Vol 17 No 1, January 2008
1674-1056/2008/17(01)/0049-06

Chinese Physics B

© 2008 Chin. Phys. Soc.
and IOP Publishing Ltd

Cavity loss induced generation of W states

Wu Huai-Zhi(吴怀志), Yang Zhen-Biao(杨贞标), Su Wan-Jun(苏万钧), Zhong Zhi-Rong(钟志荣), and Zheng Shi-Biao(郑仕标)†

Department of Electronic Science and Applied Physics, Fuzhou University, Fuzhou 350002, *China*

(Received 4 February 2007; revised manuscript received 27 April 2007)

The existence of decoherence-free subspace (DFS) has been discussed widely. In this paper, we propose an alternative scheme for generating the four-atom W states by manipulating DF qubits. The atoms are divided into two pairs and trapped in two separate optical cavities. Manipulation of atoms within DFS may generate a two-atom maximally entangled state in an individual cavity, which is a stable state. After driving the system out of DFS, the atoms will interact resonantly with the cavity field. The photons leaking from the cavities interfere at the beamsplitter, which destroys which-path information, and are finally detected by one of the detectors, leading to the generation of a W state. In addition, the numerical simulation indicates that the fidelity of the prepared state can, for a very wide parameter regime, be very close to unity.

Keywords: decoherence-free subspace, leakage of photons, W states
PACC: 0367, 0365, 4250

1. Introduction

Entanglement plays an important role in many of the most interesting applications of quantum mechanics in the development of quantum computation and quantum information.[1] It is the main point of the debate in foundation issues and interpretation of quantum mechanics. In recent years, many efforts have been made to characterize qualitatively and quantitatively the entanglement of multiparticle systems. Multiparticle maximally entangled states are referred to as Greenberger–Horne–Zeilinger (GHZ) states.[2] Three-photon GHZ entanglement has been used to verify quantum nonlocality.[3] Multiparticle GHZ states have also been experimentally realized for three Rydberg atoms and trapped ions.[4,5] On the other hand, Dür *et al* have shown that there are two inequivalent classes of tripartite entanglement states, i.e., the GHZ class and the W class, under stochastic local operation and classical communication.[6] The W state is not a maximally entangled state, but it has the highest robustness against the loss of one qubit. Fundamentally, differences between the violations of local environment exhibited by the GHZ and W states are illustrated by Cabello by considering a different set of Bell inequalities.[7] However, W states can also be used to test quantum nonlocality without inequality.[8] Several applications in quantum information processing by exploiting W states have also been proposed, such as quantum teleportation,[9] quantum secure communication,[10] and quantum information splitting.[11] With regard to the useful applications of the W entangled state, it follows that the preparation and generation of the state are becoming increasingly important. Schemes for generating such states for three or more atoms in cavity QED and ion trap systems have been proposed.[12−16] However, none of these schemes has been experimentally realized.

The main limiting factor on generating W states is decoherence. To avoid decoherence it has been proposed that decoherence-free (DF) states can be used as qubits. The existence of decoherence-free subspaces (DFS) has been discussed widely in the literature by several authors.[17−22] These subspaces arise if a system processes states which do not interact with the environment. In addition, the system's own time evolution must not drive the states out of the DFS. Recently, the existence of DFSs for photon states has been verified experimentally by Kwiat *et al*[23] and for the states of trapped ions by Kielpinski *et al*.[24] On the other hand, Beige *et al*,[25] Tregenna *et al*,[26] and more recently, Pachos *et al*[27] have theoretically shown how to manipulate a system inside a DFS by making use of environment induced quantum Zeno effect. The system behaves as if it were under continu-

†E-mail: sbzheng@pub5.fz.fj.cn

ous observation as to whether it is in a DF state or not. Initially in a DF state, the system remains DF with a probability very close to unity. In this paper, we propose an alternative scheme for generating four-atom W states by manipulating DF qubits. The atoms are divided into two pairs and trapped in two optical cavities respectively, as shown in Fig.1.[28] Initially, the atoms all in ground state and the cavities are in their

