

Transferring cold atoms in double magneto-optical trap by a continuous-wave transfer laser beam with large red detuning

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A novel scheme of transferring cold atoms in a double magneto-optical trap (MOT) system has been experimentally demonstrated. Cold cesium atoms trapped in a vapor-cell MOT are efficiently transferred to an ultrahigh-vacuum (UHV) MOT by a continuous-wave divergent Gaussian transfer laser beam. When large red detuning and moderate intensity are adopted for the transfer laser beam, enhancement of the recapturing of atoms in the UHV MOT is clearly observed. Using the divergent transfer laser beam (diameter of ~ 1.60 mm in the vapor-cell MOT region) with typical power of ~ 20.2 mW, up to $\sim 85\%$ of transfer efficiency is obtained when the frequency detuning is set to around -1.2 GHz, and it is not sensitive to small detuning variation. This transfer is much efficient compared with that in the case of continuous-wave near-resonance weak transfer laser beam (typical power of order of ~ 100 μ W and typical frequency detuning of ~ -10 MHz) which is normally used in double-MOT experiment. The enhancement is ascribed to the guiding effect on cold atomic flux by transverse dipole potential of the large red-detuned transfer laser beam. © 2008 American Institute of Physics. [DOI: 10.1063/1.3058607]

I. INTRODUCTION

Laser cooling and trapping of neutral atoms,¹ which have seen dramatic new developments over recent decades, are a rapidly expanding area of atomic physics. In particular, magneto-optical trap^{2,3} has become a versatile tool for preparing cold neutral atoms. Many experimental research works, such as Bose–Einstein condensation, cold atom collision, optical lattices, atomic fountain clock, and cavity quantum electrodynamics with cold atoms, require a cold trapped atomic sample. For alkali metal atoms, MOT can be loaded via Zeeman slower or frequency-chirping slower to slow down hot atomic beam¹ and also can be directly loaded from the slow tail of Maxwell–Boltzmann distributed atomic vapor around room temperature (so-called vapor-cell MOT).^{1,3} Moreover, if cold atoms in ultralow background pressure (ultrahigh vacuum) are required, one can adopt Zeeman slower or frequency-chirping slower to load an UHV MOT;¹ one can also adopt the double-MOT scheme,^{4,5} in which a vapor-cell MOT is utilized to prepare cold atoms conveniently; then some ways^{4–12} are used to extract cold atoms out to form pulsed or continuous cold atomic flux to load an UHV MOT. Although there are many different ways to form a cold atomic flux based on a vapor-cell MOT, the common basic idea is to create an unbalanced radiation pressure, such as pushing cold atoms out of the vapor-cell MOT and guiding by transverse magnetic potential,⁴ launching cold atoms from the vapor-cell MOT upwards to form moving molasses,⁵

adding atomic funnel between two MOTs,⁶ creating a narrow dark region in one of six cooling and trapping beams of the vapor-cell MOT by using a retroreflection mirror with a tiny hole in center⁷ and a pyramidal MOT with a small hole at the vertex.⁸ The above-mentioned schemes are a bit complicated, and in some of them special optical components have to be put inside the vacuum chamber.^{7,8} Actually a near-resonance continuous-wave weak transfer laser beam can be used to extract cold atoms out of the vapor-cell MOT to load the UHV MOT;^{9–11} also a hollow blue-detuned laser beam can be used to confine the cold atomic flux transversely to enhance loading of the UHV MOT.^{12,13} These two schemes are technically simple but efficient.

In this paper, we present a novel transfer scheme in double MOT, in which only a continuous-wave divergent Gaussian transfer laser beam with moderate intensity and large red detuning is used to extract cold atoms out of the vapor-cell MOT and guide the cold atomic flux for loading the UHV MOT. Enhancement of transferring cold atoms is clearly demonstrated experimentally. We ascribe the transfer enhancement to guiding effect due to transverse dipole potential formed by the large red-detuned transfer laser beam.^{14,15} Compared with the above-mentioned schemes, this one does not need putting any optical element inside the vacuum chamber,^{7,8} it also does not require an extra blue-detuned hollow laser beam besides a pushing laser beam,^{12,13} and transfer is much efficient than that in the case of continuous-wave near-resonance weak transfer laser beam.^{9–11}

