

Temperature determination of cold atoms based on single-atom countings

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Based on the real sense of the time-of-flight, we demonstrate an alternative method of measuring the temperature of cold atoms in magneto-optical traps (MOTs) using a high-finesse optical microcavity, which acts as a pointlike single-atom counter. A cloud of atoms trapped in magneto-optical traps is positioned about 5 mm above the cavity, and the atoms fall freely down through the cavity. The temperature of the cold atoms in the MOT is determined by counting the exact arrival times of the single atoms. A theoretical model based on a ballistic expansion of a cloud of trapped atoms falling in the earth's gravitational field is used to fit the probability distribution of atom arrivals, and the fittings agree very well with the experimental results. This method could be used for systems with little room, where an extra probe beam is hard to involve, or with fewer atoms initially. © 2011 Optical Society of America

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1. INTRODUCTION

Laser cooling and trapping [1] has played an active role in fundamental research and applications from its inception. With magneto-optical traps (MOTs) [2], it is now very easy to obtain samples of cold atoms with temperatures around 100 μ K. The determination of the temperature of the cold atomic sample is one of the most important tasks, because the initial temperature determines many aspects of the succeeding atomic manipulation. In the last two decades, people have proposed several methods for the determination of the temperature. The standard method is called time-of-flight (TOF) [3–6], which is performed by measuring either the absorption signal of the atoms or the fluorescence of the atoms excited by the resonant probe light, or by directly imaging the atom cloud. Other methods have also been developed, such as release–recapture technique [3], forced-oscillation of atomic sample [7], fluorescence spectrum analysis [8], recoil-induced resonance [9], and nonstationary four-wave mixing [10]. Because of its simplicity and reliability, TOF is still the ultimate method of verifying the temperature in many laboratories. This method is routinely based on the measurement of atom samples with large numbers of atoms and for relatively long distances of atom flight. Recently, a sensitive camera has been used in the technique of imaging the expansion, due to the rather small number of atoms in the MOT, and it has been shown to work up to the ultimate limit of a single atom (and a single detected photon) [11]. However, the corrections due to the shape of the probe beam usually need to be considered, which make the whole procedure complex, and the shape of the TOF signal sometimes differs significantly from the one obtained in standard TOF measurements [5].

In this paper, we demonstrate a method that essentially comes from the real sense of the TOF [6]: measuring directly the exact arrival of the atoms one by one with a pointlike atom detector based on our cavity quantum electrodynamics (QED)

[12] system. In 2005, Ottl *et al.* investigated the correlations and counting statistics of an atom laser using a high-finesse optical cavity [13] as a single-atom counter. Since both the intracavity mode and the distance between the cavity and the atom cloud are very well defined, we can, therefore, neglect the probe beam profile or other precise deviations from the geometry of the experiment. Because the microcavity is very small, it can be regarded as a pointlike single-atom detector, so it is not necessary to consider the three-dimensional model, and use, for example, a Monte Carlo simulation to treat the procedure. Moreover, recent theoretical and experimental results demonstrate that single atoms can be detected by a moderate finesse cavity [14,15] or other single-atom detection systems such as microfabricated chips [16], and the method introduced in this paper may be extended to these systems.

2. THEORETICAL MODEL

Figure 1 shows the schematic diagram of our cavity QED experiment. A cold atom sample is trapped just 5 mm directly above a high-finesse optical microcavity. The traditional methods of determining the temperature of the cold atom sample [3–10] are complicated for this system.

We first give a theoretical model to get the distribution of atom arrival times with atoms falling down from the MOT to the cavity. The velocity distribution of atoms in the MOT is a Maxwell–Boltzmann distribution. The temperature, T , of cold atoms in the MOT is determined by the most probable velocity of the cold atoms, σ_v , with $\sigma_v = \sqrt{k_B T/M}$, where M stands for the atomic mass and k_B is the Boltzmann constant. Thus, the Maxwell–Boltzmann velocity distribution of atoms in the MOT can be described by

$$N(v)d^3v = \left(\frac{M}{2\pi k_B T}\right)^{3/2} \exp\left[-\frac{M(v_x^2 + v_y^2 + v_z^2)}{2k_B T}\right] d^3v, \quad (1)$$

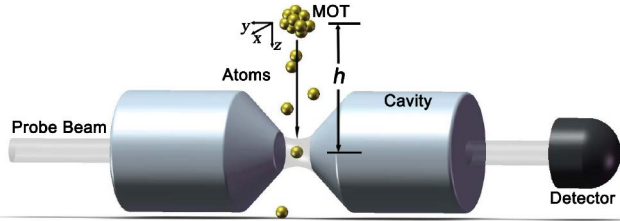


Fig. 1. (Color online) Diagram of experimental setup. Optical cavity is formed by two spherical mirrors with ultrahigh reflectivity. MOT is positioned 5 mm right above the cavity. The system is in a strong coupling regime with the parameters $(g_0, k, \gamma)/2\pi = (23.9, 2.6, 2.6)$ MHz. SPCMs are used to detect the cavity transmission. Atoms fall down freely from the MOT and pass through the cavity.

