Real-Time Tracking and Trapping of Single Atoms in Cavity QED

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Cavity quantum electrodynamics (QED) offers powerful possibilities for the deterministic control of atom-photon interactions quantum by quantum [1]. Indeed, modern experiments in cavity QED have achieved the exceptional circumstance of strong coupling, for which single quanta can profoundly impact the dynamics of the atom-cavity system. The diverse accomplishments of this field set the stage for advances into yet broader frontiers in quantum information science for which cavity QED offers unique advantages, such as the realization of quantum networks by way of multiple atom-cavity systems linked by optical interconnects [2].

The primary technical challenge on the road toward such scientific goals is the need to trap and localize atoms within a cavity in a setting suitable for strong coupling. Beginning with the work of Ref. [3], several groups have been pursuing the integration of the techniques of laser cooling and trapping with those of cavity quantum electrodynamics (QED). Two separate experiments in our group have recently achieved significant milestones in this quest, namely the trapping of single atoms in cavity QED [4, 5].

In both these experiments, the arrival of a single atom into the cavity mode can be monitored with high signal-to-noise ratio in *real time* by a near resonant field with mean intracavity photon number $\bar{n} < 1$. In one experiment, an atom's arrival triggers *ON* an auxiliary field that functions as a far-detuned dipole-force trap (FORT) [4], thereby trapping the atom within the cavity mode. When the FORT is turned *OFF* after a variable delay, strong coupling likewise enables detection of the atom. Repetition of such measurements for single atoms yields a trap lifetime $\tau = (28 \pm 6)$ms, which has been limited by fluctuations in the intensity of the FORT arising from the intracavity conversion of FM to AM, but should extend well beyond 1s.

In a second experiment depicted in the accompanying Figure 1, we rely upon light forces at the single-photon level to trap a single atom within the cavity mode [5]. Because a single atom moving within the resonator generates large variations in the transmission of a weak probe laser, we have been able to develop an inversion algorithm to reconstruct the trajectories of individual atoms from the cavity transmission. These reconstructions reveal single atoms bound in orbit by the mechanical forces associated with single photons. Our *atom-cavity microscope* yields 2μm spatial resolution in a 10μs time interval. Over the duration of the observation, the sensitivity is near the standard quantum limit for sensing the motion of a Cesium atom.

Stated in units of the coupling parameter g_0 (where $2g_0$ is the single-photon Rabi frequency), our experiments with trapped atoms in cavity QED achieve $g_0\tau \geq 10^5\pi$, whereas experiments with conventional atomic beams have $g_0T \simeq \pi$, with T as the atomic transit time through the cavity mode. These initial realizations of trapped atoms in cavity QED should enable diverse protocols in quantum information science.

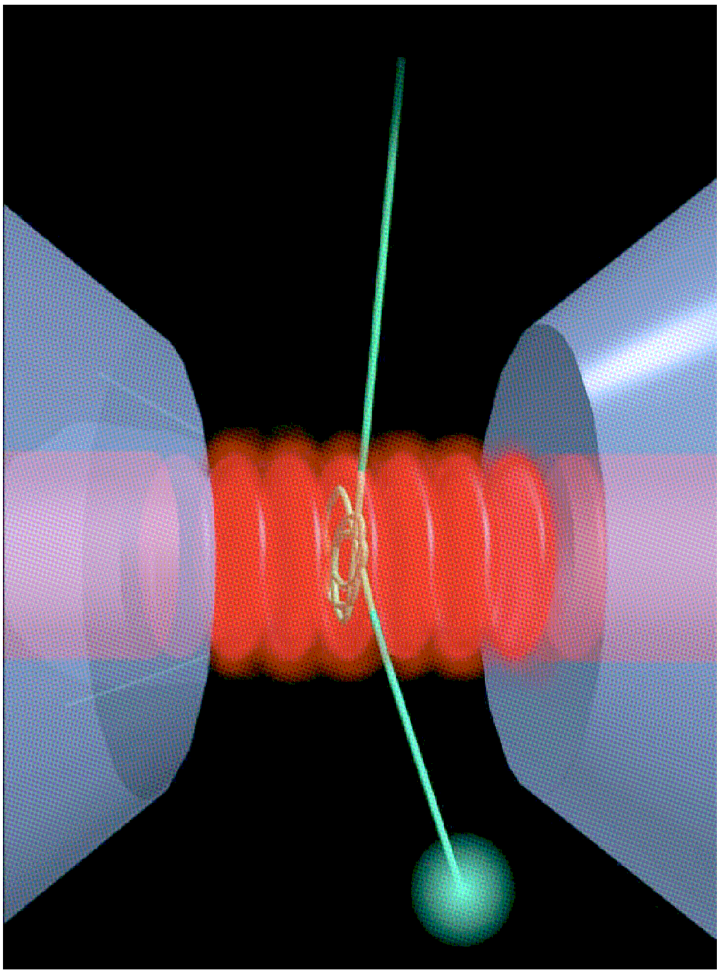

Figure 1: Illustration of the tracking and trapping of a single atom with the atom-cavity microscope. Shown is a reconstructed trajectory for an atom as it enters into the cavity mode, orbits, and finally exits.

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