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REVIEW ARTICLE

Experimental progress in the measurement and control of single atom trajectory

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In this review article, the progress and recent developments in the measuring and controlling of single atom trajectories are reviewed. With the development of laser cooling and trapping technology, it is possible to achieve the measurement and control of single atom trajectory experimentally. The experiment of tracking a single atom trajectory with high resolution and the endeavor of eliminating the degeneracy of the trajectories are then introduced.

Keywords single atoms, trajectory, laser cooling and trapping, cavity QED

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1 Introduction

It is well known that matter is made up of atoms. However, half a century ago, there were some physicists who did not believe that the single atom existed in reality even if quantum mechanics had been established. As Schrödinger said in 1952, "···We never experiment with just one electron or atom or (small) molecule. In thought-experiments we sometimes assume that we do; this invariably ridiculous consequences···." [1]. Those people questioned the existence of the atom as it was impossible to do experiments with single atoms and nobody could see the isolated single atoms with his own eyes! However, this situation has been changed with the development of laser cooling and trapping techniques in the last decades, such as magneto–optical trap (MOT) [2, 3] which provide the effective tools to get neutral cold atoms and makes it possible to control the external and internal state of single particles [4, 5]. The way to realize the real-time and deterministic manipulation of neutral atoms is an important issue. The control of single atoms provides not only a method for investigating the fundamental phenomena in quantum optics and atomic physics, such as the vibration excitations of trapped Bose–Einstein condensates [6], the decay of coherent oscillations of atoms in an optical lattice [7] and strongly coupled cavity quantum electrodynamics (cavity QED) which offers the possibilities for deterministically controlling the atom–photon interactions on single quanta level [8, 9], but also an effective approach to demonstrate many applications, such as quantum information [10–12] and quantum metrology [13–15]. However, it is a big challenge to control and measure the single atom trajectory with high spatial and temporal resolutions. In free space, due to the diffraction limit of the trap beam, the size of the micro-trap is on a scale of micrometers [16–18], thus the precision of atom position is limited by the minimum size of the

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optical trap, which has reached about 1 μm by a complex objective with large numerical aperture [19]. An optical microcavity can be used to improve the detection sensitivity and the position measurement precision of a single atom, and eventually to track the single atom trajectory in real time with high spatial resolution which is beyond the minimum size of the micro-trap [20]. The idea is to detect the transmitted light from a high-finesse optical cavity which has a well-defined cavity mode and it can be strongly coupled to single atoms, and then the atomic trajectories inside the cavity mode can be reconstructed from the transmission spectra [21]. Thus the cavity QED system provides the capability of measuring the atom trajectory. When the atom is strongly coupled to the cavity, the presence of an atom in the cavity leads to a significant modification of the cavity transmissions and details of the atom position, depending on the spatial structure of the cavity mode, can be obtained with high precision. As a result, the real-time observation of a single moving atom becomes practicable [22].

In this review, following the experimental progress of single atom manipulation, we give a brief introduction to single atom detection at the early stage of cavity QED experiments with hot atoms in Section 2. In Section 3, we introduce the real-time trajectory measurement of single atoms by intracavity trap [21], or by atom conveyor belt [23], and the feedback control of a single-atom trajectory [24]. In Section 4, we introduce the measurement of single atom trajectory by higher-order cavity mode which is strongly coupled to a single atom. The last section is a summary.

2 Early experiments of single atom detection by cavity QED

It is well known that a cavity can enhance the interaction between an atom and the electromagnetic field and it can be used as a single atom detector. However, for a large sized cavity, such as a microwave cavity, despite the interaction between atom and super-conducting cavity being reached in strong coupling regime in 1980s [25, 26], details of the atom position were lost. Optical cavity provides much smaller mode volume which greatly enhances the spatial resolution of single atoms, but it is relatively difficult to reach the strong coupling regime in optical domain and the lifetime of atom-cavity interaction is very short without cold atoms [27, 28].

