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Sensitive Detection of Individual Neutral Atoms in a Strong Coupling Cavity QED System *

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We experimentally demonstrate real-time detection of individual cesium atoms by using a high-finesse optical micro-cavity in a strong coupling regime. A cloud of cesium atoms is trapped in a magneto-optical trap positioned at 5 mm above the micro-cavity center. The atoms fall down freely in gravitation after shutting off the magneto-optical trap and pass through the cavity. The cavity transmission is strongly affected by the atoms in the cavity, which enables the micro-cavity to sense the atoms individually. We detect the single atom transits either in the resonance or various detunings. The single atom vacuum-Rabi splitting is directly measured to be $\Omega = 2\pi \times 23.9$ MHz. The average duration of atom-cavity coupling of about 110 µs is obtained according to the probability distribution of the atom transits.

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Sensitive detection of single atoms has always been a difficult task during the development of atomic physics.[1] Fortunately, cavity quantum electrodynamics (CQED)[2,3] in strong coupling regimes provide a powerful tool to detect single atoms sensitively. In the early period, Kimble *et al.*[4,5] observed the atoms from a thermal atom beam by means of a high-finesse optical cavity. In the experiment the average atom number $N < 110$ was detected, however a deterministic single atom could not be observed due to the large velocities of thermal atoms. The durations of thermal atoms in the cavity are only several microseconds. This situation has changed until the naissance of the cold atom technology. In 1996, Mabuchi *et al.*[6] investigated the real-time detection of individual atoms falling through a high-finesse optical Fabry–Perot cavity. Later, Hood *et al.*[7] observed the single atoms passing through a cavity with various detunings and the "vacuum-Rabi" splitting was obtained. Other schemes such as optical fountain were also used to launch cold atoms into micro-cavities to reach the strong coupling between atoms and photons.[8] Although in free space the substantial extinction of a light beam by a single atom was observed, which could be used to sense the single atom,[9] the strongly coupled cavity QED can greatly enhance the ability of single atom sensing, not only for the sensitivity of a single atom[7] but also for the spatial resolution.[10] With the help of spatial symmetry breaking of the tilted high-order transverse cavity mode, the measurement of spatial resolution of single atoms can be essentially improved.[11] The detection of individual atoms can be used to investigate the statistical properties of the thermal atoms or an atom laser.[12]

As an important and subtle system, cavity quantum electrodynamics in the strong coupling regime has greatly promoted the development of quantum optics and quantum information science[13] during the past two decades. Besides the single atom detection, it has been used in diverse areas such as the generation of deterministic and controllable single-photon sources.[14−16] Strongly coupled CQED has comprehensively improved the performance of single atom detection and quantum state control. By using the vacuum-stimulated Raman adiabatic passage (v-STIRAP), quantum states can be generated, such as the well-defined single photon state[16] and quantum entangled state between atoms and photons.[17] The strong coupling is also necessary to achieve the reversible mapping of quantum states between atoms and photons, which provides the basis for quantum optical interconnects and is a fundamental primitive for networks.[18]

A common and effective method to achieve strong coupling is to reduce the effective mode volume of cavity. The optimal coupling coefficient g_0 between atoms and photons is $g_0 = d\sqrt{\hbar\omega/2\varepsilon_0 V_m}$, where d is the atomic matrix element, ω the transition frequency, V_m the cavity mode volume. For a real system[19] there are two decays, i.e. the atomic dipole decay rate γ

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and the cavity decay rate κ. When the coupling coefficient g_0 is larger than the decay rates γ and κ, the strong coupling between atoms and cavity is achieved. The detuning between cavity and atom is described by $\Delta_{\rm ca} = \omega_{\rm cavity} - \omega_{\rm atom}$ and the detuning between probe and atom is $\Delta_{\rm pa} = \omega_{\rm probe} - \omega_{\rm atom}$. The cavity transmission in the weak-field limit of small excitation is

$$\begin{aligned} T(x,y) =&\kappa^2(\gamma^2+\Delta_{\rm pa}^2)\times\Big\{\big[g_{\rm eff}(x,y)^2-\Delta_{\rm pa}^2\\ &+\Delta_{\rm ca}\Delta_{\rm pa}+\gamma\kappa\big]^2\\ &+(\kappa\Delta_{\rm pa}+\gamma\Delta_{\rm pa}-\gamma\Delta_{\rm ca})^2\Big\}^{-1}, \end{aligned} \quad (1)$$

