Introduction to Cavity QED: fundamental tests and application to quantum information

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A very active research field: Code information in simple systems (atoms, photons..) and use state superpositions and entanglement to manipulate information more efficiently than by classical means…

…but one must understand well decoherence and know how to fight it: the fundamental issue of classical-quantum boundary

A model system: atoms and photons in high Q cavities: (Cavity QED)

Course outline

1.

A reminder about concepts and an overview of experiments: how to entangle atoms and photons and realise quantum gates

2.

Exploration of the classical-quantum boundary with field coherent states: Schrödinger cats and decoherence studies

First lecture

1.1 A reminder about entanglement, complementarity and decoherence

1.2 A brief survey of quantum information

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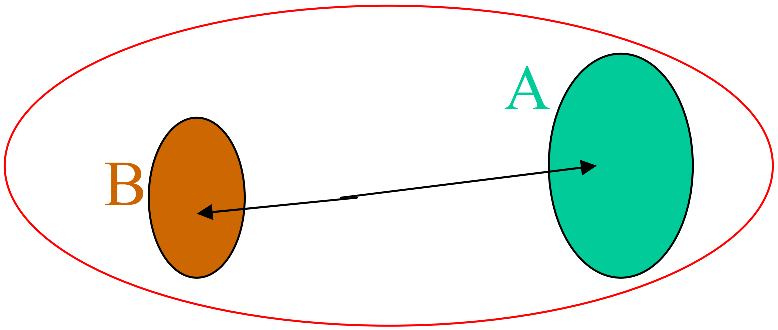
1.5 An introduction to cat state studies in CQED

Entanglement: non-separability of quantum physics

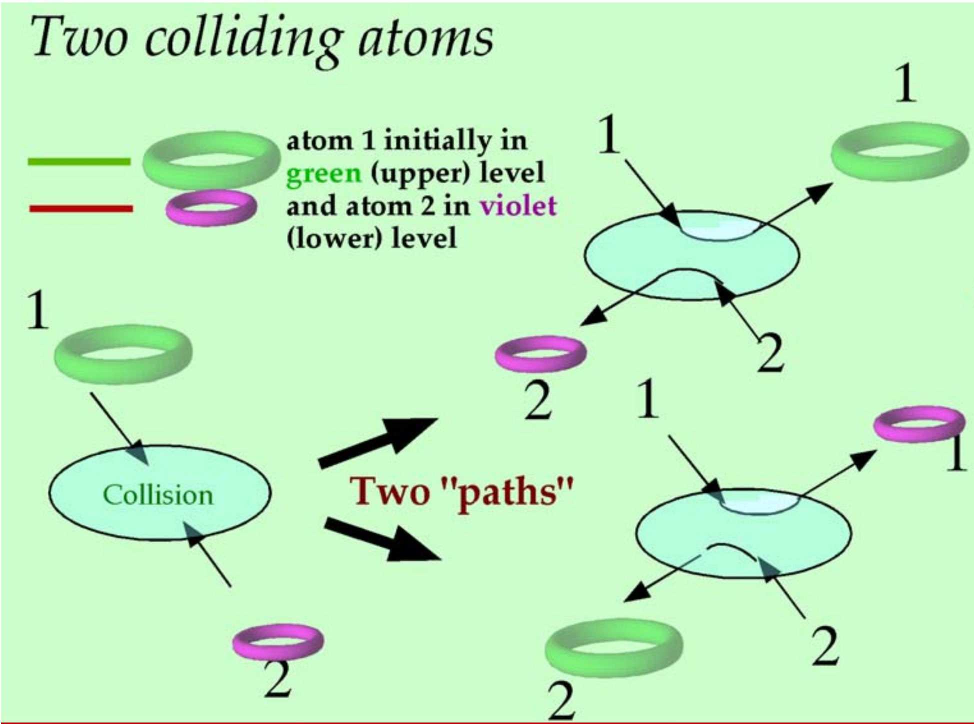


$$|\Psi_{AB}\rangle \neq |\Psi_A\rangle \otimes |\Psi_B\rangle$$

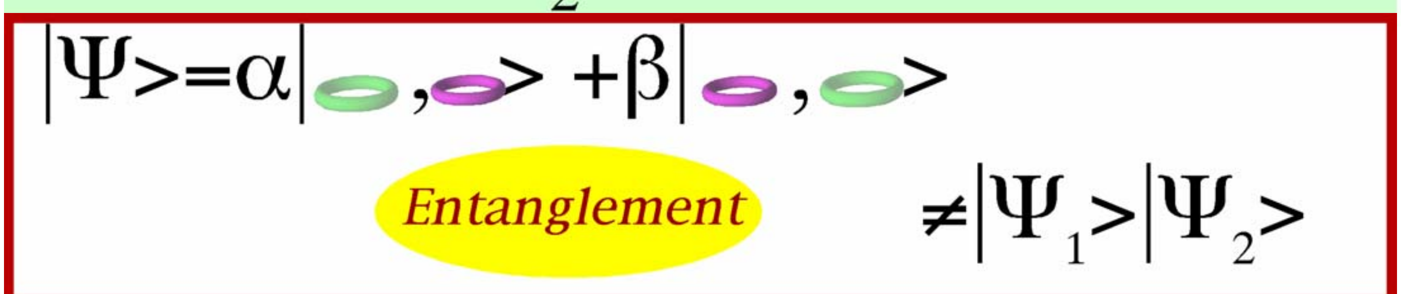
$$\rho_A = Tr_B(|\Psi_{AB}\rangle\langle\Psi_{AB}|)$$

« Entanglement is the essence of the quantum »
(Schrödinger, 1935)

Entanglement survives to spatial separation of system's parts (Einstein, Podolsky and Rosen–1935: EPR paradox)



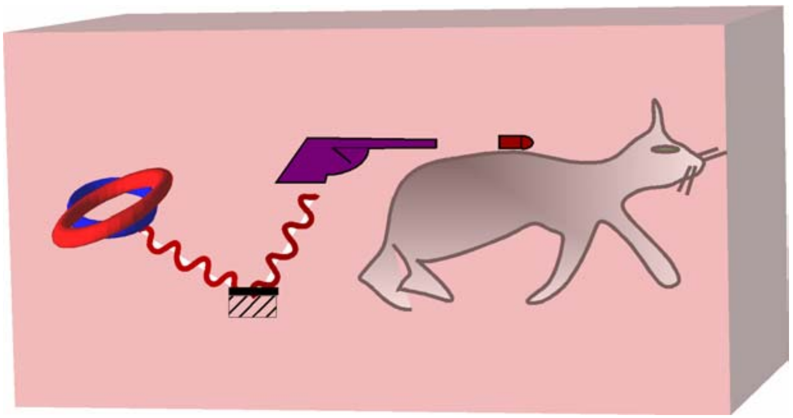
*The final state generally corresponds to a non-separable **entangled** superposition of two "outcomes"*



Results of subsystem measurements are random, but perfectly correlated (if 1 is in [green], 2 is in [violet]) whatever the distance between the atoms.

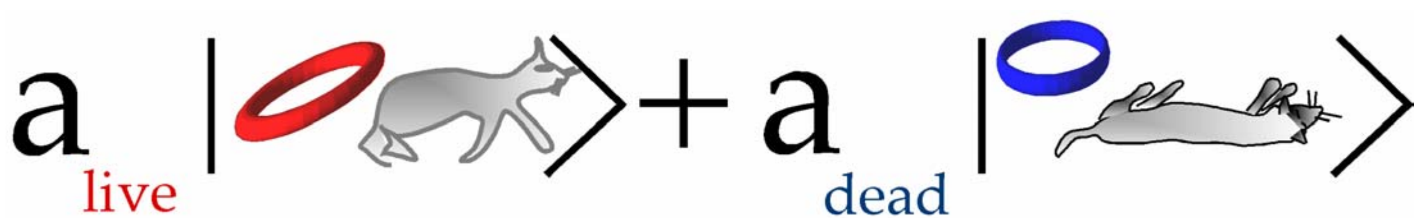
The non locality of quantum physics cannot be understood in classical terms (Bell's inequalities). The experimental violation of these inequalities vindicates quantum mechanics

Entanglement is «strange» because never observed in macro-world ...