II. EXPERIMENT SETUP

As schematically shown in Fig. 1, two stainless-steel vacuum chambers are connected vertically with a tapered

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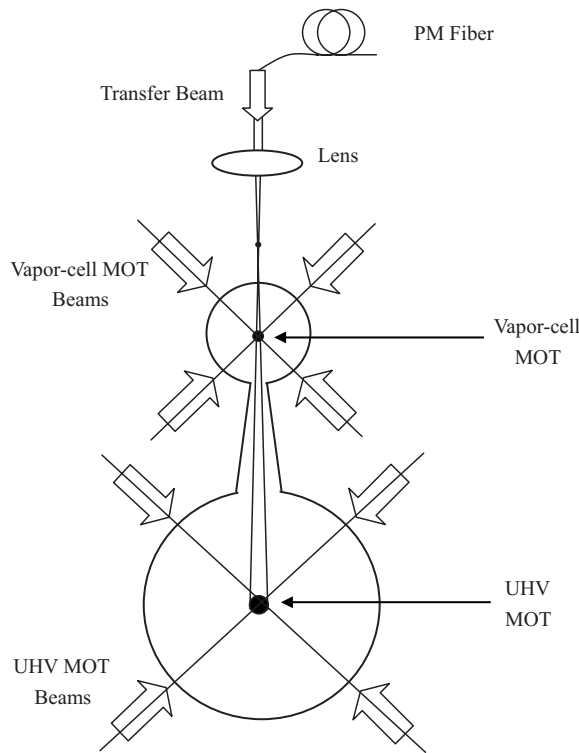


FIG. 1. Schematic of the cesium double-MOT system. The continuous-wave transfer laser is spatially filtered and guided by a SM PM optical fiber and focused by a lens ($f=30$ mm) positioned ~ 90 mm above the vapor-cell MOT. Typical diameters of the TEM₀₀-mode transfer beam at the vapor-cell MOT and the UHV MOT regions are ~ 1.60 and ~ 5.04 mm, respectively.

hollow copper pipe and differentially pumped by two ion pumps (not shown). The distance between the centers of the two chambers is 193 mm. The upper one is for the vapor-cell MOT, which cools and traps atoms from background cesium vapor for loading the UHV MOT beneath it. Typical pressures are $\sim 1 \times 10^{-6}$ Pa for the vapor-cell MOT chamber with cesium vapor inside and $\sim 2 \times 10^{-8}$ Pa for the UHV MOT chamber.

The vapor-cell MOT and the UHV MOT both run in orthogonal retroreflected-three-beam MOT configuration. The cooling and trapping beams of the double MOT are provided by a high-power grating-external-cavity 852 nm diode laser (not shown) with typical linewidth of ~ 500 kHz, and the hyperfine repumping laser beams of the double MOT are provided by Bragg-distributed-reflector diode laser (not shown) with a typical linewidth of ~ 3 MHz. Both lasers are frequency stabilized via saturation absorption technique, and residual frequency fluctuations after locking are less than 1 MHz. Frequency detuning of the cooling and trapping beams to cesium $6S_{1/2}$ Fg=4- $6P_{3/2}$ Fe=5 cycling transition is $\delta = -2\gamma$ ($\gamma = 5.2$ MHz is the natural linewidth of the cycling transition), while the repumping beams are resonant with cesium $6S_{1/2}$ Fg=3- $6P_{3/2}$ Fe=4 hyperfine transition. The cooling and trapping beams of the double MOT are expanded to ~ 12 mm of $1/e^2$ diameter by a telescope. Typical parameters of the double MOT are as follows: $s'_{\text{total}} \sim 23.7$ (here $s'_{\text{total}} = I'_{\text{total}}/I_{\text{sat}}$ is the saturation parameter of cooling/trapping beams for the vapor-cell MOT, I'_{total} is the total intensity, and $I_{\text{sat}} = 1.12$ mW/cm² is the saturation intensity),

