Reconstruction of non-classical cavity field states with snapshots of their decoherence

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Introduction

What is done:
Complete reconstruction and representation of different radiations states in a cavity.

How:
Single atoms crossing the cavity probe the field state.

Why:
To study decoherence and energy relaxation rates.

Setup

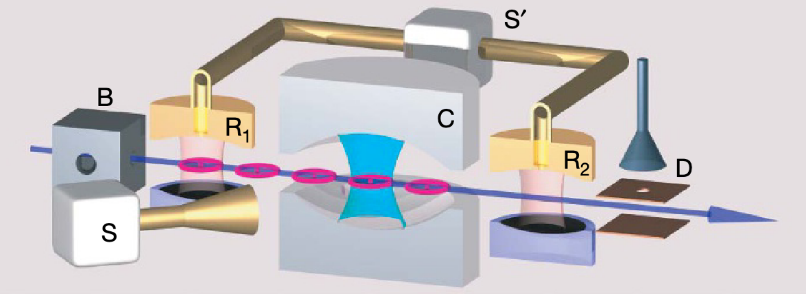


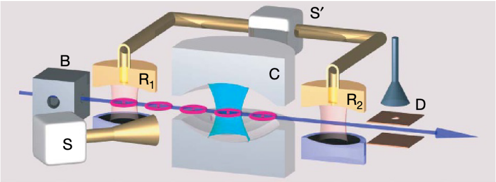
Figure: Experimental setup

Setup

- Cavity damping time $T_c = 0.13\,\text{s}$
- Cavity resonance $\omega_c \simeq 51\,\text{GHz}$
- Coherent field $\left|\sqrt{n_m}\right\rangle$
- Residual thermal photons $n_b = 0.05$

- Atom: Rb $|g\rangle_{n=50} \to |e\rangle_{n=51}$, $\omega_{ge} \simeq 51\,\text{GHz}$
- Atom lifetime $T_{\text{at}} \approx 30\,\text{ms}$ [a]
- Interaction time $T_{\text{int}} = \frac{L}{v_{\text{at}}} \approx 20\,\mu\text{s}$

- Detuning $\delta \sim 10^2\,\text{kHz}$



[a] J. M. Raimond, M. Brune, and S. Haroche, Colloquium: Manipulating quantum entanglement with atoms and photons in a cavity

Reconstruction process

1. Phase shift $\Phi(N, \delta) \sim \frac{2g^2 N}{\delta}$

2. No translation: $P_e - P_g = Tr[\rho \cos\left(\Phi(N, \delta) + \phi\right)$

No information about coherences (off-diagonal elements)!

Reconstruction process

3. Field is mixed with $|\alpha\rangle$, $\rho \to \rho^{(\alpha)} = D(\alpha)\rho D(-\alpha)$

4. Measures with translation:

$$P_e - P_g = Tr[\rho^{(\alpha)} \cos\big(\Phi(N,\delta) + \phi\big)]$$
$$|$$
$$= Tr[\rho \cdot G(\alpha,\phi,\delta)] = g(\alpha,\phi,\delta)$$

where $G(\alpha,\phi,\delta) = D(-\alpha)\cos\big(\Phi(N,\delta) + \phi\big)D(\alpha)$

Reconstruction process

5. Sampling on different $|\alpha\rangle \Rightarrow$ reconstruct ρ
6. Obtain $W(\alpha) = \frac{2}{\pi} Tr[D(-\alpha)\rho D(\alpha) e^{i\pi N}]$

Note: $W(\alpha) = \frac{2}{\pi} \langle e^{i\pi N} \rangle$

Coherent state

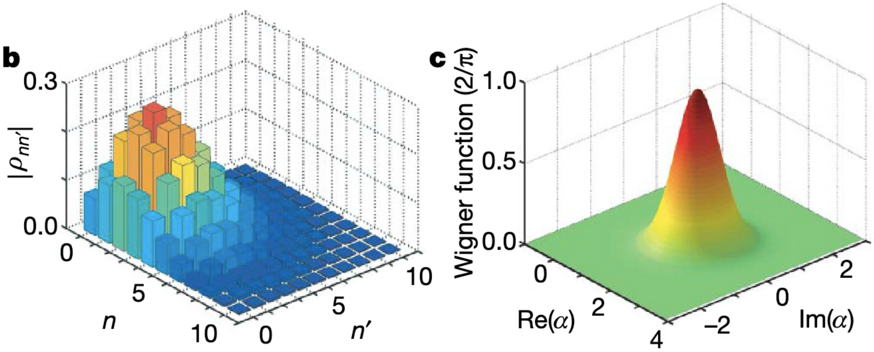


Figure: Coherent state reconstruction ($|\beta\rangle$ with $\beta = \sqrt{2.5}$, F=0.98)

