Front. Phys. 13(5), 134209 (2018)
https://doi.org/10.1007/s11467-018-0826-7

RESEARCH ARTICLE

Engineering multipartite steady entanglement of distant atoms via dissipation

Zhao Jin[1], S.-L. Su[2], Ai-Dong Zhu[3], Hong-Fu Wang[3], Shou Zhang[1,3†]

[1] *Department of Physics, Harbin Institute of Technology, Harbin 150001, China*
[2] *School of Physics and Engineering, Zhengzhou University, Zhengzhou 450001, China*
[3] *Department of Physics, College of Science, Yanbian University, Yanji, Jilin 133002, China*
Corresponding authors. E-mail: [†] *szhang@ybu.edu.cn*
Received March 26, 2018; Accepted July 5, 2018

We propose a scheme for generating an entangled state for three atoms trapped in separate optical cavities that are coupled to each other through two optical fibers based on coherent driving and dissipation, which are induced by the classical fields and the decay of non-local bosonic modes, respectively. In our scheme, the interaction time need not be controlled strictly in the overall dynamics process, and the cavity field decay can be changed into a vital resource. The numerical simulation shows that the fidelity of the target state is insensitive to atomic spontaneous emission, and our scheme is good enough to generate the W state of distant atoms with a high fidelity and purity. In addition, the present scheme can also be generalized to prepare the N-partite W state of distant atoms.

Keywords steady-state entanglement, dissipative dynamics, laser manipulation

PACS numbers 42.50.-p, 42.50.Pq, 03.67.-a, 03.67.Bg

1 Introduction

Quantum entanglement, is a very important resource because of its potential application in quantum information sciences. It was originally proposed by Einstein, Podolsky, and Rosen [1], and later interpreted with two spin-1/2 particles by Bohm [2]. During the the past few decades, a variety of physical systems have been chosen to investigate the controlled entangled states. Among these are trapped ions [3], neutral atoms [4], spins in nuclear magnetic resonance (NMR) [5], cavity quantum electrodynamics (QED) systems [6], Josephson junctions [7], and quantum dots (QDs) [8]. Compared with bipartite entanglement, multipartite entanglement has a more significant importance in its fundamental aspects, such as violation of non-locality [9–11] and many vital applications in quantum computation [12] and quantum communication, such as quantum teleportation [13–15], quantum state sharing [16], quantum secret sharing [17], and so on. There usually exist two inequivalent classes of multipartite entangled states, i.e., Greenberger–Horne–Zeilinger (GHZ) state [18] and W state [19]. They cannot be obtained from the states of the other even under stochastic local operation and classical communication. Recently, it is shown that the correlation between two qubits selected from a W state violate the Clauser–Horne–Shimony–Holt (CHSH) inequality more than the correlation between two qubits in any quantum state [20]. In addition, W states have many interesting features: their entanglement is not only maximally persistent and robust under particle loss, but also immune against global dephasing, and rather robust against bit flip noise.

Neutral atoms are good candidates for quantum information processing (QIP), since they are suited to store the information in stationary nodes. In particular, when they are excited to the Rydberg states, which leads to strong and long-range van der Waals or dipole-dipole interactions. These interactions offers an interesting perspective for applications in quantum information [21–23]. Nevertheless, the interaction between system and environment is unavoidable, which degrade the coherence of the system. Overcoming the decoherence is a formidable physical challenge both in experiments and in theory. From this perspective, it seems rather conflicting that dissipation also can be used as a powerful resource to realize QIP. However, The recent surge of interest and progress in quantum information theory allows one to take a more positive for the view of dissipation and regard it as an essential resource. Several works for entanglement gneration utilizing dissipation-assisted have been considered with many quantum optical and solid state systems, such as cavity and circuit QED system [24–41], atomic ensembles [42–44], ion traps [45–47], plasmonic systems [48–50], and optical lattices [51, 52]. Particularly, Busch *et al.* [26] showed that two atoms in an optical cavity can be cooled to a maximally entangled state by employing level shifts induced by laser fields. Reiter and coworkers [27, 28] proposed a scheme for dissipative preparation of entanglement via engineering the decay process. Moreover, several schemes for dissipatively preparing multipartite entangled state are also investigated [53–57]. However, most of the previous theoretical schemes [26–28, 53–55] concentrate on the case in which two atoms are trapped in a single cavity.

On the other hand, realizing entanglement and deterministic quantum gates between separate subsystems is of great importance for distributed quantum computation (DQC) [58], it is a basic requirement to perform state transfer and quantum gate operation between separate nodes of a quantum network. The atom-cavity-fiber system [59, 60] has been attracted much attentions and have been an excellent platform for DQC due to the application in long distance and large-scale QIP. For the most of theoretical schemes focused on the traditional coherent unitary dynamics requiring precise timing [61–65], in which atomic spontaneous emission, cavity decay, and fiber loss are three main and undesirable dissipative factors, which would bring a detrimental effect in the QIP.

In this paper, we explore the possibility of preparing three-partite W state of distant atoms in an atom-cavity-fiber system. The scheme is based on the competition between coherent driving and collective dissipation for bosonic mode induced by classical laser field and cavity field decay. Interestingly, the dispersive atom-field interaction and cavity-fiber coupling make our schemes robust with respect to the atomic spontaneous and fiber loss. In contrast with the unitary evolution schemes, the operation time of our scheme need not be controlled accurately. By suitable choice of system parameters, the W-type steady entanglement can be obtained with a high fidelity. In addition, the present scheme can also be extended to prepare the N-partite W state of distant atoms.

2 Dissipative preparation and stabilization of entanglement

2.1 The basic model

We consider an atom-cavity-fiber coupling system consisting of three distant cavities connected by two single-transverse-mode optical fibers, as shown in Fig. 1(a). In

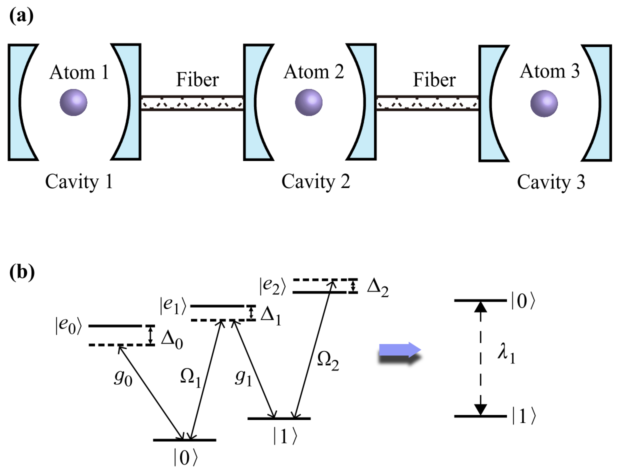

Fig. 1 **(a)** Schematic of the setup. The three distant W-type atoms are trapped in separate cavities connected by two optical fibers. **(b)** The level configuration of atoms. Each atom is driven by two dispersive laser fields and simultaneously coupled to its own cavity mode, which is then reduced to an effective two-level atom.

