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Cluster-state preparation in thermal cavities without single-qubit operation*

Zhang Xiao-Long(张小龙)[a)b)c)], Feng Mang(冯 芒)[b)], and Gao Ke-Lin(高克林)[b)]

[a)] *Center for Modern Physics and Department of Physics, Chongqing University, Chongqing* 400044, *China*
[b)] *State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan* 430071, *China*
[c)] *Graduate School of the Chinese Academy of Sciences, Beijing* 100080, *China*

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A potential scheme is proposed for generating cluster states of many atoms in cavity quantum electradynamics (QED), in which an unorthodox encoding is employed with the ground state being qubit $|0\rangle$ while two closely spaced upper states being qubit $|1\rangle$. Throughout the scheme the cavities can be in thermal states but are only virtually excited. We show how to create the cluster states by performing a two-step but no single-qubit operation. Discussion is also carried out on the experimental feasibility of our scheme.

Keywords: cluster-state, cavity QED, entanglement, quantum computing
PACC: 0367

Quantum computers are possessed of great advantages over existing computers in the sense of solving some special problems. It has been shown that the building blocks for performing a general quantum computing cover quantum single-qubit rotations and two-qubit gates, and some physical systems such as nuclear magnetic resonance (NMR), trapped ions, cavity quantum electrodynamics (QED) and optical photons that can achieve these quantum logic gates.

Recently, a new quantum computing idea named one-way quantum computing has been proposed,[1,2] in which information is encoded in cluster states and single-qubit operations on an array of qubits in the cluster state along a certain way, could achieve desired quantum gates. Consider a lattice structure. For any site a of the lattice, the cluster state $|\phi_{\{k\}}\rangle_{\rm C}$ obeys a set of eigenvalue equations

$$K^{(a)}|\phi_{\{k\}}\rangle_{\rm C} = (-1)^{\kappa_a}|\phi_{\{k\}}\rangle_{\rm C} \tag{1}$$

with the correlation operators

$$K^{(a)} = \sigma_x^{(a)} \bigotimes_{b\in nghb(a)} \sigma_z^{(b)}, \tag{2}$$

where $nghb(a)$ is a set of all the neighbours of the site a and $\kappa_a \in \{0,1\}$. The operators $K^{(a)}$ with $\{a \in \text{lattice}\}$ form a complete family of commuting operators on the lattice. The cluster state, as a universal resource for general quantum computing, has aroused great interest.[3−10] The nonlocality test of the cluster states was proposed[4] and an experiment has been performed by following that idea,[6] which shows the violation of Bell inequalities in a four-qubit cluster state. Moreover, the original cluster states are produced via Ising interaction, which cannot be obtained perfectly in experiment. Recently, an alternative way was proposed to create a cluster state with a Heisenberg interaction.[7] We have also noticed that one-way quantum computing by optical elements based on four-qubit cluster states, demonstrating of single-qubit rotations, two-qubit gates and a quantum search algorithm, which were recently realized experimentally.[8]

Cavity QED is an excellent device to achieve few-qubit entanglement and quantum computing, for example, entanglement state preparation,[11,12] two-qubit quantum gate [13,14] and quantum search.[15] Recently some schemes were proposed to generate cluster states in cavity QED.[16,17] In the present paper, we propose a potential scheme to prepare many-qubit cluster states by sending atoms passing through mi-

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crowave cavities. In each of these atoms, we have an unorthodox encoding where the ground state is qubit $|0\rangle$ while two closely spaced upper states are qubit $|1\rangle$. The distinct advantage of the scheme is that the preparation of the cluster state can be carried out in thermal cavities and the atoms interact only with virtually excited cavities throughout the scheme, which effectively suppresses the detrimental influence from the cavity decay. Moreover, no single-qubit operation is required in our implementation.

We first consider a simplest case, i.e. two identical atoms simultaneously interacting with a single-mode cavity field, with the help of a classical driving field. There are three levels in each atom under consideration as shown in Fig.1, including two excited levels $|e\rangle$ and $|i\rangle$, and a ground state $|g\rangle$.