where v_i ($i = x, y, z$) are the atom velocities along the x , y , and z directions labeled in Fig. 1. The distance between the MOT and the cavity mode is h . Here we have chosen coordinates such that the cavity center is located at $x = y = 0$ and $z_0 = -h$. In order to get the probability distribution of the atom arrivals at the point of the cavity mode, the function of (v_x, v_y, v_z) in Eq. (1) can be transformed to the function of (x, y, z) . Here t is the time when the falling atom arrives at the center of the cavity mode. Let us consider the relationship between the atomic velocity and the position

$$v_z = \left(\frac{1}{2}gt^2 - h\right)/t, \quad v_x = x/t, \quad v_y = y/t, \quad (2)$$

where g is the earth's gravitational acceleration. The Jacobian determinant [6]

$$J = \begin{vmatrix} \frac{\partial v_x}{\partial x} & \frac{\partial v_x}{\partial y} & \frac{\partial v_x}{\partial z} \\ \frac{\partial v_y}{\partial x} & \frac{\partial v_y}{\partial y} & \frac{\partial v_y}{\partial z} \\ \frac{\partial v_z}{\partial x} & \frac{\partial v_z}{\partial y} & \frac{\partial v_z}{\partial z} \end{vmatrix} = \begin{vmatrix} \frac{1}{t} & 0 & \frac{-x^2}{t^2} \\ 0 & \frac{1}{t} & \frac{-y^2}{t^2} \\ 0 & 0 & \frac{1}{2}g + \frac{h}{t^2} \end{vmatrix} = \frac{\frac{1}{2}gt^2 + h}{t^4} \quad (3)$$

is used to transform Eq. (1) to the function of (x, y, t) . We only consider the distribution of the atoms arriving at the cavity mode. In the $x-y$ plane, the area of the microcavity mode is about $47.6\mu\text{m} \times 86\mu\text{m}$ ($2\omega_0 \times l_0$, where ω_0 is the waist of TEM₀₀ and l_0 is the length of the cavity), which is very small. The distance between the MOT and the cavity mode is 5 mm, which is not long in the standard TOF method, but is much larger than the size of the cavity mode. The microcavity can thus be regarded as a pointlike detector (coordinates are $x = 0, y = 0$). We thus obtain the time-dependent probability $P(t)$ for one atom arriving in the cavity mode after it is released from the MOT:

$$P(t) \propto \left(\frac{M}{2\pi k_B T}\right)^{3/2} e^{-\frac{m}{2k_B T}(\frac{1}{2}gt^2 - h)^2} \times \frac{h + \frac{1}{2}gt^2}{t^4}. \quad (4)$$

This distribution is only dependent on the temperature, T , and the height, h . Because the height can be determined with very good precision, the distribution is thus only determined by the initial temperature of the atoms in the MOT. Figure 2 shows some atom-arriving probabilities for different temperatures.

3. EXPERIMENTAL SETUP AND RESULTS

We deal with cesium atoms in this experiment. The system is intentionally designed for cavity QED research, but the method introduced here elegantly provides an alternative way to

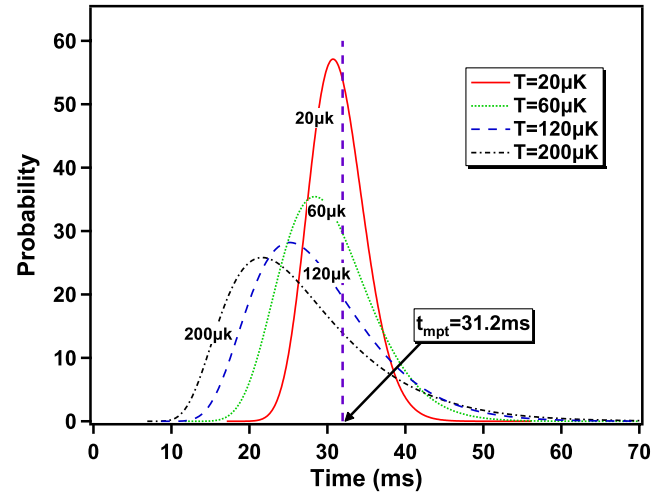


Fig. 2. (Color online) Probability distribution of atom arrivals at different time with different temperatures ($T = 200\mu\text{K}, 120\mu\text{K}, 60\mu\text{K}, 20\mu\text{K}$) according to Eq. (4). Parameters: $M = 2.21 \times 10^{-25}$ kg, $h = 5$ mm, $k_B = 1.38 \times 10^{-23}$ J/K, $g = 9.8$ m/s².

demonstrate the temperature determination by single-atom countings. The interaction between the high-finesse cavity and the atoms is so strong that a single atom falling through the cavity mode will have a big effect on the cavity transmission. The arrival time of a single atom can be obtained. The probability of the atom arrivals can be fitted by the above-mentioned model; thus the temperature of the atoms in the MOT can be determined.