the short fiber limit $(l\bar{\upsilon})/(2\pi c)$, where l is the length of the fiber and $\bar{\upsilon}$ is the decay rate of the cavity fields into a continuum of fiber modes, only one fiber mode interacts with the cavity mode. The atomic level configuration is shown in Fig. 1(b). The energy of level $|0\rangle$ is taken to be 0 as the energy reference point. The lower-lying level $|1\rangle$ and the upper levels $|e_0\rangle$, $|e_1\rangle$, and $|e_2\rangle$ have the energy ω', ω_{e0}, ω_{e1}, and ω_{e2}, respectively ($\hbar = 1$). The transitions $|1\rangle \leftrightarrow |e_1\rangle$ and $|0\rangle \leftrightarrow |e_0\rangle$ are driven by the cavity mode at frequency ω_c, whereas the transitions $|0\rangle \leftrightarrow |e_1\rangle$ and $|1\rangle \leftrightarrow |e_2\rangle$ are driven by classical laser fields Ω_1 and Ω_2, respectively. For this case, the Hamiltonian for the whole system is written as

$$H = H_0 + H_{int} + H_{c,f}, \tag{1}$$

where

$$\begin{aligned} H_0 = & \sum_{i=1}^{3}(\omega_c^i a_i^\dagger a_i + \omega' |1\rangle_{ii}\langle 1| + \omega_{e_0}|e_0\rangle_{ii}\langle e_0| \\ & + \omega_{e_1}|e_1\rangle_{ii}\langle e_1| + \omega_{e_2}|e_2\rangle_{ii}\langle e_2|) + \sum_{k=1}^{2}\omega_b^k b_k^\dagger b_k, \\ H_{int} = & \sum_{i=1}^{3}[(g_0|e_0\rangle_{ii}\langle 0| + g_1|e_1\rangle_{ii}\langle 1|)a_i \\ & + (\Omega_1 \mathrm{e}^{-\mathrm{i}\omega_1 t}|e_1\rangle_{ii}\langle 0| + \Omega_2 \mathrm{e}^{-\mathrm{i}\omega_2 t}|e_2\rangle_{ii}\langle 1|)] + \mathrm{H.c.}, \\ H_{c,f} = & \sum_{k=i=1}^{2} \nu \left[b_k^\dagger (a_i + a_{i+1}) \right] + \mathrm{H.c.}, \end{aligned} \tag{2}$$

where H_0 is the energy of the system consisting of atoms, cavity fields, and fiber modes; H_{int} denotes the atom-cavity and atom-laser interaction Hamiltonian; and $H_{c,f}$

describes the coupling between the cavity modes and fibers; a_i is the annihilation operator for the ith cavity mode; b_k is the annihilation operator for the kth fiber mode; g_0 and g_1 are the atom-cavity coupling constants; ω_1 and ω_2 are the frequencies of classical laser fields; ω_c^i and ω_b^k denote the frequencies of the i cavity mode and the k fiber mode, respectively; ν is the cavity-fiber coupling strength. We adjust the frequency of cavity mode ω_c^i to resonate with the frequency of fiber mode ω_b^k and work under the two-photon resonance condition ($\omega' = \omega_1 - \omega_c$). In the interaction picture with respect to H_0, H_{int} and $H_{c,f}$ can be rewritten as

$$
\begin{aligned}
H'_{int} &= \sum_{i=1}^{3} [(g_0 \mathrm{e}^{\mathrm{i}\Delta_0 t}|e_0\rangle_{ii}\langle 0| + g_1 \mathrm{e}^{\mathrm{i}\Delta_1 t}|e_1\rangle_{ii}\langle 1|)a_i \\
&\quad + (\Omega_1 \mathrm{e}^{\mathrm{i}\Delta_1 t}|e_1\rangle_{ii}\langle 0| + \Omega_2 \mathrm{e}^{-\mathrm{i}\Delta_2 t}|e_2\rangle_{ii}\langle 1|)] + \mathrm{H.c.}, \\
H'_{c,f} &= \sum_{k=i=1}^{2} \nu \left[b_k^\dagger (a_i + a_{i+1}) \right] + \mathrm{H.c.},
\end{aligned} \tag{3}
$$

where $\Delta_0 = \omega_{e0} - \omega_0$, $\Delta_1 = \omega_{e1} - \omega_c - \omega'$, and $\Delta_2 = \omega_{e2} - \omega' - \omega_2$. In order to investigate the dynamics of the system further, we introduce the non-local bosonic modes

$$
\begin{aligned}
c_1 &= \frac{1}{\sqrt{3}}(a_1 - a_2 + a_3), \\
c_2 &= \frac{1}{2}(a_1 + b_1 - b_2 - a_3), \\
c_3 &= \frac{1}{2}(a_1 - b_1 + b_2 - a_3), \\
c_4 &= \frac{1}{\sqrt{12}}(a_1 + \sqrt{3}b_1 + 2a_2 + \sqrt{3}b_2 + a_3), \\
c_5 &= \frac{1}{\sqrt{12}}(a_1 - \sqrt{3}b_1 + 2a_2 - \sqrt{3}b_2 + a_3),
\end{aligned} \tag{4}
$$

Then we can rewrite the whole Hamiltonian in the interaction picture as

$$
H = H'_0 + H_i, \tag{5}
$$

where

$$
H'_0 = \nu c_2^\dagger c_2 - \nu c_3^\dagger c_3 + \sqrt{3}\nu c_4^\dagger c_4 - \sqrt{3}\nu c_5^\dagger c_5, \tag{6}
$$

and

$$
\begin{aligned}
H_i &= \frac{1}{2} g_1 \left[\frac{2\sqrt{3}}{3} c_1 + c_2 + c_3 + \frac{\sqrt{3}}{3}(c_4 + c_5) \right] \mathrm{e}^{\mathrm{i}\Delta_1 t}|e_1\rangle_{11}\langle 1| - \frac{\sqrt{3}}{3} g_1 [c_1 - (c_4 + c_5)] \mathrm{e}^{\mathrm{i}\Delta_1 t}|e_1\rangle_{22}\langle 1| \\
&\quad + \frac{1}{2} g_1 \left[\frac{2\sqrt{3}}{3} c_1 - c_2 - c_3 + \frac{\sqrt{3}}{3}(c_4 + c_5) \right] \mathrm{e}^{\mathrm{i}\Delta_1 t}|e_1\rangle_{33}\langle 1| + \frac{1}{2} g_0 \left[\frac{2\sqrt{3}}{3} c_1 + c_2 + c_3 + \frac{\sqrt{3}}{3}(c_4 + c_5) \right] \mathrm{e}^{\mathrm{i}\Delta_0 t}|e_0\rangle_{11}\langle 0| \\
&\quad - \frac{\sqrt{3}}{3} g_0 [c_1 - (c_4 + c_5)] \mathrm{e}^{\mathrm{i}\Delta_0 t}|e_0\rangle_{22}\langle 0| + \frac{1}{2} g_0 \left[\frac{2\sqrt{3}}{3} c_1 - c_2 - c_3 + \frac{\sqrt{3}}{3}(c_4 + c_5) \right] \mathrm{e}^{\mathrm{i}\Delta_0 t}|e_0\rangle_{33}\langle 0| \\
&\quad + \sum_{i=1}^{3} (\Omega_1 \mathrm{e}^{\mathrm{i}\Delta_1 t}|e_1\rangle_{ii}\langle 0| + \Omega_2 \mathrm{e}^{-\mathrm{i}\Delta_2 t}|e_2\rangle_{ii}\langle 1|) + \mathrm{H.c.}.
\end{aligned} \tag{7}
$$

