Cooling of rubidium atoms in pulsed diffuse laser light*

Cheng Hua-Dong(成华东), Wang Xu-Cheng(王旭成), Xiao Ling(肖 玲), Zhang Wen-Zhuo(张文卓), Liu Liang(刘 亮)†, and Wang Yu-Zhu(王育竹)

Key Laboratory of Quantum Optics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, *China*

(Received 12 April 2010; revised manuscript received 12 August 2010)

This paper reports an experiment on laser cooling of ^{87}Rb atoms in pulsed diffuse light, which is the key step towards a compact cold atom clock. It deduces an empirical formula to simulate the pulse cooling process based on the loading of cold atoms in cooling time and the loss in the dead time, which is in agreement with the experimental data. The formula gives a reference to select the parameters for the cold atom clock.

Keywords: diffuse light, pulsed cooling, rubidium, atom clock

PACS: 37.10.De, 42.50.Ct, 42.62.Fi **DOI:** 10.1088/1674-1056/20/2/023701

Laser cooling of atoms directly from background vapour in diffuse light in a sphere has received a lot of attention because of its importance in building a compact cold atom clock. The cooling atoms in diffuse laser light is very robust because it does not require any careful alignment of laser beams, and is efficient because it has a wide velocity capture range.[1,2] It is very different from the common laser cooling methods, such as magneto-optical trap (MOT) and optical molasses. On the other hand, the sphere generating diffuse light can be machined as a microwave cavity. Such a design is the key to build a compact cold atom clock, e.g. the HORACE project[3−5] which reaches a few $10^{-13}\tau^{-1/2}$ stability.[6]

Typically, the cold atom clock operates in a pulsed mode, that is, a sequence of laser pulses with pulse duration $T_{\rm cool}$, cools atoms, and during the times between two pulses, called the dead time $T_{\rm dead}$, the microwave interrogation with cold atoms occurs. The $T_{\rm dead}$ determines the interrogation time, but both $T_{\rm cool}$ and $T_{\rm dead}$ determine the number of cooled atoms, which affects the performance of the clock. Tremine *et al.* first cooled caesium atoms by a sequence of laser pulses.[3,4] When the dead time is fixed at 20 ms, they found that after 15 cycles, the number of cold atoms becomes stationary.[3]

Different from the works of Tremine *et al.* which use caesium as the atomic medium, in this paper, we study the cooling of ^{87}Rb in pulsed diffuse laser light. We found that the cooling of ^{87}Rb in a pulsed diffuse light is very different from that of caesium. And found that in our system, within only 5 cycles, the number of cold atoms can reach stationary. Such a result is very important for rubidium cold atom clock. Besides, ^{87}Rb has less collision shift than caesium, and thus better performance of the cold rubidium clock is expected.

In pulsed diffuse cooling, if the dead time is smaller than the lifetime of cold atoms in the integrating sphere, the remaining cold atoms can be recaptured by next pulse. The recapturing rate is related to the loss rate of cold atoms in the dead time, where the determinant effect is the gravity on earth.[7] The number of captured cold atoms reaches stationary after several cooling pulses. We deduce an empirical formula to simulate this pulsed cooling process, which is necessary for the estimation of parameters used for cold atom clock.

The experimental setup has been described in detail in our previous paper.[2,8,9] A spherical glass cell with an inner diameter of 43 mm is mounted on a vacuum pump and connected to an Rb reservoir. The background pressure in the glass cell is about 10^{-7} Pa. The glass cell is surrounded by a ceramic sphere whose diffuse reflection coefficient is about 98% at the inner surface, which is used to produce the diffuse light. The cooling laser is provided by the external cavity diode laser which is red detuned to $5^2{\rm S}_{1/2}$, $F = 2 \rightarrow 5^2{\rm P}_{3/2}$,

*Project supported by the National Natural Science Foundation of China (Grant Nos. 10604057 and 10874193), the National High-Tech Programme (Grant No. 2006AA12Z311) and the National Basic Research Programme of China (Grant No. 2005CB724506).

