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Preparation of Fock states and quantum entanglement via stimulated Raman adiabatic passage using a four-level atom

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Abstract. We study the behaviour of an atom-cavity system exposed to a stimulated Raman adiabatic passage (STIRAP) process in a four-level system, with a coupling scheme which generate two degenerate dark states. We find that the non-adiabatic interaction of the two dark states guarantees that the cavity Fock states can always be generated by both intuitively and counterintuitively ordered pulses. Furthermore, we propose a method to entangle two atoms. Depending on the ordering of the pulses two orthogonal entangled states can be prepared. Since these entangled states do not have component of the excited states included, the technique is robust against the detrimental consequences of spontaneous emission.

PACS. 42.50.Dv Nonclassical field states; squeezed, antibunched, and sub-Poissonian states; operational definitions of the phase of the field; phase measurements – 03.65.Ta Foundations of quantum mechanics; measurement theory

1 Introduction

The state of a coupled quantum system is said to be entangled if it can not be expressed as a product of states of the individual subsystems. This implies that the system is correlated. Entangled states of two particles were first proposed by Einstein, Podolsky and Rosen (EPR states) [1], and they have long been demonstrated experimentally [2]. Such two-particle entanglement is in the realm of the original derivation of Bell's theorem [3], which states that local hidden-variable theories of quantum mechanics are not valid. Entangled states are the basis of important quantum effects, such as teleportation of quantum states [4], and certain types of quantum cryptography [5]. Greenberger, Horne and Zeilinger [6] have shown that much stronger refutations of local realism can be provided by an entangled state involving three or more particles (GHZ state). The entangled states of two or more particles have been proposed by many authors [7–10]. Recently, a three-photon GHZ state has been observed experimentally [11] based on the method proposed by Zeilinger *et al.* [12], and Sackett *et al.* [13] have experimentally realized an entangled state of four ions. Entangled states of two- or multi-particle are fascinating quantum systems; the realization of such states will stimulate novel applications in quantum information processing [14,15].

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Coherent population transfer between atomic ground-state levels originates from the concept of coherent population trapping [16]. The technique of stimulated Raman adiabatic passage (STIRAP) [17,18] allows, in principle, a complete population transfer from a single initial state to another single target state. Two different classical laser pulses are used in this method: the first (pump) laser pulse couples the ground state to the excited state which is connected by a second (Stokes) laser pulse to the final state. If the pump and Stokes frequencies maintain two-photon resonance, and if the Stokes laser pulse precedes the pump laser pulse (counterintuitively ordered pulses), then an efficient population transfer occurs when the evolution is adiabatic, that is when an adiabatically decoupled (dark) state exists.

An important feature of this scheme is that the adiabatic transformation is applied to the dark eigenstate of the system, *i.e.*, the relevant eigenstate contains no contribution from the excited atomic state. Therefore the technique is immune to the detrimental consequences of atomic spontaneous emission. The remarkable properties of the process have lead to interesting applications in chemical-reaction dynamics [19], laser-induced cooling [20], atomic optics [21], cavity QED [22–24] and preparation of entanglement and quantum computation [25,26]. In reference [22], Parkins *et al.* considered one of the light (Stokes) fields to be the field mode of a high finesse cavity and showed how to prepare a Fock state in the cavity.

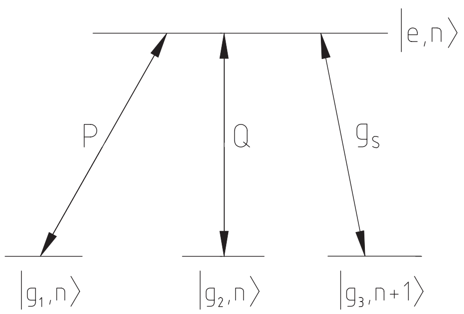

Fig. 1. A four-level atom with excited state $|e\rangle$, and degenerate ground states $|g_1\rangle$, $|g_2\rangle$ and $|g_3\rangle$. The pump pulse $P(t)$ couples state $|g_1\rangle$ to the excited state $|e\rangle$. The control pulse $Q(t)$ couples state $|g_2\rangle$ to $|e\rangle$. The Stokes pulse is provided by the cavity field, it couples state $|g_3\rangle$ to $|e\rangle$. The atom-cavity-mode coupling strength is $g_\mathrm{S}(t)$.

