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Robust entangling two distant Bose–Einstein condensates via adiabatic passage

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ABSTRACT

We propose a robust scheme to prepare entangled states among two ^{87}Rb Bose–Einstein Condensates (BECs) via a stimulated Raman adiabatic passage (STIRAP) technique. The atomic spontaneous radiation, the cavity decay, and the fiber loss are efficiently suppressed by engineering an adiabatic passage. The simulation also shows that we can generate this entanglement state with high fidelity.

1. Introduction

Entanglement between distant subsystems is the crucial ingredient for practical quantum information systems [1–3]. In recent years fairish attention has been paid to exploit suitable coherent dynamics to prepare quantum entanglement between distant subsystems [4–9]. Atoms are trapped in separated cavities connected by optical fiber and coherent controlled by lasers are good candidates to create distant entanglement [10–15]. The main problem in this method is the decoherence due to leakage of photons from the cavity (fiber) and spontaneous radiation of the atoms.

The technique of stimulated Raman adiabatic passage (STIRAP) has some advantages in QIP because decoherence due to spontaneous emission from excited states can be compressed and it is also robust against some experimental parameter errors [16–22]. A number of theoretical protocols for entangling atoms have been proposed based on the adiabatic passage [23–29].

The Bose–Einstein condensate (BEC) is an ideal candidate for quantum bit because it has long storage times, high write–read efficiencies, and excellent internal-state preparation [30,31]. Recently, entanglement generation with Bose–Einstein condensate (BEC) was theoretically proposed [32–35] or experimentally realized [36,37]. In this paper, we will present a scheme for generating entangled state for spatially ^{87}Rb BECs via STIRA techniques. Two ^{87}Rb BECs are trapped in two distant double-mode optical cavities that are connected by an optical fiber. By choosing appropriate drive laser pulses we can create an entangled atomic state. The usage of the STIRAP technique in our scheme keeps fiber mode and the atomic excited states unpopulated during the whole interaction process so that the proposal is robust to atomic spontaneous emission noise and fiber loss.

2. The fundamental model

We consider the situation described in Fig. 1, where two ^{87}Rb BECs are trapped in two distant double-mode optical cavities, which are connected by an optical fiber. The ^{87}Rb atomic levels and transitions are also depicted in this figure [38,39]. The states $|g_L\rangle$, $|g_0\rangle$, $|g_R\rangle$ and $|g_a\rangle$ correspond to $|F=1,\ m_F=-1\rangle$, $|F=1,\ m_F=0\rangle$, $|F=1,\ m_F=1\rangle$ of $5S_{1/2}$ and $|F=2,\ m_F=0\rangle$ of $5S_{1/2}$, while $|e_L\rangle$, $|e_0\rangle$ and $|e_R\rangle$ correspond to $|F=1,\ m_F=-1\rangle$, $|F=1,\ m_F=0\rangle$ and $|F=1,\ m_F=1\rangle$ of $5P_{3/2}$, respectively. The atomic transition $|g_a\rangle\leftrightarrow|e_0\rangle$ of BEC in cavity A is driven resonantly by a π-polarized classical field with Rabi frequency Ω_A; $|e_0\rangle_A\leftrightarrow|g_R\rangle_A$ ($|e_0\rangle_A\leftrightarrow|g_L\rangle_A$) is resonantly coupled to the cavity mode a_L (a_R) with coupling constant g_A. The atomic transition $|g_L\rangle_B\leftrightarrow|e_L\rangle_B$ ($|g_R\rangle_B\leftrightarrow|e_R\rangle_B$) of BEC in cavity B is driven resonantly by a π-polarized classical field with Rabi frequency Ω_B; $|e_L\rangle_B\leftrightarrow|g_0\rangle_B$ ($|e_R\rangle_B\leftrightarrow|g_0\rangle_B$) is resonantly coupled to the cavity mode a_L (a_R) with coupling constant g_B. Here we consider BEC for a single excitation, the single excitation states is described by the state vectors $|G_f\rangle=(1/\sqrt{N_m})\sum_{j=1}^{N}|g_f\rangle_j|\chi_2\rangle_j\otimes_{k=1,k\neq j}^{N}|g_0\rangle_k|\chi_1\rangle_k$ and $|E_f\rangle=(1/\sqrt{N_m})\sum_{j=1}^{N}|e_f\rangle_j|\chi_2\rangle_j\otimes_{k=1,k\neq j}^{N}|g_0\rangle_k\ |\chi_1\rangle_k$ ($f=a,0,L,R$), here $N_m=N_A$ (N_B) denotes the atom number of BEC in a cavity