$P'_{\text{repumping}} \sim 3$ mW, and axial gradient of quadrupole magnetic coils $B' \sim 1$ mT/cm for the vapor-cell MOT; $s''_{\text{total}} \sim 28.4$ (here $s''_{\text{total}} = I''_{\text{total}}/I_{\text{sat}}$ is the saturation parameter of cooling/trapping beams for the UHV MOT), $P''_{\text{repumping}} \sim 4$ mW, and axial gradient $B'' \sim 0.8$ mT/cm for the UHV MOT. In the absence of the transfer laser beam, the vapor-cell MOT prepares a nearly spherical cold cloud with typical temperature of ~ 70 μ K (measured by the short-distance time-of-flight technique^{16,17}), typical steady-state number of trapped cold atoms is $\sim 5 \times 10^7$ (measured by absorption technique¹⁸), and typical Gaussian diameter of cold cloud is ~ 1.1 mm (measured by a magnification-calibrated image system and charge coupled device (CCD) camera), whereas the UHV MOT does not have a measurable number of trapped cold atoms.

Our transfer scheme is also illustrated in Fig. 1. The linearly polarized transfer laser beam is provided by another grating-external-cavity diode laser with typical output power of ~ 60 mW. The frequency of the transfer laser can be continuously tuned over ~ 5 GHz around cesium $6S_{1/2}$ Fg=4- $6P_{3/2}$ Fe=5 cycling transition by scanning the piezo on grating external cavity and injection current synchronously, whereas output power is kept roughly constant. Frequency detuning of the transfer laser (relative to cesium $6S_{1/2}$ Fg=4- $6P_{3/2}$ Fe=5 cycling transition) is monitored by a scanning confocal Fabry-Pérot cavity with free spectra range of 500 MHz and a wavelength meter with resolution of 0.1 pm (~ 40 MHz around 852 nm). After being spatially filtered and collimated by a single-mode (SM) polarization-maintaining (PM) optical fiber, a quasiparallel TEM₀₀-mode Gaussian laser beam with ~ 1 mm diameter is obtained. To push out cold atoms trapped in the vapor-cell MOT to form cold atomic flux but decrease influence on the UHV MOT, a divergent transfer laser beam is adopted and results that intensity of the transfer beam at the UHV MOT region is much weaker than that at the vapor-cell MOT region. In this way, the cold atoms prepared in the vapor-cell MOT can be pushed out by the transfer beam to load the UHV MOT,⁹⁻¹³ whereas the pushing effect on the UHV MOT will be much smaller. The transfer beam is focused above the vapor-cell MOT region by a planoconvex lens ($f=30$ mm). Also other planoconvex lenses with focus length of 20, 50, and 100 mm were tried, but the results were clearly worse. In experiment we find that optimized position of the focusing point locates at ~ 90 mm above the vapor-cell MOT. In this case the $1/e^2$ beam diameter is ~ 1.60 mm at the vapor-cell MOT region and is ~ 5.04 mm at the UHV MOT region, respectively. These values are also checked before mounted as shown in Fig. 1.

Fluorescence of the cold atoms recaptured in the UHV MOT, which is approximately proportional to the number of trapped atoms, is collected by a biconvex lens with a diameter of 25 mm and focus length of 25 mm (distance between the lens and center of the UHV MOT is ~ 50 mm, yielding a collection solid angle of $\sim 0.0635\pi$ sr, corresponding to a collection efficiency of $\sim 1.59\%$) and monitored by a calibrated large-area photodiode (diameter of effective area is 8 mm).

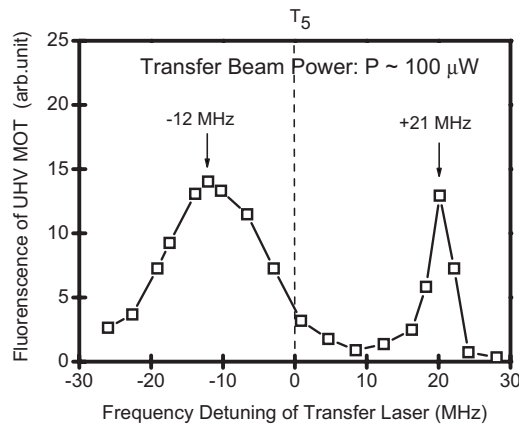


FIG. 2. Fluorescence intensity of the UHV MOT vs frequency detuning of the weak transfer laser beam (power of the transfer beam is set at $\sim 100 \mu\text{W}$). The squares show the data, and solid lines are for guiding the eyes. The dashed line T5 indicates cesium $F_g=4$ – $F_g=5$ cycling transition (zero detuning). Two peaks are clearly observed at the detunings of -12 and $+21$ MHz.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

