ENTANGLEMENT BETWEEN ATOMS SUCCESIVELY PASSING A THERMAL CAVITY

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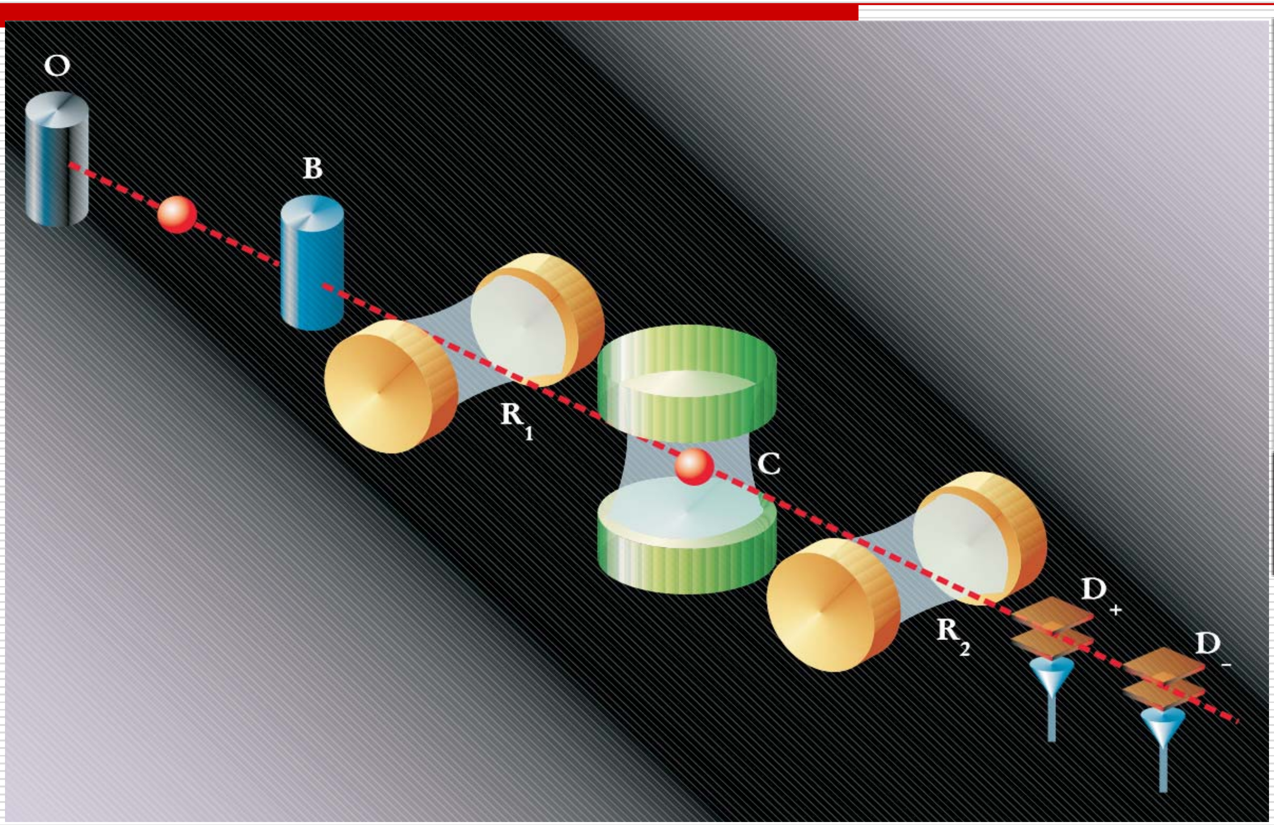
Atom-atom entanglement experiment (S. Haroche et al., 1997)



Serge Haroche, The Nobel Prize in Physics 2012

Fig. 1.The scheme of S. Haroche group one-atom maser in Paris (from Phys. Today, 1998)

