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Deterministic transfer for an unknown atomic entangled state via cavity QED

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Abstract. We present a physics scheme for transferring an unknown atomic entangled state via cavity QED. In the transfer process the interaction between atoms and a single-mode nonresonant cavity with the assistance of a strong classical driving field (substitute) replace the Bell-state measurements. The scheme is insensitive to both the cavity decay and the thermal field. In addition, the success probability can reach 1.0 in our scheme.

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Key words: transfer, unknown atomic entangled state, cavity QED

1 Introduction

Quantum entanglement is at the heart of quantum mechanics and plays a key role in quantum information processing, such as quantum teleportation [1], superdense-coding [2], quantum error correction [3] and secret key distribution [4]. Quantum teleportation is one of the most important applications of quantum entanglement in quantum communication. Quantum teleportation, first proposed by Bennett *et al*. [1] and experimentally realized by Bouwmeester *et al*. [5] and Boschi *et al*. [6], is a process to transfer unknown state to a remote location via a quantum channel aided by some classical communication. Cavity QED technique has been proved to be a promising candidate for experimentally realization of quantum communication schemes. Many teleportation schemes have been proposed based on cavity QED techniques [7–17]. Riebe *et al*. [18] and Barrett *et al*. [19] have implemented quantum teleportation of atomic qubits, respectively.

For teleportation, the joint Bell-state measurement on two particles is usually needed. Although the joint Bell-state measurement has been realized in Refs. [18, 19], it is quite

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difficult to operate. In addition, the cavity decay and thermal field are two vital obstacles to the realization of various cavity QED experiments. Recently, Wu *et al*. [20] proposed a quantum state transfer scheme for two atoms with a single resonant interaction without Bell-state measurement. But the scheme is sensitive to the cavity decay and thermal field. Wu *et al*. [21] proposed another scheme, also without Bell-state measurement, to transfer an unknown atomic entangled state, where the effect of cavity decay has been eliminated. However, it is still sensitive to the thermal field.

In this paper, we propose a scheme for transferring an unknown atomic entangled state via cavity QED. The distinct advantage of the scheme is that during the interaction between the two atoms and the cavity field, a classical field is simultaneously accompanied, thus the evolution of the quantum state is independent from the state of the cavity. So the scheme is insensitive to both the cavity decay and the cavity thermal field. Moreover, our scheme does not require the Bell-state measurement and the success probability can reach 1.0 in our scheme.

2 Interaction of two identical atoms and a sing-mode cavity

We consider two identical two-level atoms simultaneously interacting with a single-mode cavity field. At the same time, two atoms are driven by a strong classical field. In the large detuning $\delta \gg g$ and $2\Omega \gg \delta$, g limit (where δ is the detuning between the atomic transition frequency ω_0 ($e \leftrightarrow g$) and the cavity frequency ω_a, g is the atom-cavity coupling constant and Ω is the Rabi frequency of the classical field), the effective interaction Hamiltonian in the rotating-wave approximation is [22]

$$H_{eff} = \lambda \left[\frac{1}{2} \sum_{j=1}^{2} \left(|e_j\rangle\langle e_j| + |g_j\rangle\langle g_j| \right) + \sum_{j,k=1, j\neq k}^{2} \left(s_j^+ s_k^+ + s_j^+ s_k^- + H.C. \right) \right], \tag{1}$$

where $\lambda = g^2/2\delta$, $s_j^+ = |e_j\rangle\langle g_j|$, $s_j^- = |g_j\rangle\langle e_j|$, and $|e_j\rangle$ and $|g_j\rangle$ are the excited and ground states of jth atom. The evolution operator of the system is given by [22]

$$U(t) = e^{-iH_0 t} e^{-iH_{eff} t}, \tag{2}$$

where

$$H_0 = \sum_{j=1}^{2} \Omega \left(s_j^+ + s_j^- \right). \tag{3}$$

From the above evolution operator, we can get the evolution with different initial states during the interaction time t between atoms and cavity.

3 Transfer of unknown atomic entangled state

Assume the entangled atomic state to be transferred is

$$|\Psi_{12}\rangle = \alpha |g_1\rangle |e_2\rangle + \beta |e_1\rangle |g_2\rangle. \tag{4}$$

where α and β are unknown real coefficients, $|\alpha|^2+|\beta|^2=1$. In order to transfer the unknown atomic state $|\Psi_{12}\rangle$, we will introduce two auxiliary atoms which are prepared in the state $|g_3\rangle|g_4\rangle$ and two single-atom cavities (A and B) which are initially prepared in vacuum state $|0_A\rangle|0_B\rangle$. The two auxiliary atoms and two entangled atoms are identical.

The whole system is in the state

$$|\Psi_{1234}\rangle=\big(\alpha|g_1\rangle|e_2\rangle+\beta|e_1\rangle|g_2\rangle\big)|g_3\rangle|g_4\rangle. \tag{5}$$

Let atoms 1, 3 and atoms 2, 4 simultaneously interact with single-mode cavity A and B respectively for the same interaction time and at the same time atoms 1, 3 and atoms 2, 4 are driven by a strong classical field respectively.

