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Generation of three-qutrit singlet states for three atoms trapped in separated cavities

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ABSTRACT

Based on quantum Zeno dynamics and adiabatic passage, a scheme for the generation of three-qutrit singlet states for three atoms distributed in three fiber-coupled cavities is proposed, which is insensitive to the fluctuation of atom-cavity coupling rate g and fiber-cavity coupling rate ν when $\nu \geq g$. Moreover, the influence of atomic spontaneous emission and photon loss on the fidelity is greatly reduced since there are no excitations for atoms, cavities, and fibers.

1. Introduction

Quantum entanglement, a most significant resource for quantum information processing (QIP), is a distinctive feature of quantum mechanics [1]. Nowadays, there is much attention focused on high-dimensional entanglement, which offers larger vibrations of nonlocality via Bell tests [2], has applications in increased-security quantum cryptography [3], and so on. A special type of high-dimensional entanglement called *N*-particle *N*-dimensional singlet states with the form

$$|S_N\rangle = \frac{1}{N!}\sum_{permutations\ of\ 01\cdots(N-1)} (-1)^t|ij\cdots n\rangle \quad (1)$$

was discovered by Cabello [4]. Here, t is the number of transpositions of pairs of elements that must be composed to place elements in canonical order (i.e., 0, 1, 2, …, N-1). It has been proved that the total spin of $|S_N\rangle$ equals zero, which makes it possible not only to construct decoherence-free subspaces (DFS) [5], but also to solve "*N*-strangers", "secret sharing", and "liar detection" problems [6]. Taken into account these advantages, some proposals have been presented for the preparation of $|S_N\rangle$ [7–11]. However, most of them require atoms (ions) interacting with a cavity (vibrational mode), which results in a very short distance among particles.

A fiber-coupled-cavity system is viewed as one of potential candidates for the implementation of long-distance quantum communication and distributed quantum computation. The reason is that in this configuration the qubits can be manipulated easily [12]. Now there have been several potential techniques demonstrated for experimentally implementing this framework [13,14]. Based on these techniques, some protocols for quantum state preparation and distributed quantum computation have been presented [15–19]. However, it is still a challenge to construct a large-scale architecture for quantum networks under different dissipation sources such as atomic spontaneous emissions and photon loss [20,21]. Luckily, these problems may be solved by a method called quantum Zeno dynamics (QZD) which stems from quantum Zeno effect [22]. It is proved that QZD can guide a quantum-state evolution within a "Zeno subspace" defined by measurement [23,24]. By means of this method, many proposals are designed to protect quantum systems against dissipation. For instance, a robust atomic entanglement preparation and a distributed CNOT gate in two coupled cavities have been proposed [25,26]. However, both schemes require exactly controlling pulse sequences and interaction time. Luckily, the restriction may be loosened with adiabatic-passage technology [27,28].

In this paper we propose an alternative scheme for the preparation of three-qutrit singlet states for three atoms distributed in three fiber-coupled cavities via QZD and adiabatic passage. It has the following significant advantages: (i) each atom can be manipulated easily; (ii) pulse sequences, interaction time, and atom-cavity (fiber-cavity) coupling rates do not need to be exactly

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controlled; (iii) the effect of atomic spontaneous emission and photon loss on the fidelity is reduced.

2. Preparation of three-atom singlet states

Consider three atoms 1, 2, and 3 each having an excited state $|e_0\rangle$ and three ground states $|g_L\rangle$, $|g_0\rangle$, and $|g_R\rangle$ are respectively trapped in three two-mode cavities 1, 2, and 3, as shown in Fig. 1. Cavities 1, 2 and 3 are resonantly connected by a short optical fiber 1 or 2. In the kth cavity, the atomic transition $|g_L\rangle_k \leftrightarrow |e_0\rangle_k$ $\left(|g_R\rangle_k \leftrightarrow |e_0\rangle_k\right)$ for the kth atom is resonantly coupled to the left-circular (right-circular) polarization mode with coupling rate g_{Lk} (g_{Rk}), while the transition $|g_0\rangle_k \leftrightarrow |e_0\rangle_k$ is resonantly driven by a π pulse with time-dependent coupled rate $\Omega_k(t)$. In the short-fiber limit $L\lambda/2\pi c << 1$ with L the fiber length, c the speed of light, and λ the decay rate of the cavity field into a continuum of fiber modes, only the resonant fiber modes with left-circular or right-circular polarizations interact with corresponding cavity modes [12]. Then in the resolved sideband and under the rotating-wave approximation, the interaction Hamiltonian for the atom-cavity-fiber system reads