Early experiments of atom-cavity coupling were carried out in weakly-coupling regime with hot atomic beams. In these systems the interaction between atoms and the cavity was not determined because of the randomness of the arrival of atoms. One could not determine the position of a single atom. In the early 1990s, with the development of coating technology, the losses of the super-mirror were as low as 1.6 ppm and the finesse of optical cavity formed by such super-mirrors reached the order of one million [29]. The strong coupling between single atoms and the cavity became a reality in the optical domain in 1992 and the experiment was done by using a hot atomic beam [30]. The atoms coupled to the cavity TEM_{00} mode when passing through the optical cavity with a velocity of about hundred meters per second. The interaction time was only a few hundred nanoseconds. Under the weak excitation condition, the vacuum Rabi splitting was observed for the average of one cesium atom inside a microcavity. In such an experiment, the position of the atoms was limited by the size of the beam waist in the cavity.

3 Experiments with cold atoms

3.1 Real-time trajectory measurement of single atoms in cavity QED

In the 1980s the arrival of MOT technique [31, 32] greatly drove the cavity QED experiments. Several major cavity QED laboratories successfully used cold atoms in experiments. In the experiment at Caltech, a cloud of Cs atoms with a temperature of about 100 μK was captured at 7 mm above the cavity and fell freely down into the cavity mode and the trajectories of individual atoms were continuously observed by significant modification of a weak probe beam transmitted through the cavity [33]. The transmitted power was measured by using balanced heterodyne detectors and resolved the motion of a single atom over distances of 100 μm in 100 μs [33]. Even colder atoms were later obtained by sub-Doppler cooling technique and stronger interaction with even closer distance between MOT and the cavity center [34], which helped to eventually trap an atom inside the cavity with single photons and bound single atoms in orbit [21].

The concept of a photon–atom bound state was envisaged for the case of an atom in a long-lived excited state inside a high quality microwave cavity [35]. However, the force produced by a few microwave photons is not enough to compensate for gravity. Optical photons are able to offer forces of the required magnitude to trap the atoms. Due to atomic decay and cavity losses, the atom-cavity system must be continuously excited by an external laser. Therefore, the external laser plays the dual roles of trapping the single atom in the cavity and continued observing of the atom's position by monitoring the transmitted light from the cavity. Single atoms inside a microcavity were trapped by means of near-resonant probe light [21, 36]. When atoms came into the central region of the cavity, the probe was triggered and the power of the probe light was increased quickly. By this "trigger and trap" method, the atom was easily captured in the cavity. The average time of atoms in the cavity mode was increased to about 340 μs [21]. The trajectories of single atoms

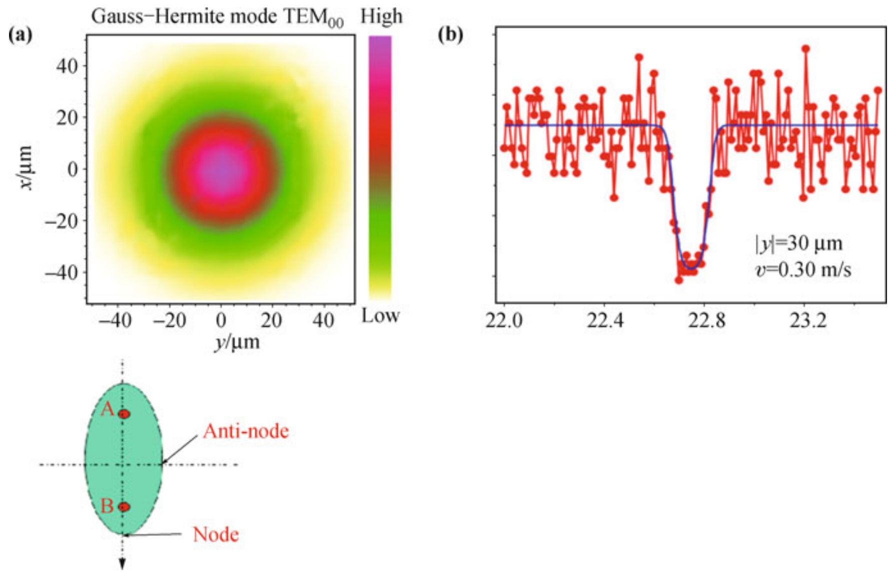

Fig. 1 Duplicate degeneracy of the single atom trajectory.

