Loading of cold ^{87}Rb atom with diffuse light in an integrating sphere

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Cold ^{87}Rb atom's loading in an integrating sphere with diffuse light is analyzed theoretically and experimentally. The experimental results show that diffuse light cooling has the greatest efficiency to cool the most atoms when the red detuning between the frequencies of cooling light and atom transition is about 3.3Γ (Γ is the natural linewidth, 6.065 MHz). Theoretical analysis using rate equation and numerical calculations on the cold atom number and loading time agree with the experimental results. This integrating sphere cooling would be a novel method for cooling atoms and lead to a new and robust cold atom source for atomic clock.

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In the last several decades, the research of laser cooling and trapping neutral atoms has achieved outstanding development. And there has been much dramatic progress in the field of cold atoms, such as cold atomic clock[1,2] and precision microwave spectroscopy[3]. Manipulating atoms has been proposed using near resonance radiation pressure forces[4]. Deceleration of sodium atomic beam has been experimentally observed by absorption of counterpropagating resonant laser light[5], then in three dimensions the trapping and cooling of sodium atoms have been realized by the radiation pressure of counterpropagating laser beams and the first result of optically trapped atom has been reported with a density of 10^{11} atoms per cubic centimeter[6−9]. Recently, novel four-well optical trap for cold atom[10] and cavity-enhanced laser cooling of solid-state materials[11] have been proposed. Now magneto-optic trapping (MOT) is a very common technology to capture cold atoms with low temperature and high density. Pritchard *et al.* have shown the possibility to confine atoms by spontaneous light forces produced by static laser beams while an external field shifts the atomic resonant frequency[12]. Monroe *et al.* have improved the MOT technology to trap the atoms without pre-cooling[13,14]. But the inevitable magnetic field and high power of laser would increase two-level Zeeman shift and thermo-radiation effect to cold atoms. An isotropic laser light cooling would be a novel method to solve this problem[15]. In 1992, slowing and cooling of an atomic beam in isotropic laser light have been demonstrated by employing a tube cavity[16], and deceleration of sodium atoms has been observed in red-detuned diffuse light[17]. Until ten years later, three-dimensional (3D) cooling of cesium atoms in a copper cylinder has been reported[18]. We have achieved great breakthrough in laser cooling of rubidium with diffuse light[19], estimated the number of cold atoms and the corresponding temperature in a ceramic integrating sphere[20], and studied nonlinear phenomena of cold atoms in diffuse laser light[21]. The results show that cold atoms in diffuse laser light are quite useful as a source for a compact cold atom clock. The research on the atomic clock[2] has discussed time sequence of a clock cycle, in a limited duration the cooling efficiency is of practical importance. In this letter, the loading process of cold atoms in the sphere is studied theoretically and experimentally. The cooling process is studied by rate equation and the collection ability of sphere cavity with the diffuse light is denoted with the cooling speed. The atom number in the cavity reaches 2.0×10^9 within 1.1 s, which would provide useful parameters for pulse cooling with diffuse light in the sphere.

The number of cold atoms N in the sphere cell is stabilized when the cooling rate R is equal to the loss one of $1/\tau$. With the research of cooling in the integrating sphere[17,19−21], it is known that diffuse light could cool atoms in a large velocity range[16,19], the typical detuning in the integrating sphere should be wider than that in MOT. Our previous work[19] has proved that the largest number of ^{87}Rb atoms would be cooled in the integrating sphere when the detuning is about -3Γ, in which Γ is the natural line width (6.065 MHz). Consider the cooling speed for atoms in the integrating sphere as $v_{\rm c} = 2\sqrt{2}\Gamma\lambda$, in which λ is the wavelength of cooling light. The corresponding red detuning is about -3Γ for the cooling system. Atoms under the cooling speed would be decelerated and cooled effectively. The cooling rate $R = n_{\rm b}2\pi r^2 v_{\rm c}^4/u^3$ represents the number of atoms per second in the sphere, where r is the radius of integrating sphere and $n_{\rm b}$ is the density of background vapor at room temperature. The loss rate $1/\tau = n_{\rm b}\sigma u$ is primarily due to collision between the background atoms and the cold ones, where σ is the cross section between the background vapor atoms and the cold ones, $u = \sqrt{2kT/m}$ is the most probable speed of the background vapor. The number of cold atoms N in the integrating sphere is given by

