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# Cooling Atoms Below 100 $^{1}$K

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We capture $^{87}$Rb atoms from room-temperature background vapor with a magneto-optical trap (MOT). The temperature of the atoms in the MOT is 320 $\mu$K as the result of Doppler cooling. We further employ polarization gradient cooling to lower atom temperature. The factors that can affect the performance of polarization gradient cooling have been systematically studied. An atom temperature of 75 $\mu$K has been reached with the optimized conditions. Temperatures are measured by the release and recapture method and the time of flight method. Such cold atoms are ready for the evaporative cooling which will finally realize the Bose-Einstein condensation.

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## I. Introduction

Laser cooling is an efficient technique to obtain dense and ultracold atoms. Cold atoms not only provide the opportunities of studying quantum phenomena at long de Broglie wavelengths, but also are promising for the scientific applications that require slow velocity or low kinetic energy of atoms. Highlights of cold atom researches include Bose-Einstein condensation (BEC), atom interferometry, atom optics, ultracold atom-atom and atom-surface collisions, atomic fountain clock, photoassociation spectroscopy, and high precision spectroscopy.

Trapping laser-cooled atoms with a magneto-optical trap (MOT) $[1, 2]$ is the starting point of our undergoing research of realizing Bose-Einstein condensation (BEC). We have captured $^{87}$Rb atoms from room-temperature background vapor with a MOT. The temperature of the trapped $^{87}$Rb atoms in our MOT is 320 $\mu$K due to Doppler cooling of laser light. The balance between Doppler cooling and the heating caused by spontaneous emissions of atoms determines the temperature of the atoms in the MOT. Such temperature is much too high to achieve the transition condition of BEC. In order to further lower the temperature of the atoms, we employed the polarization gradient cooling right after the completion of the MOT capturing and Doppler cooling process. The theories of Doppler cooling and polarization gradient cooling have been given in Ref. [3-5]. In this article, we present our experimental study of polarization gradient cooling and demonstrate the production of 75-$\mu$K atoms.

We use the standard MOT setup to collect cold $^{87}$Rb atoms in an ultrahigh vacuum cell of a pressure of $10^{i\ 11}$ torr [2]. The MOT is formed with a spherical quadrupole magnetic field, 6 trapping laser beams, and a repumping laser beam. In our MOT, trapping laser is tuned to 15 MHz below the $5S_{1/2}, F = 2 \rightarrow 5P_{3/2}, F^{0} = 3$ transition frequency of $^{87}$Rb atoms or the *red-detuning* of the trapping laser is 15 MHz. The total power of the trapping laser is about 35 mW and each of 6 trapping beams has the $1/e$ diameter of 12 mm. The axial gradient of quadrupole magnetic field is 15 G/cm. Both the trapping laser frequency and the magnetic field gradient are at the optimum values for the maximum number of the trapped atoms. Since atoms in $5S_{1/2}, F = 1$ ground state can no longer interact with the trapping laser field, the repumping beam prevents atoms from staying in $5S_{1/2}, F = 1$ ground state. Under the above condition of the MOT, we typically capture $10^7$ $^{87}$Rb atoms with a temperature of 320±40 $\mu$K. The measurements of this temperature are shown in Fig. 1(a) and (c) and the measurement methods will be described later. The number of the trapped atoms reaches the steady-state value of $10^7$ within a 100-s period, which is the collection time of the MOT.