$$H_I = \sum_{k=1}^{3} \Omega_k(t)|e_0\rangle_k\langle g_0| + \sum_{j=L,R}\sum_{k=1}^{3} g_{jk}|e_0\rangle_k\langle g_j|a_{jk} + \sum_{j=L,R} \nu_{j1}a_{j1}b_{j1}^{+} + \nu_{j2}a_{j2}b_{j1}^{+} + \nu_{j3}a_{j1}b_{j2}^{+} + \nu_{j4}a_{j3}b_{j2}^{+} + H.c. \qquad (2)$$

where the subscript j $(j = L, R)$ represents j (j=left, right)-circular polarization mode for cavities or fibers, k $(k = 1, 2, 3)$ indicates the kth atom or cavity, a (a^{+}) and b (b^{+}) are the annihilation (creation) operators for cavities and fiber modes, respectively; and ν_{jm} $(j = L, R;\ m = 1, 2, 3, 4)$ is the coupling strength between a fiber and the corresponding cavity. The state of three cavities (two fibers) containing x, y, z (α, β) photons is denoted as $|x, y, z\rangle_{a_1a_2a_3}\left(|\alpha, \beta\rangle_{b_1b_2}\right)(x, y, z, \alpha, \beta = 0, L, R)$ with $\{|1\rangle, |2\rangle, \cdots, |25\rangle\}$ representing the vacuum state, $|1\rangle = |e_0g_Lg_R\rangle_{123}|000\rangle_{a_1a_2a_3}|00\rangle_{b_1b_2}$ represents only one left (right)-circularly polarized photon but nothing for right (left)-circularly polarized photons.

For the sake of simplicity, all the atom-cavity coupling rates and fiber-cavity coupling rates are respectively set to be equal, i.e., $g_{jk} = g$ $(j = L, R;\ \ k = 1, 2, 3)$ and $\nu_{jm} = \nu (j = L, R;\ m = 1, 2, 3, 4)$.

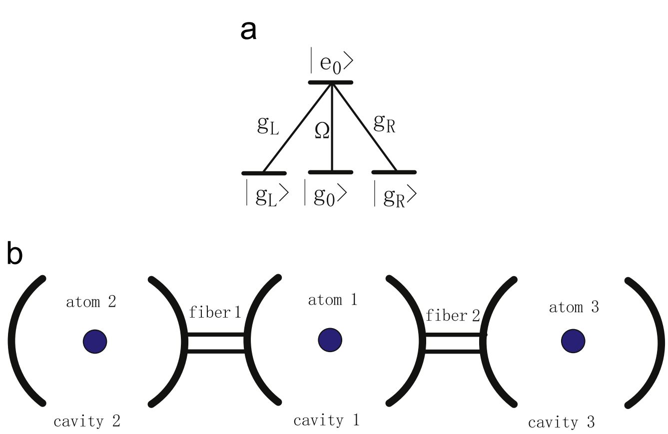

Fig. 1. (color online) (a) Sketch for atomic level configurations and transitions. (b) Diagram for preparing three-atom. singlet states. Three atoms are trapped in three spatially separated cavities 1, 2, and 3, respectively. Cavities 1 and 2 (3) are linked through the optical fiber 1 (2).

