Vol 16 No 2, February 2007
1009-1963/2007/16(02)/0416-04

Chinese Physics

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Quantum state transfer via adiabatic passage*

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(Received 18 January 2006; revised manuscript received 9 August 2006)

Based on adiabatic passage, we propose a scheme for implementing the quantum transfer of an unknown atomic state. In our scheme, we utilize photons for ideal quantum transmission between two cavities with the successful probability being about 1. Meanwhile, the scheme is robust against the effects of atomic spontaneous emission. It may be useful for transferring quantum information among spatially distant atoms.

Keywords: quantum transfer, adiabatic passage, Bell-state measurement
PACC: 4250

1. Introduction

A quantum network is an indispensable essential component for many novel applications of quantum information, for example, entangled-state cryptography,[1,2] teleportation,[3,4] purification,[5−7] and distributed quantum computation.[8] Spatially separated nodes comprise a quantum network, in which quantum transmission between the nodes of the network is realized via quantum channels. As is well known, atoms with long-lived internal states are well suited for storing qubits, and photons are the best qubit carriers for fast and reliable communication over long distances.[9,10] A protocol for using photons to achieve efficient quantum transmission between spatially distant atoms has been proposed.[11] Recently, the quantum state transfer via the quantum Hall effect has been also investigated.[12]

In this paper, we present a scheme for transferring quantum states of a trapped atom from one cavity to another. Our transmission protocol employs special laser pulses that excite the atom inside the first cavity so that atomic state is mapped onto a photon state that will be absorbed by another cavity. And the proposal is robust to atomic spontaneous emission noise.

2. Theoretical model

The involved atomic levels and transitions are depicted in Fig.1. The states $|g_{\rm L}\rangle$, $|g_0\rangle$ and $|g_{\rm R}\rangle$($|e_{\rm L}\rangle$, $|e_0\rangle$ and $|e_{\rm R}\rangle$) are the three Zeeman sublevels of electronic ground (excited) state of alkali atom. The transition of $|e_{\rm L}\rangle \to |g_0\rangle$ ($|e_{\rm R}\rangle \to |g_0\rangle$) is coupled to the left-circularly (right-circularly) polarized mode of the cavity with the coupling rate $g(t)$, which depends on time t; the transitions $|g_{\rm L}\rangle \to |e_{\rm L}\rangle$ and $|g_{\rm R}\rangle \to |e_{\rm R}\rangle$ are driven resonantly through a π-polarized classical field with Rabi frequency $\Omega(t)$; the transition $|g_0\rangle \to |e_0\rangle$ is electric dipole forbidden. The qubit is encoded in the two Zeeman sublevels $|g_{\rm L}\rangle$ and $|g_{\rm R}\rangle$.

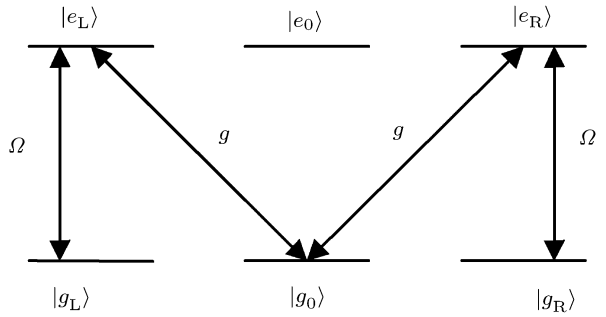


Fig.1. The involved atomic level structures and transitions. The vertical arrow represents the transitions driven by the π-polarized classical coherent field. The inclined arrow denotes the transitions due to the atom–cavity coupling.

In a rotating frame, the interaction Hamiltonian for the system of atom–cavity is in the form

$$H = \Omega(t)(|e_{\rm L}\rangle\langle g_{\rm L}| + |e_{\rm R}\rangle\langle g_{\rm R}|) + g(a_{\rm L}|e_{\rm L}\rangle\langle g_0| + a_{\rm R}|e_{\rm R}\rangle\langle g_0|) + {\rm H.c.}, \quad (1)$$

where H.c. represents the Hermitian conjugate, $a_{\rm L}$ and $a_{\rm R}$ denote the annihilation operators for the corresponding polarized modes of the cavity. Without loss of generality, we suppose that $\Omega(t)$ and $g(t)$ are real

