Vol 15 No 4, April 2006
1009-1963/2006/15(04)/0676-05

Chinese Physics

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Efficient scheme for teleportation of an unknown N-atom state via a two-atom entangled state without the Bell-state measurement in cavity QED*

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(Received 2 June 2005; revised manuscript received 16 June 2005)

We propose a scheme for teleportation of an unknown N-atom state using a two-atom entangled state within a cavity QED and show the feasibility in experiment. Our scheme does not involve the Bell-state measurement and is insensitive to the cavity decay, which is important from the experimental point of view. Another feature of the scheme is that teleporting a N-atom state just requires a small amount of entanglement (i.e. a two-atom entangled state) and less classical bits (two bits).

Keywords: atomic entangled state, teleportation, thermal cavity, vacuum cavity
PACC: 0365, 4250

1. Introduction

Since the seminal work of Bennett *et al*,[1] the research in teleportation was soon widely started, and has greatly developed, both theoretically[2−16] and experimentally.[17−21] In Ref.[4], the authors suggested a scheme for teleportation of S-level quantum pure states by L ($2^L \geq S$, and $2^{L-1} < S$) two-level EPR states. A straightforward generalization of single-body teleportation[3] shows that any state of a N-partite system can be teleported using N maximally-entangled pairs as a quantum channel and transmission of 2^N bits of classical information via a classical channel. Zeng *et al* [5] proposed a scheme for teleportation of N-particle cat-like state using $(N+1)$-particle entangled state as the quantum channel. All these methods require great entanglement resources, and the transmission of many bits of classical information. Recently, Cola *et al* [16] presented a scheme for teleportation of bipartite state using a single entangled pair.

Usually, there are three steps required to complete the teleportation of an quantum state. The first step is that the auxiliary particles are prepared in the maximally entangled state as a quantum channel. Then a Bell-state measurement on two particles is performed. Finally, the result of the joint measurement is sent to a receiver through a classical channel and the receiver can perform a unitary operation to reconstruct the initial state of his particles. Recently, Zheng[14] proposed a scheme for the approximate conditional teleportation of an unknown atomic state without the Bell-state measurement, and the probability of success is only 0.25. Ye *et al* [15] also presented a scheme for teleportation of an unknown atomic state without the Bell-state measurement within a vacuum cavity. It is insensitive to cavity decay, but the probability of success is also only 0.5.

Inspired by Refs.[14–16], here we propose a scheme for teleportation of an unknown N-atom state ($N \geq 1$) via a two-atom entangled state without the Bell-state measurement in a cavity QED. There are three distinct advantages in our scheme: the first one is that during the passage of the atoms through the cavity field, the cavity is only virtually excited and no transfer of quantum information will happen between the atoms and the cavity, thus the scheme is insensitive to cavity decay, which is important from

*Project supported by the National Natural Science Foundation of China (Grant No 10374025) and the Scientific Research Fund of Hunan Provincial Education Department (Grant No 01c260).

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the experimental point of view; the second one is that teleporting an unknown multi-atom state only needs a two-atom entangled state, which reduces the amount of entanglement and less classical bits (2 bits); the third one is that it does not involve the Bell-state measurement.[14,15] Meanwhile, the probability of success in our scheme is much higher than that in Refs.[14,15], and the state to be reconstructed is exactly the initial state.

In Section 2 we describe the evolution of atomic states in two types of cavities involved in our scheme for teleportation. How to implement our teleportation scheme is presented in Section 3. Finally, we give a brief discussion on the experiment and draw some conclusions in Section 4.