In a rotating frame with respect to the H'_0, the Hamiltonian H_i is transformed to

$$
\begin{aligned}
H'_i &= \frac{1}{2} g_1 \left[\frac{2\sqrt{3}}{3} c_1 \mathrm{e}^{\mathrm{i}\Delta_1 t} + c_2 \mathrm{e}^{\mathrm{i}(\Delta_1 - \nu)t} + c_3 \mathrm{e}^{\mathrm{i}(\Delta_1 + \nu)t} + \frac{\sqrt{3}}{3}(c_4 \mathrm{e}^{\mathrm{i}(\Delta_1 - \sqrt{3}\nu)t} + c_5 \mathrm{e}^{\mathrm{i}(\Delta_1 + \sqrt{3}\nu)t}) \right] |e_1\rangle_{11}\langle 1| \\
&\quad - \frac{\sqrt{3}}{3} g_1 [c_1 \mathrm{e}^{\mathrm{i}\Delta_1 t} - (c_4 \mathrm{e}^{\mathrm{i}(\Delta_1 - \sqrt{3}\nu)t} + c_5 \mathrm{e}^{\mathrm{i}(\Delta_1 + \sqrt{3}\nu)t})] |e_1\rangle_{22}\langle 1| \\
&\quad + \frac{1}{2} g_1 \left[\frac{2\sqrt{3}}{3} c_1 \mathrm{e}^{\mathrm{i}\Delta_1 t} - c_2 \mathrm{e}^{\mathrm{i}(\Delta_1 - \nu)t} - c_3 \mathrm{e}^{\mathrm{i}(\Delta_1 + \nu)t} + \frac{\sqrt{3}}{3}(c_4 \mathrm{e}^{\mathrm{i}(\Delta_1 - \sqrt{3}\nu)t} + c_5 \mathrm{e}^{\mathrm{i}(\Delta_1 + \sqrt{3}\nu)t}) \right] |e_1\rangle_{33}\langle 1| \\
&\quad + \frac{1}{2} g_0 \left[\frac{2\sqrt{3}}{3} c_1 \mathrm{e}^{\mathrm{i}\Delta_0 t} + c_2 \mathrm{e}^{\mathrm{i}(\Delta_0 - \nu)t} + c_3 \mathrm{e}^{\mathrm{i}(\Delta_0 + \nu)t} + \frac{\sqrt{3}}{3}(c_4 \mathrm{e}^{\mathrm{i}(\Delta_0 - \sqrt{3}\nu)t} + c_5 \mathrm{e}^{\mathrm{i}(\Delta_0 + \sqrt{3}\nu)t}) \right] |e_0\rangle_{11}\langle 0| \\
&\quad - \frac{\sqrt{3}}{3} g_0 [c_1 \mathrm{e}^{\mathrm{i}\Delta_0 t} - (c_4 \mathrm{e}^{\mathrm{i}(\Delta_0 - \sqrt{3}\nu)t} + c_5 \mathrm{e}^{\mathrm{i}(\Delta_0 + \sqrt{3}\nu)t})] |e_0\rangle_{22}\langle 0| \\
&\quad + \frac{1}{2} g_0 \left[\frac{2\sqrt{3}}{3} c_1 \mathrm{e}^{\mathrm{i}\Delta_0 t} - c_2 \mathrm{e}^{\mathrm{i}(\Delta_0 - \nu)t} - c_3 \mathrm{e}^{\mathrm{i}(\Delta_0 + \nu)t} + \frac{\sqrt{3}}{3}(c_4 \mathrm{e}^{\mathrm{i}(\Delta_0 - \sqrt{3}\nu)t} + c_5 \mathrm{e}^{\mathrm{i}(\Delta_0 + \sqrt{3}\nu)t}) \right] |e_0\rangle_{33}\langle 0| \\
&\quad + \sum_{i=1}^{3} (\Omega_1 \mathrm{e}^{\mathrm{i}\Delta_1 t}|e_1\rangle_{ii}\langle 0| + \Omega_2 \mathrm{e}^{-\mathrm{i}\Delta_2 t}|e_2\rangle_{ii}\langle 1|) + \mathrm{H.c.}.
\end{aligned} \tag{8}
$$

Under the conditions $\{\Delta_0, |\Delta_0 \pm \sqrt{3}\nu|\} \gg g_0$, $\{\Delta_1, |\Delta_1 \pm \sqrt{3}\nu|\} \gg \{g_1, \Omega_1\}$, and $\Delta_2 \gg \Omega_2$, the excited states $|e_0\rangle$, $|e_1\rangle$, and $|e_2\rangle$ can be eliminated adiabatically. H_i' is reduced to an effective interaction Hamiltonian,

$$\begin{aligned}H_{eff} = &-[(\lambda_1 c_1 + \lambda_2 c_2 \mathrm{e}^{-\mathrm{i}\nu t} + \lambda_3 c_3 \mathrm{e}^{\mathrm{i}\nu t} \\ &+\lambda_4 c_4 \mathrm{e}^{-\mathrm{i}\sqrt{3}\nu t} + \lambda_5 c_5 \mathrm{e}^{\mathrm{i}\sqrt{3}\nu t})|0\rangle_{11}\langle 1| \\ &-(\lambda_1 c_1 - 2\lambda_4 c_4 \mathrm{e}^{-\mathrm{i}\sqrt{3}\nu t} - 2\lambda_5 c_5 \mathrm{e}^{\mathrm{i}\sqrt{3}\nu t})|0\rangle_{22}\langle 1| \\ &-(\lambda_1 c_1 - \lambda_2 c_2 \mathrm{e}^{-\mathrm{i}\nu t} - \lambda_3 c_3 \mathrm{e}^{\mathrm{i}\nu t} \\ &+\lambda_4 c_4 \mathrm{e}^{-\mathrm{i}\sqrt{3}\nu t} + \lambda_5 c_5 \mathrm{e}^{\mathrm{i}\sqrt{3}\nu t})|0\rangle_{33}\langle 1| + \mathrm{H.c.}] \\ &- \sum_{m=1}^{5} c_m^\dagger c_m [\varepsilon_m (|1\rangle_{11}\langle 1| + |1\rangle_{33}\langle 1|) \\ &+\eta_m (|0\rangle_{11}\langle 0| + |0\rangle_{33}\langle 0|)] \\ &-(\varepsilon_1 c_1^\dagger c_1 + 4\varepsilon_4 c_4^\dagger c_4 + 4\varepsilon_5 c_5^\dagger c_5)|1\rangle_{22}\langle 1| \\ &-(\eta_1 c_1^\dagger c_1 + 4\eta_4 c_4^\dagger c_4 + 4\eta_5 c_5^\dagger c_5)|0\rangle_{22}\langle 0| \\ &- \sum_{j=1}^{3} (\mu|0\rangle_{jj}\langle 0| + \delta|1\rangle_{jj}\langle 1|), \end{aligned} \tag{9}$$

where

$$\begin{aligned} &\lambda_1 = \frac{\sqrt{3} g_1 \Omega_1}{3\Delta_1}, \quad \lambda_2 = \frac{g_1\Omega_1}{4}\left(\frac{1}{\Delta_1} - \frac{1}{\nu}\right), \\ &\lambda_3 = \frac{g_1\Omega_1}{4}\left(\frac{1}{\Delta_1} + \frac{1}{\nu}\right), \quad \lambda_4 = \frac{\sqrt{3} g_1\Omega_1}{12}\left(\frac{1}{\Delta_1} - \frac{1}{\sqrt{3}\nu}\right), \\ &\lambda_5 = \frac{\sqrt{3} g_1\Omega_1}{12}\left(\frac{1}{\Delta_1} + \frac{1}{\sqrt{3}\nu}\right), \\ &\varepsilon_1 = \frac{g_1^2}{3\Delta_1}, \quad \varepsilon_2 = \frac{g_1^2}{\Delta_1 - 4\nu}, \quad \varepsilon_3 = \frac{g_1^2}{\Delta_1 + 4\nu}, \\ &\varepsilon_4 = \frac{g_1^2}{\Delta_1 - 12\sqrt{3}\nu}, \quad \varepsilon_5 = \frac{g_1^2}{\Delta_1 + 12\sqrt{3}\nu}, \\ &\eta_1 = \frac{g_0^2}{3\Delta_0}, \quad \eta_2 = \frac{g_0^2}{\Delta_0 - 4\nu}, \quad \eta_3 = \frac{g_0^2}{\Delta_0 + 4\nu}, \\ &\eta_4 = \frac{g_0^2}{\Delta_0 - 12\sqrt{3}\nu}, \quad \eta_5 = \frac{g_0^2}{\Delta_0 + 12\sqrt{3}\nu}, \\ &\mu = \frac{\Omega_1^2}{\Delta_1}, \quad \delta = \frac{\Omega_2^2}{\Delta_2}. \end{aligned} \tag{10}$$

