Generation of two-photon EPR and W states

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Abstract

In this paper we present a scheme for generation of two-photon EPR and W states in the cavity QED context. The scheme requires only one three-level Rydberg atom and two or three cavities. The atom is sent to interact with cavities previously prepared in vacuum states, via a two-photon process. An appropriate choice of the interaction times allows one to obtain the mentioned states with maximized fidelities. These specific times and the values of success probability and fidelity are discussed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Entanglement is present in a diversity of applications of quantum mechanics, such as quantum teleportation [1], quantum computation [2], one-way quantum computation [3], quantum communication via teleportation [4, 5], quantum metrology [6], quantum state engineering [7] and quantum information escaping from black holes [8]. There are various kinds of entangled states depending on the number of involved parties and of the entanglement ‘structure’, e.g. for bipartite entanglements, there is only one example: the EPR state [9]; for 3-partite, there are two kinds of entangled states: the GHZ [10] and W [11] states; for 4-partite, more interesting is the 4-qubit cluster state [12] whose correlations cannot be described in terms of the local realism as experimentally demonstrated in [13]. In fact, this state is not biseparable and has a genuine 4-qubit entanglement.

With respect to the tripartite entangled states, it is known that W states are robust against losses of qubits since they retain bipartite entanglement if we trace out any one qubit whereas GHZ states are fragile since the remaining two partite states result in separable states. This property turns the W states very attractive for various quantum information tasks, such as a quantum channel for teleportation of entangled pairs [14], probabilistic teleportation [15] and quantum key distribution [16]; however, one should manipulate it with care since it is not appropriate for perfect quantum teleportation and superdense coding in the form presented in [17, 18]. Several schemes have been proposed to generate the W state in QED cavities [19], trapped ions [20], quantum dots [21], superconducting quantum interference devices [22] and superconducting flux qubits [23].

A class of W states that can be used for perfect teleportation and superdense coding was recently presented in [24], given by

\[ |W_\zeta\rangle = \frac{1}{\sqrt{2 + 2\zeta}} (|001\rangle + \sqrt{\zeta}e^{i\gamma}|010\rangle + \sqrt{\zeta + 1}e^{i\delta}|100\rangle) \]

(1)

where \(\zeta\) is a real number and \(\gamma, \delta\) are the phases. Additionally, in [25] Li and Qiu generalized the states of the W-class for multi-qubit systems and multi-particle systems with higher dimension.

In view of the applications of the entangled states discussed above, in this work we present a scheme for the generation of two-photon EPR and W states in QED cavities. To this end, a Rydberg three-level atom is sent to interact with the cavities previously prepared in the vacuum state via a two-photon process. It is worth mentioning that the two-photon process has been demonstrated in [26] for microwave cavity QED and offers some advantages in relation to the one-photon process, as the reduction of interaction times due to the increasing atom–field coupling strength and lower decoherence induced by stray fields [27]. In addition, the two-photon process can be easily obtained with Rydberg...
atoms with principal quantum number \( n > 89 \), which can be state-sensitively detected using tunnelling field ionization with quantum efficiencies above 80% and an ionization efficiency above 98% [28]. As another application, two-photon states are required for quantum protocols involving more than one-photon states, e.g. protocols based on qutrit states that involve zero-, one- and two-photon states [29]. In the next section we discuss the theoretical model and give details of our scheme.

2. Theoretical model

Consider a three-level atom that interacts with a single cavity-field mode via the two-photon Jaynes–Cummings model described in the interaction picture by the Hamiltonian [30]

\[
H_I = \hbar g_1(a|e⟩⟨f| + a^+|f⟩⟨e|) + \hbar g_2(a|f⟩⟨g| + a^+|g⟩⟨f|),
\]

where \( g_1 \) and \( g_2 \) stand for the one-photon coupling constant with respect to the transitions \(|e⟩ ↔ |f⟩\) and \(|f⟩ ↔ |g⟩\), respectively. The detuning \( \delta \) is given by

\[
\delta = \Omega - (\omega_e - \omega_f) = (\omega_f - \omega_g) - \Omega,
\]

where \( \Omega \) is the cavity-field frequency, and \( \omega_e, \omega_f \) and \( \omega_g \) are the frequencies associated with the atomic levels \(|e⟩\), \(|f⟩\) and \(|g⟩\), respectively. Figure 1 shows a schematic representation of the atomic levels.