2. Evolution of atomic states in two types of cavities

First we give the evolution of the atomic states in a thermal cavity. Considering K identical two-level atoms simultaneously interacting with a single-mode cavity field and driven by a classical field. In the strong driving regime $2\Omega \gg \delta, g$ and in the case of $\delta \gg g/2$ (Ω is the Rabi frequency of the classical field, g is the atoms-cavity coupling strength and δ is the detuning between the atomic transition frequency and the cavity field frequency), there exists no energy exchange between the atomic system and the cavity. Then in the interaction picture, the effective interaction Hamilton (let $\hbar = 1$) reads[22]

$$H_e = 2(\Omega S_x + \lambda S_x^2), \tag{1}$$

where $\lambda = g^2/2\delta$, $S_x = \frac{1}{2}\sum_{j=1}^{K}(S_j^+ + S_j^-)$, $S_j^+ = |e_j\rangle\langle g_j|$, $S_j^- = |g_j\rangle\langle e_j|$, with $|e_j\rangle$ and $|g_j\rangle$ $(j = 1, 2, \cdots, K)$ being the excited and ground states of the jth atom. Here we have assumed that the transition frequency of atoms is equal to the frequency of classical field. We note that the effective Hamilton is independent of the cavity field state, allowing it to be in a thermal state. Then the evolution operator of the system is given by

$$U(t) = \mathrm{e}^{-\mathrm{i}H_e t} = \mathrm{e}^{-\mathrm{i}2(\Omega S_x + \lambda S_x^2)t}. \tag{2}$$

Using the representation of the operator S_z, the atomic states $|g_1 g_2 \cdots, g_K\rangle$ and $|e_1 e_2 \ldots e_K\rangle$ can be expressed as $|K/2, -K/2\rangle$ and $|K/2, K/2\rangle$, respectively. On the other hand, such states can be expanded in terms of the eigenstates of S_x[22]

$$|K/2, -K/2\rangle = \sum_{M=-K/2}^{M=K/2} C_M |K/2, M\rangle_x,$$
$$|K/2, K/2\rangle = \sum_{M=-K/2}^{M=K/2} C_M (-1)^{K/2-M} |K/2, M\rangle_x. \tag{3}$$

Thus, if the K atoms are initially in the state $|g_1 g_2 \cdots g_K\rangle$, the evolution of the system will be

$$\sum_{M=-K/2}^{M=K/2} C_M \mathrm{e}^{-2i(\Omega M + \lambda M^2)t} |K/2, M\rangle_x.$$

When K is even, M is an integer. With the choice of $\lambda t = \pi/4$ and $\Omega t = n\pi$, we obtain

$$\begin{aligned}&\frac{1}{\sqrt{2}} \sum_{M=-K/2}^{M=K/2} C_M [\mathrm{e}^{-\mathrm{i}\pi/4} + \mathrm{e}^{\mathrm{i}\pi/4}(-1)^M] |K/2, M\rangle_x \\ =&\frac{1}{\sqrt{2}} [\mathrm{e}^{-\mathrm{i}\pi/4} |g_1 g_2 \cdots g_K\rangle \\ &+ \mathrm{e}^{\mathrm{i}\pi/4}(-1)^{K/2} |e_1 e_2 \cdots e_K\rangle]. \end{aligned} \tag{4}$$

On the other hand, for the case where K is odd we choose $\lambda t = \pi/4$ and $\Omega t = (2n + 3/4)\pi$. Then we obtain

$$\begin{aligned}&\frac{1}{\sqrt{2}} \mathrm{e}^{\mathrm{i}(7/8)\pi} [\mathrm{e}^{-\mathrm{i}\pi/4} |g_1 g_2 \cdots g_K\rangle \\ &+ \mathrm{e}^{\mathrm{i}\pi/4}(-1)^{(1+K)/2} |e_1 e_2 \cdots e_K\rangle]. \end{aligned}$$

In this way we obtain a multi-atom Greenberger–Horne–Zeilinger state which will be used as a quantum channel for teleportation scheme later (with choice of $K = 2$). If the K atoms are initially in the state $|e_1 e_2 \cdots e_K\rangle$, or $|g_1 e_2 \cdots e_K\rangle$ or $|e_1 g_2 \cdots g_K\rangle$, from Eqs.(5) and (6), we obtain the following evolution:

