The Cavity-QED Microlaser

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First Single-Atom Laser

- Supercavity with $F=980,000$.
- Strong coupling condition is satisfied: $(\Gamma_{\text{cav}}, \Gamma_{\text{a}}, g) = 2\pi \times (150, 50, 340)$ kHz.

Contents

• Conditions for single-atom interaction
• Observation of nonclassical photon statistics
• Observation of quantum jumps
• Controlled atom-cavity coupling: bipolar atom-cavity coupling
• Transmission study of this atom-cavity composite

First Single-Atom Lasing Data

Standing wave mode, averaged coupling, from PRL 73, 3375,(1994)
Rabi Oscillation (Bloch Vector Picture)

\[
\begin{align*}
    S_z(0) &= \rho_{ee} - \rho_{gg} = 1 \\
    \Omega &= 2\sqrt{n+1}g \\
    \frac{dS}{dt} &= S \times \Omega \\
    \Omega &= (2g\sqrt{n+1}, 0, \Delta)
\end{align*}
\]

Probability that a photon is emitted.

Simple Rate Equation for Steady-State Mean Photon Number

\[
\begin{align*}
    P_g(t) &= \frac{1 - S_z(t)}{2} = \frac{1 - \cos \Omega t}{2} = \sin^2\left(\sqrt{n+1}gt\right)
\end{align*}
\]
Uniform Atom-Cavity Coupling

- Atomic beam aperture, 250 µm x 25 µm, used just before the cavity.

\[ \text{\textit{minimizing the variation in } g} \]

Rate equation solution - realistic case

\[
\frac{dn}{dt} = \frac{N \sin^2(\sqrt{n + 1} \Gamma_{\text{int}})}{\Gamma_{\text{int}}} - \Gamma_{\text{cav}} n
\]

Damping of gain curve due to residual broadening in \( g \) and \( t_{\text{int}} \)
Experimental Proof of Existence of the Second Branch

seeded with initial photons in the cavity

unseeded

Observation of Nonclassical Radiation
Gain-Loss Feedback

- Cavity decay removes a photon whereas the gain adds a photon.
- For temporary excessive photons, restoring rate is proportional to cavity loss minus gain function, $L(n) - G(n)$.
- Restoring rate due to “cavity loss” $L(n)$ alone gives rise to a Poissonian photon-number distribution.
- Additional restoring rate due to $-G(n)$ results in sub-Poissonian photon-number distribution.

High efficient $g^{(2)}$ measurement system

- Record the arrival times of all the photons detected at both detectors from a common trigger
- Correlate all the photons at one detector with all the other. 
  
  Multiple-start, multiple-stop.
- Conventional method: Single-start, single or multiple-stop. Our method is $10^5$ times more efficient.

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RSI 76, 083109 (2005)
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Transition from Super- to sub-Poissonian photon statistics

\[ g^{(2)}(t) = 1 + \frac{Q}{\langle n \rangle} e^{-t/\tau} \]

Observation of Quantum Jumps

PRL 96, 093603 (2006)

1/17/07 KIAS Winter Camp 2007
Quantum Theory Predicts Quantum Jumps

\[ (g t_{\text{int}})^2 n \]

\[ \left( \frac{g^2 t_{\text{int}}}{\Gamma_{\text{cav}}} \right)^N \]

Microlaser Output vs. Detuning

just above the first threshold

atom-cavity detuning

well above the first threshold

- Strong coupling condition is satisfied: \((\Gamma_c, \Gamma_p, 2g) = 2\pi \times (150, 50, 530) \text{ kHz}\).
Observation of quantum jumps and hysteresis

Even the second quantum jumps and hysteresis:

PRA 73, 041802(R) (2006)
Semiclassical theory (Bloch picture) reproduces jumping levels but not why and where jumps occur.

Bipolar Atom-Cavity Coupling
**Polarity Control of Atom-Cavity Coupling**

We can manipulate the quantum state of atoms by controlling the atom-cavity coupling. → One example is the *bipolar* coupling.

\[ g(x) = \frac{\mu}{\hbar} E_{\text{vac}} \psi(x) \]

*E_{\text{vac}}*: Electric field by vacuum fluctuations

\[ \psi(x) : \text{cavity-mode function} \]

A single mode vs. two separate cavity modes

The cavity *automatically* prepares the perfect out-of-phase bipolar pulses.

