\omega_{\rm R}$ is the Rabi frequency), and the probability of spontaneous emission p_{sp} is far smaller than one ($p_{sp} \ll 1$), hence no more than one spontaneous emission occurs per reflection.

When a doughnut-shaped hollow beam[23] with a constant beam waist w_{00} and radius R_{00} is used to form a PHB, due to the diffraction effect of the black square-plate and the convergent lens, we assume that the intensity distribution of the PHB on the (x, Z) or (y, Z) plane can be approximated by

$$I(\xi,\alpha,\beta,Z) = \frac{P_0}{\pi w^2(\beta,Z)}\left\{\exp\left[-\frac{2(\xi-R)^2}{w^2(\beta,Z)}\right] + \exp\left[-\frac{2(\xi+R)^2}{w^2(\beta,Z)}\right]\right\}, \tag{1}$$

and

$$\begin{cases} R = R_0 + Z\tan\alpha, \\ w^2(\beta,Z) = w_0^2 + 2\tan\beta\left(w_0 + \dfrac{1}{2}Z\tan\beta\right)Z, \end{cases} \tag{2}$$

where $\xi = x, y, w_0$ and $w(\beta, Z)$ are the waists of two modified Gaussian beams on the $Z = 0$ plane (at the focal point) and Z-plane, respectively, R_0 and R are the beam radii of the PHB (the distance between two peaks of the PHB intensity distribution) at $Z = 0$ and $Z = Z$. Here $\alpha = \tan^{-1}(R_{00}/f)$ and $\beta = \tan^{-1}(R_{00}/f) - \tan^{-1}[(R_{00} - w_{00})/f]$ are the divergent angles of the PHB and the Gaussian beam, respectively. Then, the light-shift potentials of the two hyperfine ground states are approximately given by[21]

$$U_i(\xi,\alpha,\beta,Z) = \frac{1}{12}\frac{\hbar\Gamma^2}{\delta_{F_i}}\frac{I(\xi,\alpha,\beta,Z)}{I_{\rm s}} \qquad (i = 1, 2), \tag{3}$$

where $\delta_{F_1} = \delta$ for the lower hyperfine ground state and $\delta_{F_2} = \delta + \Delta_{\rm hfs}$ for the upper hyperfine ground stae. Γ and $I_{\rm s}$ are the natural linewidth and saturation intensity of the alkali atoms, respectively. $\Delta_{\rm hfs}$ is the hyperfine splittering between the two hyperfine ground states. The total probability p_{sp} of the spontaneous transition for an inelastic reflection of an atom in the dark PHB trap due to the three decay channels from $|1, n\rangle$ to $|i, n-1\rangle$(i=1–3 are the three dressed states) is given by[21]

$$p_{sp} = 1 - \exp\left[-\frac{m\bar{w}_a\Gamma}{\hbar\delta}v_r\right], \tag{4}$$

where $v_r = v_\perp\cos\theta$ is the transverse velocity of trapped atoms in the PHB, and $\bar{w}_a$ is the mean fitting parameter, its definition can be found in Ref.[21](see Eqs.(14) and (18)).

For the case of PHB trap, although near the MOT, the average number of spontaneous emission of an atom during a bounce, $N_{sp} = m\bar{v}_r\bar{w}_a\Gamma/(\hbar\delta)$[16], may be larger than one. From the Maxwell-Boltzmann distribution of atoms in the gravity field, however, the initial and final mean heights of trapped ^{87}Rb atoms in the GOT are $< Z >= k_{\rm B}T/mg \approx 1.8\,{\rm mm}$ and $10\,\mu{\rm m}$ when $T = T_{\rm MOT} = 120\,\mu{\rm K}$ and $T = T_{\rm GOT} \approx 1\,\mu{\rm K}$, respectively. And the results of Monte-Carlo simulations show that most of trapped atoms will accumulate at the bottom of the PHB trap after $t \leq 0.5$ s starting from the release of cold atoms from the MOT (see Fig.2). In other words, the trapped alkali atoms will spend most of their time within $< Z >= 0$ ∼a few millimeters above the tip of the PHB trap under the action of gravity field and PHB-induced Sisyphus cooling effect. Therefore, one can greatly increase the detuning of the PHB after 0.5 s so as to reduce the parameter $\bar{w}_a$ and spontaneous-emission probability p_{sp}.For example, when $P_0 = 500\,{\rm mW}$, $\delta \geq 3.0\,{\rm GHz}$, and $\bar{v}_r < 10\,{\rm cm/s}$, we obtain $\bar{w}_a < 1\mu{\rm m}$ and $p_{sp} \leq 0.3$. In this case, Eq.(2) can be approximated as

