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Realization of High Optical Density Rb Magneto-optical Trap *

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We report experimental demonstration of a magneto-optical trap (MOT) of Rb atoms with a high optical density. With 2.2-cm-diameter cooling laser beams, we achieve an optical density of nearly 11 for about 2.6×10^{10} trapped Rb atoms with the beam intensity of about 6.6 mW/cm^2 per beam. The temperature of the cold atoms is about 250 μK. Furthermore, by ramping the magnetic field gradient from 8 G/cm to about 20 G/cm, the atomic cloud in the MOT is compressed and the optical density is up to 16.

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Since the first experimental realization of a magneto-optical trap (MOT) was demonstrated by Raab *et al.*,[1] the magneto-optical trap approach has been greatly developed and proven to be an effective way to cool and trap atoms.[2−5] Such cold atoms can cancel the Doppler effect and provide a desired sample to observe ultrahigh resolution spectroscopy,[6] perform atomic fountain clocks,[7] realize Bose–Einstein condensation,[8−10] and demonstrate atomic memory.[11] In such experimental studies, the large number of trapped atoms is important in studies involving cold collisions[12] and reaching the Bose–Einstein condensation (BEC).[8−10]

The dependence of the number of trapped atoms on the operating parameters of the MOT,[13] such as the background density, the magnetic field gradient, the cooling laser diameters, intensity and detuning, has been extensively studied.[13−16] The results have shown that the number of trapped atoms is independent of the background density n,[13] while it strongly depends on the magnetic field gradient, the cooling laser diameters and intensity. Several groups experimentally obtained a large number trapped atoms and high atomic density by improving MOT systems.[11−13] Ketterle *et al.*[14] trapped more than 10^{10} sodium atoms by using a dark spontaneous-force optical trap. By extending diameters of cooling laser beams (4 cm), Gibble *et al.*[13] achieved a large number of trapped Cs atoms (3.6×10^{10}) corresponding to an atomic density of 3.6×10^{10}/cm^3. Recently, an experiment of frequency mixing using electromagnetically induced transparency (EIT) in cold Rb atoms was demonstrated, in which a cold cloud with 5×10^8 Rb atoms was trapped in a dark MOT, and the optical density of the sample was up to about 13.[17] Recent years, generation of entanglement between atoms and photon pairs in a cloud of cold Rb atoms has been reported.[11,17−20] In these experiments, an important key is the retrieval efficiency of atomic memory, which depends on the number of trapped atoms. A large number of trapped atoms will provide high optical density to lead to the retrieve light coherently to emit into a smaller cone angle.[21] One can achieve a higher retrieval efficiency of atomic memory. Thus, a sample of cold atoms with high optical density is required in the experiment for quantum memory.

In this Letter, we report an experiment demonstration of a MOT of Rb atoms with high optical density. With 2.2-cm-diameter laser beams, a nearly 8 G/cm magnetic field gradient, a 23-MHz detuning below the transition of $5S_{1/2}$, $F = 2$ to $5P_{3/2}$, $F' = 3$, we measured the dependence of the optical density and the number of trapped Rb atoms on the intensity per beam. An optical density of about 11 and nearly 2.6×10^{10} trapped atoms were achieved for a trapping intensity in each beam in intensity of about 6.6 mW/cm^2, and the temperature of the cold atoms is about 250 μK. Furthermore, by ramping the magnetic field gradient from 8 G/cm to 20 G/cm, the atomic cloud in MOT was compressed and the optical density was up to 16.

The dependence of the number of trapped atoms on the MOT parameters was theoretically and experimentally studied.[16] These works pointed out that the trapped atoms in the MOT could reach a large number for about 8 G/cm magnetic field gradient, and the detuning of nearly 3Γ ($\Gamma = 2\pi \times 6$ MHz is the decay rate of upper level).[16] Based on the steady-state rate equation $\partial N/\partial t = R - \Gamma_C N = 0$, Ref. [13] gave a simple relation of the number to relay on the diameter and cooling beam intensity in the magneto-optical

