Simple schemes for generation of W-type multipartite entangled states and realization of quantum-information concentration*

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We propose simple schemes for generating W-type multipartite entangled states in cavity quantum electrodynamics (CQED). Our schemes involve a largely detuned interaction of Λ-type three-level atoms with a single-mode cavity field and a classical laser, and both the symmetric and asymmetric W states can be created in a single step. Our schemes are insensitive to both the cavity decay and atomic spontaneous emission. With the above system, we also propose a scheme for realizing quantum-information concentration which is the reverse process of quantum cloning. In this scheme, quantum-information originally coming from a single qubit, but now distributed into many qubits, is concentrated back to a single qubit in only one step.

Keywords: cavity quantum electrodynamics, W-state generation, quantum-information concentration

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1. Introduction

Entanglement of two or more particles is the most intriguing characteristic of quantum mechanics. Entangled states not only are recognized as an essential ingredient for testing the foundations of quantum mechanics, but also have many significant applications in quantum-information processing (QIP).[1] Generally, the more particles that can be entangled, the more clearly nonclassical effects are exhibited,[2] and the more useful the states are for quantum applications.[3,4] Thus generation and manipulation of multipartite entangled states are very important tasks and have been attracting much attention. W state is one of the most typical entanglement among the multipartite entangled states.[5] The entanglement of W states is robust against particle loss, global dephasing, and bit flip noise.[5] Because of these properties, W states may lead to stronger nonclassicality and implement quantum tasks more robustly than other types of entangled states,[6] and even can achieve many QIP tasks[7−10] that other types of states cannot. Thus, preparation of W-type multipartite entangled states deserves intensive investigation.

On the other hand, the cavity quantum electrodynamics (CQED) system is a proper candidate for implementing quantum-information processing and quantum state engineering.[11] In the context of CQED, many schemes for generating the fully symmetric W states have been proposed.[12−16] Recently, it has been shown that some asymmetric W states can be better suited than the symmetric W states for some QIP tasks.[7,17−21] Several generation schemes of such asymmetric W states have also been proposed in CQED.[22,23] In all the above schemes, however, the atomic excited states take part in the temporal evolution of the system, which means that these schemes are sensitive to the atomic spontaneous emission.

In this paper, we propose robust schemes for generation of W-type multipartite entangled states in CQED. Our schemes involve a largely detuned interaction of Λ-type three-level atoms with a single-mode cavity field and a classical laser, and both the symmetric and asymmetric W states can be created in a

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single step. The atomic spontaneous emission can be effectively suppressed due to the fact that the excited states of the atoms are adiabatically eliminated under the large-detuning limit condition. The cavity is only virtually excited because of the largely detuned interaction between atoms and the cavity, and thus the schemes are insensitive to the cavity decay. With the same system mentioned above, we also propose a scheme for realizing quantum-information concentration which is the reverse process of quantum cloning. In this scheme, quantum-information originally coming from a single qubit, but now distributed into many qubits, is concentrated back to a single qubit in only one step. In the above schemes, the required atoms–cavity interaction time decreases with the increase of number of qubits. This is contrary to usual entanglement generation and quantum manipulation schemes which take more and more time with the increase of the number of qubits.

2. Interaction model of atoms and cavity field

The system considered here consists of N three-level atoms simultaneously passing through a single-mode cavity field. The level structure of the atoms is shown in Fig.1.

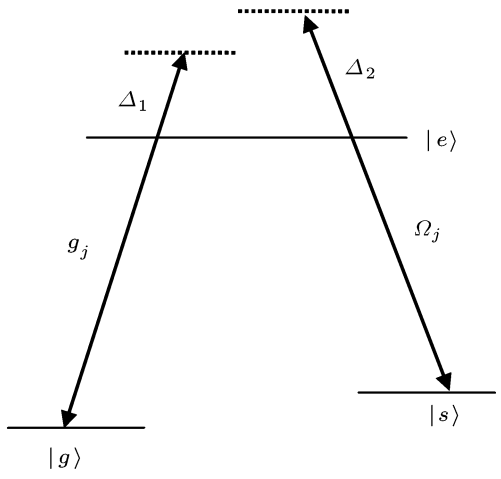


Fig. 1. The configuration of the three-level atoms and the corresponding level transition.

