Continuously transferring cold atoms in caesium double magneto-optical trap

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Continuously transferring cold atoms in caesium double magneto-optical trap*

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We have established a caesium double magneto-optical trap (MOT) system for cavity-QED experiment, and demonstrated the continuous transfer of cold caesium atoms from the vapour-cell MOT with a pressure of $\sim 1 \times 10^{-6}$ Pa to the ultra-high-vacuum (UHV) MOT with a pressure of $\sim 8 \times 10^{-8}$ Pa via a focused continuous-wave transfer laser beam. The effect of frequency detuning as well as the intensity of the transfer beam is systematically investigated, which makes the transverse cooling adequate before the atoms leak out of the vapour-cell MOT to reduce divergence of the cold atomic beam. The typical cold atomic flux got from vapour-cell MOT is $\sim 2 \times 10^7$ atoms/s. About 5×10^6 caesium atoms are recaptured in the UHV MOT.

Keywords: cold atoms, double magneto-optical trap, continuous transfer, ultra-high-vacuum magneto-optical trap

PACC: 3280P, 4250V

1. Introduction

In recent decades the magneto-optical trap (MOT)[1,2] of neutral atoms has become a workhorse in the fields of laser spectroscopy, atomic physics, quantum optics and quantum metrology. MOT can efficiently offer cold samples of neutral atoms, which is the starting point for much experimental research, such as on Bose–Einstein condensation (BEC), cold atoms collision, optical lattices, atomic fountains, and cavity-quantum electrodynamics (cavity-QED). For alkali metal atoms, the MOT can be loaded by slowing a thermal atomic beam via Zeeman slower[1,3] or frequency-chirp slower,[4] and also can be loaded directly from dilute atomic vapour with the Maxwell–Boltzmann velocity distribution.[2] The vapour-cell MOT plays a more and more important role in cold atom physics because the complicated setup for atomic beam deceleration is no longer needed. But in some experiments, such as BEC as well as cavity-QED, an ultra-cold atom cloud with a much cleaner background is desired. To meet this demand based on the vapour-cell MOT, a second stage MOT operating in a lower pressure chamber is added (the so-called double-MOT).

Various methods can achieve the cold atomic flux from a vapour-cell MOT to load a UHV MOT. The common basic idea is to create an unbalanced radiation pressure to produce a cold atomic flux from the vapour-cell MOT. The free falling scheme[5] is comparatively simple, without the use of transfer beam to achieve recapture in lower UHV MOT by releasing the atoms trapped in upper vapour-cell MOT, but a possible problem is how to eliminate the reciprocal influence between the vapour-cell MOT's and the UHV MOT's quadrupole magnetic fields. The up-moving molasses scheme[6] is the process in which the trapped atoms in the vapour-cell MOT are launched upwards in an up-moving frame and then recaptured in the upper UHV MOT. The low-velocity intense source of atoms scheme[7] creates a narrow dark region in one of the six cooling/trapping beams of vapour-cell MOT by using a mirror with a tiny hole in its centre. A pyramidal funnel[8,9] is constructed of four identical pyramidal mirrors with a small hole at mirrors' vertex. Schemes in Refs.[7]–[9] all need to set

up some optical parts inside the vacuum chamber, so they are technically complicated. Differently, the groups of Dalibard[10] and Tino[11] used a focused continuous-wave laser beam to cross the vapour-cell MOT and create the extraction column, which provides a very efficient way to transfer trapped atoms into a low-divergence cold atomic beam for loading UHV MOT. Though we can classify Refs.[7]–[11] as continuous transfer schemes, they are not fully identical. Being different from Refs.[7]–[9], additional push beam is needed for Refs.[10,11].

We have established a caesium double-MOT system for cavity-QED experiment. In order to avoid the above-mentioned problems, especially to set up special components in the vacuum chamber, we adopt the continuous transfer scheme similar to Refs.[10,11] for loading our UHV MOT. In this paper, continuously transferring cold atoms from the vapour-cell MOT to the UHV MOT is presented. The effect of frequency detuning as well as intensity of transfer beam is systematically investigated.