After the interaction t, the state of the total system will evolve into

$$\begin{aligned}|\Psi_{1234}\rangle \xrightarrow{U(t)} \alpha e^{-i2(\lambda t)}\Big\{&\cos(\lambda t)[\cos(\Omega t)|g_1\rangle-i\sin(\Omega t)|e_1\rangle][\cos(\Omega t)|g_3\rangle-i\sin(\Omega t)|e_3\rangle]\\&-i\sin(\lambda t)[\cos(\Omega t)|e_1\rangle-i\sin(\Omega t)|g_1\rangle][\cos(\Omega t)|e_3\rangle-i\sin(\Omega t)|g_3\rangle]\Big\}\\&\Big\{\cos(\lambda t)[\cos(\Omega t)|e_2\rangle-i\sin(\Omega t)|g_2\rangle][\cos(\Omega t)|g_4\rangle-i\sin(\Omega t)|e_4\rangle]\\&-i\sin(\lambda t)[\cos(\Omega t)|g_2\rangle-i\sin(\Omega t)|e_2\rangle][\cos(\Omega t)|e_4\rangle-i\sin(\Omega t)|g_4]\Big\}\\+\beta e^{-i2(\lambda t)}\Big\{&\cos(\lambda t)[\cos(\Omega t)|e_1\rangle-i\sin(\Omega t)|g_1\rangle][\cos(\Omega t)|g_3\rangle-i\sin(\Omega t)|e_3\rangle]\\&-i\sin(\lambda t)[\cos(\Omega t)|g_1\rangle-i\sin(\Omega t)|e_1][\cos(\Omega t)|e_3\rangle-i\sin(\Omega t)|g_3]\Big\}\\&\Big\{\cos(\lambda t)[\cos(\Omega t)|g_2\rangle-i\sin(\Omega t)|e_2\rangle][\cos(\Omega t)|g_4\rangle-i\sin(\Omega t)|e_4\rangle]\\&-i\sin(\lambda t)[\cos(\Omega t)|e_2\rangle-i\sin(\Omega t)|g_2\rangle][\cos(\Omega t)|e_4\rangle-i\sin(\Omega t)|g_4\rangle]\Big\}.\end{aligned} \tag{6}$$

By choosing appropriately the interaction time t, we can get $\lambda t=\pi/4$, and by modulating the driving field, the condition $\Omega t=\pi$ also can be realized. At the moment, the state of the total system is:

$$\begin{aligned}|\Psi\rangle=&-\frac{1}{2}i|g_1\rangle|g_2\rangle(\alpha|g_3\rangle|e_4\rangle+\beta|e_3\rangle|g_4\rangle)+\frac{1}{2}|g_1\rangle|e_2\rangle(\alpha|g_3\rangle|g_4\rangle-\beta|e_3\rangle|e_4\rangle)\\&+\frac{1}{2}|e_1\rangle|g_2\rangle(-\alpha|e_3\rangle|e_4\rangle+\beta|g_3\rangle|g_4\rangle)-\frac{1}{2}i|e_1\rangle|e_2\rangle(\alpha|e_3\rangle|g_4\rangle+\beta|g_3\rangle|e_4\rangle).\end{aligned} \tag{7}$$

At the moment, if atoms 1, 2 are detected in the states $|g_1\rangle|g_2\rangle$, we can obtain directly the initial state of atoms 1, 2 on atoms 3, 4. If atoms 1, 2 are detected in the states $|g_1\rangle|e_2\rangle$

or $|e_1\rangle|g_2\rangle$, or $|e_1\rangle|e_2\rangle$, then we only need to make standard rotation, on atoms 3 , 4 to reconstruct the initial entangled state of atoms 1, 2. So the total successful probability of the transfer scheme is $P_{succ} = 1/4 \times 4 = 1.0$.

4 Discussion and conclusion

In the following let us briefly discuss the feasibility of the scheme. For the Rydberg atoms with principal quantum numbers 49, 50 and 51, the radiative time is about $T_r = 3\times 10^{-2}$s, and the coupling constant is $g = 2\pi \times 24$ KHz in Refs. [23,24]. The required atom-cavity-field interaction time is on the order of $T \approx 10^{-4}$s, which is much shorter than the atomic radiative time T_r. So the scheme is realizable by using available cavity QED techniques.

In summary, we have proposed a deterministic scheme that can transfer an unknown atomic entangled state via cavity QED. In our scheme, we can achieve quantum state transfer directly by detecting the states of atoms. The joint Bell-state measurement can be converted into separate atomic measurement. In addition, the scheme is insensitive to cavity decay and thermal field owing to the large-detuned interaction between two driven atoms and a single-mode cavity.

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