Two regimes of the transfer laser (near-resonant weak laser beam and large red-detuned moderate-intensity laser beam) have been investigated in our experiment. In the regime of near-resonant weak transfer laser beam, the power of the transfer beam is set at $P \sim 100 \mu\text{W}$, whereas frequency detuning of the transfer laser is changed from -30 MHz to $+30$ MHz. The measured fluorescence intensity of the UHV MOT versus frequency detuning of the transfer laser is shown in Fig. 2. Clearly two peaks are observed, which are similar to the results of Refs. 9–11, and located at $\delta_{\text{transfer}} \sim -12$ MHz and $\sim +21$ MHz. Around these two peaks, atoms are pushed out of the vapor-cell MOT to form a continuous cold atomic flux and transversely cooled by the vapor-cell MOT beams before atoms completely leave the vapor-cell MOT region.^{9,11} This transverse cooling, which was theoretically simulated in Ref. 9, more or less reduces the divergence angle of the cold atomic flux and results that some atoms can be recaptured in the UHV MOT. With $P \sim 100 \mu\text{W}$ and $\delta_{\text{transfer}} \sim -12$ MHz of the transfer beam's parameters, the maximum steady-state number of cold atoms recaptured in the UHV MOT is $\sim 7 \times 10^6$, compared with the steady-state number of cold atoms of $\sim 5 \times 10^7$ trapped in the vapor-cell MOT in the absence of transfer laser beam, so this corresponds to transfer efficiency of $\sim 14\%$. Considering the uncertainty of atom number measurement by collecting fluorescence, $\sim 5\%$ of transfer efficiency uncertainty can be roughly estimated. If the transfer laser beam is blocked, the detected fluorescence signal will decay exponentially with a typical lifetime of ~ 20 s (limited by background collision) because no cold atom is loaded into the UHV MOT anymore.

In the case of large red-detuned moderate-intensity transfer laser, power and frequency detuning of the transfer laser beam are extended to ~ 20 mW and ~ -2.0 GHz, respectively. Measured results are shown in Fig. 3 with powers of ~ 5.2 mW [for Fig. 3(a)] and ~ 20.2 mW [for Fig. 3(b)]. When the transfer laser frequency is tuned closing to cesium $F_g=4$ to $F_g=3, 4$, and 5 hyperfine transitions [T3, T4, and

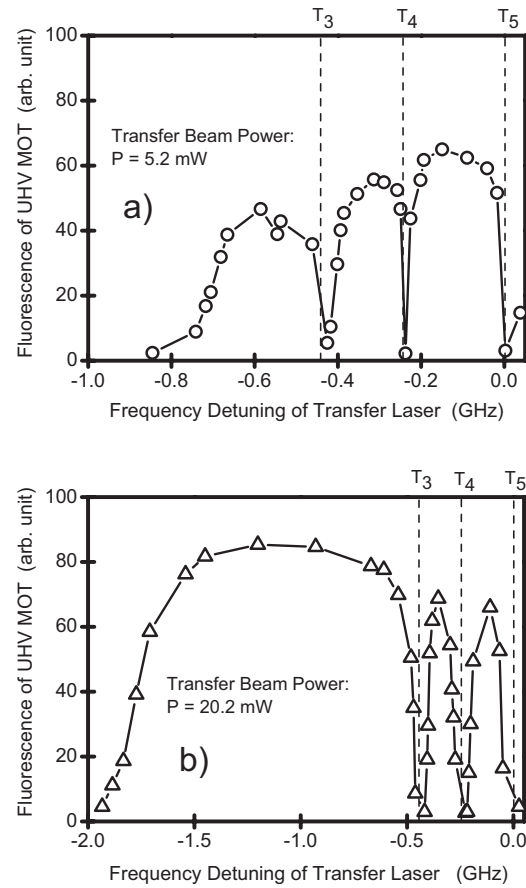


FIG. 3. Fluorescence intensity of the UHV MOT vs frequency detuning of the moderate-intensity transfer beam. (a) and (b) indicate the cases of 5.2 and 20.2 mW of the transfer beam's power. The circles and triangles show the data, and solid lines are for guiding the eyes. The dash lines T3, T4, and T5 correspond to cesium hyperfine transitions from $F_g=4$ to $F_g=3, 4$, and 5 , respectively. Zero detuning means the transfer beam is resonant with $F_g=4$ – $F_g=5$ cycling transition.