were reconstructed from the cavity transmission spectra. It showed that the atom moved in elliptical orbits in the plane which was perpendicular to the cavity axis with about 2 μm of the spatial resolution in 10 μs [21]. Compared to the micro trap of atom in free space [17–19], the cavity provides a special environment which not only enhances the interaction between atom and cavity, but also brings in some new cooling mechanisms [37, 38] which can extend substantially the dwelling time of the atoms inside the cavity and this is very important for tracking the single atom trajectories and demonstrating the feedback control. However, for all the experiments mentioned above, the atom was coupled to the Hermit–Gaussian TEM_{00} mode whose rotational symmetry results in the degeneracy of the trajectories. Figure 1 shows this degeneracy of the atom trajectories. For the spatial symmetry of the TEM_{00} mode [see Fig. 1(a)], from the cavity transmission we obtained Fig. 1(b) [39], one can determine the off-axis $|y|$, but cannot distinguish which side (point A or B in Fig. 1) the atom passed through. That means the atom can go either from point A or point B and the trajectory of the atom is duplicate degeneracy. Therefore, it is impossible to determine the displacements of off-axis of the atom along the cavity axis.

Similar experiments were done by Rempe's group with cold rubidium atoms [40, 41]. Instead of dropping the atoms into the cavity, they used an atomic fountain to launch the atoms upwards into an ultrahigh-finesse optical resonator. The main advantage of the system is that the velocity and density of the cold atoms entering the cavity could be finely adjusted by changing the parameters of the atomic fountain. The entrance velocity of the atoms can be tuned from 2 m/s down to less than 0.25 m/s. As a result, the atom-cavity interaction time was extended to the scale of milliseconds [40]. In order to eliminate the degeneracy of the atom trajectories and improve the precision of measurement, the approach used the higher-order modes of cavity to break the spatial symmetries. The asymmetry and complex patterns with small lobes of high-order transverse modes can not only eliminate the degeneracy of the atom trajectories, but also improve the measurement precision. In 2003, Puppe *et al.* measured the single atom trajectories using the TEM_{10} and TEM_{01} cavity modes [42]. Figure 2 shows their result. One can see that the atom trajectories are still degenerate as the modes are spatial symmetries for these almost horizontally-located TEM_{10} and TEM_{01} modes [42].

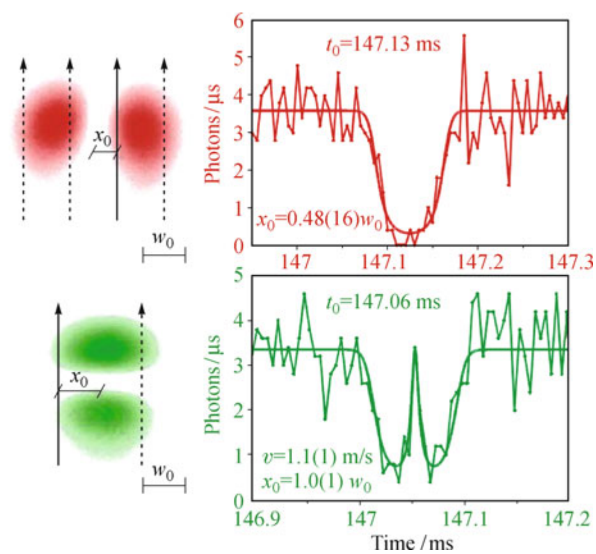

Fig. 2 The transit signals of a single atom passing through an $HG_{1,0}$ mode (upper) and an $HG_{0,1}$ mode (lower) of cavity [42].

