Quantum Feedback in cavity QED

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SUNY Stony Brook Quantum Optics group:  
(Moving to University of Maryland College Park at the end of the summer)  
http://funk.physics.sunysb.edu/lab/index.html  

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Hanbury-Brown and Twiss **Intensity-Intensity Correlations**

The correlation is largest at equal time

\[
g^{(2)}(\tau) = \frac{\langle I(t)I(t + \tau) \rangle}{\langle I(t) \rangle^2}
\]

Cauchy-Schwarz

The correlation is largest at equal time

\[
g^2(0) \geq g^2(\tau)
\]
Intensity correlation function measurements:

\[ g^{(2)}(\tau) = \frac{\langle \hat{I}(t)\hat{I}(t+\tau) \rangle}{\langle \hat{I}(t) \rangle^2} \]

Gives the probability of detecting a photon at time \( t + \tau \) given that one was detected at time \( t \). This is a conditional measurement:

\[ g^{(2)}(\tau) = \frac{\langle \hat{I}(\tau) \rangle_c}{\langle \hat{I} \rangle} \]
Cavity QED
Quantum Electrodynamics for pedestrians. No renormalization needed. A single mode of the electromagnetic field of a cavity.

ATOMS + CAVITY MODE
Non perturbative regime: Coupling > dissipation

Dipole coupling between the atom and the cavity.

\[ g = \frac{d \cdot E_v}{\hbar} \]

The field of one photon in a cavity with Volume \( V_{\text{eff}} \) is:

\[ E_v = \sqrt{\frac{\hbar \omega}{2 \varepsilon_0 V_{\text{eff}}}} \]
Cavity QED System

Cavity length ≈ 850 μm

\[ \left( \frac{g}{2\pi}, \frac{\kappa}{2\pi}, \frac{\gamma}{2\pi} \right) \approx (5.1, 3.7, 6.0) \text{MHz} \]
Steady State:

Exchange of Excitation:

Cavity Mode and Atoms
Regression of the field to steady state after the detection of a photon.

\[
\frac{X(t)}{X_{ss}}
\]
Each escape of a photon creates a very large disturbance.

We want to monitor that disturbance or fluctuation.

But we can only get one photon at best every time there is a disturbance.

We have to average the conditional intensity.

How does the data look in the lab?
mean = 13
mean = 100

$g^{(2)}(\tau)$ vs $\tau$ (ns)
7 663 536 starts
mean = 913
1 838 544 stops
Non-classical antibunched

Classically $g^{(2)}(0) > g^{(2)}(\tau)$ and also $|g^{(2)}(0) - 1| > |g^{(2)}(\tau) - 1|$
Conditioned measurements in the language of correlation functions allow the study of the dynamics of the system.

Quantum conditioning, with photodetections, provides the most ideal times for controlling the evolution of the system.

Feedback on a single photodetection.
Wade Smith and Joe Reiner
Conditional intensity and step:

1st photodetection.

Beginning of pulse
We have to satisfy three conditions:

- Amplitude
- Sign of the step (parity)
- Time of the step

We only have one bit of information, a click.

We have good knowledge of the dynamics.
Conditional dynamics of the system wavefunction

\[ |\Psi_{ss}\rangle = |0, g\rangle + \lambda |1, g\rangle - \frac{2g}{\gamma} \lambda |0, e\rangle + \frac{\lambda^2 pq}{\sqrt{2}} |2, g\rangle - \frac{2g\lambda^2 q}{\gamma} |1, e\rangle \]

\[ \lambda = \langle \hat{a} \rangle, \quad p = p(g, \kappa, \gamma) \text{ and } q = q(g, \kappa, \gamma) \]

\[ \hat{a} |\Psi_{ss}\rangle \Rightarrow |\Psi_{\text{collapse}}\rangle = |0, g\rangle + \lambda pq |1, g\rangle - \frac{2g\lambda q}{\gamma} |0, e\rangle \]

\[ |\Psi(\tau)\rangle = |0, g\rangle + \lambda \left[ f_1(\tau) |1, g\rangle + f_2(\tau) |0, e\rangle \right] + O(\lambda^2) \]

\( f_2(T) = -\frac{2g}{\gamma} f_1(T) \)

Field Atomic Polarization

Same coefficients when
Theoretical prediction.
Systematically study amplitude
Questions:

How long can we hold the system and then release it?

How sensitive is it to atomic detuning?

Where is the information stored?

What is quantum about this?

Deterministic source?
Intensity correlation without feedback

Conditional Intensity

\[ \tau^* \] 

\[ \tau \text{ (ns)} \]
Intensity correlation with feedback

![Graph showing intensity correlation with feedback]

Conditional Intensity

$\tau^*$

$\tau$ (ns)
Feedback in a detuned system

\[ \Delta = +2 \text{ MHz} \]

\[ \Delta = -2 \text{ MHz} \]
Systematically follow amplitude, model with detuning
Answers:

How long can we hold the system and then release it?  
As long as we want!

How sensitive is it to detunings?  
With our protocol we only operate well on resonance.

Where is the information stored?  
New steady state.

What is quantum about this?  
The detection of the first photon.

Deterministic source?  
No, we mostly create the vacuum: $|0,g> + \lambda|1,g> + ...$
Summary:

Knowledge of the conditional state for a continuously monitored cavity QED system → Quantum feedback protocols

We trigger on a fluctuation (photon detection) and change the drive at a particular delay after detection. Weak driving field manipulation.

The initiation is with a fluctuation, the feedback is just as for any driven coupled oscillators.