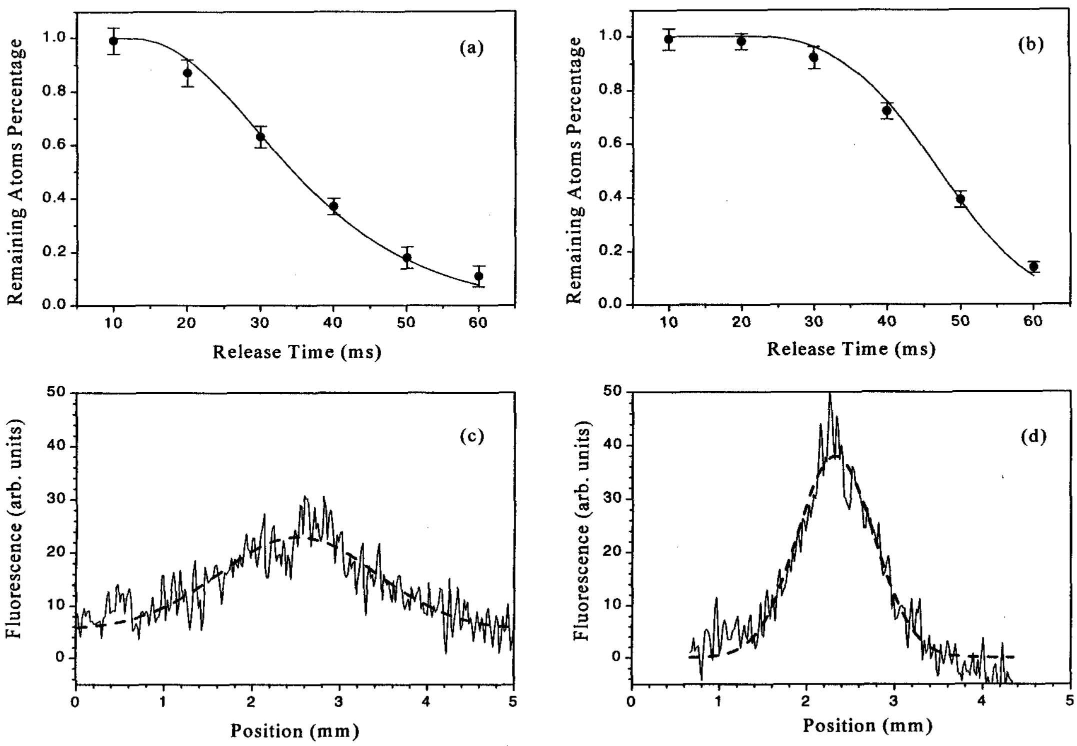


FIG. 1. (a) and (b) are the R&R measurements, where circular points are the experimental data and solid curves are the results of the theoretical calculation. (c) and (d) are the TOF measurements, where solid curves are the experimental data and dashed curves are the results of the theoretical calculation. (a) and (c) are the temperature measurements before employing polarization gradient cooling under the same experimental condition. (b) and (d) are the temperature measurements after employing polarization gradient cooling under the same experimental condition. The theoretical curves correspond to 320±40 $\mu$K in (a), 80±10 $\mu$K in (b), 320±10 $\mu$K in (c), and 66±5 $\mu$K in (d). The temperature uncertainties include the errors due to the fitting and the fluctuations between experimental runs.

To perform polarization gradient cooling, we need to rapidly shift the frequency of the trapping laser to a larger red-detuning. For the rapid and precise shift of the trapping laser frequency, the trapping laser is injection-locked by another laser (the master laser) [6]. The frequency of the master laser is fixed by an electronic feedback circuit with the method of saturated absorption spectroscopy. Light from the master laser passes through an acousto-optic modulator (AOM) in the double-pass configuration [7] and is then injected into the trapping laser. The frequency of the trapping laser is locked to the frequency of the injection beam. By varying the RF frequency of the AOM, the frequency of the trapping laser can be changed precisely and rapidly. The double-pass configuration can keep the optical alignment of the injection unchanged, when the RF frequency of the AOM is varied. With this arrangement, the absolute frequency of the trapping laser is always precise within 1 MHz and can be shifted by an amount as large as 50 MHz during a time less than 100 $\mu$s. Such fast and precisely varying the trapping laser frequency is critical to the success of polarization gradient cooling.

The experimental procedure of polarization gradient cooling starts, when the number of the trapped atoms in the MOT reaches the steady-state value. We switch off the quadrupole magnetic field and the switching-off time is less than 500 $\mu$s. Simultaneously, the frequency of the trapping laser is quickly shifted to a larger red-detuning for polarization gradient cooling. During polarization gradient cooling, the quadrupole magnetic field is absent, the frequency of the trapping laser is changed, and the repumping laser beam is intact. The polarization gradient cooling lasts for a certain time. We then measure the temperature of the atoms with two methods: the release and recapture (R&R) [8] and the time of flight (TOF) [9]. The agreement between the two temperatures determined by the R&R and the TOF methods are satisfactory. Any temperature reported in this article is the average of the measurement results of these two methods.

In the R&R method, we turn off the trapping laser beams after polarization gradient cooling. Atoms will escape away from the trapping region. After a period (release time), we turn on the trapping laser beams with the 15-MHz red-detuning and the quadrupole magnetic field and recapture the escaping atoms with the MOT. When the MOT is back on for a 50-ms recapture time, the number of the recaptured atoms is immediately measured by collecting the fluorescence emitted from the atoms. Since this 50-ms recapture time is much shorter than the collection time of the MOT, the number of the atoms captured from the room-temperature background vapor during this 50 ms is negligible. Atoms with a higher temperature escape away from the trapping region quickly and the number of the recaptured atoms decays fast with the increasing release time. On the other hand, the number of the recaptured atoms decays slowly with the increasing release time for atoms with a lower temperature. The temperature of the atoms after polarization gradient cooling is determined by fitting the R&R data with the result of the theoretical calculation. In the theoretical calculation, atoms are initially with the Maxwell-Boltzmann velocity distribution and escape ballistically during the release time. Furthermore, The spatial distribution of atoms before the release time and the effect of the gravity are taken into account in the theoretical calculation. Examples of R&R data and theoretical curves are shown in Fig. 1(a) and (b). When this method is used to measure the temperature of atoms before polarization gradient cooling, we shut off the trapping laser beams and the magnetic field of the MOT before the release time and the remaining procedures are the same.