Each atom has two stable ground states $|g\rangle$ and $|s\rangle$, and an excited state $|e\rangle$. The coherence time of the atomic ground levels is so long that these states can be used to store quantum information. The atomic transition $|g\rangle \to |e\rangle$ ($|s\rangle \to |e\rangle$) is dispersively coupled to the quantized cavity mode (a classical laser field) with coupling constant g_j (Ω_j) and detuning Δ_1 (Δ_2). The Hamiltonian of the system can be given by

$$H = \sum_{j=1}^{N}(g_j a|e_j\rangle\langle g_j|\mathrm{e}^{-\mathrm{i}\,\Delta_1 t} + \Omega_j|e_j\rangle\langle s_j|\mathrm{e}^{-\mathrm{i}\,\Delta_2 t} + \mathrm{H.c.}), \quad (1)$$

where g_j represents coupling strength between the j-th atom and the cavity, $a^\dagger$ and a are the creation and annihilation operators of the quantized cavity mode, respectively. Without loss of generality, we assume Δ_i $(i = 1, 2)$, Ω_j and g_j are real. When $\Delta_2 \gg \Omega_j$, $\Delta_1 \gg g_j$, we can eliminate adiabatically the excited level $|e\rangle$ by neglecting the effect of rapidly oscillating terms. Then the above Hamiltonian reduces to[24−27]

$$H_{\mathrm{E}} = \sum_{j=1}^{N}\left[\frac{g_j^2}{\Delta_1}a^\dagger a|g_j\rangle\langle g_j| + \frac{\Omega_j^2}{\Delta_2}|s_j\rangle\langle s_j| + \frac{g_j\Omega_j}{\Delta}(a\mathrm{e}^{\mathrm{i}\,\delta t}|s_j\rangle\langle g_j| + \mathrm{H.c.})\right], \quad (2)$$

where $1/\Delta = (1/\Delta_1 + 1/\Delta_2)/2$, $\delta = \Delta_2 - \Delta_1$. The first two terms in Eq. (2) describe the Stark shifts of the levels $|g\rangle$ and $|s\rangle$ that are induced by the cavity mode and the external classical laser field. The last two terms describe the effective atomic interaction. Under the large-detuning limit conditions $\delta \gg (g_j\Omega_j/\Delta)$, there is no energy exchange between the atomic system and the cavity mode. Then the only energy-conversing transitions are between $|s_j, g_k, n\rangle$ and $|g_j, s_k, n\rangle$, which are mediated by the energy levels $|g_j, g_k, n+1\rangle$ and $|s_j, s_k, n-1\rangle$, independent of photon-number states of the cavity mode, and the Rabi frequencies are $g_j^2\Omega_j^2/\Delta^2\delta$ (or $g_j g_k\Omega_j^2/\Delta^2\delta$). Then the effective Hamiltonian of Eq. (2) can be written as[28]

$$H'_{\mathrm{E}} = \sum_{j=1}^{N}\left(\frac{g_j^2}{\Delta_1}a^\dagger a|g_j\rangle\langle g_j| + \frac{\Omega_j^2}{\Delta_2}|s_j\rangle\langle s_j|\right) + \sum_{j=1}^{N}\frac{g_j^2\Omega_j^2}{\Delta^2\delta}\left(|s_j\rangle\langle s_j|aa^\dagger - |g_j\rangle\langle g_j|a^\dagger a\right) + \sum_{j,k=1,j\neq k}^{N}\frac{g_j g_k\Omega_j^2}{\Delta^2\delta}\sigma_j^+\sigma_k^-, \quad (3)$$

where $\sigma_j^- = |g_j\rangle\langle s_j|$, $\sigma_j^+ = |s_j\rangle\langle g_j|$. The third and the fourth terms describe the photon-number-dependent Stark shifts induced by the off-resonant driving, and the last term describes the dipole coupling between the atoms mediated by the cavity mode and the classical microwave pulse.

