Atomic motion in the strong-coupling regime of cavity QED

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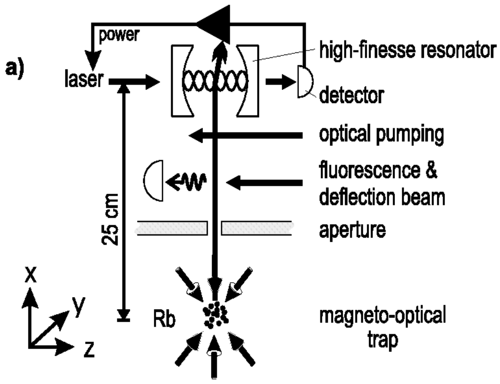
Recent years have witnessed remarkable progress in the experimental realization of intrinsically quantum mechanical systems and their real-time observation. An example in cavity quantum electrodynamics is a single atom interacting with one mode of a quantized cavity field. Experiments can now routinely be performed in the so-called strong-coupling regime, where the oscillatory exchange of a single quantum of excitation between the cavity and the atom, characterized by the coupling constant, g, is much faster than any decay rate of the excitation, in particular the decay rate of the atomic dipole, γ, and the cavity field decay rate, κ. In this regime, the presence of an atom leads to a strong change in the cavity transmission, which allows its real-time observation inside the cavity [1, 2]. Cold atoms also feel the force exerted by the light, which influences the trajectory of the atom. This leads to an intriguing dynamical atom-cavity system.

We have investigated these forces in detail in a cavity containing about one photon on average. The setup is shown in Fig. 1**a**). Ultracold rubidium atoms are collected in a magneto-optical trap. They are launched upwards and enter the high-finesse cavity ($F > 400.000$), which is pumped by a weak laser beam. Depending on the flux from the fountain we can study single atoms in transit, trap an atom or study many atoms in simultaneous transits:

Single atom transits — If the light field is red or blue detuned relative to the atomic transition, the atoms are attracted towards or repelled from the antinodes of the light field, respectively. This can be seen in the intensity autocorrelation function, $g^{(2)}(\tau)$, of the transmitted light. The $g^{(2)}(\tau)$ reveals a fast oscillation of the intracavity light field which is caused by atoms channeling through the standing light wave. One needs the dipole force, momentum diffusion and a novel velocity-dependent force to get good quantitative agreement between theory and experiment [3, 4].

Single atoms trapped by single photons — Mechanical binding was first envisioned for long-lived Rydberg atoms in a microwave cavity. It has recently been observed in the optical domain [5]. In order to trap an atom in the conservative dipole potential in the cavity, the laser light pumping the cavity is suddenly switched to a higher value when an atom is detected in the cavity. This increases the depth of the optical dipole potential and traps the atom in the cavity field. The subsequent oscillatory motion of the trapped atom is resolved in real time. An example is shown in Fig. 1**b**). By comparing the results with a quantum jump Monte Carlo simulation of the atomic trajectory, we find that the observed changes of the transmitted power are a measure of the radial excursion of the atom along the Gaussian mode profile, showing that the atom is bound. Moreover, periodic structure is visible in the fourth-order intensity



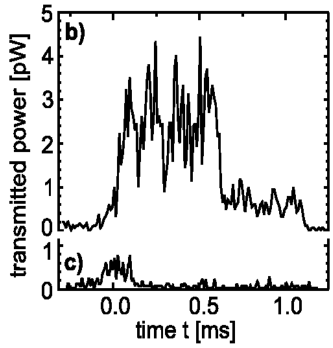


Figure 1: **a**) Experimental set-up. **b**) Transmitted power through the cavity. For trapping, the feedback switch triggers an 8-fold increase of the pump power at $t = 0$, when an atom is observed to enter the cavity. As a result, the atom causing the trigger remains in the cavity for about 0.6 ms. The pump is switched back to its original value after 1.1 ms. A single photon in the cavity corresponds to a transmitted power of 0.9 pW. **c**), Same as **b**, but without feedback switch. The atom leaves after 0.1 ms.

correlation function, attributed to sudden flights of the atom between different antinodes of the standing wave.

Long range many-atom force — If two or more atoms are placed inside the mode of the cavity, every atom can change the light field dramatically. This also changes the light forces on the other atoms. In other words, a light force between atoms is mediated by the cavity. This force is quite different from that in free-space, because the interaction strength is not a function of the interatomic distance, but rather of the position of the atoms in the cavity, which is macroscopic. We have found evidence for these long-range forces in the spectra of a high-finesse cavity filled with ultracold rubidium atoms. The forces between these strongly coupled atoms influence the spatial distribution of the atoms, which manifests itself as an asymmetric normal-mode spectrum. Good agreement between the data and calculated spectra was achieved only when using a Monte-Carlo simulation including the full motional dynamics of the many-atom system. For this purpose, we extended the existing work on the dipole force and the diffusion coefficient for a single atom [3] to that in the presence of the other atoms [6].

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