Quantum feedback experiments stabilizing Fock states of light in a cavity

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Aim of the experiments
Preparation of photon number (Fock) states of a cavity field and correction of quantum jumps due to decoherence using two quantum feedback schemes

Feedback loop components
System: Microwave cavity field
Target: Fock state $|n\rangle_{\text{target}}$
Sensor (quantum): Off resonant atoms performing a QND measurement of the field
Controller (classical): State $\rho$ estimation at each atomic detection and choice of the feedback action (real-time A/D in computer system)
Actuator: Injection of a small coherent field (classical) OR resonant atoms emitting or absorbing photons (quantum)

Two different feedback actions
- Controller $K$ calculates the optimal classical field to inject in $C$ (amplitude $A$ and phase $\phi$)
- $K$ chooses the actuator atom type: $|e\rangle$ (emitter) OR $|g\rangle$ (absorber)

Quantum Non-Demolition (QND) measurement of the photon number

Quantum state estimator
State estimation:
- Each detection projects $\rho$
- Trace over unresolved atoms
- Cavity field estimation using a Liouville superoperator obtained from solving master equation

Experimental imperfections:
- Samples with Poisson atom number distribution: $\langle n \rangle = 0.5 - 1.3$ atom/sample
- Time between samples: $T_n = 82 \mu s$
- Atom preparation errors (~1%)
- Erroneous state detection (~5%)
- Detection efficiency: 25%
- Black-body thermal field: $n_0 = 0.05$
- Cavity lifetime: $T_m = 65$ ms

Resonant interactions
- Atoms are tuned in resonance by a DC Stark field applied across the cavity.
- No coherences: considering photon number distribution $p(n)$ is enough.
- After each detection $p(n)$ updates using Bayes’ law from previous $p(n)$ and transition probabilities (Rabi oscillations in the cavity containing n photons).
- For all $n$, calibration of Rabi oscillations
- Interaction times $T_1$ to $T_7$ for $|e\rangle$ and $|g\rangle$ atoms set close to $2\pi$-pulse $\eta|n\rangle_{\text{target}}$
- Two-atom events also considered

Feedback with coherent field injection
- Injection of a small coherent field (classical) as actuator to correct for quantum jumps of the cavity field state
- State estimation needs to take into account the phase of the field and the full density operator.
- The injection of this small field displaces $\rho$
- $\rho \rightarrow D(\alpha) \rho D(-\alpha)$ with $D(\alpha) = \exp(\alpha a^+ a)$
- Quantum trajectory: feedback stabilization of $|3\rangle$

Results for feedback with atomic actuators
- Quantum trajectory: feedback stabilization of $|4\rangle$
- Photon populations of coherent states ($n = \sqrt{m_{\text{target}}}$)
- Stabilization efficiency: average populations for 4000 trajectories stopped at an arbitrary time
- Preparation efficiency: trajectory stopped when $P(n_{\text{target}}) \geq 0.8$

Perspectives
- Adaptive QND measurement of photon numbers
- Quantum feedback: stabilization of photon number cat states
- G. Sayrin et al., Nature 477, 73-77 (2011)