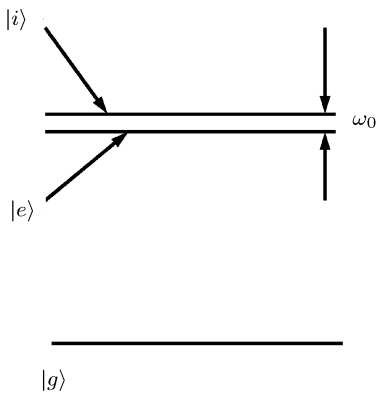


Fig.1. The atomic level configuration under consideration, where ω_0 is on the order of a few GHz, $|g\rangle$ is lower than $|i\rangle$ and $|e\rangle$ by 10^{15} Hz. $|i\rangle$ and $|e\rangle$ are driven by a quantized field of the cavity and a classical field. $|g\rangle$ remains unchanged in the scheme.

We encode qubit $|0\rangle$ into $|g\rangle$, and $|1\rangle$ into both $|e\rangle$ and $|i\rangle$. The associated Hamiltonian in units of $\hbar = 1$ is[18,19]

$$\begin{aligned} H =&\omega_0 \sum_{j=1,2} \sigma_{z,j} + \omega a^\dagger a \\ &+ \Omega \sum_{j=1,2} (\mathrm{e}^{-\mathrm{i}\omega_L t}\sigma_j^\dagger + \mathrm{e}^{\mathrm{i}\omega_L t}\sigma_j^-) \\ &+ g \sum_{j=1,2} (\sigma_j^\dagger a + \sigma_j^- a^\dagger), \end{aligned} \tag{3}$$

where $\sigma_j^- = |e_j\rangle\langle i_j|$ and $\sigma_j^\dagger = |i_j\rangle\langle e_j|$ are the lowering and raising operators, respectively; $a^\dagger$ and a are the creation and annihilation operators, respectively; ω_0, ω and ω_L are, respectively, frequencies with respect to the resonant transition between levels $|e\rangle$ and $|i\rangle$, to the cavity mode and to the classical driving field; g and Ω are the coupling constants of each atom to the cavity mode and to the driving field, respectively. Assume $\omega_0 = \omega_L$, and the rotating-wave approximation will yield an effective Hamiltonian in the rotating framework with respect to the interaction-free part of Eq.(3),

$$\begin{aligned} H_i =&\Omega \sum_{j=1,2} (\sigma_j^\dagger + \sigma_j^-) \\ &+ g \sum_{j=1,2} (\mathrm{e}^{\mathrm{i}\delta t}\sigma_j^\dagger a + \mathrm{e}^{-\mathrm{i}\delta t}\sigma_j^- a^\dagger), \end{aligned} \tag{4}$$

where $\delta = \omega_0 - \omega$. By defining the dressed states as $|\pm_j\rangle = (|e_j\rangle \pm |i_j\rangle)/\sqrt{2}$, we make a further transformation with rotation with respect to the terms regarding Ω in Eq.(4), and obtain

$$\begin{aligned} H^{\mathrm{I}} =&\frac{g}{2} \sum_{j=1,2} (|+_j\rangle\langle +_j| - |-_j\rangle\langle -_j| + \mathrm{e}^{\mathrm{i}2\Omega t} S_j^\dagger \\ &- \mathrm{e}^{-\mathrm{i}2\Omega t} S_j^-)\mathrm{e}^{-\mathrm{i}\delta t} a + \mathrm{H.c.}, \end{aligned} \tag{5}$$

where $S_j^\dagger = |+_j\rangle\langle -_j|$ and $S_j^- = |-_j\rangle\langle +_j|$. Assuming that $2\Omega \gg \delta, g$, we first neglect the fast oscillating terms regarding $\mathrm{e}^{\mathrm{i}2\Omega t}$, and then turn H^{I} into

