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Light-induced evaporative cooling in a magneto-optical trap*

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This paper presents an experimental demonstration of light-induced evaporative cooling in a magneto-optical trap. An additional laser is used to interact with atoms at the edge of the atomic cloud in the trap. These atoms get an additional force and evaporated away from the trap by both the magnetic field and laser fields. The remaining atoms have lower kinetic energy and thus are cooled. It reports the measurements on the temperature and atomic number after the evaporative cooling with different parameters including the distance between the laser and the centre of the atomic cloud, the detuning, the intensity. The results show that the light-induced evaporative cooling is a way to generate an ultra-cold atom source.

Keywords: evaporative cooling, magneto-optical trap
PACC: 3280, 3280P, 4250, 4250V

1. Introduction

The magneto-optical trap(MOT) is usually used as a cooled atomic source since it was invented.[1] It is a simple and an extremely powerful way in many physics experiments, such as atomic fountain clocks, atom optics, collision physics and Bose-Einstein condensation(BEC).[2] The temperature of cold atoms generated from the MOT is normally about a few hundreds μK, above Doppler limit. In order to get even lower temperature, one has to imply some sub-Doppler cooling techniques, for instance, polarization gradient cooling,[3] velocity selective coherent population trapping,[4,5] evaporative cooling[6] and etc. Evaporative cooling is now used widely in realizing BEC, and it was suggested as an efficient way to cool trapped atoms[7,8] soon after the first realization of the magnetic trapping of neutral atoms.[9] Evaporative cooling uses a radiation field to transfer atoms from a trapped to an untrapped state in an energy-selective way.[10] One of the most widely used radiation fields is radio frequency (RF) electro-magnetic field.[11] The RF evaporative cooling can also increase phase space density, and thus it becomes the key technique to achieve BEC in a magnetic trap.[12]

Evaporative cooling can also be realized by the collision between a surface and the atoms with higher energy. Normally, in a magnetic trap, atoms located at the edge area of the atomic cloud have higher energy than those at the central part, thus removing hot atoms at the edge area leads to decrease mean energy of remaining atoms in the trap. By collision between a surface and the edge atoms, the edge atoms can be removed from the trap, thus the temperature of the remaining atoms in the trap decreases. This position-selective evaporative cooling is especially useful for a micro-magnetic trap,[13] and with which even BEC can be realized.[14]

In fact, position-selective evaporative cooling in a magnetic trap can also be realized by using a laser beam. The laser beam is used to pump atoms at the edge of the atomic cloud in a magnetic trap into untrapped states, then those hot atoms escape out of the trap. The only experimental demonstration of light-induced evaporative (LIE) cooling was presented in a proof-of-principle in Amsterdam in 1993 with atomic hydrogen.[15]

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2. Experiment

In this paper, we demonstrate the first LIE cooling of ^{87}Rb atoms in a six-beam MOT below Doppler limit, which is 143μK for 780nm transition. Different from previous related experiments which conducted position-selective evaporative cooling in a magnetic trap either by surface or laser beam, our experiment uses light-induced position-selective evaporative cooling of atoms directly in a MOT. The MOT has capability to both cool and capture atoms from the background of atomic gas, while a magnetic trap can only store cooled atoms. For ^{87}Rb, the MOT laser beams with σ^+ and σ^- configuration are tuned at red to couple $|F = 2\rangle$ with $|F' = 3\rangle$. The atoms in the MOT encounter a force toward the centre of the MOT from three pairs of counter propagating laser beams. In order to perform position-selective evaporative cooling in a MOT, an additional laser beam with linear polarization is used to interact with the atoms at the edge of the atomic cloud. This additional laser, or LIE laser, generates additional force on atoms along the propagation direction of the LIE laser, in addition to the force from the MOT beams. Combining the MOT force and LIE force gives the total force on the atoms which deviates from the direction towards the MOT centre, and those atoms will escape from the MOT. Thus the MOT with a position-selective LIE laser beam can cool and capture only cold atoms, the temperature and number of the remaining atoms in the MOT depend on the position of the LIE beam.