Under the condition of $\nu \gg \lambda_n$ (n = 2, 3, 4, 5), the bosonic mode c_1 is resonant with the three qubits, while the bosonic modes c_2, c_3, c_4, and c_5 are largely dispersive with the three qubits, these high-frequency oscillating terms may be neglected. Besides, suppose that the bosonic mode c_m is initially in the vacuum state, the bosonic modes c_2, c_3, c_4, and c_5 do not exchange energy with the atoms, they would remain in the vacuum state during the evolution, i.e., $c_2^\dagger c_2 = c_3^\dagger c_3 = c_4^\dagger c_4 = c_5^\dagger c_5 = 0$. In this case the effective Hamiltonian H_{eff} becomes

$$\begin{aligned} H_{eff}' = -\sum_{j=1}^{3} \Big[&(\eta_1 c_1^\dagger c_1 |0\rangle_{jj}\langle 0| + \mu|0\rangle_{jj}\langle 0| + \varepsilon_1 c_1^\dagger c_1 |1\rangle_{jj}\langle 1| \\ &+\delta|1\rangle_{jj}\langle 1|) + (\lambda_1 c_1 |0\rangle_{jj}\langle 1| + \mathrm{H.c.})\Big], \end{aligned} \tag{11}$$

in which the first four terms represent the dynamics shifts of atomic levels $|0\rangle_j$ and $|1\rangle_j$, and the last two terms describe the coupling between atomic operators $|0\rangle_{jj}\langle 1|$ and the bosonic mode c_1.

2.2 Preparation of three qubits W state

We suppose that the bosonic mode c_1 is heavily damped with the decay rate κ. Then the master equation of motion for the density matrix of the system is expressed as

$$\dot{\hat{\rho}}(t) = \mathrm{i}[\rho(\hat{t}), H_{eff}'] + \frac{\kappa}{2}(2c_1\rho(\hat{t})c_1^\dagger - \rho(\hat{t})c_1^\dagger c_1 - c_1^\dagger c_1 \rho(\hat{t})). \tag{12}$$

If the initial state of the atoms is in ground state $|0\rangle_1|0\rangle_2|0\rangle_3$, the state vector of the system can be expanded in terms of the possible basis states $|\psi(t)\rangle = \sum_{n=1}^{6} d_n|\phi_n\rangle$, where d_n is the probability amplitudes for the corresponding basis states

$$\begin{aligned} |\phi_1\rangle &= |0\rangle_1|0\rangle_2|0\rangle_3|0\rangle_{c1}, \\ |\phi_2\rangle &= |\psi_T\rangle|1\rangle_{c1}, \\ |\phi_3\rangle &= |\psi_T\rangle|0\rangle_{c1}, \\ |\phi_4\rangle &= \frac{1}{\sqrt{3}}(|1\rangle_1|1\rangle_2|0\rangle_3 + |0\rangle_1|1\rangle_2|1\rangle_3 + |1\rangle_1|0\rangle_2|1\rangle_3)|2\rangle_{c1}, \\ |\phi_5\rangle &= \frac{1}{\sqrt{3}}(|1\rangle_1|1\rangle_2|0\rangle_3 + |0\rangle_1|1\rangle_2|1\rangle_3 + |1\rangle_1|0\rangle_2|1\rangle_3)|1\rangle_{c1}, \\ |\phi_6\rangle &= \frac{1}{\sqrt{3}}(|1\rangle_1|1\rangle_2|0\rangle_3 + |0\rangle_1|1\rangle_2|1\rangle_3 + |1\rangle_1|0\rangle_2|1\rangle_3)|0\rangle_{c1}, \end{aligned} \tag{13}$$

in which $|\psi_T\rangle = 1/\sqrt{3}(|1\rangle_1|0\rangle_2|0\rangle_3 + |0\rangle_1|1\rangle_2|0\rangle_3 + |0\rangle_1|0\rangle_2|1\rangle_3)$ is the maximal entanglement W state for the three distributed atoms. The corresponding eigenvalues of these basis states are shown in Table 1. State $|\phi_1\rangle$ has the energy $E_1 = 3\mu$, while state $|\phi_2\rangle$ has the corresponding energies $E_2 = 2\eta_1 + 2\mu + \varepsilon_1 + \delta$. The energy offset between state $|\phi_1\rangle$ and $|\phi_2\rangle$ is $\delta_E = E_2 - E_1 = 2\eta_1 + \varepsilon_1 + \delta - \mu$. Under the conditions $\delta = -2\eta_1$ and $\{|\delta|, |\eta_1|\} \gg \{|\varepsilon_1|, |\mu|, |\lambda_1|\}$, $|\phi_1\rangle$ is tuned on resonance with $|\phi_2\rangle$. Affected by the photon loss of bosonic mode c_1, it is easy to find that the state $|\phi_2\rangle$ would be decayed

Table 1 The eigenenergies of the basis states $|\phi_n\rangle$.

Eigenstate	Eigenenergy
$\|\phi_1\rangle$	$E_1 = 3\mu$
$\|\phi_2\rangle$	$E_2 = 2\eta_1 + 2\mu + \varepsilon_1 + \delta$
$\|\phi_3\rangle$	$E_3 = 2\mu + \delta$
$\|\phi_4\rangle$	$E_4 = 2\eta_1 + \mu + 4\varepsilon_1 + 2\delta$
$\|\phi_5\rangle$	$E_5 = \eta_1 + \mu + 2\varepsilon_1 + 2\delta$
$\|\phi_6\rangle$	$E_6 = \mu + 2\delta$

to the state $|\phi_3\rangle$ which is decoupled from the other states ($|\phi_4\rangle$, $|\phi_5\rangle$, and $|\phi_6\rangle$) due to large energy offsets and unaffected by the photon loss of bosonic mode c_1. With the coherent driving and dissipation processes continuing, the population of state $|\phi_3\rangle$ is gradually accumulated and tends to be stable.

2.3 Preparation of N-qubits W state

Up to now, based on our scheme, we have demonstrated the generation of three-partite W state. Before ending this section, we will briefly show that the present scheme also can be extended to prepare the $N-$partite W state, $|\psi_T\rangle_N = 1/\sqrt{N}(|1\rangle_1|0\rangle_2\ldots|0\rangle_N + |0\rangle_1|1\rangle_2\ldots|0\rangle_N + \ldots|0\rangle_1|0\rangle_2\ldots|1\rangle_N)$. For realizing the N-partite W state of atoms, we can choose N single-mode cavities couple synchronously with each other via $N-1$ fibers. N atoms are trapped in N cavities and driven by two classical laser fields Ω_1 and Ω_2, respectively. The level configurations of corresponding atoms are the same as in Fig. 1(b). Considering the periodic boundary conditions $a_N = a_1$ and $b_{N-1} = b_1$, and taking the advantage of bosonic transformation $A_j = (1/\sqrt{2N-1})\Sigma_{k=1}^{2N-1}\mathrm{e}^{-\mathrm{i}[2\pi/(2N-1)]jk}c_k[j = 1, 2, \ldots, (2N-1)]$, in which $\{a_N, b_N\} \in A_j$ [66]. We move to the rotation frame with respect to $\Sigma_{n=1}^{N}\omega_n c_n^\dagger c_n$, under the large detuning conditions, and the condition that cavity-fiber coupling strength ν is much larger than the effective atom-bosonic coupling strength $\lambda_m (m = 2, 3, \ldots, N)$, the terms that bosonic mode c_1 resonantly interact with the N atomic qubits can be retained. By adjusting the systemic parameters appropriately, the N-partite W state of distant atoms $|\psi_T\rangle_N$ can be generated via bosonic mode decay. Note that we are not going to further demonstrate the quantitative calculation as it is just a tedious work similar to the three-party case.

