images of quantum light

Andrew N Cleland

department of physics
university of california
santa barbara

collaborators:
John M Martinis (uc santa barbara)
Michael Geller (u georgia - athens)

theory

experiment

College de France
14 Juin 2011
11:00
historical perspective

Each atom has specific wavelengths

<table>
<thead>
<tr>
<th>Element</th>
<th>Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydrogen</td>
<td>![hydrogen spectrum]</td>
</tr>
<tr>
<td>helium</td>
<td>![helium spectrum]</td>
</tr>
<tr>
<td>oxygen</td>
<td>![oxygen spectrum]</td>
</tr>
<tr>
<td>carbon</td>
<td>![carbon spectrum]</td>
</tr>
</tbody>
</table>

Wave nature of electrons in atoms

\[ \lambda = \frac{h}{mv} \]

\[ \hat{H} |\Psi\rangle = i\hbar \frac{\partial}{\partial t} |\Psi\rangle \]
Quantum mechanics is the most precise physical theory:

atomic hydrogen 1S-2S transition frequency:

**experiment:** 2 466 061 413 187 103 Hz

**theory:** 2 466 061 413 2XX XXX Hz

limited by precision of physical constants

“Measurement of the H 1S-2S transition”


MPI Garching & Observatoire de Paris & LKB, Paris
not just for atoms

Cool to quantum ground state:
- need $T \ll \hbar \omega / k_B$
  
  $\omega / 2\pi \sim \text{GHz} \Rightarrow T \ll 0.1 \text{ K}$
- dilution refrigerator: $T = 20 \text{ mK}$
However:

Harmonic oscillators are always in the correspondence limit.

- Difficult to distinguish classical from quantum behavior
- Difficult to control at single photon level
- Difficult to measure at single photon level
- How to measure without destroying quantum effects?
how to measure a harmonic oscillator in quantum limit?

1. interpose a quantum two-level system (electronic atom)
2. electronic atom and oscillator form coherent system
3. complete quantum control & measurement possible
resonator quantum control

how to measure a harmonic oscillator in quantum limit?

1. interpose a quantum two-level system (electronic atom)
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Electronic Two-Level Atom

Phase Difference
\( \delta = \phi_T - \phi_B \)

AC & DC Josephson Relations

Thin Insulator (\(~1\, \text{nm})\)

At 20 mK, \( \delta \) is a quantum variable:

- Strong nonlinearity
- Can address just \( |g\rangle \) and \( |e\rangle \)
- Energy splitting \( \omega_{ge} \) tunable
  \( \hbar \omega_{ge} \sim 30k_B T \) at 20 mK

1. Electronic two-level system
2. Ground state below 300 mK
3. Complete quantum control
4. Single-shot measurement
qubit measurement

- State of qubit measured with SQUID at end of preparation
- Single shot measurement yields qubit state ($|g\rangle$ or $|e\rangle$)
- Repeated preparation & measurement (~1000X) yields $P(e)$
- External flux bias $\Phi$ used to adjust $|e\rangle$–$|g\rangle$ frequency, relative occupation & quantum phase
half-wave coplanar stripline resonator

- Wavelength $\lambda = 2L \sim 10 \text{ mm}$
- Resonance frequency $\omega / 2\pi \sim 5\text{-}10 \text{ GHz}$
  \[ \hbar \omega \gg k_B T \text{ at } 20 \text{ mK} \]
- Quality factor $Q \sim 10^5\text{-}10^6$
  \[ T_1 = Q / \omega \text{ is a few microseconds} \]
coupled resonator & qubit

M. Hofheinz et al.
quantum light & sound

resonator & qubit
experimental system
coupled system spectroscopy

1. set qubit frequency
2. set microwave frequency
3. pulse & measure qubit

**μwaves**

| e \rangle | g \rangle | 0 \rangle | 1 \rangle | 2 \rangle |

- resonator frequency 6.42 GHz
- coupling strength 18 MHz

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m. hofheinz et al. nature (2008)
coupled system energy levels

- **Qubit**
  - Ground state: \(|g\rangle\)
  - Excited state: \(|e\rangle\)

- **Resonator**
  - Levels: 0, 1, 2

- **Energy Levels**
  - \(\langle e | e \rangle\) tunable

- **State of System**
  - \(|g0\rangle\)
  - \(|e0\rangle\) splitting (tunable)
  - \(|e1\rangle\)
  - \(|e2\rangle\)
- qubit off resonance (system in $|g\rangle|0\rangle$ state)
- apply microwave $\pi$ pulse to qubit (goes to $|e\rangle|0\rangle$ state)
time-domain control

- qubit off resonance (system in $|g\rangle|0\rangle$ state)
- apply microwave $\pi$ pulse to qubit (goes to $|e\rangle|0\rangle$ state)
- tune qubit to resonator frequency
- Rabi oscillation: transfer photon from qubit to resonator

1 photon rate: $\Omega$

1 photon in resonator $|g1\rangle$ to $|e0\rangle$

Diagram:

\[
\begin{array}{c}
|g0\rangle \\
|g1\rangle \leftrightarrow |e0\rangle \\
|g2\rangle \leftrightarrow |e1\rangle \\
\end{array}
\]
adding more photons

- detune qubit (system in $|g\rangle|1\rangle$ state)
- apply microwave $\pi$ pulse to qubit (goes to $|e\rangle|1\rangle$ state)

1 photon in resonator

1 photon rate: $\Omega$
adding more photons

- detune qubit (system in $|g\rangle|1\rangle$ state)
- apply microwave $\pi$ pulse to qubit (goes to $|e\rangle|1\rangle$ state)
- rune qubit to resonator, Rabi (goes to $|g\rangle|2\rangle$ state)