$$\mathrm{d}N/\mathrm{d}t = R - N/\tau. \quad (1)$$

Assuming $N = 0$ at the initial time ($t = 0$), the evolution of cold atoms in the sphere cavity is obtained as

$$N(t) = N_{\rm s}[1 - \exp(-t/\tau)], \tag{2}$$

where the steady-state number $N_{\rm s}$ is given as $N_{\rm s} = R\tau$ under the condition of $\mathrm{d}N/\mathrm{d}t = 0$.

The experimental setup has been illustrated in Refs. [19,20]. A spherical glass cavity is surrounded by an integrating sphere made from ceramic material with high reflectivity up to 98% at 780 nm, as shown in Fig. 1. The cavity with an inner diameter of 45 mm is mounted on a vacuum pump and is connected to a Rb reservoir. The reservoir supplies Rb atom to spherical cavity and is kept at room temperature, the vacuum pump keeps the background pressure at $\sim 10^{-7}$ Pa. The schematic diagram of level for cooling is shown in Fig. 2. Cooling light which is red detuned from the transition of $5^2\mathrm{S}_{1/2}$, $F = 2 \rightarrow 5^2\mathrm{P}_{3/2}$, $F' = 3$ is provided by Toptica TA100 semiconductor laser. A weak repumping laser, whose frequency is locked to the transition between $5^2\mathrm{S}_{1/2}$, $F = 1 \rightarrow 5^2\mathrm{P}_{3/2}$, $F' = 2$, would remove the trapped population in the $5^2\mathrm{S}_{1/2}$, F=1 state to improve the cooling efficiency. Using a polarized beam splitter (PBS), the repumping light is mixed into the cooling one. Then the combined light is coupled into multimode fiber and injected into the cavity through two holes which are located at opposite sides of the sphere. The cooling and repumping lights are diffused by the inner surface and distributed all over the cavity. A probe beam split from cooling laser passes through the center of the glass cavity and is detected by a photodiode. The frequency of the probe laser is swept with the acousto-optic modulator (AOM) across the atomic resonance, the detector records the signal and the results are given in the oscilloscope.

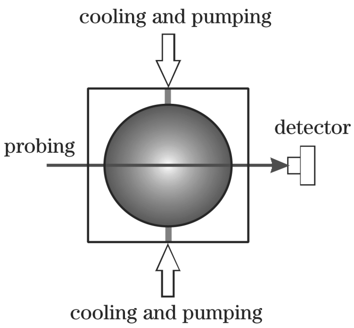

Fig. 1. Integrating sphere used for all optical cooling Rb atoms.

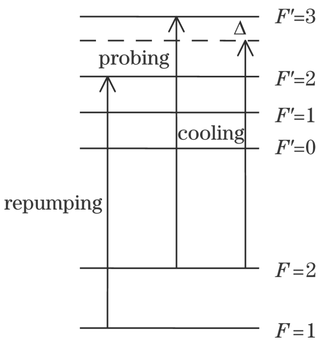

Fig. 2. Rb energy-level diagram showing the relevant transitions.

The loading process of cold ^{87}Rb atoms in the diffuse light is calculated with our experimental parameters. The number of cold atoms is estimated through detecting the transmission amplitude of the probe light. We measure the cold atom collection process in 6.0-s period in the optimal detuning. Experimental results and numerical calculations are compared, as shown in Fig. 3. The cooling process from background vapor in the integrating sphere accords with exponential form. The loading time deduced from the rate equation is about 1.1 s, which accords with the experimental fitting analysis approximately. The cooling light is diffused in the cavity and the effective interaction region is greatly increased, plenty of atoms are decelerated and cooled. The effect is calculated in the cooling rate R by using the maximal area of cross section in the sphere cavity. As described in Ref. [17], diffuse light could compensate Doppler shift successively to achieve more cooling efficiency. The compensatory effect is presented in the enlarged cooling speed of integrating sphere in the above theoretical model.

