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Laser cooling of rubidium atoms from background vapor in diffuse light

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In this paper we describe an experiment on laser cooling of ^{87}Rb atoms directly from a vapor background in diffuse light. Diffuse light is produced in a ceramic integrating sphere by multiple scattering of two laser beams injected through multimode fibers. A probe beam, whose propagation direction is either horizontal or vertical, is used to detect cold atoms. We measured the absorption spectra of the cold atoms by scanning the frequency of the probe beam, and observed both the absorption signal and the time of flight signal after we switched off the cooling light, from which we estimated the temperature and the number of cold atoms. This method is clearly attractive for building a compact cold atom clock.

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I. INTRODUCTION

Recently, laser cooling of atoms directly from a vapor background in diffuse laser light has received a lot of attention because of its application to making a compact, cold atom clock [1–3]. Such diffuse-light laser cooling behaves similarly to optical molasses [4], which can cool atoms to very low velocity. It is an all-optical technique that has some unique features that are important for such a clock. First, unlike optical molasses, diffuse laser cooling does not require any careful alignment or collimation of laser beams and is therefore very robust. Second, diffuse light can cool atoms over a relatively wide velocity range compared to optical molasses, allowing the accumulation of relatively large numbers of cold atoms. These and other features show a great potential for a compact cold atom clock, especially in a microgravity environment.

Diffuse laser cooling was first realized by Ketterle *et al.* by slowing and cooling of a Na atomic beam [5]. Here the diffuse light was generated by injecting lasers into a 30-cm-long tube with a 0.6 cm inner core. Later Batelaan *et al.* used a similar setup to observe slowing of an ^{85}Rb atomic beam [6]. Followed an early proposal of laser slowing of an atomic beam by diffuse light in an integrating sphere [7], Chen *et al.* successfully slowed and cooled a sodium atomic beam [8,9]. Aardema *et al.* carried out the slowing of Ne atoms in a diffuse reflecting cylindrical cavity and investigated the effect of stimulated emission on the transverse velocity distribution [10]. Guillot *et al.* used diffuse light to cool cesium atoms directly from an atomic vapor background to temperatures as low as 3.5 μK, which suggests that sub-Doppler cooling mechanisms are possible because of the local inhomogeneity of intensity and polarization [2]. Tremine *et al.* used this technique to develop a compact cold atom clock (the HORACE project), using a spherical microwave cavity as an integrating sphere to generate the diffuse light [11–13].

Up to now, however, very little work has studied in detail the process of laser cooling of atoms in diffuse light directly from the vapor background. In this work, we report an experiment on laser cooling of ^{87}Rb atoms from a vapor background in an integrating sphere. We focus on the time dependence of the absorption of a probe beam in the integrating sphere after the cooling light is switched off, rather than observation of the time of flight signal outside the sphere, as was done in Ref. [2]. With this method, we can eliminate the saturation effect of the cooling light on the cold atoms, and observe the real absorption of the probe beam. From this we can directly estimate the temperature and number of cold atoms in the integrating sphere.

II. EXPERIMENTAL DESCRIPTION

Figure 1 shows a schematic diagram of the experimental setup. A spherical glass cell with an inner diameter of 43 mm is mounted on a vacuum pump and connected to a Rb reservoir. The reservoir is kept at room temperature and is used to supply Rb vapor to the glass cell at a background pressure of $\sim 10^{-7}$ Pa. The glass cell is surrounded by an integrating sphere made from ceramic material whose diffuse reflection

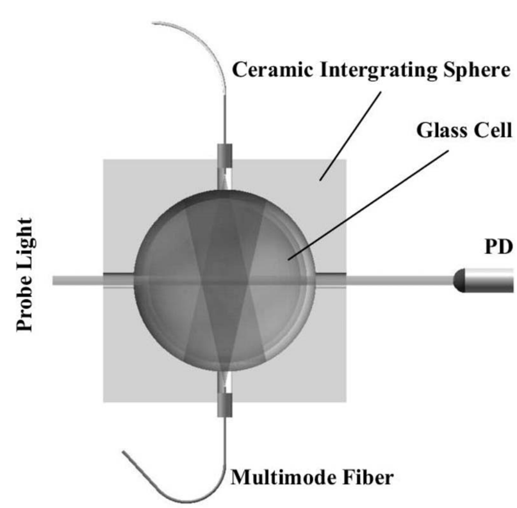

FIG. 1. A schematic of the experimental setup for diffuse cooling.