They found that adiabatic passage of an atom through the interaction region creates a single photon Fock state "out of the vacuum". Sequences of atoms can be used to generate higher photon number Fock state. Recently Hennrich *et al.* [24] succeeded in generating single photons based on the scheme discussed in reference [23]. In reference [25], Lange and Kimble considered the general case of two degenerate cavity modes with orthogonal polarization and showed that, for a suitably cavity detuning, it is possible to generate maximally entangled photon multiplets by the adiabatic passage technique. In reference [26], Pellizzari *et al.* presented a scheme for the design of a two-qubit gate using the adiabatic passage technique, in which the qubits are implemented in Zeeman ground state levels of the trapped atoms.

Recently, Unanyan *et al.* [27,28] extended the standard STIRAP technique to a four-level system. They described a method for creating an arbitrary coherent superposition of atomic states in a controlled and robust way by using a sequence of three laser pulses in the four-level system. They showed for a four-level system that due to the interaction of two dark states, a complete population transfer from the initial state to a predetermined superposition of quantum states can be realized.

In this paper, we investigate the behaviour of a four-level atom-cavity system in which the Stokes field is the field of a cavity (see Fig. 1). The ground state is a threefold degenerate state. We find that the cavity Fock states can be generated by both intuitively and counterintuitively ordered pulses due to the interaction of the two dark states. We propose a method to entangle two atoms by using the adiabatic passage scheme in an optical cavity, and show that two orthogonal entangled states can be prepared by different pulse orderings. No excited level is included in these entangled states.

The outline of this paper is as follows. In Section 2, we present the two dark states of the four-level atom-cavity coupling system, in Section 3, we investigate the preparation of Fock states in the system, in Section 4, we propose a method to entangle two atoms by using the adiabatic passage scheme. Finally, in Section 5, we offer some conclusive remarks.

2 The model of four-level atom-cavity system

We consider a four-state atomic system with an excited state $|e\rangle$, and the degenerate ground states $|g_1\rangle$, $|g_2\rangle$ and $|g_3\rangle$, as illustrated in Figure 1. The pump pulse $P(t)$ couples state $|g_1\rangle$ to the excited state $|e\rangle$. The control pulse $Q(t)$ couples the states $|g_2\rangle$ and $|e\rangle$. $P(t)$ and $Q(t)$ are classical laser fields. Unlike the case discussed in references [27,28], here the Stokes pulse $g_\mathrm{S}(t)$ is provided by a cavity field. It couples the states $|g_3\rangle$ and $|e\rangle$. The three fields interact with the atom sequentially, each of the fields is in one-photon resonance with the respective transition. The Hamiltonian for this system can be written as follows:

$$\begin{aligned} H(t) = \hbar\omega a^+ a + \hbar\omega_{eg}|e\rangle\langle e| + \hbar g_\mathrm{S}(t)\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{S}}(|e\rangle\langle g_3|a + \mathrm{H.c.}) \\ + \hbar P(t)\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{P}}\mathrm{e}^{-\mathrm{i}\omega t}(|e\rangle\langle g_1| + \mathrm{H.c.}) \\ + \hbar Q(t)\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{Q}}\mathrm{e}^{-\mathrm{i}\omega t}(|e\rangle\langle g_2| + \mathrm{H.c.}), \end{aligned} \quad (1)$$

where a and a^+ are the annihilation and creation operators for the cavity mode, respectively. The carrier frequencies of the pump, control and Stokes pulses are ω, ω_1 and ω_2 ($\omega = \omega_1 = \omega_2 = \omega_{eg}$), φ_P, φ_Q and φ_S are phases of the Rabi frequencies $P(t)$, $Q(t)$ and $g_\mathrm{S}(t)$, respectively. In order to satisfy the adiabatic passage condition for the time when $g_\mathrm{S}(t)$ reaches its peak value, we require that $g_{\max}T \gg 1$, that is a "vacuum Rabi splitting" would be observable in the coupled atom-cavity system [29–31]. The time dependence of $P(t)$, $Q(t)$ and $g_\mathrm{S}(t)$ is provided by the motion of the atoms across the laser and cavity-field profiles.