$$\begin{aligned}|e_1 e_2 \cdots e_K\rangle &\stackrel{U(t)}{\rightarrow} \frac{1}{\sqrt{2}} [\mathrm{e}^{\mathrm{i}\pi/4}(-1)^{K/2} |g_1 g_2 \cdots g_K\rangle \\ &\quad + \mathrm{e}^{-\mathrm{i}\pi/4} |e_1 e_2 \cdots e_K\rangle], \\ |g_1 e_2 \cdots e_K\rangle &\stackrel{U(t)}{\rightarrow} \frac{1}{\sqrt{2}} [\mathrm{e}^{-\mathrm{i}\pi/4} |g_1 e_2 \cdots e_K\rangle \\ &\quad + \mathrm{e}^{\mathrm{i}\pi/4}(-1)^{K/2} |e_1 g_2 \cdots g_K\rangle], \\ |e_1 g_2 \cdots g_K\rangle &\stackrel{U(t)}{\rightarrow} \frac{1}{\sqrt{2}} [\mathrm{e}^{\mathrm{i}\pi/4}(-1)^{K/2} |g_1 e_2 \cdots e_K\rangle \\ &\quad + \mathrm{e}^{-\mathrm{i}\pi/4} |e_1 g_2 \cdots g_K\rangle], \end{aligned} \tag{5}$$

when K is even (with choice of $\lambda t = \pi/4$, $\Omega t = n\pi$),

and

$$
\begin{aligned}
|e_1e_2\cdots e_K\rangle &\overset{U(t)}{\to} \frac{1}{\sqrt{2}}\mathrm{e}^{\mathrm{i}\frac{7\pi}{8}}[\mathrm{e}^{\mathrm{i}\frac{\pi}{4}}(-1)^{\frac{K+1}{2}}|g_1g_2\cdots g_K\rangle \\
&\quad + \mathrm{e}^{-\mathrm{i}\frac{\pi}{4}}|e_1e_2\cdots e_K\rangle], \\
|g_1e_2\cdots e_K\rangle &\overset{U(t)}{\to} \frac{1}{\sqrt{2}}\mathrm{e}^{\mathrm{i}\frac{7\pi}{8}}[\mathrm{e}^{-\mathrm{i}\frac{\pi}{4}}|g_1e_2\cdots e_K\rangle \\
&\quad + \mathrm{e}^{\mathrm{i}\frac{\pi}{4}}(-1)^{\frac{K+1}{2}}|e_1g_2\cdots g_K\rangle], \\
|e_1g_2\cdots g_K\rangle &\overset{U(t)}{\to} \frac{1}{\sqrt{2}}\mathrm{e}^{\mathrm{i}\frac{7\pi}{8}}[\mathrm{e}^{\mathrm{i}\frac{\pi}{4}}(-1)^{\frac{K+1}{2}}|g_1e_2\cdots e_k\rangle \\
&\quad + \mathrm{e}^{-\mathrm{i}\frac{\pi}{4}}|e_1g_2\cdots g_K\rangle], \qquad (6)
\end{aligned}
$$

when K is odd (with choice of $\lambda t = \pi/4$, $\Omega t = 2n\pi + 3\pi/4$).

Now we describe the evolutions of two identical two-level atoms in a vacuum cavity. Considering the two identical atoms $1, 2$ simultaneously interacting with a single-mode vacuum cavity field. In the case of $\delta \gg g$ (δ is the detuning between the atomic transition frequency and the cavity frequency, g is the atom-cavity coupling strength), there exists no energy exchange between the atomic system and the cavity. In the interaction picture, the effective interaction Hamilton for the system is (let $\hbar$=1)[15]

$$
H'_e = \lambda'\Big(\sum_{j=1}^{2}|e_j\rangle\langle e_j| + \sum_{i,j=1,i\neq j} S_j^+S_i^-\Big), \qquad (7)
$$

where $\lambda' = g^2/\delta$. So the corresponding evolution operator of the system is

$$
\begin{aligned}
U(t') =& \mathrm{e}^{-\mathrm{i}H'_et'} \\
=& \exp\Big[-\mathrm{i}\lambda't'\Big(\sum_{j=1}^{2}|e_j\rangle\langle e_j| + \sum_{i,j=1,i\neq j}^{2} s_j^+s_i^-\Big)\Big]. \qquad (8)
\end{aligned}
$$

Assume that two atoms are initially in the state $|e_1g_2\rangle$, then the state evolution of the system will be

$$
|e_1g_2\rangle \overset{U(t')}{\to} \mathrm{e}^{-\mathrm{i}\lambda't'}[\cos(\lambda't')|e_1g_2\rangle - \mathrm{i}\sin(\lambda't')|g_1e_2\rangle]. \qquad (9)
$$

