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REVIEW ARTICLE

Experimental progress in optical manipulation of single atoms for cavity QED

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Cavity QED, as a fundamental system and research field, not only illuminates the primary aspects of decoherence and coherence in quantum dynamics, but also advances quantum information science. Manipulation of single atoms, in the context of cavity QED, is the essential element and has been becoming a hot issue for the past two decades. In this review paper, we will concentrate on the experimental aspects for manipulating the neutral atoms strongly coupled to a high-finesse cavity in the optical regime, including atomic cooling and trapping, different configurations of atom transportation and the wide variety of quantum outgrowths based on cavity QED, such as one atom laser, single photon source, etc. The cavity QED system at Shanxi University is briefly introduced.

Keywords single atoms, cavity QED, dipole trap, cavity cooling

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Contents

1 Introduction

Cavity QED refers generally to the dynamics of the interaction of some material system (especially atoms, sometimes ions or quantum dots) with the electromagnetic field (photons) isolated from vacuum environment by walls, such as the Fabry–Perot cavity, photonic crystals and other micro or nano structures, etc. Basically, cavity QED is a modern version of the famous photon-box thought experiment, which was invoked by Einstein at the Solvay meetings in 1930 to check the consistency of quantum theory. However, the box is now replaced by mirrors or other walls that confine the photons, and the spring is changed to atoms [1].

As a clean and controllable physical system, cavity QED has long been a central paradigm for the study of open quantum systems wherein coherence and decoherence play important roles [2]. The long-lived coherence achievable in modern cavity QED experiments provides an efficient quantum interface between light and atoms, and allows us to map reversibly the quantum states between photon and atom, making them ideal candidates for quantum information processing [3−6].

The first discussion of a cavity QED concept was presented experimentally by Purcell [7]. He showed that the spontaneous emission rate for a two-state system is increased if the atom is surrounded by a cavity tuned to the transition frequency. In other words, the cavity enhances the strength of the vacuum fluctuations by a factor of Q (the quality factor of the cavity). Purcell's note was followed by a series of papers investigating spontaneous emission under some special conditions.

The story of the cavity QED experiment is unfolded along with the atom manipulation, which is always the centre role on the stage. Roughly speaking, the development of experiments in cavity QED has experienced two stages from Purcell's pioneering work.

The first stage was from the 1970s to 1992. The primary goal was to study how the radiative properties of atoms are modified when they radiate close to boundaries. It was noted by Kleppner [8] that the spontaneous emission could either be inhibited or enhanced. In this period, the atom-cavity interaction was still in the weak-coupling regime. Although the strong coupling regime in the microwave domain was reached in the middle of the 1980s [9] and a rich variety of effects were observed: Rabi oscillations [10], sub-Poissonian [11] and trapping field states [12], bistability [13], and Fock state generation [14, 15], the interactions of the successive atoms with the cavity were not individually controlled in those early times.

The second stage is from 1992 up to the present. It was not until 1992 [16] that strong coupling in the optical domain was first realized by direct spectroscopic measurement of vacuum Rabi splitting. The control was also achieved in a series of Rydberg atom-cavity experiments starting in the mid-1990s. In these experiments, atoms were injected at the precise time, with well-defined velocities. Thus, each atom's interaction time with the field could be varied at will. Compared with the microwave photon [17], the optical photon is much more favourable for producing the force compensating the gravitational pull on the atom in question. However, considering a much smaller optical cavity volume in which the atom-cavity interaction takes place, experimentalists involved in cavity QED in optical domains must try their best to manipulate the motional degrees of atoms as well as the internal ones. Completely controlling the external and internal states of single atoms in a very small space (usually on the scale of tens of microns) is a big challenge and is the central task of the cavity QED experiments.

The technical developments of laser cooling and trapping greatly promote atom manipulation, and have opened a new period in cavity QED experimentation. Now, along with the development of atom cooling and trapping plus the ultra-sensitive measurement, such as efficient single photon detection, cavity QED, as a workhorse of investigating open quantum systems, plays an important role in quantum information science and in the fundamental testing of quantum decoherence and quantum measurement [18].

This review is organized as follows. We will briefly retrace the early experiments in section two, then in Section 3 discuss atom manipulation with the help of a Magneto-Optical Trap (MOT). The far off-resonant trap (FORT) and cavity cooling are the main methods for neutral atom traps inside the cavity, which will be reviewed in Section 4 and 5, respectively. In Section 6, we will talk about a few cavity-QED effects selected from a lot of progress in this field. The experimental system of cavity QED at Shanxi University is briefly shown in Section 7. In the end, we summarize this review.