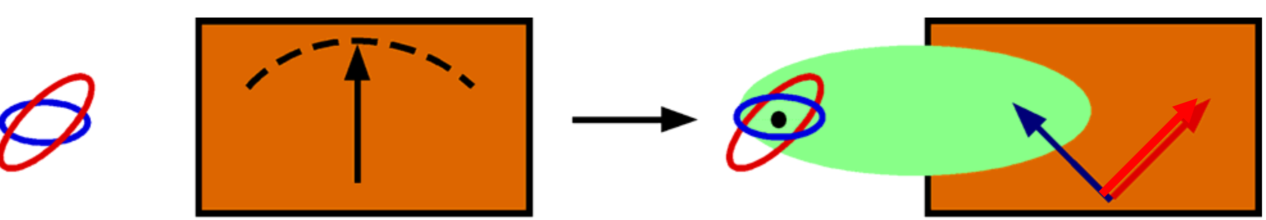


Schrödinger Cat paradox (1935)

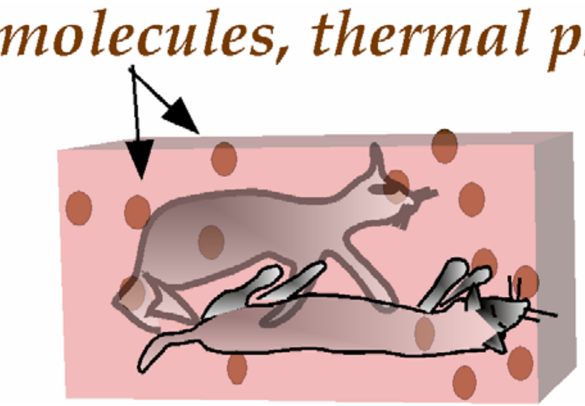
The atom evolves in a state superposition…What is then the state of th cat before the box is opened? Is it entangled with the atom?



A cat coherently suspended between life and death?



Problen linked to measurement theory (entanglement between micro-system and apparatus)

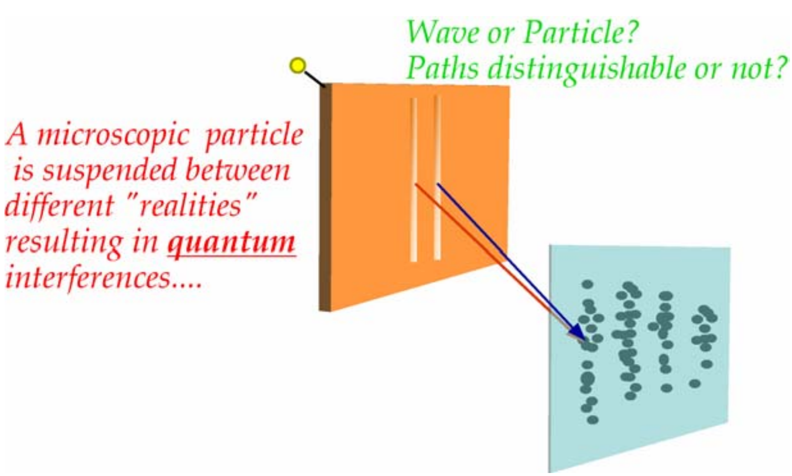


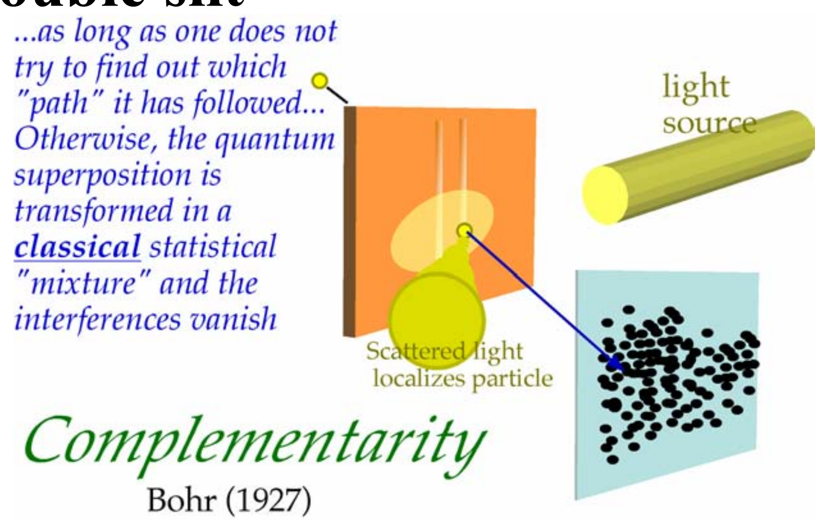
What happens to Schrödinger Cat? It gets entangled to its environment! (*Decoherence*)

The cat's « wave function » has no meaning (replaced by density operator!)

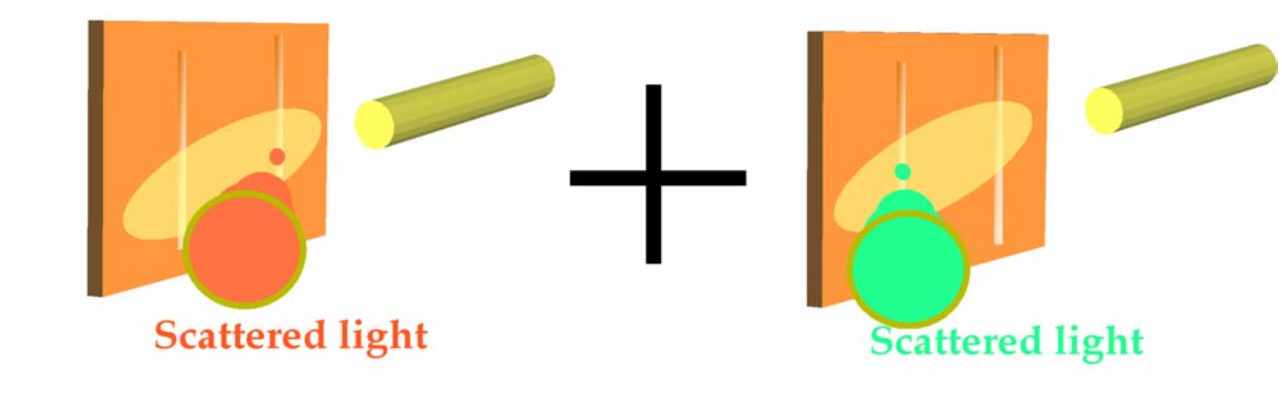
Situation linked to complementarity: quantum interferences are destroyed if information about the system's path leaks into environment:

Simple illustration with Young double slit





Decoherence, entanglement with environment and complementarity



In Young 's experiment, the scattered photon gets entangled with the particle 's path: its detection pins down the particle 's state and destroys all quantum interferences

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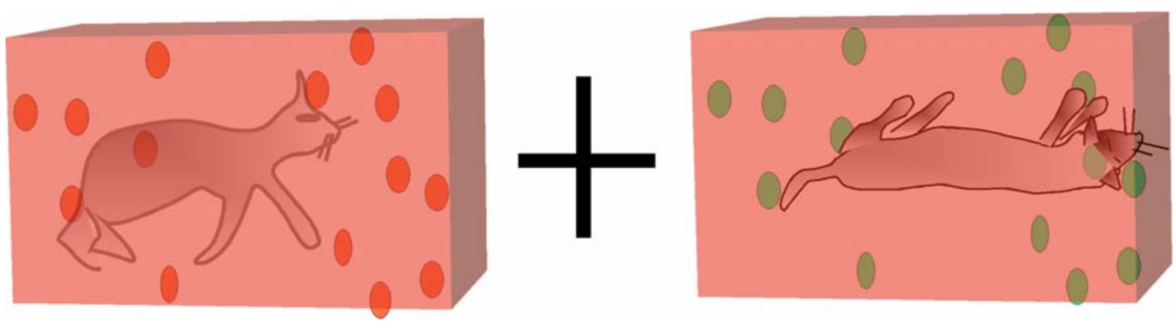