†Corresponding author. E-mail: liang.liu@siom.ac.cn

© 2011 Chinese Physical Society and IOP Publishing Ltd

$F' = 3$ of ^{87}Rb D_2 line. The second diode laser with frequency locked to the transition between $5^2S_{1/2}$, $F = 1$ and $5^2P_{3/2}$, $F' = 2$ as repumping laser is mixed together with the cooling laser by a polarizing beam splitter. The cooling and repumping lasers are injected into the ceramic sphere with two multimode fibres. The power of injected cooling laser and repumping laser are about 32 mW and 2 mW, respectively. The detuning of the cooling laser is about -3Γ (Γ is the natural linewidth). The frequency and the power of cooling laser are controlled by an acousto-optic modulator (AOM) and the repumping laser is always applied during the experiment. The pulse sequence of cooling light is controlled by the AOM.

To detect cold atoms in the glass cell, a resonant probe beam, with power of 1 μW, passes through the centre of the glass cell horizontally via two 2-mm diameter holes and the transmission intensity is recorded by a photodiode. In order to eliminate the saturation effect due to the cooling laser, we estimate the number of cooled atoms by using the absorption signal in the dead time.[2] In pulsed diffuse cooling, the cold atoms captured by each cooling pulse can be estimated with the probe transmission intensity during each dead time. The typical results are shown in Fig. 1 with 11 cooling pulses. Here the cooling time $T_{\rm cool} = 100$ ms and the dead time $T_{\rm dead} = 30$ ms. It is noticed that the transmission intensity of the probe beam decreases suddenly after each cooling pulse is shut off, and the peak position corresponds to the true absorption of the probe beam by cold atoms, as discussed in Ref. [2] in detail. After only 5 pulses, the transmission peak becomes stable. From Fig. 1, we also notice that the second peak appears after the last pulse, which is the signal of time of flight (TOF) of cold atoms above the probe light. The physical reason about the shape of the transmission signal is explained in detail in our previous paper.[2] With such a signal, the temperature of cold atoms in the sphere can be directly estimated by fitting the TOF signal, as discussed in Ref. [8].

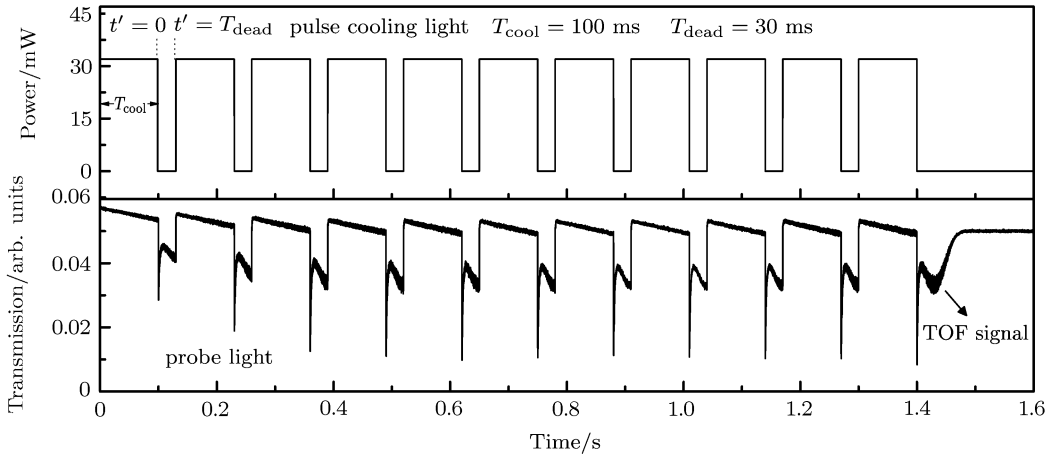


Fig. 1. The upper part is the injected power of pulsed cooling laser and the lower part is the transmission signal of the probe light in the process of pulse cooling. The cooling time $T_{\rm cool} = 100$ ms and the dead time $T_{\rm dead} = 30$ ms. The total power of injected cooling laser is 32 mW.

For a cold atom clock, longer cooling time, which can generate more cold atoms leads to better signal to noise ratio (S/N), but longer cooling time will also lead to less duty cycle which limits the short term stability due to the Dick effect. In contrast, longer dead time will lead to longer microwave interrogation time and thus narrow width of the Ramsey fringe, but bad S/N. Determination of appropriate parameters in the cooling cycle with sequence of pulsed diffuse light is very important because it directly relates to the performance of cold atom clock.