2. Experimental setup and principle

Our caesium double-MOT system is composed of two stainless-steel vacuum chambers connected vertically by a hollow taper-shaped tube (the tube has a length of 100 mm and an inner diameter of 4 mm (10 mm) at the top (bottom)), allowing differential pumping. The vapour-cell MOT chamber is evacuated by a 40 l/s ion pump and connected with a caesium reservoir via a metal valve, while the UHV MOT chamber is differentially pumped by a 300 l/s ion pump. Such configuration affords much cleaner background in UHV MOT chamber ($\sim 8 \times 10^{-8}$Pa). Sufficient pressure in the vapour-cell MOT chamber ($\sim 1 \times 10^{-6}$ Pa with caesium vapour inside) allows vapour-cell MOT be loaded from caesium vapour in a short time. The UHV MOT is loaded by the cold atomic flux coming from vapour-cell MOT. The background pressures of the two chambers are monitored directly by vacuum gauges (Varian Inc.).

The oppositely circularly-polarized (σ^+ and σ^-) cooling/trapping beam pairs and the transfer beam are provided by a 400-mW master-oscillator power-amplifier (MOPA) type diode laser system (SDL-TC40-850) with a typical linewidth of ~ 500 kHz, which is frequency locked to the crossover of caesium

$6S_{1/2}$ $F_g = 4 - 6P_{3/2}F_e = 4$ and 5 with red detuning of 51.5 MHz. All the beams mentioned above double pass the corresponding acousto-optical modulator (AOM) system. On the one hand, the double-pass system will maintain the track of the beams transmitted well, because different modulation frequency will change the output beam direction. On the other hand, such combination is convenient to control the detuning of the cooling/trapping beam between $-\Gamma$ and -5Γ to $F_g = 4 - F_e = 5$ cycling transition (here $\Gamma = 5.2$ MHz is the natural linewidth of the cycling transition), and the detuning of the transfer beam between -6Γ and $+6\Gamma$, by adjusting the DC voltage of the V_f port of the radio-frequency voltage-controlled-oscillator (RF-VCO). To prevent optical pumping into $6S_{1/2}$ $F_g = 3$ hyperfine ground level, a Bragg-distributed-reflector (DBR) type diode laser (SDL-5712-H1) with a typical linewidth of ~ 3 MHz is used for repumping laser, which is locked to $6S_{1/2}$ $F_g = 3 - 6P_{3/2}$ $F_e = 4$ transition. A combination of half-wave plate and polarizing beam splitter (PBS) cube is used to pick up a small part of power of both lasers for frequency stabilization via saturation absorption locking technique.[12,13] Typical frequency jitter for both lasers after locking is less than 1 MHz during several ten seconds.

For vapour-cell MOT, each cooling/trapping laser beam of the three beam pairs has $1/e^2$ diameter of 12 mm with intensity of ~ 5.3 mW/cm². Although the laser beam spatial profile of the diode lasers used is somewhat distorted, the near Gaussian profile can be obtained by putting a 30 μm diameter pinhole in the beam-expanded telescope. About 3 mW of the repumping light is combined with the cooling/trapping beams via a PBS. When the cooling/trapping laser is detuned -2Γ and the gradient of the quadrupole magnetic field is set at 1×10^{-3}T/cm, : 5×10^7 caesium cold atoms are accumulated in the vapour-cell MOT with a pressure of $\sim 1 \times 10^{-6}$Pa. The typical temperature of cold atoms in the vapour-cell MOT is ~ 70 μK, measured by short-distance time-of-flight (TOF) scheme[14,15], corresponding to the atom velocity of $V_{rms} \sim 6.6$ cm/s. It is compared with $V_{rms} \sim 8.8$ cm/s at the Doppler limit temperature of 125 μK for caesium atoms.