The high-finesse optical cavity [17] is formed by two spherical mirrors with ultrahigh reflectivity, and it is adjusted to resonate with the cesium D_2 ($6^2S_{1/2}, F = 4 \rightarrow 6^2P_{3/2}, F' = 5$) transition. About 10^5 atoms are collected 5 mm above the cavity in the MOT [18]. The MOT size is about $200\mu\text{m}$. The finesse of the cavity is 330,000. The optimum atom-photon coupling rate is $g_0 = 2\pi \times 23.9$ MHz, while the cavity decay rate and the atom decay rate are $k = 2\pi \times 2.6$ MHz and $\gamma = 2\pi \times 2.6$ MHz, respectively. The system obviously operates in a strong coupling regime, and the arrival time of single atoms at the center of the cavity can be measured precisely [19].

Figure 3 is a typical transmission signal from the cavity by single-photon counting modules (SPCMs, PerkinElmer, USA). The probe light is resonant with the cavity, with the average intracavity photon number being 1. It shows that there are eight atom transits in this drop. The inset in the figure is the enlarged view in the time scale for one atom transit, which clearly shows the details of a single atom entering the cavity and then leaving. The solid blue curve in the inset is the fitting of the cavity transmission in weak-field approximation [20]. The atom's arrival time can thus be measured. We repeat the measurement by this process and thus can get the probability distribution of one atom's arrival. The probability distribution based on a total of 664 atom countings is shown in Fig. 4(a) (solid red bars). The blue dashed line is the theoretical fitting according to Eq. (4). We can see that the theoretical fitting is in good agreement with the experimental results, and the temperature of the atoms in the MOT is determined as $T = 256 \pm 3\mu\text{K}$. It should be noted that the profile of the fitting curve is different from the standard TOF signal [5]. In the above measurement, the intensity of the cooling beam is 12.5mW/cm^2 , which is detuned from the $6^2S_{1/2}$,

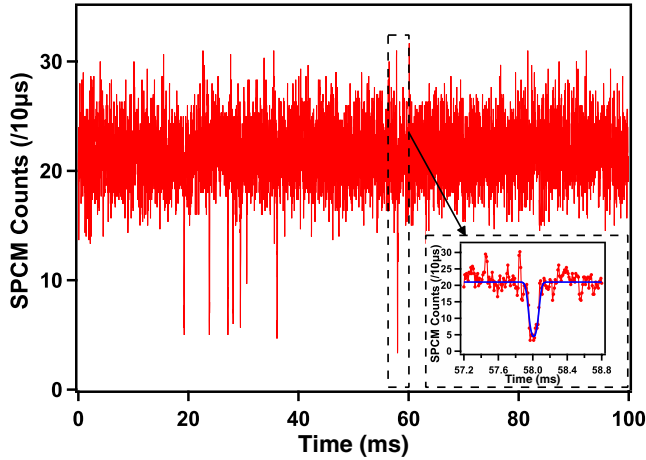


Fig. 3. (Color online) Typical atom transit signal when atoms fall down freely one by one. Eight atoms are observed in this drop and five atoms in average. Inset shows enlarged view of one of the transits in a time scale that shows the details of the transit. The solid blue curve is the fitting according to the cavity transmission in weak-field approximation.

$F = 4 \rightarrow 6^2P_{3/2}$, $F' = 5$ transition with $\Delta = -12$ MHz, and the repumping beam with 9.4 mW/cm^2 is resonant with $6^2S_{1/2}$, $F = 3 \rightarrow 6^2P_{3/2}$, $F' = 4$. The gradient of the quadrupole magnetic field is about 9.2 G/cm . The temperature is relatively high because it is our first measurement and we did not make any optimization on the MOT. By decreasing the intensity of the cooling beam and the repumping beam to 8.8 mW/cm^2 and 8.2 mW/cm^2 , respectively, we have made another measurement with the prospective lower temperature, and the results are shown in Fig. 4(b). The temperature is about $T = 117 \pm 8 \mu\text{K}$, which is approaching the Doppler cooling limit of the cesium atoms. The temperature was also measured in the cavity QED experiment with the method of fluorescence spectrum analysis at relative different experimental parameters: $\Delta = -10$ MHz, $P = 3\text{--}4 \text{ mW/cm}^2$, and $B = 25 \text{ G/cm}$, and the temperature was $T \sim 100 \mu\text{K}$ [19]. Because the beam intensity was even lower and the gradient of the quadrupole magnetic field was larger compared with our system, the temperature was slightly lower and the result was indeed consistent with the temperature we obtained here. We can see from Fig. 2 that if the temperature is getting even lower, such as $20 \mu\text{K}$, the distribution will be much narrower and the distribution profile will tend toward the symmetrical. The peak of the distribution is approaching the most probable time corresponding to the free-falling time for a 5 mm distance with zero initial velocity, i.e., $t_{\text{mpt}} = 31.95 \text{ ms}$ (see the vertical dashed line in Fig. 2).

