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Scheme for implementing perfect remote state preparation with W-class state in cavity QED

Wang Xue-Wen(王学文) and Peng Zhao-Hui(彭朝晖)†

School of Physics, Hunan University of Science and Technology, Xiangtan 411201, *China*

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In this paper we present a remote state preparation scheme with a three-qubit W-class state in cavity QED. It has been shown that a special single-qubit state and a special two-qubit entangled state can be remotely prepared perfectly. Furthermore, the classical information cost in this scheme is less than that in the corresponding teleportation scheme and only a single-qubit projective measurement is made by the sender. We also generalize this idea to the multiqubit W-class state.

Keywords: remote state preparation, W-class state, cavity QED
PACC: 0365, 4250

1. Introduction

Quantum teleportation, which was first proposed by Bennett *et al*,[1] is a nice way to transmit an unknown quantum state from the sender (Alice) to a spatially distant receiver (Bob) via a quantum channel with the help of local operations and classical communications. Recently, Lo[2] has presented a novel protocol, which is called remote state preparation (RSP), to transmit a pure known quantum state by using a prior shared entanglement and some classical communications. The main difference between RSP and teleportation is that in the RSP Alice knows fully the transmitted state to be prepared by Bob, while in the teleportation neither Alice nor Bob has knowledge of the transmitted state. It has been shown that the RSP protocol is more economical than teleportation and it requires only one classical bit from Alice to Bob for a qubit chosen from the equator or polar great circles of the Bloch sphere.[3] Bennett *et al*[4] have studied the tradeoff between the required entanglement and classical communication cost in RSP. Up to now, various RSP schemes have been proposed theoretically[5−14] and demonstrated experimentally.[15,16]

As one of the possible candidates for engineering quantum entanglement, the cavity quantum electrodynamics (QED) system has found many applications in quantum information processing (QIP). But the cavity decay is still one of the main obstacles to implement quantum information in cavity QED. Recently Zheng and Guo[17] have proposed a novel scheme in which two atoms interact with a nonresonant cavity and the cavity is only virtually excited, thus the efficient decoherence time is greatly prolonged. Osnaghi *et al*[18] have experimentally implemented the scheme and demonstrated that the scheme is essentially insensitive to the thermal field and cavity decay. Following this idea, various schemes of generating entangled states,[19−22] quantum clock synchronization,[23] quantum teleportation,[24,25] and dense coding[26] have been proposed. In a word, the method in Ref.[17] has opened new prospects for QIP in cavity QED.

As is known, there are two inequivalent classes of tripartite entangled states, i.e. the Greenberger–Horne–Zeilinger (GHZ) class and the W-class.[27] For the GHZ state we can deterministically obtain an arbitrary two-particle EPR state with local operations, so it can be used for perfect teleportation[28] and RSP,[8] but the W state cannot.[11,29] It may be mentioned that the W-class state is robust against loss of qubits, i.e. if we trace out any one qubit from the W-class state there exists still a genuine entanglement between the remaining two qubits,[27] and then how to implement the perfect quantum teleportation or the RSP with the W-class state is a challenging task. Recently Agrawal and Pati[30] have shown there to be a class of W state that can be used for perfect quantum teleportation and dense coding. They have demonstrated

†Corresponding author. E-mail: raul121991@126.com

there to be one ebit of entanglement shared between Alice and Bob when they use this class of W state. At the same time Zheng[31] also proposed a perfect scheme for splitting quantum information with this W-class state in an ion trap. It has been shown that the W-class state may be a good candidate for perfect QIP. Inspired by the schemes in Refs.[30] and [31], we have proposed to implement perfect quantum dense coding[32] and teleportation[33] with this W-class state in cavity QED. In this paper we propose a scheme to remotely prepare a special single-qubit state and a special two-qubit entangled state perfectly with a three-qubit W-class state in cavity QED. Furthermore, we also generalize this idea to remotely preparing a single-qubit state and a multiqubit entangled state with a multipartite W-class state. It has been shown that only single-qubit measurement is required and the classical information cost is less than that of the corresponding teleportation scheme.