$$\begin{aligned} H_{\mathrm{eff}} =&\frac{\lambda}{2} \sum_{j=1,2} (|e_j\rangle\langle e_j| + |i_j\rangle\langle i_j|) \\ &+ \lambda(\sigma_1^\dagger \sigma_2^\dagger + \sigma_1^\dagger \sigma_2^- + \mathrm{H.c.}), \end{aligned} \tag{6}$$

where $\lambda = g^2/2\delta$ is the effective coupling constant, and we have used the fact that there is no energy exchange between the atomic system and the cavity in the case $\delta \gg g/2$. So the possible energy-conversing transitions take place between the states $|i_1\rangle|e_2\rangle|n\rangle$ and $|e_1\rangle|i_2\rangle|n\rangle$, and between $|e_1\rangle|e_2\rangle|n\rangle$ and $|i_1\rangle|i_2\rangle|n\rangle$, mediated by virtually excited cavity states $|n \pm 1\rangle$. Since the transition paths in both the transition $|i_1\rangle|e_2\rangle|n\rangle \leftrightarrow |e_1\rangle|i_2\rangle|n\rangle$ and $|e_1\rangle|e_2\rangle|n\rangle \leftrightarrow |i_1\rangle|i_2\rangle|n\rangle$ interfere destructively, the effective coupling constant λ is independent of the photon number in the cavity.[20] This distinct feature is favourable for suppressing the error due to the fluctuation or the decay of the cavity mode in the interaction process.

If the two atoms are initially in the state $|e_1\rangle|e_2\rangle$, by solving the Schrödinger's equation

$$\mathrm{i}\frac{\mathrm{d}|\psi(t)\rangle}{\mathrm{d}t} = H_{\mathrm{eff}}|\psi(t)\rangle$$

with the help of

$$|\psi(t)\rangle = \mathrm{e}^{-\mathrm{i}H_0' t}|\psi'(t)\rangle$$

with

$$H_0' = \frac{\lambda}{2} \sum_{j=1,2} (|e_j\rangle\langle e_j| + |i_j\rangle\langle i_j|),$$

we obtain

$$\mathrm{i}\frac{\mathrm{d}|\psi'(t)\rangle}{\mathrm{d}t} = H_i'|\psi'(t)\rangle,$$

where

$$H_i' = \lambda(\sigma_1^\dagger\sigma_2^\dagger + \sigma_1^\dagger\sigma_2^- + \mathrm{H.c.}).$$

Then the state evolution of the system is given by

$$|\psi(t)\rangle \leftarrow \mathrm{e}^{-\mathrm{i}\lambda t}(\cos(\lambda t)|e_1\rangle|e_2\rangle - \mathrm{i}\sin(\lambda t)|i_1\rangle|i_2\rangle). \quad (7)$$

Equation (7) in the Schrödinger picture is rewritten as

$$\begin{aligned}|\psi(t)\rangle \rightarrow\ & \mathrm{e}^{-\mathrm{i}\lambda t}\\ & \times\{\cos(\lambda t)[\cos(\Omega t)|e_1\rangle - \mathrm{i}\sin(\Omega t)|i_1\rangle]\\ & \times[\cos(\Omega t)|e_2\rangle - \mathrm{i}\sin(\Omega t)|i_2\rangle]\\ & - \mathrm{i}\sin(\lambda t)[\cos(\Omega t)|i_1\rangle - \mathrm{i}\sin(\Omega t)|e_1\rangle]\\ & \times[\cos(\Omega t)|i_2\rangle - \mathrm{i}\sin(\Omega t)|e_2\rangle]\}.\end{aligned}$$