2 Experiments with the thermal atomic beam

In the early 1990s, the super-mirror technology facilitated the assembling of an optical cavity with finesse of 10^6 or even higher [19], thus the rate of energy exchange between atom and cavity, determined by the atom-field coupling strength inside the cavity, could be appreciable even for a vacuum field.

The first records [16, 20] of strong-coupled cavity QED were carried out using the atomic beam, with a velocity of about hundreds of meters per second, transiting through the TEM_{00} mode of a high-finesse cavity. For weak excitation, the vacuum Rabi splitting, predicted by the Jaynes-Cummings model [21] for the atom-cavity system was observed for an average of about one intracavity cesium atom [16]. Using a similar arrangement, laser oscillation with one atom was reported for the first time in the strong coupling regime by Feld's group [20]. In their experiment, a beam of ^{138}Ba atoms, flying at a rms thermal velocity of 320 m/s, traversed a single-mode cavity with a finesse of 8×10^5. The atoms were excited by a π pulse from the ground state to the excited state before entering the cavity. Laser oscillation from one atom was then observed.

The brief interaction time (about 0.1–0.3 μs) during the atomic transit and the difficulty in reducing the uncertainty of atom-field coupling restrict extracting more information in these atomic beam experiments.

3 Trapping the atom with few photons

3.1 MOT as atomic source for cavity QED

The advent of the MOT technology [22−25] fueled the quest to observe quantum effects in cavity QED experiments, which were plagued by difficulties of using thermal atomic beams as the source of atoms. The combinations of the technology of MOT and that of the cavity were developed by Kimble's group at Caltech [26] and Rempe's group at Garching [27, 28] to prepare a sample of cold, slow atoms as the source, or even a single trapped atom within the cavity. In Kimble's experiment, a cloud of Cs atoms were cooled down to sub-Doppler temperatures in a MOT, which was located a few millimeters over the gap between the cavity mirrors. After a mean time delay corresponding to that required for atoms free falling from MOT to the center of the cavity, the trajectories of individual atoms falling into cavity mode were observed [29]. For an atom traversing the cavity mode, the position-dependent coupling, due to the standing-wave structure of the vacuum field within the cavity, resulted in a time-dependent probe transmission. Hence, the vacuum-Rabi spectrum was extracted from the transmission of a weak probe interacting with the amount of individual atom-cavity systems. Meanwhile, in Rempe's experiment an atomic ^{85}Rb fountain, injecting slow atoms from below into the mode volume of an ultrahigh-finesse optical resonator, served as the cold atom source. Similar dynamics presenting the strong atom-field coupling was observed.

In the above experiments, the velocity of the atom entering into the cavity was less than 0.3 m/s and the duration of the interaction between the atom and the cavity mode was around hundreds of microseconds, which is much improved compared to those systems with a thermal atomic beam, but still far from enough for implementing the diverse goals of quantum information processing, wherein the generation of a steady continuous single photon source with "one-and-the same" atom and the long-lived coherence control of the atom–photon interface require robust and complete manipulation of single atoms.

3.2 Near-resonant trap without feedback

It has been suggested by Haroche [17] that the attractive potential could trap neutral atoms. The forces produced by several microwave photons, however, are insufficient to compensate the gravitational forces, which can be circumvented in the optical domain. The evidence of mechanical light forces on the intracavity atoms was reported [30] by Hood et al. for intracavity photon numbers even less than one, which triggered exploiting the underlying physics in order to conceive of the dynamics occurring in the strongly coupled quantum system [31–33].

Two experiments were accomplished [29, 34] later by catching and trapping a slowly-moving atom inside a high-finesse cavity. With appropriate cavity-atom detuning $\Delta_{\text{ac}} \equiv \omega_{\text{cavity}} - \omega_{\text{atom}}$ and probe detuning to atom $\Delta_{\text{probe}} \equiv \omega_{\text{probe}} - \omega_{\text{atom}}$, a weak probe beam induces transitions between the dressed energy levels to compensate for the decays from atomic spontaneous transition and the cavity, which lead to the destruction of the atom-cavity entity. The atom entering near the center of the cavity triggers the intensity of the probe beam to a higher level to trap itself. With the triggering method [29], atoms could dwell in the cavity for a period of the order of 1 ms until heating, resulting from spontaneous photon scattering of the trap light, has increased atomic kinetic energy to a value comparable to the trap depth.