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**Bloch Vector Picture: Geometric Interpretation**

\[ \frac{dS}{dt} = S \times \Omega, \]

where \[ S_3 = \rho_{ee} - \rho_{gg} \]

\[ \Omega = (\pm 2g_0 \sqrt{n+1}, 0, \Delta) \]

- Rotation around \( \Omega_+ \) for \( \tau \) and rotation around \( \Omega_- \) for another \( \tau \)
**Bloch Vector Picture: Geometric Interpretation**

\[
\frac{dS}{dt} = S \times \Omega,
\]

where

\[
S_3 = \rho_{ee} - \rho_{gg}
\]

\[
\Omega = (\pm 2g_0 \sqrt{n + 1}, 0, \Delta)
\]

- Rotation around $\Omega_+$ for $\tau$ and rotation around $\Omega_-$ for another $\tau$
- We may find optimal detuning for the largest net inversion.

\[
\tan \theta = \frac{\Delta}{2g_0 \sqrt{n + 1}}
\]

For $\theta = \pi/4$, one can reach maximum gain, that is, $S_3 = -1$ with $\Omega \tau = \pi$.

cf) $\Omega \tau = 2\pi$ gives $S_3 = 1$ (zero gain) → periodicity of gain.

Maximum contrast of oscillation when

\[
\theta = \frac{\pi}{4} \Rightarrow 2g_0 \sqrt{n + 1} = \Delta
\]
**Bloch Sphere Analysis: Gain with Detuning**

For successive maxima of gain function, $\Delta$ first satisfies the relation

$$\Delta = 2g_0\sqrt{n+1} \quad (45^\circ \text{condition})$$

In addition, with proper $n$, $\Delta$ satisfies

$$\Omega = \sqrt{\Delta_m^{-2} + 4g_0^2(n+1)\tau} = m\pi \quad (m = 1, 3, 5, \ldots)$$

$$\Rightarrow \Delta_m = \frac{m\pi}{\sqrt{2}} \times \frac{1}{\tau} \quad \text{(independent of } n \text{ and } g_0)$$

Other multipolar coupling cases show similar but more complex structure.

**Determination of Steady-State**

- Double peak resonance
- $\Delta_{\text{exp}} \approx \Delta_{m=1} \propto 1/\tau$

![Diagram](image)


**Experiment: Bipolar Atom-Cavity Coupling**

Two level atoms \(^{138}\text{Ba}\) with 50kHz decay \(^{1}\text{S}_0 \leftrightarrow ^{3}\text{P}_1\)

The cavity prepares the out-of-phase vacuum fields!

\[
g_0 = 390 \text{kHz}
\]

\[
g(x) = \frac{\mu}{\hbar} E_{\text{vac}} \psi(x)
\]

oven

pump

Cavity with 170kHz decay

Click here for the setup picture

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**Experiment: Cavity-scan Curve**

8.0 MHz

\[
2 (\Delta/2\pi) = 8.8 \text{ MHz}
\]

Recall \(\Delta_{\exp} < \Delta_1\)

CCD image of output: TEM10 mode

APD Count (Mcps)

-40 -20 0 20 40

atom-cavity detuning (MHz)

0.4 0.6 0.8 1.0

Rest-atom resonance

Doppler shift

Mode structure

\(\pm \hbar / \Delta_c\)

\(\pm \Delta_m\)
Evidence: Dependence on Atomic-Beam Tilt Angle

Doppler shift $2kv\theta$

Proportional to the tilt angle $\theta$ as expected

Separation between 1 and 2

Constant & independent of the tilt angle $\theta$ as expected

Effect of Velocity Distribution

Recall $v \uparrow \rightarrow \Delta_m \uparrow \rightarrow kv\theta \uparrow$
Final Remark

“Cavity-QED microlaser, as a rudimentary laser driven by quantum nature of light and coherent interaction between light and matter, is still not fully understood. It keeps generating a lot of surprises.”

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