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Scheme for generating the singlet state of three atoms trapped in distant cavities coupled by optical fibers

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ABSTRACT

An effective scheme is proposed to generate the singlet state with three four-level atoms trapped in three distant cavities connected with each other by three optical fibers, respectively. After a series of appropriate atom–cavity interactions, which can be arbitrarily controlled via the selective pairing of Raman transitions and corresponding optical switches, a three-atom singlet state can be successfully generated. The influence of atomic spontaneous decay, photon leakage of cavities and optical fibers on the fidelity of the state is numerically simulated showing that the three-atom singlet state can be generated with high fidelity by choosing the experimental parameters appropriately.

1. Introduction

Quantum entanglement is one of the most significant features of quantum mechanics. Entangled states have many promising practical applications in different areas such as quantum computing

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[1–5], quantum teleportation [6–8], quantum cryptography [9,10], quantum dense coding [11], precision measurements [12] and quantum information processing [13,14]. Over the past few years, a large number of schemes have been proposed to generate entangled states in various physical systems, including cavity quantum electrodynamics (QED) [15–19], trapped ions [20,21], semiconductor quantum dots [22], linear optics [23–25], and so on. The problem of multi-particle entanglement is very important for studying the further characterization of multi-body physics modes [26]. It is well known that Greenberger–Horne–Zeilinger (GHZ) state and W state are the representatives of multi-particle entangled states. Both of them have many useful applications in quantum information processing and many theoretical and experimental schemes have been proposed for generating multi-particle GHZ state and W state [27–30]. However, they cannot be converted to each other by local operations and classical communications (LOCC). Different from the above two types of multipartite entangled states, there exists another type of genuine multi-particle entangled state [31]

$$|S_N\rangle = \frac{1}{\sqrt{N!}} \sum_{\substack{\text{permutations}\\ \text{of } 01\ldots(N-1)}} (-1)^t |ij\ldots n\rangle, \tag{1}$$

which is called N-particle N-level singlet state and where t is the number of transpositions of pairs of elements that must be composed to place the elements in canonical order (i.e., $0, 1, 2, \ldots, N-1$). It has been proved that some types of singlet states can be used to test quantum mechanics against local hidden theory [32,33] and construct decoherence-free subspaces which are immunized to collective decoherence [34]. Moreover, the singlet state is important to solve certain practical problems without classical solutions [31,35], such as the N strangers problem, the secret sharing problem, and the liar detection problem. Although the singlet state $|S_N\rangle$ has many potential applications, it is still a formidable physical challenge to generate the states $|S_N\rangle$ for $N \geq 3$ experimentally. So far only a few schemes were proposed to generate the three-particle singlet state $|S_3\rangle$ [36–38]. In 2005, Jin et al. [36] proposed a scheme to generate the singlet state $|S_3\rangle$ by three atoms sequentially sent through three different microwave cavities. In the scheme, the cavity fields, which store the information of atomic systems and transfer them back to the atomic systems, act as memories, and the measurement of the cavity field are required. Subsequently, Lin et al. [37] proposed a simpler scheme to engineer the singlet state $|S_3\rangle$ using three atoms in cavity QED via Raman transitions. The scheme is insensitive to cavity decay and it does not need to detect the states of the cavity fields. However, both of the schemes mentioned-above need to control and drive the atoms precisely entering and exiting the cavities back and forth during the operation processes.

In this paper, we propose a scheme for generating the three-atom singlet state $|S_3\rangle$ with the following form,

$$\frac{1}{\sqrt{6}}\Big(|efg\rangle_{123} - |egf\rangle_{123} - |gef\rangle_{123} + |gfe\rangle_{123} + |fge\rangle_{123} - |feg\rangle_{123}\Big), \tag{2}$$

where $|g\rangle$, $|e\rangle$, and $|f\rangle$ are the three ground states of a four-level atom. In the scheme, each atom is trapped in an individual optical cavity and each two cavities are connected by an optical fiber. The three ground states of each atom are coupled via the cavity mode and different classical fields in the Raman processes and the atoms do not undergo the real Raman transitions due to the large detuning. Furthermore, the Hamiltonian of the atom–cavity–fiber system is decoupled from the cavity modes and fiber modes and the quantum state just be mediated by virtual excitation and transportation of photons. Compared with the previous schemes [36,37], our scheme has the following advantages: (i) it does not need to control and drive the atoms entering and exiting the cavities time and again during the operation process, which greatly simplify the experimental realization; (ii) the scheme is insensitive to the cavity decay, fiber loss, and atomic spontaneous emission. We numerically simulated effects of the atomic spontaneous decay and photon leakage out of the fibers and the cavities, the numerical results show that the three-atom singlet state can be generated with high fidelity by choosing the parameters appropriately.

The paper is organized as follows: In Section 2, we describe the model under considering the certain conditions and derive the effective Hamiltonian of the system. In Section 3, we demonstrate how to generate the three-atom singlet state deterministically. In Section 4, we study the influence of