$$p_{sp} \approx \frac{m\bar{w}_a\Gamma}{\hbar\delta}v_r \qquad (p_{sp} \ll 1), \tag{5}$$

the corresponding time-averaged spontaneous-emission rate γ_{sp} for a reflected atom in the PHB trap is given by[16]

$$\gamma_{sp} \approx \frac{m\bar{w}_a\Gamma}{2\hbar\delta\sin\theta}g. \tag{6}$$

When $P_0 = 500\,{\rm mW}$, $\delta = 5.0\,{\rm GHz}$(or 3.0GHz), Z=0–3 mm, $\bar{w}_a \approx 0.55\,\mu$ m (or $0.87\,\mu$m), $\bar{v}_r \approx 10\,{\rm cm/s}$, and $\theta = 3°$–$60°$, we obtain $p_{sp} \approx 0.1$(or 0.3) and γ_{sp} ≈94–6/s(or 250–16/s).

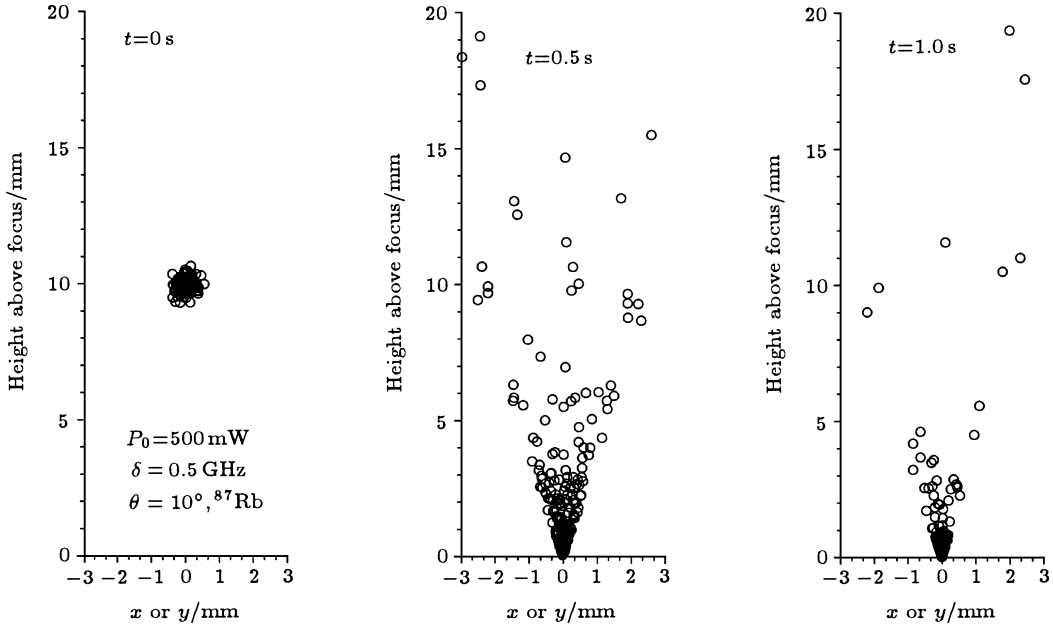


Fig.2. Spatial distribution of trapped ^{87}Rb atoms in the GOT at times $t = 0, 0.5\,{\rm s}$ and $1.0\,{\rm s}$. The method of Monte-Carlo simulations is similar to that in Ref.[24], which includes the PHB-induced Sisyphus cooling and RPB-induced geometrical cooling, the gravity and spontaneous-emission heating effects. The results in Fig.2 show that after $t \leq 0.5\,{\rm s}$, most of cold atoms will be accumulated within Z=0–3 mm above the tip of the PHB trap.