The Hamiltonian $H(t)$ couples only states within the manifold of dressed states $|g_1, n\rangle$, $|g_2, n\rangle$, $|g_3, n+1\rangle$ and $|e, n\rangle$, where $|g, n\rangle \equiv |g\rangle|n\rangle$, $|e, n\rangle \equiv |e\rangle|n\rangle$, and $|n\rangle$ represents a n-photon Fock state of the cavity mode. Such a family is shown in Figure 1. In a frame rotating at the frequency ω, the $H(t)$ has the following eigenvalues, two of which are degenerate:

$$E_n^{(1)} = E_n^{(2)} = n\hbar\omega, \quad (2)$$

$$E^{(\pm)} = n\hbar\omega \pm \frac{\hbar}{2}\sqrt{P^2(t) + Q^2(t) + g_\mathrm{S}^2(t)(n+1)}. \quad (3)$$

The two degenerate eigenstates are:

$$|\Phi_n^1(t)\rangle = \cos\theta(t)\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{S}}|g_1, n\rangle - \sin\theta(t)\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{P}}|g_3, n+1\rangle, \quad (4)$$

$$\begin{aligned} |\Phi_n^2(t)\rangle = \sin\theta(t)\sin\phi(t)\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{S}}|g_1, n\rangle \\ + \cos\theta(t)\sin\phi(t)\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{P}}|g_3, n+1\rangle \\ + \cos\phi(t)\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{Q}}|g_2, n\rangle, \end{aligned} \quad (5)$$

where

$$\tan\theta(t) = \frac{P(t)}{g_\mathrm{S}(t)\sqrt{n+1}}, \quad (6)$$

$$\tan\phi(t) = \frac{Q(t)}{\sqrt{P^2(t) + g_\mathrm{S}^2(t)(n+1)}}\cdot \quad (7)$$

The angle $\theta(t)$ is the mixing angle used in standard STIRAP [18], whereas $\phi(t)$ is an additional mixing angle related to the control pulse $Q(t)$ [27,28]. If the control pulse $Q(t)$ is absent, the system reduces to a three-state atom-cavity system. Indeed equation (4) recovers the result from Parkins *et al.*'s [22].

Here we don't show the non-degenerate eigenstates $|\Phi_n^{\pm}(t)\rangle$. This is because the coupling of the states $|\Phi_n^1(t)\rangle$ and $|\Phi_n^2(t)\rangle$ to $|\Phi_n^{\pm}(t)\rangle$ can be disregarded in the adiabatic limit. However, due to the degeneracy of $|\Phi_n^1(t)\rangle$ and $|\Phi_n^2(t)\rangle$, the coupling between these states cannot be neglected [27,28]. Equations (4, 5) show that these eigenstates do not contain any contribution from the excited state, hence this four-level atom-cavity system has two degenerate "dark" eigenstates. Since the two dark states are degenerate, nonadiabatic coupling between them will occur. The evolution of the four-level atom-cavity system will be significantly influenced by that coupling.

3 Preparation of Fock states using intuitively or counterintuitively ordered pulses

In the adiabatic limit, the time derivatives of the mixing angles $\theta(t)$ and $\phi(t)$ are small compared to the splitting of eigenvalues, given by $\Omega_0 = \sqrt{P^2 + Q^2 + g_S^2(n+1)}$. That is, the effective pulse area must be very large to assure adiabatic evolution. The criteria for adiabatic evolution have been met in recent cavity QED experiments with high finesse optical resonators [32–34]. Therefore, we take into account only transitions between the degenerate states $|\Phi_n^1(t)\rangle$ and $|\Phi_n^2(t)\rangle$.