Some parameters and ideas of the experimental setup

One-atom maser parameters

- The superconducting microwave cavity *C* is is cooled to 0.6 K (mean value of cavity thermal photon is less than 0.05)
- The frequency of atomic transition between excited and groung states is 51.1 GHz
- The detuning betweem TEM_{900} cavity mode and atomic frequence is 170 kHz)
- The cavity mirror separation is 2.7 cm
- The mode waist is about 6 mm
- The cavity photon damping time is 112 μs
- The Rabi frequency of the Rydberg atom transition $\Omega/2\pi$ is 48 kHz
- The atoms velocity of the first atom is 413 m/s
- The time interval between atoms flying in C is 37 ms and a maximum separation of 1.5 cm just before detection

Experimental ideas

Rb atoms, effusing from an oven O are prepared in box R_1 in one of the two Rydberg states n= 51 or n=50 (respectively, e and g) before crossing cavity C.

- The first one is prepared in e and the second one in g states. The C vacuum field initially
- The duration τ of the first atom interaction with C is such that $\Omega\tau=\pi/2$
- The duration t of the second atom interaction with C is such that $\Omega t=\pi$
- The cavity R_2 and ionizing detector D_+ and D_- can determine the final state of the atoms

As a result one can obtain a pair of atoms in a maximally entangled atomic EPR state (with a “purity” which is equal 1) in the presence of an empty cavity

Experimental results

We authors have shown that Cavity QED setup can entangle with a “purity” larger than 0.63 two atoms separated by a macroscopic distance.

The main goal is to investigate the entanglement of two atoms succesively passing a thermal cavity in the presence of the initial atomic coherence

The two-qubits entanglement induced by thermal field in lossless cavity

- Kim M.S., Lee J., Ahn D., Knight P.L., Phys. Rev. 2002. V.~ A65;
- Zhou L., Song H.S., J. Opt. 2002. V.B4;
- Aguiar L.S., Munhoz P.P., Vidiella-Barranco A., Roversi J.A., J. Opt. 2005. V. B7.
- Bashkirov E.K., Laser Phys. Lett., 2006, V.
- Bashkirov E.K., Stupatskaya M.P., Laser Physics. 2009. V. 19.

The influence of initial atomic coherence on two-qubits entanglement induced by thermal field

- Hu Y.H., Fang M.F., Wu Q., Chin. Phys. 2007. V.~B16;
- Bashkirov E.K., Mastyugin M.S., Opt. Comm., 2014. V.~313;
- Bashkirov E.K., Mastyugin M.S., Optics and Specroscopy, 2014, V.114.

Model description

- The system consists of two separate atoms passing through a cavity one after another
- We consider the exact resonance of the field with the atoms and two atoms are identical
- The atom-field coupling is constant (thus we neglect the dependence of the spatial structure of the cavity mode)
- Following the exit of the first atom, a second atom enters the cavity and interacts with the field modified by interaction with the first atom
- Assume that the total atom-cavity interaction time is considerably less than the cavity lifetime and that we can ignore the effects of cavity dissipation

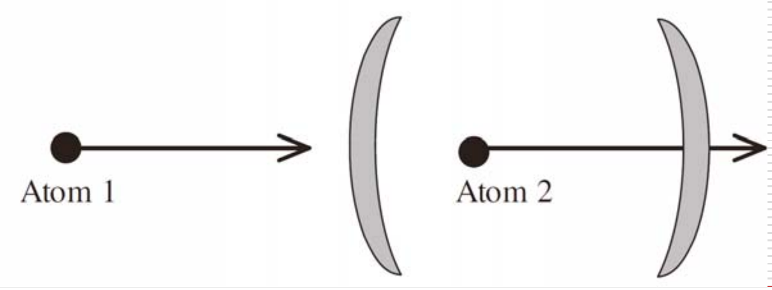


Fig. 2 The physical model

The model solution

Atom-field interaction Hamiltonian

$$H = \hbar g(a^{+}\sigma^{-} + \sigma^{+}a)$$

Density matrix for one-mode initial thermal field

$$\rho_F(0) = \sum_n p_n \,|n\rangle\langle n|,$$

where $p_n = \dfrac{\bar{n}^n}{(1+\bar{n})^{n+1}}$ and $\bar{n} = (\exp[\hbar\omega_i / k_B T] - 1]^{-1},$