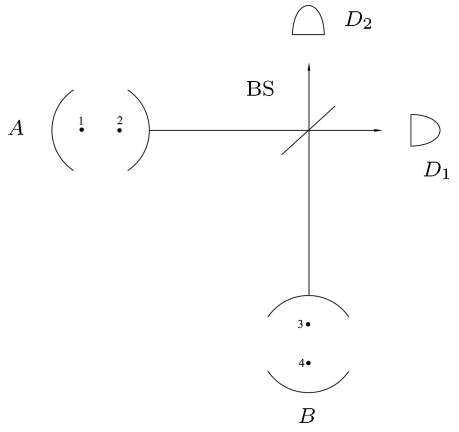


Fig.1. The experimental setup. Four atoms are divided into two pairs and trapped in two separate optical cavities. Photons can leak though the sides of the cavities facing the beamsplitter BS and then detected by the photondetectors D_1 and D_2.

vacuum state. In this case, the system state is a DF state. The system evolves into another DF state at time T under the action of weak laser pulses. Then we drive the system state out of DFS. Photons are allowed to leak from both cavities and mixed in a beam-splitter, which destroys the which-path information. Finally, the photons are detected by the photondetectors D_1 and D_2, and then the atoms collapse to a W state.

The paper is organized as follows. Section 2 describes the generation of maximally entangled states with the system manipulated in DFS, which was discussed in detail by Beige *et al.*[21] In order to force the atoms to interact with cavity fields, a strong laser pulse is used, which is presented in Section 3. The detection of photons leaking from the cavities after the atom–cavity interaction leads to the generation of W state. In Section 4 we offer the numerical results by considering the uncertainty of the atoms' initial position and the effect of the atomic spontaneous emission rate. Finally, we summarize our results in Section 5.

2. Atoms (Ions) in DFS

We first consider a system consisting of two metastable two-level atoms (or ions) confined to fixed positions inside an optical cavity, which can be implemented using the current technology of the recent calcium ion experiment.[29−31] We assume that the distance between the atoms is much larger than an optical wavelength and therefore dipole–dipole interactions can be neglected. In addition, this requirement allows us to assume that each atom can be individually addressed with laser light. To describe the time evolution of the system we will make use of quantum jump approach. This method gives the time evolution under the condition that no photon is emitted, as well as the probability for no photon emission, $P_1(t)$. The system is described by a non-Hermite Hamiltonian which can be evaluated by second-order perturbation theory and is given by

$$H_{\rm cond} = (\mathrm{i}\hbar \sum_{i=1}^{2} g_i b\sigma_i^+ + \mathrm{h.c.}) - \mathrm{i}\hbar\Gamma \sum_{i=1}^{2} \sigma_i^+\sigma_i - \mathrm{i}\hbar\kappa b^+ b, \tag{1}$$

where $\sigma_i = |1\rangle_{ii}\langle 2|$ is the atomic lowering operator, $|1\rangle_i$ and $|\,2\rangle_i$ denote the ground and the excited state of atom i $(i = 1, 2)$, respectively, and b denotes the annihilation operator for the cavity mode. The atoms coupling to the cavity field with a coupling strength denoted by g_i. A photon inside the cavity leaks out through the cavity mirrors with a rate denoted by κ. The atomic spontaneous emission rate is denoted by Γ. In what follows, we assume that the couplings of the atoms to the cavity mode are equal, but the scheme presented here can also be carried over to more general case, which is discussed in Section 4 by numerical simulation. If at $t = 0$ the state of the system is $|\,\Psi(0)\rangle$, the state at time t is given by

$$|\,\Psi(t)\rangle = \mathrm{e}^{-\mathrm{i}H_{\rm cond}t/\hbar}|\,\Psi(0)\rangle. \tag{2}$$