Typical UHV MOT parameters are given as follows: $I_{cooling} \sim 12.7$ mW/cm², $\Delta \sim -2\Gamma$, $P_{repumping} \sim 4$mW, and the quadrupole magnetic field gradient $\sim 8 \times 10^{-4}$T/cm. The combined beam of repumping and cooling/trapping beams with PBS is spatially filtered by a polarization-maintained (PM)

optical fibre, then expanded to $1/e^2$ diameter of 10 mm by a telescope system. Also the three pairs of cooling/trapping beams with retro-reflection configuration are used for UHV MOT.

By applying the quadrupole magnetic field to the upper and lower trap regions, the position-dependent force will be created. In order to counteract the mutual magnetic disturbing of the two pairs of quadrupole magnetic coils to the trapped atoms in the vapour-cell MOT and UHV MOT, additional two compensating coils are placed: one above the upper trap and the other beneath the lower trap. Other three pairs of big square coils are utilized to compensate the geomagnetic field.

The transfer scheme is illustrated in Fig.1. The continuous-wave transfer laser beam is guided and spatially filtered by a PM optical fibre. The $1/e^2$ diameter of $\Phi \approx 1$ mm of the near parallel laser beam is obtained after the fibre. It is focused by a lens ($f = 30$ mm), then hits the vapour-cell MOT with a typical beam spot $2\omega_1 \sim 1.6$ mm, which is larger than the cold atomic cloud in vapour-cell MOT (~ 1 mm). The focus point is ~ 90 mm above vapour-cell MOT. The distance between upper and lower traps is about 193 mm. In the recapture region of UHV MOT, the typical beam spot is $2\omega_2 \sim 5.1$ mm. The optical intensity is much lower than that in vapour-cell MOT, so it makes the impact of transfer beam on the recaptured cold atoms much weaker.
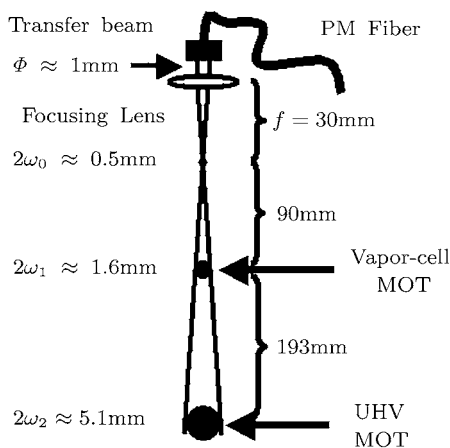

Fig.1. Schematic diagram of the caesium double-MOT (vapour-cell MOT + UHV MOT) for cavity QED experiment. Two stainless-steel vacuum chambers are connected with a hollow tapered pipe and differential pumped by two ion pumps. Typical pressures are $\sim 1 \times 10^{-6}$ Pa and $\sim 8 \times 10^{-8}$ Pa for vapour-cell MOT chamber and UHV MOT chamber, respectively. The continuous-wave transfer beam is filtered and guided by a polarization-maintained (PM) optical fibre. Typical sizes of the transfer beam at vapour-cell MOT and UHV MOT are $2\omega_1 \approx 1.6$ mm and $2\omega_2 \approx 5.1$ mm, respectively.

A simple picture can be used to illustrate the cold atoms transfer process. When cooling/trapping laser beams impinge on the atoms from all six directions, the radiation pressure force will oppose the motion of the atoms, which provides strong damping on atoms to reduce their thermal velocity and hold them around the zero point of quadrupole magnetic field. With the transfer beam introduced, the balance of the optical radiation pressure forces in vapour-cell MOT is broken. Along the transfer laser direction an extraction column is generated[10,11]. Appropriate acceleration will guide the atoms leaking out of the vapour-cell MOT to form a cold atomic flux. During the period of leaking out the atoms which are pushed by transfer laser will be transversely cooled in vapour-cell MOT region, and efficient transverse cooling will reduce the divergence of the cold atomic flux.[10,11] After leaving the upper trap, the atoms irradiated by the transfer laser beam will be optically pumped into $F_g = 3$ ground hyperfine state.