3.2 Control of atomic position in optical cavity by atom conveyor belt

Another method of controlling the atom position in the cavity is to use an atom conveyor belt. With a far off-resonant trap (FORT), a large number of atoms or even single atoms from the re-cooled atom ensemble can be trapped and moved. An atom conveyor belt was built in 2001 by Meschede's group [43]. A single or certain number of neutral atoms can be controlled to transport over a distance of a centimeter in their experiment with sub-micrometer precision and they can place single atoms at a predetermined position along the trap axis with precision of 300 nm [44]. In 2004, single or multiple atoms were transported into the microcavity by using an atom conveyor belt in Chapman's group [45, 46]. The coupling between atom and the cavity was controlled later by Rempe *et al*. [23]. They used a one dimensional optical lattice to trap and move the individual atoms in a high-finesse optical cavity. In their experiment, a cloud of ^{85}Rb atoms was captured in the MOT. Cold atoms were then moved over a distance of 14 mm into the cavity by means of a horizontally running-wave dipole-force trap perpendicular to the cavity axis. The running-wave dipole-force trap was formed by a single mode Yb:YAG laser (5 W, 1030 nm) which was red-detuned far off from the atomic transitions. Therefore, the atoms were drawn to the region of maximum intensity. As soon as the atoms arrived at the cavity, the dipole trap was transferred from the guiding dipole trap to a standing wave trap in the cavity. The atoms were trapped at the antinodes of the standing wave, where the depth of potentials was 2.5 mK with a periodic distance of 515 nm. The fine shift of the atom's position, relative to the cavity mode, was determined by tilting a glass plate, which could change the relative phase of the two counter-propagating laser beams and shift the optical lattice continuously. Once the atoms were trapped in the lattice, they could be moved to any place along the axis of the dipole-trap beams within ± 250 μm depending on the thickness of the glass plate. It was reported that the atom could be moved in the cavity mode back and forth with a repositioning precision of 135 nm and the lifetime of atom in the cavity was 15 seconds [23]. The implement of the atom conveyor belt in the cavity QED makes it possible to determine and finely-control the measurement of the single atom position. It provides the capability of active control of the coupling between cavity and atom, which is crucial for demonstrating quantum information processing with a quantum register consisting of a few atomic qubits [47–50].

3.3 Feedback control of single atom trajectory

Actually, the atomic position involves three Cartesian coordinates. Only the off-axis distance is relevant to this discussion, i.e., the y direction in Fig. 3. When single atom cooling and feedback control are employed, the position of the single atom could be confined in three dimensions. Feedback control has been successfully implemented in the quantum domain, either for single ions [51] or neutral atoms [52–55]. Compared with the conventional means of laser cooling and trapping, feedback provides a new method to cool particles in the systems in which atoms are located in a smaller space and the spatial confinement provides better position measurement. In 2002, it was demonstrated that the motion of a single neutral atom in a microcavity was successfully controlled by the feedback technique [56], where the core of feedback strategy was to adjust the depth of intracavity dipole trap in real time according to the transmission of the cavity. Specifically, when the atom was moving away from the cavity axis, the depth of dipole trap was raised, otherwise, it was decreased. In this way, the atom could in principle be trapped in the bottom of the dipole trap. In their experiments, the laser at 780 nm was not only a probe beam but also a trap beam. The trapping time of the atoms inside the cavity was increased by 30% compared with the case without the feedback. In 2009, they improved the experiment scheme in which the average storage time of atom in the dipole trap increased to about 24 ms and the maximum observed trapping time exceeded 250 ms [24]. Most importantly, in the position and trajectory measurement, due to the spatial confinement in radial direction, the feedback control enabled the atom to keep in the vicinity of the cavity axis with an average excursion of less than 4.5 μm, which was improved by a factor of two compared with the result without the feedback [24, 57]. Feedback control technique could also be used to reduce the temperature of the atoms [58]. All in all, feedback control not only provides a useful approach for atom cooling and manipulation, but also brings about the possibility of measuring the position and trajectory of single atoms with better spatial resolution in three Cartesian coordinates.

4 Elimination of degenerate single atom trajectories with tilted higher-order cavity modes

A strongly coupled cavity QED system offers a useful tool to detect a single atom with high sensitivity. It even provides an approach to track and measure the trajectory of single neutral atoms in real time. However, performing this challenging experimental measurement still presents some difficulties. In the earlier experiment, the observation of the atomic trajectory of atoms falling through the mode of a high-finesse optical cavity based on observing the transmitted light through the resonator was demonstrated. However, due to spatial symmetry, the single atom trajectories are actually degenerate, as was mentioned above. For symmetric TEM_{00} or TEM_{10} mode, the atom trajectories are double-degenerate. Here, we demonstrate a technique for measuring trajectories of single atoms using the dispersive interaction with an optical resonator. By using higher-order transverse cavity modes whose nodal planes are oriented at an angle of about 45 degrees with respect to the atomic trajectory, the system breaks the spatial symmetry. This makes it possible, in contrast to the earlier experiments, to distinguish between trajectories to either side of the resonator axis. This allows us to determine unambiguously the location at which an atom's trajectory crossed the resonator mode. Thus the scheme makes resonator-based detection of atomic trajectories a very interesting technique for state-selective imaging since it offers high spatial resolution.