3.3 Near-resonant trap with feedback

Beyond passive observation of the atomic motion in the dipole-force trap produced by the near-resonant probe field [29, 34] mentioned above, feedback technology has been exerted to prolong the duration of the atom inside the cavity [35]. In Rempe's experiment, the dynamical information of atomic motion in the cavity mode was extracted from the very weak leakage of the probe light from the end mirror of the cavity, and was fed back to the servo loop in real time to control the depth of the optical trap constructed by the same probe field, hence the motional degrees of the atom were influenced. However, because of the intrinsic limitations, the lifetime of the atom inside the cavity increased only 30% better than that of a comparable constant-intensity dipole trap, and the feedback cooling was not essentially demonstrated.

4 Far off-resonant trap (FORT)

4.1 FORT along the cavity axis

The dipole force induced by the near-resonant pump field, which acts as a continuous probe simultaneously, will severely heat the atom while functioning as a trap, i.e., although atomic confinement with the probe field offers a significant advantage in obtaining well-localized, trapped atoms, it remains preferable to decouple the trapping from the sensing within the cavity. FORTs consisting of an auxiliary far-detuned optical beam were successfully invoked by different groups [36, 37] to form a dissipative, attractive force on one atom or several atoms inside the cavity along its axial direction, and caused very weak atomic excitation.

The principle of FORT, when applied to a two-state atom, is rather straightforward [38]. The FORT light, with detuning $\varDelta$ from the atomic transition frequency, ω_{a}, produces dipole potential, $U_{\text{dip}}(r)$, and scattering rate, $\varGamma_{\text{sc}}(r)$, represented as follows:

$$U_{\text{dip}}(r) = \frac{3\pi c^2}{2\omega_{\text{a}}^3} \frac{\varGamma}{\varDelta} I(r) \tag{1}$$

$$\varGamma_{\text{sc}}(r) = \frac{3\pi c^2}{2\hbar\omega_{\text{a}}^3} \left(\frac{\varGamma}{\varDelta}\right)^2 I(r) \tag{2}$$

Here $I(r)$ is the intensity of the beam at r, $\varGamma$ is the atom decay and c is the light velocity in vacuum. Two essential properties are shown clearly by these equations:

(i) For a red-detuned field ($\Delta < 0$), an atom in its ground state is confined in the potential minima wherein the maximum field intensity are found. Within a cavity, ground-state atoms with kinetic energy $E_k < U_{\rm dip}$ will be trapped around the anti-nodes of the red-detuned FORT field, coincident with the resonance of the cavity but n cavity free spectral ranges away from the probe light, where n is an integer and usually determined by the parameters of the cavity and the actual atom.

(ii) The dipole potential scales as I/Δ, whereas the scattering rate scales as I/Δ^2. Therefore, the first intracavity standing-wave FORT light, used in Ref. [36], with $\lambda_{\rm FORT} = 869$ nm considerably reduces the scattering, which heats the atom, by several orders of magnitude compared with the near-resonant probe light utilized in Hood's experiment [29].

By using the FORT, the lifetimes of the single atoms trapped within the cavity mode reached 28 ms [36], which was limited by the intensity-fluctuation-induced heating [39]. The use of FORT, as a significant milestone, substantially improves the performance of atom-cavity interaction as well as the atom confinement.

4.2 State-insensitive trapping

The main problem of the conventional red-detuned FORT for the optical cavity QED experiments mentioned above [36] is that the atomic excited states experience a positive ac Stark shift, whereas the ground state experiences a negative shift of comparable magnitude [38]. This leads to the unfortunate consequence that the detuning and the effective coupling between the atom and the cavity mode become strongly dependent upon the atomic position within the trap [40] and complicates the parameters relevant to cavity QED. However, such a problem can be solved, for the $6S_{1/2} \rightarrow 6P_{3/2}$ transition of the cesium atom, for example, by choosing a specific wavelength of the trapping laser, $\lambda_{\rm FORT}$. The specific wavelength was called the "magic" wavelength. As demonstrated in Refs. [41−43], the "magic" wavelength is around 935 nm for the abovementioned transition. This trapping beam is also resonant with the cavity mode (an integer number of longitudinal-mode orders below the $6S_{1/2} \rightarrow 6P_{3/2}$ transition of cesium atom). Around the "magic" wavelength, the ac Stark shifts of the excited and ground states are in the same direction and show almost the same magnitude, thus the ac Stark shift difference, δ_0, between excited and ground states was so small that it, despite being spatially dependent, was considerably less than the half-photon Rabi frequency g_0 (i.e., the coupling rate of an atom with the cavity field for one photon), whereas in a conventional FORT, as in Ref. [36], $\delta_0 \gg g_0$.

