

# Laser cooling of rubidium 85 atoms in integrating sphere

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We cool <sup>85</sup>Rb atoms in an integrating sphere directly from a vapor background using diffuse light generated by multiple reflections of laser beams in the inner surface of the integrating sphere. We compare and analyze the different features of cold <sup>85</sup>Rb atoms and cold <sup>87</sup>Rb atoms in diffuse light cooling, which are important in applying <sup>85</sup>Rb and <sup>87</sup>Rb isotopes in many experiments on testing fundamental physics.

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In recent years, many groups have focused on compact atomic clocks, such as the coherent population trapping (CPT) clocks based on vapor cells<sup>[1,2]</sup>, and the compact cold atomic clocks<sup>[3,4]</sup>. In establishing cold atomic clocks, efforts have been exerted to reduce the influence of cold collision frequency shift<sup>[5]</sup>. Kokkelmans *et al.* have reported that Rb isotopes are promising species, especially <sup>85</sup>Rb, because its cold collision frequency shift can be canceled by adjusting the populations of two  $m_F = 0$  clock states<sup>[6]</sup>. In measuring the fundamental constants and testing Einstein's equivalence principle, many groups have carried out comparison experiments between isotopes of the same ions or atoms<sup>[7,8]</sup>, such as <sup>201</sup>Hg<sup>+</sup> and <sup>199</sup>Hg<sup>+</sup> clocks<sup>[9]</sup>, and <sup>87</sup>Rb and <sup>85</sup>Rb atomic interferometers<sup>[10]</sup>. In addition, the method of cooling <sup>85</sup>Rb and <sup>87</sup>Rb simultaneously can be used to investigate ultracold <sup>85</sup>Rb-<sup>87</sup>Rb heteronuclear molecules with Feshbach resonance<sup>[11]</sup>. The vast potential applications of cold <sup>85</sup>Rb are the main motivations to realize diffuse light cooling of <sup>85</sup>Rb based on the integrating sphere.

The principle of laser cooling of neutral atoms based on integrating sphere has been studied<sup>[12]</sup>. In Ref. [13], the influence of configuration in designing the integrating sphere has been examined carefully. In 2009, we have demonstrated the diffuse laser cooling of <sup>87</sup>Rb atoms in an integrating sphere<sup>[14]</sup>, measured the lifetime and loading time<sup>[15,16]</sup>, and demonstrated its application for compact atomic clock<sup>[17]</sup>. In this letter, we cool <sup>85</sup>Rb atoms in an integrating sphere and compare this with <sup>87</sup>Rb.

Figure 1 shows the energy levels of D<sub>2</sub> transition for <sup>85</sup>Rb. The transitions used for cooling is similar to that used in <sup>87</sup>Rb<sup>[14]</sup>.

Figure 2 gives the experimental schematic, which has been described in Ref. [14]. The setup was exactly same as used for cooling of <sup>87</sup>Rb. Cooling and repumping lasers were injected into the integrating sphere with two multimode fibers, and the transmission of probe light was detected with a photodiode. The power and frequency for the probe and cooling lights were controlled by acousto-optic modulators (AOMs).

In this experiment, the frequency of cooling light is red

detuned to the transition of  $5^2S_{1/2}$ ,  $F = 3 \rightarrow 5^2P_{3/2}$ ,  $F' = 4$ , and the probe light was resonant with this transition. The repumping laser was frequency-locked to the transition of  $5^2S_{1/2}$ ,  $F = 2 \rightarrow 5^2P_{3/2}$ ,  $F' = 3$  with the power of 4.8 mW.

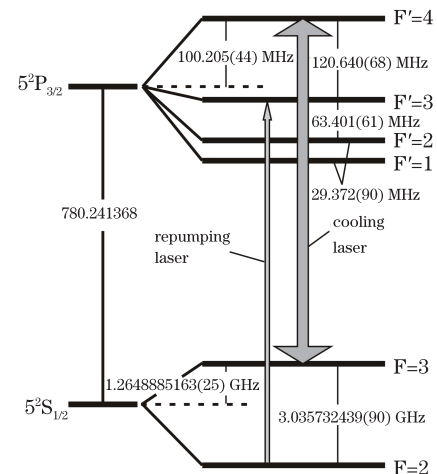


Fig. 1. D<sub>2</sub> hyperfine energy level for <sup>85</sup>Rb.