$\bar{n}$ is mean phton number and T is the cavity temperature

I. The coherent nonentangled atomic states

$$|\Psi_1(0)\rangle = \cos\theta_1 \,|e\rangle_1 + e^{i\varphi_2} \sin\theta_1 \,|g\rangle_1.$$

$$|\Psi_2(0)\rangle = \cos\theta_2 \,|e\rangle_2 + e^{i\varphi_1} \sin\theta_2 \,|g\rangle_2,$$

The entanglement parameter calculations

The reduced atomic density matrix in two-atom basis $|e,e\rangle, |e,g\rangle, |g,e\rangle, |g,g\rangle$

$$\rho_{at}(\tau,t)=\begin{pmatrix} \rho_{11} & \rho_{12} & \rho_{13} & \rho_{14} \\ \rho_{12}^{*} & \rho_{22} & \rho_{23} & \rho_{24} \\ \rho_{13}^{*} & \rho_{23}^{*} & \rho_{33} & \rho_{34} \\ \rho_{14}^{*} & \rho_{24}^{*} & \rho_{34}^{*} & \rho_{44} \end{pmatrix}.$$

The partial transpose atomic density matrix

$$\rho_{at}^{T_1}(\tau,t)=\begin{pmatrix} \rho_{11} & \rho_{12} & \rho_{13}^{*} & \rho_{23}^{*} \\ \rho_{12}^{*} & \rho_{22} & \rho_{14}^{*} & \rho_{24}^{*} \\ \rho_{13} & \rho_{14} & \rho_{33} & \rho_{34} \\ \rho_{23} & \rho_{24} & \rho_{34}^{*} & \rho_{44} \end{pmatrix}.$$

The Peres-Horodetski entanglement parameter (“negativity”)