Our experiment is different from other evaporative cooling in a magnetic trap. For example, in the RF evaporative cooling, the atoms in a magnetic trap is a close system and during evaporative cooling the number of atoms would only reduce. In our system, the evaporative cooling and the MOT work at the same time. While the LIE laser beam forces the hot atoms out of the MOT, the MOT beams keep on cooling and trapping atoms in the MOT at same time. Before adding the LIE laser, the temperature of the cold atoms in MOT is 185μK and the number is 2×10^7. Then we use this method to decrease the atomic temperature to 55 μK and the number to 3.4×10^6.

The experimental scheme is shown in Fig.1. It is a typical six beam MOT setup with an additional laser beam for the LIE cooling. The detuning of the MOT laser beams is -18MHz and the intensity of each beam is $s = 2$ ($s = I/I_s$, I is the laser intensity and I_s is the saturation intensity of atoms). Two of the MOT laser beams are counter propagating in the direction of z axis and the other 4 beams are 45° oblique pairwise counter-propagating. The LIE laser, with the diameter of 2 mm, is cut off into half as shown in Fig.2. In the figure, d is the distance from the LIE laser to the centre of the cold atom cloud. We carefully adjust the optics of the LIE beam in order to avoid the diffraction fringe when it arrived at the cold atom cloud.

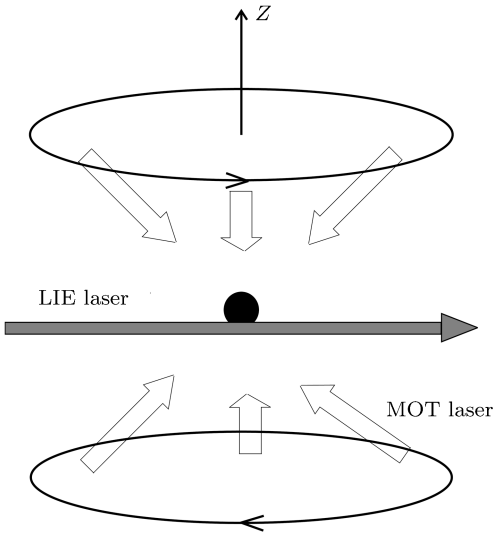


Fig.1. The LIE cooling experimental scheme. The MOT laser is the cooling laser and the LIE laser is the additional laser for evaporative cooling.

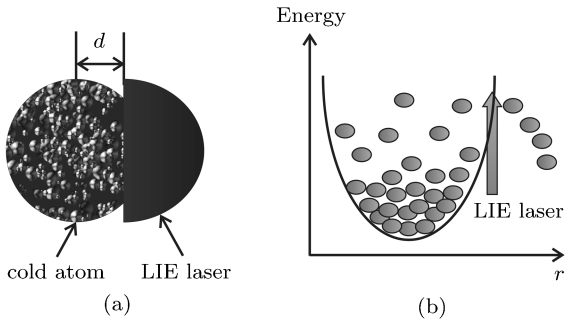


Fig.2. (a) The LIE laser beam at the MOT, d is the distance from the LIE laser to the centre of the cold atom cloud, d can be adjusted at 0.01 mm step. (b) Schematic show of the LIE cooling in a MOT.

We use the time-of-flight method to measure cold atoms. The MOT collects about 2×10^7 ^{87}Rb atoms with temperature 185 μK in a high-vacuum system. The atomic cloud has a diameter about 2.4 mm. The cooling laser of the MOT is red-shift of the transition between the ground state $|F = 2\rangle$ and the excited state $|F' = 3\rangle$. Then we turn on the LIE laser, whose frequency detuning is -3 MHz from resonance and intensity is $s = 3$. The interaction time of LIE laser

and the MOT beams with atoms is $T = 2400\,\text{ms}$. We measure the temperature and the number of the cold atoms in MOT at different distance d as shown in Fig.3. We can see that the number and the temperature of cold atoms are reduced when the LIE laser is close to the centre of the atom cloud. When the LIE laser is close to the cold atomic cloud, it optically forces more atoms out of the MOT. In the other words, the potential of the MOT is reduced. We obtained lowest temperature at $55\,\mu\text{K}$ when $d = 0.7\,\text{mm}$. When the LIE beam is even more close to the centre, the atom number keeps dropping, but the temperature becomes higher. The reason is that when the LIE beam has already cut the central part of the atomic cloud, it will heat the atoms. The remaining atoms are the balance between heating by LIE beam and cooling by the MOT beams. Similar phenomena also happens in the RF evaporative cooling.

