Rapid Communication

Improved atom number with a dual color magneto–optical trap*

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We demonstrate a novel dual color magneto–optical trap (MOT), which uses two sets of overlapping laser beams to cool and trap ^{87}Rb atoms. The volume of cold cloud in the dual color MOT is strongly dependent on the frequency difference of the laser beams and can be significantly larger than that in the normal MOT with single frequency MOT beams. Our experiment shows that the dual color MOT has the same loading rate as the normal MOT, but much longer loading time, leading to threefold increase in the number of trapped atoms. This indicates that the larger number is caused by reduced light induced loss. The dual color MOT is very useful in experiments where both high vacuum level and large atom number are required, such as single chamber quantum memory and Bose–Einstein condensation (BEC) experiments. Compared to the popular dark spontaneous-force optical trap (dark SPOT) technique, our approach is technically simpler and more suitable to low power laser systems.

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1. Introduction

Vapor cell magneto–optical trap (MOT) has become one of the most important experimental apparatus in the cold atomic physics field.[1−4] The atoms from slow velocity tail of the background atom ensemble are first slowed down by big diameter slowing laser beams and then trapped at the center of the MOT, forming a dense cloud of the cold atoms. The system can collect typically 10^9 atoms with temperature around tens of micro Kelvin. This technique is simple, robust, and especially fitted to popular alkali atoms such as Rb and Cs.[5]

The number of atoms in a MOT is determined by the loading rate and the loss rate.[6] The loading rate is mainly limited by the loading laser power, and is proportional to the background vapor pressure. The loss rate is determined by two processes, the collisional loss of the trapped atoms with the background gas and the light induced collisional loss between two atoms in the trap.[7] When the background gas pressure is dominated by alkali vapor, and the light induced collisional loss rate is much smaller than the background collisional loss rate, the number of trapped atoms is not related to the background alkali vapor pressure. However, when very high vacuum level is required, for example in single chamber Bose–Einstein condensation (BEC) experiment, the background alkali vapor pressure is very low, the effect of the light induced loss becomes much more significant, causing much smaller number of trapped atoms.

Reducing the light induced loss rate can greatly increase the atom number. Several ideas have been successful in achieving a few times more atoms with reduced light induced loss rate. Ketterle *et al.*[8] developed a dark spontaneous-force optical trap (dark SPOT) technique, in which a dark central spot in the repumping laser beam decreased the bright state population, giving rise to fivefold increase in the number of trapped atoms. Because this scheme requires center blocked MOT beams, it is more complicated in light beam alignment, especially for Rb[9] and Cs[10] an additional depumping beam is required. Sinclair

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et al.[11] developed a similar technique, which used a center blocked slowing beam and a capture beam to obtain a doubling of the trap filling-rate, leading to fivefold increase in atom number. Pradhan *et al.*[12] developed a new technique, which used a blue detuned control laser without interacting with the cold cloud of atoms to pump the inaccessible Zeeman states into the stretched states, achieving a twofold increase in the capture rate and the same increase in the number of trapped atoms.

In this paper we describe a dual color MOT with threefold increase in the number of trapped atoms. This technique uses two sets of overlapping beams to cool and trap ^{87}Rb atoms. It does not require a dark center spot in the MOT beams, making it easier to align. It also does not need additional depumping beam for Rb. One set of the laser beams only needs to cover the tiny region of the cold atomic cloud in the MOT and can be naturally used for the further compressed MOT[13] and polarization gradient cooling.[14] Thus the technique is specially suitable for low power diode laser. This technique can be very useful in experiments where both high vacuum level and large atom number are required, such as single chamber quantum memory and BEC experiments.

2. Experimental setup

The experimental setup is described as follows. A stainless-steel vacuum chamber is pumped by a 150-L/s ion pump and Ti sublimation pump, producing a base pressure of 10^{-11} Torr (1 Torr = 1.33322 × 10^2 Pa). A rubidium getter is mounted on the top of the chamber. A 32 mm × 32 mm × 300 mm quartz glass cell is vertically mounted on the bottom of the chamber. Three pairs of orthogonal laser beams pass through the center of the glass cell to form the MOT as shown in Fig. 1(a). A pair of coils with anti-Helmholtz configuration generates a quadruple field for the MOT. The background magnetic field is compensated by three orthogonal pairs of Helmholtz coils. A charge-coupled device (CCD) camera is used for absorption imaging of the atom cloud in the trap.

A 780-nm single mode distributed feedback (DFB) laser is locked to the ^{87}Rb D2 transition line with saturated absorption spectroscopy. Two low power slave lasers, loading laser and cooling laser are used in the injection locked configuration to replace expensive high power amplifier. The detuning of the seed light is controlled by two acousto–optic modulators (AOM). The repumping laser is 3 MHz red detuned to the $F = 1$ to $F' = 2$ transition, with total power of 10 mW and a $1/e^2$ diameter of 20 mm. All the three laser frequencies with respect to the atom transitions of ^{87}Rb are shown in Fig. 1(b).