The probability $P_1(t)$ of observing no photon up to time t by a broadband detector of unit efficiency is given by the squared norm

$$P_1(t) = \langle\,\Psi(t)|\,\Psi(t)\rangle. \tag{3}$$

According to the above analyses, a necessary and sufficient criterion for establishing DFS can be found, which is described as[21]

$$P_1(t) \equiv 1 \;\forall\; t \geq 0, \tag{4}$$

and

$$J_-|\varphi\rangle \equiv \sum_{i=1}^{2} |1\rangle_{ii}\langle 2|\varphi\rangle = 0, \tag{5}$$

where $|\varphi\rangle$ is the atomic state. Thus, with regard to DF states, besides the superpositions of atomic ground states $|g\rangle = |1\rangle_1|1\rangle_2$ the atoms inside the cavity can also be in a superposition with the trapped state $|a\rangle = \frac{1}{\sqrt{2}}(|1\rangle_1|2\rangle_2 - |2\rangle_1|1\rangle_2)$, a maximally entangled state of the two atoms, and the cavity is in the vacuum state $|0\rangle$. If the system is initially in a DF state, it remains in this state with a probability very close to unity. In order to manipulate the state inside the DFS a weak interaction must be used. As long as the interaction is weak enough, the state of the system dose not move out of DFS. Now a weak laser is applied and the conditional Hamiltonian of the system can be written as

$$H_{\rm cond} = (\mathrm{i}\hbar g \sum_{i=1}^{2} b\sigma_i^+ + \mathrm{h.c.}) + H_{\rm laser} - \mathrm{i}\hbar\Gamma \sum_{i=1}^{2} \sigma_i^+\sigma_i - \mathrm{i}\hbar\kappa b^+ b, \tag{6}$$

where

$$H_{\rm laser} = \mathrm{i}\hbar \sum_{i=1}^{2} \Omega_i \sigma_i^+ + \mathrm{h.c.}$$

Consider the condition

$$\Gamma \ll \Omega_i \ll \frac{g^2}{\kappa} \text{ and } \kappa. \tag{7}$$

After an interaction time t, the system, initially in the state $|\Psi(0)\rangle = |0g\rangle$, will evolve to

$$|\Psi(t)\rangle = \mathrm{e}^{-(k_1+k_2)t/2}\left[(\cos(St) - \frac{k_1-k_2}{2S}\sin(St))|0g\rangle - \mathrm{i}\frac{\Omega_-^*}{S}\sin(St)|0a\rangle\right], \tag{8}$$

where $k_1 = \frac{|\Omega_+|^2\kappa}{2g^2}$, $k_2 = \frac{|\Omega_-|^2(\kappa^2+2g^2)}{2g^2\kappa}$, $S = |\Omega_-|\left[1-(\frac{k_1-k_2}{2|\Omega_-|})^2\right]^{\frac{1}{2}}$, $\Omega_\pm = \frac{(\Omega_1 \pm \Omega_2)}{2\sqrt{2}}$. All terms much smaller than $\frac{\Omega\kappa}{g^2}$, $\frac{\Omega}{\kappa}$ and $\frac{\Gamma}{\Omega}$ have been neglected. We simultaneously switch off the weak laser when the interaction time $t = T = \frac{1}{S}\,\mathrm{arccot}(\frac{k_1-k_2}{2S})$, then the atoms are prepared in the maximally entangled state $|a\rangle$, which is a stable state. The success probability of this step is given by

$$P_1(T) = \mathrm{e}^{-(k_1+k_2)T}\left|\frac{\Omega_-}{S}\sin(ST)\right|^2, \tag{9}$$

which is correlated to the coupling strength of atoms in the weak lasers and cavity field, as well as to the cavity decay rate. We will discuss how these parameters affect the probability in Section 4 by numerical simulation. Actually, we can interpret the sum $(k_1 + k_2)$ as the decay rate of the system. As long as this rate is much smaller than $\frac{1}{T}$, the probability is close to unity. Besides, the fidelity of the prepared state F_1, for a very wide parameter regime, is very close to unity. Note that the same DF states now are prepared in both optical cavities via the process described above, the experimental setup is shown in Fig.1.