We first investigate the loading and recapturing of cold atoms in pulsed diffuse cooling with fixed $T_{\rm cool}$ by changing $T_{\rm dead}$. Figure 2 shows the detected cold atoms with $T_{\rm cool} = 100$ ms and the dead time $T_{\rm dead}$ from 30 ms to 60 ms. It is shown that the larger $T_{\rm dead}$, the smaller stabilized cold atom number is, which needs the smaller cooling pulse number. In our previous work,[7] we measured the lifetime of cold atoms in the glass cell, and found that the half of cold atoms

remain in the cell at 50 ms after the cooling light is switched off, it means more than half of cold atoms can be recaptured by next laser pulse if $T_{\rm dead} < 50$ ms.

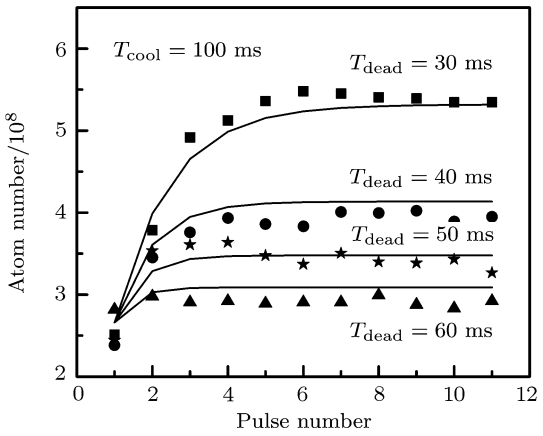


Fig. 2. The pulse sequence cooling with the same cooling time of 100 ms and the dead time of 30 ms, 40 ms, 50 ms, and 60 ms. The solid curves are the theoretical results.

Figure 3 gives the transmission signal with the cooling time $T_{\rm cool}$ from 40 ms to 160 ms and fixed dead time of 30 ms. It is noticed that all absorption signals reaches stable after 5 pulses for all $T_{\rm cool}$, which implies that the recapture rate is independent of cooling time. The number of cold atoms is determined by the cooling time $T_{\rm cool}$ after fixing the dead time.

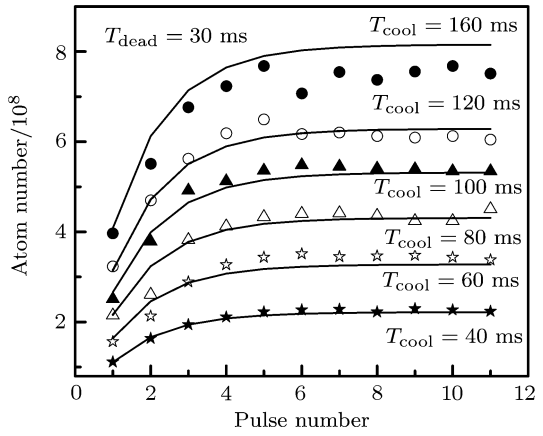


Fig. 3. The pulse sequence cooling with the same dead time of 30 ms and the cooling time of 40 ms, 60 ms, 80 ms, 100 ms, 120 ms, and 160 ms. The solid curves are the theoretical results.

We know that atoms are cooled in the cooling time and the cold atoms fall freely due to the gravity and diffuse in the dead time. If the cold atoms have left away from the capture region of cooling laser, they would not be recaptured by the latter cooling pulses. In order to obtain the best performance for a cold atom clock, we need to consider the recapture rate of cold atoms.

In the ceramic sphere, the loading of cold atoms can be described as:[10]

$$N(t) = N_0(1 - {\rm e}^{-t/\tau_l}), \tag{1}$$

where $N(t)$ is the number of cooled atoms at time t after the cooling laser is switched on, N_0 is the maximum number of cooled atoms, and τ_l is the loading time. With our current experimental conditions, $N_0 = 2 \times 10^9$ and $\tau_l \approx 700$ ms.