Without loss of generality we consider the case that initially $|\Psi(t)\rangle$ coincides with $|\Phi_n^1(t)\rangle$,

$$|\Psi_n(-\infty)\rangle = |\Phi_n^1(-\infty)\rangle \cdot \quad (8)$$

At a later time, due to the coupling of the two degenerate eigenstates, $|\Psi_n(t)\rangle$ acquires a component along $|\Phi_n^2(t)\rangle$. The state vector then takes the form (see Ref. [28]), written as

$$|\Psi_n(t)\rangle = \sum_j B_{ij}(t)|\Phi_n^j(t)\rangle \quad (i,j=1,2), \quad (9)$$

where the matrix B, after the interaction, is given by

$$B(\infty) = \begin{pmatrix} \cos\gamma_f & \sin\gamma_f \\ -\sin\gamma_f & \cos\gamma_f \end{pmatrix}, \quad (10)$$

$$\gamma_f = \oint_C \frac{Q\sqrt{n+1}}{\sqrt{P^2 + g_S^2(n+1)}\sqrt{P^2 + Q^2 + g_S^2(n+1)}} \times (g_S \mathrm{d}P - P\mathrm{d}g_S), \quad (11)$$

and C is the closed path in the parameter space. Here γ_f has a geometric origin [35]. It is independent of pulse areas, it depends only on the ratios τ/T, P_0/Q_0 and G_0/Q_0, where T and τ are the pulse lengths and the delay between the Stokes and pump pulses, respectively, and P_0, Q_0 and G_0 are the peak values of P, Q and g_S. Kimble *et al.* [22,25] have considered a similar system (but without $Q(t)$). In their systems, both cavity modes and the pump beam are assumed to have a Gaussian transverse shape with a full width $T = 10\Gamma^{-1}$, here Γ^{-1} is the population lifetime. The maximum Rabi frequency P_0 of the pump field is chosen to be twice the coupling constant G_0, and $G_0 \geq 10\Gamma$, or $G_0 T \geq 100$.

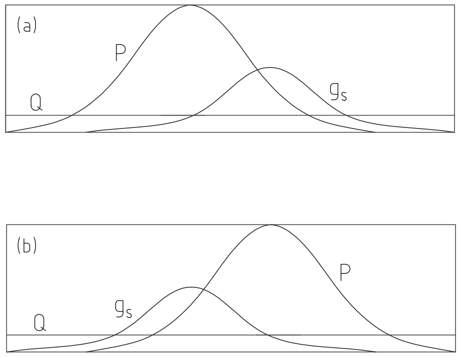

Fig. 2. The intuitively (a) and the counterintuitively (b) ordered pulses.

Now we investigate the scheme for the preparation of Fock states *via* STIRAP in the four-level system based on the equations (4, 5, 9 10). We keep the control pulse $Q(t) \simeq const$ (which implies that the diameter of the Q-laser beam is large compared to the waist of the cavity mode and the P-beam) and require $QT \gg 1$. Using the values from references [22,25], the adiabatic condition is met even if Q is as small as $Q = \Gamma$ (in this case $QT \sim 10$).

In the following we consider both the intuitively ordered (the pump pulse precedes the Stokes pulse, Fig. 2a), and the counterintuitively ordered pulses (the Stokes pulse precedes the pump pulse, Fig. 2b). The intuitively ordered pulse sequence does not allow the preparation of cavity field Fock states in the three-level atom-cavity system [22], *i.e.*, when $Q(t) \equiv 0$. We will show, however, that the cavity field Fock states can be prepared by both the intuitively and counterintuitively ordered pulses in the four-level atom-cavity system for $Q(t) \neq 0$.