2 photons in resonator $|g2\rangle \xrightarrow{\text{detune_qubit}} |e1\rangle$ 2 photon rate: $\sqrt{2} \Omega$

1 photon in resonator $|g1\rangle \xrightarrow{\text{detune_qubit}} |e0\rangle$ 1 photon rate: $\Omega$

|g0\rangle
adding more photons

- detune qubit (system in $|g\rangle|1\rangle$ state)
- apply microwave $\pi$ pulse to qubit (goes to $|e\rangle|1\rangle$ state)
- tune qubit to resonator, Rabi (goes to $|g\rangle|2\rangle$ state)
- repeat for $n$ photons: each transfer $\sqrt{n}$ faster

2 photons in resonator: $|g2\rangle$ --- $|e1\rangle$ --- $|e2\rangle$

- 2 photon rate: $\sqrt{2}\Omega$
- 1 photon rate: $\Omega$
time-domain control

measure resonator state with qubit

- qubit in $|g\rangle$
- resonator in $|n\rangle$
- tune qubit into resonance

\[ |g\rangle|n\rangle \leftrightarrow |e\rangle|n - 1\rangle \]

Rabi oscillation:

Rabi frequency scales as $\sqrt{n}$
quantum state tomography

arbitrary superposition states:
\[ |g\rangle|0\rangle \Rightarrow |g\rangle(a|0\rangle + b|1\rangle + c|2\rangle + \cdots) \]

- adapt Law & Eberly protocol (ion physics)
- reverse engineering: sequence from final state to ground state
- apply sequence in reverse order: ground state to final state

measure Wigner function \( W(\alpha) \):

- quasiprobability distribution
- negative values \( \Leftrightarrow \) quantum coherence
- equivalent to measuring density matrix

\[ W(\alpha): |\Psi\rangle = |1\rangle + |3\rangle \]

\[ \begin{array}{c|c|c|c|c|c|c|c|c|c} m & 0 & 1 & 2 & 3 \\ \hline n & 0 & 1 & 2 & 3 \\ \hline \end{array} \]

\[ \rho_{mn} \]

\[ \begin{array}{c|c|c|c} m & 0 & 1 & 2 \\ \hline n & 0 & 1 & 2 \\ \hline \end{array} \]
superpositions

prepare and measure $|0\rangle + |n\rangle$ states in resonator

$|\psi\rangle = |0\rangle + |1\rangle$

\[ |\psi\rangle = |0\rangle + e^{\frac{0}{8}i\pi} |3\rangle + |6\rangle \]
\[ |\psi\rangle = |0\rangle + e^{i\frac{\pi}{8}} |3\rangle + |6\rangle \]
superpositions

\[ |\psi\rangle = |0\rangle + e^{\frac{2i\pi}{8}} |3\rangle + |6\rangle \]
superpositions

\[ |\psi\rangle = |0\rangle + e^{\frac{3i\pi}{8}} |3\rangle + |6\rangle \]

M. Hofheinz et al.
Nature (2009)
\[ |\psi\rangle = |0\rangle + e^{4i\pi/8} |3\rangle + |6\rangle \]
\[ |\psi\rangle = |\alpha = 2\rangle + |\alpha = 2e^{i2\pi/3}\rangle + |\alpha = 2e^{i4\pi/3}\rangle \]
the ex-voodoo cat

time evolution of a superposed state

$$|\psi\rangle = |0\rangle + i |2\rangle + |4\rangle$$

(note that no cats were actually harmed in this experiment, nor were any cats directly involved)
entangling two resonators

M. Mariantoni et al.
Nat Phys (2011)
entangling two resonators

entangling two resonators

Storing delocalized photons in two resonators

One photon: $|1\rangle_A$
Zero photons: $|0\rangle_C$
Superposed with
Zero photons: $|0\rangle_A$
One photon: $|1\rangle_C$

$$|\Psi\rangle = |1\rangle_A|0\rangle_C + |0\rangle_A|1\rangle_C$$
Storing delocalized photons in two resonators

Procedure:
1. Entangle qubits through resonator B: $|e\rangle_0|g\rangle_1 + |g\rangle_0|e\rangle_1$
2. Transfer state to resonators A & C: $|1\rangle_A|0\rangle_C + |0\rangle_A|1\rangle_C$
3. “Amplify” by boosting photon number to $N$

$$|\Psi\rangle \Rightarrow |N\rangle_A|0\rangle_C + |0\rangle_A|N\rangle_C$$
entangling two resonators

Coincidence measurement:

\[ N=1: |1\rangle_A |0\rangle_C + |0\rangle_A |1\rangle_C \implies |e\rangle_0 |g\rangle_1 + |g\rangle_0 |e\rangle_1 \]

Density matrix from bipartite Wigner tomogram:

\[ |2\rangle_A |0\rangle_C + |0\rangle_A |2\rangle_C \]

- strong off-diagonal terms
- good fidelity with target
- clear entanglement
summary:

- generation & detection of photon Fock states
- synthesis of arbitrary synthesis
- movies of decoherence
- delocalized photons in two resonators

we are still very far from an actual quantum computer
images of quantum light

Andrew N Cleland
John M Martinis
Rami Barends
Jörg Bochmann
Yu Chen
(Max Hofheinz)
Matteo Mariantoni
(Haohua Wang)
Yi Yin

Julian Kelly
Erik Lucero
Peter O’Malley
Daniel Sank
James Wenner
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postdocs

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graduate students

E. Lucero

cleland / phase qubit group