To transfer the cold atoms effectively, the key point is to adjust the orientation and position of the transfer laser beam. Moreover, the transfer laser beam should step a little bit aside from the centre of the UHV MOT to avoid influencing the recaptured cold atoms. The beam intensity is conveniently controlled by the combination of half-wave plate and PBS, and the frequency detuning can be altered ±30MHz about the resonance through radio-frequency voltage-controlled-oscillator, which is connected with power amplifier (Mini Circuits ZHL-1-2W) to drive the corresponding AOM.

3. Experimental results and discussion

Firstly, the optical power of the transfer laser beam is kept at ~ 100 μW. When the detuning of the transfer laser to $F_g = 4$ - $F_e = 5$ cycling transition is changed from -30 MHz to +30 MHz, the steady-state fluorescence intensity of the UHV MOT is measured. The fluorescence intensity is proportional to the number of the steady-state atoms in the UHV MOT. The data are shown in Fig.2. At the detuning of -12 MHz and +21 MHz, two peaks are clearly observed. This behaviour can be qualitatively explained by studying the extraction process. When the transfer beam detuning is much larger than that of the upper trap's cooling/trapping laser, the radiation pressure is very

weak, so it is not able to push the atoms out of vapour-cell MOT. At the detuning of -12 MHz, the intensity and frequency detuning of the transfer beam is comparable to the cooling beams for vapour-cell MOT, which makes the transverse cooling efficient and reduces the divergence of cold atomic flux. In this case, the unbalanced radiation pressure accelerates atoms out of the trap and produces a low divergence cold atomic beam, so more atoms are recaptured in the UHV MOT. As the transfer laser is resonant with $F_g = 4 - F_e = 5$ cycling transition, the impulse produced by radiation pressure force is enhanced, which gives the atoms a bigger acceleration. On the one hand, the atoms cannot acquire the transverse cooling in vapour-cell MOT due to short interaction time, so they will have a larger divergence. On the other hand, the bigger acceleration makes the atoms gain a big final velocity while reaching the trapped region of UHV MOT, making them pass through the trapped region of the UHV MOT and cannot be recaptured. So we can draw a conclusion that the resonant frequency is not perfect as is imagined. We choose the transfer laser with detuning of -12 MHz in our following experiment. Although the experimental data in Fig.2 show two peaks with almost the same height, the transfer will be more sensitive to the detuning at +21 MHz, which is similar to the experimental results obtained in Ref.[10].
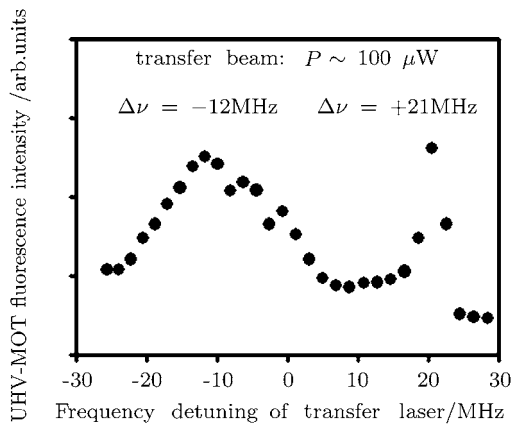
celerated out of the trap. At the same time, the transverse cooling is efficient, and the beam flux reaches its maximum value at this point. When the optical power increases further, atoms will obtain bigger acceleration due to stronger radiation pressure force of transfer beam. The bigger the acceleration, the shorter the time of leaking out of the trap region. Thus the atoms leaking out of the vapour-cell MOT cannot be efficiently cooled in transverse direction, and the cold atomic beam will have larger divergence. The distance is fixed from vapour-cell MOT to UHV MOT, and from a simple computation we can draw a conclusion that the bigger the acceleration, the larger the final velocity of the cold atoms. Once the velocity exceeds the capture speed v_c of the UHV MOT, the atoms cannot be recaptured. Of course, the weak power is not able to push cold atoms out of the vapour-cell MOT adequately.
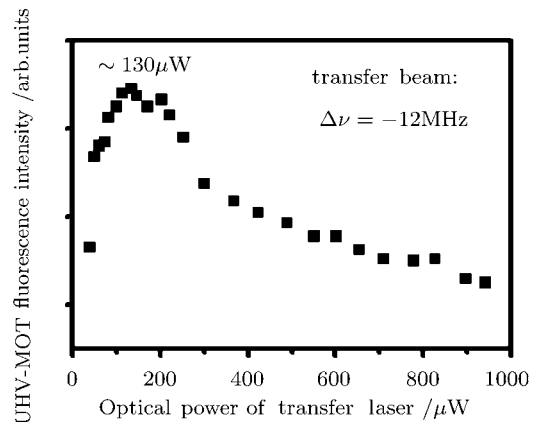