Then in the symmetrical subspace $\{|1\rangle, |2\rangle, \cdots, |25\rangle\}$ with

$$\begin{aligned}
|1\rangle &= |e_0g_Lg_R\rangle_{123}|000\rangle_{a_1a_2a_3}|00\rangle_{b_1b_2},\\
|2\rangle &= \frac{1}{\sqrt{2}}\left(|g_Lg_Lg_R\rangle_{123}|L00\rangle_{a_1a_2a_3} + |g_Rg_Lg_R\rangle_{123}|R00\rangle_{a_1a_2a_3}\right)|00\rangle_{b_1b_2},\\
|3\rangle &= \frac{1}{\sqrt{2}}\left(|g_Lg_Lg_R\rangle_{123}|0L\rangle_{b_1b_2} + |g_Rg_Lg_R\rangle_{123}|R0\rangle_{b_1b_2}\right)|000\rangle_{a_1a_2a_3},\\
|4\rangle &= \frac{1}{\sqrt{2}}\left(|g_Lg_Lg_R\rangle_{123}|00L\rangle_{a_1a_2a_3} + |g_Rg_Lg_R\rangle_{123}|0R0\rangle_{a_1a_2a_3}\right)|00\rangle_{b_1b_2},\\
|5\rangle &= \frac{1}{\sqrt{2}}\left(|g_Lg_Lg_R\rangle_{123}|L0\rangle_{b_1b_2} + |g_Rg_Lg_R\rangle_{123}|0R\rangle_{b_1b_2}\right)|000\rangle_{a_1a_2a_3},\\
|6\rangle &= \frac{1}{\sqrt{2}}\left(|g_Lg_Lg_R\rangle_{123}|0L0\rangle_{a_1a_2a_3} + |g_Rg_Lg_R\rangle_{123}|00R\rangle_{a_1a_2a_3}\right)|00\rangle_{b_1b_2},\\
|7\rangle &= \frac{1}{\sqrt{2}}\left(|g_Le_0g_R\rangle_{123} + |g_Rg_Le_0\rangle_{123}\right)|000\rangle_{a_1a_2a_3}|00\rangle_{b_1b_2},\\
|8\rangle &= \frac{1}{\sqrt{2}}\left(|g_Lg_Rg_R\rangle_{123}|0R0\rangle_{a_1a_2a_3} + |g_Rg_Lg_L\rangle_{123}|00L\rangle_{a_1a_2a_3}\right)|00\rangle_{b_1b_2},\\
|9\rangle &= \frac{1}{\sqrt{2}}\left(|g_Lg_Rg_R\rangle_{123}|R0\rangle_{b_1b_2} + |g_Rg_Lg_L\rangle_{123}|0L\rangle_{b_1b_2}\right)|000\rangle_{a_1a_2a_3},\\
|10\rangle &= \frac{1}{\sqrt{2}}\left(|g_Lg_Rg_R\rangle_{123}|R00\rangle_{a_1a_2a_3} + |g_Rg_Lg_L\rangle_{123}|L00\rangle_{a_1a_2a_3}\right)|00\rangle_{b_1b_2},\\
|11\rangle &= \frac{1}{\sqrt{2}}\left(|g_Lg_Rg_R\rangle_{123}|0R\rangle_{b_1b_2} + |g_Rg_Lg_L\rangle_{123}|L0\rangle_{b_1b_2}\right)|000\rangle_{a_1a_2a_3},\\
|12\rangle &= \frac{1}{\sqrt{2}}\left(|g_Lg_Rg_R\rangle_{123}|00R\rangle_{a_1a_2a_3} + |g_Rg_Lg_L\rangle_{123}|0L0\rangle_{a_1a_2a_3}\right)|00\rangle_{b_1b_2},\\
|13\rangle &= \frac{1}{\sqrt{2}}\left(|g_Lg_Re_0\rangle_{123} + |g_Re_0g_L\rangle_{123}\right)|000\rangle_{a_1a_2a_3}|00\rangle_{b_1b_2},\\
|14\rangle &= \frac{1}{\sqrt{2}}\left(|g_Lg_Rg_L\rangle_{123}|00L\rangle_{a_1a_2a_3} + |g_Rg_Rg_L\rangle_{123}|0R0\rangle_{a_1a_2a_3}\right)|00\rangle_{b_1b_2},\\
|15\rangle &= \frac{1}{\sqrt{2}}\left(|g_Lg_Rg_L\rangle_{123}|0L\rangle_{b_1b_2} + |g_Rg_Rg_L\rangle_{123}|R0\rangle_{b_1b_2}\right)|000\rangle_{a_1a_2a_3},\\
|16\rangle &= \frac{1}{\sqrt{2}}\left(|g_Lg_Rg_L\rangle_{123}|L00\rangle_{a_1a_2a_3} + |g_Rg_Rg_L\rangle_{123}|R00\rangle_{a_1a_2a_3}\right)|00\rangle_{b_1b_2},\\
|17\rangle &= \frac{1}{\sqrt{2}}\left(|g_Lg_Rg_L\rangle_{123}|L0\rangle_{b_1b_2} + |g_Rg_Rg_L\rangle_{123}|0R\rangle_{b_1b_2}\right)|000\rangle_{a_1a_2a_3},\\
|18\rangle &= \frac{1}{\sqrt{2}}\left(|g_Lg_Rg_L\rangle_{123}|0L0\rangle_{a_1a_2a_3} + |g_Rg_Rg_L\rangle_{123}|00R\rangle_{a_1a_2a_3}\right)|00\rangle_{b_1b_2},\\
|19\rangle &= |e_0g_Rg_L\rangle_{123}|000\rangle_{a_1a_2a_3}|00\rangle_{b_1b_2},\\
|20\rangle &= |g_0g_Lg_R\rangle_{123}|000\rangle_{a_1a_2a_3}|00\rangle_{b_1b_2},\\
|21\rangle &= |g_Lg_0g_R\rangle_{123}|000\rangle_{a_1a_2a_3}|00\rangle_{b_1b_2},\\
|22\rangle &= |g_Rg_Lg_0\rangle_{123}|000\rangle_{a_1a_2a_3}|00\rangle_{b_1b_2},\\
|23\rangle &= |g_Lg_Rg_0\rangle_{123}|000\rangle_{a_1a_2a_3}|00\rangle_{b_1b_2},\\
|24\rangle &= |g_Rg_0g_L\rangle_{123}|000\rangle_{a_1a_2a_3}|00\rangle_{b_1b_2},\\
|25\rangle &= |g_0g_Rg_L\rangle_{123}|000\rangle_{a_1a_2a_3}|00\rangle_{b_1b_2}, \qquad (3)
\end{aligned}$$