$$\varepsilon=-2\sum_{i}\mu_{i}^{-},$$

Временная зависимость атомного перепутывания

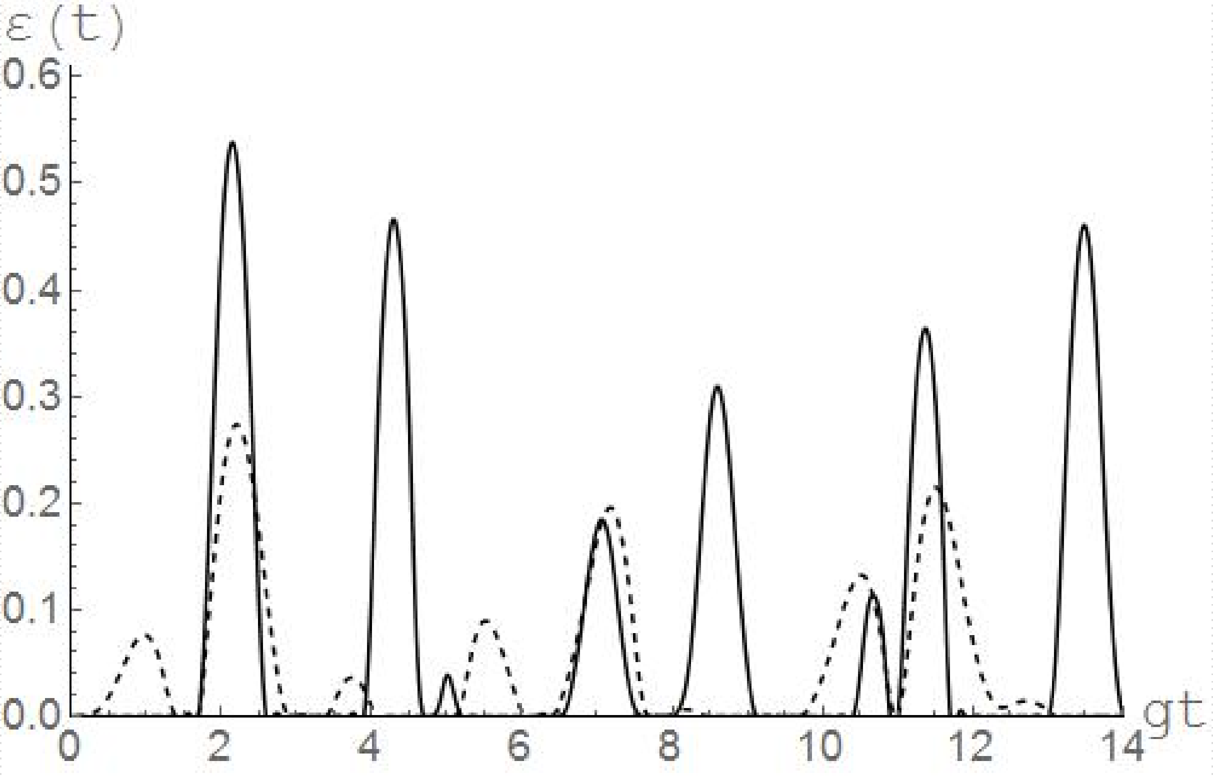


Fig3. The negativity *vs* gt for initial incoherent $\theta_1=\theta_2=0$ $(|e,e\rangle)$ (solid) and $\theta_1=\theta_2=\pi/4$ coherent (dashed) atomic states. The mean photon number $\bar{n}=0.1$

Временная зависимость атомного перепутывания

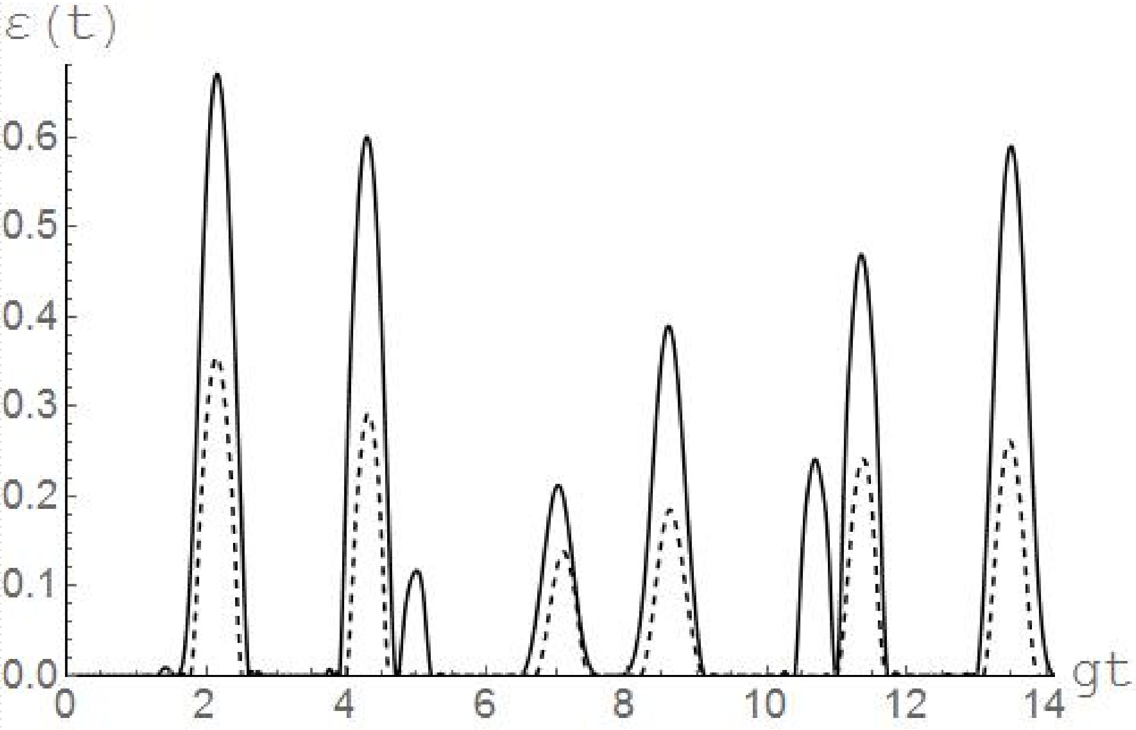


Fig4. The negativity *vs* gt for initial incoherent atomic state ($|e,e\rangle$) The mean photon number $\bar{n}=0$ (solid), $\bar{n}=0{,}5\ (T=2{,}4K)$ (dashed).