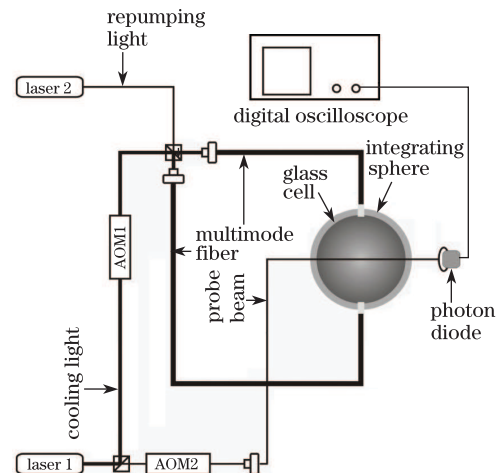


Fig. 2. Schematic diagram of the experimental system.

We obtained the absorption spectrum by sweeping the frequency of the probe light while the cooling and re-pumping lights were switched on (Fig. 3). Here, the power of cooling light is about 55.5 mW with a detuning of 15 MHz below the transition of  $5^2S_{1/2}$ ,  $F = 3 \rightarrow 5^2P_{3/2}$ ,  $F' = 4$ . The probe light power is about 1  $\mu$ W. The linewidth of  $5^2S_{1/2}$ ,  $F = 3 \rightarrow 5^2P_{3/2}$ ,  $F' = 4$  is about 15 MHz (Fig. 3), indicating that the atoms have been cooled with the diffuse light. By estimating with the time-of-flight (TOF) signal, We find that the temperature of cold  $^{85}\text{Rb}$  atoms is about 80  $\mu\text{K}$ , which is lower than 150  $\mu\text{K}$  for  $^{87}\text{Rb}$ <sup>[14]</sup> under the same cooling conditions.

The differences between  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  in laser cooling are discussed from the following aspects: the influences of the frequency detuning and the power of cooling light on the cold atomic numbers, and the loading times of cold atoms.

Figure 4(a) presents the number of cold atoms versus the frequency detuning of cooling light when the power levels are about 62 and 40 mW for cooling  $^{87}\text{Rb}$  and  $^{85}\text{Rb}$ , respectively. From Fig. 4(a), there is a special detuning for  $^{85}\text{Rb}$ , where the cold atomic number is at maximum; we define it as the optimized detuning, which is about  $-9.8$  MHz ( $-1.6$   $\Gamma$ ) for  $^{85}\text{Rb}$ . However, for  $^{87}\text{Rb}$ , the optimized detuning is about  $-18$  MHz ( $-3\Gamma$ ).

The power of cooling light is another important parameter for capturing the cold atoms. We set the cooling time as long as 5 s, and fixed the frequencies of cooling lights both at their own optimized detunings for  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$ , respectively. Figure 4(b) shows the relations of cooled  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  atoms with the power of cooling lights. By increasing the power of

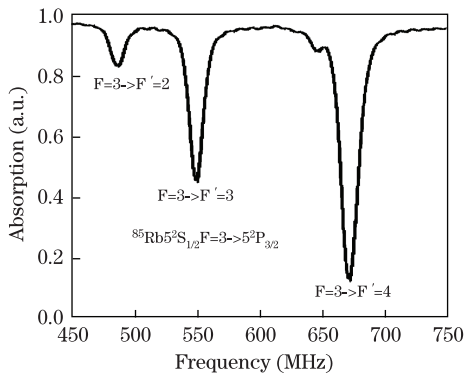


Fig. 3. Absorption spectrum of cold  $^{85}\text{Rb}$  hyperfine energy levels by sweeping the frequency of the probe light.