Fock states

How do we generate it? QND measure projects the field onto a $|n_0\rangle$

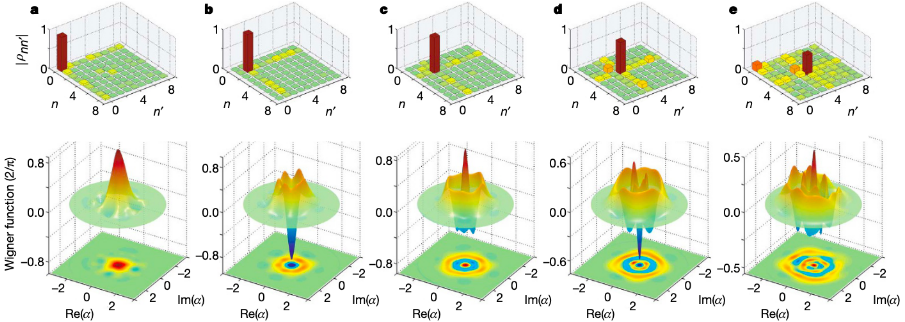


Figure: $|n_0\rangle$ reconstruction with $n_0 = 0, 1, 2, 3, 4$ respectively ($F > 0.8$ for $n_0 < 4$)

Cat states

How do we generate it? Prepare an atom in $(|e\rangle + |g\rangle)/\sqrt{2}$ and a coherent state $|\beta\rangle$in the cavity.

Interacting with the field we obtain $\left(\left|e, \beta e^{i\chi}\right\rangle + \left|g, \beta e^{-i\chi}\right\rangle\right)/\sqrt{2}$. After R_2 action, measuring the atom projects the field in (+ even, - odd):

$$\frac{\left|\beta e^{i\chi}\right\rangle \pm \left|\beta e^{-i\chi}\right\rangle}{\sqrt{2}}$$

Cat states

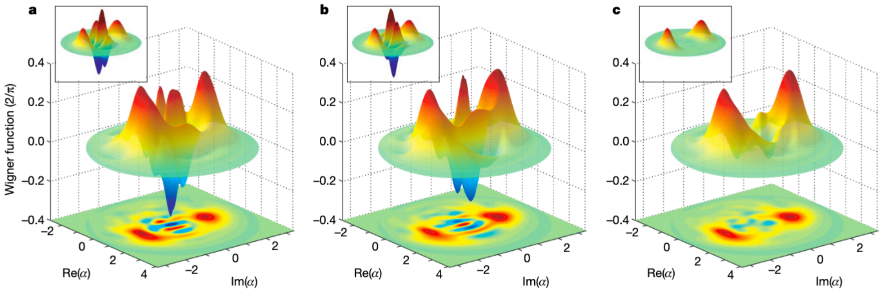


Figure: Cat state reconstruction, a even, b odd (F=0.72) (videos)

Decoherence

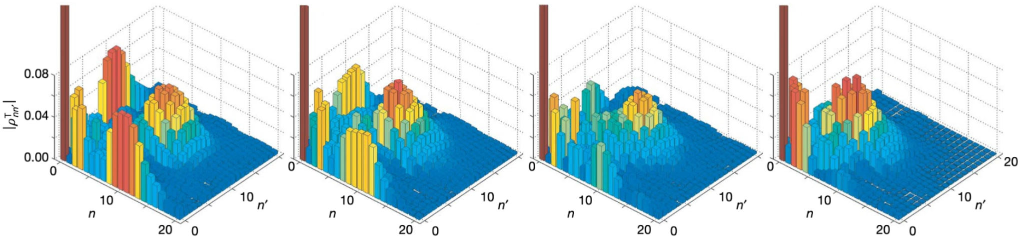


Figure: Movie of decoherence of odd cat state

Decoherence

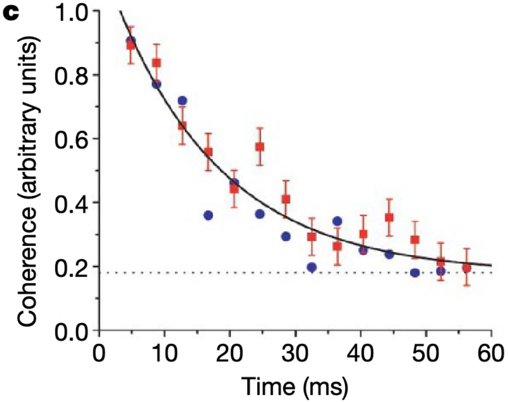


Figure: Decay of cat states: even red, odd blue

- Fitted $T_d = 17 \pm 3\, ms$
- Analytical model @ 0.8K
  $T_d = 19.5\, ms$
- $d^2 \approx 4 n_m \sin^2 \chi = 11.8$ photons
- $d^2 = 8 \;\Rightarrow\; T_d = 28\, ms$

Main message

- How coherent, Fock, and cat states are produced
- How to measure ρ and reconstruct $W(\alpha)$
- Visualize decoherence through fully reconstructed ρ and $W(\alpha)$
- Dependence of T_d on d^2