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COOPERATIVE NONLINEAR TRANSFER OF INFORMATION BETWEEN THREE Q-BITS THROUGH CAVITY VACUUM FIELD

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Abstract. Following the theory of two-photon resonance interaction between two dipole active and one dipole forbidden atoms in the two-photon resonance, we propose to study this effect in the two-mode resonance situation of the cavity. In this case the non-Markovian transfer of energy from two dipole active radiators to dipole-forbidden atom is discussed. The nonlinear quantum nutation of this system of radiators is studied. The entanglement between radiators and field is obtained.

Keywords: two-photon resonance, nonlinear quantum nutation, entanglement.

1. NONLINEAR INTERACTION OF RADIATORS THROUGH THE VACUUM FIELD OF CAVITY

From quantum mechanical points of view the combination of the *single*- and *two*-photon masers [1, 2] and lasers [3] opens the new perspectives in the studies of the quantum processing of information taking into consideration the excitation transfer between the radiators in nonlinear interaction with the vacuum of the cavity field (Fig. 1a). This conditional transfer of the excitations from one of atomic subsystem to another in *single-two*-quantum resonances occurs through nonlinear vacuum nutations of *q-bits* in the resonators. In order to understand this we emphasize here, that micro-maser in single-photon interaction was realized using the rubidium atom relative to the transition $63p_{3/2}$ to $61d_{3/2}$ ($61d_{5/2}$) at transition frequency 21.5 GHz [2]. The nonlinear interaction of excited atoms with a cavity field in the two-photon micro-maser and laser processes was in the center of attention of many experimental studies [2, 3]. In many cases cavity quantum oscillator needs the external ignition sources in order to reside the effective nonlinear interaction with the cavity mode [3]. The realistic approach was used in Ref. [2], where the authors used two-photon transition between the levels 40S and 39S of rubidium atoms, placed in the supercoducting cavity at 68.41587 GHz. In order to stimulate the two-photon interaction with vacuum field, it was realized a three level system in cascade configuration in which the state 39*P* is shifted from the resonance in the cavity mode.

The new cavity transfer of excitations between the single and two-photon transitions of atoms through the cavity vacuum field is proposed in the Sec. 2. The similar effect was proposed in the free space during the spontaneous decay of the three radiators [4, 5]. Below we study the reversible effects of quantum notations between the atomic subsystems in the nonlinear interaction with the cavity field; see also Refs. [4, 5].

2. HAMILTONIAN OF THE SYSTEM IN TWO AND SINGLE MODE APPROXIMATION

Let us name the two atomic beams in single-photon resonance with the cavity field by **S** and **I** radiators. The interaction Hamiltonian of each atom during the flying time can be represented by the expression

$$\hat{H}_I^S = g_S \hat{S}^- \hat{a}^+ + g_i \hat{I}^- \hat{b}^+ + hc.$$

The interaction of the Rydberg atom in two-photon micro-maser with the single mode cavity field can be described by *D* radiators with double excited frequency $\omega_d = 2\omega_0$

$$\hat{H}_I^d = G(\hat{D}^- \hat{a}^+ \hat{b}^+ + hc)/2 \,.$$

The situation becomes attractive, when the sum of the frequencies, ω_s and ω_i atoms enters in the two-photon resonance with *D* radiator through the vacuum field of *a* and *b* resonator modes. This simple resonance can be realized in the degenerate situation when instead of two modes *a* and *b* and two atomic fluxes *S* and *I* we have only one with the same frequency. In this case the total Hamiltonian of two atomic fluxes *S* and *D* can be simply represented by the expression

$$\hat{H}_I = g \ \{(\hat{S}_1^- + \hat{S}_2^-) \ \hat{a}^+ + hc\} + G \ \{\hat{D}^- (\hat{a}^+)^2 + hc/2\}.$$

These two fluxes of *S* and *D* *q*-bits can be propagated in the collinear, perpendicular or in other directions through the resonators. Achieving the ionizing detector, we can check if the excitation passed from atom *D* or from atom *S* of subsystem *S* as this is proposed in [2]. In this case the eigenvalues and eigenvectors of the above Hamiltonian,

$$\hat{H}_I \ |\psi\lambda\rangle - \lambda \ |\psi\lambda\rangle,$$

can be represented through the combination of atomic-field Hilbert states. Below we discuss two situations: A) degenerate and B) non-degenerate states.