Временная зависимость атомного перепутывания

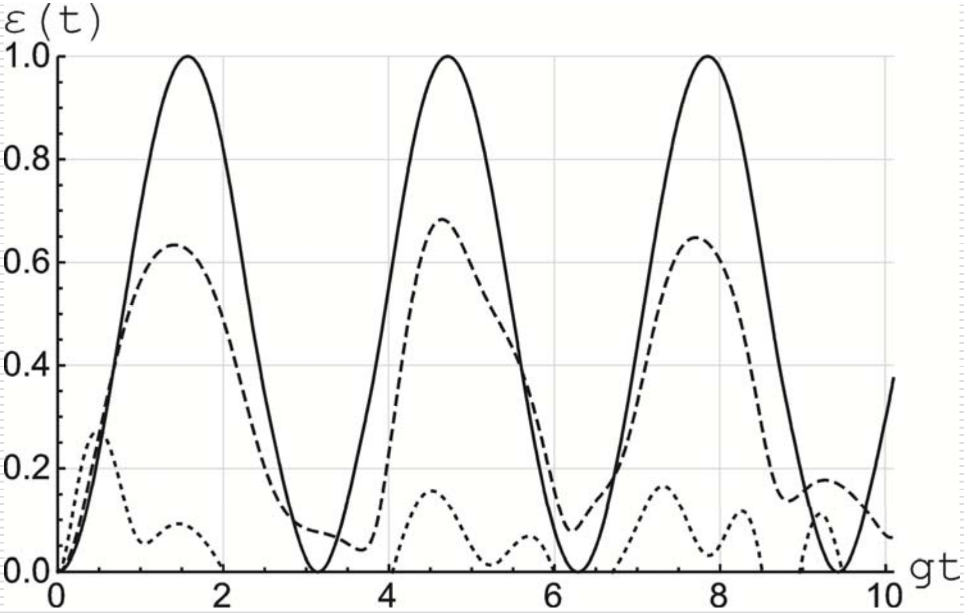


Fig5. The negativity *vs* gt for initial incoherent atomic state ($|e,g\rangle$) The mean photon number $\overline{n}=0\ (T=0)$ (solid) $\overline{n}=0{,}5\ (T=2{,}4K)$ (dashed) $\overline{n}=3(T=9{,}2K)$ (dotted).