The typical temperature of cold atoms in present detuning of cooling light (about -3Γ) is about 100 μK. At this temperature, the gravity dominates the loss of cold atoms during the dead time, as explained in detail in our recent paper on the lifetime measurement of the cold atoms in a glass cell.[7] When the m-th cooling laser is switched off for the time $t' = T_{\rm dead}$, the remnant cold atom number in the glass cell is approximately

$$N'_m(t' = T_{\rm dead}) = N'_m(t' = 0)\frac{r_0^3}{(r_0^2 + \bar{v}^2 t'^2)^{3/2}} \times \left(1 - \frac{3gt'^2}{8r_0} + \frac{g^3 t'^6}{128 r_0^3}\right), \tag{2}$$

where $0 \le t' \le T_{\rm dead}$, as marked in the upper part of Fig. 1 for the first pulse $m = 1$, $N'_m(t' = 0)(m \ge 1)$ is the number of cold atoms in the cell right after the m-th cooling pulse is switched off, r_0 is the initial radius of atom cloud (our setup has $r_0 = 21.5$ mm), $\bar{v}$ is the root mean square velocity of cold atoms, and g is the acceleration of gravity. In this model, we assume that the atomic density is uniform in the glass cell and both temperature and gravity are considered.

Considering that both the loading in pulsed diffuse cooling and the loss of cold atoms in the glass cell can be described with Eqs. (1) and (2), the pulse cooling mechanism gives an empirical formula for the description of the number of captured cold atoms in the glass cell:

$$N_{m+1} = N_0\left(1 - {\rm e}^{-T_{\rm cool}/\tau_l}\right) \times \left(1 + \frac{N'_m(t' = T_{\rm dead})}{N_1}{\rm e}^{-T_{\rm dead}/\tau_{\rm p}}\right), \tag{3}$$

where N_1 corresponds to the captured cold atoms in the first cooling duration, which can be calculated from Eq. (1), $\tau_{\rm p}$ is the lifetime when the remained cold atoms become $1/e$ of the initial value, which is about 60 ms according to the previous lifetime measurement.[7] With this formula, we can calculate the captured cold atoms N_m in each cooling pulse, and thus we can estimate the whole pulse cooling processes with different cooling and dead time.

The solid curves in Figs. 2 and 3 give the number of captured cold atoms after each cooling pulse. The theoretical results are calculated with Eq. (1) for the first pulse and with Eq. (3) for the latter pulses. It is found that the theoretical curves are in good agreement with the experimental data.

In conclusion, the pulsed diffuse cooling of rubidium atoms with different cooling time and dead time has been presented. Based on the experimental results and the pulsed diffuse cooling mechanism, we deduced an empirical formula to simulate the pulse cooling process successfully. The results are important for the estimation of the detailed parameters in pulsed diffuse cooling scheme of the integrating sphere atom clock.

References

[1] Guillot E, Pottie P E and Dimarcq N 2001 *Opt. Lett.* **26** 1639

[2] Cheng H D, Zhang W D, Ma H Y, Liu L and Wang Y Z 2009 *Phys. Rev.* A **79** 0234071

[3] Tremine S, Guerandel S, Holleville D, Clairon A and Dimarcq N 2004 in *Proceedings of the 2004 IEEE International Frequency Control Symposium and Exposition* (Montreal: the Institute of Electrical and Electronics Engineers) p. 65

[4] Tremine S, Guerandel S, Holleville D, Delporte J, Dimarcq N and Clairon A 2005 in *Proceedings of the 2005 IEEE International Frequency Control Symposium and Exposition* (Vancouver: the Institute of Electrical and Electronics Engineers) p. 111

[5] Esnault F X, Perrin S, Tremine S, Guerandel S, Holleville D, Dimarcq N, Hermann V and Delporte J 2007 in *Proceedings of the 2007 IEEE International Frequency Control Symposium*, Joint with the 21st European Frequency and Time Forum (Geneva: Switzerland) the Institute of Electrical and Electronics Engineers p. 1342

[6] Esnault F X, Perrin S, Holleville D, Guerandel S, Dimarcq N and Delporte J 2008 in *Proceedings of the 7th Symposium on Frequency Standards and Metrology (IEEE)* p. 381

[7] Zhang W Z, Wang X C, Cheng H D, Xiao L, Liu L and Wang Y Z 2009 *Chin. Phys. Lett.* **26** 0837031

[8] Zhang W Z, Cheng H D, Liu L and Wang Y Z 2009 *Phys. Rev.* A **79** 0538041

[9] Ma H Y, Cheng H D, Zhang W Z, Liu L and Wang Y Z 2009 *Acta Phys. Sin.* **58** 1569 (in Chinese)

[10] Xiao L, Wang X C, Cheng H D, Zhang W Z, Liu L and Wang Y Z 2010 *Chin. Opt. Lett.* **8** 1