2. Remote state preparation with three-qubit W-class state

We consider three identical three-level atoms, whose states are denoted by $|g\rangle$, $|e\rangle$ and $|f\rangle$, interacting with the microwave cavity C_1 in sequence. There is no more than one photon in the cavity so that the state of the cavity field can be described in terms of the basis $\{|0\rangle, |1\rangle\}$. The transition frequency between the states $|e\rangle$ and $|f\rangle$ is highly detuned from the cavity frequency, thus the state $|f\rangle$ is not affected during the atom–cavity interaction (However, this auxiliary energy level $|f\rangle$ will be useful for implementing the nonlocal controlled-NOT (CNOT) operation[17]). Suppose that the atomic transition between $|g\rangle$ and $|e\rangle$ is resonant with the cavity field. Then, in the interaction picture, the atom–cavity interaction is described by the Jaynes–Cummings Hamiltonian (assuming $\hbar = 1$)

$$H_{\rm I} = {\rm i}\hbar g_1 \left(a_1^\dagger |g\rangle\langle e| - a_1 |e\rangle\langle g|\right), \tag{1}$$

where a_1 and $a_1^\dagger$ are the annihilation and creation operators of the cavity mode, and g_1 is the coupling strength between atoms and cavity C_1. In the basis of atomic vectors the evolution operator of the atom–field system can be described as

$$U(t) = \begin{pmatrix} \cos(\Omega_{n+1}t) & \dfrac{-g_1 a_1 \sin(\Omega_n t)}{\Omega_n} \\ \dfrac{g_1 a_1^\dagger \sin(\Omega_{n+1}t)}{\Omega_{n+1}} & \cos(\Omega_n t) \end{pmatrix}, \tag{2}$$

where $\Omega_n^2 = g_1^2 n$ with $n = a_1^\dagger a_1$. We assume that the cavity C_1 is initially in a vacuum state. Atom 1 is initially in an excited state while atoms 2 and 3 are in ground states. Three atoms are sent through the cavity one by one. After one atom has flown out of the cavity another atom is sent into the cavity immediately. The interaction time of atoms 1 and 2 with the cavity field is $t = \dfrac{\pi}{4g_1}$, while for atom 3 the interaction time is $t = \dfrac{\pi}{2g_1}$. The evolution of the atom-field system can be written as

$$\begin{aligned} &|\psi\rangle_{123{\rm c}} \\ &= U_1(t_1)U_2(t_2)U_3(t_3)|egg0\rangle_{123{\rm c}} \\ &= \frac{1}{2}|0\rangle_{\rm c}(\sqrt{2}|egg\rangle_{123} - |gge\rangle_{123} - |geg\rangle_{123}). \end{aligned} \tag{3}$$

After atom 3 has flown out of the cavity, we can see that the cavity field is still in the vacuum state and three atoms are in the following W-class state:

$$|W\rangle_{123} = \frac{1}{2}(|gge\rangle_{123} + |geg\rangle_{123} - \sqrt{2}|egg\rangle_{123}). \tag{4}$$

Suppose that Alice, Bob and Carol share this three-qubit W-class state, where atoms 1, 2 and 3 belong to Alice, Bob and Carol respectively. The state that Alice wants to help Bob or Carol remotely prepare is $|\phi\rangle = \alpha|g\rangle + \beta|e\rangle$, which is known to Alice but unknown to Bob or Carol. We also assume that the parameter α is real and β is a complex number and $|\alpha|^2 + |\beta|^2 = 1$. In order to help Bob or Carol prepare the state $|\phi\rangle$, she performs a projective measurement on atom 1 in the 'qubit basis' $\{|\psi\rangle_1, |\psi_\perp\rangle_1\}$,[3] which is related to the computation basis$\{|g\rangle_1, |e\rangle_1\}$

$$|\psi\rangle_1 = \alpha|g\rangle_1 + \beta|e\rangle_1, \tag{5}$$

and

$$|\psi_\perp\rangle_1 = \alpha|e\rangle_1 - \beta^*|g\rangle_1. \tag{6}$$

Then the W-class state can be rewritten as

$$\begin{aligned} &|W\rangle_{123} \\ &= \frac{1}{2}[(\alpha|\psi\rangle_1 - \beta|\psi_\perp\rangle_1)|ge\rangle_{23} + (\alpha|\psi\rangle_1 \\ &\quad -\beta|\psi_\perp\rangle_1)|eg\rangle_{23} + \sqrt{2}(\beta^*|\psi\rangle_1 + \alpha|\psi_\perp\rangle_1)|gg\rangle_{23}] \\ &= \frac{1}{2}[|\psi\rangle_1(\alpha|ge\rangle_{23} + \alpha|eg\rangle_{23} + \sqrt{2}\beta^*|gg\rangle_{23}) \\ &\quad +|\psi_\perp\rangle_1(-\beta|ge\rangle_{23} - \beta|eg\rangle_{23} + \sqrt{2}\alpha|gg\rangle_{23})]. \end{aligned} \tag{7}$$