We assume that initially all population is in state $|g_1\rangle$. For the intuitively ordered pulses, we have initially $\theta = \pi/2$. Because $Q(t) \simeq const$, we have initially and finally $Q^2 \gg P^2 + g_S^2$ leading to $\phi = \pi/2$. Therefore

$$|\Phi_n^2(-\infty)\rangle = \mathrm{e}^{-\mathrm{i}\varphi_S}|g_1, n\rangle, \quad (12)$$

which means that the state vector is initially identical to the adiabatic state $|\Phi_n^2(t)\rangle$. After the interaction, the mixing angles are $\theta = 0$, and $\phi = \pi/2$ so that $|\Phi_n^1(\infty)\rangle = \mathrm{e}^{-\mathrm{i}\varphi_S}|g_1, n\rangle$ and $|\Phi_n^2(\infty)\rangle = \mathrm{e}^{-\mathrm{i}\varphi_P}|g_3, n+1\rangle$, according to equation (9), we obtain

$$|\Psi_n^{(2)}(\infty)\rangle_{\mathrm{in}} = -\sin\gamma_f \mathrm{e}^{-\mathrm{i}\varphi_S}|g_1, n\rangle + \cos\gamma_f \mathrm{e}^{-\mathrm{i}\varphi_P}|g_3, n+1\rangle \cdot \quad (13)$$

Here and in what follows the subscript "in" ("cin") denotes the ordering scheme, intuitively (counterintuitively) ordered pulses, while the superscript "(2)" ("(1)") means that the state vector is initially identical to $|\Phi_n^2\rangle$ ($|\Phi_n^1\rangle$).

From reference [28] we know that $\gamma_\mathrm{f} \simeq \pi/2$ for $Q \gg P_0, G_0$ and $\gamma_\mathrm{f} \simeq 0$ for $Q \ll P_0, G_0$, and find

$$|\Psi_n^{(2)}(\infty)\rangle_\mathrm{in} = \begin{cases} -\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{S}}|g_1, n\rangle, & \text{for} \quad Q \gg P_0, G_0, \\ \mathrm{e}^{-\mathrm{i}\varphi_\mathrm{P}}|g_3, n+1\rangle, & \text{for} \quad Q \ll P_0, G_0. \end{cases} \tag{14}$$

If the atom is initially in $|g_3\rangle$, then $\theta = \pi/2$ at early time, but $\theta = 0$ and $\phi = \pi/2$ at late time. Therefore, the state vector emerges into

$$|\Psi_n^{(1)}(\infty)\rangle_\mathrm{in} = -\cos\gamma_\mathrm{f}\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{S}}|g_1, n\rangle - \sin\gamma_\mathrm{f}\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{P}}|g_3, n+1\rangle, \tag{15}$$

and

$$|\Psi_n^{(1)}(\infty)\rangle_\mathrm{in} = \begin{cases} -\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{P}}|g_3, n+1\rangle, & \text{for} \quad Q \gg P_0, G_0, \\ -\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{S}}|g_1, n\rangle, & \text{for} \quad Q \ll P_0, G_0. \end{cases} \tag{16}$$

Therefore, intuitive ordering of P and g_S (interaction with the pump beam precedes interaction with the cavity) allows the preparation of a Fock state of the system through the adiabatic transformation $|g_1, n\rangle \to |g_3, n+1\rangle$ (or $|g_1, 0\rangle \to |g_3, 1\rangle$). Similarly, if the system is initially in the state $|g_3, n+1\rangle$ it will be transform into $|g_1, n\rangle$ (or $|g_3, 1\rangle \to |g_1, 0\rangle$).

For the counterintuitively ordered pulses, we obtain with the atoms initially in state $|g_1\rangle$,

$$|\Psi_n^{(1)}(\infty)\rangle_\mathrm{cin} = -\cos\gamma_\mathrm{f}\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{P}}|g_3, n+1\rangle + \sin\gamma_\mathrm{f}\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{S}}|g_1, n\rangle, \tag{17}$$

and

$$|\Psi_n^{(1)}(\infty)\rangle_\mathrm{cin} = \begin{cases} +\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{S}}|g_1, n\rangle, & \text{for} \quad Q \gg P_0, G_0, \\ -\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{P}}|g_3, n+1\rangle, & \text{for} \quad Q \ll P_0, G_0, \end{cases} \tag{18}$$

or for the reverse process, when the atom is initially in $|g_3\rangle$

$$|\Psi_n^{(2)}(\infty)\rangle_\mathrm{cin} = \sin\gamma_\mathrm{f}\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{P}}|g_3, n+1\rangle + \cos\gamma_\mathrm{f}\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{S}}|g_1, n\rangle, \tag{19}$$

$$|\Psi_n^{(2)}(\infty)\rangle_\mathrm{cin} = \begin{cases} \mathrm{e}^{-\mathrm{i}\varphi_\mathrm{P}}|g_3, n+1\rangle, & \text{for} \quad Q \gg P_0, G_0, \\ \mathrm{e}^{-\mathrm{i}\varphi_\mathrm{S}}|g_1, n\rangle, & \text{for} \quad Q \ll P_0, G_0. \end{cases} \tag{20}$$