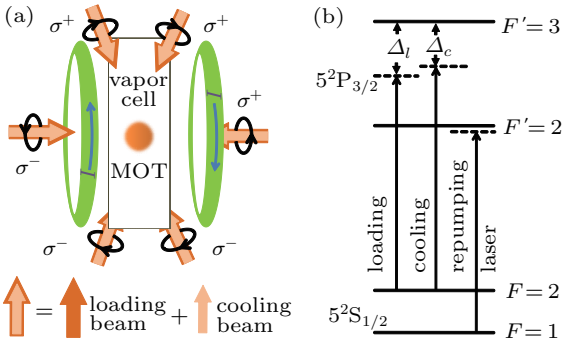


Fig. 1. (colour online) (a) Dual color MOT with overlapping cooling beams and loading beams. (b) The laser frequencies with respected to the atom transitions of ^{87}Rb. Loading laser and cooling laser are tuned $|\Delta_l|$ and $|\Delta_c|$ to the red of the $F = 2$ to $F' = 3$ trapping transition, respectively. Repumping laser is tuned 3 MHz to the red of the $F = 1$ to $F' = 2$ transition.

Loading laser, cooling laser, and repumping laser are combined and split into six beams. The six beams are then circularly polarized by quarter wave plates to obtain proper helicities for the MOT. The loading beams have total power of 80 mW and a $1/e^2$ diameter of 20 mm. The cooling beams have maximum power of 20 mW and a $1/e^2$ diameter of 12 mm. The loading beams with large diameter and high power are critical to achieve large loading rate. The cooling beams with size just covering the 2-mm cold cloud of atoms will be further used for compressed MOT and polarization gradient cooling.

In the following section, the dual color MOT with different cooling laser frequencies and intensities is investigated.

3. Results

The conventional normal MOT with only loading laser beams is optimized by varying the magnetic field gradient and the detuning of the loading beams. The optimum number of atoms is 1.8×10^7 with the magnetic field gradient of 10 Gs/cm (1 Gs = 10^{-4} T) and laser detuning Δ_l of −16 MHz. When an additional set of cooling beams with certain detuning difference is applied, the cold cloud of atoms becomes significantly larger in size and atom number.

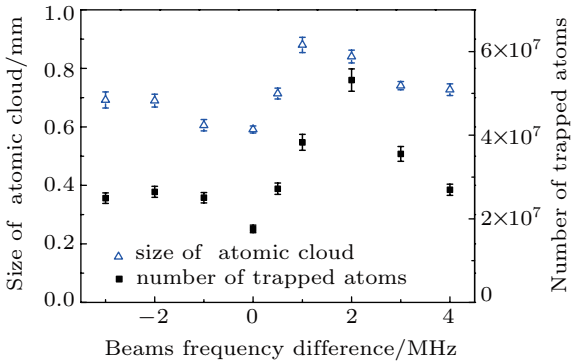


Fig. 2. (colour online) The size of atomic cloud (empty blue triangles) and the number of trapped atoms (solid black squares) in dual color MOT plotted versus the beams frequency difference $\Delta_c - \Delta_l$.

Figure 2 shows the dependence of the size of the cold cloud and the number of trapped atoms on the frequency difference between the two sets of beams. The size of the cold cloud r_0 is measured by time-of-flight (TOF) method

$$r_0 = \sqrt{r_2^2 - \frac{(r_2^2 - r_1^2)t_2^2}{t_2^2 - t_1^2}}, \tag{1}$$

where r_1 and r_2 are the $1/e$ radius by fitting of a Gaussian curve to the trap profile at the expansion time $t_1 = 3$ ms and $t_2 = 6$ ms, respectively, t_1 and t_2 are chosen to make sure that the absorption of the MOT is neither too large nor too small for the absorption imagining. The detuning of the cooling beams is scanned from -3 MHz to 4 MHz with respect to the loading beams. When $\Delta_c - \Delta_l > 0$, it is called blue detuning. While $\Delta_c - \Delta_l < 0$, it is called red detuning. In Fig. 2 the smallest size of atomic cloud is 0.59 mm at 0 MHz detuning. The size increases slightly with red detuning. It increases much faster with blue detuning until reaching the maximum size of 0.9 mm at 1-MHz blue detuning. It is found that the trend of the atom number and the trend of the size agree with each other very well. The minimum atom number is 1.7×10^7 at 0 MHz detuning and the maximum one is increased by a factor of 3 to 5.3×10^7 at 2-MHz blue detuning. The volume of the cold cloud is proportional to the cube of the size and the maximum volume is 3.3 times larger than the minimum one. It is not clear why small detuning change causes large cloud volume change. We suspect certain interference pattern and dipole force could be the reason. Figure 3 shows the loading process of the normal MOT and the dual color MOT in which the frequency of the cooling beams is 2-MHz blue detuned to the loading beams. The slope of the loading curve at the beginning of the loading process decides the loading rate R_f. From the curve we find that the normal MOT and the dual color MOT have the same loading rate. This is expected because the cooling beams have much smaller size than the loading beams. The cooling beams contribute negligibly to the loading rate comparing to the loading beams. As the loading process goes on the normal MOT reach the saturation around 30 seconds with the number of trapped atoms of 1.8×10^7. But the dual color MOT continues to load atoms until 90 seconds with the saturated atom number of 5.3×10^7. The loading process measurement clearly shows the light induced loss in dual color MOT has been reduced significantly.