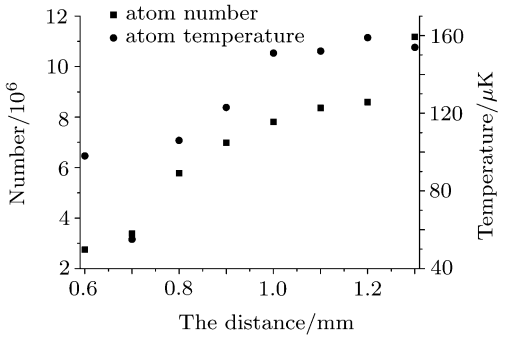


Fig.3. The number and the temperature of cold atoms vs distance d. Here $s = 3$, $\delta = -3\,\text{MHz}$, $T = 2400\,\text{ms}$.

At a fixed distance d, the parameters of the LIE laser decide the process of the evaporation cooling. We can obtain the force of LIE laser on the atoms from the optical Bloch equation,[2]

$$F = \frac{\hbar k s(\gamma/2)}{1 + s + (2\delta/\gamma)^2}, \tag{1}$$

where $\hbar$ is the Planck's constant, k is the wave vector of laser, γ is the natural width of atoms and δ is the detuning of the laser. Obviously, the larger the force, the better the LIE cooling. We measured the temperature and number of cold atoms vs the intensity of the LIE laser at $d = 0.9\,\text{mm}$ and $\delta = -3\,\text{MHz}$ as shown in Fig.4. The number of atoms keeps falling down when the intensity of LIE laser increases. The temperature is firstly reduced as Eq.(1) indicates, but begin to increase at the point of laser intensity increased to $s = 5.4$. The increase of the temperature is caused by the heating of the high intensity of LIE laser.

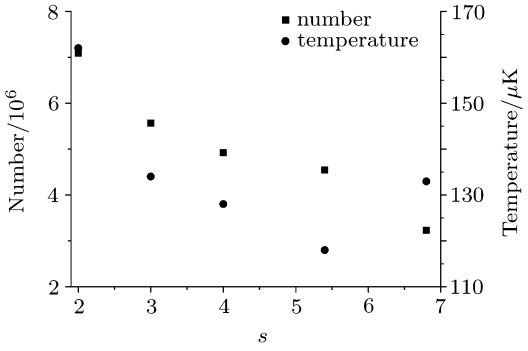


Fig.4. The number and the temperature of cold atoms vs the saturation parameter s of LIE laser. Here, $d = 0.9\,\text{mm}$, $\delta = -3\,\text{MHz}$, $T = 2400\,\text{ms}$.

The frequency of LIE laser can also affect the evaporative cooling. We fix d at 0.9 mm and intensity of the LIE laser ($s = 3$), then change the frequency of LIE laser. The result is shown in the Fig.5. From Eq.(1), the optical pumping efficiency is the largest when detuning $\delta = 0$, which is proved by the experimental results in Fig.5.

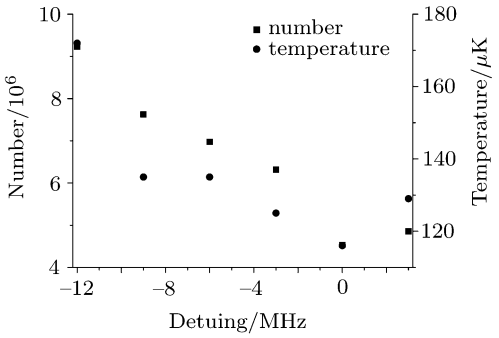


Fig.5. The number and the temperature of cold atoms vs the detuning of LIE laser. Here $s = 3$, $d = 0.9\,\text{mm}$, $T = 2400\,\text{ms}$.

