Effects of quantum jumps in the Jaynes-Cummings dynamics of a trapped ion

C. Di Fidio and W. Vogel

Arbeitsgruppe Quantenoptik, Fachbereich Physik, Universität Rostock,
Universitätsplatz 3, D-18051 Rostock, Germany
Tel +49-381-4981713, Fax +49-381-4981716
E-mail: difidio@physik5.uni-rostock.de, http://www.physik5.uni-rostock.de/

The Jaynes-Cummings model has been widely used in quantum optics to describe the fundamental interaction of a quantized radiation mode with a two-level atom. Another system that has recently revealed quantum dynamics of the Jaynes-Cummings-type is a trapped and laser-driven ion [1]. The quantized vibrational center-of-mass motion of the ion in the trap potential plays the role of the boson mode, which is coupled via the lasers to the internal electronic states of the ion. The characteristic dynamics is observed in the population of the lower atomic state. In the Lamb-Dicke and resolved-sideband limit the original Jaynes-Cummings dynamics is obtained [2]. When the Lamb-Dicke limit is not fulfilled, the system is described by a nonlinear Jaynes-Cummings Hamiltonian [3].

In the experiment the observed Jaynes-Cummings dynamics was found to show damping effects. A variety of possible sources of decoherence has been studied, including technical problems in the experiment [4]. The Jaynes-Cummings dynamics is realized by driving an electronic transition by two Raman beams. The lasers are far-detuned from an auxiliary state that provides the Raman coupling. Usually this state is treated as a virtual one that can be eliminated from the dynamics. Nevertheless, quantum jumps to this auxiliary state may occur with a small probability. In this contribution we consider their effects on the decoherence of the system. Note that decoherence due to quantum jumps in a trapped ion has already been discussed for other types of Raman excitations [5].

The master equation that describes the dynamics of the system can be solved using quantum trajectories methods, where the density matrix is obtained by an ensemble average over the realizations of the trajectories. In Fig. 1 we present the result of our simulations of the population dynamics of the electronic ground state, for the case we start in the electronic and motional ground state $|1,0\rangle$ and the atom is driven on the first blue sideband. In the absence of quantum jumps undamped Rabi oscillations between the states $|1,0\rangle$ and $|2,1\rangle$ occur. When the jumps are included in the dynamics, the system shows damped Rabi oscillations. The damping rate obtained from our simulations is very close to the one observed in the experiment. Moreover, as a function of time the Rabi oscillations are shifted from their usual average value of $1/2$. This is due to the fact that the state $|2,0\rangle$, which is decoupled from the dynamics, can be populated by the quantum jumps. When populated, this state no longer contributes to the Rabi oscillations. This asymmetric behavior is also seen in the measured data [1].

The quantum jumps under consideration give an explanation of the leading damping effects observed in this particular situation without the need of assuming technical noise in the experiment. For other transitions $|1,n\rangle \leftrightarrow |2,n+1\rangle$ $(n \neq 0)$ the damping of the measured signal cannot be explained by the quantum jumps alone. Anyway, their effects are important for the interpretation of the experimental data and may yield new insight in the nature of the additional technical noise sources.

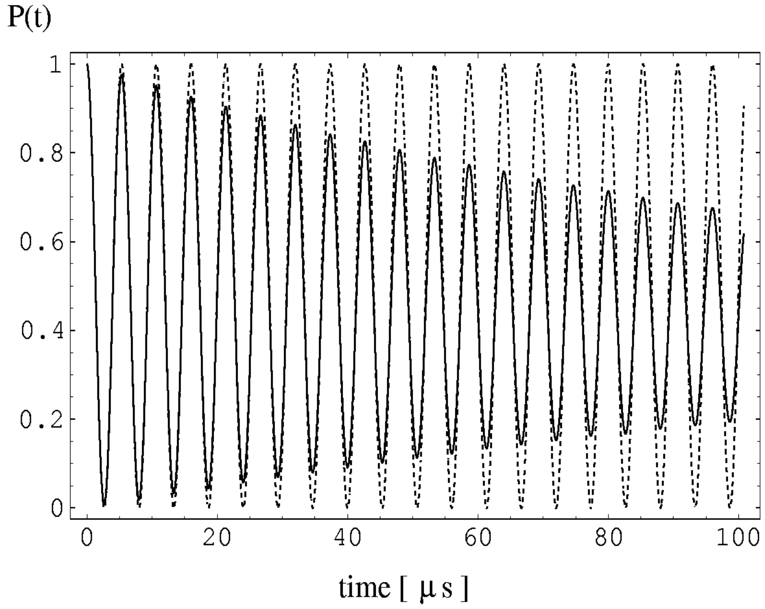

Figure 1: Time-evolution of the probability $P(t)$ to be in the electronic ground state $|1\rangle$ for an initial electronic and vibrational ground state $|1,0\rangle$. Damped Rabi oscillations and a shift from their usual average value of 1/2 are clearly visible. The ensemble average is performed over 10000 trajectories. The dashed lines shows the undamped case in the absence of quantum jumps.

[1] D.M. Meekhof, C. Monroe, B.E. King, W.M. Itano and D.J. Wineland, Phys. Rev. Lett. **76**, 1796 (1996).

[2] C.A. Blockley, D.F. Walls, and H. Risken, Europhys. Lett. **17**, 509 (1992).

[3] W. Vogel and R.L. de Matos Filho, Phys. Rev A. **52**, 4214 (1995).

[4] D.J. Wineland, C. Monroe, W.M. Itano, D. Leibfried, B.E. King, and D.M. Meekhof, J. Res. Natl. Inst. Stand. Technol. **103**, 259 (1998); D.F. James, Phys. Rev. Lett. **81**, 317 (1998); S. Schneider and G.J. Milburn, Phys. Rev A. **57**, 3748 (1998); M. Murao and P.L. Knight, Phys. Rev. A **58**, 663 (1998).

[5] C. Di Fidio, S. Wallentowitz, Z. Kis, and W. Vogel, Phys. Rev. A **60**, R3393 (1999).