3. One-step generation of N-qubit W states

Now, we begin to demonstrate how to yield the N-qubit W states in the CQED system introduced in the above section. Assume that the coupling strength of atom 1 with the cavity is g_1 and the coupling strengths of the other atoms with the cavity are g_2, and the coupling strengths of all the atoms with the classical laser are the same and are equal to Ω_L. The different coupling strengths can be realized by locating the atoms at different positions in the cavity. If the cavity field is initially in the vacuum state $|0\rangle$, it will remain in this state throughout the process since $[a^\dagger a,\ H'_{\rm E}]=0$. Then the effective Hamiltonian of Eq. (3) reduces to

$$H_{\rm eff} = \eta'_1|s_1\rangle\langle s_1| + \eta_1\sum_{j=2}^{N}\left(\sigma_1^+\sigma_j^- + \sigma_1^-\sigma_j^+\right) + \eta'_2\sum_{j=2}^{N}|s_j\rangle\langle s_j| + \eta_2\sum_{j,k=2,j\neq k}^{N}\sigma_j^+\sigma_k^-, \quad (4)$$

where $\eta'_1 = \Omega_L^2/\Delta_2 + g_1^2\Omega_L^2/\Delta^2\delta$, $\eta_1 = g_1g_2\Omega_L^2/\Delta^2\delta$, $\eta'_2 = \Omega_L^2/\Delta_2 + g_2^2\Omega_L^2/\Delta^2\delta$, and $\eta_2 = g_2^2\Omega_L^2/\Delta^2\delta$. We define the excitation number operator $\hat{M} = a^\dagger a + \sum_{j=1}^{N}\sigma_j^+\sigma_j^- = \sum_{j=1}^{N}\sigma_j^+\sigma_j^-$ (the cavity is in the vacuum state). Because $[H_{\rm eff},\ \hat{M}]=0$, the dynamics is separable into subspaces having a prescribed eigenvalue M of $\hat{M}$. In the $M=1$ subspace, there are the following N basis states:

$$|1_1\rangle = |s_1g_2g_3\cdots g_{N-1}g_N\rangle\,, \quad (5)$$

$$|1_2\rangle = |g_1s_2g_3\cdots g_{N-1}g_N\rangle\,, \quad (6)$$

$$\vdots$$

$$|1_N\rangle = |g_1g_2g_3\cdots g_{N-1}s_N\rangle\,. \quad (7)$$

Assume that the N atoms are initially in the state $|1_1\rangle$. After an interaction time τ, the state of the system is

$$|\psi(\tau)\rangle = \left[\cos(\alpha\tau) - {\rm i}\,\frac{(\eta'_1-\eta'_2)-(N-2)\eta_2}{2\alpha}\sin(\alpha\tau)\right]|1_1\rangle - {\rm i}\,\frac{\eta_1}{\alpha}\sin(\alpha\tau)\sum_{j=2}^{N}|1_j\rangle, \quad (8)$$

where

$$\alpha = \sqrt{(N-1)\eta_1^2 + \frac{[(N-2)\eta_2-(\eta'_1-\eta'_2)]^2}{4}}$$

and the global phase factor ${\rm e}^{-{\rm i}[(\eta'_1+\eta'_2)+(N-2)\eta_2]\tau/2}$ is discarded.

By choosing $\sin(\alpha\tau) = \alpha/(\eta_1\sqrt{N})$, we can obtain an N-atom symmetric W-type entangled state

$$|W\rangle = \frac{1}{\sqrt{N}}\left[\exp\left[{\rm i}\,(\pi/2-\varphi_1)\right]|1_1\rangle + \sum_{j=2}^{N}|1_j\rangle\right], \quad (9)$$

where a global phase factor $\exp(-{\rm i}\,\pi/2)$ is omitted, and φ_1 is defined as

$$\tan(\varphi_1) = \frac{(\eta'_1-\eta'_2)-(N-2)\eta_2}{\sqrt{4\eta_1^2-[(N-2)\eta_2-(\eta'_1-\eta'_2)]^2}}. \quad (10)$$