We choose an interaction time t and a Rabi frequency Ω such that $\lambda t = \pi/2$ and $\Omega t = k\pi$, with k being an integer. So we have

$$|e_1\rangle|e_2\rangle = -|i_1\rangle|i_2\rangle, \quad (8)$$

and the evolution of other qubit states,

$$\begin{aligned}|g_1\rangle|g_2\rangle &\rightarrow |g_1\rangle|g_2\rangle,\\ |g_1\rangle|e_2\rangle &\rightarrow |g_1\rangle|e_2\rangle,\\ |e_1\rangle|g_2\rangle &\rightarrow |e_1\rangle|g_2\rangle.\end{aligned}$$

If we start from states $|i_1\rangle|i_2\rangle$, $|e_1\rangle|i_2\rangle$ and $|i_1\rangle|e_2\rangle$, we have by repeating the above steps,

$$\begin{aligned}|i_1\rangle|i_2\rangle &\rightarrow -|e_1\rangle|e_2\rangle,\\ |e_1\rangle|i_2\rangle &\rightarrow -|i_1\rangle|e_2\rangle,\\ |i_1\rangle|e_2\rangle &\rightarrow -|e_1\rangle|i_2\rangle,\end{aligned}$$

with other possible states unchanged. So with our encoding $|g\rangle \rightarrow |0\rangle$, and both $|e\rangle$ and $|i\rangle \rightarrow |1\rangle$, we have the following truth table:

$$\begin{aligned}|0_1\rangle|0_2\rangle &\rightarrow |0_1\rangle|0_2\rangle,\\ |0_1\rangle|1_2\rangle &\rightarrow |0_1\rangle|1_2\rangle,\\ |1_1\rangle|0_2\rangle &\rightarrow |1_1\rangle|0_2\rangle,\\ |1_1\rangle|1_2\rangle &\rightarrow -|1_1\rangle|1_2\rangle,\end{aligned} \quad (9)$$

which is a typical quantum phase gate independent of the cavity state.

Before discussing the experimental feasibility of the above phase gate in a real physical system, we first consider how to generate the cluster states in thermal cavities by means of the phase gate above. We consider N two-level atoms prepared initially in a product state $|\phi_0\rangle = \otimes_i|+\rangle_i$, where indices $i = 1, 2, 3, \ldots$ refer to the sites of the atoms and $|+\rangle_i$ are the eigenstates of $\sigma_x^{(i)}$ with an eigenvalue 1. The cluster states can be obtained in two steps as shown in Fig.2. In the first step we let atoms 1 and 2, atoms 3 and 4, …. simultaneously pass through the single-mode cavities, respectively. From the above deduction, we know that the whole system evolves to

$$\begin{aligned}|\phi\rangle_{1,2\ldots,n} =& (|g_1\rangle|g_2\rangle + |g_1\rangle|e_2\rangle + |e_1\rangle|g_2\rangle - |i_1\rangle|i_2\rangle)\\ & \otimes(|g_3\rangle|g_4\rangle + |g_3\rangle|e_4\rangle + |e_3\rangle|g_4\rangle - |i_3\rangle|i_4\rangle)\\ & \otimes\cdots.\end{aligned}$$

In the second step, we let atoms 2 and 3, atoms 4 and 5, …, repeat the above interaction process as shown in Fig.2. Since only qubit state $|1\rangle|1\rangle$ (i.e. $|e_1\rangle|e_2\rangle$, $|e_1\rangle|i_2\rangle$, $|i_1\rangle|e_2\rangle$, or $|i_1\rangle|i_2\rangle$) can have a π phase rotation, we finally have

$$\begin{aligned}|\phi\rangle_{1,2,\ldots,n} =& (|0\rangle + |1\rangle\sigma_z^{(2)})(|0\rangle + |1\rangle\sigma_z^{(3)})\\ & \otimes(|0\rangle + |1\rangle\sigma_z^{(4)})(|0\rangle + |1\rangle\sigma_z^{(5)})\\ & \otimes\cdots,\end{aligned} \quad (10)$$

which, as a matter of fact, is the standard cluster state defined in Ref.[1],

$$|\phi_N\rangle = \frac{1}{2^{N/2}}\otimes_{a=1}^{N}(|0\rangle_a\sigma_z^{(a+1)} + |1\rangle_a).$$

