Scalable preparation of multiple-particle entangled states via the cavity input-output process

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We propose schemes for generating multiple-atom entangled states and a multiple-photon Greenberger-Horne-Zeilinger state, respectively, based on the input-output relation of the cavity. The numerical simulations show that produced multiple-particle entangled states have high fidelity even if the atoms are not localized in the Lamb-Dicke regime. Some practical quantum noises, such as atomic spontaneous emission and output coupling inefficiency, only decrease the success probability but exert no influence on the fidelity of prepared multiple-particle entangled states. The successful probabilities of our protocols approach unity in the ideal case. In addition, no need for individually addressing keeps the schemes easy to implement from the experimental point of view.

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I. INTRODUCTION

Recently, considerable efforts have been made for generating and investigating multipartite entanglement states [1] since they play a crucial role in fundamental tests of quantum mechanics and exhibit a conflict with local realism for nonstatistical predictions of quantum mechanics [2]. Further, graph states [3,4] have been proven to be a useful resource for many quantum information protocols. They include the Greenberger-Horne-Zeilinger (GHZ) state which is one of the important classes of multipartite entanglement state and can be employed as a quantum channel for quantum key distribution [5] and quantum secret sharing [6], cluster states, which is a universal resource for one-way quantum computing, and Calderbank-Shor-Steane (CSS) error correction codeword states. Small graph states, for example GHZ and cluster states are current topic in the laboratory [7–12].

It is well known that optics system and cavity QED system are two ideal candidates for quantum communication and quantum computation. There are a number of theoretical schemes proposed to generate small graph states (for example GHZ states) of multiple-photon or multiple-atom. However, the multiple-atom GHZ state is probabilistically prepared in Refs. [13,14] while a high-Q cavity field is required in some cavity QED proposals due to neglecting decoherence caused by cavity decay [15]. Similarly, the deterministic preparation of multiple-photon GHZ states is also difficult [7,16]. For example, the success probability of generating an n-photon GHZ state is only $1/2^{n-1}$ in Ref. [16]. Recently, some robust schemes which are insensitive to cavity decay have been proposed for entangling many atoms [17]. In particular, Cho *et al.* proposed a novel scheme for robust generation of atomic cluster states via the cavity input-output process and the single photon polarization measurement [12]. In this paper, we show with the similar unitary operations our schemes can prepare n-atom and n-photon GHZ states, and the protocol can be expanded to the generation of an arbitrary multiple-atom graph state. A single-sided optical cavity with a single-trapped atom is employed as the crucial resource for implementing this purpose. The schemes proposed in this paper have the following significant advantages: (i) The produced multiple-particle entangled states have high fidelity even if the atoms are not localized in the Lamb-Dicke regime. (ii) They are inherently robust to some practical quantum noises, such as atomic spontaneous emission and output coupling inefficiency, which simply decrease the success probability but exert no influence on the fidelity of prepared multiple-particle entangled states. (iii) Compared with previous protocols [7,13,14,16], the successful probability for generating an n-particle entangled state approaches unity in the ideal case. (iv) No requirement for individually addressing further lowers experimental difficulties.

The paper is arranged as follows: In Sec. II, we concretely describe the behavior of single-photon pulse reflected by the cavity with a trapped atom. Based on the relation between the input pulse, output pulse, and the atom trapped in a cavity, in Secs. III–V we present schemes for generating a multiple-atom GHZ state, multiple-atom graph state, and multiple-photon GHZ state, respectively, and make a brief discussion depending on the numerical simulation results. Finally, we conclude in Sec. VI.