where the effective coupling coefficient is $g_{\rm eff}(x,y) = g_0\Psi_{m,n}(x,y,z)/\Psi_{0,0}(0,0)$. The mode functions read

$$\begin{aligned} \Psi_{m,n}(x,y) =&C_{m,n}\exp\Big(-\frac{x^2+y^2}{w_0^2}\Big)\\ &\times H_m\Big(\frac{\sqrt{2}x}{w_0}\Big)H_n\Big(\frac{\sqrt{2}y}{w_0}\Big), \end{aligned} \quad (2)$$

where $C_{m,n} = (2^m2^nm!n!)^{-1/2}(w_0^2\pi/2)^{-1/2}$ and $H_{m,n}$ are the corresponding Hermite polynomials of order m and n; w_0 is the waist of the cavity mode; λ is the wavelength.

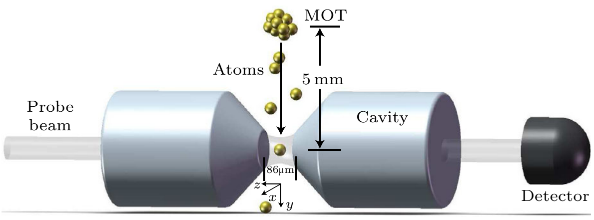

Fig. 1. (Color online) Schematic of the experimental setup. The length of the cavity is 86 μm. The finesse of cavity is $F = 330000$ and the parameters of the system are $(g_0,\kappa,\gamma) = 2\pi\times(23.9, 2.6, 2.6)$ MHz. The MOT with about 10^5 atoms is positioned at 5 mm above the cavity. The atoms fall down and through the cavity mode after shutting off the MOT and the transmissions of the cavity are detected by the SPCMs.

In this study, we demonstrate the ultra-sensitive detection of individual cesium atoms passing through a high-finesse optical micro-cavity. The distinct result is that both the position and the velocity of the individual atoms are determined with high precision and a theoretical model is used to fit the experimental data. The micro-cavity is a Fabry–Perot cavity composed of two spherical mirrors with ultrahigh reflectivity and the length of the cavity is 86 μm. The system is shown in Fig. 1. The MOT with about 10^5 atoms[20−22] is located at 5 mm above the cavity. The waist of TEM_{00} mode is $w_0 = 23.8$ μm. The finesse of cavity is $F = 330000$ and the parameters of the system are $(g_0,\kappa,\gamma) = 2\pi\times(23.9, 2.6, 2.6)$ MHz.[23] The optimal coupling coefficient g_0 is much larger than the cavity decay rate κ and the atom decay rate γ, corresponding to the critical atom number $N_0 = 2\kappa\gamma/g_0^2 = 0.024$ and critical photon number: $m_0 = \gamma^2/(2g_0^2) = 0.006$, so the CQED system reaches the strong coupling regime. The intra-cavity mean photon number is $m \approx 1$. The cavity transmission is detected by single photon counting modules (SPCMs, PerkinElmer).[24,25] The probe light is adjusted to resonance with the cesium D2 ($6^2S_{1/2}$, $F = 4 \rightarrow 6^2P_{3/2}$, $F' = 5$) transition (wavelength is $\lambda = 852.36$ nm).

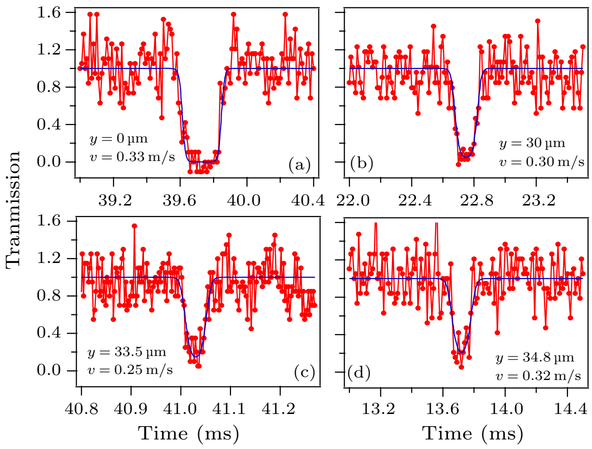

Fig. 2. The cavity transmissions versus time with atoms passing through the TEM_{00} mode of cavity for $\Delta_{\rm ca} = \Delta_{\rm pa} = 0$. The intra-cavity mean photon number is $m \approx 1$. The atom is released at t=0 with shutting off the MOT. The position and the velocity of the atom for each transit are shown.