In Schrödinger's « experiment », the thermal bath gets entangled with cat. Information about its fate very quickly leaks into environment, destroying quantum coherences

Decoherence transforms « quantum + » into « classical or »:
Environment acts as a spy lifting quantum ambiguity. « Bad entanglement » with environment kills « good entanglement » with single atom. <u>Decoherence occurs faster and faster as size of system increases (Zurek, Physics Today, Oct 91)</u>

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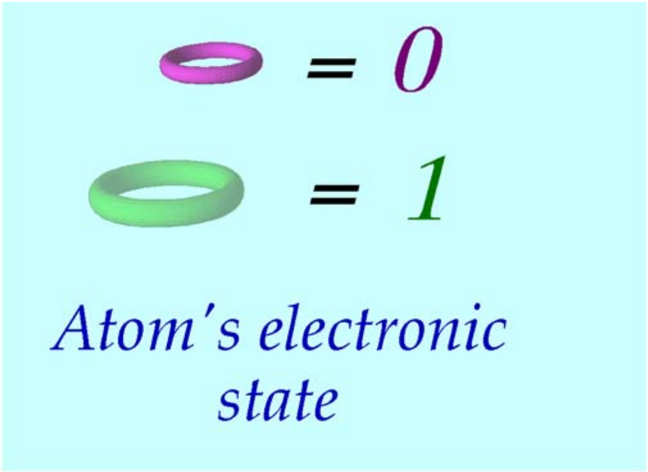
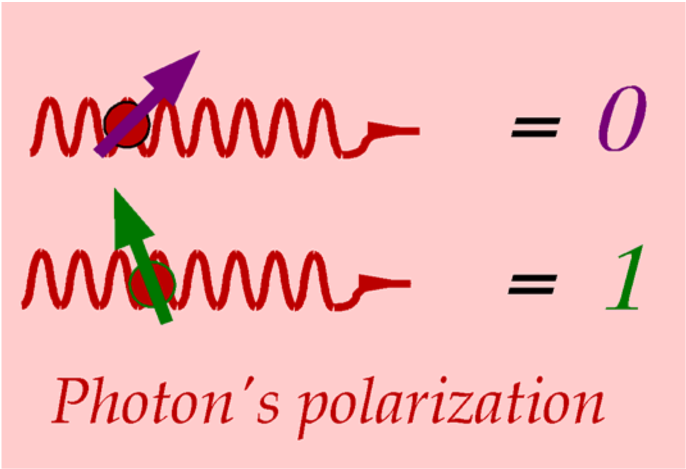
What can entanglement do for us ?
(provided environment is kept in check)

Information can be coded in two state particles (quantum bits or qubits)





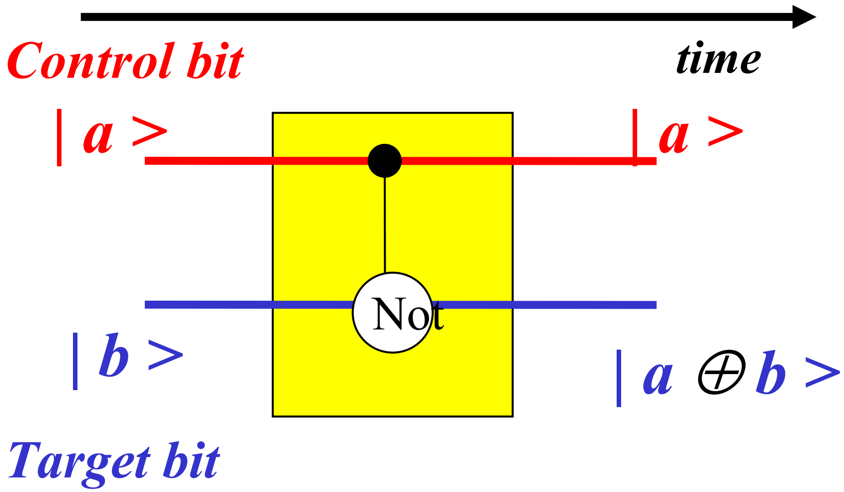
and « entangled information » can be...

…shared securely between two parties (quantum cryptography)...

…used to « teleport » the unknown quantum state of a particle...

…manipulated by quantum logic gates in order to explore the possibilities of quantum computing...

Computing with quantum logic

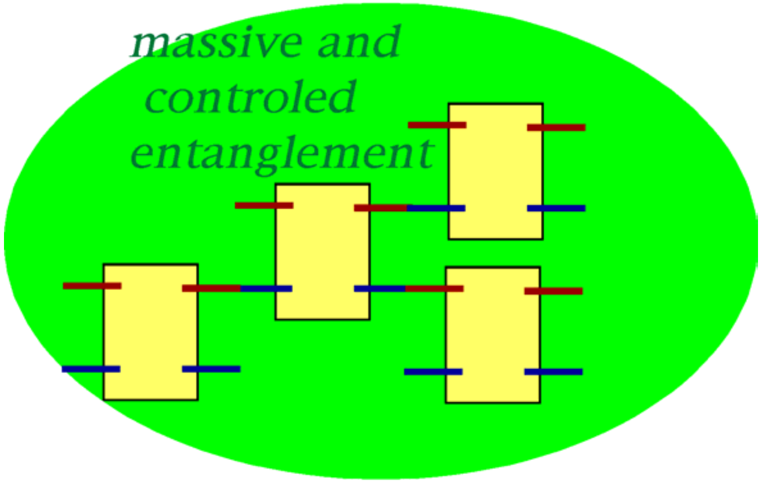


A quantum gate couples two qubits through a conditional unitary operation (if A is true, then do B..).
Here the CNOT gate:
if the control bit is 1, flip the target bit (performs addition modulo 2 of the two qubits in the target output and leaves control unchanged)

Universal gate

***A* quantum gate can generate entanglement (if control in state superposition):**

$$(|0> + |1>) |0> \rightarrow |0> |0> + |1> |1>$$



Combining gates opens in principle fantastic perspectives for computation (*massive parallelism and interference of outputs*..)…but beware of decoherence (this is a very large Schrödinger cat!)

The dreams: factorizing large numbers (Shor), sorting data in a large basis (Grover)….

Requirements for implementing quantum logic

Efficient manipulation and read out of individual two state particles

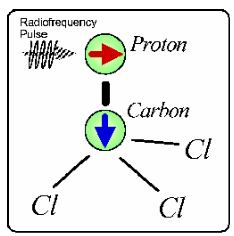
Strong coupling between particles (fast gate operation)

Weak coupling to environment (slow decoherence)

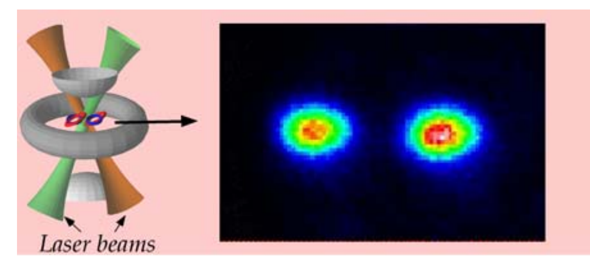
Scalability: possibility of juggling with many particles