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trap. The steady-state number of atoms can be expressed by

$$N = \frac{R}{\Gamma_C} = \frac{d^2}{\sigma}\Big(\frac{v_C}{u}\Big)^4,$$

where $R \approx \frac{nd^2 v_C^4}{u^3}$ is the loading rate, $\Gamma_C \approx n\sigma u$ is the loss rate, σ is the collision cross section, v_C is the capture velocity, d is the cooling laser beam diameter, n is the background Rb density, and $u = 240\,\mathrm{m/s}$ is the most probable speed. In the interaction region of the cooling laser beams, when an atom scatters one photon, the velocity of the atom will decrease by a recoil velocity v_{rc} (5.88 mm/s) for Rb atoms. When it scatters r photons per second, the deceleration of the atoms is $r \times v_{rc}$. For each cooling laser beam with intensity I_c, the scatting rate $r = p\cdot\Gamma/[2(1+p)]$. Here $p = (I_C/I_s)/(1+4\Delta^2/\Gamma^2)$ is the saturation parameter, I_s is the atomic saturation intensity (3.576 mW/cm^2 for D_2 line of Rb atoms), and Δ is the laser detuning. $\Gamma = 2\pi \times 6\,\mathrm{MHz}$ is the decay rate of the upper level. Thus, the distance required to stop an atom of velocity is $d = v_C^2/2rv_{rc}$. Hence, the number of trapped atoms N can be rewritten as

$$\begin{aligned} N &= \frac{d^2}{\sigma}\frac{1}{u^4}(d2rv_{rc})^2 \\ &= \frac{d^4}{\sigma}\frac{1}{u^4}\Big[\Big(\frac{I_C}{I_s}\Big)\Big(\frac{I_C}{I_s}+1+\frac{4\Delta^2}{\gamma_n^2}\Big)^{-1}v_{rc}\Gamma\Big]^2, \end{aligned}$$

The above relation shows that one can achieve a large number of trapped atoms by increasing the cooling laser beam diameter d, which is a simple method and is used by us in the presented work.

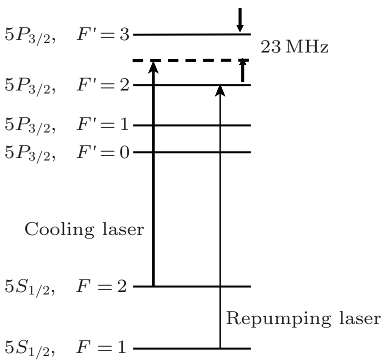

Fig. 1. Relevant energy diagram of the D_2 line of the ^{87}Rb atoms.

In our experiment, an external-cavity diode laser (Toptica, DL100) with narrow bandwidth (2 MHz) and a power of 80 mW was divided into three laser beams of nearly equal power. The power of each laser beam was then amplified by injecting into a taper-amplified laser diode system up to 600 mW. After beam shaping, frequency shifting by an acousto-optic modulator (AOM) and spatial filtering by a single-mode fibre, the power of each cooling laser beam changed into about 60 mW. Then, each cooling beam was split into two beams with opposite helicity and counter-propagate through a Rb cell. The three orthogonal pairs of laser beams overlapped in the zero point of the magnetic field created by a pair of coils in the anti-Helmholtz configuration thus formed a MOT system which is similar to that previously used by other researchers.[22−24] The Rb cell is a 4 cm-wide 4-cm-thick 10.5-cm-long glass cell, which was filled with 10^{-8} Torr room-temperature Rb atoms and was placed in this zero point of the magnetic field. The diameter of each cooling laser beam is about 2.2 cm. Such a large diameter of each beam in the presented work is two times larger than that in our previous work.[25] In the present work, the cooling laser is locked to about 23 MHz detuning below the transition of $5S_{1/2}$, $F = 2$ to $5P_{3/2}$, $F' = 3$ (as shown in Fig. 1) by a saturation absorption setup. To prevent the atoms depositing to the level $5S_{1/2}$, $F = 1$, another laser with diameter of about 20 mm locked to the transition $5S_{1/2}$, $F = 1$ to $5P_{3/2}$, $F' = 2$ was used as the repumping laser, which overlapped with the z-axis cooling laser beams. The z-axis magnetically field gradient is about 8 G/cm.

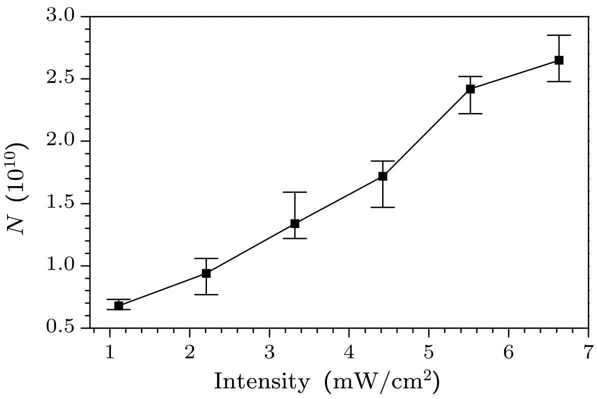

Fig. 2. Measured the number of the cold atoms as a function of the intensity per cooling laser.

