Vol 17 No 9, September 2008
1674-1056/2008/17(09)/3217-03

Chinese Physics B

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Generation of four-photon W state via cavity QED*

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(Received 20 August 2007; revised manuscript received 16 November 2007)

This paper proposes an alternative scheme for generating four-photon W state via cavity QED. The scheme bases on the resonant interaction of a Λ-type three level atom with two bimodal cavities. The detection of atom collapses the cavity to the desired state. Comparing with previous schemes, the advantage of this scheme is that the interaction time can be greatly shortened since it uses the resonant interaction between atom and cavities. Moreover, the proposed scheme is more experimentally feasible than the previous ones.

Keywords: W state, resonant interaction
PACC: 0367, 4250

Entanglement is not only the most striking feature of quantum mechanics, but also an important physical resource in quantum information processing (QIP), such as quantum teleportation,[1] quantum dense coding,[2] and quantum cryptography.[3] Recently, multiparticle entanglement has attracted much interest due to its potential applications in QIP. The analysis of entanglement and its properties for multiparticle states are much more complex than that of biparticle states. In Ref.[4], the authors have proved that there exists another kind of genuine triparticle entangled state such as $W = \left(1/\sqrt{3}\right)\left(|001\rangle + |010\rangle + |100\rangle\right)$, which is inequivalent to the GHZ state in the sense that they cannot be converted to each other even under stochastic local operations and classical communication (SLOCC).[5]

Numerous proposals have been proposed to generate W state in cavity QED.[6−13] As described in Ref.[6], atoms, interacting with a nonresonant single-mode cavity, can be entangled through virtual excitation of the cavity mode, which can reduce the quality requirement of the cavity. However, the scheme requires that the atom–cavity coupling strength is much smaller than the detuning between atomic transition frequency and cavity frequency, which restricts the operation speed. Guo and Zhang[7] have proposed a scheme to generate both the three-atom W state and three-cavity W state via resonant cavity QED. The disadvantage of this scheme is that it requires that the atom interacts with the cavity with different interaction time. Yu *et al*[9] have given another scheme for the preparation of three distant atoms in W state which are trapped in three cavities. The advantages of the scheme are robustness against detection inefficiency and asynchronous emission of the photons. However, the scheme also requires a multi-cavity and multi-atom system. In Ref.[10], the W state is investigated by adiabatic passages and decoherence free subspace. Zou *et al*[11] have presented a scheme to generate a four-photon W state. This scheme requires four atoms and four single-mode optical cavities. Moreover, the proposed scheme requires linear optical elements and photon detectors with single-photon sensitivity. Recently, Deng *et al*[12] have proposed a scheme to generate an n-qubit W state, which based on the atoms simultaneously interacting with a single-mode cavity field. The drawback of this method requires that n atoms must be absolutely simultaneously sent through the cavity. It is experimentally problematic since the manipulation on atoms is difficult under the current technology.

In this paper, we propose an alternative scheme to generate four-photon W state via resonant cavity QED. In this scheme, we only employ a Λ-type three level atom and two bimodal cavities. Compared with the scheme in Ref.[6], we find that our scheme is much faster due to the resonant interaction. Moreover, the proposed scheme is more experimentally feasible because we only employ one atom and two cavities, while in Refs.[7,9,12] multi-atom and multi-cavity are re-

*Project supported by National Natural Science Foundation of China (Grant No 10674025) and the Development Funds of Fuzhou University of China (Grant No 2007-XY-15).
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quired. In principle, the scheme can be extended to generate a $2n$-photon W state.

The resonant interaction of a Λ-type three-level atom with a bimodal cavity field is shown in Fig.1.

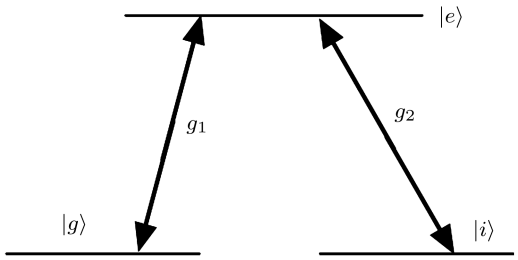


Fig.1. Schematic diagram of the λ-type three level atom coupling to a two-mode field ($|e\rangle$ is the upper level of the atom, $|g\rangle$ and $|i\rangle$ are the lower levels of the atom, g_1, g_2 are the coupling coefficients).

The interaction Hamiltonian for such a system can be described as ($\hbar = 1$)[14−16]

$$\begin{aligned} H_{\rm I} = \; & g(a_1^+|g\rangle\langle e| + a_1|e\rangle\langle g|) \\ & +g(a_2^+|i\rangle\langle e| + a_2|e\rangle\langle i|), \end{aligned} \tag{1}$$

where $|e\rangle$, $|g\rangle$ and $|i\rangle$ denote the states of the atom. a_i^+ and a_i ($i = 1, 2$) are the creation and annihilation operators for the cavity fields, respectively, $g = g_1 = g_2$ is the coupling constant of the interaction of atom with the cavity mode.