3. Dynamical evolution of the system out of DFS

According to Section 2 we have known that $|a\rangle$ is a stable DF state and the system cannot evolve without extra interaction. This case is changed when a strong classical laser irradiates one atom. We first take the atoms trapped in cavity A into account. By controlling the phases of the classical fields and interaction time appropriately, we obtain the required transformation

$$|1\rangle_i \to |1\rangle_i,\ |2\rangle_i \to -|2\rangle_i,\ i = 1 \text{ or } 2. \tag{10}$$

The state of the atoms trapped in cavity A evolves to

$$\frac{1}{\sqrt{2}}(|1\rangle_1|2\rangle_2 + |2\rangle_1|1\rangle_2), \tag{11}$$

which is not a DF state. Then the atoms interact resonantly with the cavity mode for a time τ, the system evolves to

$$\frac{1}{\sqrt{2}}\{\frac{1}{g_1^2+g_2^2}\left[(g_2^2-g_1g_2)\mathrm{e}^{-\frac{\Gamma}{2}\tau}+\mathrm{e}^{-\frac{\kappa+\Gamma}{4}\tau}\cos(\frac{\Omega\tau}{2})(g_1^2+g_1g_2)\right]|0\rangle_A|2\rangle_1|1\rangle_2$$
$$+\frac{1}{g_1^2+g_2^2}\left[(g_1^2-g_1g_2)\mathrm{e}^{-\frac{\Gamma}{2}\tau}+\mathrm{e}^{-\frac{\kappa+\Gamma}{4}\tau}\cos(\frac{\Omega\tau}{2})(g_2^2+g_1g_2)\right]|0\rangle_A|1\rangle_1|2\rangle_2$$
$$-2\mathrm{i}\frac{g_1+g_2}{\Omega}\mathrm{e}^{-\frac{\kappa+\Gamma}{4}\tau}\sin(\frac{\Omega\tau}{2})|1\rangle_A|1\rangle_1|1\rangle_2\}, \tag{12}$$

where $\Omega=\sqrt{4(g_1^2+g_2^2)-\frac{(\kappa-\Gamma)^2}{4}}$. Assume that $g_1=g_2=g$, then Eq.(12) can be rewritten as

$$\frac{1}{\sqrt{2}}[\mathrm{e}^{-\frac{\kappa+\Gamma}{4}\tau}\cos(\frac{\Omega\tau}{2})(|0\rangle_A|2\rangle_1|1\rangle_2+|0\rangle_A|1\rangle_1|2\rangle_2)-\mathrm{i}\frac{4g}{\Omega}\mathrm{e}^{-\frac{\kappa+\Gamma}{4}\tau}\sin(\frac{\Omega\tau}{2})|1\rangle_A|1\rangle_1|1\rangle_2]. \tag{13}$$

The same case occurs in cavity B, leading to

$$\frac{1}{\sqrt{2}}[\mathrm{e}^{-\frac{\kappa+\Gamma}{4}\tau}\cos(\frac{\Omega\tau}{2})(|0\rangle_B|2\rangle_3|1\rangle_4+|0\rangle_B|1\rangle_3|2\rangle_4)-\mathrm{i}\frac{4g}{\Omega}\mathrm{e}^{-\frac{\kappa+\Gamma}{4}\tau}\sin(\frac{\Omega\tau}{2})|1\rangle_B|1\rangle_3|1\rangle_4], \tag{14}$$

where we have assumed that dissipation of the two cavities are equal. Then, we wait the detectors to click. The registering of a click at one of the photon-detectors at time $\tau=T_1$ corresponds to the action of the jump operators $(b_A+b_B)/\sqrt{2}$ on the whole system state. Thus the whole system is projected to