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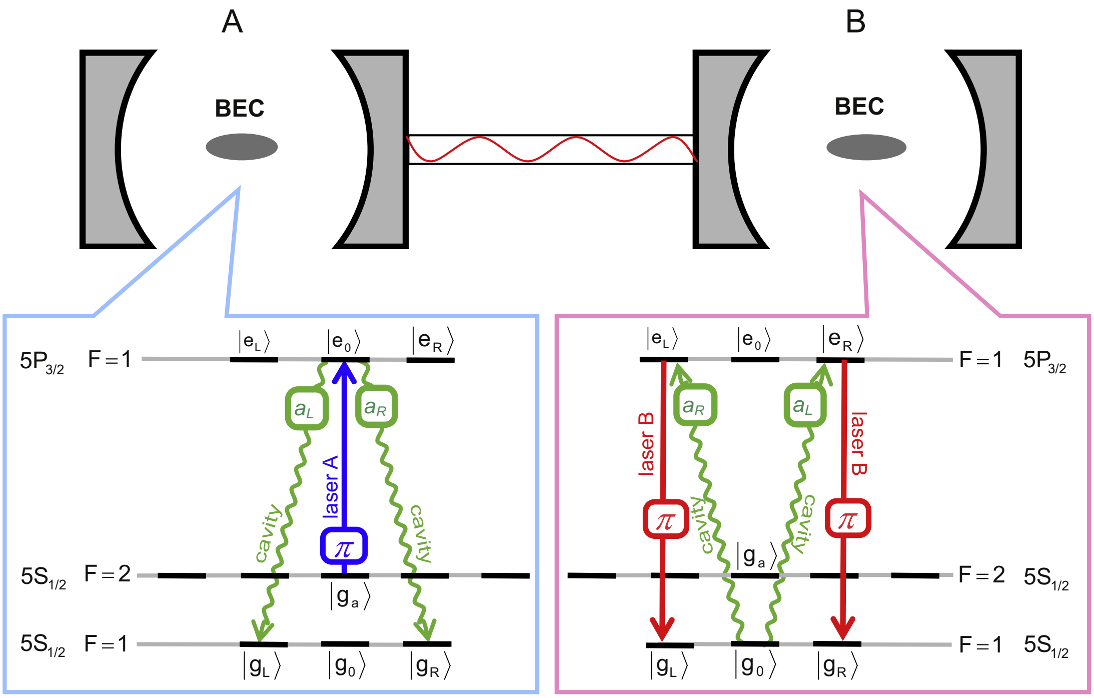

Fig. 1. Two ^{87}Rb BECs are trapped in two distant double-mode optical cavities, which are connected by an optical fiber. The states $|g_L\rangle$, $|g_0\rangle$, $|g_R\rangle$ and $|g_a\rangle$ correspond to $|F=1,\ m_F=-1\rangle$, $|F=1,\ m_F=0\rangle$, $|F=1,\ m_F=1\rangle$ of $5S_{1/2}$ and $|F=2, m_F=0\rangle$ of $5S_{1/2}$, while $|e_L\rangle$, $|e_0\rangle$ and $|e_R\rangle$ correspond to $|F=1,\ m_F=-1\rangle$, $|F=1,\ m_F=0\rangle$ and $|F=1,\ m_F=1\rangle$ of $5P_{3/2}$. The atomic transition $|g_a\rangle \leftrightarrow |e_0\rangle$ of BEC atoms in cavity A is driven resonantly by a π-polarized classical field with Rabi frequency Ω_A; $|e_0\rangle_A \leftrightarrow |g_L\rangle_A$ ($|e_0\rangle_A \leftrightarrow |g_R\rangle_A$) is resonantly coupled to the cavity mode a_L (a_R) with coupling constant g_A. The atomic transition $|g_L\rangle_B \leftrightarrow |e_L\rangle_B$ ($|g_R\rangle_B \leftrightarrow |e_R\rangle_B$) of BEC atoms in cavity B is driven resonantly by a π-polarized classical field with Rabi frequency Ω_B; $|e_R\rangle_B \leftrightarrow |g_0\rangle_B$ ($|e_L\rangle_B \leftrightarrow |g_0\rangle_B$) is resonantly coupled to the cavity mode a_L (a_R) with coupling constant g_B.

A (B), $|\ldots\rangle_j$ describes the state of the jth atom in the BEC, and χ_1 and χ_2 are spatial wave functions [37].

