Temperature measurement of cold atoms using single-atom transits and Monte Carlo simulation in a strongly coupled atom-cavity system

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We investigate the transmission of single-atom transits based on a strongly coupled cavity quantum electrodynamics system. By superposing the transit transmissions of a considerable number of atoms, we obtain the absorption spectra of the cavity induced by single atoms and obtain the temperature of the cold atom. The number of atoms passing through the microcavity for each release is also counted, and this number changes exponentially along with the atom temperature. Monte Carlo simulations agree closely with the experimental results, and the initial temperature of the cold atom is determined. Compared with the conventional time-of-flight (TOF) method, this approach avoids some uncertainties in the standard TOF and sheds new light on determining temperature of cold atoms by counting atoms individually in a confined space. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4869031]

Magneto-optical traps (MOTs) make it possible to cool atoms toward the Doppler limit. Measuring the temperature of cold atoms is important in cold atomic physics. Until now, there have been few effective methods to determine the temperature of atoms in a MOT, such as the time-of-flight (TOF),[1–4] which is based on measuring either the absorption or the fluorescence of the atoms or directly imaging the atom cloud.[5–9] The TOF method is widely used in verifying the temperature of cold atoms owing to its simplicity and reliability. It works well for determining the temperature of atom clouds with large numbers of atoms and for relatively long distances. For shorter distances, one should consider some modifications of the TOF signal.[3] However, factors such as the spatial shape of the probe beam, the intensity and the fluctuation of the probe beam, and the number of initial atoms must be taken into account. These complicate the whole measurement procedure and introduce uncertainties.

A strongly coupled cavity quantum electrodynamics (QED) system provides the means for sensitively detecting single atoms, making it possible to extract the temperature. In 2011, a method of determining the temperature by using a statistical atom distribution was proposed;[10] however, this basically stemmed from the TOF method.[4] In this Letter, we develop an approach for determining temperature based on the absorption profile from cavity transmissions of single-atom transits in a strongly coupled cavity QED system. A corresponding Monte Carlo simulation is also performed for comparison. The experimental results agree well with the simulation.

The central part of the experimental setup is shown in Fig. 1. The MOT and microcavity are placed in the ultra-high-vacuum cell with a pressure of about 1×10^{-10} Torr. Roughly, 4×10^4 atoms are initially accumulated in a MOT located 6 mm above the center of a microcavity. The atoms

can be further cooled by polarization gradient cooling (PGC). The cold atoms drop freely down under the action of gravity. Only a few atoms enter into the cavity mode for each release, and most of the atoms fall elsewhere. Those atoms falling into the cavity can be monitored individually since each atom strongly couples to the cavity field and induces a tremendous change in the cavity transmission. The high-finesse Fabry-Perot cavity is made with two super-polished spherical mirrors with a cavity length of 86.8 μm. The waist of the intra-cavity TEM_{00} mode at 852.356 nm is $\omega_0 = 23.8$ μm, and the finesse of this cavity is 3.3×10^5. The system operates in the strong coupling regime with the parameters $(g_0, \kappa, \gamma) = 2\pi \times (23.9, 2.6, 2.6)$ MHz for the TEM_{00} mode, where g_0 is the peak atom-field coupling coefficient between the cavity TEM_{00} mode and atoms, and κ and γ are the cavity decay rate and atom decay rate, leading to 0.006 and 0.024 of the critical photon and atom numbers, respectively.[11]

A weak probe beam at 852 nm is tuned close to the transition of the cesium D_2 line. An auxiliary diode laser at 828 nm, which is tuned by six free-spectral ranges (FSRs)
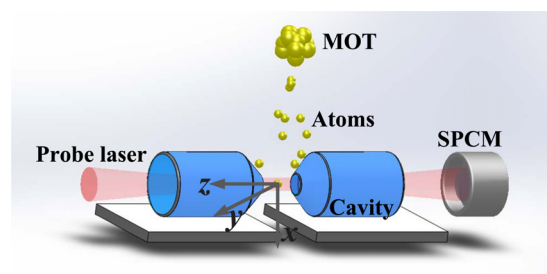

FIG. 1. Schematic diagram of the experiment. The MOT is 6 mm above the center of the cavity. The single-photon counting module is the single-photon detector. Atoms from the MOT fall freely when the cooling laser and magnetic field are switched off. Most atoms hit the top of the mirror or leave the gap between the two mirrors, while only a few atoms couple to the cavity mode.