$$\frac{-\mathrm{i}}{2}\mathrm{e}^{-\frac{\kappa+\Gamma}{2}T_1}\frac{4g}{\Omega}\cos(\frac{\Omega T_1}{2})\sin(\frac{\Omega T_1}{2})(|2\rangle_1|1\rangle_2|1\rangle_3|1\rangle_4+|1\rangle_1|2\rangle_2|1\rangle_3|1\rangle_4+|1\rangle_1|1\rangle_2|2\rangle_3|1\rangle_4$$
$$+|1\rangle_1|1\rangle_2|1\rangle_3|2\rangle_4)|0\rangle_A|0\rangle_B-\frac{8g^2}{\Omega^2}\mathrm{e}^{-\frac{\kappa+\Gamma}{2}T_1}\sin^2(\frac{\Omega T_1}{2})|1\rangle_1|1\rangle_2|1\rangle_3|1\rangle_4(|0\rangle_A|1\rangle_B+|1\rangle_A|0\rangle_B). \tag{15}$$

Then we switch on the classical fields, tune the atoms far off-resonant with the cavity mode via stark effect so that the atom–cavity interaction is frozen.[32] We wait for another time T_2. If no photons decay from either cavity during this period, the system evolves to

$$\frac{-\mathrm{i}}{2}\mathrm{e}^{-\frac{\kappa+\Gamma}{2}T_1}\mathrm{e}^{-\Gamma T_2}\frac{4g}{\Omega}\cos(\frac{\Omega T_1}{2})\sin(\frac{\Omega T_1}{2})(|2\rangle_1|1\rangle_2|1\rangle_3|1\rangle_4+|1\rangle_1|2\rangle_2|1\rangle_3|1\rangle_4+|1\rangle_1|1\rangle_2|2\rangle_3|1\rangle_4$$
$$+|1\rangle_1|1\rangle_2|1\rangle_3|2\rangle_4)|0\rangle_A|0\rangle_B-\frac{8g^2}{\Omega^2}\mathrm{e}^{-\frac{\kappa+\Gamma}{2}T_1}\mathrm{e}^{-\kappa T_2}\sin^2(\frac{\Omega T_1}{2})|1\rangle_1|1\rangle_2|1\rangle_3|1\rangle_4(|0\rangle_A|1\rangle_B+|1\rangle_A|0\rangle_B). \tag{16}$$

In the case that $\kappa T_2\gg 1$, we have $\mathrm{e}^{-\kappa T_2}\ll 1$ and can neglect the last two terms. In this case the four atoms are approximately in the W state

$$\frac{1}{2}(|2\rangle_1|1\rangle_2|1\rangle_3|1\rangle_4+|1\rangle_1|2\rangle_2|1\rangle_3|1\rangle_4+|1\rangle_1|1\rangle_2|2\rangle_3|1\rangle_4+|1\rangle_1|1\rangle_2|1\rangle_3|2\rangle_4). \tag{17}$$

The success probability of this step is

$$P_2(T_1)=\mathrm{e}^{-(\kappa+\Gamma)T_1}[\frac{4g}{\Omega}\cos(\frac{\Omega T_1}{2})\sin(\frac{\Omega T_1}{2})]^2, \tag{18}$$

which is dependent on Rabi frequency g, spontaneous emission rate Γ and cavity decay rate κ. Γ and κ are the main factors of decoherence, and decrease the success probability of our scheme. The fidelity F_2 of prepared state approximately equals unity.