Similarly, we obtain the following evolutions:

$$
\begin{aligned}
&|g_1e_2\rangle \overset{U(t')}{\to} \mathrm{e}^{-\mathrm{i}\lambda't'}[\cos(\lambda't')|g_1e_2\rangle - \mathrm{i}\sin(\lambda't')|e_1g_2\rangle], \\
&|g_1g_2\rangle \overset{U(t')}{\to} |g_1g_2\rangle, \\
&|e_1e_2\rangle \overset{U(t')}{\to} \mathrm{e}^{-\mathrm{i}2\lambda't'}|e_1e_2\rangle. \qquad (10)
\end{aligned}
$$

3. Teleportation scheme

In this section, we describe how to implement teleportation of an unknown N-atom state via only one two-atom entangled state without the Bell-state measurement. Assume Alice and Bob to share a two-atom entangled state

$$
|\Phi\rangle = \frac{1}{\sqrt{2}}(|g_Ag_B\rangle - \mathrm{i}|e_Ae_B\rangle) \qquad (11)
$$

generated by the way discussed above, with the choice of K=2 and the global phase discarded). Suppose that the atom B belongs to Bob, and the atom A belongs to Alice who has other N ($N \geq 1$) atoms assumed to be in the form of cat-like state[5]

$$
|\varphi\rangle = \alpha|g_1g_2\cdots g_N\rangle + \beta|e_1e_2\cdots e_N\rangle, \qquad (12)
$$

where α and β are unknown coefficients, and $|\alpha|^2 + |\beta|^2 = 1$. So the whole system is in the state of

$$
\begin{aligned}
|\Psi\rangle_{\mathrm{total}} =& \frac{1}{\sqrt{2}}(|g_Ag_B\rangle - \mathrm{i}|e_Ae_B\rangle) \\
&\times(\alpha|g_1g_2\cdots g_N\rangle + \beta|e_1e_2\cdots e_N\rangle). \qquad (13)
\end{aligned}
$$

Alice has the atoms $A, 1, 2, \cdots, N$ simultaneously across a single-mode cavity in thermal state, and at the same time these atoms are driven by a classical field. The system evolution is described by Eq.(2), with the choices of $\lambda t = \pi/4$, and $\Omega t = n\pi$ ($\Omega t = 2n\pi + 3\pi/4$) when N is odd (even), the whole state evolves to

$$
\begin{aligned}
|\Psi\rangle =& \frac{1}{2}\{|g_Ag_1g_2\cdots g_N\rangle\mathrm{e}^{\mathrm{i}\phi}[\alpha|g_B\rangle - b(N)\beta|e_B\rangle] \\
&+ |e_Ae_1e_2\cdots e_N\rangle\mathrm{e}^{\mathrm{i}\psi(N)}[\alpha|g_B\rangle + b(N)\beta|e_B\rangle] \\
&+ |g_Ae_1e_2\cdots e_N\rangle\mathrm{e}^{\mathrm{i}\phi}[\beta|g_B\rangle - b(N)\alpha|e_B\rangle] \\
&+ |e_Ag_1g_2\cdots g_N\rangle\mathrm{e}^{\mathrm{i}\psi(N)}[\beta|g_B\rangle + b(N)\alpha|e_B\rangle]\}, \qquad (14)
\end{aligned}
$$

where $\phi = 5\pi/8$ ($\phi = -\pi/4$) when N is even (odd), $\psi(N)$ and $b(N)$, which are functions of N, are defined as

$$
\psi(N) = \begin{cases} 5\pi/4, & \text{if} \quad N = 4k-3, \\ \pi/4, & \text{if} \quad N = 4k-1, \\ \pi/8, & \text{if} \quad N = 4k, \\ 9\pi/8, & \text{if} \quad N = 4k-2, \end{cases} \qquad (15)
$$

$$
b(N) = \begin{cases} 1, & \text{if} \quad N = 4k-3, \\ -1, & \text{if} \quad N = 4k-1, \\ 1, & \text{if} \quad N = 4k, \\ -1, & \text{if} \quad N = 4k-2, \end{cases} \qquad (16)
$$

where k is a natural number. Then Alice performs measurement on the single atoms $A, 1, 2, \cdots, N$ (In fact, Alice only needs to measure the atoms $A, 1$)

with the base $\{|g\rangle, |e\rangle\}$ and informs Bob of the results through a classical channel. Then Bob performs corresponding unitary transformation on the atom B, which is given in Table 1 (these operations can be realized by single atoms interacting resonantly with a homochromatic classical field and choosing an appropriate iteration time.[23]),

