A scheme for quantum state transfer between distant atoms

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A scheme is proposed to implement quantum state transfer between two distant atoms through sending the atoms across two distant cavities connected via an optical fiber. The field state, which preserves the information of the first atom, is transmitted from one cavity to the other along the fiber. After the field interacts with the second atom for a defined time, the state transfer can be accomplished with unit efficiency. The realization of this scheme is within current experiment technology.

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Transmitting quantum states between distant sites is the goal of quantum communication, and it is one of the most challenging and rewarding tasks. Quantum state transfer can be completed either by the method of teleportation[1] or through quantum networking. Recently, various quantum systems have been suggested as possible candidates for generating quantum entanglement or transferring quantum state. This may be helpful for one to extend quantum cryptograph over long distance[2], and may find a variety of novel applications in performing secret sharing[3], purification[4] or distributed quantum computation[5].

The cavity quantum electrodynamics (cavity QED) systems can provide mechanisms for communicating between high-Q cavities. In the past decade, many schemes in the context of cavity QED were proposed. Most of them were based on direct or indirect interactions between the atoms whose internal states are to be transferred[6−7]. The basic idea is that the localized atoms are trapped in high-Q cavities which are spatially separated from each other, the special laser pulses are employed and an atom emits a photon into the cavity mode, and then the photon enters the second cavity and is absorbed by the other atom, thus the state transfer is completed by appropriately switching on or off the laser. There are distinct methods[8−10] either by measuring superposition of field states produced from separate atomic samples, or by probing the light field that has interacted in a prescribed way with different samples, and the indistinguishability leads to the atomic entangled state. Note that the schemes mentioned above mostly operate in a transitory regime, and as a result, imperfections may be introduced by dissipation into the desired state. Some schemes working in steady state were proposed to avoid this kind of imperfection[11−12]. Moreover, if the preparation of entanglement is through projective measurement, introduction of noise is inevitably.

Here we propose a robust scheme to transfer atomic states between spatially separated high-Q cavities connected via an optical fiber. In recent years many schemes with this feature have been known for entangling two or more atoms[13−15] and there are essential developments in using optical fiber for quantum communication on the single photon level. Based on an adiabatic passage via dark states, the quantum networking with optical fibre was established[16]. The entanglement between distant atoms is prepared through generating an effective interaction of arbitrary strength between the internal degrees of freedom for the atoms placed in distant cavities connected by an optical fiber[17]. The photon leaks out of the cavities and is coupled to an optical fiber, then through measurement the atomic system is projected into an entangled state[18]. All show that optical fibre has potential applications in quantum communication.

Our scheme is conceptually simple to implement the atomic state transfer and essentially simplifies the process in contrast with those mentioned above. In order to illustrate the scheme, we assume that the atoms have two levels. The quantum information to be transferred is initially stored in atom 1, the cavities connected via an optical fiber are prepared in the vacuum state, and atom 2 is prepared in the ground state. Firstly let atom 1 cross the cavity, when it comes out of the cavity its information is left in the coherent superposition of zero and one photon Fock states. At the same time, the field will be guided to the other cavity along the fiber. Here we must consider the reflection of the field from the second cavity and the field recoupled from the second cavity to the fiber. In order to avoid these undesired fields, we can integrate a Faraday isolator in the fiber near to the second cavity. The Faraday isolator only permits the field in the fiber to transmit in one direction, as a result, the field in the first cavity left by atom 1 can completely transmit to the second cavity, effectively switching off the dominant loss channel that would be responsible for decoherence in the communication process. Therefore, after atom 2 crosses the second cavity, it will obtain the information initially stored in atom 1.