3 Discussion

3.1 Numerical simulation

To demonstrate the feasibility of above theoretical analysis, we assess the fidelity $F(t) = \mathrm{Tr}[(|\psi_T\rangle\langle\psi_T| \otimes I_{c1})\rho(\hat{t})]$ and purity $P(t) = \mathrm{Tr}[\rho(\hat{t})^2]$ of our scheme by numerically solving Eq. (12). In Fig. 2(a), we show the fidelity of target state $|\psi_T\rangle$ when κ is chosen to λ_1, $3\lambda_1$, and $5\lambda_1$. One can observe that the fidelity becomes close to 1 when the evolution time $t \simeq 1200/g_1$. Thus the maximal entanglement W state can be achieved perfectly. At the same time, as κ decreases, the fidelity exhibits oscillatory behavior before it reaches its maximum value. This can be explained as follows. Since the target state $|\psi_T\rangle$ is determined by the combined effect of the coherent driving and dissipation, while the coherent driving is the main reason for oscillatory behavior. When the $\kappa = \lambda_1$, optical Rabi oscillation between the weight of qubits' components $|\phi_1\rangle$ and $|\phi_2\rangle$ becomes obvious in the dynamic processes of the system. As κ increases, the total photon number decreases gradually and the transition $|\phi_2\rangle \to |\phi_1\rangle$ is suppressed. Thus the oscillatory behavior disappears. In Fig. 2(b), the purity of the target state is

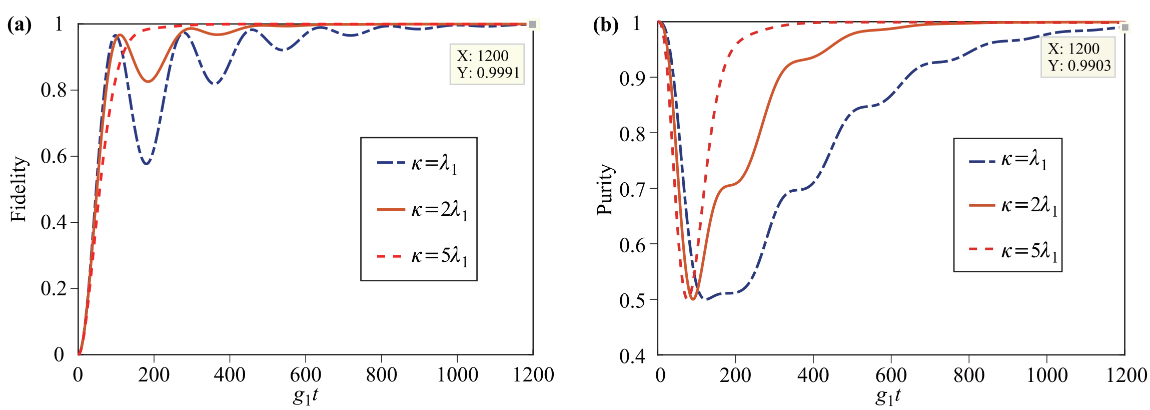

Fig. 2 Fidelity as a function of g_1t for different of κ. Parameters are chosen as $\Omega_1 = g_1$, $\Omega_2 = 200g_1$, $\Delta_1 = 100g_1$, $\Delta_2 = -20\Omega_2$, $\Delta_0 = 40g_0$, $\eta_1 = 500\lambda_1$, and $\delta = -2\eta_1$.

plotted as a function of the evolution time. The target state can be stabilized with a purity of approximately 99%. It is note that the purity curve exhibits a valley in the regime $0 < t < 300/g_1$. This valley occurs because the coherent driving is dominant in the early stages of evolution, thus leading the system to be in a mixture of a variety of quantum states. With increasing evolution time, the competition between the coherent driving and dissipation drives the system to a dynamic equilibrium, which is a mixture of specifc basis states.

The significant spontaneous emission of the current system arises from three upper levels to the other two levels. The corresponding dissipation terms are given as

$$\hat{\mathcal{L}}\rho(\hat{t}) = \sum_{j=1}^{3}\sum_{k=1}^{4}\Big[\gamma(2\hat{\mathcal{L}}_{j,k}\rho(\hat{t})\hat{\mathcal{L}}^{\dagger}_{j,k} - \hat{\mathcal{L}}^{\dagger}_{j,k}\hat{\mathcal{L}}_{j,k}\rho(\hat{t}) - \rho(\hat{t})\hat{\mathcal{L}}^{\dagger}_{j,k}\hat{\mathcal{L}}_{j,k})\Big], \tag{14}$$

where $\hat{\mathcal{L}}_{j,1} = |0\rangle_{jj}\langle e_0|$, $\hat{\mathcal{L}}_{j,2} = |0\rangle_{jj}\langle e_1|$, $\hat{\mathcal{L}}_{j,3} = |1\rangle_{jj}\langle e_1|$, and $\hat{\mathcal{L}}_{j,4} = |1\rangle_{jj}\langle e_2|$. γ is the spontaneous emission rate. These decoherence channels will not vanish, but transform into other forms after the upper levels are adiabatically eliminated. We suppose that the spontaneous emission rates for different decay channels are equal. The effective spontaneous emission effect in the Lindblad master equation takes the form [38, 67]

$$\hat{\mathcal{R}}\rho(\hat{t}) = \sum_{j=1}^{3}\sum_{k=1}^{4}\Big[\gamma(2\hat{\mathcal{R}}_{j,k}\rho(\hat{t})\hat{\mathcal{R}}^{\dagger}_{j,k} - \hat{\mathcal{R}}^{\dagger}_{j,k}\hat{\mathcal{R}}_{j,k}\rho(\hat{t}) - \rho(\hat{t})\hat{\mathcal{R}}^{\dagger}_{j,k}\hat{\mathcal{R}}_{j,k})\Big]. \tag{15}$$

with

$$\begin{aligned}
\hat{\mathcal{R}}_{j,1} &= -\frac{g_0}{\sqrt{3}\Delta_0}|0\rangle_{jj}\langle 0|c_1,\\
\hat{\mathcal{R}}_{j,2} &= -\frac{\Omega_1}{\Delta_1}|0\rangle_{jj}\langle 0| - \frac{g_1}{\sqrt{3}\Delta_1}|0\rangle_{jj}\langle 1|c_1,\\
\hat{\mathcal{R}}_{j,3} &= -\frac{\Omega_1}{\Delta_1}|1\rangle_{jj}\langle 0| - \frac{g_1}{\sqrt{3}\Delta_1}|1\rangle_{jj}\langle 1|c_1,\\
\hat{\mathcal{R}}_{j,4} &= -\frac{\Omega_2}{\sqrt{3}\Delta_2}|1\rangle_{jj}\langle 1|c_1.
\end{aligned} \tag{16}$$

In Fig. 3, we plot the fidelity as a function of time $\lambda_1 t$ and atomic spontaneous emission rate γ/λ_1 for the given photon decay rate $\kappa = 2\lambda_1$. The results show that the fidelity decreases with increasing γ/λ_1. This is because atomic spontaneous emission might drive the system in to other states which is decoupled from the target state. However, the condition of large detuning could decrease the effective spontaneous emission rate to guarantee our scheme is insensitive to deviation of the negative dissipative factor. Hence the appropriate choice of detunings is useful to obtain a higher fidelity of the target state in the presence of atomic spontaneous emission, i.e., when the parameters satisfy the condition $|\Delta_0|$, $|\Delta_1|$, $|\Delta_2|$=$40g_0$, $100g_1$, $20\Omega_2$, the target state can be prepared with a fidelity changes from 99.96% to 94.29% corresponding to the $0 \leq \gamma \leq 8\lambda_1$.