*Project supported by the Funds of Educational Committee of Fujian Province (Grant No JB05334), the National Natural Science Foundation of China (Grant No10574022), and the Fujian Provincial Natural Science Foundation (Grant No A0410016).
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valued. The Hamiltonian has two dark states with the following forms:

$$|D_1(t)\rangle = \cos\theta(t)|g_{\rm L}\rangle|0,0\rangle - \sin\theta(t)|g_0\rangle|1,0\rangle, \quad (2)$$

$$|D_2(t)\rangle = \cos\theta(t)|g_{\rm R}\rangle|0,0\rangle - \sin\theta(t)|g_0\rangle|0,1\rangle, \quad (3)$$

where

$$\cos\theta(t) = \frac{g(t)}{\sqrt{|g(t)|^2 + |\Omega(t)|^2}},$$

$$\sin\theta(t) = \frac{\Omega(t)}{\sqrt{|g(t)|^2 + |\Omega(t)|^2}}.$$

We also use the notation $|x\rangle|n_{\rm L}, n_{\rm R}\rangle$ to describe the state of the atom–cavity system, where x is the atomic state, $n_{\rm L}$ and $n_{\rm R}$ denote the photon numbers in the respective cavity modes.

Now we describe how to implement the quantum state transfer. The schematic representation of our scheme is shown in Fig.2. The atoms 1 and 2 are trapped in cavities A and B, respectively. The two cavities are initially in the vacuum state and single-sided so that the only leakage of photons occurs through the sides of the cavities. The dynamics of the system of atom–cavity is determined by Eq.(1).

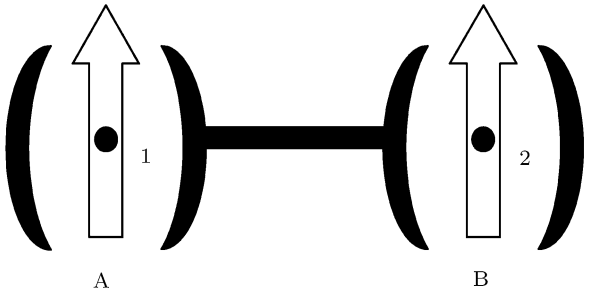


Fig.2. The schematic setup to teleport the unknown atomic state. The arrow represents the classical driving field. Two cavities are connected by optical fibres.

Assume atom 1 to be initially in a transferred state

$$|\varphi\rangle_1 = \alpha|g_{\rm L}\rangle_1 + \beta|g_{\rm R}\rangle_1\,, \quad (4)$$

where α and β are unknown coefficients, and $|\alpha|^2 + |\beta|^2 = 1$. In the adiabatic limit, the state of the atom 1–cavity A in the initial state

$$|\varphi(0)\rangle_{1\rm A} = |\varphi\rangle_1|0,0\rangle_{\rm A} \quad (5)$$

evolves into the following dark state:

$$|\varphi(t)\rangle_{1A} = \alpha|D_1(t)\rangle_{\rm A} + \beta|D_2(t)\rangle_{\rm A}$$
$$= \cos\theta_1(t)(\alpha|g_{\rm L}\rangle_1 + \beta|g_{\rm R}\rangle_1)|0,0\rangle_{\rm A}$$
$$- \sin\theta_1(t)|g_0\rangle_1(\alpha|1,0\rangle + \beta|0,1\rangle)_{\rm A}\,. \quad (6)$$

When we adiabatically increase the Rabi frequency $\Omega(t)$ to satisfy the condition $|\Omega(t)| \gg |g(t)|$, the state of the atom 1–cavity A evolves into the following state:

$$|\varphi\rangle_1{\rm A} = |g_0\rangle_1(\alpha|1,0\rangle + \beta|0,1\rangle)_{\rm A}\,. \quad (7)$$

Owing to the imperfection of cavity A, the produced photons leak out from it and enter cavity B. As a result, the system of atom 2–cavity B is in the state

$$|\varphi(0)\rangle_{2\rm B} = |g_0\rangle_2(\alpha|1,0\rangle + \beta|0,1\rangle)_{\rm B}\,. \quad (8)$$

Similarly, in the adiabatic limit, Eq.(8) evolves into the following state:

$$|\varphi(t)\rangle_{2\rm B} = \alpha|D_1(t)\rangle_{2\rm B} + \beta|D_2(t)\rangle_{2\rm B}$$
$$= \cos\theta(t)(\alpha|g_{\rm L}\rangle_2 + \beta|g_{\rm R}\rangle_2)|0,0\rangle_{\rm B}$$
$$- \sin\theta(t)|g_0\rangle_2(\alpha|1,0\rangle + \beta|0,1\rangle)_{\rm B}\,. \quad (9)$$

With the adiabatically increasing $g(t)$ to meet the inequality $|g(t)| \gg |\Omega(t)|$,[13] the state (9) evolves into the following state:

$$|\varphi\rangle_{2\rm B} = (\alpha|g_{\rm L}\rangle_2 + \beta|g_{\rm R}\rangle_2)|0,0\rangle_{\rm B}, \quad (10)$$

which is the product state of atom 2 and cavity B. It is obvious that atom 2 is initially in the transferred state of the atom 1, i.e. we have realized the transfer of an unknown atomic state.