Assume that the cavities are initially prepared in the vacuum state $|0,0\rangle_1 |0,0\rangle_2$. Now we send the atom initially prepared in the state

$$\left|\Psi_a^1\right\rangle = |e\rangle \tag{2}$$

through the first cavity, after an interaction time t_1, the atom–cavity system evolves into the state:

$$|\Psi(t_1)\rangle = \frac{1}{\sqrt{2}}\left[\cos(\sqrt{2}gt_1)\,|e\rangle\,|0,0\rangle_1 - \frac{\mathrm{i}}{\sqrt{2}}\sin(\sqrt{2}gt_1)\,[|g\rangle\,|1,0\rangle_1 + |i\rangle\,|0,1\rangle_1]\right]|0,0\rangle_2\,. \tag{3}$$

Then we let the atom pass through the second cavity, and after an interaction time t_1' the atom–cavity system evolves into the state

$$\begin{aligned} |\Psi(t_1')\rangle = \; & \cos(\sqrt{2}gt_1)\,|0,0\rangle_1\,[\cos(\sqrt{2}gt_1')\,|e\rangle\,|0,0\rangle_2 - \frac{\mathrm{i}}{\sqrt{2}}\sin(\sqrt{2}gt_1')\,|g\rangle\,|1,0\rangle_2 \\ & -\frac{\mathrm{i}}{\sqrt{2}}\sin(\sqrt{2}gt_1')\,|i\rangle\,|0,1\rangle_2] - \frac{\mathrm{i}}{\sqrt{2}}\sin(\sqrt{2}gt_1)\,[|g\rangle\,|1,0\rangle_1 + |i\rangle\,|0,1\rangle_1]\,|0,0\rangle_2\,. \end{aligned} \tag{4}$$

If the interaction time is chosen such as $\sqrt{2}gt_1 = \dfrac{\pi}{4}$, $\sqrt{2}gt_1' = \dfrac{\pi}{2}$, the atom–cavity system reads

$$\left|\Psi(t_1')\right\rangle = -\frac{\mathrm{i}}{2}\left[g\,|0,0\rangle_1\,|1,0\rangle_2 + \mathrm{i}\,|0,0\rangle_1\,|0,1\rangle_2\right] - \frac{\mathrm{i}}{2}\left[g\,|1,0\rangle_1\,|0,0\rangle_2 + \mathrm{i}\,|0,1\rangle_1\,|0,0\rangle_2\right]. \tag{5}$$

Then let the atom pass through a classical field, where it undergoes the transitions

$$|g\rangle \to \frac{1}{\sqrt{2}}\left(|g\rangle + |i\rangle\right), \quad |i\rangle \to \frac{1}{\sqrt{2}}\left(|i\rangle - |g\rangle\right). \tag{6}$$

Then the atom–cavity field system evolves into the state

$$\begin{aligned} |\Psi_1\rangle = \; & -\frac{\mathrm{i}}{2}\left[\frac{1}{\sqrt{2}}\left(|i\rangle + |g\rangle\right)|0,0\rangle_1\,|1,0\rangle_2 + \frac{1}{\sqrt{2}}\left(|i\rangle - |g\rangle\right)|0,0\rangle_1\,|0,1\rangle_2\right] \\ & -\frac{\mathrm{i}}{2}\left[\frac{1}{\sqrt{2}}\left(|i\rangle + |g\rangle\right)|1,0\rangle_1\,|0,0\rangle_2 + \frac{1}{\sqrt{2}}\left(|i\rangle - |g\rangle\right)|0,1\rangle_1\,|0,0\rangle_2\right]. \end{aligned} \tag{7}$$

We can perform a measurement on the atom, if the atom is detected in the state $|i\rangle$ or $|g\rangle$, the cavity field collapses onto the following state, respectively,

$$|\Psi\rangle_i = \frac{-\mathrm{i}}{2\sqrt{2}}\;\left(|1,0\rangle_1\,|0,0\rangle_2 + |0,1\rangle_1\,|0,0\rangle_2 + |0,0\rangle_1\,|1,0\rangle_2 + |0,0\rangle_1\,|0,1\rangle_2\right), \tag{8}$$

$$|\Psi\rangle_g = \frac{-\mathrm{i}}{2\sqrt{2}}\;\left(|1,0\rangle_1\,|0,0\rangle_2 - |0,1\rangle_1\,|0,0\rangle_2 + |0,0\rangle_1\,|1,0\rangle_2 - |0,0\rangle_1\,|0,1\rangle_2\right). \tag{9}$$

Now the states $|\Psi\rangle_i$ and $|\Psi\rangle_g$ are in the four-photon W state. The probability of success to generate $|\Psi\rangle_i$ or $|\Psi\rangle_g$ is 0.5.

We briefly discuss the experimental feasibility of the proposed scheme. For Rydberg atoms with principal quantum numbers 50, 51 and 52, the radiative time is $T_{\rm r} = 30\,{\rm ms}$. In the experiment reported in Ref.[17], the photon lifetime in the cavity is $T_{\rm c} = \dfrac{Q}{2\pi\upsilon} \simeq 130\,{\rm ms}$. Set $g = 2\pi\times 25\,{\rm kHz}$. Thus we have the interaction $t_1 = \dfrac{\pi}{4\sqrt{2}g} = 3.5\,\mu{\rm s}$, $t_2 = \dfrac{\pi}{2\sqrt{2}g} = 7\,\mu{\rm s}$. Considering the travelling time of atom, we have the total time which is about $105\,\mu{\rm s}$, which is much shorter than the $T_{\rm r}$ or $T_{\rm c}$. Therefore, there is sufficient time to complete the procedure. Moreover, with the improvement of technology, higher Q cavities might be available, the proposed scheme might be realizable.

In summary, we have proposed a method to generate a four-photon W state via cavity QED. In the scheme, a Λ-type three-level atom is sent through two bimodal cavities orderly to resonantly interact with the cavities. One of the advantages of the proposed scheme is that the interaction time can be greatly shortened, which is very important in the view of decoherence. Moreover, the scheme is more experimentally feasible than the previous ones. In principle, the scheme can be extended to generate a $2n$-photon W state.

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