The coupling coefficient between the cavity TEM_{00} mode and atom is dependent on the spatial position and can be described by the relation $g(\boldsymbol{r}) = g_0\exp[-(x^2+y^2)/w_0^2]\cos(2\pi z/\lambda)$, where x, y and z are the spatial coordinates shown in Fig. 1. It is found that the coupling coefficient can be changed from 0 (atom is at a node) to maximum (atom is at an antinode), depending on the location of the atom. When both the detunings are set to be $\Delta_{\rm ca} = \Delta_{\rm pa} = 0$, the empty cavity transmission keeps the maximum because of the resonance between the cavity and probe light. As the atom enters into the cavity, depending on its exact location, the cavity transmission will decrease since the strong coupling between the cavity and the atom causes the Rabi splitting and the probe beam will not be resonant to the cavity anymore. The cavity transmission will recover later to the maximum as the atom leaves the cavity. Figure 2 shows the typical four transits. The red dots and lines are experimental data and the blue solid curves are theoretical fitting according to Eq. (1). The process described above is clearly seen and the exact time when the atom arrives at the center of the cavity mode can be determined after it is released at $t = 0$. The experimental results show that the depth of each dip is different. From Fig. 2(a)–2(d), we can find that the coupling coefficients decrease. In Fig. 2(a) the transmission decreases to zero, which corresponds to $g_{\max}(\boldsymbol{r}) \approx g_0$ and implies that the atom almost flies through an antinode of the TEM$_{00}$ mode, i.e, $y = 0$. From the depth of the dip, we can thus determine the position of the atom in the y direction. The shallower the dip is, the farther the atom is from the cavity axis. In Fig. 2(d), y is about 34.8 µm, which is even larger than the radius of the mode waist. This means that even if the atom is far away from the cavity mode, it can still be detected sensitively. Actually, according to the theory, based on our system, even if the atom has 39 µm off-axis, 50% of the dip could still be observed. By measuring the transit time precisely, the velocity of the atom flying through the cavity can also be determined, as shown in Fig. 2.

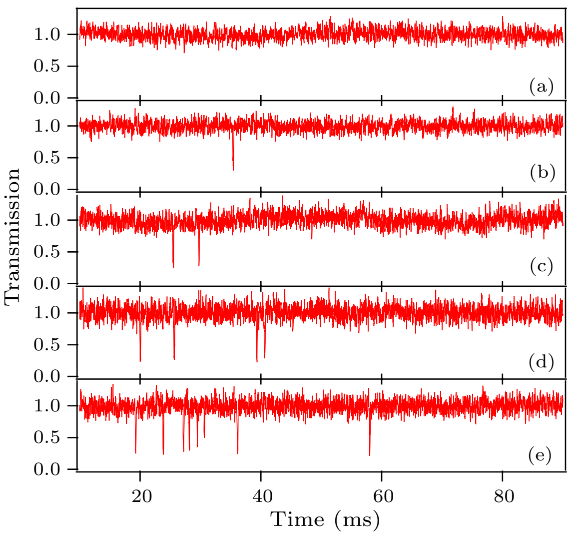

Fig. 3. The time-varying cavity transmissions with repetitious drops. There are 0, 1, 2, 4 and 8 atoms [(a)–(e)] flying through the cavity mode, respectively.

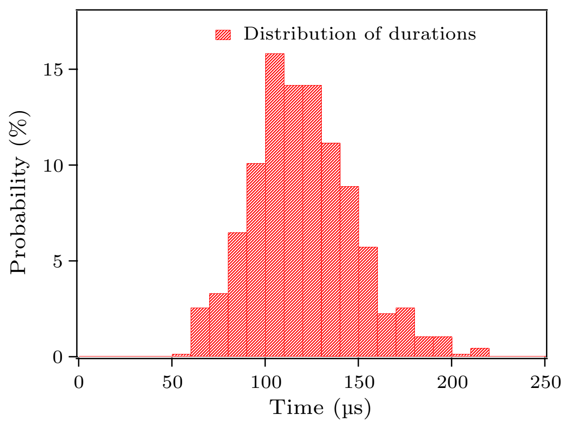

Fig. 4. Histogram of atom durations inside the cavity. The duration is obtained by the full width half maximum of the dips. The average atom duration is about 110 µs.