Thus as far we have had three sets of high-fineness optical cavity systems [59]. The experiment of atom trajectory measurement was done on the cavity QED system I which is shown in Fig. 3. The length of the optical cavity is 86.8 μm and the finesse is $F = 3.3 \times 10^5$. The beam waist of TEM_{00} mode is $w_0 = 23.8$ μm and the parameters of the system for TEM_{00} mode are $(g_0, \kappa, \gamma) = 2\pi \times (23.9, 2.6, 2.6)$ MHz and the corresponding critical atom number and critical photon number [60] are 0.024 and 0.006, respectively, which shows the system is in a strong coupling regime. In order to maintain an average photon number of about one inside the cavity, a probe laser at 852 nm is sent to the cavity and is finely tuned close to cesium atoms ($6^2\mathrm{S}_{1/2}$, $F = 4 \rightarrow 6^2\mathrm{P}_{3/2}, F = 5$) transition by a frequency chain system. An external-cavity diode laser at 828nm is used to lock the cavity length. In the initial experiment, about 10^5 cesium atoms are captured in the MOT with a temperature of about 117 μK [61] which is located about 5mm above the cavity. When the cooling trapping beams and the magnetic field are shut off, the atoms fall down freely through the cavity mode. The transmitted cavity photons are collected and detected by a single-photon counting detector and the overall efficiency is $\eta = 0.075$.

The whole process is simply described by the well-known J–C model of the interaction between a single two-level atom and a single-mode of the electromagnetic field. On the condition of both zero detunes of laser and cavity with the atom ($\Delta_{\mathrm{ca}} = \Delta_{\mathrm{pa}} = 0$), the cavity transmission will be greatly decreased when the atom goes into the cavity and strongly couples to it, since the probe beam is no longer resonant with the cavity. The significant modification of the cavity transmission depends on the coupling strength of the atom-cavity, which relies on the atom's position in the cavity.

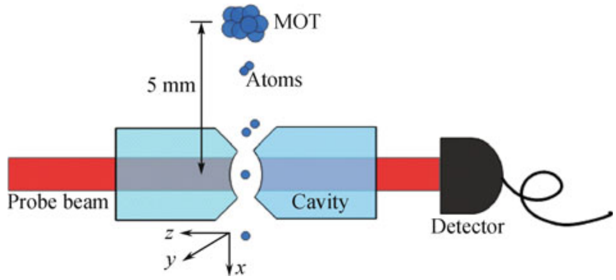

Fig. 3 The schematic diagram of the experiment. The cesium MOT lies 5 mm above the cavity axis, the mirror substrate diameter is 1 mm, and the cavity length is 86.8 μm.

Figure 4 shows the typical four transmissions of single atoms passing through the TEM_{00} mode [39]. Since the atoms in the experiment are freely falling and the MOT is located right above and far from the cavity, the atoms can be reasonably assumed as the well-collimated sources and each atom travels in a straight line vertically downwards. With this atomic motion, the position where its trajectory intersected the horizontal plane can be obtained by analyzing the cavity transmission history. The red dots and lines in Fig. 4 are experimental data and the

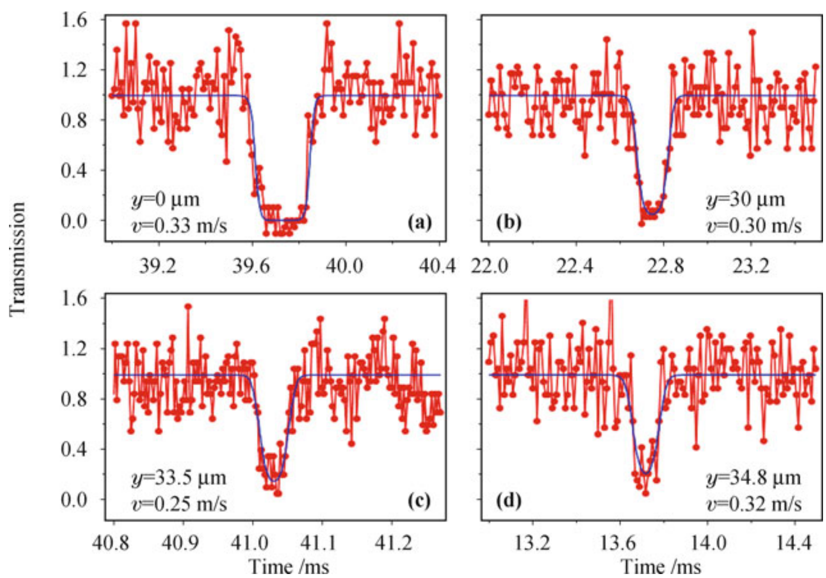

Fig. 4 Four transit signals associated with the single atoms passing through the TEM_{00} mode of cavity.

