Dr. Serge Haroche, ENS & College de France (ITP 9-26-01)
Manipulating Entanglement in Cavity QED Experiments

Various aspects of Entanglement

Quantum non-demolition measurement of photons

Complementary boundary experiments at the quantum-classical boundary

Entanglement and decoherence studies
Schrodinger cat states


Future Projects

Step-by-step entanglement engineering

Entanglement and interference in cavity QED experiments

Rydberg atoms cross one at a time

A cavity storing 0, 1, 2, 3... photons

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Manipulating Entanglement in Cavity QED Experiments

20 years of development in Cavity QED

Altering for precise separable atom multiplications
atom and readout of each atom determined at any time

Femtosecond interferometry

Large microwave pulses R1 and R2 before and after atom passage

Superpositions of states can be prepared by classical

Binary information:

Atoms detected in D by state selection ionization

Cavity cooled below 1K

State preparation

Pulsed circular

Circular Ruhberg atoms

Two essential ingredients:

Easy state selective detection

Large circular orbit (n = 50, 1250 mm)

Easy transparency

Strong coupling to microwaves

Long radiation life time (30 ms)

Great immunity by Stark effect

(integration by time 1.5 nW/m)

Improved by large round mirrors

Long photon life time (1ms)
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Electric field $F(t)$ is used to tune atoms in resonance with $C_{\tilde{r}}$ for a

Determination line, realizing proper Rabi pulse conditions.

The Quantum Rabi Oscillation

An Essential Tool:

Useful Quantum Rabi Pulses

Excitation swapping between atom and field and "quantum"

Entanglement.

Vacuum fluctuations

Atom-field correlations between atom and field.

$\left\langle \mathcal{I} | \mathcal{H}_{\text{atom-field}} | \mathcal{I} \right\rangle = \frac{1}{2} \left\langle \mathcal{I} \left| \mathcal{H}_{\text{atom}} \right| \mathcal{I} \right\rangle$
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A third absorbing probe atom reads out the field

+ +

(Three-atom correlations)

Also a quantum gate...

If initial field is in a superposition of 0 and 1

methe measuring the field

ND method with atom acting as a classical fields, not with quantum fields:

Energy is exchanged with Ramsey

(2R Rabi pulse in 1 one photon field),
in the other if there is 1 photon
one state if there is 0 photon in cavity,
Phases adjusted so that atom exits in...

Preparing a photon

effect which destroys the photoin

Quite different from Einstein’s photoelectric

can be measured again

without being destroyed and

A single photon is measured

Quantum Non-Demolition Measurement of a single photon

(C. Nogues et al., Nature, 400, 239 (1999))
\[ \langle \chi \rangle \langle \psi \rangle - \langle \xi \rangle \langle \eta \rangle \]

Complementarity between path information and entanglement.

\[ \langle \chi \rangle \langle \psi \rangle - \langle \xi \rangle \langle \eta \rangle \]

Complementarity and entanglement.

Quantum interference term (I):

\[ \langle \chi \rangle \langle \psi \rangle - \langle \xi \rangle \langle \eta \rangle \]

In Young's experiment, the scattered photon 8els.

Entanglement

Interferences result in quantum mechanical interference and the mixture of the classical emissions are transformed into a superposition of the quantum particles. Therefore, the quantum path is followed... as long as one does not observe the entanglement.
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Quantum beam splitter: $|\Phi\Theta\rangle = \langle \Phi|\langle \Phi|\langle \Theta|\langle \Theta| + \langle \Phi|\langle \Theta|\langle \Phi|\langle \Theta|$}

Classical beam splitter: $I = 1 = \langle \Phi|\langle \Theta|\langle \Phi|\langle \Theta|$

In Ramsey interferometer, BS is small coherent field:

Quantum beam splitter: $|\Phi\Theta\rangle = \langle \Phi|\langle \Phi|\langle \Theta|\langle \Theta| + \langle \Phi|\langle \Theta|\langle \Phi|\langle \Theta|$

Classical beam splitter: $I = 1 = \langle \Phi|\langle \Theta|\langle \Phi|\langle \Theta|$

$<\Phi|\langle \Phi|\langle \Phi|\langle \Theta| + \langle \Phi|\langle \Theta|\langle \Phi|\langle \Theta|$

Classical vs. Quantum beam splitter

Mach-Zehnder analogy

S. Zehnder, Optcom. 177, 765 (1991)


A Gedanken experiment

Complementarily experiment detector of atom's path in Photon in box vs. Welschereqs

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Conditional Quantum Eraser

\[ |\psi\rangle = \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle) \]

Einstein-Bohr criterion: You have no information about the choice of path, but you have information about the interference pattern.

\[ <\psi|\psi> = \frac{1}{2} \]

From Quantum to Classical

Entanglement and Quantum Eraser

Which-path information can be recovered using a conditional quantum eraser, which selects one of the two possible paths by measuring the state of a second system prepared in a superposition of states |0⟩ and |1⟩.

\[ |\psi\rangle = \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle) \]

This allows us to determine which path the original system took, even though the measurement was made on a different system.

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The unconditional quantum eraser: Interferences with two coupled Mach-Zehnder analogies. What matters is the long correlation time of pulses. The interference is no "phase" in these pulses, and there is no "phase" in these pulses, and the phase fluctuation of the quantum field.

A quantum eraser test.
Entanglement involving mesoscopic field states with different phases.

A Schrödinger cat situation!

Two field states with different phases:

1. S feeds field in cavity
2. Non-resonant Atom prepared in state superposition

Detectable amplitudes and phase variations

Entanglement in non-resonant

Maximal absorption

Entanglement in cavity QED experiments

A 12 order of magnitude difference with ordinary index

1 Non single atom index: N = 1, 10 - 1

Freqency shift

No photon absorption on emission

Amount of off resonant by

Atom and cavity
Decoherence at the classical-quantum boundary
A glimpse of the microscopic

Decoherence Time: T_{coherence} - Transition from quantum to classical altemative

As soon as one photon escapes in environment it
becomes in principle possible, by detecting it to
distinguish the two parts of the superposition
system loses ability to produce interferences

Statistical mixture of states:

Decoherence + Superposition

\[ |\psi\rangle = \rho |\psi\rangle + (1-\rho) |\phi\rangle \]

Gain a complementary interpretation

\textbf{How long does the mesoscopic environment and complementarity exist?}

Decoherence, entanglement with environment in Cavity OED Experiments

\[ W. \text{Zurek, PhysRevD (1991)} \]

\[ \text{Entanglement gets "spontaneously" lost; lifting quantum ambiguity} \]

\[ \text{information about the very quick losses into} \]

\[ \text{thermal bath, goes enhanced to entantle} \]

\[ \text{environment destroying all quantum interference} \]

\[ \text{in Young experiment, the scattered photon gets} \]

\[ \text{environment and complementarity exist} \]
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Entanglement cavity

Principle of two-atom correlation

Schematics of

Decoherence

Decoherence with cold atom physics

Perspectives: marrying CQED

Other decoherence studies with trapped ion (Boulder)

Faster the decoherence, the separation the signal

The larger the state

AcI

Caught in the

Decoherence

4887, 1996
Phys. Review A.

"Probe's state" (quantum mechanics)

"cat" precession

Atom #1

Atom #2

Proper "cat" state

A two-atom correlation experiment

A delay:

Probing the quantum coherence after
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