4. Numerical simulation

In this section we will show the different numerical results of the success probability and fidelity when the atoms are not trapped in the ideal positions. In

Section 2, we have obtained a two-atom maximally entangled state by solving the conditional Hamiltonian, but it also can be obtained by solving an effective Hamiltonian with the help of the quantum Zeno effect,[21] which is given by

$$H_{\text{eff}} = \frac{\hbar}{2\sqrt{2}}(\Omega_1 - \Omega_2)|0g\rangle\langle 0a| + \text{h.c.} \qquad (19)$$

We mainly discuss the effect of the Rabi frequency Ω_1 and Ω_2 on the success probability in this process, as shown in Fig.2. By numerical calculation with the parameter given in Fig.2, the success probability $P_1(T)$ can reach 0.9983 when $\Gamma = 0$ and $\Omega_1/g = 0.001$, but for finite values of Γ, such as $\Gamma = 0.001g$ and $\Gamma = 0.01g$, the maximal successful probability $P_1(T)$ is 0.888 with $\Omega_1/g = 0.037$, and 0.700 with $\Omega_1/g = 0.115$. The fidelity of the prepared state can, for a very wide parameter regime, be very close to unity (higher than 99% with the parameter given in Fig.2).

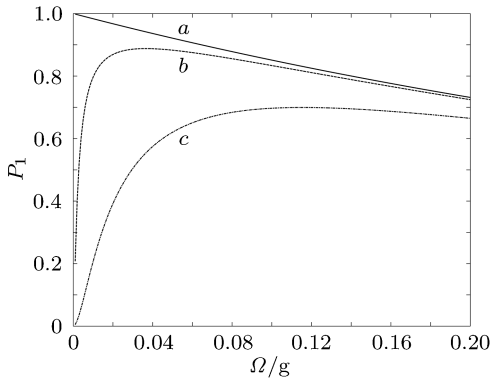


Fig.2. Success probability for generating two atom maximal entangled state in DFS versus Ω_1/g, where $\Omega_1 = -\Omega_2, \kappa = g$ and (a)$\Gamma = 0$, (b)$\Gamma = 0.001$, (c)$\Gamma = 0.01$.

In order to see how the success probability $P_2(T_1)$ and fidelity F_2 depend on g and Γ, we plot $P_2(T_1)$ versus the scaled interaction time gt for different values of coupling strength in Fig.3 and plot F_2 versus gt for different values of Γ in Fig.4. For the three cases given in Fig.3, the maximal success probabilities, occurring around $gt \sim 0.53$, are 32.08%, 29.24% and 30.78%, respectively. The fidelities, corresponding to maximal success probabilities, are 1, 0.995 and 0.999, respectively. It can be seen that the maximal success probability about 30% and fidelity higher than 0.99 can also be obtained, even if the atoms are not trapped in ideal positions. On the other hand, the scheme proposed here must work in the Lamb–Dicke regime, i.e., the spatial extension of the atomic wave function should be much smaller than the wavelength of the cavity mode. Recent advances in the combination of ion trapping and cavity QED techniques allow the achievement of the Lamb–Dicke limit.[29−31] In these experiments, single $^{40}Ca^{+}$ ions are localized at a fixed position in the cavity with a high precision for indefinite times, so the spatial variation of the coupling strength can be neglected. Figure 4 shows that Γ has a little effect on success probability P_2 and fidelity F_2 in the process of dynamical evolution out of DFS. According to all the above calculations, the maximal success probability of the whole process is about 21% for $\Gamma = 0.01g$, and the fidelity higher than 98% can be achieved.