For the trapped atoms bouncing up and down on the surface of the plug beam, when $Z_{\rm GOT} = 0$, the time-averaged spontaneous-emission rate can be estimated by

$$\gamma_{sp}^{\rm (PB)} \approx \frac{2\bar{v}_Z}{Z_{\rm MOT}}\left[1 - \exp\left(-\frac{m\bar{w}_b\Gamma}{\hbar\delta}\bar{v}_Z\right)\right], \tag{7}$$

where w_b and v_Z are, respectively, the mean fitting parameter and the average vertical velocity of trapped atoms. When P_0 = 100 mW, δ = 50–100 MHz, $Z_{\rm MOT}$=20–5 mm, and $\bar{v}_Z \approx \bar{v}_r \approx 10\,{\rm cm/s}$, we get $\gamma_{sp}^{\rm (PB)} \approx$ 10–40/s.

In the dressed-state picture, and atom in the lower dressed state $|1, n\rangle$ entering the PHB (the plug beam) can make a spontaneous transition to the less repulsive, upper dressed state $|2, n-1\rangle$ by scattering a PHB (plug beam) photon. Soon after the reflection, the atom is pumped back to the original dressed state $|1, n-1\rangle$ by the repumping beam. In such an in-

elastic reflection process, the atom loses a part of the kinetic energy, which is proportional to the difference between the light-shift potentials of the two dressed states: $\int_{-\infty}^{\infty}(U_1-U_2)\Gamma_{12}\mathrm{d}t$. During the repumping process, the random recoils of the emitted photons heat the atoms up, but the downward-directed photons from the repumping beam are absorbed by the atoms bouncing up. This will reduce the kinetic energy of the atoms and result in spontaneous geometrical cooling near the bottom of the PHB trap.[16] Thus, a closed and repeatable Sisyphus cooling cycle is formed during the inelastic reflection and repumping processes.

In the reflection of the atom, the reflected atoms in the dressed state $|1,n\rangle$ may also spontaneously decay into the dressed states $|1,n-1\rangle$ or $|3,n-1\rangle$. The decay from $|1,n\rangle$ to $|1,n-1\rangle$ will lead to a small heating by two recoil energies $2E_{\mathrm{R}}=(\hbar k)^2/\mathrm{m}$ due to the absorption of a PHB (a plug beam) photon and the recoil of a photon emitted in a random direction. The decay from $|1,n\rangle$ to $|3,n-1\rangle$ will make the atom to jump from the dressed state of the repulsive potential to the dressed state with the attractive potential, which may repel the atom out of the trap. However, this effect can be neglected because its transition probability is negligibly small in comparison with other decay channels.[16,21]

In the equilibrium, the Sisyphus cooling and geometrical cooling balance all of the spontaneous-emission heating and the recoil induced heating from the absorption of the PHB (including the plug beam) and the repumping beam, from which we derive an equation similar to that in Refs.[16,21] to estimate the final equilibrium rms momentum of the cold atoms in the PHB trap near the focal point of the PHB

$$-\frac{1}{3}\frac{\Delta_{\mathrm{hfs}}}{\delta+\Delta_{\mathrm{hfs}}}\left(\frac{p_{\mathrm{rms}}}{\hbar k}\right)^2-\frac{\sin\theta}{q_r}\left(\frac{p_{\mathrm{rms}}}{\hbar k}\right)+\frac{1}{q_r^2}+\frac{1}{1-q_{ev}}=0. \tag{8}$$

Here $q_r(q_{ev})$ is mean branching ratio into the lower hyperfine ground state for the excitation of the upper hyperfine ground state by the repumping beam (the PHB). For ^{23}Na, ^{87}Rb and ^{133}Cs atom, $q_r\approx 0.60, q_{ev}\approx 0.75$.[16] θ is the trapping angle of the PHB, which can be continuously changed from a few degrees to $\sim 60^\circ$ by adjusting the focal-length f of the convergent lens. Alternatively, we can move the plug beam upward to a position at which the vertical motion of the ultracold atoms is largely confined by the plug beam. In this case, the trapping angle θ can be regarded as $\sim 90^\circ$. Figure 3 plots the 3D equilibrium temperature T versus (a) the detuning δ and (b) the trapping angle θ of the PHB. When $\delta=0.1$–$1.0\,\mathrm{GHz}$ and $\theta=45^\circ$, we obtain $T\approx 7.8$–9.9μK for ^{23}Na, $\sim 1.2\mu$K for ^{87}Rb, and $\sim 0.65\mu$K for ^{133}Cs. For $\delta=0.1$–$1.0\,\mathrm{GHz}$, and $\theta\approx 60^\circ(5^\circ)$, we obtain $T\approx 6.64\,\mu\mathrm{K}(15.6\,\mu\mathrm{K})$ for ^{23}Na, $0.97\,\mu\mathrm{K}(2.25\,\mu\mathrm{K})$ for ^{87}Rb, and $0.54\,\mu\mathrm{K}(1.24\mu\mathrm{K})$ for ^{133}Cs. The corresponding equilibrium rms momentum is $\sim 3\hbar k(\theta\approx 60^\circ)$ for ^{23}Na, ^{87}Rb and ^{133}Cs atoms, which are consistent with the results of Monte-Carlo simulations. These results show that the final equilibrium temperature depends strongly on the trapping angle θ and is relatively insensitive to the blue detuning θ (especially for ^{87}Rb and ^{133}Cs atoms).