Since $|\sin(\alpha\tau)| \leq 1$, the atom–cavity coupling strengths g_1 and g_2 need to satisfy the condition

$$g_1^4 + (N-1)^2g_2^4 \leq 2(N+1)g_1^2g_2^2. \quad (11)$$

If setting $\sin(\alpha\tau) = \alpha/[\eta_1\sqrt{2(N-1)}]$, we can obtain an N-atom asymmetric W-type entangled state

$$|W'\rangle = \frac{1}{\sqrt{2(N-1)}}\left[\sqrt{(N-1)}\exp\left[{\rm i}\,(\pi/2-\varphi_2)\right]|1_1\rangle + \sum_{j=2}^{N}|1_j\rangle\right], \quad (12)$$

where a global phase factor $\exp(-{\rm i}\,\pi/2)$ is omitted, and φ_2 is defined as

$$\tan(\varphi_2) = \frac{(\eta'_1-\eta'_2)-(N-2)\eta_2}{\sqrt{4(N-1)\eta_1^2-[(N-2)\eta_2-(\eta'_1-\eta'_2)]^2}}. \quad (13)$$

Since $|\sin(\alpha\tau)| \leq 1$, the atom–cavity coupling strengths g_1 and g_2 need to satisfy the condition

$$g_1^4 + (N-1)^2g_2^4 \leq 6(N-1)g_1^2g_2^2. \quad (14)$$

Note that the asymmetric W' state of Eq. (12) can be better suited than the symmetric W state of Eq. (9) for some QIP tasks.[7,17–20,22]

4. Quantum-information concentration with a single atoms–cavity coupling

In this section, we propose a simple scheme for realizing quantum-information concentration[29] which is the reverse process of corresponding quantum cloning. Assume that the information of the

phase-covariant state $|\phi\rangle = \frac{1}{\sqrt{2}}(|g_c\rangle + e^{i\varphi}|s_c\rangle)$ has been originally distributed into $N-1$ qubits by phase-covariant quantum cloning or telecloning.[7,3] The $(N-1)$-qubit cloning state of $|\phi\rangle$ is given by[7,3]

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|g_2 g_3 \cdots g_N\rangle + e^{i\varphi}|W_s\rangle_{23\cdots N}\right), \quad (15)$$

where

$$\begin{aligned}|W_s\rangle_{23\cdots N} &= \frac{1}{\sqrt{N-1}}(|s_2 g_3 g_4 \cdots g_{N-1} g_N\rangle \\ &+ |g_2 s_3 g_4 \cdots g_{N-1} g_N\rangle \\ &+ \cdots |g_2 g_3 g_4 \cdots g_{N-1} s_N\rangle) \\ &= \frac{1}{\sqrt{N-1}}\left(\sum_{j=2}^{N}|1_j\rangle\right)\end{aligned}$$

is an $(N-1)$-qubit symmetric W state.

The idea of our information concentration is to concentrate the distributed information back to a qubit, i.e., $|\psi\rangle \to |\phi\rangle$. In principle, such a transformation operation can be realized by constructing an appropriate quantum network. However, it is very difficult to construct the desired quantum network in practice when many particles are involved. Here we show that such a transformation can be realized in a single step. In order to show our idea clearly, we demonstrate it in the aforementioned CQED system.

Assume that the $N-1$ atoms are initially in the cloning state of Eq. (15), and there is another atom A which is initially in the ground state $|g_A\rangle$. We now let the N atoms simultaneously interact with the aforementioned cavity field. The effective Hamiltonian is described by Eq. (4) with atom 1 replaced by atom A. In the $M=1$ subspace, the time evolution operator of the system can be described by