There are some uncertainties that cause the deviation of the temperature measurement of atoms in the MOT. From the experimental results in Fig. 4, the deviation is about a few microkelvins. Reasons would include systematic errors, such as net initial velocity, residual magnetic fields, slight intensity imbalances of the MOT beams, imperfect polarization, and intensity gradients. We need to adjust the MOT's status, including the balances of the MOT beams and the compensation for residual magnetic field, to ensure that the atoms are freely falling after shutting off the MOT. The optimization of the MOT status is dependent on the adjusting process, and that is why the precision of the temperature measurement is case by case. Another reason is the measurement uncertainties, because the

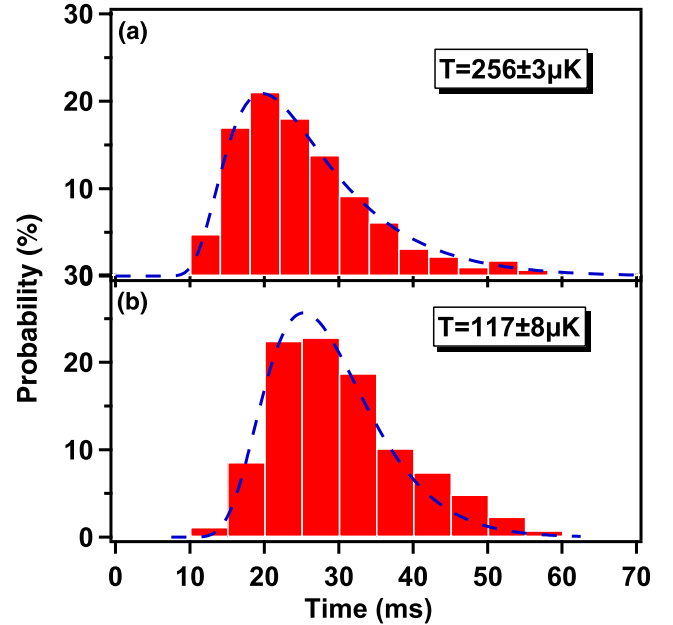


Fig. 4. (Color online) Probability distribution of atom arrivals based on total of 664 times of transits (red solid bars) fitted by the theoretical model according to Eq. (4) (dashed blue line) in two different experimental situations. The corresponding temperatures of atoms in the MOT are (a) $T = 256 \pm 3 \mu\text{K}$ and (b) $T = 117 \pm 8 \mu\text{K}$, according to the fittings. Experimental parameters for (a) detuning of cooling beam, $\Delta = -12$ MHz; optical intensity of cooling and repumping beams, 12.5 mW/cm^2 and 9.4 mW/cm^2 , respectively; and gradient of quadrupole magnetic field, 9.2 G/cm . Corresponding parameters for (b) $\Delta = -10$ MHz, 8.8 mW/cm^2 , 8.2 mW/cm^2 , and 9.2 G/cm , respectively.

numbers of transition signals have a remarkable effect on the precision of the temperature. In the experiments mentioned above, a total of 664 times of transit were detected to get the atom temperature. In principle, increasing the number of measurements will improve the measurement precision.

4. CONCLUSION

In conclusion, we have demonstrated a method to determine the temperature of the atoms in the MOT by just counting the single-atom arrivals with a high-finesse optical cavity, which is strongly coupled to the atoms. Like some new TOF techniques, the advantages of the method given in this paper are: (1) it works well, even for a small number of atoms; and (2) the shape of the probe beam and the geometry-induced deviation do not need to be considered. The microcavity is a natural pointlike single-atom detector.

We have finished the measurements of the distributions of the arrival times in two experimental situations. The distributions are in agreement with the theory. Accordingly, we get $T = 256 \pm 3 \mu\text{K}$ and $T = 117 \pm 8 \mu\text{K}$ for these two tests. The experiment reported here provides a good way of determining the temperature of cold atoms based on single-atom countings. However, in our experiment, the single-atom arrivals are measured in the strong coupling system with a high-finesse optical cavity. There is, of course, little justification in building a microcavity just for measuring the temperature. Actually, the requirement of a high-finesse cavity and strong coupling is not necessary. The method may be extended to other systems, such as microfabricated chips [16] or even a

moderate finesse cavity [14,15], where a single atom can be detected.

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