By using the FORT at "magic" wavelength, together with the transverse beams arranged perpendicularly to the cavity axis and used for cooling and repumping, the lifetime of single cesium atoms inside the cavity mode was extended up to 2−3 seconds while still maintaining strong coupling [44]. This great improvement allows continuous observation of trapped atoms by way of the atom-cavity coupling.

4.3 FORT perpendicular to the cavity axis: atom conveyor

The problem of the FORT along with the cavity axis is that there are at least three beams simultaneously resonant with the cavity: the probe beam, the trapping beam and the cavity locking beam. This complex configuration limits the flexibility of manipulating single atoms inside the cavity. People were seeking independent control over the atoms from the side of the cavity. As demonstrated in Refs. [45−48], a translating optical dipole trap, known as the atom conveyor, enabled experimentalists to deliver from the side one or, in principle, any desired number of cold atoms from a magneto-optical trap into the mode volume of a high-finesse optical cavity adiabatically. The implement of the atom conveyor in the field of the cavity QED in the strong coupling regime represents an important step towards scale cavity QED interaction for multiple atomic qubits, which is a prerequisite for the diverse protocols of quantum information processing [49]. It is well noted that the use of the atom conveyor to deterministically transport and trap individual atoms inside a cavity allows the control of the atom-cavity coupling via position-dependent interaction. The adjustable parameter of coupling in cavity QED also provides an efficient control variable in quantum feedback [2, 50].

5 Cooling atom inside cavity

With the help of an auxiliary red-detuned FORT light, cavity QED in the regime of strong coupling is facilitated in a high-finesse optical resonator. Yet, the heating mechanisms (e.g., dipole heating along the cavity axis direction) still exist, which precludes further improvement of confinement times of the atom. Solutions are required to decrease the motional velocities of the atom inside the standing-wave dipole trap constructed between the two high-reflective cavity mirrors.

5.1 Cavity cooling with weak probe field

Apart from the conventional laser cooling mechanism, cavity cooling (CC) has been proposed [32, 51] for a single atom strongly coupled to a high-finesse cavity. CC does not rely on repeated cycles of optical pumping and spontaneous emission of photons by the atom, but on the escape of photons from the cavity. It would further prolong the storage times and improve the localization of single atoms for cavity QED.

As was pointed out in Refs. [32, 33, 51], the cavity cooling force acts mainly by exciting the cavity part of the atom-cavity entity in the strong coupling regime. For properly chosen parameters of the probe beam, the dynamics of the cavity field (probe field) introduces a Sisyphus-type cooling mechanism yielding final atomic temperatures much below the Doppler limit. Because of avoiding the cyclic pumping and spontaneous emission exerted in conventional Doppler cooling, CC can extend its application to many other fields needing cooling [51, 52]. In Ref. [37], the strength of the CC force is much stronger than the force expected for free-space Sisyphus cooling and Doppler cooling and the storage time of a single atom was increased by a factor of two.

5.2 Raman sideband cooling to ground state

Raman sideband cooling [53], as a standard tool, has been widely used in experiments involving trapped ions and alkali atoms in free space. By taking advantage of the FORT light and an auxiliary field that is frequency down-shifted by the hyperfine splitting of atomic ground state in addition to double harmonic frequency of the FORT, the intracavity Raman sideband cooling scheme was carried out successfully, achieving cooling of the atomic motion along the cavity axis [54]. Consequently a clearly resolved spectrum of vacuum Rabi splitting of the normal modes in a strongly coupled atom-cavity entity was extracted from the transmission with one-and-the-same atom inside the cavity mode [55].

5.3 Cooling single atoms in three dimensions

To prolong the limited storage times resulting from the axial geometry of the laser-cavity system, an orthogonal arrangement of cooling laser, trapping laser and cavity vacuum field produces a combination of dissipative forces that act along all the three directions so that a single atom can be cooled and trapped inside a high-finesse optical resonator up to 17 s [56]. By using a similar set-up simultaneously, individual atoms were strongly coupled to the cavity mode for time scales exceeding 15 s [45]. The three-dimensional cooling technique proved to be an efficient method to manipulate atoms in the context of cavity QED.