Table 1. Corresponding unitary transformation on the atom B according to the measurements on the atoms $A, 1, 2, \cdots, N$.

the measurements on the atoms $A, 1, 2, \cdots, N$	corresponding unitary transformation on the atom B
$\|g_A g_1 g_2 \cdots g_N\rangle$	$(I_B)^{[1-b(N)]/2}(\sigma_{zB})^{[1+b(N)]/2}$
$\|e_A e_1 e_2 \cdots e_N\rangle$	$(I_B)^{[1+b(N)]/2}(\sigma_{zB})^{[1-b(N)]/2}$
$\|g_A e_1 e_2 \cdots e_N\rangle$	$(\sigma_{xB})^{[1-b(N)]/2}(\mathrm{i}\sigma_{yB})^{[1+b(N)]/2}$
$\|e_A g_1 g_2 \cdots g_N\rangle$	$(\sigma_{xB})^{[1+b(N)]/2}(\mathrm{i}\sigma_{yB})^{[1-b(N)]/2}$

Then the state of the atom B will be in the form of

$$\alpha|g_B\rangle + \beta|e_B\rangle.$$

Now Bob introduces the additional atoms $N+1, N+2, \cdots, 2N-1$, each with ladder-type three levels denoted by $|g\rangle$, $|e\rangle$, and $|i\rangle$ that is an auxiliary level. The initial states of these atoms are prepared using

$$\frac{1}{\sqrt{2}}(|g_{N+1}\rangle - |i_{N+1}\rangle)\frac{1}{\sqrt{2}}(|g_{N+2}\rangle - |i_{N+2}\rangle)$$
$$\cdots \frac{1}{\sqrt{2}}(|g_{2N-1}\rangle - |i_{2N-1}\rangle).$$

Then Bob has atom pairs $(B, N+1), (B, N+2), \cdots, (B, 2N-1)$ simultaneously across a single-mode vacuum cavity field described in Eq.(8). Here we assume that the transition frequency between the states $|e\rangle$ and $|i\rangle$ is highly detuned from the cavity frequency and thus the state $|i\rangle$ is not affected during the atom-cavity interaction, the quantum information is stored in the states $|e\rangle$ and $|g\rangle$. With the choice of $\lambda' t' = \pi$, the whole system of the atoms is

$$\frac{1}{(\sqrt{2})^{N-1}}[\alpha|g_B\rangle(|g_{N+1}\rangle - |i_{N+1}\rangle)(|g_{N+2}\rangle - |i_{N+2}\rangle)$$
$$\cdots(|g_{2N-1}\rangle - |i_{2N-1}\rangle)$$
$$+\beta|e_B\rangle(|g_{N+1}\rangle + |i_{N+1}\rangle)(|g_{N+2}\rangle + |i_{N+2}\rangle)$$
$$\cdots(|g_{2N-1}\rangle + |i_{2N-1}\rangle)].$$

Subsequently, let atoms $N+1, N+2, \cdots, 2N-1$ cross two classical fields tuned to the transitions $|e\rangle \leftrightarrow |i\rangle$ and $|g\rangle \leftrightarrow |e\rangle$, separately. Choose the amplitudes and phases of the classical fields appropriately such that these atoms undergo the transition

$$|i\rangle \to |e\rangle \to \frac{1}{\sqrt{2}}(|e\rangle - |g\rangle),$$
$$|g\rangle \to |g\rangle \to \frac{1}{\sqrt{2}}(|e\rangle + |g\rangle). \qquad (17)$$

Then we obtain

$$\alpha|g_B g_{N+1} g_{N+2} \cdots g_{2N-1}\rangle$$
$$+\beta|e_B e_{N+1} e_{N+2} \cdots e_{2N-1}\rangle,$$

which is exactly the initial state and indicates the success in the teleportation.