The state describing the combined atom–field system reads

\[
|ψ(t)⟩ = \sum_n [C_{e,n}(t)|e,n⟩ + C_{f,n}(t)|f,n⟩ + C_{g,n}(t)|g,n⟩],
\]

where \(|k,n⟩\), with \( k = e, f, g \), indicates the atom in the state \(|k⟩\) and the field in the Fock state \(|n⟩\). The coefficients \( C_{k,n}(t) \) stand for the corresponding probability amplitudes.

Inserting equations (2) and (4) into the time-dependent Schrödinger equation one obtains the coupled first-order differential equations for the probability amplitudes:

\[
\frac{dC_{e,n}(t)}{dt} = -i g_1 C_{f,n+1}(t) \sqrt{n + 1} e^{i\delta t},
\]

\[
\frac{dC_{f,n+1}(t)}{dt} = -i g_1 C_{e,n}(t) \sqrt{n + 1} e^{i\delta t} - i g_2 C_{g,n+2}(t) \sqrt{n + 2} e^{i\delta t},
\]

\[
\frac{dC_{g,n+2}(t)}{dt} = -i g_2 C_{f,n+1}(t) \sqrt{n + 2} e^{-i\delta t},
\]

As usual, we consider that the entire atom–field system is decoupled at the initial time \( t = 0 \),

\[
C_{e,n}(0) = C_{e,0}(0),
\]

\[
C_{f,n+1}(0) = C_{f,n+1}(0),
\]

\[
C_{g,n+2}(0) = C_{g,n+2}(0),
\]

where \( C_n(0) \) stand for the amplitudes of the arbitrary initial field state and \( C_{a} \), \( a = e, f, g \), are the atomic amplitudes of the (normalized) initial atomic state

\[
|\chi⟩ = C_{e}|e⟩ + C_{f}|f⟩ + C_{g}|g⟩.
\]

Solving these coupled differential equations with the initial conditions in (6) we get the time-dependent coefficients as

\[
C_{e,n}(t) = \left[ \frac{g_1^2(n + 1)}{\Lambda_n \alpha_n^2} \gamma_n(t) + 1 \right] C_{e,0} C_n
\]

\[
+ \frac{g_1 \sqrt{n + 1}}{\Lambda_n} \sin(\Lambda_n t) e^{-i\delta t} C_{f,n+1}
\]

\[
+ \left[ \frac{g_1 g_2 \sqrt{(n + 1)(n + 2)}}{\Lambda_n \alpha_n^2} \gamma_n(t) \right] C_{g,n+2},
\]

\[
C_{f,n+1}(t) = -i \frac{g_1 \sqrt{n + 1}}{\Lambda_n} \sin(\Lambda_n t) e^{i\delta t} C_{e,0} C_n
\]

\[
+ \left( \cos(\Lambda_n t) - i \frac{\delta}{2 \Lambda_n} \sin(\Lambda_n t) \right) e^{i\delta t} C_{f,n+1}
\]

\[
- i \frac{g_2 \sqrt{n + 1}}{\Lambda_n} \sin(\Lambda_n t) e^{i\delta t} C_{g,n+2},
\]

\[
C_{g,n+2}(t) = \left[ \frac{g_1 g_2 \sqrt{(n + 1)(n + 2)}}{\Lambda_n \alpha_n^2} \gamma_n(t) C_{f,0} C_n
\]

\[
- i \frac{g_2 \sqrt{n + 1}}{\Lambda_n} \sin(\Lambda_n t) e^{-i\delta t} C_{f,n+1}
\]

\[
+ \left[ \frac{g_2^2(n + 2)}{\Lambda_n \alpha_n^2} \gamma_n(t) + 1 \right] C_{g,n+2},
\]

where

\[
\gamma_n(t) = \left[ \Lambda_n \cos(\Lambda_n t) + \frac{\delta}{2} \sin(\Lambda_n t) - \Lambda_n e^{i\delta t} \right] e^{-i\delta t},
\]

\[
\Lambda_n = \sqrt{\frac{g_1^2(n + 1) + g_2^2(n + 2)}{4}} + \alpha_n^2,
\]

\[
\alpha_n = \sqrt{\frac{g_1^2(n + 1)}{4} + \frac{g_2^2(n + 2)}{4}},
\]

\( \Lambda_n \) being the Rabi frequency. The substitutions \( n \rightarrow n - 1 \) in equation (9) and \( n \rightarrow n - 2 \) in equation (10) allow one to obtain \( C_{f,n}(t) \) and \( C_{g,n}(t) \), respectively.