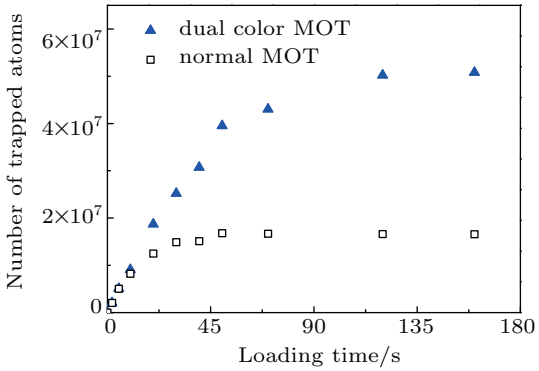


Fig. 3. (colour online) Loading process measured by absorption imaging in dual color MOT with 2-MHz blue detuning (solid blue triangles) and normal MOT (empty black squares).

The following theory can be used to explain the relationship between the atom number and the volume of cold cloud. The loading process is described by equation[6]

$$\mathrm{d}N/\mathrm{d}t = R_f - \gamma N - \beta n^2 V, \tag{2}$$

where N is the trapped atom number, γN is the loss due to the collisions with the background gas in the vacuum chamber, n is the density of trapped atoms, V is the volume of the cold atomic cloud and $\beta n^2 V$ is the light induced collisional loss, due to two dominant mechanisms: fine structure changing collisions and radiative redistribution.[15,16] In a fine-structure collision process, the atoms gain kinetic energy equal to the potential between the fine structure states. In a radiative redistribution process, the atoms gain kinetic energy from the attractive interaction between the excited state and the ground state. Kinetic energy gained from both mechanism are more than enough to eject the two atoms from the MOT.

In the steady state we have $\mathrm{d}N/\mathrm{d}t = 0$. The last term can be rewritten by $\beta N^2/V$. Thus

$$R_f - \gamma N - \beta N^2/V = 0. \tag{3}$$

γ is independent of the volume of atomic cloud. Considering that the background vapor pressure is very low, γN is negligible. R_f is constant in both normal MOT and dual color MOT. So approximately we have $N \propto V^{1/2}$. Indeed we find the number of trapped atoms in the dual color MOT increases with the volume of trapped atomic cloud and the scale generally agrees. There are a few points not scaling very well, we suspect the light induced loss rate β varies with different cooling laser detuning. This could also be the reason why the maximum number of MOT appears at 2-MHz blue detuning instead of 1-MHz blue detuning where the MOT volume reaches the maximum.

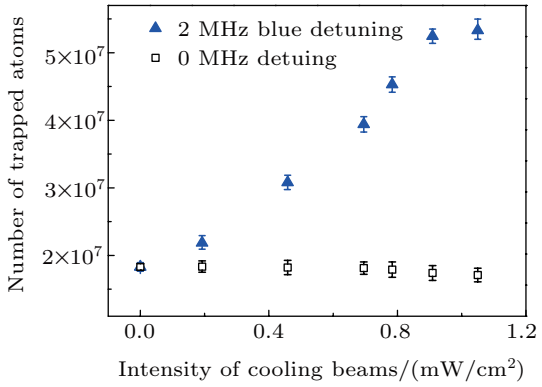


Fig. 4. (colour online) Number of trapped atoms in dual color MOT at 2-MHz blue detuning (solid blue triangles) and at 0 MHz detuning (empty black squares) plotted against the intensity of cooling beams.

To find out the cooling beams intensity needed for the dual color MOT to trap more atoms, we vary the intensity of cooling beams at 2-MHz blue detuning and 0 MHz detuning, as shown in Fig. 4. At 0 MHz detuning there is no change of the MOT size and the saturated MOT numbers are almost the same. The slight decrease of the saturated number is due to the increase of laser intensity that gives rise to bigger light induced loss. For the 2-MHz case, as the intensity of cooling beams increases the size and the MOT atom number increases simultaneously. This effect saturates at 0.9 mW/cm^2.

4. Conclusions

In summary, we have demonstrated a dual color MOT which uses two sets of overlapping laser beams to cool and trap atoms. We observe sensitive dependence of the cold cloud volume on laser detunings in the dual color MOT. The number of trapped atoms can be up to three times larger than that in the normal MOT. Our experiment discovers that the increase of the atom number is due to the reduced light induced loss. Unlike the dark SPOT technique, the dual color MOT achieves lower light induced loss from lower MOT density. Compared to the popular dark SPOT technique, our approach is technically simpler and more suitable to low power laser systems which can be easily achieved from a low cost injection locked diode laser. The technique is successfully used in our single chamber BEC experiment,[17] and is also useful in experiments where both ultra high vacuum level and large atom number are required.

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