The two-atom dynamics for initially entagled atoms

II. The entangled atomic states of the Bell's type

$$|\Psi(0)\rangle_A = \cos\theta\,|+,-\rangle + \sin\theta\,|-,+\rangle, (1)$$

$$|\Psi(0)\rangle_A = \cos\theta\,|+,+\rangle + \sin\theta\,|-,-\rangle, (2)$$

Временная зависимость атомного перепутывания

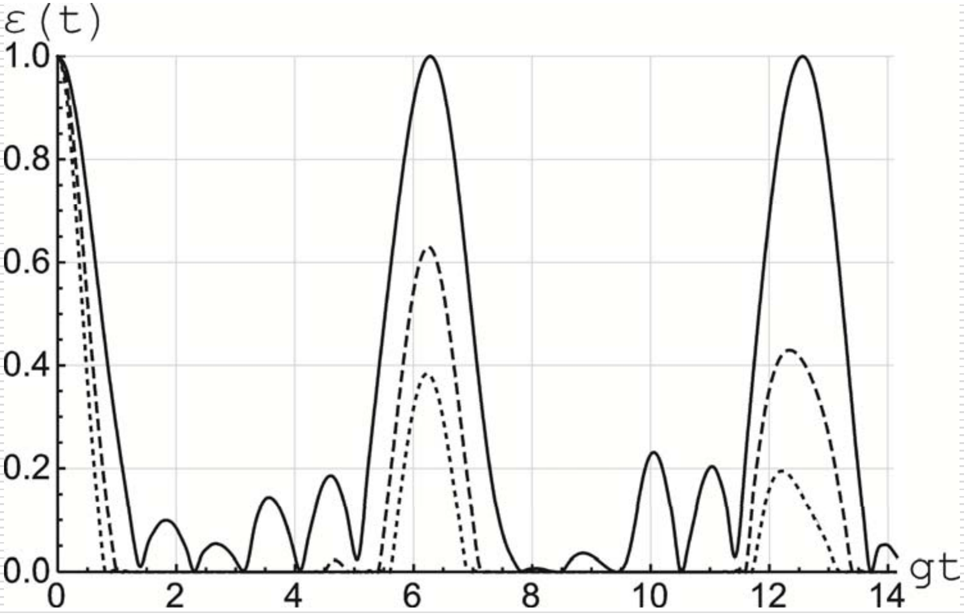


Fig3. The negativity *vs* gt for initial coherent atomic state (1) with $\theta = \pi / 4$. The mean photon number $\overline{n} = 0\ (T = 0)$ (solid) $\overline{n} = 0,5\ (T = 2,4K)$ (dashed) $\overline{n} = 3 (T = 9,2K)$ (dotted).

Временная зависимость атомного перепутывания

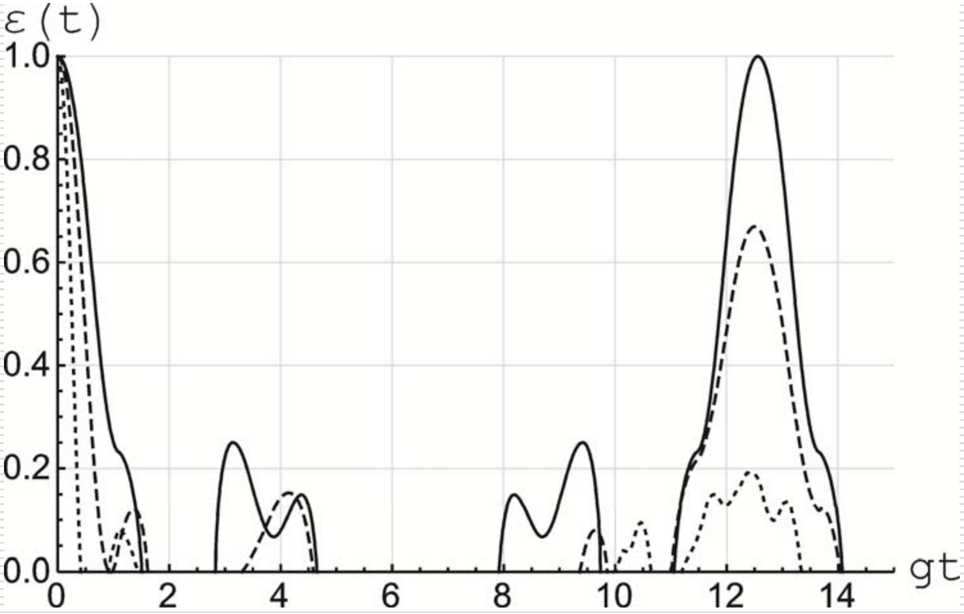


Fig3. The negativity *vs* gt for initial coherent atomic state (2) with $\theta = \pi / 4$. The mean photon number $\overline{n} = 0 \; (T = 0)$ (solid) $\overline{n} = 0,5 \; (T = 2,4K)$ (dashed) $\overline{n} = 3 (T = 9,2K)$ (dotted).

CONCLUSIONS

- The thermal field can induce the high degree of entanglement for relatively hight cavity temperature

- The initial atomic coherence leads to decreasing of the atomic entanglement

- The initial atomic entanglement can persist in the interaction of atoms through a common thermal field