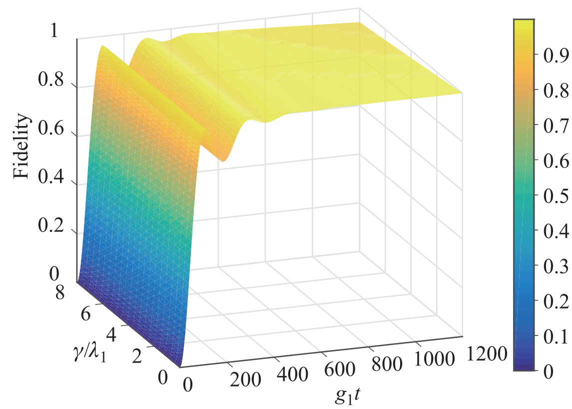

Fig. 3 Plot of fidelity for target state $|\phi_3\rangle$ versus time g_1t and atomic spontaneous emission rate γ/λ_1 at $\kappa = 2\lambda_1$. Other parameters are the same as in Fig. 2.

Before ending this section, let us briefly discuss the experimental feasibility of our scheme. Based on resent experiments in realizing high-Q cavity [68], we can choose $g_0 = g_1 = \Omega_1 = 2.5$ GHz, $\Omega_2 = 25$ GHz, $\Delta_0 = 100$ GHz, $\Delta_1 = 2.5 \times 10^3$ GHz, $\Delta_2 = -1.5 \times 10^4$ GHz, $\kappa = 10$ MHz, and $\gamma = 10$ MHz as the basal system parameters of our schemes. Similar to Ref. [69], we assume the classical field Ω_1 has a Gaussian subsection function form $\Omega_1 \mathrm{e}^{-[(t-\tau_1)/T]^2}$ $(t \leq \tau_1)$, $\Omega_1(\tau_1 < t \leq \tau_2)$, and $\Omega_1 \mathrm{e}^{-[(t-\tau_2)/T]^2}$ $(t > \tau_2)$ where $T = 2$ GHz^{-1} is the duration of the classical field. τ_1 and τ_2 are chosen to be $0.1\pi/\lambda_1$ and $3\pi/\lambda_1$, respectively. Using these parameters the fidelity is higher than 80%. In addition, the condition $\{|\delta|, |\eta_1|\} \gg \{|\varepsilon_1|, |\mu|, |\lambda_1|\}$ should be satisfied by adjusting g_0 and Ω_2, which ensure that the transitions between target state and other states are largely detuned. Moreover, in our scheme, under the large detuning case, the fiber modes b_k is only virtually excited in the whole interaction process, and the atom exchange energy with one bosonic mode c_1 which is independent of the fiber mode hence the fiber loss rate can be approximately neglected. Lastly, along with the progress of fiber-cavity coupling techniques [70, 71], we believe that the W state of distant atoms can be realized with high fidelity based on our schemes.

3.2 The validity of scheme

Our scheme involves that three identical five-level atoms trapped in three distant cavities which are connected by

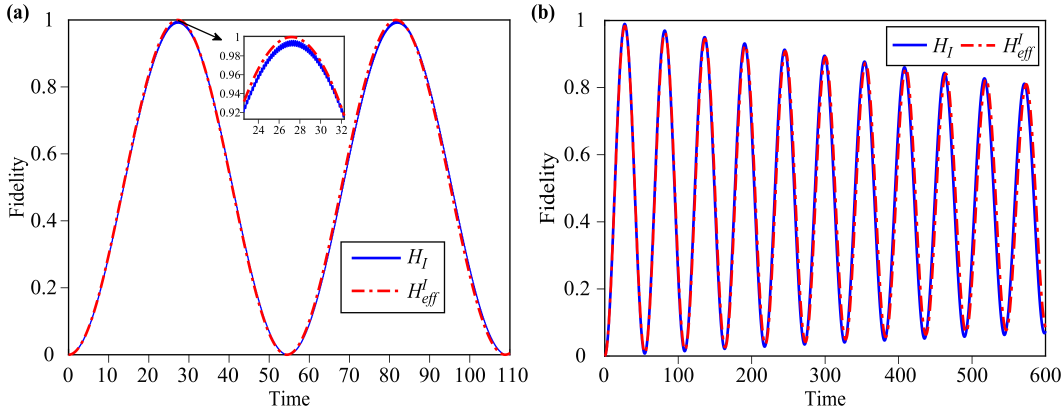

Fig. 4 **(a)** Time evolution of fidelities for the final state $|11\rangle_{ii}$ from initial state $|00\rangle_{ii}$ with effective Hamiltonian compared with the full one. **(b)** The effects of effective atomic spontaneous emission and original atomic spontaneous emission on the fidelities plotted in (a). The corresponding system parameters are chosen as $g_0 = \Omega_1$=1, $g_1 = 2g_0$, $\Omega_2 = \sqrt{3}g_0$, $\Delta_0 = 20g_0$, $\Delta_1 = \Delta_2 = 20\sqrt{3}g_0$, and $\gamma = 0.1g_0$.

two optical fibers, it would be very difficult to simulate the dynamical evolution of system with original Hamiltonian in Eq. (1) due to the whole dimensions beyond the computational power of computational software. In order to inspect the validity of above numerical simulations, we extract a basic model from our original scheme, a single atom i is coupled to the corresponding cavity mode, and two classical laser fields Ω_1 and Ω_2, the full Hamiltonian can be written as follows:

$$H_I = [(g_0 e^{i\Delta_0 t}|e_0\rangle_{ii}\langle 0| + g_1 e^{i\Delta_1 t}|e_1\rangle_{ii}\langle 1|)a_i + (\Omega_1 e^{i\Delta_1 t}|e_1\rangle_{ii}\langle 0| + \Omega_2 e^{-i\Delta_2 t}|e_2\rangle_{ii}\langle 1|)] + \text{H.c.}, \quad (17)$$

with the large-detuning conditions $\Delta_0 \gg g_0$, $\Delta_1 \gg \{\Omega_1, g_1\}$, and $\Delta_2 \gg \Omega_2$, the excited states $|e_0\rangle$, $|e_1\rangle$, and $|e_2\rangle$ can be eliminated adiabatically. H_I is reduced to an effective form

$$H_{eff}^I = \left[\frac{g_0^2}{\Delta}|0\rangle_{ii}\langle 0|a_i^\dagger a_i + \frac{\Omega_1^2}{\Delta_1}|0\rangle_{ii}\langle 0| + \frac{g_1^2}{\Delta_1}|1\rangle_{ii}\langle 1|a_i^\dagger a_i + \frac{\Omega_2^2}{\Delta_2}|1\rangle_{ii}\langle 1| + \left(\frac{g_1\Omega_1}{\Delta_1}|0\rangle_{ii}\langle 1|a_i + \text{H.c.}\right)\right]. \quad (18)$$

In Fig. 4(a), we plot the fidelity of ideal final state $|11\rangle_{ii}$ as a function of evolution time for the initial state $|00\rangle_{ii}$, the blue solid line and red dash-dot line represent the dynamical evolution for full Hamiltonian in Eq. (17) and effective Hamiltonian in Eq. (18), respectively, which shows a fast rabi oscillation induced by cavity field and classical laser fields. In Fig. 4(b), we consider the effects of original atomic spontaneous emission and effective atomic spontaneous emission described by Lindblad operator in Eq. (14) and Eq. (15), respectively, which exhibits a behavior of asymptotically decaying rabi oscillation. From Fig. 4, one can see that the curves plotted with the full Hamiltonian and effective Hamiltonian fit well with each other, which can indirect proves that with the effective processes to simulate the dynamical evolution of our scheme is valid.