Many qubit candidates….but no ideal one so far

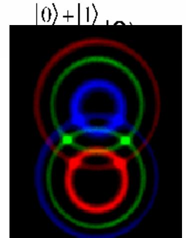
Nuclear spins in molecules



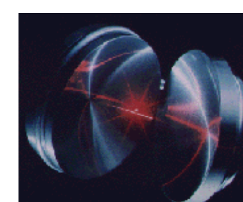
Ions in traps



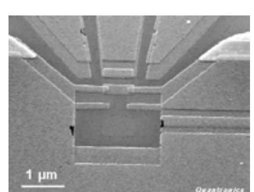
Photon pairs and beam splitters



Atoms in cavities



Superconducting circuits



Quantum dots…

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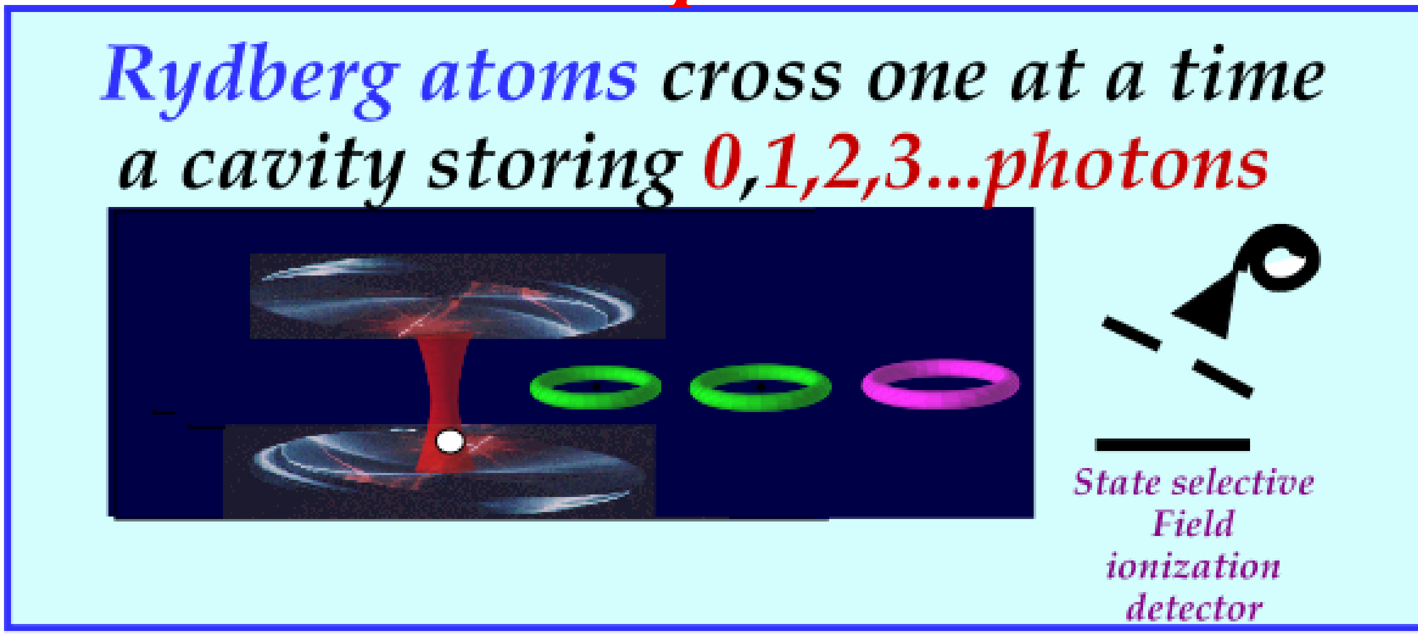
The Qubit candidates:

4. Atoms and photons in cavities



Experiments at ENS, Paris. Also Garching, Caltech..

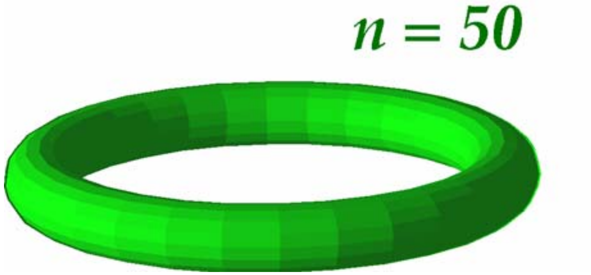
Qubit realized either by atom (in e or g state) or by photon field (0 or 1 photon in cavity)

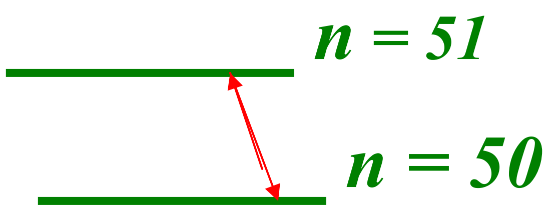
A simple system to learn how to manipulate quantum information

Increasing complexity one atom or one photon at a time: from microscopic to mesoscopic world

For a review of ENS work, see Raimond, Brune and Haroche, RMP, July 2001

Two essential ingredients





Circular Rydberg atoms

Large circular orbit

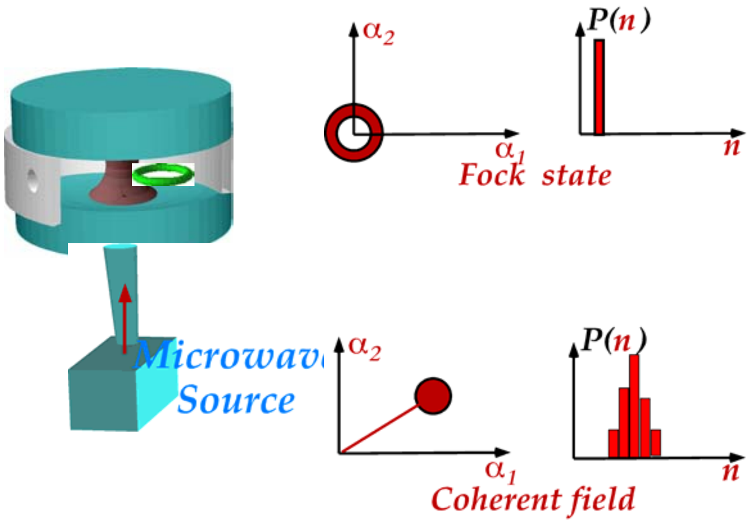
Strong coupling to microwaves

Long radiative lifetimes (30ms)

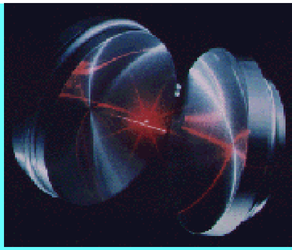
Level tunability by Stark effect

Easy state selective detection

Quasi two-level systems



Superconducting mirror cavity



Gaussian field mode with 6mm waist

Large field per photon

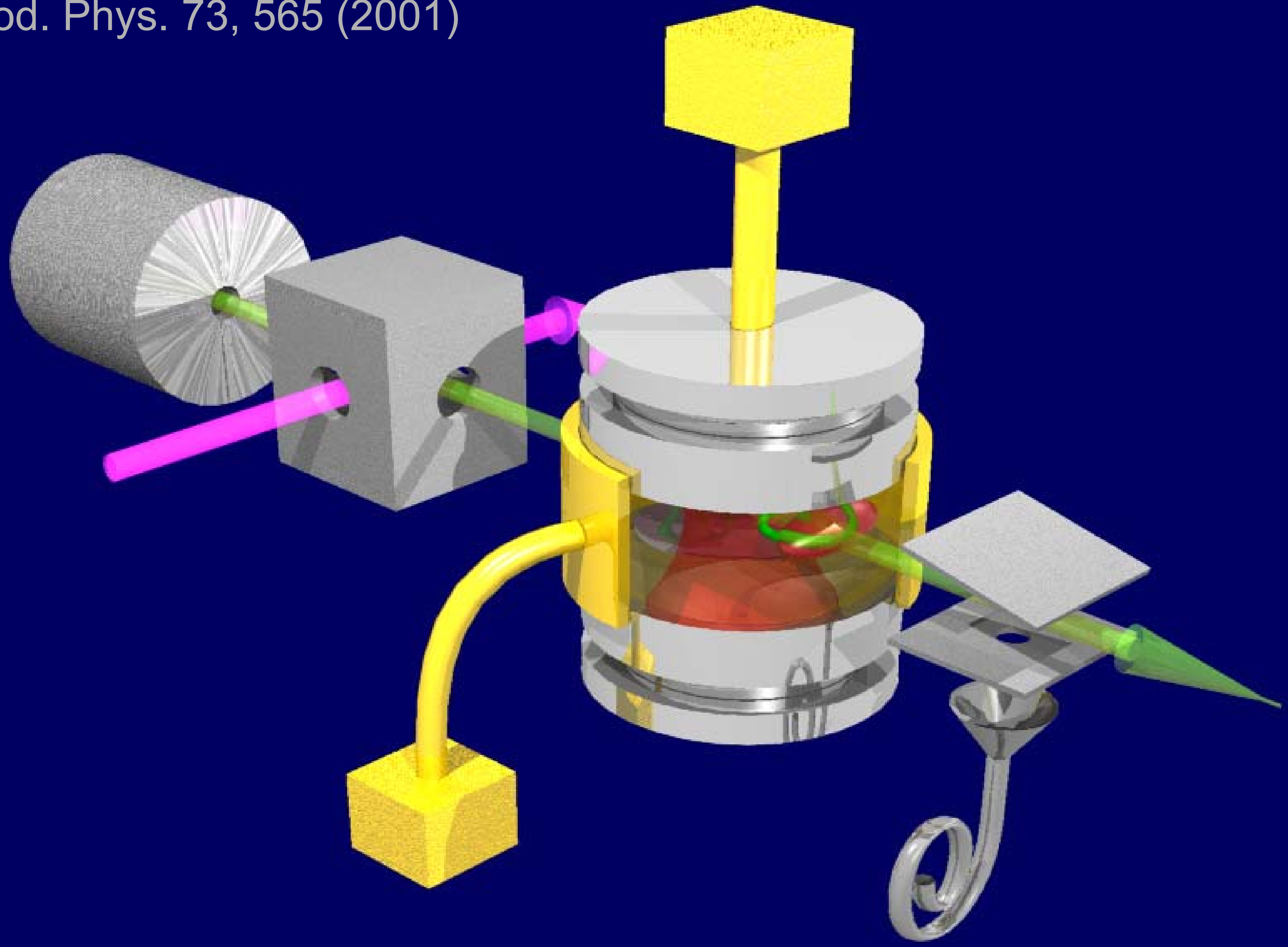
Long photon life time improved by ring around mirrors (1ms)