$$U(t) = \chi(t)\begin{pmatrix} \cos(\alpha t) - i\frac{(\eta_1' - \eta_2') - (N-2)\eta_2}{2\alpha}\sin(\alpha t) & -i\frac{\eta_1}{\alpha}\sin(\alpha t) & -i\frac{\eta_1}{\alpha}\sin(\alpha t) & \cdots & -i\frac{\eta_1}{\alpha}\sin(\alpha t) \\ -i\frac{\eta_1}{\alpha}\sin(\alpha t) & \xi(t) & \beta(t) & \cdots & \beta(t) \\ -i\frac{\eta_1}{\alpha}\sin(\alpha t) & \beta(t) & \xi(t) & \cdots & \beta(t) \\ \vdots & \beta(t) & \beta(t) & \ddots & \beta(t) \\ -i\frac{\eta_1}{\alpha}\sin(\alpha t) & \beta(t) & \beta(t) & \cdots & \xi(t) \end{pmatrix}, \quad (16)$$

where

$$\chi(t) = e^{-i\left[(\eta_1' + \eta_2') + (N-2)\eta_2\right]t/2}, \quad (17)$$

$$\xi(t) = \frac{\cos(\alpha t)}{N-1} + \frac{\exp\left[i(\eta_2' - \eta_2)t\right](N-2)}{\chi(t)(N-1)} + i\frac{(\eta_1' - \eta_2') - (N-2)\eta_2}{2\alpha(N-1)}, \quad (18)$$

$$\beta(t) = \frac{\cos(\alpha t)}{N-1} - \frac{\exp\left[i(\eta_2' - \eta_2)t\right]}{\chi(t)(N-1)} + i\frac{(\eta_1' - \eta_2') - (N-2)\eta_2}{2\alpha(N-1)}. \quad (19)$$

In the subspace with excitation M=0, there is only one basis state $|g_A\rangle|g_2 \cdots g_N\rangle$, and if the system is initially in this state, it will remain in the state during the interaction. When the system is initially in the state $|g_A\rangle \otimes |W_s\rangle_{23\cdots N}$, after an interaction time τ', the state of the system is

$$\begin{aligned}|\psi(\tau')\rangle = \chi(\tau')\Big[&-i\frac{\eta_1}{\alpha}\sin(\alpha\tau')|1_A\rangle + \xi(\tau')|1_2\rangle + \beta(\tau')\sum_{j=3}^{N}|1_j\rangle \\ &- i\frac{\eta_1}{\alpha}\sin(\alpha\tau')|1_A\rangle + \xi(\tau')|1_3\rangle + \beta(\tau')\sum_{j=2,j\neq 3}^{N}|1_j\rangle \\ &\vdots \\ &- i\frac{\eta_1}{\alpha}\sin(\alpha\tau')|1_A\rangle + \xi(\tau')|1_k\rangle + \beta(\tau')\sum_{j=2,j\neq k}^{N}|1_j\rangle \\ &\vdots \\ &- i\frac{\eta_1}{\alpha}\sin(\alpha\tau')|1_A\rangle + \xi(\tau')|1_N\rangle + \beta(\tau')\sum_{j=2,j\neq k}^{N-1}|1_j\rangle\Big]\end{aligned}$$

$$= \chi(\tau')\left[\frac{\xi(\tau')+(N-2)\,\beta(\tau')}{\sqrt{N-1}}\sum_{j=2}^{N}|1_j\rangle\prod_{k=2,k\neq j}^{N}|0_k\rangle - \mathrm{i}\sqrt{N-1}\frac{\eta_1}{\alpha}\sin(\alpha\tau')|1_A\rangle\right]. \quad (20)$$

Setting $(\eta_1' - \eta_2') = (N-2)\eta_2$, $\eta_1' = 3\eta_1\sqrt{N-1}$ (i.e., $g_2 = g_1/\sqrt{N-1}$), and $\tau' = \pi/2\eta_1\sqrt{N-1}$, the state $|\psi(\tau')\rangle$ reduces to $|1_A\rangle = |s_A g_2 g_3\cdots g_{N-1}g_N\rangle$ (see Eqs. (5)–(7)). According to the above discussion, we have

$$\frac{1}{\sqrt{2}}|g_A\rangle\otimes\left(|g_2g_3\cdots g_N\rangle + \mathrm{e}^{\mathrm{i}\,\varphi}\,|W_{\mathrm{s}}\rangle_{23\cdots N}\right)\xrightarrow{U(\tau')}\frac{1}{\sqrt{2}}\left(|g_A\rangle + \mathrm{e}^{\mathrm{i}\,\varphi}\,|s_A\rangle\right)\otimes|g_2g_3\cdots g_N\rangle\,. \quad (21)$$