Now Alice performs a single-qubit measurement on atom 1, and the outcome $|\psi_\perp\rangle_1$ reduces atoms 2 and 3 to the state of $(-\beta|ge\rangle_{23} - \beta|eg\rangle_{23} + \sqrt{2}\alpha|gg\rangle_{23})$. As is known, the nonclone theorem allows only one of the atoms to be in the original state. Thus, in order to construct the initial state, Bob and Carol must cooperate with each other. In the usual protocol, Bob can ask Carol to make the projective measurement on his atom in the atomic basis. Apparently, in our scheme Bob cannot reconstruct the initial state no matter what results Carol has obtained. Here, in order to construct the initial state, we assume that Carol agrees to send his atom to Bob and lets Bob reconstruct the initial state. First, Bob performs the rotation $|e\rangle_2 \rightarrow \mathrm{i}|e\rangle_2$ on atom 2, leading to $(-\beta|ge\rangle_{23} - \mathrm{i}\beta|eg\rangle_{23} + \sqrt{2}\alpha|gg\rangle_{23})$. Then he lets atoms 2 and 3 simultaneously interact with a single-mode cavity field C_2. In the interaction picture, the interaction Hamiltonian of the system is

$$H_i = g_2 \sum_{j=2}^{3} \left(\mathrm{e}^{-\mathrm{i}\delta t} a_2^\dagger S_j^- + \mathrm{e}^{\mathrm{i}\delta t} a_2 S_j^+ \right), \tag{8}$$

where $S_j^+ = |e_j\rangle\langle g_j|$, $S_j^- = |g_j\rangle\langle e_j|$ with $|g_j\rangle$ and $|e_j\rangle (j = 2, 3)$ being the ground and the excited states of the jth atom; $a_2^\dagger$ and a_2 are the creation and annihilation operators of the cavity mode; g_2 is the atom–cavity coupling strength; δ is the detuning between the atomic transition frequency ω_0 and the cavity field frequency ω. In the case of $\delta \gg g_2$, there is no energy exchange between the atomic system and the cavity. Then the effective Hamiltonian is[17]

$$H = \lambda \Bigg[\sum_{j=2}^{3} \left(|e_j\rangle\langle e_j| a_2 a_2^\dagger - |g_j\rangle\langle g_j| a_2^\dagger a_2 \right) + S_2^+ S_3^- + S_2^- S_3^+ \Bigg], \tag{9}$$

where $\lambda = g_2^2/\delta$. Assume that initially the cavity field is in a vacuum state, then the Hamiltonian will reduce to

$$H = \lambda \left(\sum_{j=2}^{3} |e_j\rangle\langle e_j| + S_2^+ S_3^- + S_2^- S_3^+ \right). \tag{10}$$

Choosing the interaction time $\lambda t = \dfrac{\pi}{4}$, the evolution of different initial states goes as follows:

$$|eg\rangle_{23} \rightarrow \frac{1}{\sqrt{2}} \mathrm{e}^{-\mathrm{i}\frac{\pi}{4}} (|eg\rangle_{23} - \mathrm{i}|ge\rangle_{23}), \tag{11}$$

$$|ge\rangle_{23} \rightarrow \frac{1}{\sqrt{2}} \mathrm{e}^{-\mathrm{i}\frac{\pi}{4}} (|ge\rangle_{23} - \mathrm{i}|eg\rangle_{23}), \tag{12}$$

$$|gg\rangle_{23} \rightarrow |gg\rangle_{23}, \tag{13}$$

$$|ee\rangle_{23} \rightarrow \frac{1}{\sqrt{2}} \mathrm{e}^{-\mathrm{i}\frac{\pi}{2}} |ee\rangle_{23}, \tag{14}$$

leading to the following transformation:

$$\left(-\beta|ge\rangle_{23} - \mathrm{i}\beta|eg\rangle_{23} + \sqrt{2}\alpha|gg\rangle_{23}\right) \rightarrow \left(-\sqrt{2}\beta \mathrm{e}^{-\mathrm{i}\frac{\pi}{4}} |ge\rangle_{23} + \sqrt{2}\alpha|gg\rangle_{23}\right). \tag{15}$$