Easy tunability

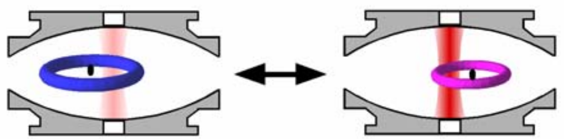
Possibility to prepare Fock or coherent states with controlled mean photon number

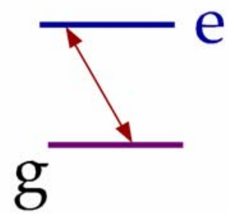
General scheme of the experiments

Rev. Mod. Phys. 73, 565 (2001)



An essential tool: the Quantum Rabi oscillation





$|e,0\rangle \leftrightarrow |g,1\rangle$

Reversible photon emission and absorption

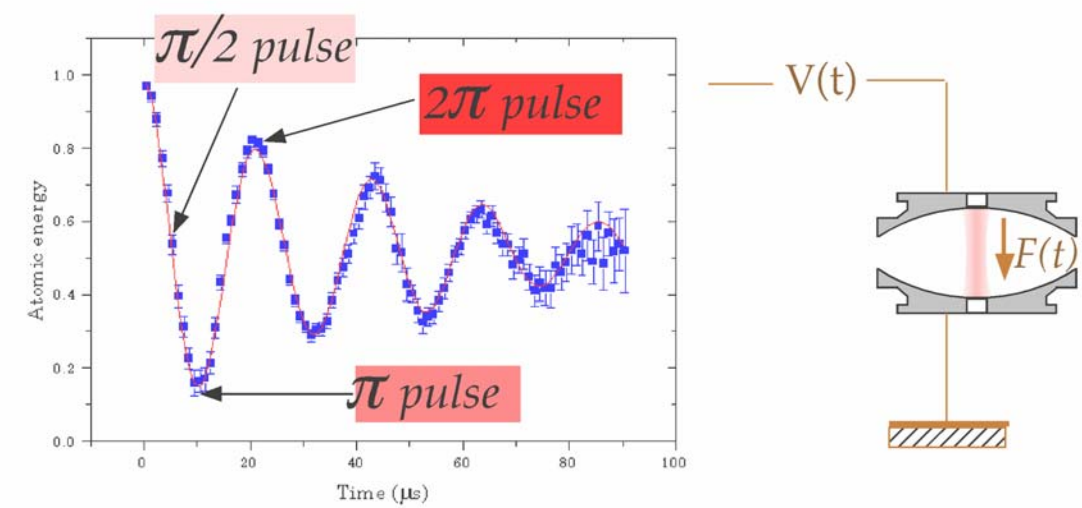
Realizes controlled atom-field entanglement which survives after atom leaves cavity (EPR situation)

$$|\psi(t)\rangle = \cos(\Omega\, t/2)\,|e,0\rangle - i\sin(\Omega\, t/2)\,|g,1\rangle$$

Couplage fort:

$\Omega \gg \; 1/T_{cav},\; 1/T_{at}$

$3.10^5\ s^{-1} \gg 10^3\ s^{-1},\ 30\ s^{-1}$



Electric field F(t) used to tune atoms in resonance with C for a determined time, realizing proper Rabi pulse conditions...

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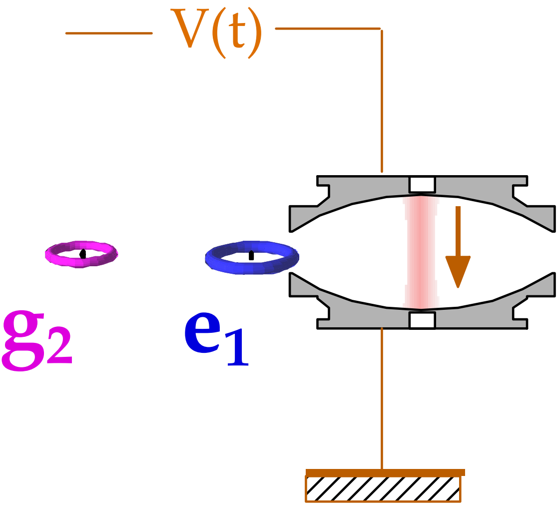
Entangled atom-atom pair mediated by real photon exchange



Atom #1 : $\Omega t = \pi/2$

$$|e_1, 0\rangle . |g_2\rangle \longrightarrow \frac{1}{\sqrt{2}}\{|e_1, 0\rangle - |g_1, 1\rangle\}.|g_2\rangle$$

Atom #1 - Photon entanglement

Atom #2 : $\Omega t = \pi$

Atom - Atom entanglement (a massive E.P.R.pair)

$$\frac{1}{\sqrt{2}}\{|e_1, g_2\rangle - |g_1, e_2\rangle\}.|0\rangle$$

Electric field F(t) used to tune atoms #1 and #2 in resonance with C for a determined time t realizing $\pi/2$ or π Rabi pulse conditions

Atoms entangled in deterministic way without directly interacting

Cavity acts as a catalyst for entanglement

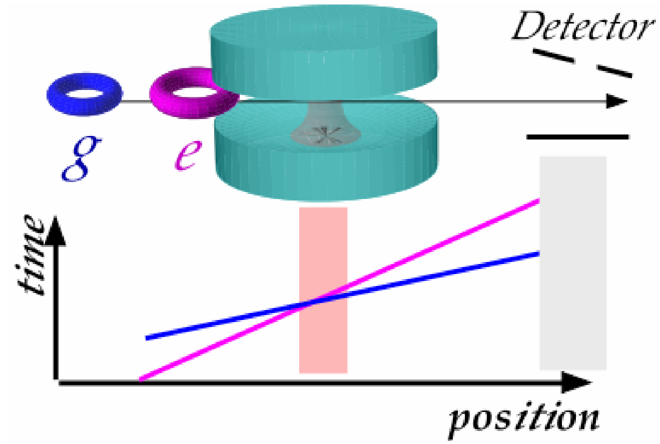
Field generated in a transient stage

Is it possible to entangle directly two atoms, without creating a transient photon?

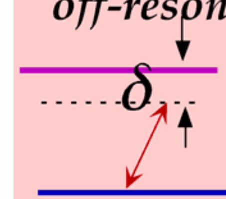
Hagley et al, P.R.L. 79,1 (1997)

Direct entanglement of two atoms via virtual photon exchange: a cavity-assisted controlled collision

(after S.B.Zeng and G.C.Guo, PRL 85, 2392 (2000)).