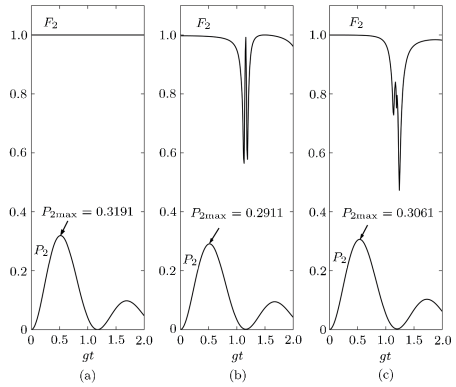


Fig.3. (a) Success probability P_2 and fidelity F_2 vs dimensionless time gt for $g_1 = g_2 = g_3 = g_4 = g, \kappa_1 = \kappa_2 = g$, and $\Gamma_1 = \Gamma_2$=0.01g. (b) Success probability P_2 and fidelity F_2 vs dimensionless time gt for $g_1 = g_2 = g, g_3 = g_4 = 0.9g, \kappa_1 = g, \kappa_2 = 0.9g$ and $\Gamma_1 = \Gamma_2$=0.01g. (c) Success probability P_2 and fidelity F_2 vs dimensionless time gt for $g_1 = g, g_2 = 0.9g, g_3 = 0.95g, g_4 = 0.9g$, $\kappa_1 = 0.9g, \kappa_2 = 0.9g$, and $\Gamma_1 = \Gamma_2$=0.01g.

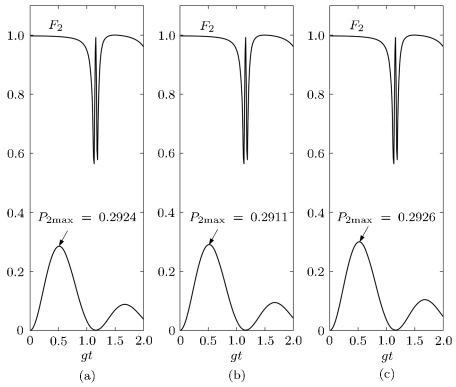


Fig.4. (a) Success probability P_2 and fidelity F_2 vs dimensionless time gt for $g_1 = g_2 = g, g_3 = g_4 = 0.9g, \kappa_1 = g, \kappa_2 = 0.9g$, and $\Gamma_1 = \Gamma_2$=0.001g. (b) Success probability P_2 and fidelity F_2 vs dimensionless time gt for $g_1 = g_2 = g, g_3 = g_4 = 0.9g, \kappa_1 = g, \kappa_2 = 0.9g$ and $\Gamma_1 = \Gamma_2$=0.01g. (c) Success probability P_2 and fidelity F_2 vs dimensionless time gt for $g_1 = g_2 = g, g_3 = g_4 = 0.9g, \kappa_1 = g, \kappa_2 = 0.9g$ and $\Gamma_1 = \Gamma_2$=0.

Note that our scheme is based on the detection of single-photon and works under the condition $g \sim \kappa$. In

current optical cavity QED experiment,[33] the atom–cavity coupling strength is $2\pi \times 34\,\mathrm{MHz}$ and the decay rate of the cavity-mode is about $0.1g$, a strong coupling condition can be achieved. Since our scheme is less stringent than strong coupling condition and the cavity decay can be changed by adjusting the length, waist, and refinement of cavity, the single-photon detection is realizable. Besides, in Ref.[33], the cavity length was $42.2\,\mu$m and the wavelength 852.4 nm. Then it is possible that two atoms are trapped in one cavity with the distance between them much larger than an optical wavelength. Hence, our scheme is experimentally realizable.

5. Summary

In this paper, we have discussed in detail concrete proposal for the generation of four-atom W state. The atoms are divided into two pairs and trapped in two separate optical cavities. Initially, all atoms are in ground state. To activate a time evolution, two laser fields are applied simultaneously. After that, the two atoms in an individual cavity are entangled. Then the system state is driven out of DFS, and the atoms interact resonantly with the cavity field. The photons leaking from the cavities interfere with each other at the beamsplitter, which destroys which-path information, and are finally detected by one of the detectors, leading to the generation of W state. The numerical results indicate that the maximal success probability of this scheme is about 21% for $\Gamma = 0.01g$, and the fidelity higher than 0.98 can be obtained. The scheme not only can be used to test quantum nonlocality, but also has practical applications in quantum information processing.