The system considered here consists of two atoms (atom 1 and atom 2) and two cavities (cavity A and cavity B). The atoms are sent through the cavities in the direction perpendicular to the cavity axis, respectively. To describe how the quantum state transfer works, we first consider the interaction between a two-level atom and a single-mode cavity field. It is well known that this interaction is described by the Jaynes-Cummings model. The atom-field Hamiltonian reads in the dipole and rotating-wave approximations ($\hbar = 1$)

$$H = \omega a^+ a + \frac{1}{2}\omega\sigma_z - ig\left(\sigma_+ a - a^+\sigma_-\right), \qquad (1)$$

where ω is the atomic transition frequency, which is in resonance with the cavity mode. a and a^+ are the photon annihilation and creation operators of the cavity mode, σ_z, σ_+ , and σ_- are the Pauli operators of the atom. The atom-field coupling coefficient g, in general, is position-dependent during the atom-field interaction due to the transverse spatial structure of the cavity mode. Here for simplicity, we use its average. The time-evolution operator[19] is

$$U(t) = \cos\left(gt\sqrt{a^+a+1}\right)|e\rangle\langle e| + \cos\left(gt\sqrt{a^+a}\right)|g\rangle\langle g| - \frac{\sin\left(gt\sqrt{a^+a+1}\right)}{\sqrt{a^+a+1}}a|e\rangle\langle g| + a^+\frac{\sin\left(gt\sqrt{a^+a+1}\right)}{\sqrt{a^+a+1}}|g\rangle\langle e|, \quad (2)$$

where $|g\rangle$ and $|e\rangle$ are the atomic ground and excited states, respectively. We denote the vacuum state and the one-photon Fock state as $|0\rangle$ and $|1\rangle$, respectively. If the system is initially in the state $|\psi(0)\rangle = |e,0\rangle$, considering $|\psi(t)\rangle = U(t)|\psi(0)\rangle$, its state at time t can easily be obtained

$$|\psi(t)\rangle = \cos(gt)|e,0\rangle + \sin(gt)|g,1\rangle. \quad (3)$$

If the system starts from the state $|\psi(0)\rangle = |g,1\rangle$, its state at time t becomes

$$|\psi(t)\rangle = \cos(gt)|g,1\rangle - \sin(gt)|e,0\rangle. \quad (4)$$

Clearly the unitary operator (2) will not change the initial state $|g,0\rangle$ during the interaction, and the state $|e,0\rangle$ and $|g,1\rangle$ will experience the vacuum Rabi oscillation which corresponds to the oscillatory regime of the spontaneous emission in the high-Q cavity.

Next we demonstrate the process of the state transfer. We assume that atom 1 is initially in an unknown quantum state

$$|\psi\rangle_1 = \alpha|g\rangle_1 + \beta|e\rangle_1, \quad (5)$$

where α and β are unknown arbitrary coefficients. The state $|\psi\rangle = \alpha|g\rangle + \beta|e\rangle$ is to be transferred from atom 1 to atom 2. We use the terms $\pi/2$ pulse, π pulse, and 3π pulse to denote three equivalent times τ_1, τ_2 and τ_3 of the atom through the cavity satisfying $2g\tau_1 = \pi/2$, $2g\tau_1 = \pi$, and $2g\tau_1 = 3\pi$, respectively. The time τ_1, τ_2, and τ_3 are determined by selecting the atomic velocity. One of the favorable features of our scheme is that the cavities mode is prepared in the vacuum state $|0\rangle$ before transferring the state.

Atom 1 is sent through cavity A and is only allowed to experience a π pulse, and then the initial state of the whole system $|\psi\rangle_1|0\rangle_{\rm A}$ will evolve according to

$$(\alpha|g\rangle_1 + \beta|e\rangle_1)|0\rangle_{\rm A} \rightarrow |g\rangle_1(\alpha|0\rangle_{\rm A} + \beta|1\rangle_{\rm A}). \quad (6)$$

In general, if a pulse is irradiated on an atom, we can obtain a time-varying entanglement between the atom and the cavity field. However, in the particular case of a π pulse the atomic state does not correlate with the cavity mode, leaving in the cavity a superposition of the zero- and one-photon Fock states. The atomic state is mapped onto the cavity mode.