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coefficient at the inner surface is 98% at 780 nm.

The ~100 mW of cooling light is provided by an extended-cavity diode laser (Toptica TA100) with linewidth smaller than 1 MHz that is detuned red of the transition of $5\,^2S_{1/2}$, $F=2 \rightarrow 5\,^2P_{3/2}$, $F'=3$ of ^{87}Rb. In order to keep the population from being trapped in the $5\,^2S_{1/2}$, $F=1$ state, a weak repumping laser with total power of 4.7 mW that is frequency locked to the transition between $5\,^2S_{1/2}F=1$ and $5\,^2P_{3/2}$, $F'=2$, is mixed into the cooling beam with a polarizing beam splitter. The repumping laser does not play an important role in the cooling process because the cooling occurs between the $5\,^2S_{1/2}$, $F=2$ and $5\,^2P_{3/2}$, $F'=3$ levels. The frequency and power of the cooling laser are controlled by an acousto-optic modulator. In order to block the cooling laser completely, a mechanical shutter with rise and fall time of 250 μs is used to switch on and off the cooling light.

The combined cooling and repumping light is split into two beams that are each coupled into multimode fibers. The fibers have a core diameter of 600 μm and a numerical aperture of 0.22 ± 0.02. The two output beams from the fibers are injected into the integrating sphere through two 1-mm-diameter holes located at opposite sides of the sphere, either vertically as shown in Fig. 1 or horizontally when the sphere is rotated over 90°, depending on the probe beam position. No collimation lenses are used at the output of the fibers so that the light is diverging in the sphere before being reflected (see Fig. 1). With multiple diffuse reflections of the injected light by the inner surface of the sphere, diffuse light containing both cooling and repumping frequencies is distributed throughout the glass cell. In the sphere, the intersection region of the two injected beams has slightly higher intensity, shown shaded in Fig. 1, which may collect more atoms. The integrating sphere is shielded with μ metal that reduces the residual magnetic field to be less than 30 mG in the cooling zone.

To detect cold atoms in the glass cell, a probe beam, with power of 1 μW, passes through the center of the glass cell via two 2-mm-diameter holes and is detected by a photodiode. When the frequency of the probe beam is swept across the atomic resonance, an absorption spectrum is recorded. The reduced Doppler width of cold atoms allows resolution of the atomic hyperfine structure. We set the probe beam either horizontally or vertically to detect the gravitational acceleration of the cold atoms.

III. RESULTS AND DISCUSSION

We first set the cooling light beams vertical and the probe beam horizontal, as shown in Fig. 1. An absorption spectrum is recorded by scanning the frequency of the probe beam across the transition of $5\,^2S_{1/2}F=2 \rightarrow 5\,^2P_{3/2}F'=1,2,3$ with the cooling laser locked 20 MHz below the transition $F=2 \rightarrow F'=3$, as shown in Fig. 2. The total power of the cooling laser injected into the integrating sphere from the two multimode fibers is 20 mW. Three hyperfine transitions $F=2 \rightarrow F'=1,2,3$ are clearly shown in the spectrum, which provides convincing evidence that atoms are cooled by the diffuse light in the integrating sphere. But because the absorption spectrum of cold atoms is obtained when the diffuse

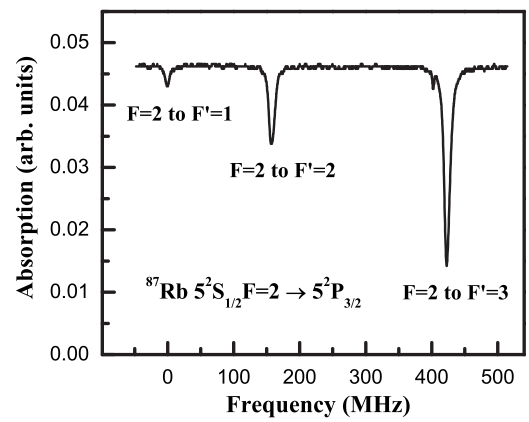

FIG. 2. An absorption spectrum when the probe light is scanned and the cooling light locked to 20 MHz below the transition of $5\,^2S_{1/2}F=2 \rightarrow 5\,^2P_{3/2}F=3$. The injected cooling power is about 20 mW, and the width of the hyperfine structure is about 10 MHz.