3. Two-photon EPR state

Now we describe the scheme for the generation of the maximally entangled two-photon EPR state, written in the form

\[
|ψ⟩_{12} = \frac{1}{\sqrt{2}} (|02⟩_{12} + |20⟩_{12}),
\]
where the subscripts 1 and 2 concern the cavities 1 and 2, respectively. Assume the two cavities previously prepared in the vacuum state and the atom in its excited state (|e⟩).

First, the atom crosses cavity 1, interacting with the field mode for a time $t_1$. Thus, the initial state describing the atom plus the two cavities evolves to

$$|\phi\rangle_{12} = C_{e_0}^{(e)}(t_1)|e00\rangle_{a12} + C_{j_1}^{(e)}(t_1)|f10\rangle_{a12} + C_{g_2}^{(e)}(t_1)|g20\rangle_{a12},$$

where $C_{ij}^{(e,f)}$ are the coefficients in equations (8)–(10) considering the input atomic state in $k$ and the field state in $l$.

Next, the atom enters cavity 2 and interacts for a time $t_2$. So the state of the whole system is written as

$$|\phi\rangle_{12} = C_{e_0}^{(e)}(t_1)[C_{e_0}^{(e)}(t_2)|e00\rangle_{a12} + C_{f_1}^{(e)}(t_2)|f01\rangle_{a12} + C_{g_2}^{(e)}(t_2)|g02\rangle_{a12}] + C_{j_1}^{(e)}(t_1)[C_{j_1}^{(f)}(t_2)|f10\rangle_{a12} + C_{g_2}^{(f)}(t_2)|g11\rangle_{a12}] + C_{g_2}^{(e)}(t_1)|g20\rangle_{a12}.$$ 

To get the two-photon EPR state we may choose to realize the atomic detection or not. In the affirmative case, the detection of the atomic state $|g\rangle$ leads to

$$|\phi''\rangle_{12} = N[C_{e_0}^{(e)}(t_1)|e00\rangle_{a12} + C_{f_1}^{(e)}(t_1)|f01\rangle_{a12} + C_{g_2}^{(e)}(t_1)|g02\rangle_{a12}] + C_{j_1}^{(e)}(t_1)|j11\rangle_{a12} + C_{g_2}^{(e)}(t_1)|g20\rangle_{a12},$$

with the success probability given by

$$P_s = \frac{1}{N^2} = |C_{e_0}^{(e)}(t_1)|^2 |C_{j_1}^{(e)}(t_1)|^2 + |C_{j_1}^{(f)}(t_1)|^2 + |C_{g_2}^{(e)}(t_1)|^2,$$

and the respective fidelity ($F = |\langle \phi''|\psi_{12}\rangle|^2$)

$$F = \frac{1}{2P_s} |C_{e_0}^{(e)}(t_1)C_{g_2}^{(e)}(t_2) + C_{g_2}^{(e)}(t_1)|^2.$$

According to the definition, this fidelity compares the generated state $|\phi''\rangle_{12}$ with that we want to generate, $|\psi\rangle_{12}$. The success probability and fidelity of the EPR state with atomic detection is displayed in figures 2(a) and (b), respectively. Based on the experimental values of parameters used in [26, 27], we take $g_1 = g_2 = g = 17.5$ MHz and $\delta = 30$ g. In this case, figure 3 presents the values of the success probability and fidelity for two different times. Note that an appropriate choice of the interaction time allows one to optimize the fidelity.

On the other hand, if we choose to realize no atomic detection, the maximum value of the fidelity decreases to a value close to 0.8, with the form

$$F = \frac{1}{2} |C_{e_0}^{(e)}(t_1)C_{g_2}^{(e)}(t_2) + C_{g_2}^{(e)}(t_1)|^2,$$

as used in figure 4.

4. Two-photon W state

The W state to be constructed is written as

$$|\psi\rangle_{123} = \frac{1}{\sqrt{3}}(|002\rangle_{123} + |020\rangle_{123} + \sqrt{2}|200\rangle_{123}),$$

where the subscripts concern cavities 1, 2 and 3. Also, we can generate the two-photon W state using a similar procedure for

Figure 2. Plots of (a) the success probability of the detection of the atomic state in $|g\rangle$ and (b) the respective fidelity for the two-photon EPR state, for parameters $g_1 = g_2 = g = 17.5$ MHz, $\delta = 30$ g.

Figure 3. Comparison of the fidelity and success probability versus the time $t_2$. We use the values $t_1 = 2 \, \mu s$ for the fidelity as shown by the dashed line (green) and for success probability by the dotted line (red), and $t_1 = 5 \, \mu s$ for the fidelity shown by the solid line (blue) and for the success probability by the dashed-dotted line (black), with same conventions as in figure 2.