blue solid curves are theoretical fitting according to the transmission spectra [8, 42, 62]. The results show that the absolute distance in y-direction $|y|$ can be well determined, but due to the spatial symmetry of the TEM_{00} mode, one could not discriminate between $+y$ and $-y$. In addition, the velocity of the atom passing through the cavity is also determined. By measuring a large number of atom transits, the most probable dwell time of single atoms inside the cavity is obtained, which is about 110 μs, as showed in Fig. 5.

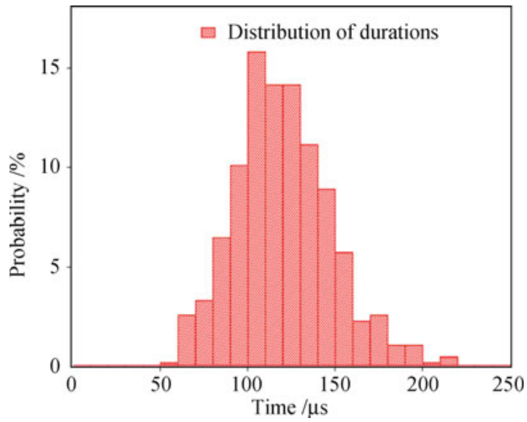

Fig. 5 Histogram of atom durations inside the cavity.

In order to eliminate the double degenerate trajectories of the atoms, we use a tilted higher-order transverse mode, the TEM_{10} mode, to measure it again. As was mentioned above, an exactly horizontally-located TEM_{10} mode still keeps the spatial symmetry [42]. However, the tilted nodal planes can break the spatial symmetry, thus helping to discriminate between $+y$ and $-y$ when the atom crosses the cavity mode. Of course, the axial degeneracy ($+z$ and $-z$) is still present for the higher-order transverse modes, and the vertical degeneracy ($+x$ and $-x$) has been broken in any case just getting the direction of atomic motion.

It should be mentioned that the single-photon coupling strength between single atoms and the cavity will decrease for higher order Hermits–Gaussian modes. Figure 6 shows the coupling strength as the function of the orders of the transverse modes. Fortunately, in our system, even if we choose Hermits–Gaussian mode order $m+n=8$, the system is still in the strong coupling regime. Actually, in the experiment with TEM_{10}, the parameters are $(g_{10}, \kappa, \gamma) = 2\pi \times (20.5, 2.6, 2.6)$ MHz, where g_{10} is the single-photon coupling strength of an atom at the position of maximum coupling in either of the two lobes of the TEM_{10} mode. Normally the mode waist is away from the cavity axis for higher order modes.

Figure 7 shows the transmission spectra of the cavity when the atoms cross the TEM_{10} mode whose nodal line is tilted 45 degrees with respect to the vertical axis. We can clearly see the double-peak transmission spectra which are caused by the two lobes of the TEM_{10} mode.

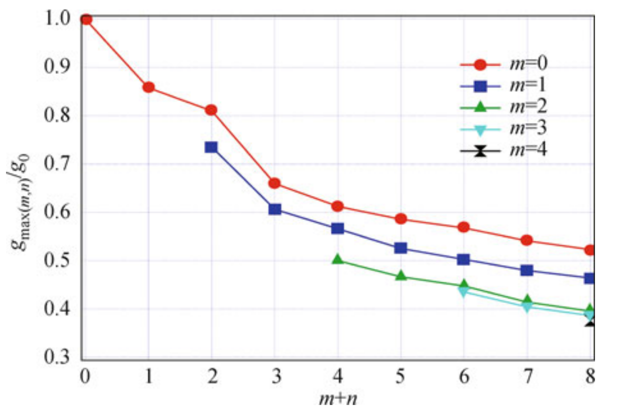

Fig. 6 The single-photon coupling strength between atom and cavity as a function of the orders of the cavity transverse modes. $g_{\max(m,n)}$ is the maximum coupling strength between the atom and the corresponding TEM_{mn} mode.