Some remarks should be made. First, the qubit encoding in our proposal looks strange, because two physical levels $|e\rangle$ and $|i\rangle$ correspond to the same encoding state $|1\rangle$.To carry out the single-qubit rotation in a one-way quantum computing, we have to use hard pulses with a bandwidth wider than the energy difference between $|e\rangle$ and $|i\rangle$, with which a gating could be achieved within very short time. Suppose that $|e\rangle$ and $|i\rangle$ are in an arbitrary state $\alpha|e\rangle - \beta|i\rangle$ with $|\alpha|^2 + |\beta|^2 = 1$ when we have obtained the cluster state. Then a single-qubit rotation by a hard pulse to achieve $\cos\theta|0\rangle + \mathrm{i}\sin\theta|1\rangle$ can also be rewritten as $\cos\theta|g\rangle + \mathrm{i}\sin\theta(\alpha|e\rangle - \beta|i\rangle)$. This is a physically reasonable state, because when we perform an X gate, we use hard pulses and can simply consider a unitary transform between two encoding states $|0\rangle$ and $|1\rangle$, and in the case of a state measurement, we may employ selective pulses to detect the populations: $\cos^2\theta$ (regarding $|0\rangle$) or $\sin^2\theta$ (regarding $|1\rangle$). Since the difference between $|e\rangle$ and $|i\rangle$ is on the order of GHz, and the level $|g\rangle$ is lower than them by 10^{15} Hz, such

a hard pulse implementation is available in principle. Such hard pulses are also necessary in refocusing (or say, spin echo) to remove dephasing in a quantum computing.[21] Moreover, in the time evolution, some undesired phases (or say, dephasing) will appear due to energy difference between the states. More specifically, an initial state $\cos\theta|0\rangle + \mathrm{i}\sin\theta|1\rangle$ will be $\cos\theta|g\rangle + \mathrm{i}\sin\theta(\alpha \mathrm{e}^{-\mathrm{i}\omega_{eg}t}|e\rangle - \beta \mathrm{e}^{-\mathrm{i}\omega_{ig}t}|i\rangle)$ with ω_{eg} and ω_{ig} being the differences in frequency between $|e\rangle$ and $|g\rangle$, and between $|i\rangle$ and $|g\rangle$, respectively. To remove the dephasing, by means of $\mathrm{e}^{-\mathrm{i}\pi\sigma_x/2}\sigma_z\mathrm{e}^{\mathrm{i}\pi\sigma_x/2} = -\sigma_z$ by hard pulses, we may have a fast flip of the encoding states $|0\rangle$ and $|1\rangle$ (i.e. flips between $|g\rangle$ and $|e\rangle$, and between $|g\rangle$ and $|i\rangle$, simultaneously), which would yield a reverse evolution of the states.[21] As a result, a clever design of such refocusing pulses could guarantee a high-fidelity quantum computing.

Second, the production of a cluster atomic state without single-qubit rotation is the advantage of our scheme. As shown in Fig.2, the atoms passing through the cavities simultaneously in two steps can achieve the cluster state, which, in the case of many atoms, much simplifies the experimental implementation, compared with the previous schemes with single-qubit rotation[13,15] or different qubit encodings[13] involved. Since more operations would inevitably bring in more imperfections, our scheme can reduce the probability of imperfection and particularly remove imperfection due to single qubit operations. Moreover, the introduction of the strong classical field eliminates the influence from the cavities.[15] As it is independent of the photon number in the cavities, our scheme can work in thermal cavities, which also reduces the experimental challenge. In contrast, in recent schemes for generating cluster states in cavity QED,[16,17] the cavities are required to be initially in vacuum states. Furthermore, in Refs.[16, 17], the cluster state is formed by sending atom(s) or photon(s) through a cavity or cavities one by one, whose implementation time increases with the size of the prepared cluster states increasing. In contrast, our scheme, with atom pairs passing through the cavities simultaneously, works only by two steps. More importantly, there is no limitation to the size of the cluster state in our scheme. Since the atoms pass through the cavities in the way shown in Fig.2, the cluster state can be infinitely large in principle as long as there are infinite cavities involved.