Atom and cavity slightly off-resonant



S.Osnaghi et al,
Phys. Rev. Lett. 87, 037902 (2001)

$$|e,g;0\rangle \longrightarrow |g,g;1\rangle \longrightarrow |g,e;0\rangle$$

Virtual photon exchange process

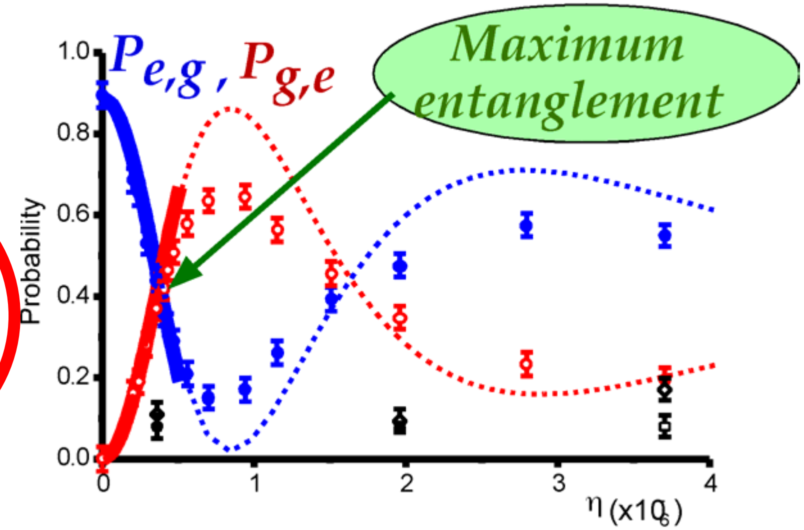
$$|\Psi\rangle = \cos\theta \; |e,g\rangle + \sin\theta \; |g,e\rangle$$

$$\theta = (\Omega^2/\delta)\,T$$

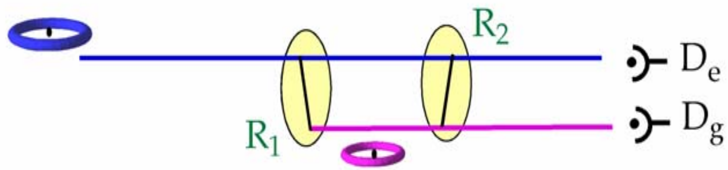
Collision angle adjusted by tuning δ

huge impact parameter (typically millimeters)

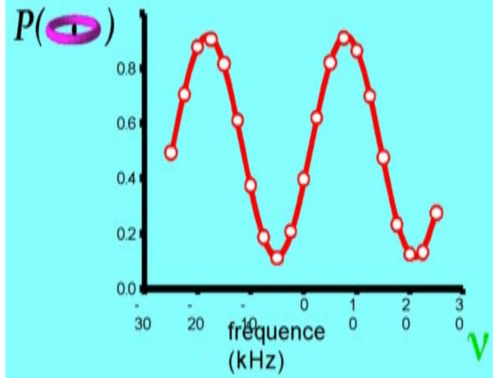
realizes a quantum gate



Analyzing state superpositions by Ramsey interferometry

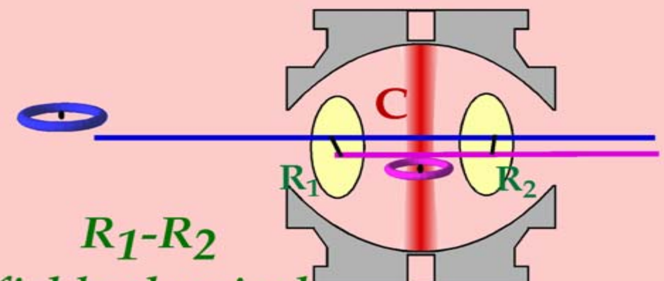


The microwave pulses "split" the atomic states (R_1) and recombine them (R_2) at two separate times: The atom follows two "pathes" and the probability to detect it in or exhibits fringes when the phase difference ϕ between the two pathes is tuned (e.g.by sweeping the frequency ν of R_1 and R_2):



Ramsey interferometer

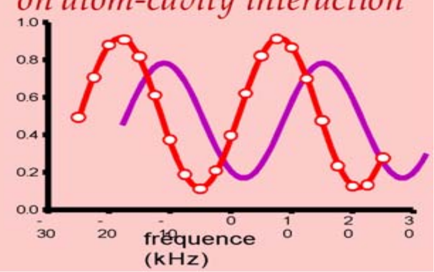
$$P(g) = \frac{A}{2}(1 + \cos(\phi))$$



R1-R2 fields classical (many photons)

C-field quantum (few photons)

Cavity field affects in different ways the two interfering pathes:fringes phase ϕ and contrast A are modified: provides useful information on atom-cavity interaction

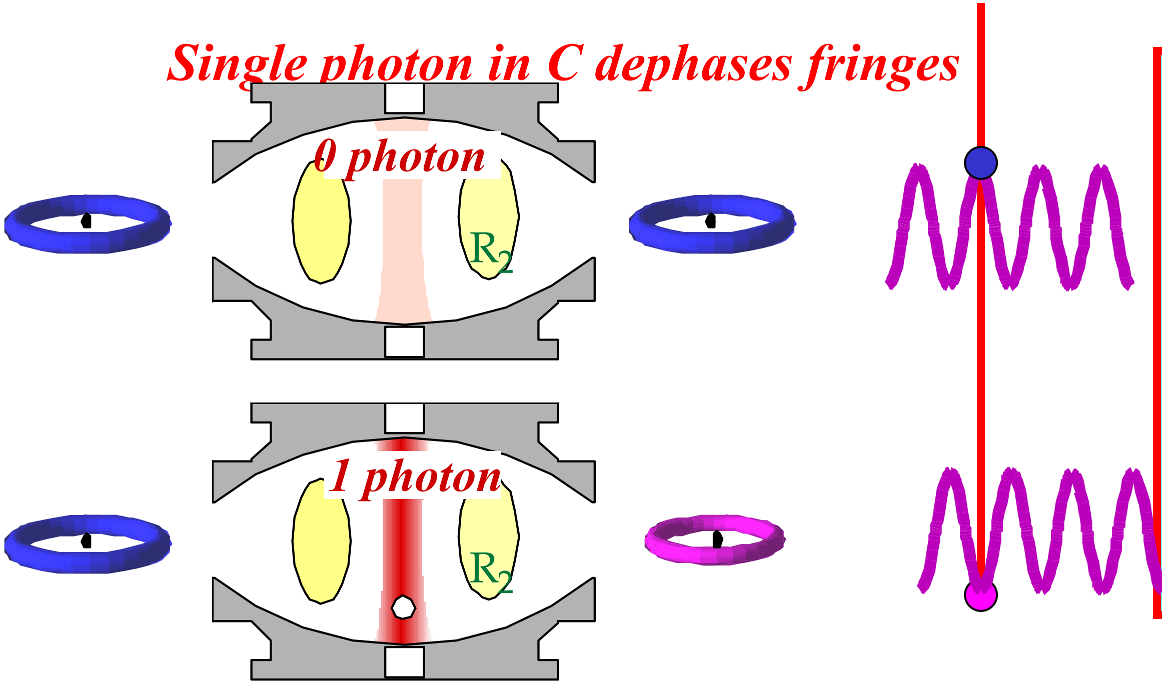


A special situation:

A 2π Rabi pulse induced by one photon in one arm of interferometer flips by π the phase of fringes: QND detection of single light quantum

Quantum Non Demolition measurement of a photon

G.Nogues et al, Nature, 400, 239 (1999)

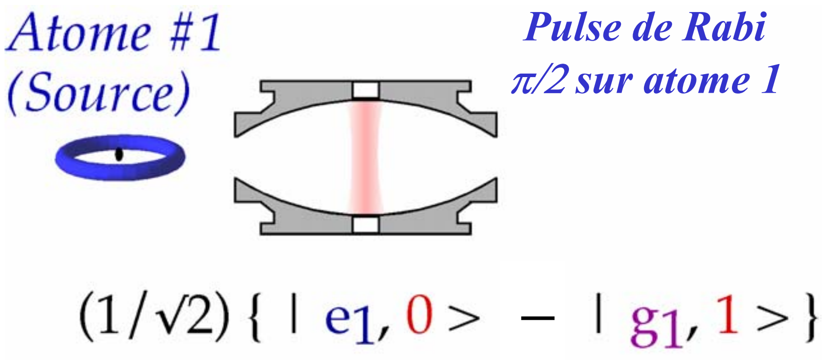


Phases adjusted so that atom exits in one state if there is 0 photon in C, in the other if there is 1 photon (2π Rabi pulse in a one photon field)