References

[1] Nielsen M A and Chuang I L 2000 *Quantum Computation and Quantum Information* (Cambridge: Cambridge University Press)

[2] Greenberger D M, Horne M A and Zeilinger A 1990 *Am. J. Phys.* **58** 1131

[3] Pan J W, Bouwmeester D, Daniell M, Weinfurter H and Zeilinger A 2000 *Nature* **403** 515

[4] Rauschenbeutel A, Nogues G, Osnaghi S, Bertet P, Brune M, Raimond J M and Haroche S 2000 *Science* **288** 2024

[5] Leibfried D, Barrett M D, Schaetz T, Britton J, Chiaverini J, Itano W M, Jost J D, Langer C and Wineland D J 2004 *Science* **304** 1476

[6] Düe W, Vidal G and Cirac J I 2000 *Phys. Rev.* A **62** 062314

[7] Cabello A 2002 *Phys. Rev.* A **65** 032108

[8] Zheng S B 2002 *Phys. Rev.* A **66** 014103

[9] Joo J, Park Y J, Oh S and Kim J 2003 *New J. Phys.* **5** 136

[10] Joo J, Lee J, Jang J and Park Y J 2002 quant-ph/0204003

[11] Zheng S B 2006 *Phys. Rev.* A **74** 054303

[12] Guo G P, Li C F, Li J and Guo G C 2002 *Phys. Rev.* A **65** 042102;
Zheng S B 2004 *Phys. Rev.* A **70** 045804

[13] Zhang J and Ye L 2004 *Chin. Phys.* **13** 1438

[14] Zheng S B 2005 *J. Opt.* B*: Quantum Semiclass. Opt.* **7** 10

[15] Zheng S B 2006 *J. Phys.* B **39** 2505

[16] Guo G C and Zhang Y S 2002 *Phys. Rev.* A **65** 054302

[17] Palma G M, Suominen K A and Ekert A K 1996 *Proc. Roy. Soc. London Ser.* A **452** 567

[18] Zanardi P and Rasetti M 1997 *Phys. Rev. Lett.* **79** 3306

[19] Lidar D A, Chuang I L and Whaley K B 1998 *Phys. Rev. Lett.* **81** 2594

[20] Duan L M and Guo G C 1998 *Phys. Rev.* A **58** 3491

[21] Beige A, Braun D and Knight P L 2000 *New J. Phys.* **2** 22

[22] Beige A, Bose S, Braun D, Huelga S F, Knight P L, Plenio M B and Vedral V 2000 *J. Mod. Opt.* **47** 2583

[23] Kwiat P G, Berglund A J, Altepeter J B and White A 2000 *Science* **290** 498

[24] Kielpinski D, Meyer V, Rowe M A, Sackett C A, Itano W M, Monroe C and Wineland D J 2001 *Science* **291** 1013

[25] Beige A, Braun D, Tregenna B and Knight P L 2000 *Phys. Rev. Lett.* **85** 1762

[26] Tregenna B, Beige A and Knight P L 2001 quant-ph/0109006

[27] Pachos J K and Beige A 2004 *Phys. Rev.* A **69** 033817

[28] Bose S, Knight P L, Plenio M and Vedral V 1999 *Phys. Rev. Lett.* **83** 5158

[29] Guthöhrlein G R, Keller M, Hayasaka K, Lange W and Walther H 2001 *Nature* (London) **414** 49

[30] Mundt A B, Kreuter A, Becher C, Leibfried D, Eschner J, Schmidt-kaler J and Blatt R 2002 *Phys. Rev. Lett.* **89** 103001

[31] Keller M, Lange B, Hayasaka K, Lange W and Walther H 2004 *New J. Phys.* **6** 95

[32] Zheng S B and Guo G C 1998 *Phys. Lett.* A **244** 512

[33] Boca A, Miller R, Birnbaum K M, Boozer A D, McKeever J and Kimble H J 2004 *Phys. Rev. Lett.* **93** 233603