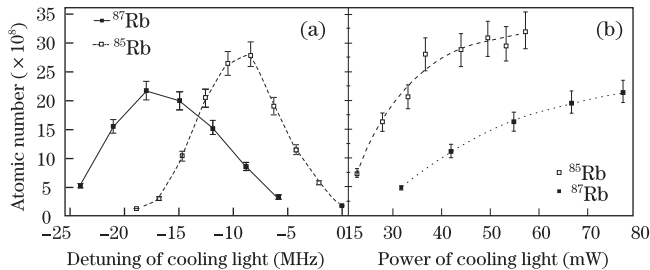


Fig. 4. Influence of cooling laser on the cold atomic number. (a) Number of cooled atoms versus detuning of cooling light; (b) number of cooled atoms versus the power of cooling laser.

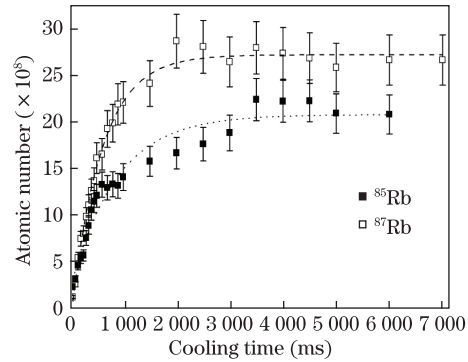


Fig. 5. Loading of cold  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  atoms.

cooling lights, the numbers of cooled atoms are increased dramatically at first, and then stabilized to fixed values of about  $3.3 \times 10^9$  and  $2.2 \times 10^9$  for  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$ , respectively. The ratio of captured cold  $^{85}\text{Rb}$  to cold  $^{87}\text{Rb}$  atoms is about 1.5:1, which is smaller than the natural abundance ratio of 2.6:1. This is because  $^{85}\text{Rb}$  has a higher collision rate.

We have captured more cold  $^{85}\text{Rb}$  atoms than cold  $^{87}\text{Rb}$  atoms at their own optimized detunings. These may help us improve the signal-to-noise ratio (SNR) when making a compact cold atomic clock.

Figure 5 shows the loading curves of cold  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  atoms. The powers of cooling light are 43 mW for  $^{85}\text{Rb}$  and 65 mW for  $^{87}\text{Rb}$ <sup>[16]</sup>, and the frequencies are detuned to the optimized detunings (Fig. 4(a)).

In an optical molasses, the loading of cold atoms can be described as

$$N_t = N_s(1 - e^{-t/\tau}), \quad (1)$$

where  $N_s = R\tau$  is the number of steady state cold atoms, and  $1/\tau$  is determined by the collision rate due to the collisions between the background gas and the cold atoms<sup>[18]</sup>. By fitting the loading curves with this equation, we find that for  $^{85}\text{Rb}$ ,  $\tau \approx 570$  ms,  $N_s \approx 2.79 \times 10^9$ ; and for  $^{87}\text{Rb}$ ,  $\tau \approx 863$  ms,  $N_s \approx 1.96 \times 10^9$ . The loading time is much shorter for  $^{85}\text{Rb}$  than that for  $^{87}\text{Rb}$  when the captured cold atomic numbers are the same. It can be expected that for  $^{85}\text{Rb}$ , the cycle time of the clock can be decreased, and then the frequency stability of the clock can be improved<sup>[19]</sup>.

Based on the above experimental results, it is clear that the integrating sphere can capture more cold  $^{85}\text{Rb}$  atoms and require less cooling time than cold  $^{87}\text{Rb}$  atoms at their own optimized detunings. This would be helpful in improving the SNR and cycle frequency of the compact cold atomic clock.

In conclusion, cooling  $^{85}\text{Rb}$  atoms by diffuse light with integrating sphere is demonstrated. We investigate the characteristics of cold  $^{85}\text{Rb}$  atoms, including the influences of detuning and power of cooling light on the cold atomic numbers and the loading time. We then compare these characteristics with cold  $^{87}\text{Rb}$  atoms. Our findings are important in applying  $^{85}\text{Rb}$  -  $^{87}\text{Rb}$  isotopes to test fundamental physics.

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