A) If we have prepared only two *S* atoms in excited states the number of the states in the Hilbert space is four:

$$\left|e_s g_d\right\rangle\left|0\right\rangle_{ph},\ \left|i_s g_d\right\rangle\left|1\right\rangle_{ph},\ \left|g_s g_d\right\rangle\left|2\right\rangle_{ph}\ \text{ and }\ \left|g_s e_d\right\rangle\left|0\right\rangle_{ph}.$$

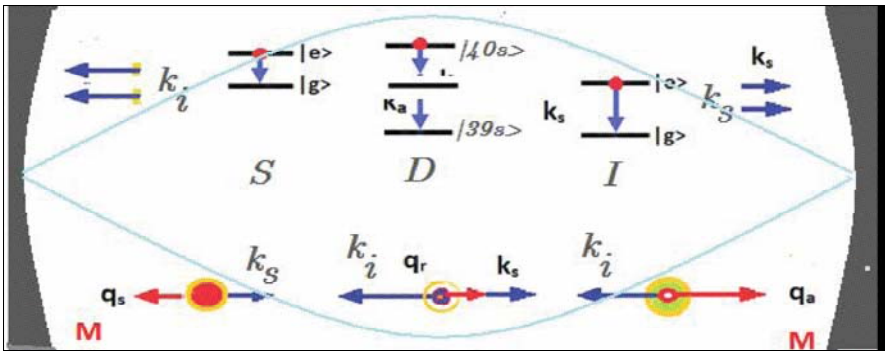

Fig. 1a – Transfer of energy between the *S, I* radiators and the *D* atom in the cavity.

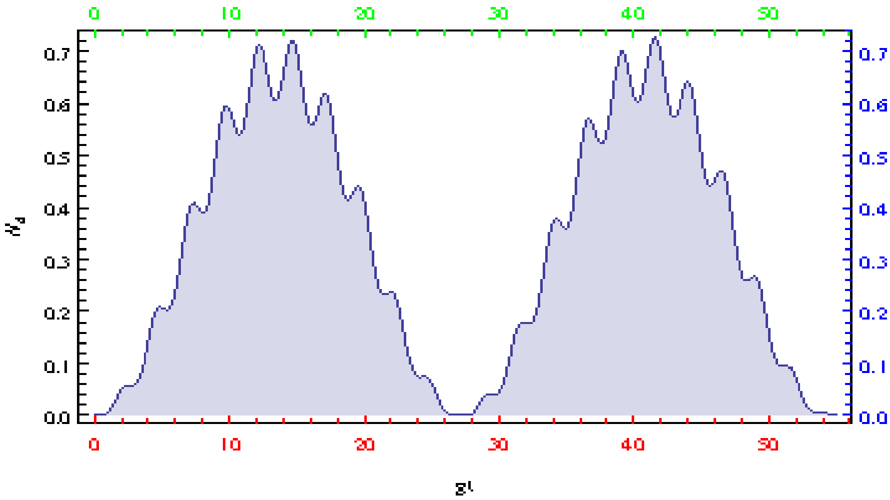

Fig. 1b – Transfer of energy between two undistinguished *S* atoms to the *D* radiator through the vacuum field.

Here the first eigenvector $|\alpha s, \beta d>$ represents the atomic states for *S*, $\alpha = e, i, g$ and *D*, $\beta = e, g$ subsystems, respectively. The vector $|I>_{ph}$ describes the possible photon states, $i = 0, 1, 2$, when the two atoms of subsystem *S* enter in the resonator together with the *D* atom. We obtain the following eigenvalues:

$$\lambda_1 = \sqrt{6g^2 + G^2 - \sqrt{36g^4 + 4g^2G^2 + G^4}} \,/\, \sqrt{2},$$

$$\lambda_3 = \sqrt{6g^2 + G^2 + \sqrt{36g^4 + 4g^2G^2 + G^4}} \,/\, \sqrt{2},$$

$\lambda_2 = -\lambda_1$; $\lambda_4 = -\lambda_3$. These two new quantum Rabbi frequencies describe the coupling between the *S* and *D* radiators through the vacuum field. In the degenerate situation, when all three atoms are initially prepared in the excited states, the Hilbert space in which we can describe the evolution of the system is characterized by five vectors:

$$|\psi_1\rangle = |e_{s,}e_{i,}g_d\rangle|0_a,0_b\rangle,\ |\psi_2\rangle = |e_{s,}g_{i,}g_d\rangle|0_a,1_b\rangle,\ |\psi_3\rangle = |g_{s,}e_{i,}g_d\rangle|1_a,0_b\rangle,$$
$$|\psi_4\rangle = |g_{s,}g_{i,}g_d\rangle|1_a,1_b\rangle,\ |\psi_5\rangle = |g_{s,}g_{i,}e_d\rangle|0_a,0_b\rangle.$$

The preparation of one of the above-mentioned initial state can be realized by special decomposing the wave function of the system of the new eigenvectors of the system $|\psi(t)> = \Sigma j\, A_j\, |\psi_j\ (t)>$, where the coefficients $\{A_j\}$ are determined from the initial conditions.