After performing the rotation $|e\rangle_3 \rightarrow \mathrm{e}^{-\mathrm{i}\frac{3\pi}{4}}|e\rangle_3$ on atom 3, Bob can reconstruct an unknown state on atom 3. If Bob wants to reconstruct the original state $|\phi\rangle$ on atom 2, first he performs the rotation $|e\rangle_2 \rightarrow -\mathrm{i}|e\rangle_2$ on atom 2, leading to $-\beta|ge\rangle_{23} + \mathrm{i}\beta|eg\rangle_{23} + \sqrt{2}\alpha|gg\rangle_{23}$, and then he lets atoms 2 and 3 simultaneously interact with the single-mode cavity field C_2. With the choice of the interaction time $\lambda t = \dfrac{\pi}{4}$, he can obtain the unitary transformation as follows:

$$\left(-\beta|ge\rangle_{23} + \mathrm{i}\beta|eg\rangle_{23} + \sqrt{2}\alpha|gg\rangle_{23}\right) \rightarrow \left(\sqrt{2}\mathrm{i}\beta \mathrm{e}^{-\mathrm{i}\frac{\pi}{4}} |eg\rangle_{23} + \sqrt{2}\alpha|gg\rangle_{23}\right). \tag{16}$$

After performing the rotation $|e\rangle_2 \rightarrow \mathrm{e}^{-\mathrm{i}\frac{\pi}{4}}|e\rangle_2$, Bob can construct the initial state $|\phi\rangle$ on atom 2. It is noted that Bob can also remotely prepare a two-qubit entangled state $|\psi\rangle = \alpha|gg\rangle_{23} + \beta|ee\rangle_{23}$ on atoms 2 and 3. When Bob obtains the state of atoms 2 and 3 as $\beta|eg\rangle_{23} + \alpha|gg\rangle_{23}$ or $\beta|ge\rangle_{23} + \alpha|gg\rangle_{23}$ he can make a CNOT operation, where atom 2 or 3 acts as a control bit while atom 3 or 2 is a target bit, and then he can reconstruct an initial two-qubit entangled state.

In addition, if the outcome of Alice's measurement on atom 1 is $|\psi\rangle_1$, the W-class state will reduce to $(\alpha|ge\rangle + \alpha|eg\rangle + \sqrt{2}\beta^*|gg\rangle)$. After a unitary transformation in Eq.(15) or (16) Bob can obtain $\alpha|ge\rangle + \beta^*|gg\rangle$ or $\alpha|eg\rangle + \beta^*|gg\rangle$, and he cannot convert this state of atom 2 or 3 into the desired single-qubit state, for it involves an antiunitary operation.[3] However, if the single-qubit state $|\phi\rangle$ is a real qubit chosen from the polar line or a qubit chosen from the equatorial line on Bloch sphere,[3] Bob can still construct the specially chosen qubit with the prior shared entanglement and the classical information from Alice. Then the total probability of RSP of the special ensemble of qubits is 1, which is the same as the probability of the teleportation scheme.[30,31] In our scheme, either Bob or Carol can recover the initial state on his own atom. The total information cost is paid for a classical bit from Alice and a qubit from one of the two receivers. Following the teleportation scheme, we

assume that the total system only includes two participants: one is the sender (Alice who has only one qubit) and the other is the receiver (Bob or Carol who has two qubits). In this case the total information cost is paid only for one classical bit, which is one bit and its cost is less than that in the teleportation scheme with three-qubit W-class state.[30,31] In Ref.[11] Liu and Wang used the maximally entangled W state as a shared entanglement source. However, the successful probability is only 2/3 and the classical information cost is paid for 2 bits.

In our scheme the total probability of RSP of a special two-qubit entangled state is also 1 and the classical information cost is paid only for one bit (where we assume there to be only one receiver who has two qubits). Comparing our scheme with the teleportation scheme,[33] we need only a single-qubit measurement (Bell-state measurement in the teleportation) and the classical information cost is paid for two bits, less than that in the teleportation scheme. In Ref.[9] the authors proposed to remotely prepare a two-qubit entangled state with two EPR pairs. However, the sender must make a two-qubit projective measurement (which is more complex than the single-qubit measurement) and the classical information cost is paid for two bits, i.e. the cost if paid for one bit more than that in our scheme.

