Coherent coupling and modified spontaneous emission of a single ion in a high finesse optical cavity

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Laser-cooled trapped atoms or ions are ideally suited systems for storing and processing quantum information. The transport of this quantum information over large distances via photons requires an interface between atoms and photons (J.I. Cirac et al., Phys. Rev. Lett. **78**, 3221 (1997)). Such an interface is based on the deterministic coherent coupling of a single atom or ion to macroscopic and vacuum fields inside a high finesse optical cavity. Here, we perform two experiments to investigate such an interaction of a single Ca^+ ion and a cavity field: first, we excite Rabi oscillations with short resonant laser pulses injected into the cavity, and second, we measure the modification of the spontaneous emission rate from the metastable $D_{5/2}$ level induced by the cavity-enhanced vacuum field. The latter effect leads to an enhanced spontaneous emission into the cavity mode as required for an atom-photon interface.

The $^{40}Ca^+$ ion is stored in a spherical Paul trap placed in the center of a high finesse near-confocal resonator (Finesse approx. 30.000 at 729 nm). The ion is laser-cooled to the Lamb-Dicke regime, confining its spatial wave packet to a region much smaller than the optical wavelength. We stabilize the cavity to the $S_{1/2}$ - $D_{5/2}$ quadrupole transition frequency (wavelength: 729 nm) using a transfer lock technique (A.B. Mundt et al., Appl. Phys. B **76**, 117 (2003)).

To demonstrate coherent coupling of the ion and a macroscopic cavity field, we inject resonant laser pulses of different pulse lengths at 729 nm into the cavity and record the excitation on the $S_{1/2}$ - $D_{5/2}$ transition via the electron shelving technique. We observe a Rabi oscillation frequency of up to 9 MHz when the ion is placed in a node of the cavity standing wave field.

For the measurement of the cavity modified spontaneous emission (Purcell effect), we repeat the following sequence for 100 times: first, we excite the ion with a π-pulse on the $S_{1/2}$ - $D_{5/2}$ transition. We then detect whether the excitation was successful (electron shelving), wait for a certain delay time and measure the $D_{5/2}$ population again. Every second experimental run, we shift the cavity by approx. 5 linewidths away from resonance. By repeating this procedure for many times we infer the spontaneous decay rate from the metastable level for the cavity on resonance and off resonance (equivalent to free space emission), thus excluding systematic errors due to environmental effects. For the free-space lifetime we measure a value of 1167(22) ms (see Fig.1), close to the currently most precisely measured value of 1168(7) ms (P. Barton et al., Phys. Rev. A **62**, 032503 (2000)). Experiments with various delay times show a lifetime reduction of up to approx. 15% on resonance.

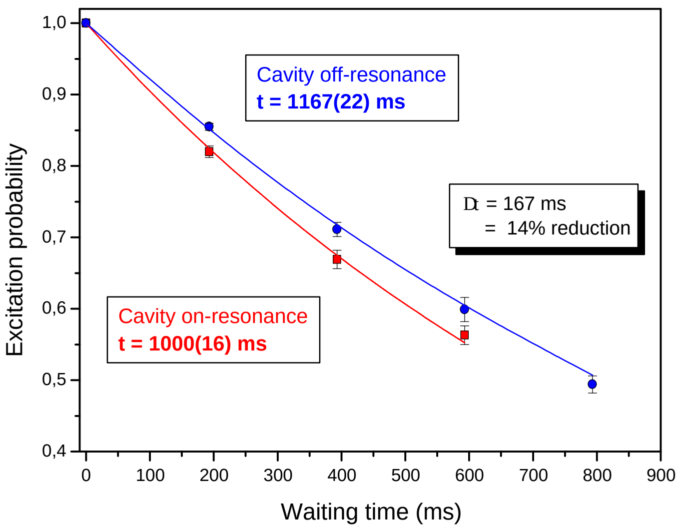

Figure 1: Measurement of the $D_{5/2}$-state lifetime with the trap cavity on-resonance (Purcell effect) and the cavity off-resonance (equivalent to free space lifetime). Shown are excitation probabilities for certain waiting times after initial excitation. Each data point is the average of up to 5000 single measurement sequences.