cooling light is on, the shape of the profiles is compromised by saturation from the cooling light [2]. The effect cannot even be estimated because the intensity distribution of cooling light in the integrating sphere is difficult to determine. The width of the absorption lines is slightly larger than Γ ($\Gamma = 6.07$ MHz is the natural linewidth). Generally, the line broadening depends on the detuning and intensity of the cooling and probe lasers, atomic motion, collisions, and optical pumping to other levels induced by the probe and cooling lasers [14]. Because the repumping laser induces the $F=1 \rightarrow F'=2$ transition, which has minimal effect on the cooling cycle, the broadening caused by optically pumping $5\,^2S_{1/2}F=2$ to $5\,^2S_{1/2}F=1$ can be neglected. The Doppler broadening for cold atoms (determined by the atomic temperature) and pressure effects are also very small. The main contribution to the line broadening may be the saturation effect of the cooling light because of its high intensity and the complex polarization configuration in the integrating sphere [15].

In order to measure the undisturbed properties of the cold atoms in the integrating sphere, we fix the frequency of the probe beam at the transition of $5\,^2S_{1/2}F=2 \rightarrow 5\,^2P_{3/2}F=3$, and switch off the cooling laser beams but keep the repumping on. Such an arrangement eliminates any saturation caused by the cooling light and gives the true absorption at a single frequency. Figure 3 shows a typical result. The absorption of the probe beam by cold atoms is suddenly increased because they are no longer saturated by the cooling light when it is switched off by the mechanical shutter within 250 μs. Then the absorption is quickly reduced within 4–8 ms, and exhibits a second broad peak at about 30 ms.

The sudden increased absorption part of the first peak is determined by the mechanical shutter speed, and the decreased absorption part can be understood as the decreasing of the cold atom's density. A rough estimation shows that the momentum diffusion of cold atoms excited with the probe beam is the main reason for the decreasing absorption. Cold atoms in the probe beam are heated and then are driven away from the beam by "random walk" due to excitation and spontaneous emission. With power of 1 μW and diameter of

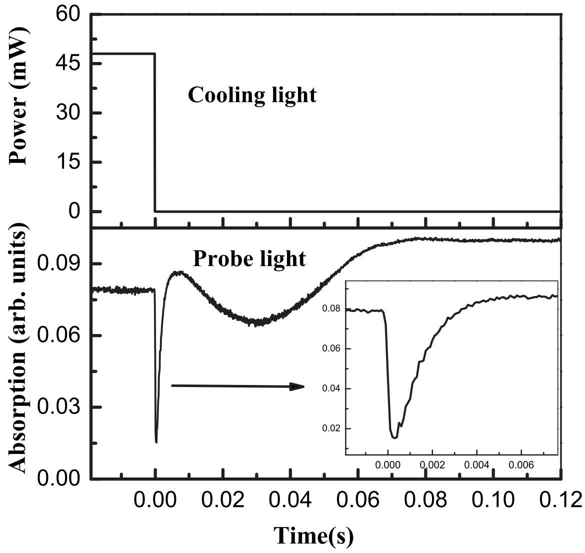

FIG. 3. The response of cold atoms to the weak probe light whose frequency is stabilized to the transition $5\,^2S_{1/2}F=2 \rightarrow 5\,^2P_{3/2}F=3$ when the cooling laser is shut off in 250 μs (the probe light is horizontally placed, as shown in Fig. 1).

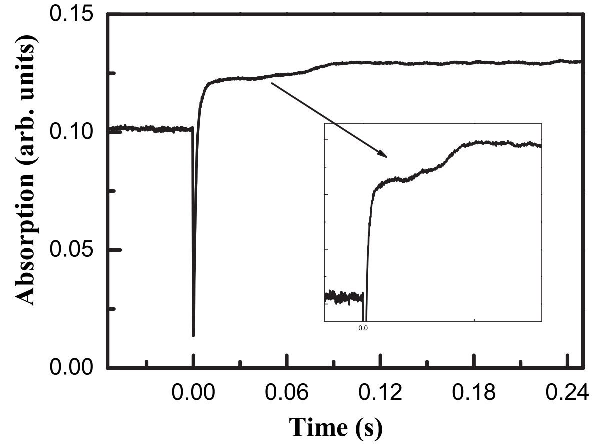

FIG. 4. Same as Fig. 3 but for the probe light being placed vertically along the direction of gravity.