When measuring the atom temperature with the TOF method, we turn off the trapping laser beams after polarization gradient cooling. Atoms move freely for a 5-ms flight time. Then, the trapping laser beams with the 15-MHz red-detuning are switched on and an image of the atom cloud is taken with a CCD camera at an exposure time of 500 $\mu$s. Atoms with a higher temperature will spread over a larger region in the image and atoms with a lower temperature will distribute within a smaller region in the image. By fitting the spatial distribution of the atoms with the result of the theoretical calculation, the temperature of the atoms after polarization is determined. The considerations in the theoretical calculation of the R&R method are all included in that of the TOF method. Theoretically, the spatial distribution of the atoms has a Gaussian profile. Examples of TOF data and theoretical curves are shown in Fig. 1(c) and (d). When measuring the temperature of atoms before polarization gradient cooling with this method, we shut off the trapping laser beams and the magnetic field of the MOT right before the flight time and the remaining procedures are the same.

We have investigated the dependence of the atom temperature on the polarization gradient cooling time. Fig. 2(a) shows atom temperature does not vary much for the cooling time longer than 1 ms. The dependence in Fig. 2(a) is quite universal for all the red-detunings of the trapping laser and all the other experimental conditions in polarization gradient cooling. Long cooling time causes the loss of atoms, since no trapping force exists during polarization gradient cooling. We typically use a 3-ms cooling time for polarization gradient cooling. For this cooling time, no atoms will be lost during polarization gradient cooling. A polarization gradient cooling time shorter than 3 ms will result in slightly higher atom temperature.

Fig. 2(b) demonstrates that atom temperatures vary with red-detunings of the trapping laser in polarization gradient cooling. There exists an optimum red-detuning of the trapping laser such that the corresponding temperature is the lowest. This optimum red-detuning depends on the intensity of the trapping laser. When the intensity of the trapping laser is higher, the optimum red-detuning shifts to a larger value. In our experimental condition, the optimum red-detuning of the trapping laser is around 50 MHz in polarization gradient cooling.

The existence of the magnetic field degrades the lowest attainable temperature of polarization gradient cooling. Although the quadrupole magnetic field of the MOT is turn off during polarization gradient cooling, the stray magnetic field in the environment keeps the lowest attainable temperature above 170 $\mu$K. We zero the stray magnetic field with the compensation coils. Consequently, the atom temperature after polarization gradient cooling is improved. Fig. 1(b) and

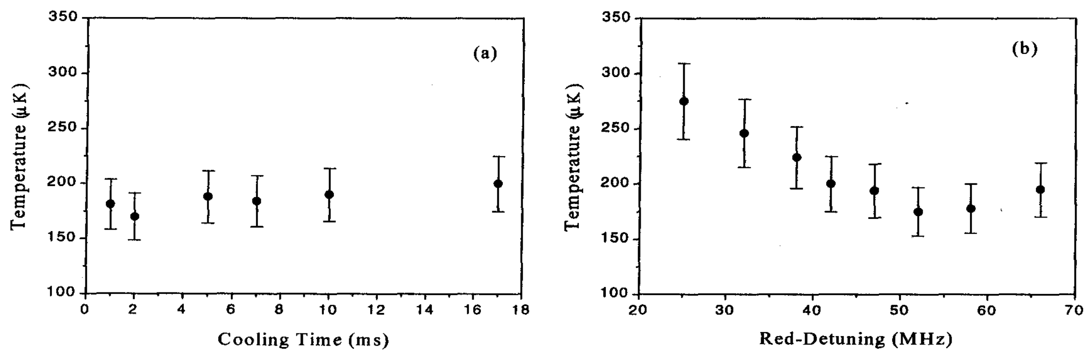


FIG. 2. (a) Atom temperatures versus polarization gradient cooling times at a constant red-detuning of 50 MHz. (b) Atom temperatures versus red-detunings of polarization gradient cooling at a constant cooling time of 3 ms.

(d) show the R&R data and the TOF data of 75($\pm$15)-$\mu$K atoms, after the stray magnetic field is zeroed and the polarization gradient cooling under the optimum conditions is performed.

In conclusion, the temperature of $^{87}$Rb atoms is initially at 320 $\mu$K and then reduced to 75-$\mu$K by performing polarization gradient cooling. Such cold atoms will be loaded into a magnetic trap for the evaporative cooling which can finally realize the Bose-Einstein condensation. This project is supported by National Science Council under the grant of NSC 88-2112-M-007-047.

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