Figure 4. Fidelity of the two-photon EPR state without atomic detection, using the same conventions as in figure 2.
the two-photon EPR state generation. However, the W state is realized in three cavities and a distinct procedure is required.

First, we consider these three cavities in the vacuum state. An atom in the excited state \( |e\rangle \) is sent to interact with the first cavity by a time \( t_1 \), leading the whole system in the state

\[
|\phi\rangle_{a123} = C_{e0}(t_1)|e000\rangle_{a123} + C_{f1}(t_1)|f100\rangle_{a123} + C_{g2}(t_1)|g200\rangle_{a123}.
\]

Next, the atom crosses cavities 2 and 3 by the times \( t_2 \) and \( t_3 \), respectively. The above state goes to the form

\[
|\phi''\rangle_{a123} = C_{e0}(t_1)[C_{e0}(t_2)[C_{e0}(t_3)|e000\rangle_{a123} + C_{f1}(t_2)|f001\rangle_{a123} + C_{g2}(t_2)|g002\rangle_{a123}]
+ C_{f1}(t_2)[C_{f0}(t_3)|f010\rangle_{a123} + C_{g1}(t_2)|g011\rangle_{a123} + C_{g2}(t_2)|g101\rangle_{a123}]
+ C_{g1}(t_3)|g110\rangle_{a123} + C_{g2}(t_3)|g200\rangle_{a123}.
\]

(21)

If we detect the atom in its ground state (\( |g\rangle \)) the state of the system collapses in the form

\[
|\phi'''\rangle_{123} = N[C_{e0}(t_1)[C_{e0}(t_2)[C_{e0}(t_3)|e000\rangle_{123} + C_{f1}(t_2)[C_{f0}(t_3)|f001\rangle_{123} + C_{g2}(t_2)|g002\rangle_{123}]
+ C_{f1}(t_2)[C_{f0}(t_3)[C_{f0}(t_3)|f010\rangle_{123} + C_{g1}(t_2)|g011\rangle_{123} + C_{g2}(t_2)|g101\rangle_{123}]
+ C_{g1}(t_3)|g110\rangle_{123} + C_{g2}(t_3)|g200\rangle_{123},
\]

(22)

with the success probability given by

\[
P_s = \left|C_{e0}(t_1)\right|^2\left|C_{e0}(t_2)\right|^2\left|C_{g2}(t_3)\right|^2 + \left|C_{f0}(t_1)\right|^2\left|C_{g2}(t_2)\right|^2 + \left|C_{g2}(t_3)\right|^2.
\]

(23)

We calculate the fidelity \( F = |\langle \psi | \phi''' \rangle|_123|^2 \), written as

\[
F = \frac{1}{4P_s}\left|C_{e0}(t_1)C_{e0}(t_2)C_{g2}(t_3) + C_{f0}(t_1)C_{g2}(t_2) + \sqrt{2}C_{g2}(t_1)\right|^2.
\]

(25)

Again an appropriate choice of the interaction times \( t_i \) (i = 1, 2, 3) allows one to obtain a maximized value of the fidelity. For example, in the case of atomic detections we choose the interaction times \( t_1 = t_2 = t_3 = 32 \mu s \) to get the success probability approximately 30% and fidelity 95%. Also, in figures 5(a) and (b) we have displayed some plots of the fidelity and success probability versus the interaction time \( t_3 \) for the two-photon W state considering the detection, or not, of the atomic state, respectively.

5. Decoherence effects

At this point we can calculate decoherence effects of the EPR and the W state through the master equation

\[
\dot{\rho} = -\frac{i}{\hbar}[H_1, \rho] + \sum_j \gamma_j (2\alpha_j \rho \alpha_j^\dagger - \alpha_j^\dagger \alpha_j \rho - \rho \alpha_j^\dagger \alpha_j),
\]