3. Remote state preparation with multiqubit W-class state

The previous scheme can be easily generalized to the multiqubit case. We assume that Alice and the $(n-1)$ receivers share the n-qubit W-class state as follows:[34]

$$\begin{aligned}&|W\rangle_{12\ldots n}\\ =\ &\frac{1}{2^{(n-1)/2}}(|e_1g_2\ldots g_n\rangle+|g_1e_2g_3\ldots g_n\rangle\\ &+\sqrt{2}|g_1g_2e_3g_4\ldots g_n\rangle+\cdots\\ &+2^{(n-2)/2}|g_1\ldots g_{n-1}e_n\rangle),\end{aligned}\tag{17}$$

where Alice has qubit n, and each receiver owns one qubit. It is noted that this n-qubit W-class state can be easily prepared with a similar procedure in Section 2.[34] Now Alice wants to help either of the receivers, say Bob, remotely prepare the single-qubit state $|\phi\rangle$, which is known to Alice but unknown to Bob. Then in the 'qubit basis' the n-qubit W-class state can be rewritten as

$$\begin{aligned}|W\rangle_{12\ldots n}\ =\ &\frac{1}{2^{(n-1)/2}}[(\alpha|\psi\rangle_n-\beta|\psi_\perp\rangle_n)(|e_1g_2\ldots g_{n-1}\rangle+|g_1e_2g_3\ldots g_{n-1}\rangle+\sqrt{2}|g_1g_2e_3g_4\ldots g_{n-1}\rangle\\ &+\cdots+2^{(n-3)/2}|g_1\ldots g_{n-2}e_{n-1}\rangle)+2^{(n-2)/2}(\beta^*|\psi\rangle_n+\alpha|\psi_\perp\rangle_n)|g_1\ldots g_{n-1}\rangle]\\ =\ &\frac{1}{2^{(n-1)/2}}\{|\psi\rangle_n[\alpha(|e_1g_2\ldots g_{n-1}\rangle+|g_1e_2g_3\ldots g_{n-1}\rangle+\sqrt{2}|g_1g_2e_3g_4\ldots g_{n-1}\rangle+\cdots\\ &+2^{(n-3)/2}|g_1\ldots g_{n-2}e_{n-1}\rangle)+2^{(n-2)/2}\beta^*|g_1\ldots g_{n-1}\rangle]+|\psi_\perp\rangle_n[-\beta(|e_1g_2\ldots g_{n-1}\rangle\\ &+|g_1e_2g_3\ldots g_{n-1}\rangle+\sqrt{2}|g_1g_2e_3g_4\ldots g_{n-1}\rangle+\cdots+2^{(n-3)/2}|g_1\ldots g_{n-2}e_{n-1}\rangle)\\ &+2^{(n-2)/2}\alpha|g_1\ldots g_{n-1}\rangle]\}.\end{aligned}\tag{18}$$

In order to help the receiver prepare the state $|\phi\rangle$, Alice performs a projective measurement on atom n, and the outcome $|\psi_\perp\rangle_n$ reduces the rest of atoms to the following state:

$$\begin{aligned}&\frac{1}{2^{(n-1)/2}}\big[-\beta(|e_1g_2\ldots g_{n-1}\rangle+|g_1e_2g_3\ldots g_{n-1}\rangle\\ &+\sqrt{2}|g_1g_2e_3g_4\ldots g_{n-1}\rangle+\cdots+2^{(n-3)/2}|g_1\ldots\\ &g_{n-2}e_{n-1}\rangle)+2^{(n-2)/2}\alpha|g_1\ldots g_{n-1}\rangle\big].\end{aligned}\tag{19}$$