Obviously, the cavity Fock states can be prepared by both intuitive and counterintuitive ordering of pulses. The comparison of equations (13, 17) reveals, that the atom-cavity entangled states emerging from $|g_1, n\rangle$ are almost the same in both case except for a difference in sign. The same is true for the reverse process (that is, starting from $|g_3, n+1\rangle$). We show in the next section that the uncertain phase φ_S cancels out. Since π is different for the intuitive and counterintuitive sequence of pulses two orthogonal entangled Bell states can be prepared.

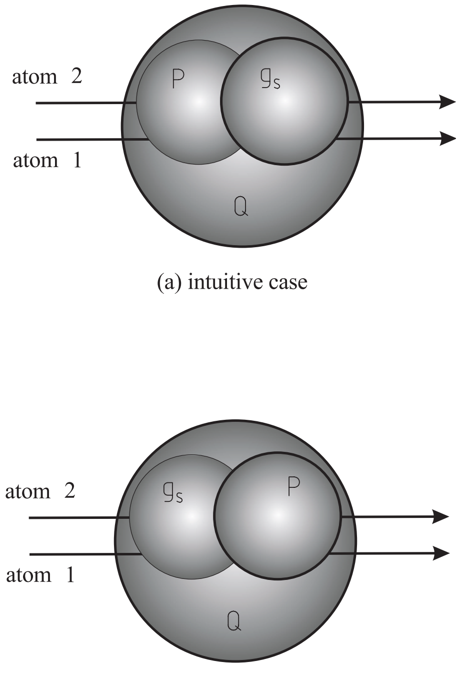

Fig. 3. The geometry of suggested setup for preparing two orthogonal entangled states of two atoms: intuitive (a) and counterintuitive (b) cases.

4 Preparation of entanglement using the tripod coupling scheme

In references [7,8], Cirac and Zoller, and Gerry discuss a scheme for the preparation of two-atom entangled states using two-level atoms and a pulse area technique in a microwave cavity. Here we consider a different ordering of pulses. We propose a method to create an entangled state of two atoms using the adiabatic transfer technique involving the tripod coupling scheme in an optical cavity. The geometry of the proposed setup is shown in Figure 3. Two trajectories, one each for atoms 1 and 2 are shown. Along those trajectories $Q \gg P, g_\mathrm{S}$ is valid at very early and very late times. Atom 1 crosses the centre of Q but the wings of P and g_S, therefore at intermediate times we have $Q \geq P, g_\mathrm{S}$. Atom 2 crosses the centre of P and g_S, but the wings of Q, therefore we have $Q \ll P, g_\mathrm{S}$. We assume that the initial state of the atom-cavity system is $|\psi_i\rangle = |g_1\rangle_1|g_3\rangle_2|0\rangle$. First we use the intuitively ordered pulses (see Fig. 3a) to transfer the population of atom 1 from $|g_1\rangle_1$ to a superposition state. The atom-cavity system is in the state

$$|\Psi(\infty)\rangle_\mathrm{in} = \left[-\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{S}}\sin\gamma_\mathrm{f}|g_1\rangle_1|0\rangle + \mathrm{e}^{-\mathrm{i}\varphi_\mathrm{P}}\cos\gamma_\mathrm{f}|g_3\rangle_1|1\rangle\right] \otimes |g_3\rangle_2, \tag{21}$$