Fig.3. Fluorescence intensity of the UHV MOT versus optical power of the transfer beam with detuning of $\sim$ -12 MHz, the number of steady-state atoms recaptured in the UHV MOT reaches maximum value when the transfer beam approaches $\sim$ 130 μW.

Fig.2. Fluorescence intensity of the UHV MOT, which is proportional to the number of steady-state atoms recaptured in the UHV MOT, versus frequency detuning of the transfer beam. Zero detuning denotes that the transfer beam is resonant with caesium $6S_{1/2}$ F_g = 4 - $6P_{3/2}$ F_e = 5 cycling transition.

Fluorescence intensity of the UHV MOT versus the transfer laser power at detuning of -12 MHz is shown in Fig.3. As the power increases approaching 130 μW, the beam intensity becomes comparable with the intensity of the vapour-cell MOT beams, and the atoms which enter the extraction column can be ac-
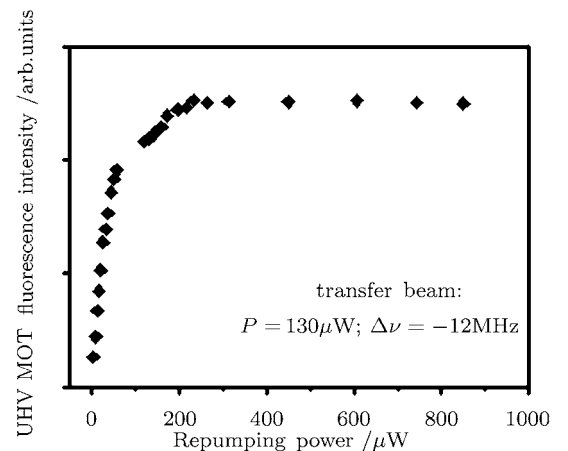

Fig.4. Fluorescence intensity of the UHV MOT versus optical power of the repumping beam while the transfer beam with power of $\sim$ 130 μW is detuned -12 MHz. Fluorescence intensity saturated when the repumping power is greater than 250 μW.

Different from Ref.[11], which showed that the repumping power must be high enough for the UHV MOT, so they used ~ 8 mW repumping light, we conclude that the number of atoms in UHV MOT is insensitive to repumping intensity. As is shown in Fig.4, the number of atoms in UHV MOT saturates after the repumping power is greater than 250μW. In the process of transferring cold caesium atoms from vapour-cell MOT to UHV MOT, the key step is to adjust the orientation and the position of the transfer beam, but

not to simply enhance the repumping power.