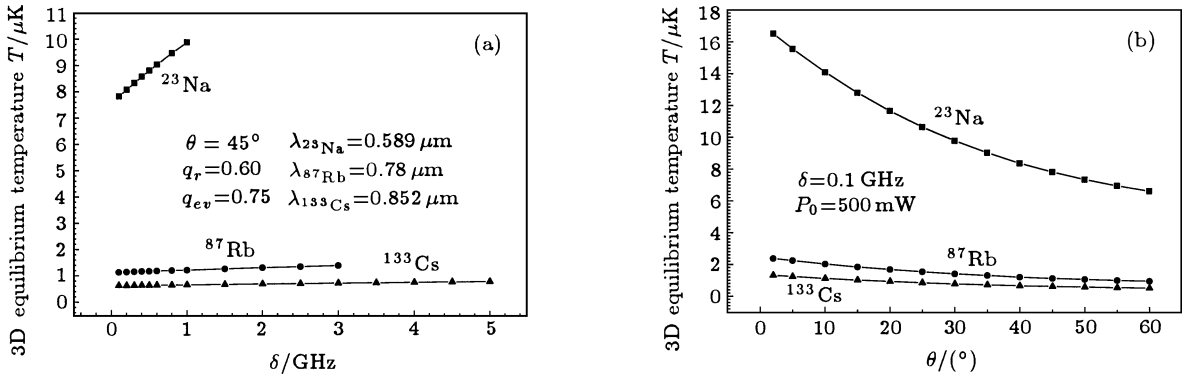


Fig.3. 3D equilibrium temperature T of the trapped ^{23}Na, ^{87}Rb and ^{133} Cs atoms in the GOT versus (a) the blue detuning δ and (b) the trapping angle θ of the bule-detuned PHB.

From the virial theorem: $< E_{\rm pot} >= 2 < E_{\rm kin} >$, and $\mathrm{d} < \Delta E_{\rm tot}/\mathrm{d}t = \mathrm{d} < \Delta E_{kin} > /\mathrm{d}t$, we can derive the Sisyphus and geometrical cooling rates as follows[16]:

$$\gamma_{\rm Sisy} = \frac{1}{\tau_{\rm Sisy}} \approx \frac{2}{9}\frac{\Delta_{\rm hfs}}{\delta + \Delta_{\rm hfs}}(1 - q_{ev})\gamma_{sp}, \qquad (9)$$

and

$$\gamma_{\rm geo} = \frac{1}{\tau_{\rm geo}} \approx \frac{2}{3}\frac{\sin\theta}{q_r}\frac{\hbar k}{p_{\rm rms}}(1 - q_{ev})\gamma_{sp}. \qquad (10)$$

Equations (9) and (10) show that the geometrical cooling rate $\gamma_{\rm geo}$ is inversely proportional to the atomic rms momentum $p_{\rm rms}$; the Sisyphus cooling rate $\gamma_{\rm Sisy}$ is independent of the atomic momentum $p_{\rm rms}$. When $\delta \ll \Delta_{\rm hfs}$, and γ_{sp} ≈100–12/s, we obtain $\gamma_{\rm Sisy}$ ≈ 6–1/s, the corresponding Sisyphus cooling time $\tau_{\rm Sisy}$ ≈0.17–1s. When the equilibrium rms momentum $p_{\rm rms}$ of the trapped atoms is below $p^*_{\rm rms} = 3\frac{\sin\theta}{q_r}\frac{\delta + \Delta_{\rm hfs}}{\Delta_{\rm hfs}}\hbar k$, the cooling in the PHB GOT is dominated by the geometric cooling effect; for $p_{\rm rms} > p^*_{\rm rms}$, the Sisyphus cooling becomes the dominant cooling mechanism. For the alkali atoms (^{23}Na, ^{87}Rb and ^{133} Cs), when $\theta = 45°(30°)$, and $\delta \ll \Delta_{\rm hfs}$, we obtain $p^*_{\rm rms} \approx 3.5\hbar k$ $(2.5\hbar k)$. This indicates that the final equilibrium temperature of the dark GOT is determined by the geometric cooling, whereas the total cooling time is mainly determined by the Sisyphus cooling, which is $\sim 1\,$s[16] when the trapping angle $\theta \geq 45°$. Since the Sisyphus cooling rate is independent of the initial momentum of the trapped atoms, the PHB can cool the trapped atoms to the final equilibrium temperature directly from the initial temperature of the MOT ($\sim$ 100–200 μK).