To measure the cloud size, we imaged the cloud of trapped atoms from two sides with a CCD camera. The results show that the size of cloud is about $8 \times 8 \times 6\,\mathrm{mm}^3$.

By measuring the trap fluorescence power in a known solid angle, we determined the number of trapped atoms N. The measured number of trapped atoms Nas a function of the intensity per beam is shown in Fig. 2. Atom number N increases with the increasing beam intensity and a maximum $N = 2.6 \times 10^{10}$ was achieved at a highest intensity of about 6.6 mW/cm^2 per cooling laser beam.

We next measured the optical density as a function of the cooling laser intensity. The probe beam with a power of 0.3 μW (corresponding to intensity $I = 0.06\,\mathrm{mW/cm}^2$, which is much less than the saturation intensity ($I_s = 4.48\,\mathrm{mW/cm}^2$ for the D_1 line of Rb atoms) goes through the cloud atoms. When the MOT is switched off, we scanned the probe frequency across the transition $5S_{1/2}$, $F = 2$ to $5P_{1/2}$, $F' = 2$ and measured the transmission signal by a detector. The record transmission $T(\Delta_P)$ for an intensity of about 6.6 mW/cm^2 per cooling beam is shown in Fig. 3. By employing the definition $D(\Delta_P) = \alpha(\Delta_P)l = -\ln T(\Delta_P)$, where $\alpha(\Delta_P)$ is the absorption coefficient and l is the length of cloud atoms, we determine the optical density $D(\Delta_P)$.[26] From the experimental results shown in Fig. 3, we calculate that the on-resonance optical density $D(0)$ is up to about 11. Figure 4 shows the on-resonance $D(0)$ as a function of cooling beam intensity. The result shows that the optical density increases with the increasing cooling beam intensity, when the intensity per cooling beam, I_c, is more than about 4.4 mW/cm^2, this increase becomes more slow. A reason may be that the atomic density will go into saturation for large I_c.

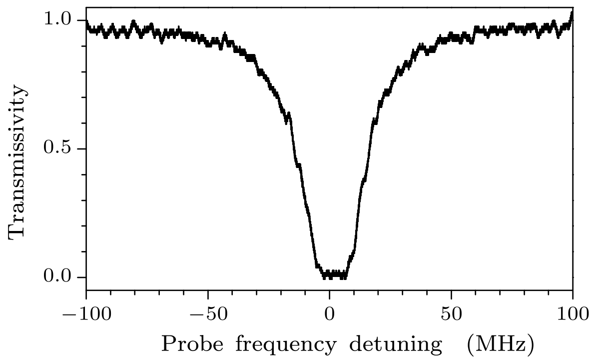

Fig. 3. Absorption spectrum of trapped Rb atoms, corresponding to optical density of 11.

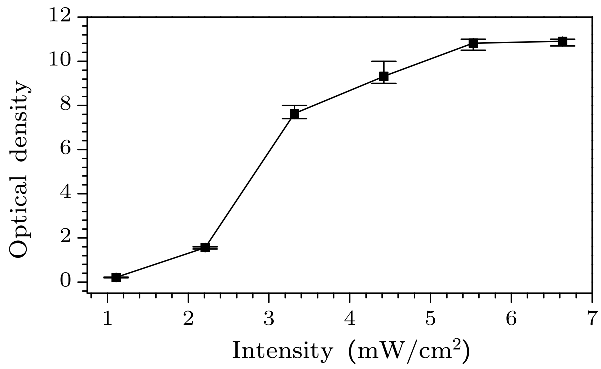

Fig. 4. Measured on-resonance optical density $D(0)$ as a function of intensity per cooling laser.

We then measured the temperature of cooling atoms by the time-of-flight (TOF) method.[27] The probe beam with a 0.8 mm diameter was set to a position 4 mm below the centre of trapped atoms in the MOT, its frequency was locked to $5S_{1/2}$, $F = 2$ to $5P_{1/2}$, $F' = 2$. When the MOT was switched off, the atomic cloud dropped due to the gravity and an absorption signal was detected when it passed the probe beam. The recorded TOF signal is shown in Fig. 5 (curve a), which corresponds to a temperature of 250 µK of the simulative calculation (curve b). It is noted that the shape of the theoretical result is not well in agreement with that of the measured TOF signal. A main reason is that the distance between the probe beam and the centre of the cloud of cold atoms is very short, which is not in agreement with the assumption of Ref. [27].