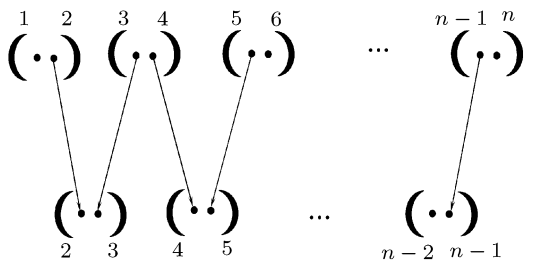


Fig.2. The schematic representation of the cluster-state preparation in cavity QED, where the atom pairs are passing through microwave cavities twice, respectively.

We have realized that our scheme is not yet fully within the reach of current techniques, although there have been several successful experiments so far in the microwave cavities,[22−24] in which the Rydberg atoms are employed. Particularly in Ref.[11], two-atom interaction via cavity assisted van de Waals collision has been achieved, while we have not yet found an experiment for two atoms passing through two microwave cavities and interacting twice with the detuned cavity modes. Moreover, manipulation of many atom–cavity subsystems requires much high skill. So we hope that further advance in cavity QED could meet our requirements.

Anyway, we argue that our scheme is very close to the reach of current techniques in cavity QED. We may consider Rydberg atoms ^{85}Rb with the qubit state $|1\rangle$ encoded in the excited levels with the principal quantum numbers 50 and 51, and the qubit $|0\rangle$ encoded in the ground state of the atom. The radiative time of the excited levels is on the order of $T_\mathrm{r} = 10^{-2}$s, and the coupling constant is about $g \simeq 2\pi \times 50$kHz.[11] The corresponding photon storage time in a cavity can reach $T_\mathrm{c} = 1$ ms (corresponding to $Q = 3\times10^8$).[23] In the present scheme the virtually excited cavities have only a small probability of excitation, about 0.01, during the atom pairs passing through them. Thus the efficient decay time T_ceff of the cavity is 0.1 s. With the choice δ=5g, the interaction time of the atom with the cavity field is on the order of 10^{-5}s, which is much shorter than T_r and T_ceff.

Shortly speaking, since no single-qubit operation is needed during the atoms passing through the cavities, in principle, once we have fixed the cavities and chosen suitable velocities of the atoms, the cluster states will definitely appear after the atoms have left the cavities as shown in Fig.2. The possible source of error in our scheme comes mainly from the fluctuation of the Rabi oscillation. If we set $\Omega = 5\delta$, the condition $\Omega/\lambda = 250$ will amplify the fluctuations $(\Delta\Omega, \Delta\lambda)$ regarding Ω and λ, which will damage our

desired phase gate in Eq.(8). Specifically, we give a fluctuation allowed in our scheme, below the upper limit. Since $t = 10/g$ for achieving Eq.(8), if we make sure that the fidelity of our phase gate is larger than 99.5%, which implies $\Delta\Omega t < 0.1$ and $\Delta\lambda t < 0.1$, both $\Delta\Omega$ and $\Delta\lambda$ must be smaller than $g/100$. Moreover, the present scheme requires atoms to be sent simultaneously through the microwave cavity. Otherwise an error would be yielded. We have assessed the infidelity for two atoms due to operational imperfection in Fig.3. For simplicity, we suppose that the atoms are moving with the same speed, but enter the microwave cavity sequentially with a time difference δt. The interaction time of the two atoms with the detuned cavity mode is thereby reduced to $(t_0 - 2\delta t)$ with t_0 being the desired time in the ideal case. In addition to the single atom resonantly interacting with the classical driving field in a time interval δt, as well as the free evolution of the atoms, we can obtain the infidelity, due to the operational imperfection, to be $[3 - \sin(4\lambda\delta t)\sin^2(4\Omega\delta t) - \cos^2(4\Omega\delta t) - 2\cos(4\lambda\delta t)\cos(4\Omega\delta t)]/4$. The numerical calculation in Fig.3 shows that the infidelity is increasing with δt, while our scheme for the two-atom case works well if $\delta t < 0.01 t_0$. Nevertheless, in the case of many atoms, i.e. $N \gg 2$, the situation turns much more complicated, and the fidelity is generally lower than that in the two-atom case.