IV. ATOMIC DENSITY, TRAP LOSSES AND POSSIBILITY OF BEC

From the Maxwell-Boltzmann distribution in the gravity field[20], the mean height of the GOT at the bottom of the PHB can be estimated to be $< Z >= k_{\rm B}T/mg$. The trap volume and the lossless density n of the atomic sample can also be estimated. Figure 4 plots the lossless density n versus the trapping angle θ without the consideration of the trap loss, in which we assume that the total number of the trapped atoms is $N = 10^9$. The atomic density decreases rapidly as the trapping angle θ is increased. For example, when θ is increased from 5° to 60°, the density of the trapped ^{23}Na, ^{87}Rb and ^{133}Cs atoms is decreased from $4.9 \times 10^{16}, 3.3 \times 10^{19}$, and 1.1×10^{20} atoms/cm^3 to $5.7{\times}10^{12}, 9.3 \times 10^{16}$, and $1.8{\times}10^{18}$ atoms/cm^3, respectively. Note that the obtainable density n of the trapped atoms in the GOT, in fact, should be far smaller than that shown in Fig.4, since there are various atom-collision losses (see discussion below). Besides varying the trapping angle, the density of trapped atoms in the GOT can also be changed by moving the plug beam up or down in the PHB.

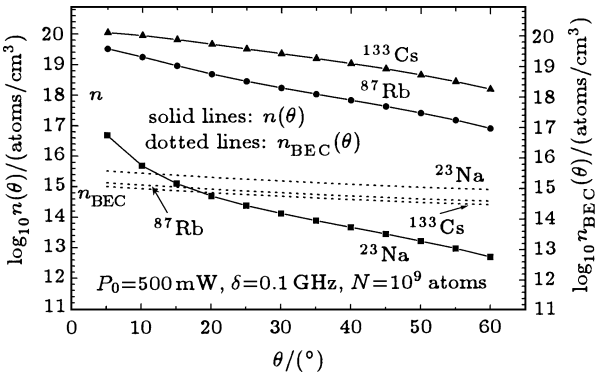


Fig.4. Lossless atomic density of the trapped ^{23}Na, ^{87}Rb and ^{133}Cs atoms in the GOT without the consideration of the trap loss versus the trapping angle θ of the blue-detuned PHB.

It is interesing to explore the possibility of BEC in the dark pyramidal-hollow-beam GOT. The atomic density of BEC is estimated by

$$n_{\rm BEC} = 2.612(p^2_{\rm rms}/6\pi\hbar^2)^{3/2} \qquad (\mathrm{atoms/cm^3}). \quad (11)$$

The BEC densities for ^{23}Na, ^{87}Rb and ^{133}Cs atoms versus the trapping angle θ are shown in Fig.4. When $P_0 = 500\,$mW, δ=0.1 GHz and $\theta = 60°$, the equilibrium rms momentum of the trapped ^{23}Na, ^{87}Rb and ^{133}Cs atoms is $p_{\rm rms} \approx 3\hbar k$ (corresponding to the 3D equilibrium temperature $T \sim 6.6\,\mu$K, $\sim 1\,\mu$K and $\sim 0.5\,\mu$K, respectively), at which the BEC density $n_{\rm BEC} \approx 1.05 \times 10^{15}, 4.51 \times 10^{14}$, and $3.45{\times}10^{14}$ atoms/cm^3, respectively. Figure 4 shows that the lossless densities of the trapped ^{87}Rb and ^{133}Cs atoms in the GOT without the consideration of the trap losses are far higher than that required by BEC, whereas the lossless density of the ^{23}Na atoms is far smaller than the BEC density when $\theta > 10°$. Only when the trapping angle θ is reduced to $< 10°$, the trapped ^{23}Na density without the consideration of the trap losses can be greater than its BEC density.