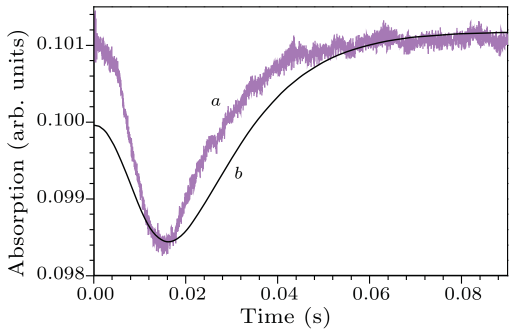

Fig. 5. Measured TOF signal (a) and the simulative calculation (b), corresponding to temperature of about 250 µK.

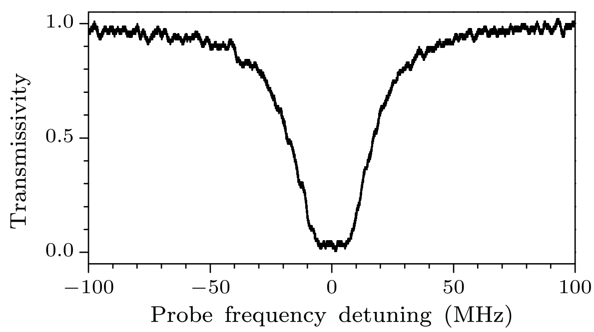

Fig. 6. Absorption spectrum of trapped Rb atoms in the compressed MOT, corresponding to optical density of about 16.

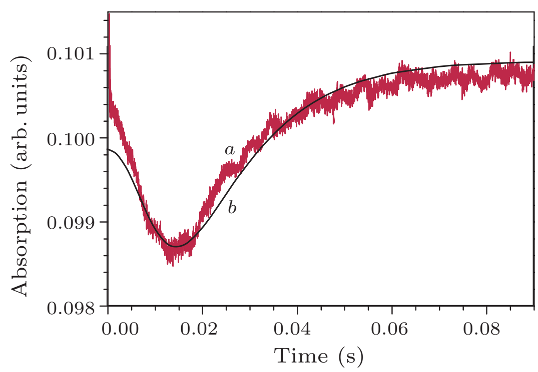

Fig. 7. Measured TOF signal (a) and the simulative calculation (b) in the compressed MOT, corresponding to temperature of about 300 µK.

We next further increased optical density by compressing the MOT. The experimental process is described as follows. In the first 4 s, we switched on the standard MOT to load about 2.6×10^{10} Rb atoms at intensity of about 6.6 mW/cm^2 per cooling beam. During the next 30 ms, the magnetic field gradient is ramped from 8 G/cm to 20 G/cm to compress the captured cloud. Then the MOT is switched off for 1 ms to probe the optical density. Figure 6 shows the transmission of the probe beams, which corresponds to an optical density of about 16, with an increase of 5 compared to the standard MOT. Figure 7 shows the measured TOF signal corresponding to a temperature of 300 μK.

In summary, we have reported an experiment demonstration of a Rb MOT with a high optical density. With 2.2-cm-diameter laser beams, a nearly 8 G/cm magnetic field gradient, a 23-MHz detuning below $5S_{1/2}$ $F = 2$ to $5P_{3/2}$ $F' = 3$, and a trapping intensity in each beam of 6.63 mW/cm^2, we realize a Rb MOT with loading about 2.6×10^{10} trapped atoms. The temperature of the cold atoms is about 250–300 μK. The measured optical density is up to about 11. Furthermore, by ramping the magnetic field gradient from 8 G/cm to about 20 G/cm, the atomic cloud in the MOT is compressed and the optical density is up to 16. Such result (optical density of about 16) is more than that achieved in Ref. [17]. Also, the dependences of the optical densities and the number of trapped Rb atoms on the cooling beam intensity are presented, which has not been reported before to our knowledge. The presented MOT system can load a large number of Rb atoms, and the measured dependences of the optical density on the cooling beam intensity may be helpful for designing a Rb MOT to carry out experimental investigations on quantum memory.[11]

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