T5 dashed lines in Figs. 3(a) and 3(b)], obviously fluorescence intensity of the UHV MOT drops nearly to zero. The reason is that cold atoms are dramatically heated and accelerated by the near-resonant moderate-intensity transfer laser. On the one hand, the cold atomic flux cannot be transversely cooled due to shorter interaction time with the vapor-cell MOT beams, so it may have a larger divergence angle (spatial distribution maybe much bigger than the UHV MOT's spatial capture range when reaching the UHV MOT region). On the other hand, cold atoms will gain a too big velocity when reaching the UHV MOT region (much bigger than the typical capture velocity of 20 m/s for the UHV MOT in our case) and cannot be recaptured by the UHV MOT. In the peaks in between T3, T4, and T5, we believe that the transverse cooling mechanism takes effect, which is similar to the case of near-resonant weak transfer laser beam. Compared with Fig. 2, when the transfer laser frequency is tuned far below to cesium $F_g=4$ to $F_g=3, 4$, and 5 hyperfine transitions [the peaks at the left side in Figs. 3(a) and 3(b)] the fluorescence intensity peak is surprisingly enhanced. Also the valid detuning range is enlarged clearly [from ~ -0.5 to ~ -0.8 GHz in Fig. 3(a) and from ~ -0.5 to ~ -2.0 GHz in Fig. 3(b)]. Of course, too large detuning of the transfer beam cannot push cold atoms out of the vapor-cell MOT region. If

the steady-state fluorescence intensity of the UHV MOT is still regarded to be approximately proportional to the number of recaptured cold atoms in the case of large red-detuned moderate-intensity transfer laser, the peaks at the left side in Figs. 3(a) and 3(b) indicate that the number of atoms trapped in the UHV MOT is obviously much more than that in the case of near-resonant weak transfer laser. Roughly the peak intensities around -0.6 GHz in Fig. 3(a) and -1.2 GHz in Fig. 3(b) are about 3.3 and 6.1 folded high, compared with Fig. 2, which means $\sim 46\%$ and $\sim 85\%$ of transfer efficiency. The temperature of cold atoms recaptured in the UHV MOT is also checked and is roughly the same as that of the vapor-cell MOT (~ 70 μ K).

In our experiment, we do not attempt to measure the flux intensity and divergence angle of the cold atomic flux. However, the guiding effect still can be inferred from the recapturing enhancement. This enhancement is not surprising considering the transverse dipole potential formed by the large red-detuned moderate-intensity divergent Gaussian transfer laser beam.^{14,15} The transverse dipole potential $U_{\text{dip}}(r, z)$ formed by the red-detuned laser beam can be described¹⁹ by $U_{\text{dip}}(r, z) = (3\pi c^2 / 2\omega_0^3)(\Gamma / \Delta)I(r, z)$; here c is the light speed in vacuum, Γ is the atomic spontaneous decay rate ($\Gamma = 2\pi \times 5.2$ MHz for cesium $6S_{1/2}$ $F_g=4-6P_{3/2}$ $F_e=5$ cycling transition), ω_0 is the atomic resonance angular frequency, Δ is the angular frequency detuning of the laser beam ($\Delta = 2\pi \times \delta$), $I(r, z)$ is the intensity distribution, z axis is the propagation direction of the laser beam, and r is the radial position. For the red-detuned TEM₀₀-mode Gaussian laser beam, it can be expressed¹⁹ by

$$U_{\text{dip}}(r, z) = \frac{3\pi c^2 \Gamma}{2\omega_0^3 \Delta} \frac{2P}{\pi w^2(z)} \exp\left[\frac{-r^2}{w^2(z)}\right].$$