Next, we consider the trap losses. Note that: 1. The PHB and plug-beam induced potential barrier is high enough to collect and trap all of the cold atoms from a MOT (with $T \sim$ 100–200 μK). 2. The pressure in the vacuum chamber can be lower than

$\sim 10^{-8}$ Pa. 3. The fraction of atoms in the excited state ($\eta_{\rm e} \approx 10^{-5}$–$10^{-6}$[20]) and in the upper hyperfine ground state ($\eta_{ug} \approx 10^{-4}$–$10^{-5}$[20]) for alkali atoms in the dark GOT is far smaller than that in the lower hyperfine ground state ($\eta_{ug} \approx 1$). 4. The trapped atoms spend most of their time in the dark region of the GOT. 5. When the trapped atoms reach the final equilibrium temperature, the repuming beam can be blocked and the detuning of the PHB can be further increased. Therefore, the atomic losses from the tunneling effect, the radiation trapping effect, the collisions of background thermal atoms, the excited-state collisions, the photoassociation three-body recombination and the heating effects due to the reabsorption of the repumping beam can be neglected. The hyperfine changing collisions between the two different ground-state atoms and the three-body recombination between three ground-state atoms in the dark region become the dominant losses in this dark GOT. The total loss rate can be estimated by

$$\gamma_{\rm GOT} = \frac{1}{n}\frac{{\rm d}n}{{\rm d}t} \approx \eta_{ug}\beta_{ggc}n + Ln^2. \qquad (12)$$

Here β_{ggc} and L are the rate coefficient of the hyperfine changing collision and the rate coefficient of the three-body recombination, respectively. For ^{23}Na atoms, $\beta_{ggc} \approx 2 \times 10^{-12}\,{\rm cm}^3/{\rm s}$[25], $L \approx 1.1 \times 10^{-30}\,{\rm cm}^6/{\rm s}$[10]; for ^{87}Rb atoms, $\beta_{ggc} \approx 5.8 \times 10^{-12}\,{\rm cm}^3/{\rm s}$[26], $L \approx 4\times10^{-30}\,{\rm cm}^6/{\rm s}$[27]; and for ^{133}Cs atoms, $\beta_{ggc} \approx 1 \times 10^{-11}$ cm^3/s[28],$L \approx 5 \times 10^{-29}$ cm^6/s.[29].

For a continuous loading of the cold atoms from the MOT into the GOT with a loading rate $L_{\rm R} = 2 \times 10^8$ atoms/s, the steady-state rate equation:

$$\frac{{\rm d}N}{{\rm d}t} = L_{\rm R} - N\gamma_{\rm GOT} = 0, \qquad (13)$$

and Eq.(12) can be used to estimate the obtainable steady-state density n^* of the trapped atoms in the GOT. Figure 5 shows the dependence of n^* on θ.When the trapping angle θ is increased from 2° to 60°, the steady-state densities n^* of the trapped ^{87}Rb and ^{133}Cs atoms in the GOT are decreased from $\sim 1.0\times10^{16}$ and 6.2×10^{15} to 1.3×10^{15} and 1.5×10^{15}, and are always higher than the corresponding BEC densities. Whereas for the trapped ^{23}Na atoms in the GOT, when $\theta > 3°$, the steady-state density is lower than its BEC density. Therefore, appearance of BEC for the ^{87}Rb or ^{133}Cs atoms in the GOT seems possible at all of the trapping angle θ, whereas for the ^{23}Na atoms, appearance of BEC may be possible only when $\theta < 3°$.

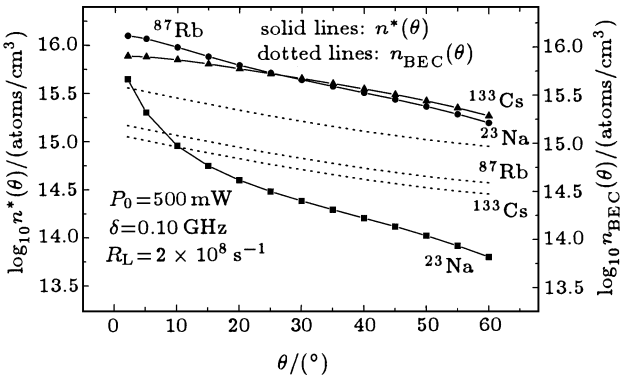


Fig.5. Steady-state densities of the trapped ^{23}Na, ^{87}Rb and ^{133}Cs atoms in the GOT versus the trapping angle θ of the blue-detuned PHB. The hyperfine changing collisions and three-body recombination of the trapped atoms in the GOT have been considered here.