We assume that the $(n-1)$ receivers cooperate with each other and agree to send their qubits to Bob. If Bob wants to prepare the original state $|\phi\rangle$ on atom 1, he can make the unitary transformations as follows:

$$\begin{aligned}&\frac{1}{2^{(n-1)/2}}\big[-\beta(|e_1g_2\ldots g_{n-1}\rangle+|g_1e_2g_3\ldots g_{n-1}\rangle\\ &+\sqrt{2}|g_1g_2e_3g_4\ldots g_{n-1}\rangle+\cdots+2^{(n-3)/2}|g_1\ldots\\ &\times g_{n-2}e_{n-1}\rangle)+2^{(n-2)/2}\alpha|g_1\ldots g_{n-1}\rangle]\\ \rightarrow\ &-\beta|e_1g_2\ldots g_{n-1}\rangle+\alpha|g_1\ldots g_{n-1}\rangle.\end{aligned}\tag{20}$$

Then he can achieve the state of $(n-1)$ atoms as $-\beta|e_1g_2\ldots g_{n-1}\rangle+\alpha|g_1\ldots g_{n-1}\rangle$. By performing a unitary operation σ_z on atom 1, Bob can construct

the initial state $|\phi\rangle$. On the other hand, suppose that Bob wants to reconstruct the initial state on the atom i, what he needs to do is make the similar unitary transformations as follows:

$$\begin{aligned}&\frac{1}{2^{(n-1)/2}}[-\beta(|e_1g_2\ldots g_{n-1}\rangle+|g_1e_2g_3\ldots g_{n-1}\rangle\\&+\sqrt{2}|g_1g_2e_3g_4\ldots g_{n-1}\rangle+\cdots+2^{(n-3)/2}|g_1\ldots\\&\times g_{n-2}e_{n-1}\rangle)+2^{(n-2)/2}\alpha|g_1\ldots g_{n-1}\rangle]\\\rightarrow\ &-\beta|g_1\ldots g_{i-1}e_ig_{i+1}\ldots g_{n-1}\rangle+\alpha|g_1\ldots g_{n-1}\rangle.\end{aligned}\tag{21}$$

Then he can obtain the state of $(n-1)$ atoms as $-\beta|g_1\ldots g_{i-1}e_ig_{i+1}\ldots g_{n-1}\rangle+\alpha|g_1\ldots g_{n-1}\rangle$. By performing a unitary operation σ_z on atom i, he can also construct the initial state $|\phi\rangle$. Here, Bob can also remotely prepare the m-qubit entangled state $|\psi\rangle_m=\alpha|g_1\ldots g_m\rangle+\beta|e_1\ldots e_m\rangle(m\leq n-1)$. When Bob obtains the state of $(n-1)$ atoms as $-\beta|g_1\ldots g_{i-1}e_ig_{i+1}\ldots g_{n-1}\rangle+\alpha|g_1\ldots g_{n-1}\rangle$, he can make a series of CNOT operations, where atom i acts as a control bit while the other $(m-1)$ atoms are target bits. After performing a unitary operation σ_z on atom i Bob can reconstruct the desired m-qubit entangled state. It is noted that the classical information cost is the same as that in the case of three-qubit W-class state. The key step to implement this scheme is the transformations in Eqs.(20) and (21), which can be realized with a similar procedure to that in cavity QED as shown in Section 2.[34]

4. Conclusion

In this paper we have proposed a simple scheme to remotely prepare a single-qubit state and a two-qubit entangled state with a three-qubit W-class state in cavity QED. We also generalize this idea to a multiqubit W-class state. It has been shown that the classical information cost in our scheme is less than that in the corresponding teleportation scheme and only a single-qubit projective measurement is needed. The interesting feature of our scheme is that the classical information cost does not increase with the number of qubits increasing and either of the receivers can reconstruct the initial state on either of the atoms. As is known, the maximally entangled W state is not suitable for perfect teleportation[29] and the RSP.[11] The best successful probability is 2/3 for the RSP of a specially chosen state.[9,11] But in our scheme the non-maximally entangled W-class state can be chosen for the perfect RSP of a special single-qubit state and multiqubit entangled state due to the fact that there exists an ebit entanglement between the two subsystems if we divide the W-class state into two appropriate subsystems.[20] So this W-class state combines the advantage of the EPR pair and the W-class state. It may be competent for completing the tasks of both the EPR pair and W state. In our scheme the key step is to implement the transformations as shown in Eqs.(15), (16), (20) and (21) in cavity QED. In this process we do not require the transfer of quantum information between the atoms and cavity due to large detuning between the atomic transition frequency and the cavity frequency, thus it is insensitive to the cavity decay, which is very important in view of experiment.

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