Here P is the optical power of the laser beam, $w(z)$ is the Gaussian radius of transfer beam at position z , and $2P/[\pi w^2(z)]$ indicates the peak intensity at position z . Based on typical parameters of the transfer laser beam (20.2 mW of power, -1 GHz of detuning) in the region of large red detuning in Fig. 3(b), the depth of transverse dipole potential can be approximately calculated. Compared with the initial temperature of ~ 70 μ K of cold atoms prepared in the vapor-cell MOT, transverse trap depths of ~ 240 and ~ 24 μ K are obtained at the vapor-cell MOT region and the UHV MOT region, respectively. After cold atoms are extracted out of the vapor-cell MOT by radiation pressure of the transfer laser beam, the cold atomic flux will be guided by the transverse dipole potential. So the divergence angle of the cold atomic flux will be reduced by this guiding effect, which yields that more atoms can be trapped by the UHV MOT.

Even if the transfer laser beam's intensity at the UHV MOT region is much lower than that at the vapor-cell MOT region due to the beam divergence, actually disturbance on the UHV MOT always exists, but it should be much smaller than that on the vapor-cell MOT. On the one hand, the radiation pressure of the transfer beam will slightly displace the UHV MOT center. On the other hand, even if the number of cold atoms recaptured in the UHV MOT is not changed, a light shift accompanied with guiding due to the large red-

detuned Gaussian transfer laser beam should decrease fluorescence intensity of the UHV MOT because the effective red detuning of the cooling and trapping lasers will be slightly increased. This point is confirmed in our experiment. When the transfer beam's power is increased to 20 mW and the frequency detuning is kept on -1.2 GHz, quick blocking the transfer beam (the light shift abruptly goes to zero) yields that fluorescence intensity increased suddenly. We believe that this is also the evidence of formation of transverse dipole potential. Several points should be addressed as follows. The light shift (~ 1 MHz compared with cesium $F_g=4-F_e=5$ cycling hyperfine transition in the absence of the transfer laser) in the UHV MOT region can be approximately calculated. If this value is taken into account in the cases of Figs. 3(a) and 3(b), the number of the recaptured atoms in the UHV MOT will be slightly underestimated from the fluorescence intensity. This means that the transfer enhancement [~ 3.3 folded and ~ 6.1 folded for the large red-detuning region in Figs. 3(a) and 3(b)] now are slightly underestimated compared with the case of near-resonant weak transfer laser beam. For the vapor-cell MOT, this light shift is a bit larger than that of the UHV MOT because of the smaller diameter of transfer beam. The transfer laser beam will also disturb the vapor-cell MOT, but we did not pay attention to this point in experiment. Possible ways to further enhance cold atom transfer are enlarging the cooling and trapping laser beams' diameter and increasing the cooling and trapping laser's power for the UHV MOT to extend the capture volume and capture velocity.

IV. CONCLUSION

In conclusion, we experimentally investigated the recapturing of the UHV MOT based on a cold atomic flux extracted from the vapor-cell MOT by using a continuous-wave divergent Gaussian transfer laser beam. We demonstrate the clear enhancement of recapturing in the UHV MOT in the case of large red-detuned moderate-intensity Gaussian transfer laser beam and ascribe the transfer enhancement to the guiding effect of the transverse dipole potential formed by the transfer laser beam. This novel scheme can be applied to various double-MOT systems. It is simple to implemented but quite efficient. Another obvious advantage of this scheme is that no frequency locking of the large red-detuned moderate-intensity transfer laser is needed because the recapturing is almost not sensitive to the transfer laser detuning.

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In our recent publication Ref. [1](#), we find that several points in the reference list should be revised or added as follows. In the original Ref. [11](#), page number 702 should be 1746. Also a proper conference report² and a proper paper³ should be added at the end of the reference list.

¹Junmin Wang, Jing Wang, S. Yan, T. Geng, T. Zhang, *Rev. Sci. Instrum.*

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²The main experimental results described in Ref. [1](#) were first reported by J. Wang, S. Yan, T. Geng, *et al.*, The 12th National Conference on Quantum Optics (19-22 August 2006, Nanchang, China), See the conference abstract on Acta Sinica Quantum Optica, **12** (supplement), 22 (25 August 2006) (in Chinese).

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