In this paper our key point is that the superposition field $\alpha|0\rangle_{\rm A} + \beta|1\rangle_{\rm A}$, left by atom 1 in cavity A, will enter the fiber, and then be guided to cavity B. Both the field reflected by cavity B along the fiber and the field recoupled from cavity B to the fiber will lead to decoherence in the communication process. However, the Faraday isolator integrated in the fiber avoids these undesired effects, increasing the efficiency drastically.

After a little time related to retardation on the propagation in the fiber, the field enters cavity B entirely and will establish oscillations in it, preserving the quantum information of atom 1. At the moment, atom 2, initially prepared in the ground state $|g\rangle_2$, is sent through cavity B, and experiences a 3π pulse during the interaction with cavity B, then the process can be described as

$$(\alpha|0\rangle_{\rm B} + \beta|1\rangle_{\rm B})|g\rangle_2 \rightarrow |0\rangle_{\rm B}(\alpha|g\rangle_2 + \beta|e\rangle_2). \quad (7)$$

After atom 2 comes out of cavity B, its internal state does not correlate with the cavity mode, leaving the field in cavity B the original vacuum state $|0\rangle_B$, and atom 2 acquires the state $|\psi\rangle = \alpha|g\rangle + \beta|e\rangle$, i.e., the state has been transferred from atom 1 to atom 2.

Another important issue is the preparation of quantum entanglement between distant atoms. In spirit of our present scheme the entanglement between distant atoms can be realized without sending the atom from one cavity to the other[20]. First, we prepare atom 1 in the excited state $|e\rangle_1$ and cavity A in the vacuum state $|0\rangle_A$, then let atom 1 experience a $\pi/2$ pulse in cavity A. The state of the system is obtained

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|e,0\rangle + |g,1\rangle). \quad (8)$$

When atom 1 comes out of the cavity, it is entangled with the cavity mode. The light field in cavity A, entangled with atom 1, will leak into the fiber. As the light field is propagating in the fiber, the entanglement state (8) will not be destroyed. Consequently, the field preserving the entanglement state (8) enters cavity B initially prepared in the vacuum state $|0\rangle_{\rm B}$, and we apply a π pulse to atom 2 initially prepared in the ground state $|g\rangle_2$, so that preparation of the entanglement between distant atoms can be demonstrated as

$$\frac{1}{\sqrt{2}}(|e\rangle_1|0\rangle_{\rm B} + |g\rangle_1|1\rangle_{\rm B})|g\rangle_2 \rightarrow \frac{1}{\sqrt{2}}(|e\rangle_1|g\rangle_2 - |g\rangle_1|e\rangle_2)|0\rangle_{\rm B}, \quad (9)$$

i.e., we obtain the atomic entanglement state $\frac{1}{\sqrt{2}}(|e\rangle_1|g\rangle_2 - |g\rangle_1|e\rangle_2)$, leaving the cavity modes in their initial vacuum states. In the same way, the GHZ states [21] can also be prepared using three two-level atoms that are far apart from each other.

In a real experiment the velocity of the atom cannot be fixed, i.e., we have to consider dispersion in the velocity of both atoms. In order to get the desired state, Cirac et al.[22] have shown that the high velocity of the atoms is needed, however, it is available in the current experiment. Once it is said to the quantum state transfer, one has to care about the fidelity since the interaction of the atom and the cavity with environment may result in decoherence which impedes in general the realization of any quantum communication or computational protocol. In the present scheme, the desired states are insensitive to the cavity damping mechanisms before and after the interaction, since the cavities are in the vacuum states, and during the interaction the cavity dissipation may be ignored.

In principle, the quantum state transfer can be accomplished with unit efficiency. However, because of both the non-ideal input coupling from cavity A into the fiber and from the fibre into cavity B, and the photon absorption either in the mirrors or in the fiber, in order to improve efficiency we must resort to perfecting the technique and establishing corresponding error correction scheme. What is more, considering losses in the optical fiber, it is unrealistic for long transmission distance, but the present idea can be extended to a number of distant atoms — let atom 2 cross the third cavity connected to the forth cavity via a fiber, and let the third atom cross the forth cavity, as a result, the third atom can obtain the quantum state of atom 1.