Initially, if two BECs are prepared in the state $|G_a\rangle_A$ and $|G_0\rangle_B$, the cavity mode is in the vacuum state. In the rotating wave approximation, the interaction Hamiltonian of the BEC-cavity system can be written as (setting $\hbar=1$) [40]

$$H_{ac} = \sum_{k=L,R} (\sqrt{N_A}\Omega_A(t)|E_0\rangle_A\langle G_a| + \sqrt{N_A} g_A(t) a_A |E_0\rangle_A\langle G_k| + \sqrt{N_B}\Omega_B(t)|E_k\rangle_B\langle G_k| + \sqrt{N_B} g_B(t) a_B |E_k\rangle_B\langle G_0| + H.c.). \tag{1}$$

In the short fibre limit, the coupling between the cavity fields and the fiber modes can be written as the interaction Hamiltonian [11,12,15]

$$H_{cf} = \sum_{k=L,R} \nu_k [b_k (a^+_{A,k} + a^+_{B,k}) + H.c.]. \tag{2}$$

In the interaction picture the total Hamiltonian now becomes

$$H_I = H_{ac} + H_{cf}. \tag{3}$$

3. Generation of the BEC entanglement state

In this section, we begin to investigate the generation of the BEC entangled state in detail. The time evolution of the whole system state is governed by the Schrodinger equation

$$i\frac{\partial}{\partial t}|\psi(t)\rangle = H_I|\psi(t)\rangle. \tag{4}$$

The subspace S spanned by states

$$\begin{aligned}
|\phi_1\rangle &= |G_a\rangle_A|G_0\rangle_B|0000\rangle_c|00\rangle_f,\\
|\phi_2\rangle &= |E_0\rangle_A|G_0\rangle_B|0000\rangle_c|00\rangle_f,\\
|\phi_3\rangle &= |G_L\rangle_A|G_0\rangle_B|1000\rangle_c|00\rangle_f,\\
|\phi_4\rangle &= |G_R\rangle_A|G_0\rangle_B|0100\rangle_c|00\rangle_f,\\
|\phi_5\rangle &= |G_L\rangle_A|G_0\rangle_B|0000\rangle_c|10\rangle_f,\\
|\phi_6\rangle &= |G_R\rangle_A|G_0\rangle_B|0000\rangle_c|01\rangle_f,\\
|\phi_7\rangle &= |G_L\rangle_A|G_0\rangle_B|0010\rangle_c|00\rangle_f,\\
|\phi_8\rangle &= |G_R\rangle_A|G_0\rangle_B|0001\rangle_c|00\rangle_f,\\
|\phi_9\rangle &= |G_L\rangle_A|E_R\rangle_B|0000\rangle_c|00\rangle_f,\\
|\phi_{10}\rangle &= |G_R\rangle_A|E_L\rangle_B|0000\rangle_c|00\rangle_f,\\
|\phi_{11}\rangle &= |G_L\rangle_A|G_R\rangle_B|0000\rangle_c|00\rangle_f,\\
|\phi_{12}\rangle &= |G_R\rangle_A|G_L\rangle_B|0000\rangle_c|00\rangle_f,
\end{aligned} \tag{5}$$

is an 12-dimensional invariant subspace of the Hamiltonian (3) [41]. $|n_{AL},\ n_{AR},\ n_{BL},\ n_{BR}\rangle_c$ denotes the field state with n_{Ai} (i=L, R) photons in the i polarized mode of cavity A, n_{Bi} in the i polarized mode of cavity B, and $|n_L, n_R\rangle_f$ represents n_i photons in i polarized mode of the fiber. The Hamiltonian H_I has the following dark state:

$$|D(t)\rangle = K\{2g_A\Omega_B(t|\phi_1\rangle - \Omega_A(t)\Omega_B(t)[|\phi_3\rangle + |\phi_4\rangle - |\phi_7\rangle - |\phi_8\rangle] - g_B(t)\Omega_A(t)[|\phi_{11}\rangle + |\phi_{12}\rangle]\}, \tag{6}$$

which is the eigenstate of the Hamiltonian corresponding to zero eigenvalue. Here and in the following g_i, Ω_i are real, and $K^{-2} = g_A^2\Omega_B^2 + 4\Omega_A^2\Omega_B^2 + 2g_B^2\Omega_A^2$. Under the condition

$$g_A(t), g_B(t) \gg \Omega_A(t), \Omega_B(t), \tag{7}$$

we have

$$|D(t)\rangle \sim 2g_A(t)\Omega_B(t)|\phi_1\rangle - g_B(t)\Omega_A(t)[|\phi_{11}\rangle + |\phi_{12}\rangle]. \tag{8}$$

Suppose the initial state of the system is $|\phi_1\rangle$, if we design pulse shapes such that

$$\lim_{t\to-\infty}\frac{g_B(t)\Omega_A(t)}{g_A(t)\Omega_B(t)} = 0, \quad \lim_{t\to+\infty}\frac{g_A(t)\Omega_B(t)}{g_B(t)\Omega_A(t)} = 0, \tag{9}$$