3. Discussion

Next we concretely discuss the pulse sequence used for the population transfer process via adiabatic passage. As shown in Fig.3, atom 1 drops with a rate v (on the $y = 0$ plane and $z = z_0$ line) through cavity A, and then meets the laser beam, which is parallel to the y- axis and orthogonal to the cavity axis and atomic trajectory. The time dependent and delayed Rabi frequencies of the cavity and the laser fields are as follows:

$$g_1(t) = g_0\exp\Big[\frac{(-\nu t)^2}{W_{\rm C}^2}\Big]\cos\Big(\frac{2\pi z_0}{\lambda}\Big) \quad (11)$$

and

$$\Omega_1(t) = \Omega_0\exp\Big(\frac{-z_0^2}{W_{\rm L}^2}\Big)\exp\Big[\frac{-(\nu t - d)^2}{W_{\rm L}^2}\Big], \quad (12)$$

where g_0 and Ω_0 are the maximal values of $g(t)$ and $\Omega(t)$, respectively; $W_{\rm L}$ and $W_{\rm C}$ are the laser beam waist and the cavity waist,[14] respectively; $d(z_0)$ is the distance between the centre of the cavity and the

laser (atomic motion) axis; $t = 0$ is defined as the instant when atom 1 encounters the centre of the cavity.

Figure 4 shows (a) the corresponding Rabi frequencies of the cavity-mode and laser field for atom 1, and (b) the time evolution of population, where we have chosen $d = 60$ μm, $z_0 = 10$ μm, and pulse parameters as $W_{\rm L} = 20$ μm, $W_{\rm C} = 30$ μm, $v = 2$ m/s, $\lambda = 780$ nm, $\Omega_0 = 50v/W_{\rm L}$, and $\rm G_0 = 50v/W_C$.[10] It is obvious that all the population is completely transferred from the state

$$|\varphi(0)\rangle_{1\rm A} = (\alpha|g_{\rm L}\rangle_1 + \beta|g_{\rm R}\rangle_1)|0,0\rangle_{\rm A}$$

into the state

$$|\varphi\rangle_{1\rm A} = |g_0\rangle_1(\alpha|1,0\rangle + \beta|0,1\rangle)_{\rm A}$$

at the end of interaction time.

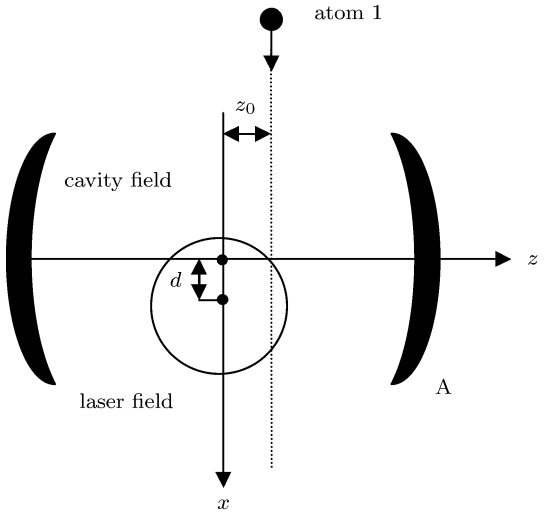


Fig.3. The trajectory of atom 1 and the geometry of cavity A and the laser fields.

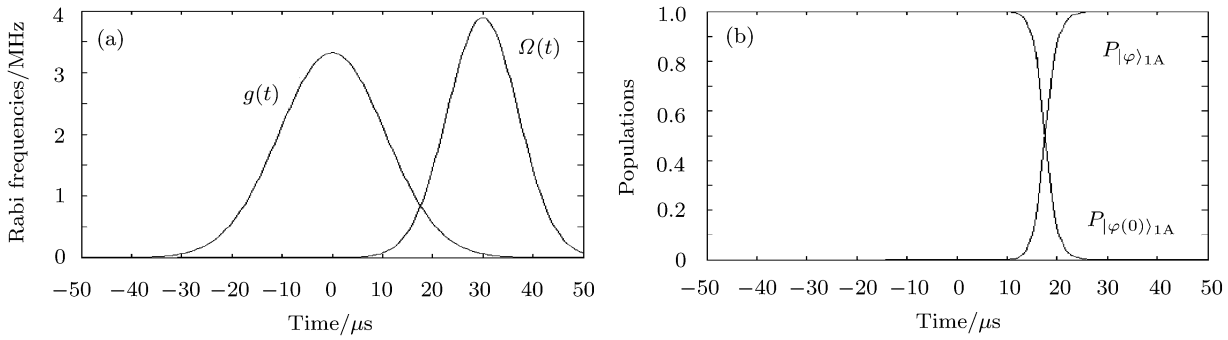


Fig.4. (a) Rabi frequencies of the cavity-mode and the laser fields for atom 1 travelling on the line $z_0 = 10$ μm with pulse parameters being $W_{\rm L} = 20$ μm, $W_{\rm C} = 30$ μm, $v = 2$ m/s, $\lambda = 780$ nm, $\Omega_0 = 50v/W_{\rm L}$, $\rm G_0 = 50v/W_C$ and the specific values $d = 60$ μm. (b) Time evolution of the populations.