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from the probe laser, is used to keep the stability of the cavity length, which is itself stabilized relative to the cesium D_2 line by a frequency chain system.[12] The transmitted light power of the cavity is normally of the order of picowatts. This is measured by single-photon counting modules (SPCM-AQR-15, PerkinElmer) with an overall photon detection efficiency of $\eta = 0.075$, including the cavity escape efficiency, the propagation efficiency, and the detection efficiency. When an atom falls into the cavity mode, the transmission spectra can be measured in real time by recording large fractional modifications of the cavity field, and information on the atom's "trajectory" can thus be retrieved.[13–16]

Figure 2(a) shows a typical transmission spectrum from a single atom release, for which every peak corresponds to a transit signal of a single atom. The lower the peak becomes the stronger the coupling between the atom and cavity is, which depends on the location of the atom inside the cavity.[14] The corresponding spectra of the Monte Carlo simulation are shown in Fig. 2(b), in which the initial parameters of our practical setup have been used. The simulation results depend on the initial temperature T, which is the key unknown parameter. Other parameters include the initial atomic number N in the MOT, the diameter D and location of the atom clouds of the MOT, and the cavity length L. The average intracavity photon number is set to $n \approx 1$. The simulation also relies on the detuning between the probe light and atomic transition Δ_{pa}, the cavity and atom Δ_{ca}. In Fig. 2(b)), an initial temperature of 24.4 μK was chosen. Other parameters are as follows: $N = 4 \times 10^4$, $D = 350\,\mu m$, $(x, y, z) = (0, 0, -6\,mm)$, $L = 86.8\,\mu m$, and $\Delta_{ca} = \Delta_{pa} = 0\,MHz$ in terms of our system. We found that the experimental result in Fig. 2(a) and the simulation in Fig. 2(b) are similar but not exactly identical, although both are based on the same experimental conditions. The reason is that for each release cycle, the falling status of each individual atom, including its initial position, direction, and velocity, cannot be controlled precisely. Thus, it is impossible to have a simulation that exactly duplicates the experiment.
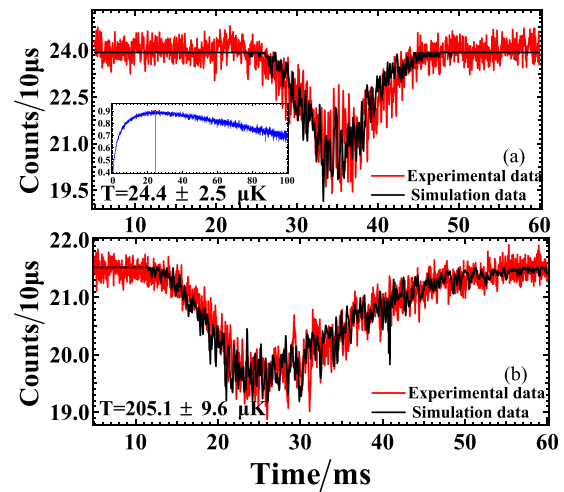
FIG. 3. Superposed spectrum obtained by adding all the atom transits for a certain temperature. Red curve: experimental data; black: Monte Carlo simulation. (a) Spectra with PGC. The inset blue is the correlation coefficient as a function of simulation temperature. (b) Spectrum without PGC stage.

The experiment can be repeated by releasing atoms and obtaining a large number of atom transits as in Fig. 2(a). The profile of the transmission spectrum can then be retrieved eventually by superposing all the falling events, as shown in Fig. 3. The red curve shows this superposed spectrum, which actually reveals the cavity-enhanced absorption for 1600 falling atoms for a certain temperature. This spectrum is different from the absorption signal from the usual TOF experiment. The absorption spectrum contains the following information: The transmission depth of each atom, which is determined by the effective coupling from the position of a single atom in the cavity mode and the initial velocity distribution of the atoms given by the initial temperature of the MOT. In the same manner, the corresponding Monte Carlo simulation can be performed by using the same number of atom transits as in the experiment, and the results are shown with the black curve in Fig. 3. The spectra of the simulation agree well with those of the experiment. The parameters for the simulation are the same as those for Fig. 2(a), except the initial temperature. The process of the Monte Carlo simulation is as follows. The atoms are randomly selected from 4×10^4 samples, in compliance with the Maxwell-Boltzmann distribution. The atoms fall down one by one under gravity. Then a judgment is made on whether the individual atom enters the cavity mode. The probability of the atoms entering the cavity mode is related to the geometry of the cavity, such as the length of the cavity L and the size of the cavity mirrors, and the initial temperature of the atoms in the MOT. Most of the atoms hit the top of the mirror substrates or the mirror faces, and only a few atoms enter into the mode. For those atoms entering the cavity mode, the transmission spectra are obtained according to theory. For example, there are on average about 24 atoms out of 4×10^4 samples that can survive the total journey for our system at a temperature around 24.4 μK. In this way, we get the transmission spectrum shown in Fig. 2(b). This Monte Carlo process just simulates what we have done in one experimental cycle (see Fig. 2(a)). We repeat this process to simulate the cyclic process of atom recapture and release. About
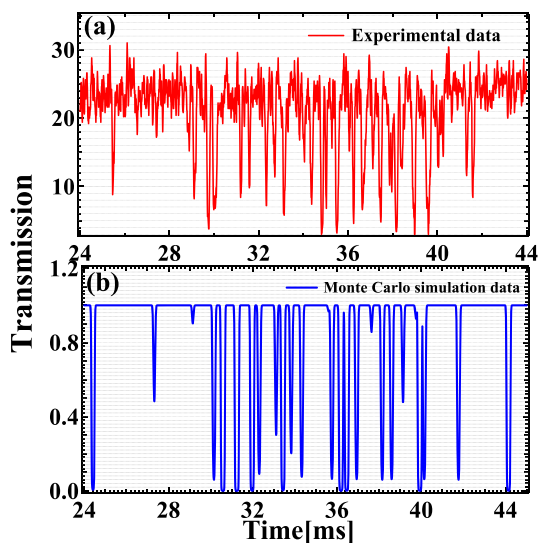