Energy is exchanged with Ramsey classical fields, not with quantum field: QND method with atom acting as a meter measuring the field…Also a quantum gate

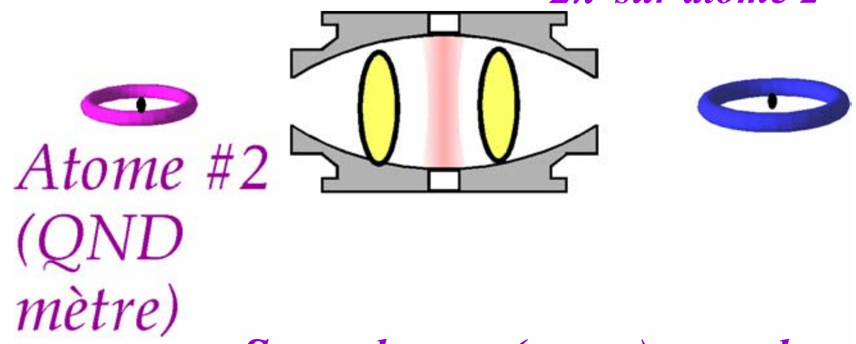
If initial field is in a superposition of 0 and 1 photon states, the process generates entanglement

An experiment with two or three atoms: generation and non destructive measurement of a single photon



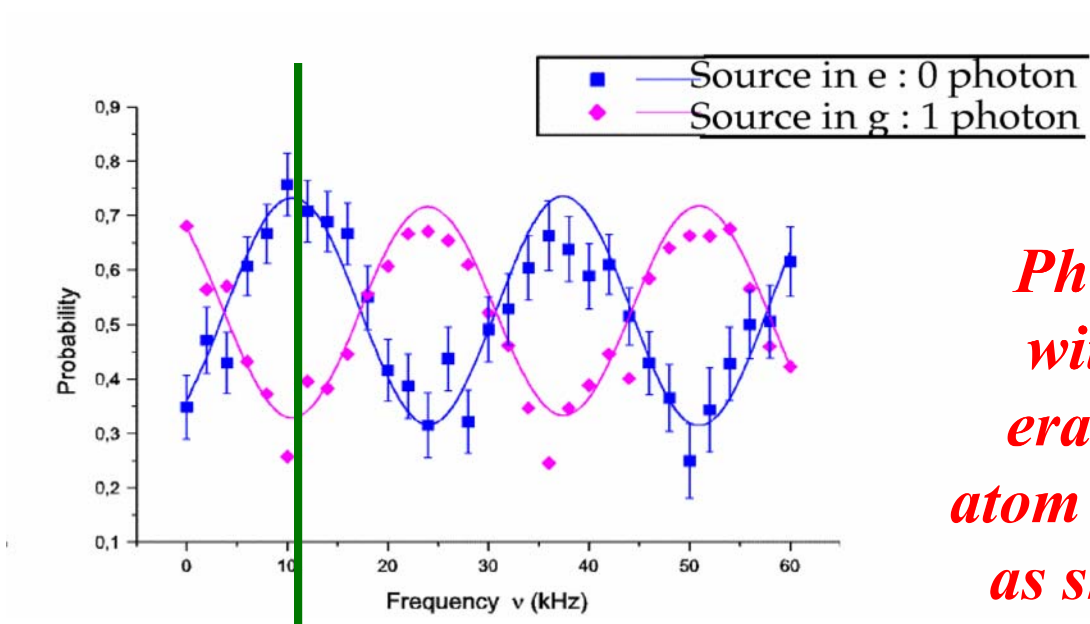
Pulse de Rabi
π/2 sur atome 1

Pulse de Rabi
2π sur atome 2



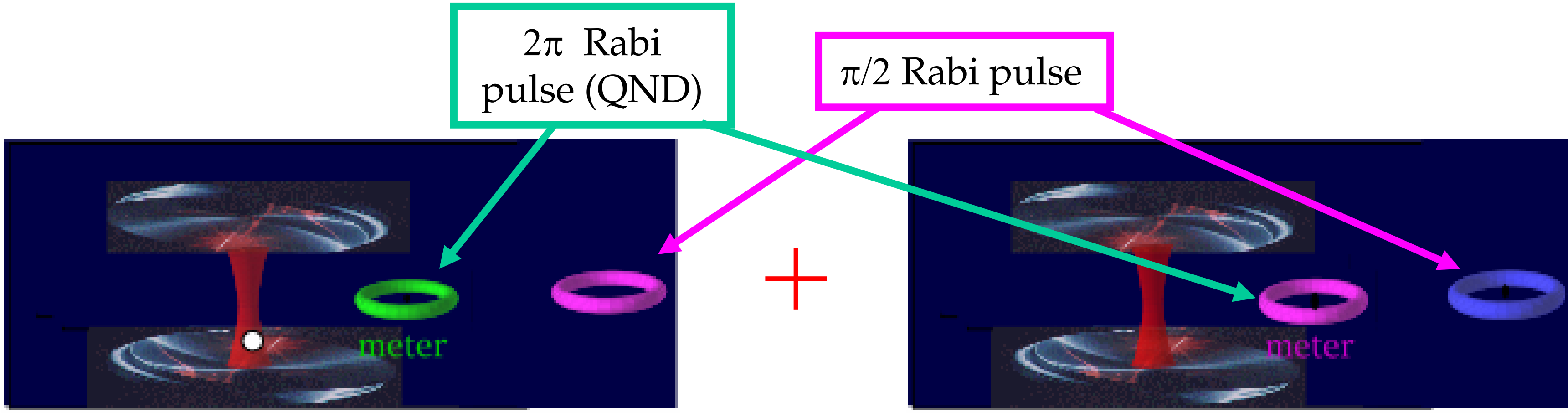
First atom (« source ») emits with 50% a photon in C. Subsequent atomic detection projects field in 0 or 1.

Second atom (meter) « reads » photon number by Ramsey interferometry

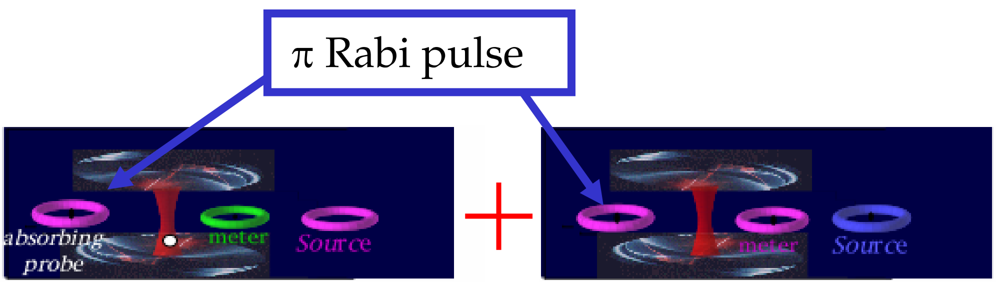


Photon is read without being erased (a third atom still « sees » it as shown below)

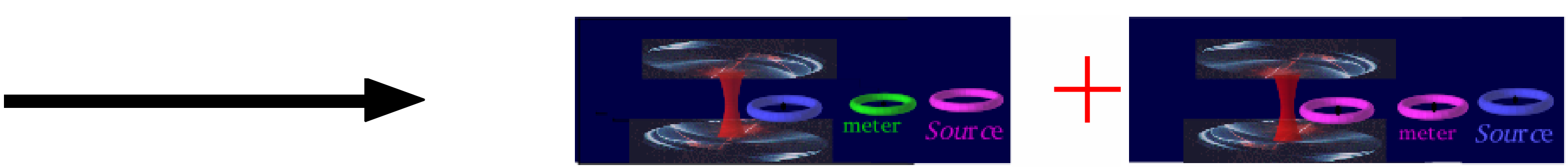
Combining Rabi pulses to « knit » multiparticle entanglement