The interaction time between the LIE laser and cold atoms is also an important element of the evaporative cooling. We change the interaction time and measured the effect of the evaporative cooling under the condition $d = 0.9\,\text{mm}$, $s = 3$ and $\delta = -3\,\text{MHz}$. Figure 6 shows the result. We can see that there is almost no cooling effect when the interaction time was as short as 100ms. With increasing the interaction time, the number and the temperature begin to reduce, as far as the time reached the point 1500ms. Then the atom temperature became some kind of hotter. It shows that the too long interaction time would cause heating of the cold atoms. The number changes

a little near the point 1500 ms.

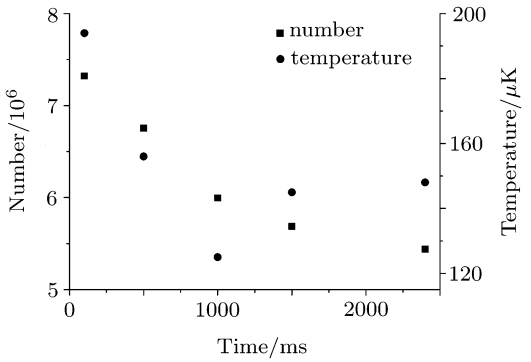


Fig.6. The number and the temperature of cold atoms vs the interaction time T. Here, $s = 3$, $d = 0.7$ mm, $\delta = -3$ MHz.

3. Conclusion

In conclusion, we have performed sub-Doppler LIE cooling in MOT. We use this method to efficiently cool the atom from 185 μK to 55 μK, the atomic number drops one degree. We studied the relation of the intensity, the detuning and the interaction time of LIE laser with the effect of the evaporative cooling. The experimental results are in good agreement with the theoretical prediction.

Our experimental results confirm that the LIE cooling method can be used as a way to get sub-Doppler temperature in a MOT. And we will optimize our experimental parameters to reduce the temperature of cold atom.

References

[1] Raab E L, Prentiss M, Cable A, Chu S and Pritchard D E 1987 *Phys. Rev. Lett.* **59** 2631
[2] Metcalf H and van der Straten P 1999 *Laser Cooling and Trapping* (New York: Springer)
[3] Dalibard J and Cohen-Tannoudji C 1989 *J. Opt. Soc. Am.* B **6** 2023
[4] Aspect A, Arimondo E, Kaiser R, Vansteenkiste N and Cohen-Tannoudji C 1988 *Phys. Rev. Lett.* **61** 826
[5] Liu L, Bellanca M J and Metcalf H 2002 *Phys. Rev.* A **65** 043401
[6] Anderson M H, Ensher J R, Matthews M R, Wieman C E and Cornell E A 1995 *Science* **269** 198
[7] Hess H F 1986 *Phys. Rev.* B **34** 3467
[8] Yin J P, Gao W J, Wang H F, Long Q and Wang Y Z 2002 *Chin. Phys.* **11** 1157
[9] Migdall A L, Prodan J V, Phillips W D, Bergeman T H and Metcalf H J 1985 *Phys. Rev. Lett.* **54** 2596
[10] Ketterle W and van Druten N J 1996 *Adv. At. Mol. Opt. Phys.* **37** 181
[11] Davis K B, Mewes M O, Joffe M A, Andrews M R and Ketterle W 1995 *Phys. Rev. Lett.* **74** 5202
[12] Davis K B, Mewes M O, Andrews M R, Druten N J, Durfee D S, Kurn D M and Ketterle W 1995 *Phys. Rev. Lett.* **75** 3969
[13] Reichel J, Hänsel W and Hänsch 1999 *Phys. Rev. Lett.* **83** 3398
[14] Harber D M, McGuirk J M, Obrecht J M and Cornell E A 2003 *J. Low Temp. Phys.* **133** 229
[15] Setija I D, Werij C, Luiten O J, Reynolds M W, Hijmans T W and Walraven M 1993 *Phys. Rev. Lett.* **70** 2257