Applications of QND measurement of the photon number: Quantum Zeno effect and Tomography of the relaxation process


Aim of the experiment
- Demonstrate quantum Zeno effect in the cavity QED context (inhibition of the coherent growth of the field in a cavity coupled to a classical microwave source by repeatedly measuring the photon number).
- Use a statistical ensemble of quantum trajectories obtained by quantum non-destruction measurement of the photon number in each cavity to perform the tomography of the relaxation superoperator.

Methods
- Quantum non-destruction (QND) measurement of the photon number: by inserting a high finesse cavity in an atomic interferometer, we detect the induced light shift on the atoms crossing the cavity field mode.

Results
- First demonstration of Quantum Zeno effect on a runaway system [1].
- Experimental determination of all jump rates between Fock states [2].

References

Quantum Zeno effect

“A watched kettle never boils”

\[ T = N \cdot \delta t \]

Probability not to jump at first measurement:
\[ \tau_1 = |A|^2 \delta t \]

Probability to have no jump before n'th measurement:
\[ \tau_n = (1 - |A|^2 \delta t)^{n-1} \]

Mean photon number:
\[ \bar{n}(T) = |\alpha|^2 \delta t^n \]

Linear increase ≠ quadratic

Tomography of decoherence of pure photon number states

Improving the time resolution
110 atoms to converge = 26 ms > lifetime for n=7 (18 ms)

Experimental results
Cavity is prepared in the vacuum state
A series of injection pulses inject a field in the cavity.
\[ |\alpha| \approx 0.047 \] (n = |\alpha|^2 = 2.2 \times 10^{-2} photons)

1. Without intermediate measurements: varying number of injection pulses is applied. The field is then measured by atoms.
2. A series of 100 injection pulses is performed. The field is measured by 10 atoms crossing the cavity between successive pulses.
3. A zoom on the last curve shows a linear initial increase of n, followed by saturation due to cavity damping.

Reconstructed jump rates

Decoherence superoperator

Experimental determination

Theory at T=0K

Previous observations of Zeno effect
The first observation of Zeno effect was performed with trapped ions in 1980. Quantum Zeno effect was observed since then in several physical systems:
- Atoms
- Molecules
- Bose-Einstein condensates

So far, Zeno effect was only demonstrated on two-level systems. The repeated measurements inhibit a Rabi oscillation-like behaviour.

A random walk in phase space

Without measurements
\[ \langle 2(\alpha) \rangle \quad \langle 9(\alpha) \rangle \]

Number of pulses
Amplitude
Amplitude injected in each pulse

With measurements
\[ \langle 3(\alpha) \rangle \quad \langle 9(\alpha) \rangle \]

\[ \bar{n} = |\alpha|^2 \]

Statistical ensemble of Quantum trajectories

1. Prepare vacuum state
2. Inject a coherent field (+3 photons)
3. Measure continuously the photon number with probe atoms for 700 ms

1/8 of the initial coherent state.

\[ \bar{n} = |\alpha|^2 \]

QND measurement projects an initial coherent field into a random Fock state, decay of which appears as a cascade-like successions of quantum jumps.

By averaging many individual trajectories, we find the mean photon number evolution of the initial coherent state.

In contrast to the Quantum Zeno Effect, decay rate is unaffected by the measurement because:
\[ \tau_c < < \tau_{meas} \]
\[ \tau_{meas} : memory time of the environment \]
\[ \tau_{meas} : time to perform a measurement \]

Average over 2000 realizations

Statistical ensemble of Quantum trajectories

Decoherence superoperator

Time (ms)

Average photon number \( P(n) \)

Abs: experimental determination

Decoherence superoperator

Theory at T=0K

P(n) is the population distribution at the middle time of the window

25 atoms = 6 ms!