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Generation correlated four-mode states in cavity QED

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Abstract

A scheme for preparing correlated four-mode states with controllable weighting factors is presented. In the scheme, a sequence of suitably prepared four-level atoms are orderly sent through two bimodal cavities, the detection of all atoms in ground state collapses cavity fields to the desire state. The distinct advantage of our scheme is that the interaction time can be greatly shortened, which is important in view of decoherence.

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Keywords: Correlated four-mode states; Four-level atom; Resonant interaction

One of the central topics in quantum optics is quantum state engineering. So far, a number of schemes have been presented for generating various quantum states. In cavity QED, schemes have been proposed for the generation of Schrodinger cat states of a cavity field [1–3]. On the other hand, many schemes have been proposed to prepare any Fock state superposition of an electromagnetic field. Vogel et al. [4] have firstly proposed a method for producing an arbitrary superposition of $n+1$ photon number states from the vacuum state by injecting n approximately prepared atoms into a cavity and detecting all of them in the ground state. Parkins et al. [5] have proposed a scheme for generating such superposition states via adiabatic passage. Zheng [6] has shown that such states can be generated via the interaction of a multilevel atom with a single-mode cavity field. Recently, the correlated quantum states of a multi-mode field have aroused much interest and many schemes have been presented for preparing such states [7–11]. Sanders et al. [8] have presented a scheme to generate entangled coherent states with the help of a Mach–Zehnder interferometer. Davidovich et al. [9] have proposed a method for producing quantum superpositions of coherent microwave field states located simultaneously in two cavities by using two quantum switches.

More recently, many people are interested in the multi-dimensional (more than two) quantum systems. The proof of Bell's theorem without the inequalities presented by Greenberger, Horne, and Zeilinger was extended to multiparticle multi-dimensional systems [12,13]. It has been shown that quantum key distributions based on N-dimensional systems are more secure than those based on two-dimensional systems [14,15]. It also has been demonstrated that violations of local realism caused by two entangled N-dimensional ($N \geqslant 3$) systems are stronger than that by two-dimensional systems [16].

In the context of cavity QED, various schemes have been proposed for preparing maximally entangled states. Zheng [17] has proposed an alternative scheme for generating multi-dimensional entanglement between two or more multilevel atoms in a thermal cavity. Shu et al. [18] have presented a scheme for generating four-mode multiphoton entangled states.

In this paper, we propose a scheme to generate correlated four-mode states with controllable weighting factors via four-level atom resonantly interacting with two bimodal cavities, which are initially prepared in the two-mode vacuum state. In

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the scheme, atoms which are produced in zone B by the excitation of a velocity selected atomic beam effusing from oven O, pass through the first cavity. Before the atoms enter the second cavity, they are sent through two classical fields F_1 and F_2 in turn. As is described in Fig. 1. The distinct advantage of our scheme is that the interaction time can be greatly shortened, which is important in view of decoherence. As the application of this scheme, we show how to generate four-mode multiphoton maximally entangled states.

Suppose the atom has four states denoted by $|e\rangle$, $|g\rangle$, $|i\rangle$, and $|g'\rangle$, with the energy-level ω_i, ω_g, ω_e and $\omega_{g'}$, respectively. Let us consider the resonant interaction of a four-level atom with a two-mode field, as sketched in Fig. 2. The transition between $|e\rangle$ and $|g\rangle$ is coupled to cavity mode 1, while the transition between $|g\rangle$ and $|i\rangle$ is coupled to cavity mode 2. The transition between $|e\rangle$ ($|g\rangle$, $|i\rangle$) and $|g'\rangle$ is highly detuned from both the cavity modes, respectively, thus the state $|g'\rangle$ is a auxiliary level which performs the transformation $|g\rangle$ to $|g'\rangle$ so that the interaction of the atom with the second cavity is frozen if the atom is in the state $|g\rangle$ after exit the first cavity. The Hamiltonian for such a system is written as ($\hbar = 1$) [19]

$$H = \omega_e|e\rangle\langle e| + \omega_g|g\rangle\langle g| + \omega_i|i\rangle\langle i| + \omega_1 a_1^+ a_1 + \omega_2 a_2^+ a_2 + g_1(a_1^+|g\rangle\langle e| + a_1|e\rangle\langle g|) + g_2(a_2^+|i\rangle\langle g| + a_2|g\rangle\langle i|) \tag{1}$$

where a_i^+ and a_i ($i = 1, 2$) are the creation and annihilation operators for the cavity fields, g_1 (g_2) is the coupling constant of the transition between $|e\rangle$ ($|i\rangle$) and $|g\rangle$ with the cavity field, ω_1, ω_2 are the frequencies of two-mode cavity field. In the interaction picture, the interaction Hamiltonian is given by

$$H_I = \lambda(a_1^+|g\rangle\langle e| + a_2^+|i\rangle\langle g|) + H.c, \tag{2}$$

we here assume that $g_1 = g_2 = \lambda$. The basis states for the system are of the form

$$|n_1, n_2, n_3, n_4, s\rangle = |n_1\rangle|n_2\rangle|n_3\rangle|n_4\rangle|s\rangle, \tag{3}$$

where n_i ($i = 1, 2, 3, 4$) refers to the number of excitations in modes of two bimodal cavities and s refers to the state of four-level atom.

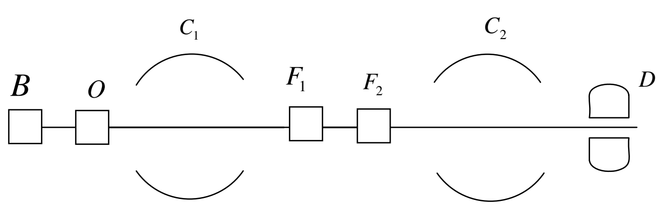

Fig. 1. The displays of the set-up for engineering correlated four-mode states. The atom is produced in zone B by the excitation of a velocity selected atomic beam effusing from oven O, F_1 and F_2 are two classical fields tuned to the transitions $|e\rangle \leftrightarrow |i\rangle$, and $|g\rangle \leftrightarrow |g'\rangle$, respectively, C_1, C_2 are the two-mode cavities, D is the detector for the state $|i\rangle$.

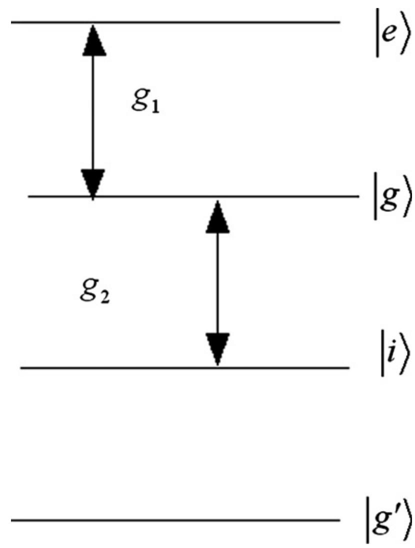

Fig. 2. Schematic diagram of energy level of four-level atom with corresponding transition ($|e\rangle$, $|g\rangle$, $|i\rangle$ and $|g'\rangle$ denote the states of the atom, g_1, g_2 are the coupling coefficients).