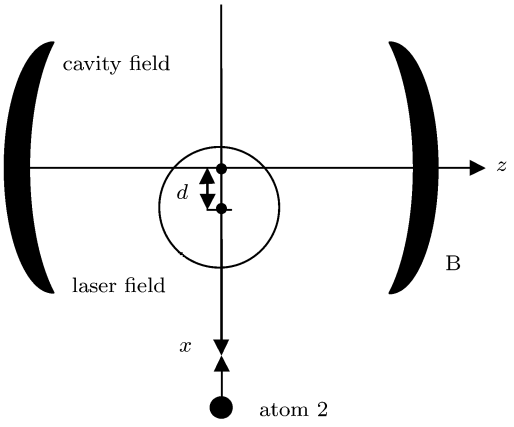


Fig.5. The geometry of the cavity-mode and the laser fields, and the trajectory of atom 2.

Let atom 2 move on the line $z_0 = 0$ in the same plane as shown in Fig. 5. The two Rabi frequencies are written as follows:

$$g_2(t) = g_0 \exp\Big[\frac{(-\nu t)^2}{W_{\rm C}^2}\Big], \tag{13}$$

$$\Omega_2(t) = \Omega_0 \exp\Big[\frac{-(\nu t + d)^2}{W_{\rm L}^2}\Big]. \tag{14}$$

The corresponding Rabi frequencies and distribution of population are shown in Fig.6, where we have taken $d = 40$ μm. Similarly, the population in the state $|\varphi(0)\rangle_{2\rm B} = |g_0\rangle_2(\alpha|1,0\rangle + \beta|0,1\rangle)_{\rm B}$ is completely transferred into the state $|\varphi\rangle_{2\rm B} = (\alpha|g_{\rm L}\rangle_2 + \beta|g_{\rm R}\rangle_2)|0,0\rangle_{\rm B}$ at the end of interaction time.

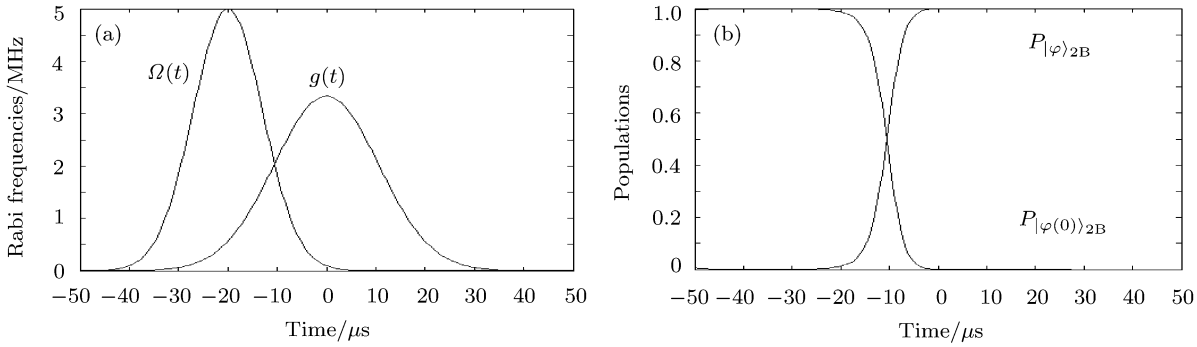


Fig.6. (a) Rabi frequencies of the cavity-mode and the laser field for atom 2 with the same pulse parameters and the specific value $d = 40$ μm. (b) Time evolution of the populations.

4. Conclusion

We have proposed a robust protocol for realizing the quantum transfer of an unknown atomic state. The scheme has several favourable advantages. Firstly, since the qubit is represented by long-lived two ground states and the atomic state evolves only in the ground dark space (that does not involve the atomic excited state) through adiabatic passage, the scheme is robust against the effects of atomic spontaneous emission. Secondly, as a result of adopting photons as flying qubits,[15] information transmission in our scheme is at the light speed so that the distance of information transmission is much longer. Finally, the successful probability of the scheme is about 1 in an ideal case.

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