2 mm, the scattering rate from the on-resonant probe beam is around 5.4×10^4/s. Thus 1 ms interaction will lead to scattering an average of more than 50 photons. Since the recoil velocity of Rb is 0.6 cm/s, 4 ms can lead to around 3 mm average displacement of atoms due to the random walk, which is larger than the size of the probe beam. This is proved by the experimental results as Fig. 3 shows. The minor reason is the expanding of the cloud of cold atoms, but in our case, the expanding of the cloud is not fast enough to leave the probe beam based on its initial temperature.

The second absorption peak comes from the free fall of cold atoms located over the probe beam. When cold atoms fall across the probe beam the absorption signal appears, similar to the time-of-flight (TOF) signal used to determine the temperature in magneto-optic trap or in an optical molasses. To support this argument we rotated the integrating sphere 90 degrees so that the cooling beams become horizontal and the probe beam vertical. In this case, gravity is in the same direction as the probe beam, and thus cold atoms do not fall into it. The experimental result is shown in Fig. 4. Clearly, the prompt enhanced absorption peak still exists as before, but the TOF signal disappears. Instead, the absorption signal changes slightly corresponding to the absorption of cold atoms across the probe beam from diffusion during free fall.

The temperature of atoms cooled by diffuse light can be estimated with the above TOF signal. The typical temperature of cold atoms is about 150 μK by fitting the TOF signal. Further cooling can be obtained when polarization-gradient cooling is applied [2]. Of course, cold atoms may be heated up when they collide with the inner surface of the glass cell. So the signals of the TOF shown in Fig. 3 and the diffusion shown in Fig. 4 may connect with the shape of the glass cell.

We also compare the absorption signals of circularly and linearly polarized probe beams, as shown in Fig. 5. Clearly the absorption of the probe light with circular polarization is stronger than that with linear polarization. The ratio of absorption between circular and linear polarizations is $P_{\rm cir}/P_{\rm lin}=1.62$ (the intensity of the probe light is about 0.03 mW/cm^2), which is basically in accord with the ratio of the scattering rates of the two beams, $R_{\rm cir}/R_{\rm lin}=1.49$. This is also evidence for the absorption enhancement being linear, which corresponds to a real absorption when the saturation effect disappears.

The first absorption peak in Figs. 3 and 4 represents a real absorption of the probe beam for cold atoms in the glass cell. Based on Beer's law, we can determine the optical density of the cold atom's cloud with the assumption that the density of cold atoms is uniform in the glass cell. Figure 6 gives the number of cold atoms vs power of total injected cooling laser with detuning −20 MHz. As expected, more cooling power has the ability to cool more atoms, and a maximum 2.0×10^9 cold atoms are obtained. As the cooling laser power increases further, the number of cold atoms tends to saturate, as Doppler cooling is expected to do.

Figure 7 shows the result of the number of captured cold atoms vs the detuning. Here, the total injected cooling power is 48 mW. The maximum number of captured atoms occurs

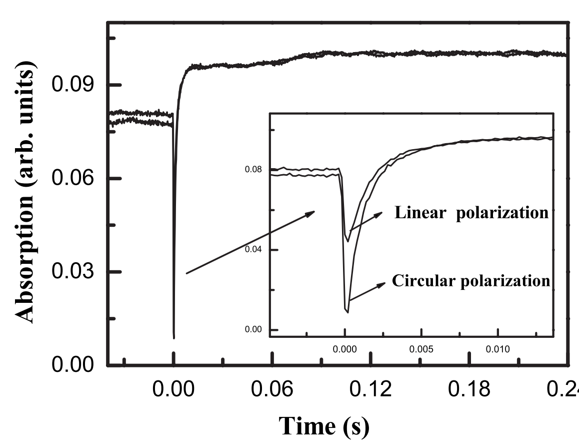

FIG. 5. The absorption signals of the probe light with circular and linear polarizations when the cooling laser is shut off within 250 μs. In this case, the probe light is frequency locked and placed vertically.