(26)

where \( j = 1, 2 \) for the EPR case and \( j = 1, 2, 3 \) for the W case; \( \rho = \rho(t) \) is the reduced density operator that describes the cavities; \( \alpha_j (\alpha_j^\dagger) \) are the annihilation (creation) operators of the field mode \( j \) and \( \gamma_j \) is the damping coefficient for the mode \( j \). We assume in the master equation (26) that the reservoir that corresponds to the cavity walls is at zero temperature. Also, we consider the two distinct cases: (i) \( \gamma_j = \gamma \), by assuming the same damping effects for all cavities and (ii) \( \gamma_j \) different for all cavities (asymmetric cavities). Equation (26) allows us to obtain the damping effects of the cavities after the generation of the two-photon EPR or W state and estimating the behaviour of their fidelities, defined as \( F = \langle \psi | \rho | \psi \rangle \). However, for simplicity, we use a by-pass procedure that uses the phenomenological-operator approach [31] which allows us to get damping effects similar to those obtained through equation (26). For the case of \( n \) photons in the cavity, the evolution of the whole state vector can be phenomenologically...
assuming the atom detected in its ground state we find respectively.

\[ F = \Delta t \]

same. As usual, the reduced density matrix for the cavity field \( n \)-photon state and also the probability that it will remain the probability that a given state has originated from the initial | state is given by

\[ \rho_S(t) = \text{Tr}_R [\rho_{S+R}(t)] , \]

\[ \rho_{S+R}(t) = |\Psi_{S+R}(t) \rangle \langle \Psi_{S+R}(t)| , \]

where the subscripts \( S \) and \( R \) refer to the system and the reservoir, respectively.

Now, we get the fidelity of the EPR and W states: assuming the atom detected in its ground state we find

\[ F_{\text{EPR}} = \frac{e^{-2\gamma t}}{2P_g} |C_{e0}^{(0)}(t_1)C_{g2}^{(0)}(t_2) e^{-\Delta_1 t} + C_{g2}^{(0)}(t_1)|^2 , \]

\[ F_W = \frac{e^{-2\gamma t}}{4P_g} |C_{e0}^{(0)}(t_1)C_{g0}^{(0)}(t_2)C_{g2}^{(0)}(t_3) e^{-\Delta_2 t} + C_{g2}^{(0)}(t_2) e^{-\Delta_1 t} |^2 , \]

where we have considered the time \( t \) starting at the end of the state preparation, which is justified by the fact that the decoherence time is much longer than the time for the state preparation, as discussed below. In this case, note that the initial fidelities (\( t = 0 \)) are 97% and 95% for the EPR and W cases, respectively. We also consider \( \gamma_1 = \gamma \), \( \Delta_1 = \gamma_2 - \gamma_1 \), \( \Delta_2 = \gamma_3 - \gamma_1 \), with \( \gamma_1 = \gamma_2 = \gamma_3 = \gamma \) for the symmetric case and \( \Delta_2 = -\Delta_1 = 0.05\gamma \), i.e. we consider asymmetric cavities with a difference of 5% in their parameters \( \gamma_i \), as an example. Actually, the case of symmetric cavities \( (\gamma_1 = \gamma_2 = \gamma_3 = \gamma) \) neglects the realistic in practice given the difficulties to construct such high-Q cavities. In this case one observes no significant change in the fidelity. Figure 6 shows the fidelity for symmetric cavities of the two-photon EPR and W states under decoherence effects. Note that the damping factor \( \exp(-2\gamma t) \) (symmetric cavities) is the same as in EPR and W cases. This occurs due to the association of damping with the mean number of photons inside the cavities, being the same as in the two cases.

On the other hand, the spread in the velocity of the atoms may also affect the fidelity of the state to be generated. Nowadays, in typical QED-cavity experiments, velocity-selected atomic beams have fluctuations less than 0.5% [32], which reduces the fidelity of the EPR (W) state by 1% (2%). So the atomic velocity spread plays a milder role in the fidelity.

### 6. Conclusion

In conclusion, we presented a scheme for the generation of the two-photon EPR and W states in the cavity QED context. Concerning the experimental feasibility, the devices used here were based on [27] concerned with the Rydberg atoms with the quantum number \( n \sim 90 \). The coupling constant of these atoms with the cavity is taken close to \( g = 17.5 \text{ MHz} \). In our simulations we have used this value and a detuning of 30 \( g \) [27]. As an example, by choosing the interaction times as \( t_1 = t_2 = 3 \mu s \) for the two-photon EPR state the success probability and fidelity result approximately 40% and 97%, respectively; if we consider \( t_1 = t_2 = 32 \mu s \) for the two-photon W state, the success probability and fidelity result 30% and 95%, respectively. The time spent for the entire procedure is approximately \( 10^{-4} \text{s} \) for the EPR and W states. This time is much smaller than the decoherence time of the cavity (0.05 s) [33], which shows the experimental feasibility of the scheme. We have also verified such a statement for our scenario by explicitly calculating the decoherence effects upon these two states.

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