The number of atoms in the vapour-cell MOT is determined by the balance between the capture rate R and the loss rate,[16] while the loading process is governed by the following equation:

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = R - \frac{N(t)}{\tau} - \beta\frac{N^2(t)}{V}.$$

The function of the number of trapped atoms $N(t)$ versus loading time t is expressed as follows:

$$N(t) = \alpha \times \frac{\left(\frac{1}{\tau} + \sqrt{\frac{V + 4R\beta\tau^2}{V\tau^2}}\right)^2 - \left(\frac{1}{\tau} - \sqrt{\frac{V + 4R\beta\tau^2}{V\tau^2}}\right)^2 \exp t\sqrt{\frac{V + 4R\beta\tau^2}{V\tau^2}}}{2\frac{\beta}{V}\left[\left(\frac{1}{\tau} - \sqrt{\frac{V + 4R\beta\tau^2}{V\tau^2}}\right)\exp t\sqrt{\frac{V + 4R\beta\tau^2}{V\tau^2}} - \left(\frac{1}{\tau} + \sqrt{\frac{V + 4R\beta\tau^2}{V\tau^2}}\right)\right]},$$

which is the solution to the Riccati equation $\frac{\mathrm{d}N(t)}{\mathrm{d}t} = R - \frac{N(t)}{\tau} - \beta\frac{N^2(t)}{V}$ (just like $\frac{\mathrm{d}y}{\mathrm{d}t} = A + By + Cy^2$), under the physical condition $\frac{1}{\tau^2} > 4R(-\frac{\beta}{V})$(the same as $B^2 > 4AC$) and $N(t = 0) = 0$,[2] where α is a compensation factor and the steady-state number N_s is given by $N_\mathrm{s} = R\tau$, τ being the lifetime of atoms in the trap. We measure the loading curve of the vapour-cell MOT at a cooling laser detuning of -2Γ. By fitting the loading curve we obtain the lifetime $\tau \approx 5.4$s. Typically, $N_\mathrm{s} = 5 \times 10^7$ caesium atoms are trapped in our vapour-cell MOT. So we can have $R = N_\mathrm{s}/\tau \sim 9 \times 10^6$ atoms/s. As in Ref.[11], the atomic flux Φ from the vapour-cell MOT is given by $\Phi = R/(1 + \Gamma_\mathrm{c}/\Gamma_\mathrm{t}) = R/(1 + \frac{1/\Gamma_\mathrm{t}}{\tau})$, where $\Gamma_\mathrm{c} = 1/\tau$ is the collision rate, and Γ_t is the transfer rate of atoms into the cold atomic flux. $1/\Gamma_\mathrm{t}$ is comparable to the atomic damping time which is on the order of several tens ms.[7,11] Because $\tau \approx 5.4$s $\gg 1/\Gamma_\mathrm{t}$, we have $\Phi \approx R \approx 9 \times 10^6$ atoms/s.

4. Conclusion

For loading the UHV MOT in our caesium double-MOT system, we have demonstrated a simple scheme

to produce a cold atomic flux from the vapour-cell MOT by using a focused continuous-wave transfer laser beam. We have investigated how the parameters of the continuous-wave transfer laser, such as laser intensity and frequency detuning, affect the transfer process.

At optimized transfer beam's intensity, frequency detuning and transfer beam spot, we have obtained the cold atomic flux of the order of $\Phi \approx 2 \times 10^7$ atoms/s. Finally, $\sim 5 \times 10^6$ cold caesium atoms are recaptured in the UHV MOT at a loading time of $\sim$ 10s. Probably the divergence of cold atomic beam from our vapour-cell MOT is still large, so higher recapture rate, which is proportional to the cooling/trapping beam size, is needed for loading more atoms in the UHV MOT. The intensity balance between cooling/trapping beams pair in the UHV MOT is also very important. But at the current stage $\sim 5 \times 10^6$ cold caesium atoms in our UHV MOT are enough to meet the requirement of our following cavity-QED experiment. So unlike the case of the double-MOT for BEC experiment, which requires recaptured cold atoms in the UHV MOT to be as many as possible, we need not try our best to maximize the number of atoms in our UHV MOT.

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