Monroe *et al.* have proved that cold atomic lifetime τ is inversely proportional to the background vapor pressure, the cold atomic lifetime increases when the vapor pressure decreases for the background the vapor pressure P decides the atomic density as $n_{\rm b} = P/k_{\rm B}T$ ($k_{\rm B}$ is the Boltzmann constant)[13]. According to the loading curve in the integrating sphere, the cold atomic lifetime is similar to that in MOT. Since the cooling process is carried out in a wider area and collisions are effectively reduced, cooling in the integrating sphere is faster than that in MOT, which meets the practical need of atomic clock. While both of loss rate and loading rate are proportional to the background vapor pressure from the theoretical model, it is deduced that the number of steady state cold atoms in the integrating sphere is dependent on the cooling speed. In the diffuse light, a larger velocity range improves the effective detuning in the cooling speed, which means Doppler shift is compensated in a wider range. The cooling speed is extended and the number of cold atoms in steady state is correspondingly enlarged compared with MOT.

The above results are obtained under the optimal detuning. According to the dispersion force, diffuse cooling light with larger detuning would operate atoms in a wider velocity range and more atoms can be cooled from the background vapor. We have measured transmission amplitudes of probe light under different detunings. The

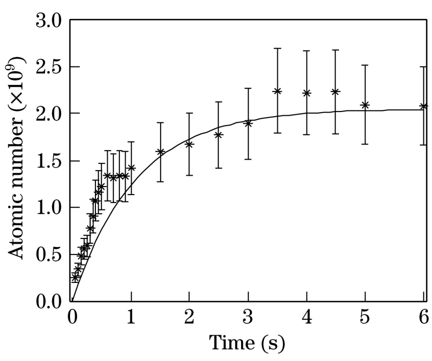

Fig. 3. Comparison between calculations about cooling process (solid line) and experimental results (stars).

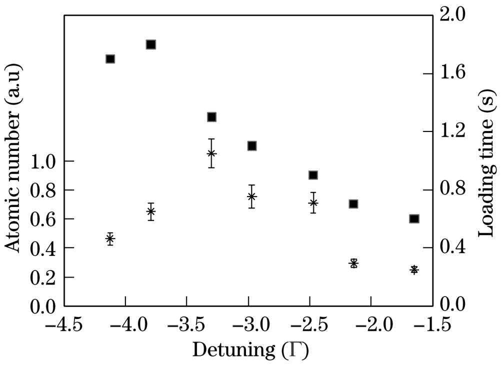

Fig. 4. Comparison between loading time and cold atomic number with detuning. Squares refer to the loading time, stars refer to the cold atomic number.

fitting calculations of the number of cold atoms and loading time are plotted in Fig. 4. It is found that the number of cold atoms increases while the absolute value of detuning is enlarged at first. Correspondingly, the loading time is prolonged when the number of cold atoms increases. However, if the detuning is beyond the Doppler shift too much, dispersion force to atoms decreases and the number of cold atoms rapidly drops correspondingly. It is clear that diffuse light in the integrating sphere needs longer time to operate and cool atoms. With the increase of red-detuning, the interaction between atom and cooling light would be off-resonance, and the efficiency of cooling would decrease beyond the optimal detuning. When the detuning is -3.8Γ, the loading time reaches the maximum; but the number of cold atoms decreases rapidly. Under the experimental condition, an appropriate detuning for optimum cold atomic number and loading time is about -3.3Γ, with which we would cool maximum atoms in 1.3 s in the diffuse light.

In conclusion, we study the loading process of cold atoms with the diffuse light in the integrating sphere. We use the rate equation to describe the cold atom number along the cooling time. The numerical calculation agrees approximately with the experimental results. Because the diffuse light could compensate the Doppler shift successively, cooling in the integrating sphere has less loading time, which has the practical need for the atomic clock. The research shows that the maximum number of Rb atoms cooled in the diffuse light reaches 2.0×10^9 and theoretically the loading time is about 1.1 s, according with the experimental results. The number of cold atoms and loading time are compared under different detunings. Under our experimental condition, -3.3Γ is the optimum detuning to cool atoms in 1.3 s. It is proved that cooling in the diffuse light is a novel method to achieve cold atom source for cold atomic clock.

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