That is, the quantum information, initially distributed in $N-1$ qubits via phase-covariant cloning or telecloning, is concentrated to a single qubit A. Combining with the phase-covariant cloning or telecloning which can play an important role in quantum-information depositing or encoding,[7,30] our quantum-information concentration idea may have potential applications in quantum-information withdrawing or decoding.[17,19,20,22]

5. Discussion and conclusion

We now give a brief discussion on the experimental feasibility of the proposed schemes within current CQED technology. We can take ^{87}Rb to meet the required level structures for our proposal.[24–27] The ground states $|g\rangle$ and $|s\rangle$ may correspond to Zeeman levels of $|F=1,\ m=0\rangle$ of $5\mathrm{S}_{1/2}$ and $|F=2,\ m=2\rangle$ of $5\mathrm{S}_{1/2}$, while the excited state $|e\rangle$ is denoted by the Zeeman level $|F=2, m=2\rangle$ of the $5\mathrm{P}_{1/2}$. On the one hand, the schemes require the atoms to have different coupling strengths with the cavity mode. The coupling constants depend on the atomic positions $g_j = g_0\mathrm{e}^{-r^2/\omega^2}$, where g_0 is the coupling strength at the cavity centre, ω is the waist of the cavity mode, and r represents the distance between the atom and cavity centre.[26,27] Thus the condition of different coupling strengths of atoms with cavity can be achieved by putting different atoms at different positions of the cavity. For example, $g_2 = g_1/\sqrt{N-1}$ can be satisfied by locating atom 1 or A at the centre of the cavity and the other atoms at the position $r = \omega\left(\ln\sqrt{N-1}\right)^{1/2}$. On the other hand, we can choose the experimental parameters $g_1 = g$, $\Omega_L = 0.1g$, $\Delta_1 = 10g_1$, $\Delta_2 = 10.2g_1$, so that $\delta = 0.2g_1$. It is easy to check that the large detuning conditions $\Delta_i \gg \{g_1^2/\Delta_1,\ g_2^2/\Delta_1,\ \Omega_L^2/\Delta_2\}$, $\delta \gg \{g_1\Omega_L/\Delta,\ g_2\Omega_L/\Delta\}$, and $g_2^2 = \Delta^2\delta/2\Delta_2(N-1)$ can be well satisfied. It is worth while noticing that the required atoms–cavity interaction time is proportional to $1/(N-1)$ and thus decreases with the increase of the number of qubits, which is important in view of decoherence. Take realization of quantum-information concentration for instance, the interaction time tends to about 32 ns ($t = \pi\Delta^2\delta/2g^2\Omega_L^2\,(N-1)$), using the experimental parameters $g = 16\times 2\pi$ MHz[31] of the ^{87}Rb atoms trapped in an optical cavity, when N reaches to 10^3. Therefore, the interaction time can be greatly speeded up when the number of atoms is large. Moreover, since the cavity is only virtually excited, the decoherence arising from the cavity decay is strongly suppressed. The main experimental challenge for our schemes is to control multiple atoms to interact with a cavity simultaneously. However, it has been shown that the small time-difference of the interaction between the atoms and the cavity only slightly affects the quantum-information schemes in CQED.[12,32–34]

In summary, we have proposed simple schemes to generate both symmetric and asymmetric W states as well as to realize quantum-information concentration by one step in the CQED system with a large detuned interaction between Λ-type three-level atoms and a single-mode cavity field. During the operation, the atoms are always populated in the ground states and the cavity remains in a vacuum state. Thus the decoherence arising from the atomic spontaneous emission and cavity decay can be well suppressed. All the involved facilities in our proposed schemes are state of the art.

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