***First atom** prepares a photon with 50% probability (π/2 pulse) and **second atom** reads it by QND method (2π pulse)*



Three particle engineered entanglement (Rauschenbeutel et al, Science, 288, 2024 (2000)



A third absorbing atom (π pulse) also reads the photon, resulting in three atom correlations

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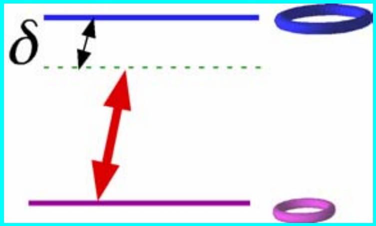
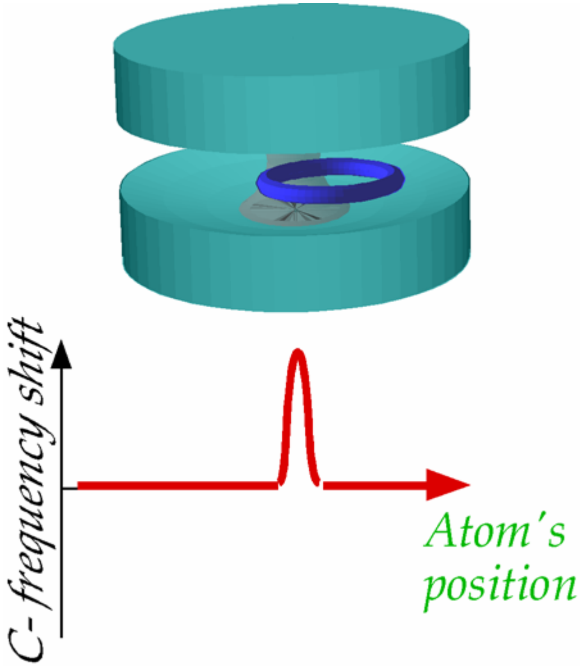
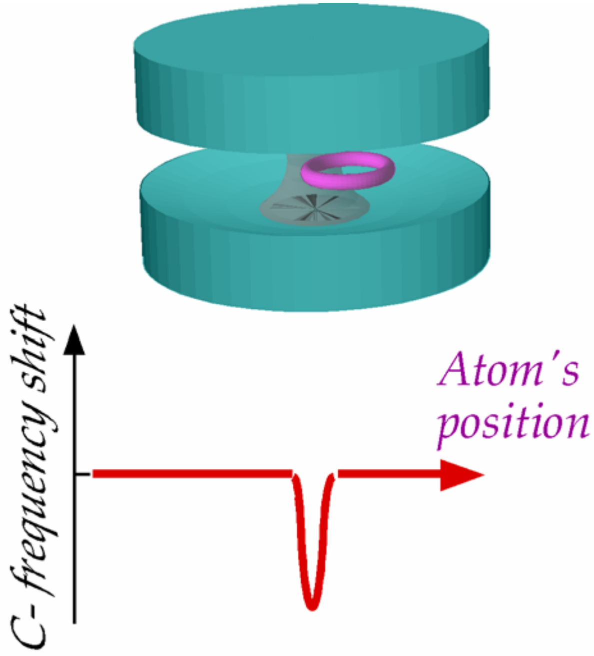
Dispersive entanglement in non-resonant Cavity QED

Atom and cavity off-resonant by amount δ

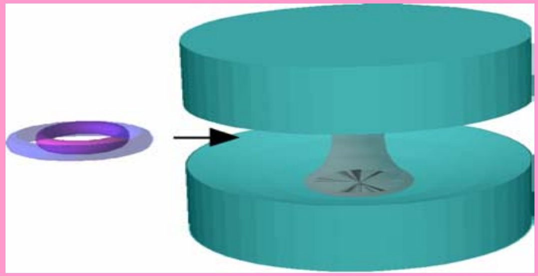


No photon absorption or emission….but atomic transition and cavity mode exhibit frequency shifts (single atom index effect)





Sign of effect ($+\Delta\omega$ or $-\Delta\omega$) depends upon energy state (e or g)

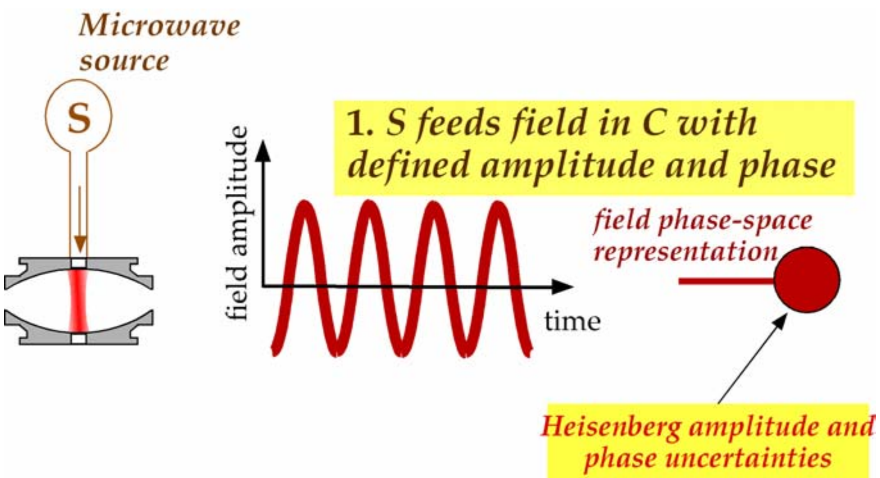


When atom is sent in state superposition, is the shift $+\Delta\omega$ or $-\Delta\omega$?

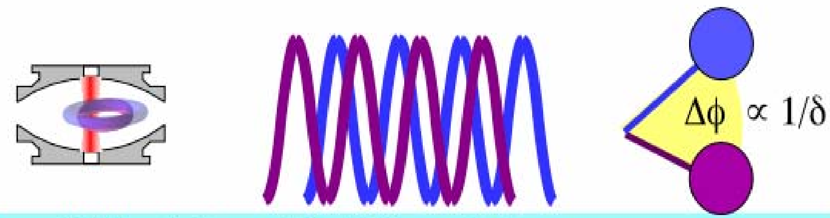
Ambiguous quantum answer leads to dispersive atom-field entanglement

Entanglement involving mesoscopic field states with different phases

(Brune et al, P.R.L. 77, 4887, 1996; S. Haroche, Physics Today, July 1997)

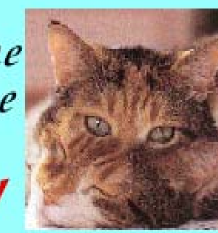


2. Non-resonant Atom prepared in state superposition dephases field, giving it two different phases at once

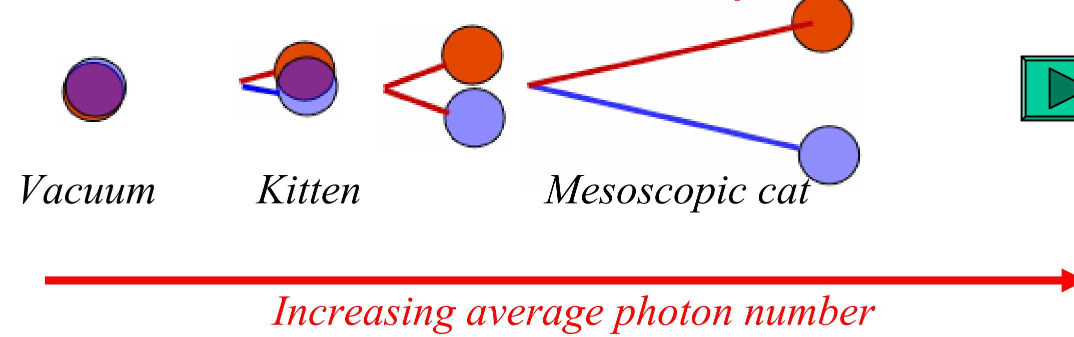


Two field states with different phases entangled to two atomic states : now, the field is a QND meter which points to the atom's energy!

Schrödinger cat situation!



15 to 40 photons



By increasing the field 's amplitude in C, we can explore the quantum classical boundary

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