We have measured the time-varying cavity transmission spectra with repetitious atom droppings, as shown in Fig. 3. Without atoms, the empty cavity transmission is shown in Fig. 3(a). From Figs. 3(b)–3(e), one can see 1, 2, 4 and 8 atoms flying through the cavity mode, respectively. Single atoms can thus be counted one by one and the micro-cavity here acts just as a point-like single atom detector. From Fig. 3 we can see that the arrival times and the dip depths of the atom transits are stochastic. We can change the average atom number passing through the cavity mode every drop by adjusting the initial atom number of the atoms in the MOT and the falling status. There is an average of three atoms for every drop in our experiment. We have finished 220 drops and obtained a total of 664 atom transits. The histogram of atom transits is displayed in Fig. 4, which shows that the average single atom duration inside the cavity is about 110 µs.

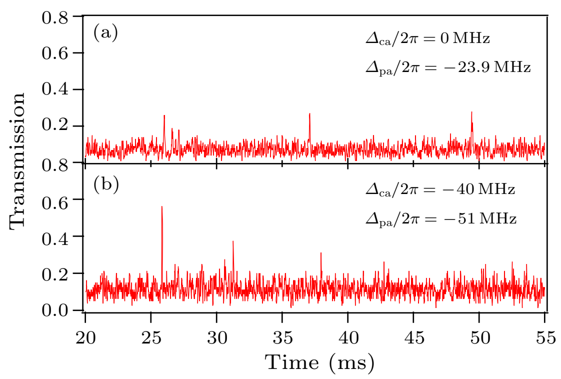

Fig. 5. The cavity transmission spectra with different probes and cavity detunings when the atom passes through the cavity mode. (a) $\Delta_{ca}/2\pi = 0$ and $\Delta_{pa}/2\pi = -23.9$ MHz $= -g_0$, (b) $\Delta_{ca}/2\pi = -40$ MHz and $\Delta_{pa}/2\pi = -51$ MHz.

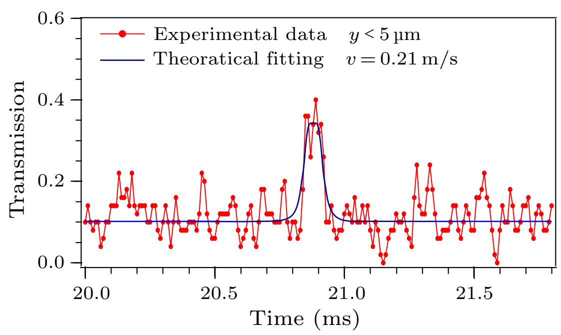

Fig. 6. The close look of the cavity transmission with the detunings $\Delta_{ca}/2\pi = 0$ and $\Delta_{pa}/2\pi = -23.9$ MHz $= -g_0$. The red dots and line are the experimental results while the blue curve is the theoretical fitting according to the experimental parameters.

A single atom can also be detected in the case of non-resonance. We present the cavity transmission spectra with different detunings in Fig. 5. With $\Delta_{ca}/2\pi = 0$ and $\Delta_{pa}/2\pi = -23.9$ MHz $= -g_0$, the cavity transmission keeps at low level when there is no atom in the cavity. As the atom flies through the cavity, we obtain a transmission peak, as shown in Fig. 5(a). Similar observation of the cavity transmission with the detuning of $\Delta_{ca}/2\pi = -40$ MHz and

$\Delta_{pa}/2\pi = -51$ MHz is shown in Fig. 5(b).

According to the experimental parameters, the maximum coupling coefficient is $g_0 = 2\pi \times 23.9$ MHz. Figure 6 is the close-up view of the cavity transmission for the detunings of $\Delta_{ca}/2\pi = 0$ and $\Delta_{pa}/2\pi = -23.9$ MHz. The peak in the center is the left peak due to the vacuum Rabi splitting, which can be seen clearly. The blue curve is the theoretical fitting according to our experimental parameters and the weak-field approximation. The experimental result agrees well with the theoretical simulation. Vacuum Rabi frequency $\Omega = 2g_0 = 2\pi \times 47.8$ MHz is thus confirmed directly.

In summary, we have experimentally investigated the sensitive measurement of individual neutral cesium atoms based on a strong coupling CQED system. The high-finesse optical micro-cavity can sense the single atom even if the atom is far away from the center of the cavity mode. The position and the velocity of the atom are both determined by the transmission spectra of the cavity. The average duration of the single atom in the cavity is about 110 μs. By setting the proper cavity and probe detunings, the transmission peak due to the vacuum Rabi splitting is observed directly, which confirms the strong coupling interaction and the vacuum Rabi frequency $\Omega = 2g_0 = 2\pi \times 47.8$ MHz. Such a strong coupling CQED system can be used for demonstrating the quantum manipulation and quantum measurement on the single quanta level.

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