4. Discussion and conclusion

Now we give a brief discussion on the experiment. 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.[24] With the choice of $\delta = 10$g,[24] the required atom–thermal-cavity-field interaction time is on the order of $T \approx 10^{-4}$s and atom–vacuum-cavity-field interaction time is about $T' \approx 2 \times 10^{-4}$s. Then the time required to complete the whole procedure is much shorter than T_r.

The scheme requires that $N+1$ atoms be sent simultaneously through a thermal cavity and two atoms be sent simultaneously through a vacuum cavity, otherwise there will appear an error. Besides, the fluctuation of the Rabi frequency will also bring about an error. Here we take an example for $N = 2$ to estimate the fidelity of teleportation. Assume that one atom is Δt ($\Delta t \ll t$) earlier than the other two when three atoms cross the thermal cavity and fluctuation of the Rabi frequency Ω is $\Delta\Omega$ ($\Delta\Omega \ll \Omega$), and when two atoms enter the vacuum cavity one atom is $\Delta t'$ ($\Delta t' \ll t'$) earlier than the others. Then we obtain the fidelity of teleportation

$$F \approx \frac{\cos^8[\Delta t(\Omega-\Delta\Omega)]\cos^8[(t-\Delta t)(\Omega-\Delta\Omega)]}{(1-|\beta|^2)\cos^4[(t-\Delta t)\lambda]+\frac{|\beta|^2}{4}\sin^4[(t-\Delta t)\lambda][\cos(t'-\Delta t')\lambda'-1]^2 \times\{(1-|\beta|^2)\cos^2[(t-\Delta t)\lambda] +\frac{|\beta|^2}{2}\sin^2[(t-\Delta t)\lambda]\cos[(t'-\Delta t')\lambda'][\cos(t'-\Delta t')\lambda'-1]\}^2}. \quad (18)$$

Here we assume $\Delta t = 0.01t$, $\Delta\Omega = 0.01\Omega$ and $\Delta t' = 0.01t'$ for example, and show the fidelity F with different β in Fig.1, where it is shown that the fidelity caused by these experimental errors is less than 0.03, which indicates that our scheme is slightly affected in these cases. Here for simplicity we have omitted the errors caused maybe by other experimental causes.

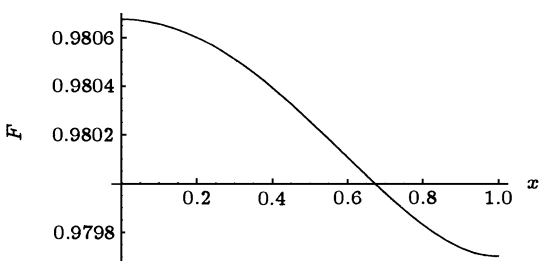


Fig.1. The fidelity of teleportation F as a function of $|\beta|$, with the choice of $\Omega t = \pi$, $\lambda' t' = \pi$ and $\lambda t = \pi/4$. Here **x**= $|\beta| \in [0,1]$, $\Delta t = 0.01t$, $\Delta\Omega = 0.01\Omega$, and $\Delta t' = 0.01t'$.

In summary, we have proposed a simple scheme to realize teleportation of an unknown multi-atom state via only one two-atom entangled state. This scheme does not require any auxiliary levels and classical fields for implementing Control-NOT gate and Hadamard transformation to discriminate the Bell-state, which can largely reduce the experimental steps and time and thus will increase the fidelity of teleportation in experiment. Besides, during the passage of the atoms through the two types of cavity fields, the cavities are only virtually excited and there appears no transfer of quantum information between the atoms and the cavities. Thus the scheme is insensitive to the cavity decay, which will also contribute to the fidelity of teleportation in practice. Another important feature is that teleporting a multi-atom state requires just a small amount of entanglement and 2-bit classical information much less than that in Refs.[3,5], which is very useful in quantum communication[25,26] and quantum computation based on a network.[27,28]

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