the interaction Hamiltonian described in Eq. (2) reduces to

$$\begin{aligned}
H_I' &= H_{al} + H_{acb}\\
H_{al} &= \frac{1}{\sqrt{2}}\Big[\sqrt{2}\Omega_1(t)|20\rangle\langle 1| + \sqrt{2}\Omega_1(t)|25\rangle\langle 19|\\
&+ \Omega_2(t)|21\rangle\langle 7| + \Omega_2(t)|24\rangle\langle 13| + \Omega_3(t)|22\rangle\langle 7| + \Omega_3(t)|23\rangle\langle 13|\Big]\\
&+ H.c.\ H_{acb} = \sqrt{2}g|1\rangle\langle 2| + \nu(|2\rangle\langle 3| + |3\rangle\langle 4| + |2\rangle\langle 5| + |5\rangle\langle 6|)\\
&+ g(|6\rangle\langle 7| + |7\rangle\langle 8|) + \nu(|8\rangle\langle 9| + |9\rangle\langle 10| + |10\rangle\langle 11| + |11\rangle\langle 12|)\\
&+ g(|12\rangle\langle 13| + |13\rangle\langle 14|) + \nu(|14\rangle\langle 15| + |15\rangle\langle 16| + |16\rangle\langle 17|\\
&+ |17\rangle\langle 18|) + \sqrt{2}g|16\rangle\langle 19| + H.c. \qquad (4)
\end{aligned}$$