The symmetrical transmission spectrum appears only when the atom passes exactly through the antinode, i.e., $y=0$ [see Fig. 7(e)]. In most cases, however, one observes the asymmetrical transmission spectra, as shown in Figs. 7(d) and (f), which correspond to $y = -16.3 \pm 0.1$ μm and $y = 18.0 \pm 0.1$ μm, respectively. Thus, by using the tilted TEM_{10} mode which is spatial asymmetric, we can discriminate which side the atom crosses to and the degeneracy of the atom trajectory is eliminated. The spatial resolution in off-axis (y direction) is 0.1 μm and about 5.6 μm for vertical direction (x axis). This resolution is obtained from the statistical uncertainties based on the theoretical fittings. The better resolution for the off axis is due to the break of the spatial symmetry of cavity mode and the depth of the two transmission dips.

The precision of the measurement is mainly limited by the uncertainty from the fluctuation of the Poisson

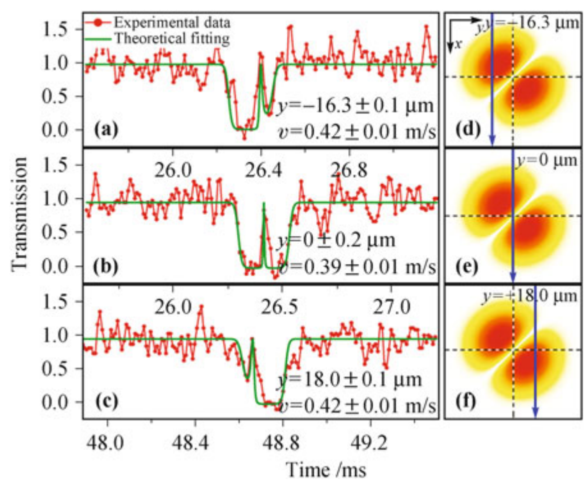

Fig. 7 The cavity transmission spectra of a single atom coupled to the tilted TEM_{10} mode of a high-finesse optical cavity. The red dots and lines are experimental data and the blue solid curves are theoretical fittings. **(d)**, **(e)**, and **(f)** on the right-hand side show the unique atom trajectories corresponding to **(a)**, **(b)**, and **(c)**, respectively. The experimental parameters used for fitting $\Delta_{ca} = \Delta_{pa} = 0$, $\omega_0 = 23.8$ μm and $(g_{10}, \kappa, \gamma) = 2\pi \times (20.5, 2.6, 2.6)$ MHz [62].

photon-counting statistics. The horizontal movement along the cavity axis during the transit process caused by the probe light is very small. Actually, the scattering rate due to the intracavity probe beam is about 2 photons/s and the suffering recoil kick energy is about 2π×2 kHz. However, the kinetic energy of atoms along the vertical direction (x axis) is about 2π×18 MHz after falling from MOT to the cavity mode, which is much larger than the recoil kick energy. During the average dwelling time of the atom inside the cavity, about 110 microseconds, it is rare for the atom to scatter a photon and suffer a recoil kick. Thus the suffering force due to the probe light can be neglected if we only choose the experimental results with atoms passing through the modes in the range around $z = 0$. In Hood *et al.*'s experiment [21], the atom was trapped by what they called "trigger and trap" method, and the atom's trajectory inside the trap was strongly affected by the dipole forces, but in our case, as the atom is not really trapped inside the cavity, just passing along vertical direction, the deflection due to the dipole forces is negligible.

We know that the position of the atom in z-direction has a remarkable effect on the cavity transmission. However, in a relatively wide range, for example, from z=−150 nm to +150 nm (see Fig. 8), the simulation shows that the transmission drops down to almost zero. What we have observed is most likely in this range. We do not choose those events beyond $z = \pm 150$ nm. When the position is too far from the range of −150 nm<z<+150 nm, the fitting is worse due to the poor signal-to-noise ratio. From the simulation in Fig. 8, it is difficult to distinguish the transmission spectra within the range of −150 nm<z<+150 nm, and we could thus estimate that the precision in z-direction is about 0.3 micrometer.