6 Experiments with trapped atoms

6.1 One-atom laser

The one-atom laser, similar to the one-atom maser [9], has been theoretically discussed extensively [57–62]. In the model, a single atom bound to a resonant cavity functions as the gain medium which emits photons into the resonant mode of the optical cavity. As the important experimental proving grounds of cavity QED, the one–atom laser can be realized with an injected atom [17], single trapped ion [63, 64] or single trapped atom [65]. As mentioned above, the first laser oscillation was demonstrated with one atom in an optical resonator [20]. Though the mean number of atoms inside the mode ranges only from 0.1 to 1.0, the probability of having more than one atom inside the resonator simultaneously does not vanish, as Poissonian statistics dictates. This can easily destroy the ideal one-atom laser operation. Only using the one-and-the-same atom trapped and strongly coupled to a high-finesse optical resonator, the one-atom laser can be realized as demonstrated in Refs. [65, 66]. The emission from such a device exhibits qualitatively differences from a conventional laser with many atoms. The relation between the intracavity photon number and the pump intensity shows that there is no threshold for lasing, and the output flux of photons exhibits plainly a variety of nonclassical properties, such as photon anti-bunching and sub-Poissonian photon statistics.

6.2 Deterministic narrow-band single-photon sources

Due to its application potentials, the single photon source is becoming the key quantum source for quantum information processing [67] and for tests of basic quantum properties of photons [68]. Although single-photon emission has been observed on a variety of sources [69], such as trapped atoms or ions in free space, embedded molecules, quantum dots and color centers, etc, the lack of control on such irreversible decay process limits their applications in quantum networks, wherein the reversible transfer of quantum states between the stationary qubits (atoms) and the flying qubits (photons) is a primitive requirement [3, 6]. To realize a reversible single-photon source, schemes based on a stimulated Raman process driving an adiabatic passage (STIRAP) between two ground states of a strong-coupled atom inside a high-finesse optical resonator were proposed [70, 71]. Such a source was first accomplished by using atoms falling through an optical cavity 20 cm below at MPQ [72], rather than a trapped atom in the cavity volume at Caltech [73]. In the prior experiment, only few single photons on demand could be acquired during the brief interaction between atom and cavity field, whereas in the latter, an average of 1.4×10^4 photons could be produced by each trapped atom. By improving the experimental arrangement, an atom was trapped inside a cavity for a considerably long time and provided a continuous narrow-band single-photon source for the entire duration (28s) [74]. By this time, we can say that a proof-of-principle single-photon source has progressed to a useful device for the quantum interface and quantum network.

6.3 Other experiments

As expected, by using atoms strongly bound to a high-finesse optical resonator, many other perfect experiments have been demonstrated, including the vacuum-Rabi spectrum of one-and-the-same atom [54], photon blockade effect [75] and nonlinear spectrum of high-order dressed states in optical cavity QED [76]. These experiments all demonstrate the basic properties of quanta in the cavity QED context. All these achievements should be credited to the better and better manipulation of single atoms in optical cavity QED.

7 Single-atom manipulation at Shanxi University

To achieve a deterministic single-photon source based on cavity-assisted STIRAP and set up a stage for reversible exchange of quantum information between atoms and photons [3, 4], three sets of high-finesse optical cavities have been built up at Shanxi University. The parameters of these three cavities are shown in Table 1, including one cavity, denoted by 1#, located in a renewed UHV chamber and the other two, denoted by 2# and 3#, placed in two silicon cells which share a common UHV chamber. The background pressures of these two UHV chambers are about 2×10^{-10} Torr. The principal cavity QED parameters of the three systems are tabled below. Strong couplings [$g_0 \gg (\kappa, \gamma)$] could thereby be achieved in these three systems, where coupling rate g_0 is based on the reduced dipole moment for the transition of $6S_{1/2}$, $F = 4$ $\leftrightarrow$ $6P_{3/2}$, $F' = 5'$ in cesium.

Table 1 Three micro-cavities for the cavity QED experiment.