4 Conclusion

In conclusion, we have proposed an efficient scheme to prepare the distributed three-atom maximal entanglement W state in the atom-cavity-fiber system via bosonic mode decay. In our scheme, the population of target state is gradually accumulated until the entire qubit population is driven to stabilization, so it is not necessary to control the interaction time strictly. We also analyze the effective influence of atomic spontaneous emission on the fidelity of target state, and demonstrate the validity of numerical simulation by extracting a basic model from our original scheme. In addition, we have briefly shown that the N-partite W state of distant atoms can be realized. Finally, the experimental feasibility of our scheme is discussed, we believe that our schemes may be useful for the distributed quantum information processing tasks in the near future.

Acknowledgements This work was supported by the National Natural Science Foundation of China under Grant Nos. 11564041, 11747096, 11165015, 11264042, 11465020, and 61465013; the Project of Jilin Science and Technology Development for Leading Talent of Science and Technology Innovation in Middle and Young and Team Project under Grant No. 20160519022JH; China Postdoctoral Science Foundation under Grant Nos. 2017M612411, 2018T110735; the Education Department Foundation of Henan Province under Grant No. 18A140009.

References

1. A. Einstein, B. Podolsky, and N. Rosen, Can quantum-mechanical description of physical reality be considered complete? *Phys. Rev.* 47(10), 777 (1935)
2. D. Bohm, Quantum Theory, Prentice-Hall, Englewood Cliffs, NJ, 1951
3. J. I. Cirac and P. Zoller, Quantum computations with cold trapped ions, *Phys. Rev. Lett.* 74(20), 4091 (1995)
4. I. E. Protsenko, G. Reymond, N. Schlosser, and P. Grangier, Conditional quantum logic using two atomic qubits, *Phys. Rev. A* 66(6), 062306 (2002)
5. N. A. Gershenfeld and I. L. Chuang, Bulk spinresonance quantum computation, *Science* 275(5298), 350 (1997)
6. P. Domokos, J. M. Raimond, M. Brune, and S. Haroche, Simple cavity-QED two-bit universal quantum logic gate: The principle and expected performances, *Phys. Rev. A* 52(5), 3554 (1995)
7. Y. Makhlin, G. Schön, and A. Shnirman, Quantumstate engineering with Josephson-junction devices, *Rev. Mod. Phys.* 73(2), 357 (2001)
8. D. Loss and D. P. DiVincenzo, Quantum computation with quantum dots, *Phys. Rev. A* 57(1), 120 (1998)
9. N. D. Mermin, Extreme quantum entanglement in a superposition of macroscopically distinct states, *Phys. Rev. Lett.* 65(15), 1838 (1990)
10. D. Collins, N. Gisin, S. Popescu, D. Roberts, and V. Scarani, Bell-type inequalities to detect true n-body nonseparability, *Phys. Rev. Lett.* 88(17), 170405 (2002)
11. M. D. Reid, Q. Y. He, and P. D. Drummond, Entanglement and nonlocality in multi-particle systems, *Front. Phys.* 7(1), 72 (2012)
12. M. A. Nielsen and I. L. Chuang, Quantum Computation and Quantum Information, Cambridge University Press, 2000
13. A. Karlsson and M. Bourennane, Quantum teleportation using three-particle entanglement, *Phys. Rev. A* 58(6), 4394 (1998)
14. P. Y. Xiong, X. T. Yu, H. T. Zhan, and Z. C. Zhang, Multiple teleportation via partially entangled GHZ state, *Front. Phys.* 11(4), 110303 (2016)
15. M. D. G. Ramírez, B. J. Falaye, G. H. Sun, M. Cruz-Irisson, and S. H. Dong, Quantum teleportation and information splitting via four-qubit cluster state and a Bell state, *Front. Phys.* 12(5), 120306 (2017)
16. R. Cleve, D. Gottesman, and H. K. Lo, How to share a quantum secret, *Phys. Rev. Lett.* 83(3), 648 (1999)
17. M. Hillery, V. Bužek, and A. Berthiaume, Quantum secret sharing, *Phys. Rev. A* 59(3), 1829 (1999)
18. D. M. Greenberger, M. A. Horne, A. Shimony, and A. Zeilinger, Bell's theorem without inequalities, *Am. J. Phys.* 58(12), 1131 (1990)
19. W. Dür, G. Vidal, and J. I. Cirac, Three qubits can be entangled in two inequivalent ways, *Phys. Rev. A* 62(6), 062314 (2000)
20. A. Cabello, Two qubits of a W state violate Bell's inequality beyond Cirel'son's bound, *Rev. Rev. A* 66(4), 042114 (2002)
21. S. L. Su, Y. Z. Tian, H. Z. Shen, H. P. Zang, E. J. Liang, and S. Zhang, Applications of the modified Rydberg antiblockade regime with simultaneous driving, *Phys. Rev. A* 96(4), 042335 (2017)
22. S. L. Su, Y. Gao, E. J. Liang, and S. Zhang, Fast Rydberg antiblockade regime and its applications in quantum logic gates, *Phys. Rev. A* 95(2), 022319 (2017)
23. S. L. Su, E. J. Liang, S. Zhang, J. J. Wen, L. L. Sun, Z. Jin, and A. D. Zhu, One-step implementation of the Rydberg–Rydberg-interaction gate, *Phys. Rev. A* 93(1), 012306 (2016)
24. M. B. Plenio, S. F. Huelga, A. Beige, and P. L. Knight, Cavity-loss-induced generation of entangled atoms, *Phys. Rev. A* 59(3), 2468 (1999)
25. S. Clark, A. Peng, M. Gu, and S. Parkins, unconditional preparation of entanglement between atoms in cascaded optical cavities, *Phys. Rev. Lett.* 91(17), 177901 (2003)
26. J. Busch, S. De, S. S. Ivanov, B. T. Torosov, T. P. Spiller, and A. Beige, Cooling atom-cavity systems into entangled states, *Phys. Rev. A* 84(2), 022316 (2011)
27. M. J. Kastoryano, F. Reiter, and A. S. Sørensen, Dissipative preparation of entanglement in optical cavities, *Phys. Rev. Lett.* 106(9), 090502 (2011)
28. F. Reiter, M. J. Kastoryano, and A. S. Sørensen, Driving two atoms in an optical cavity into an entangled steady state using engineered decay, *New J. Phys.* 14(5), 053022 (2012)
29. L. T. Shen, X. Y. Chen, Z. B. Yang, H. Z. Wu, and S. B. Zheng, Steady-state entanglement for distant atoms by dissipation in coupled cavities, *Phys. Rev. A* 84(6), 064302 (2011)
30. L. T. Shen, X. Y. Chen, Z. B. Yang, H. Z. Wu, and S. B. Zheng, Distributed entanglement induced by dissipative bosonic media, *Europhys. Lett.* 99(2), 20003 (2012)
31. L. T. Shen, X. Y. Chen, Z. B. Yang, H. Z. Wu, and S. B. Zheng, Cooling distant atoms into steady entanglement via coupled cavities, *Quantum Inf. Comput.* 13, 281 (2013)
32. L. T. Shen, X. Y. Chen, Z. B. Yang, H. Z. Wu, and S. B. Zheng, Preparation of two-qubit steady entanglement through driving a single qubit, *Opt. Lett.* 39(20), 6046 (2014)
33. S. L. Su, X. Q. Shao, H. F. Wang, and S. Zhang, Scheme for entanglement generation in an atom-cavity system via dissipation, *Phys. Rev. A* 90(5), 054302 (2014)
34. S. L. Su, Q. Guo, H. F. Wang, and S. Zhang, Simplified scheme for entanglement preparation with Rydberg pumping via dissipation, *Phys. Rev. A* 92(2), 022328 (2015)

35. S. B. Zheng and L. T. Shen, Generation and stabilization of maximal entanglement between two atomic qubits coupled to a decaying resonator, *J. Phys. At. Mol. Opt. Phys.* 47(5), 055502 (2014)

36. X. Q. Shao, T. Y. Zheng, C. H. Oh, and S. Zhang, Dissipative creation of three-dimensional entangled state in optical cavity via spontaneous emission, *Phys. Rev. A* 89(1), 012319 (2014)