Furthermore, the use of even higher-order modes may improve the resolution. In Fig. 9(a), we plot the transmission spectra of cavity when a single atom crosses the titled TEM_{30} mode 45 degrees according to our experimental parameters. Figure 9(b) shows the corresponding transmission spectra as functions of the coordinates x and y. We find that in some range for y-direction, for example, 0 μm < y < 9 μm or 12 μm < y < 20 μm, the transmission of cavity is very sensitive to certain x-ranges, which implies that atoms located in these ranges could be detected with better resolution. It clearly shows that the resolution of the transmission spectra is greater for higher-order modes. As above-mentioned, when the mode number is higher, the atom-cavity coupling obviously goes down and the signal-to-noise ratio is lower. Therefore, there is certainly a "tradeoff". However, at present, we do not know which mode number is the best for optimum measurement. It is an important issue for future work.

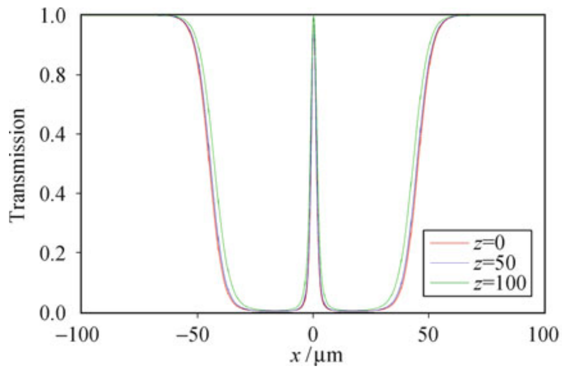

Fig. 8 Cavity transmission spectra as a function of x for different parameters of z. Other parameters are the same as those in Fig. 7.

5 Summary

We have reviewed the challenging problem of measuring the trajectory of a single atom. We mainly focus on the measurement and control of trajectories of single atoms in cavity QED experiment, including the real-time detection of single atoms passing through a high-finesse optical cavity, single atom trapping with few photons, atom conveyor belt and feedback control of single atom

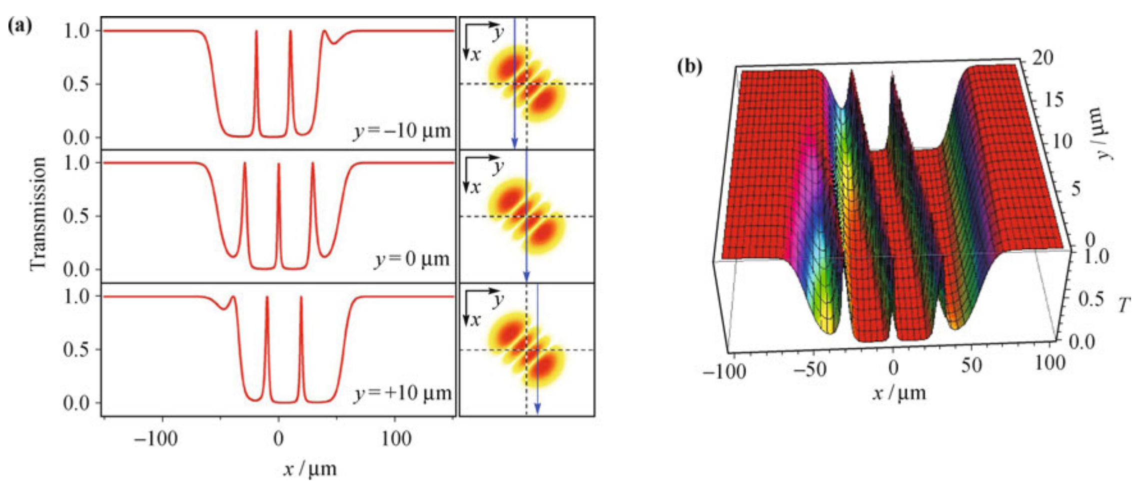

Fig. 9 The cavity transmission spectra of the single atom passing through the tilted cavity TEM_{30} mode.

position. The recent experimental work on eliminating the degenerate trajectories of single atoms is introduced. We demonstrate a technique of measuring single atom trajectories using higher-order transverse cavity modes whose orientation is tilted by 45 degrees with respect to the vertical axis. The measuring resolution of the atom trajectory along off-axis direction, i.e., the y direction, reaches 0.1 micrometer. Better resolution might be achieved by employing even higher-order cavity modes in the future. The system makes microcavity-based detection of atomic trajectories a very interesting technique for atom control and imaging. With even higher-order modes and feedback techniques, the motion of the single atom in three Cartesian coordinates can be controlled and measured with unprecedented precision and this is very important for quantum feedback control of the internal state of single atoms and for revealing new quantum features at single quantum level.

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