For a single-time loading of the atoms from the MOT with$\sim 10^9$ atoms into the GOT, we can estimate the total loss rate $\gamma_{\rm GOT}$ and the observation time $\tau_{\rm obs}$ of the trapped atoms in the GOT. Figure 6 plots the total loss rate $\gamma_{\rm GOT}$ and the observation time $\tau_{\rm obs}$ versus the trapping angle θ. When $\theta = 5°$ and $n = n_{\rm BEC} = 3.19 \times 10^{15}, 1.37 \times 10^{15}$, and 1.05×10^{15} atoms/cm^3 for the trapped ^{23}Na, ^{87}Rb and ^{133}Cs atoms, respectively, we obtain $\gamma_{\rm GOT} \approx 14.2, 8.3$, and 56.2/s. Figure 6 shows that when $\theta = 5°$, the total loss rate in the PHB trap for the trapped ^{23}Na and ^{87}Rb atoms is ~ 10/s, which is similar to that in Ref.[16].This shows that 10^8 atoms can be observed for up to about one second with the density above $n_{\rm BEC} \approx 1 \times 10^{15}$ atoms/cm^3 when 10^9 atoms are released from the MOT into the GOT. Whereas for the trapped ^{133}Cs atoms in the GOT, the corresponding observation time is less than 0.02 s. Therefore, the appearance of BEC for the trapped ^{23}Na and ^{87}Rb atoms in the GOT seems to be possible, whereas it is impossible to observe BEC for the trapped ^{133}Cs atoms in the GOT. However, when the trapping angle θ is increased to 60°, at which $n = n_{\rm BEC} = 1.05 \times 10^{15}, 4.5 \times 10^{14}$, and 3.45×10^{14} atoms/cm^3 for the ^{23}Na, ^{87}Rb and ^{133}Cs atoms, respectively, we get $\gamma_{\rm GOT} \approx 1.4, 1.1$, and 6.3/s (see Fig.6). It then seems that the appearance of BEC for the trapped ^{87}Rb and ^{133}Cs atoms in the GOT is possible, and the corresponding observation times are ∼10 and ∼1.5s, respectively. While $\theta > 12°$, the observation of BEC for the ^{23}Na atoms is impossible because the lossless density of the trapped ^{23}Na atoms in this GOT without considering any loss is always lower than its BEC density ($\sim 10^{15}$ atoms/cm^3).

Recently, two sub-recoil cooling mechanisms in optical dipole traps were demonstrated experimentally.[30,31] One is evaporative cooling of

Na atoms in a far-off-resonant, red-detuned crossed dipole trap[30], from which a cold Na atomic sample with a temperature of $\sim 4\mu$K($\sim 1.7T_{\rm R}$) and an atomic density of $\sim 6\times10^{11}$ atoms/cm^3 was obtained. Another is Raman cooling of Na atoms in a far-off-resonant, blue-detuned optical dipole trap[31], which produces an atomic density and temperature of $\sim 4\times10^{11}$ atoms/cm^3 and $\sim 1\mu K(\sim 0.4T_{\rm R})$ for Na atoms, respectively. This shows that an atomic temperature below the photon-recoil limit can be obtained in a pure optical trap, just like the case in a magnetic atom trap.

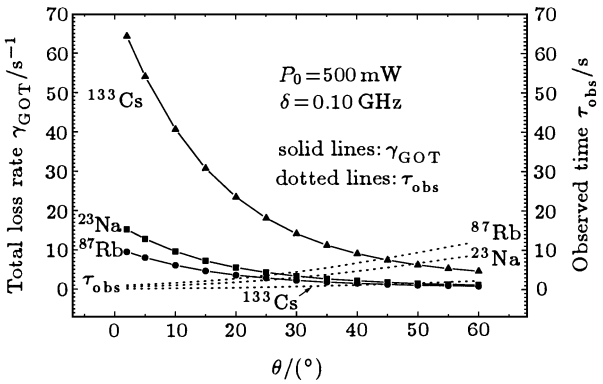


Fig.6. Total loss rate and observation time versus the trapping angle θ of the PHB for the trapped ^{23}Na, ^{87}Rb and ^{133}Cs atoms in the GOT.