37. X. Q. Shao, J. B. You, T. Y. Zheng, C. H. Oh, and S. Zhang, Stationary three-dimensional entanglement via dissipative Rydberg pumping, *Phys. Rev. A* 89(5), 052313 (2014)

38. J. Song, X. D. Sun, Q. X. Mu, L. L. Zhang, Y. Xia, and H. S. Song, Direct conversion of a four-atom W state to a Greenberger–Horne–Zeilinger state via a dissipative process, *Phys. Rev. A* 88(2), 024305 (2013)

39. P. B. Li, S. Y. Gao, H. R. Li, S. L. Ma, and F. L. Li, Dissipative preparation of entangled states between two spatially separated nitrogen-vacancy centers, *Phys. Rev. A* 85(4), 042306 (2012)

40. C. Li, S. Yang, J. Song, Y. Xia, and W. Q. Ding, Generation of long-living entanglement between two distant three-level atoms in non-Markovian environments, *Opt. Express* 25(10), 10961 (2017)

41. S. L. Ma, Z. Y. Liao, F. L. Li, and M. S. Zubairy, Dissipative production of controllable steady-state entanglement of two superconducting qubits in separated resonators, *Europhys. Lett.* 110(4), 40004 (2015)

42. A. S. Parkins, E. Solano, and J. I. Cirac, Unconditional two-mode squeezing of separated atomic ensembles, *Phys. Rev. Lett.* 96(5), 053602 (2006)

43. C. A. Muschik, E. S. Polzik, and J. I. Cirac, Dissipatively driven entanglement of two macroscopic atomic ensembles, *Phys. Rev. A* 83(5), 052312 (2011)

44. E. G. Dalla Torre, J. Otterbach, E. Demler, V. Vuletic, and M. D. Lukin, Dissipative preparation of spin squeezed atomic ensembles in a steady state, *Phys. Rev. Lett.* 110(12), 120402 (2013)

45. J. F. Poyatos, J. I. Cirac, and P. Zoller, Quantum reservoir engineering with laser cooled trapped ions, *Phys. Rev. Lett.* 77(23), 4728 (1996)

46. J. Cho, S. Bose, and M. S. Kim, Optical pumping into manybody entanglement, *Phys. Rev. Lett.* 106(2), 020504 (2011)

47. J. T. Barreiro, M. Muller, P. Schindler, D. Nigg, T. Monz, M. Chwalla, M. Hennrich, C. F. Roos, P. Zoller, and R. Blatt, An open-system quantum simulator with trapped ions, *Nature* 470(7335), 486 (2011)

48. A. Gonzalez-Tudela, D. Martín-Cano, E. Moreno, L. Martin-Moreno, C. Tejedor, and F. J. Garcia-Vidal, Entanglement of two qubits mediated by one-dimensional plasmonic waveguides, *Phys. Rev. Lett.* 106(2), 020501 (2011)

49. M. Gullans, T. G. Tiecke, D. E. Chang, J. Feist, J. D. Thompson, J. I. Cirac, P. Zoller, and M. D. Lukin, Nanoplasmonic lattices for ultracold atoms, *Phys. Rev. Lett.* 109(23), 235309 (2012)

50. A. González-Tudela and D. Porras, Mesoscopic entanglement induced by spontaneous emission in solid-state quantum optics, *Phys. Rev. Lett.* 110(8), 080502 (2013)

51. S. Diehl, A. Micheli, A. Kantian, B. Kraus, H. P. Büchler, and P. Zoller, Quantum states and phases in driven open quantum systems with cold atoms, *Nat. Phys.* 4(11), 878 (2008)

52. M. Foss-Feig, A. J. Daley, J. K. Thompson, and A. M. Rey, Steady-state many-body entanglement of hot reactive fermions, *Phys. Rev. Lett.* 109(23), 230501 (2012)

53. D. X. Li, X. Q. Shao, J. H. Wu, and X. X. Yi, Dissipation-induced W state in a Rydberg-atom-cavity system, *Opt. Lett.* 43(8), 1639 (2018)

54. F. Reiter, D. Reeb, and A. S. Sørensen, Scalable dissipative preparation of many-body entanglement, *Phys. Rev. Lett.* 117(4), 040501 (2016)

55. X. Q. Shao, J. H. Wu, X. X. Yi, and G. L. Long, Dissipative preparation of steady Greenberger–Horne–Zeilinger states for Rydberg atoms with quantum Zeno dynamics, *Phys. Rev. A* 96(6), 062315 (2017)

56. G. D. de Moraes Neto, V. F. Teizen, V. Montenegro, and E. Vernek, Steady many-body entanglements in dissipative systems, *Phys. Rev. A* 96(6), 062313 (2017)

57. J. Song, C. Li, Z. J. Zhang, Y. Y. Jiang, and Y. Xia, Implementing stabilizer codes in noisy environments? *Phys. Rev. A* 96(3), 032336 (2017)

58. I. Cohen and K. Mølmer, Deterministic quantum network for distributed entanglement and quantum computation, arXiv: 1802.08124 (2018)

59. J. I. Cirac, P. Zoller, H. J. Kimble, and H. Mabuchi, Quantum state transfer and entanglement distribution among distant nodes in a quantum network, *Phys. Rev. Lett.* 78(16), 3221 (1997)

60. T. Pellizzari, Quantum networking with optical fibres, *Phys. Rev. Lett.* 79(26), 5242 (1997)

61. G. W. Lin, X. B. Zou, X. M. Lin, and G. C. Guo, Scalable, high-speed one-way quantum computer in coupled-cavity arrays, *Appl. Phys. Lett.* 95(22), 224102 (2009)

62. K. Zhang and Z. Y. Li, Transfer behavior of quantum states between atoms in photonic crystal coupled cavities, *Phys. Rev. A* 81(3), 033843 (2010)

63. M. Notomi, E. Kuramochi, and T. Tanabe, Large-scale arrays of ultrahigh-Q coupled nanocavities, *Nat. Photonics* 2(12), 741 (2008)

64. S. B. Zheng, Generation of Greenberger–Horne–Zeilinger states for multiple atoms trapped in separated cavities, *Eur. Phys. J. D* 54(3), 719 (2009)

65. S. B. Zheng, C.P. Yang, and F. Nori, Arbitrary control of coherent dynamics for distant qubits in a quantum network, *Phys. Rev. A* 82(4), 042327 (2010)

66. H. F. Wang, A. D. Zhu, and S. Zhang, One-step implementation of a multiqubit phase gate with one control qubit and multiple target qubits in coupled cavities, *Opt. Lett.* 39(6), 1489 (2014)

67. X. Q. Shao, Z. H. Wang, H. D. Liu, and X. X. Yi, Dissipative preparation of a tripartite singlet state in coupled arrays of cavities via quantum feedback control, *Phys. Rev. A* 94(3), 032307 (2016)

68. M. J. Hartmann, F. G. S. L. Brandão, and M. B. Plenio, Strongly interacting polaritons in coupled arrays of cavities, *Nat. Phys.* 2(12), 849 (2006)

69. D. Daems and S. Guérin, Adiabatic quantum search scheme with atoms in a cavity driven by lasers, *Phys. Rev. Lett.* 99(17), 170503 (2007)

70. S. M. Spillane, T. J. Kippenberg, O. J. Painter, and K. J. Vahala, Ideality in a fiber-taper-coupled microresonator system for application to cavity quantum electrodynamics, *Phys. Rev. Lett.* 91(4), 043902 (2003)

71. P. E. Barclay, K. Srinivasan, O. Painter, B. Lev, and H. Mabuchi, Integration of fiber-coupled high-Q SiN_x microdisks with atom chips, *Appl. Phys. Lett.* 89(13), 131108 (2006)