FIG. 2. (a) Cavity transmission spectra directly recorded by single-photon counting modules for one release. (b) Monte Carlo simulation corresponding to (a) with the same conditions as in the experiment.
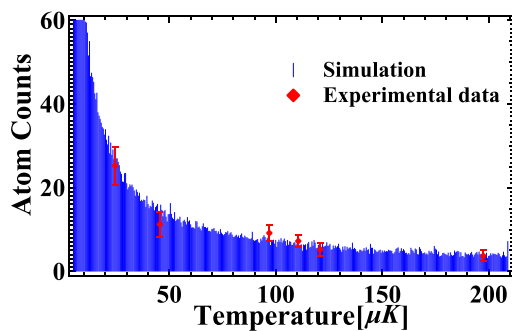
FIG. 4. Monte Carlo simulation of the number of atoms entering into the cavity mode as a function of temperature (blue histogram). The initial number of atoms in the MOT is 4×10^4. The red diamonds are the experimental measurement.

2.6×10^6 samples are used, among which 1600 atoms successfully fall into the cavity to form the envelope of the superposed signals as shown in Fig. 3 (black line). Similarly, simulation of the other atom samples for different temperatures can use the above process.

To find out which temperature is closest to that corresponding to the recorded experimental spectrum in Fig. 3, we complete the Monte Carlo simulations by changing the temperature parameter T with a step of $0.05\,\mu K$, and for each simulation we obtain the correlation coefficient R between the experimental result and the simulation. The inset blue curve in Fig. 3(a) shows R as a function of temperature with a maximum coefficient of $R = 0.9$, and the corresponding optimal temperature for the sample is $24.4 \pm 2.5\,\mu K$. The temperature of the initial atoms in the MOT is thus determined. Then, we perform another measurement corresponding to a higher temperature (Fig. 3(b)) without PGC. Using the same process as before, we find the temperature of the initial atoms in the MOT to be $205.1 \pm 9.6\,\mu K$. Specifically, in the PGC stage, the intensities of the cooling laser beams in Fig. 3(a) are reduced to 50% of the original value, and the detuning of the cooling laser is passively changed to -5.7γ within 15 ms.

Clearly, the probability of an atom falling into a cavity is closely related to the initial temperature, and the number of atoms entering into the cavity is temperature-dependent. The lower the temperature, the more atoms fall into the optical cavity. The Monte Carlo simulation is again used to find out the relation between the number of atoms entering the cavity and the initial temperature of the MOT, which is shown as the blue histogram in Fig. 4. The graph clearly shows that the number of atoms entering the cavity exponentially decreases as the temperature is increasing. The average number of atoms entering into the microcavity for six different temperatures has been counted (see red diamonds in Fig. 4), and the results are in accordance with the simulation.

In summary, we have presented a method to determine the initial temperature of the cold atoms in the MOT based on the cavity transmission spectrum in a strongly coupled cavity QED system, which sheds new light on determining the temperature of cold atoms by counting atoms individually. The approach is quite different from previous methods such as the TOF. The result of the Monte Carlo simulation is in good agreement with the experimental measurement. The initial temperature of the cold atoms is determined by searching for the best correlations between the experimental transmission spectrum and the Monte Carlo simulations. The regular cavity mode and deterministic single-atom measurement reduce some uncertainties in conventional TOF measurement. The method is based on statistical measurement with thousands of atom transits, and improving the stability of the whole system and increasing measurement times can improve the measurement precision.

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