after atom 1 has left the cavity. We select the second atom in $|g_3\rangle_2$, which passes through the region where $Q \ll P_0, G_0$ (see Fig. 3a). For an atom in $|g_3, 1\rangle$ the interaction sequences starting with P and ending with g_S is counterintuitive. According to equation (20), $|g_3\rangle_2|0\rangle$ remains unaltered, whereas $e^{-i\varphi_P}|g_3\rangle_2|1\rangle \Longrightarrow e^{-i\varphi_S}|g_1\rangle_2|0\rangle$ after the atom crosses the cavity. As a result we have the two-atom entanglement:

$$|\Phi(\infty)\rangle_{\rm in} = -\sin\gamma_{\rm f}|g_1\rangle_1|g_3\rangle_2 + \cos\gamma_{\rm f}|g_3\rangle_1|g_1\rangle_2. \quad (22)$$

The cavity state is left in its vacuum state.

Now we use the counterintuitively ordered pulses to transfer the population in $|g_1\rangle_1$ (see Fig. 3b). The atom-cavity state is $|\Psi(\infty)\rangle_{\rm cin} = [e^{-i\varphi_S}\sin\gamma_{\rm f}|g_1\rangle_1|0\rangle - \cos\gamma_{\rm f}e^{-i\varphi_P}|g_3\rangle|1\rangle] \otimes |g_3\rangle_2$ after the first atom has left the cavity. After the second atom in $|g_3\rangle_2$ crosses the cavity, $|g_3\rangle|0\rangle$ is unchanged, but $e^{-i\varphi_P}|g_3\rangle_2|1\rangle \Longrightarrow -e^{-i\varphi_S}|g_1\rangle|0\rangle$, see equation (16). This leads to the entanglement of the two atoms

$$|\Phi(\infty)\rangle_{\rm cin} = -\left[\sin\gamma_{\rm f}|g_1\rangle_1|g_3\rangle_2 + \cos\gamma_{\rm f}|g_3\rangle_1|g_1\rangle_2\right]. \quad (23)$$

Equations (22, 23) show that, the two orthogonal entangled states of two atoms are prepared in the four-level atom-cavity for different ordering of pulses due to the different phase factors of the atom-cavity states: a singlet entanglement is prepared for intuitively ordered pulses, whereas for counterintuitive ordering of pulses, one of the triplet entangled states is created.

We have noted that the entangled states of two atoms prepared by this approach are general entangled states. We can create the maximal entangled state in terms of practical application. One method is to choose the parameters, so that $\gamma_{\rm f} = \pi/4$. The maximal entangled state is then created. Another way is entanglement concentration by local operations and classical communication [36] or purification *via* entanglement swapping [37]. The maximal entangled states can be created from the general entangled states (22) and (23) by such manipulations.

In the process of preparing two-atom entanglement, we used the STIRAP technique, which does not require careful control of pulse area. Equations (22, 23) show that no excited state exists in these entangled states, they are immune to the detrimental consequences of atomic spontaneous emission.

5 Summary and discussion

Using the stimulated Raman adiabatic passage (STIRAP) technique in a four-level system, we have studied the properties of the atom-cavity states in an optical cavity. We found that a cavity-mode Fock states can always be generated by both the intuitively and counterintuitively ordered pulses due to the interaction of the two dark states. Furthermore we proposed a method to entangle two atoms by using the adiabatic passage scheme in the optical cavity. For the preparing a two-atom entanglement, we suggest to use the STIRAP technique, which does not require careful control of pulse area. We showed that two orthogonal entangled states can be prepared by different ordering of pulses. In these entangled states, there is no excited states included. This technique is robust against the detrimental consequences of spontaneous emission. The results are relevant for the realization of entanglement. The adiabatic passage technique requires the fulfilment of condition [22]: $\Omega_0, G_0 \gg 1/T \gg n_{\max}\kappa, \Gamma$. Here κ is the cavity linewidth and $n_{\max}$ is the maximum photon number attained by the cavity mode. The realization of parameters satisfying the condition appears feasible with realistic improvements to experiments reported recently [29–34]. In addition, we note that we need not rely on the existence of the degenerate ground state. However, for a practical realization it is convenient, because we can couple the excited state $|e\rangle$ with the ground states $|g_1\rangle$ and $|g_2\rangle$ using only one classical laser field with different polarization.

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