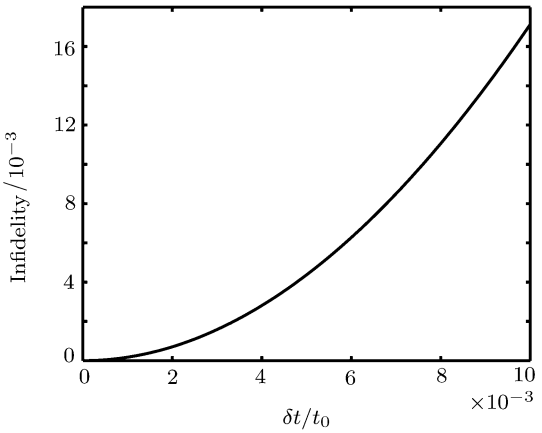


Fig.3. Infidelity versus time difference δt in the case of two atoms, where t_0 is the desired time in the ideal situation. The atoms with the exactly same speed are assumed to enter the microwave cavity non-simultaneously, but with a time difference δt.

Before finishing this paper, we consider the other two points of the cluster state we have prepared. The first is the possible error from the hard pulse implementation (with pulses of short straight rectangular form) in the single-qubit operation in a one-way quantum computing due to insufficient pulse sensitivity.[25] To solve this problem, we may employ the composite pulse technique widely used in NMR[25] and ion-trap experiments,[26] which could reduce the error to a negligible level. Moreover, since the duration of the hard pulse is shorter than 0.1 ns in our case, detrimental effect from decoherence in the implementation of our hard pulses is also negligible. Furthermore, for the readout of the qubits, which, we suppose, happen at the end of a one-way quantum computing, we may employ two weak selective pulses to replace a hard pulse, which may induce accurately resonant transitions. The resonant transitions between $|g\rangle$ and $|i\rangle$ and between $|g\rangle$ and $|e\rangle$ happening simultaneously guarantee a full acquirement of the quantum information encoded in $|e\rangle$ and $|i\rangle$.

The other point is how to carry out quantum information processing based on the flying atoms. In Refs.[13, 15], the quantum algorithm is performed during atoms passing through the cavity. While in our case, we obtain the cluster state only after the atoms have left the cavities. As an application of our prepared cluster state, we may implement a teleportation on three of the atoms in our scheme as done with flying photons in Ref.[8]. To have a one-way quantum computing, however, we have to first fix the atoms, which is still an open question. For example, the authors in Ref.[16] only focused on the preparation of the cluster states without further discussing the usage of the states. Nevertheless, we have noticed the recent advances[27] in optical cavity regime for strong coupling and the identification regarding individual atoms. Although these advances for trapping atoms are not suitable for our case with 'hot' atoms, we expect that the flying atoms could be employed for quantum computing in a clever way in the future with the improvement of our technique in individual atom control.

In conclusion, we have proposed a potential scheme for creating cluster states in cavity QED. In our scheme, the cavities are not required to be initially prepared in vacuum states, but only virtually excited throughout the scheme. Moreover, no single-qubit operation is necessary in our state preparation. To make a one-way quantum computing, however, we need two- or three-dimensional cluster states. As a many-qubit cluster state could be created step by step by connecting the few-qubit cluster states through quantum phase gates on the end qubits of the neighbouring spin chains, the high-dimensional cluster states in a lattice structure can be generated in a similar way.

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