In summary, we have proposed a novel scheme to transfer quantum state by sending atoms across the cavities connected via fiber. Compared with recent similar teleportation schemes, our scheme has following favorable features: it does not need to continuously excite the atoms trapped in the cavities[6−12], does not require the tailed optical pulses[6−7,18], does not involve projective measurements[8−10], and particularly, does not need to appropriately switch on or off the laser[6−7]. At the same time, unlike Ref.[23], in which an error may result due to the requirement of sending two atoms simultaneously through the cavity, in our scheme the atom can be send across the cavities sequentially, and our scheme is within the current experiment technology with Rydberg atoms and microwave cavities, and partially, relies on the technological advances and realizations as described in Ref.[24].

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References

1. C. H. Bennett, G. Brassard, C. Crepeau, R. Jozsa, A. Peres, and W. K. Wootters, Phys. Rev. Lett. **70,** 1895 (1993).
2. H.-J. Briegel, W. Dur, J. I. Cirac, and P. Zoller, Phys. Rev. Lett. **81,** 5932 (1998).
3. R. Cleve, D. Gottesman, and H.-K. Lo, Phys. Rev. Lett. **83,** 648 (1999).
4. C. H. Bennett, G. Brassard, S. Popescu, B. Schumacher, J. A. Smolin, and W. K. Wootters, Phys. Rev. Lett. **76,** 722 (1996).
5. R. Cleve and H. Buhrman, Phys. Rev. A **56,** 1201 (1997).
6. J. I. CiracJ, P. Zoller, H. J. Kimble, and H. Mabuchi, Phys. Rev. Lett. **78,** 3221 (1997).
7. S. J. van Enk, J. I. Cirac, and P. Zoller, Phys. Rev. Lett. **78,** 4293 (1997).
8. L.-M. Duan and H. J. Kimble, Phys. Rev. Lett. **90,** 253601 (2003).
9. C. Cabrillo, J. I. Cirac, P. Garcia-Fernandez, and P. Zoller, Phys. Rev. A **59,** 1025 (1999).
10. X.-L. Feng, Z.-M. Zhang, X.-D. Li, S.-Q. Gong, and Z.-Z. Xu, Phys. Rev. Lett. **90,** 217902 (2003).
11. B. Kraus and J. I. Cirac, Phys. Rev. Lett. **92,** 013602 (2004).
12. S. Clark, A. Peng, M. Gu, and S. Parkins, Phys. Rev. Lett. **91,** 177901 (2003).
13. M. B. Plenio, S. F. Huelga, A. Beige, and P. L. Knight, Phys. Rev. A **59,** 2468 (1999).
14. J. Hong and H.-W. Lee, Phys. Rev. Lett. **89,** 237901 (2002).
15. D. E. Browne, M. B. Plenio, and S. F. Huelga, Phys. Rev. Lett. **91,** 067901 (2003).
16. T. Pellizzari, Phys. Rev. Lett. **79,** 5242(1997).
17. S. Mancini and S. Bose, Phys. Rev. A **70,** 022307 (2004).
18. B. Yu, Z.-W. Zhou, Y. Zhang, G.-Y. Xiang, and G.-C. Guo, Phys. Rev. A **70,** 014302 (2004).
19. M. O. Scully and M. S. Zubairy, *Quantum Optics* (Cambridge, London, 1997).
20. A. Biswas and G. S. Agarwal, Phys. Rev. A **70,** 022323 (1994).
21. D. M. Greenberger, M. Horne, and A. Zeilinger, in*Bell's Theorem, Quantum Theory, and Conceptions of the Universe*, M. Kafatos(ed.) (Kluwer, Dordrecht, 1989).
22. J. I. Cirac and P. Zoller, Phys. Rev. A **50,** 2799 (1994).
23. X.-B. Zou, K. Pahlke, and W. Mathis, Phys. Rev. A **67,** 044301 (2003).
24. J. M. Raimond, M. Brune, and S. Haroche, Rev. Mod. Phys. **73,** 565 (2001).