Since the collision-loss rate in the blue-detuned PHB trap is far lower than that in the red-detuned optical trap[30], and the spontaneous-emission rate can be made smaller than the optical-potential evaporative cooling rate, the trapped ^{87}Rb atoms in the dark GOT may be cooled to near, even below, the photon-recoil limit by the optical-potential evaporative cooling. For example, using the experimental result of Chu's group, $T\approx 1.7T_{\rm R}$[30], we can obtain $T\approx 0.35\mu$K, which is lower than the highest BEC temperature (0.5μK) of the trapped ^{87}Rb atoms in a magnetic trap.[6] In fact, under the same trapping-beam parameters, the collision-loss rate and spontaneous-emission rate of the trapped atoms in a red-detuned Gaussian-beam trap is far higher than that in a blue-detuned PHB trap, the final obtainable GOT temperature T by the optical-potential evaporative cooling should be lower than $1.7T_{\rm R}$. On the other hand, after the temperature of trapped atoms in the PHB GOT reaches the final 3D equilibrium temperature, one can greatly increase the detuning of the PHB to a few 1000 GHz from several GHz and reduce the power of the PHB (from several 100 mW to a few mW, even below 1 mW), then perform the optical-potential evaporative cooling and further cool the atomic temperature to near, even below, the photonrecoil limit. Finally, before the atomic temperature reaches a new equilibrium state passing through the elastic collisions between trapped atoms, one can reduce the trapping angle θ to a few degrees from several tens of degrees, or increase the power of the PHB from several mW to a few 100 mW so as to efficiently compress the trapped atomic sample and increase atomic density n, thus realize an optically-trapped BEC. Therefore, one may start from the dark GOT with the PHB cooling and trapping, then use the optical-potential evaporative cooling[30] or Raman cooling[31] or other subrecoil cooling[32−34] to further cool the trapped atoms to near or below the recoil limit and thus realize BEC in the PHB GOT. A detailed discussion will be given elsewhere.

V. CONCLUSIONS

We have proposed a blue-detuned, dark GOT for alkali atoms with a PHB. The spontaneous emission in the PHB and two sub-Doppler cooling mechanisms, Sisyphus cooling and spontaneous geometric cooling, are discussed and analyzed. We have estimated the final equilibrium temperature, the total loss rate and atomic density in the dark GOT. Our study shows that an extremely cold and dense atomic sample with an equilibrium rms momentum of $\sim 3\hbar k$ and an atomic density above that required by BEC may be obtained in the GOT. It is possible to directly observe BEC in this optical trap. On the other hand, starting from the GOT based on dark-hollow-beam cooling, the optical-potential evaporative cooling[30] or Raman cooling[31] or other sub-recoil cooling[32−34] may be used to realize BEC in this pure optical trap.

Recently, Bigelow's group has produced a MOT that contains a mixture of Na and Rb atoms[35,36] and studied theoretically the properties of two-species BEC in a magnetic trap.[36,37] A PHB gravito-optical trap studied here may be used to trap and cool two isotope species such as ^{85}Rb and ^{87}Rb, and realize an optically-trapped BEC of two isotope samples. Two overlapped, collimated dark hollow beams can be generated from a micron-sized hollow optical fiber coupled by two overlapped Gaussian laser beams with different wavelengths[22] and used to construct a two-species GOT, which may be used to explore a new way to realize two-species BEC[36,37] in an optical trap.

In addition, so far all of magnetically-trapped BECs have been realized by evaporative cooling, the condensed atomic number is 10^3–10^6 atoms so that

the output lasting time of atom laser with 5×10^5 condensed atoms is only 0.1s[38], whereas the preparation of a BEC sample usually needs about 30s. Therefore, in order to generate a real CW atom laser, one must have a BEC with more than 1.5×10^8 condensed atoms, this is difficult to obtain by using the conventional evaporative cooling in magnetic traps. However, Raman cooling in a blue-detuned optical dipole trap may produce a BEC with 10^8–10^9 condensed atoms as the trapped number in the MOT is about 10^9–10^{10} atoms. So it is possible to generate a real CW atom laser by using a Raman cooled and optically-trapped BEC.

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