Cavity No.	$\frac{g_0}{2\pi}$/MHz	$\frac{\gamma}{2\pi}$/MHz	$\frac{\kappa}{2\pi}$/MHz	$N_0 \equiv \frac{2\kappa\gamma}{g_0^2}$	$n_0 \equiv \frac{\gamma^2}{(2g_0^2)}$
1#	24	2.6	2.6	0.024	0.006
2#	11.4	2.6	2.51	0.1	0.026
3#	11.4	2.6	2.51	0.1	0.026

The use of cesium dispensers and ultraviolet light-induced atom desorption [77], instead of the previous two-stairs vacuum chambers [78, 79], facilitates sufficient preparation of cold atoms above the cavities, meanwhile the high degree of vacuum around the cavity is still maintained. We have realized a single atom trap either from mini-MOT with a large gradient of the magnetic field (Fig. 1) [80] and a traveling-wave dipole trap [81] or from an optical micro-trap directly from the usual MOT (Fig. 2). Based on the trapped single atom, nonclassical properties can be demonstrated by using sensitive single-photon-counting technology [82, 83].

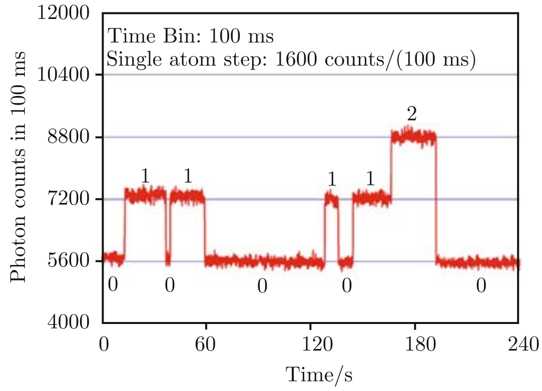

Fig. 1 Fluorescence of single atom from mini-MOT.

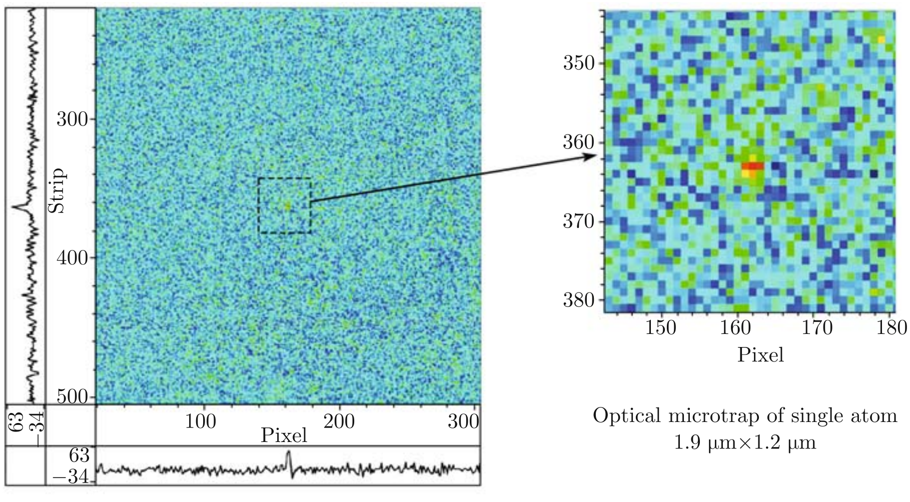

Fig. 2 Single atom by optical micro-trap from MOT.

Deterministic delivery and control of individual atoms proceed either by releasing the cold atoms into cavity and capturing by standing wave optical lattice or transporting by an atomic conveyor or specially designed system by a controllable optical dipole trap.

8 Concluding remarks

This paper reviews the evolution of single-atom manipulation for optical cavity QED in the strong coupling regime, focusing on the far off-resonant trap and cavity cooling, which enable single atoms strongly coupled to a high-finesse optical resonator. We also demonstrate the experiments involving single-atom manipulation, including trapping single atoms with few photons, trapping single atoms inside an optical cavity, one-atom laser, deterministic single-photon source, etc.

Boosted by the progressing single-atom manipulation technologies, optical cavity QED is getting its stride [84]. Cavity QED has extended its field from traditional bulk Fabry–Perot cavities to microsphere, microtoroid, and photonic crystal cavities, etc. [85]. In the new era of quantum information, it will continue to play an important role as a paradigm, through interplay with quantum information science as it demonstrates basic quantum physics.

Cavity QED, together with the related single-atom manipulation, is a fast developing area [86]. Here we just review it from the experimental aspect based on the historic progressing. Recently, Cavity QED also finds its new position in the fields of many-body physics, interplaying with the collisional interactions between atoms, and provides a new resource for exploring the wondrous quantum world for fundamental and practical purpose [87−94].

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