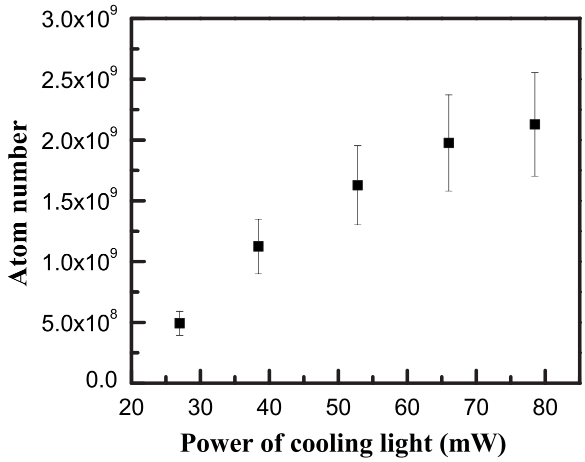

FIG. 6. Number of captured cold atoms vs total injected power of the cooling light.

at the detuning of −20 MHz ($\sim -3.3\Gamma$). Since the velocity capture range is $|\Delta| \leq kv \leq 2|\Delta|$ [5], where Δ is the detuning of the cooling light, k is the wave vector, and v is the atomic velocity, an appropriate detuning for efficient capture of cold atoms needs to be chosen. Obviously, for capturing atoms with large velocity in diffuse cooling, Δ needs to be large. Therefore, in order to cool a large number of atoms, a multidetuned set of cooling frequencies would be more effective [16].

Because the probe beam is on resonance with the cooling transition, it will heat cold atoms, as shown in Fig. 8. Here

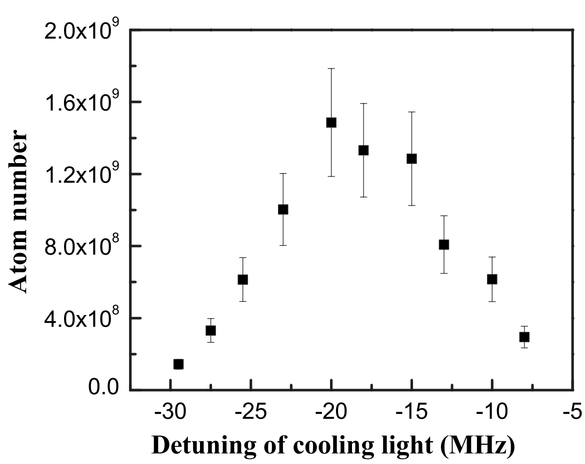

FIG. 7. Number of captured cold atoms vs detuning of the cooling light.

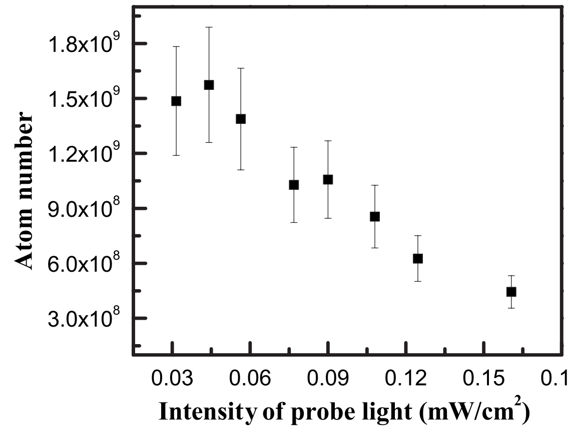

FIG. 8. Number of captured cold atoms vs intensity of the probe light.

the injected cooling and repumping lasers are still 48 and 4.7 mW, respectively, and the detuning of cooling laser is −20 MHz. It can be seen that, as the intensity of the probe beam increases, the number of captured atoms decreases. Thus, in the previous measurement, we have carefully chosen a very weak probe beam in order to avoid heating of cold atoms by the probe beam. In the present experiment, the error of the cold atom number is about 20%.

IV. SUMMARY AND CONCLUSION

In summary, we have demonstrated cooling of ^{87}Rb atoms directly from a vapor background by diffuse light in an integrating sphere made from ceramic material. We measured the absorption spectrum by scanning the probe beam frequency and investigated its broadening mechanism, and measured the absorption enhancement of cold atoms by shutting off the cooling light. We observed the TOF signal from the free fall of cold atoms over the probe beam. With these measurements, we are able to estimate the temperature and number of cold atoms directly in the integrating sphere. Our results show that the laser cooling of atoms in diffuse light is robust and very useful as a cold atom source for a compact cold atom clock.

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