The dependence of the number of photons on the excited state of the *D* atom is represented in Figs. 2a and 2b, as function of the relative time *gt* and the relative two-photon Rabi frequency *G/g.* This type of nutation with the transferring of two-photon excitations from two *S* undistinguished atoms to *D* atom through the vacuum field represents an attractive correlation process between linear and nonlinear quantum oscillators.

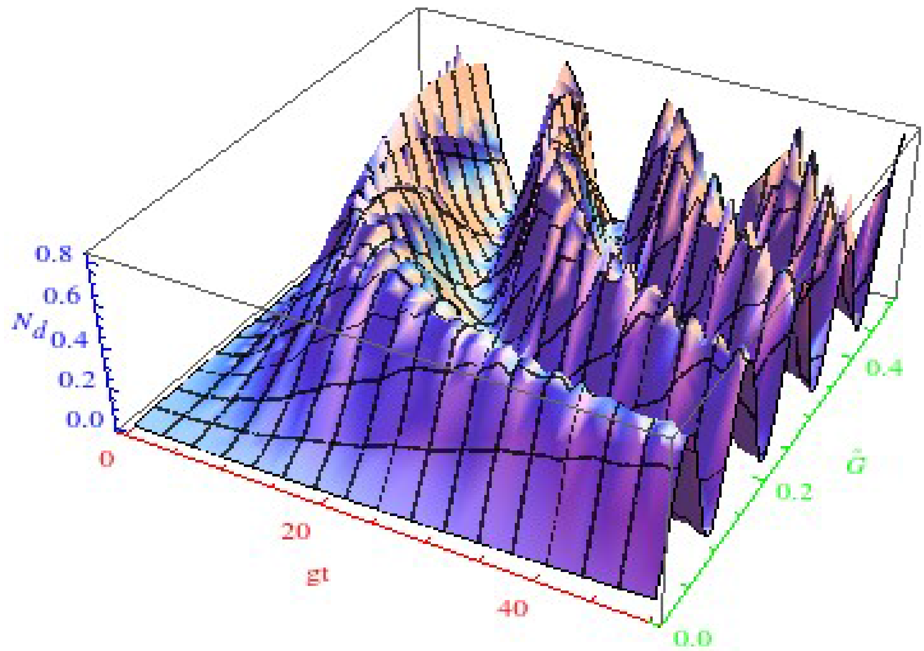

Fig. 2a – The time dependence of the energy transfer as function of two-photon interaction constant *G*.

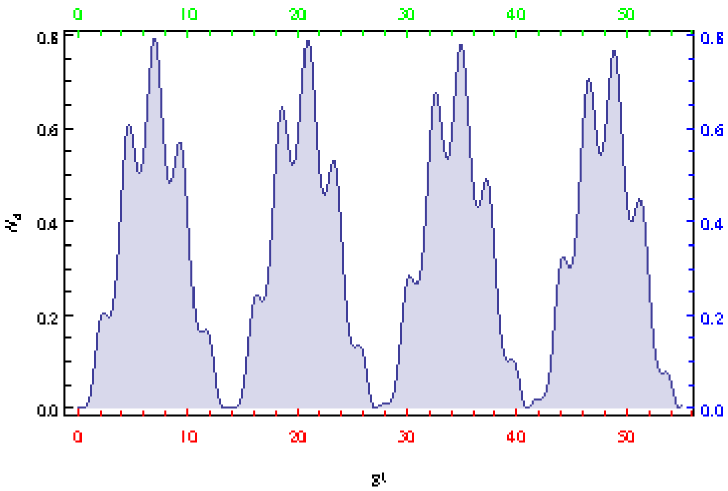

Fig. 2b – The section of the three-dimensional dependence of nutation of the excitation from *S* to *D* atoms.

3. CONCLUSIONS

The reversible quantum transfer of energies between two types of radiators through the cavity vacuum field is studied taking into consideration the exact solution of the radiators in interaction with single- and two-cavity modes. This solution shows that the energy transfer between the radiators is possible in the nutation regime in the good cavity limit. Due to the reduction of this transfer to a single mode of cavity field, it was possible to observe the energy migrations between the radiators without the decomposition on the small parameter of the perturbation theory as in Refs. [4, 5].

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