II. THE FUNDAMENTAL MODEL

The basic building model involved in our schemes is shown in Fig. 1. A single-photon pulse with horizontal (h) polarization enters the one-sided cavity, which traps a three-level atom (as shown in Fig. 2). Atomic states $|0\rangle$ and $|1\rangle$ are hyperfine states of an alkali atom in the ground-state manifold, while $|e\rangle$ is an excited state. The transition $|1\rangle \rightarrow |e\rangle$ is resonantly coupled to the cavity mode a_h with h polarization and is resonantly driven by the input single-photon pulse. In the rotating wave approximation and the rotating frame, the

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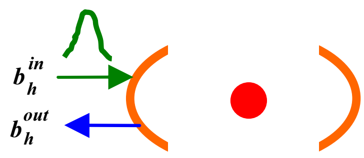

FIG. 1. (Color online) A schematic representation of the input and output fields for a single-sided cavity with a trapped atom.

whole Hamiltonian of the system of atom-cavity and free space is as the following form (setting $\hbar=1$):

$$H=-i\frac{\gamma}{2}|e\rangle\langle e|+ga_h|e\rangle\langle 1|+ga_h^\dagger|1\rangle\langle e|+\delta a_h^\dagger a_h + \int_{-\infty}^{\infty}\omega d\omega b_h^\dagger(\omega)b_h(\omega)+i\sqrt{\frac{\kappa}{2\pi}}\int_{-\infty}^{\infty}d\omega[a_hb_h^\dagger(\omega) - a_h^\dagger b_h(\omega)], \quad (1)$$

where γ is the spontaneous emission rate from the state $|e\rangle$, g represents the coupling rate of the atom to cavity field, δ (here $\delta=0$, but we remain it for the following analysis) denotes the detuning of the cavity field mode a_h from the atomic transition, $b_h(\omega)$ with the standard relation $[b_h(\omega),b_h^\dagger(\omega')]=\delta(\omega-\omega')$ denotes the one-dimensional free-space modes which couple to the cavity mode a_h, and κ describes the cavity decay rate. According to the quantum Langevin equation and the boundary condition of the cavity, we can gain that the single-sided cavity input and output field operators $b_h^{\rm in}(t)$ and $b_h^{\rm out}(t)$ are connected with the cavity mode $a_h(t)$ through the following relations [18,19]:

$$\dot{a}_h(t)=-i[a_h(t),H_I]-\left(i\delta+\frac{\kappa}{2}\right)a_h(t)-\sqrt{\kappa}b_h^{\rm in}(t) \quad (2)$$

and

$$b_h^{\rm out}(t)=b_h^{\rm in}(t)+\sqrt{\kappa}a_h(t), \quad (3)$$

where the Hamiltonian

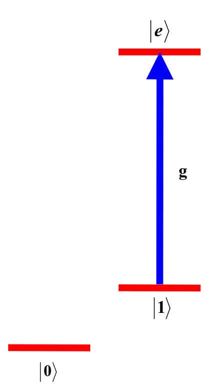

FIG. 2. (Color online) The relevant atomic level structure and transitions. The states $|0\rangle$, $|1\rangle$ correspond to hyperfine levels of an alkali atom in the ground-state manifold while $|e\rangle$ is an excited level, the transition $|1\rangle\to|e\rangle$ is resonantly coupled to the cavity mode a_h with coupling constant g.

$$H_I=g(a_h|e\rangle\langle 1|+a_h^\dagger|1\rangle\langle e|) \quad (4)$$

depicts the coherent interaction between the atom and the cavity mode a_h, $b_h^{\rm in}(t)$ and $b_h^{\rm out}(t)$ satisfy the following commutation relations:

$$[b_h^{\rm in}(t),b_h^{\rm in\dagger}(t')]=\delta(t-t'), \quad (5)$$

$$[b_h^{\rm out}(t),b_h^{\rm out\dagger}(t')]=\delta(t-t'). \quad (6)$$

If the atom is in the state $|0\rangle$, the Hamiltonian H_I shown in Eq. (4) does not work and induces $\delta=0$. When the input pulse shape changes slowly with time t compared with the cavity decay rate κ, from Eqs. (2) and (3), we can obtain

$$b_h^{\rm out}(t)\approx\frac{i\delta-\kappa/2}{i\delta+\kappa/2}b_h^{\rm in}(t). \quad (7)$$

Therefore, in the case of resonant interaction $\delta=0$, we have $b_h^{\rm out}(t)\approx-b_h^{\rm in}(t)$. However, if the atom is in the state $|1\rangle$, for the case of strong coupling [20], the effective detunings of two dressed cavity modes from the input pulse are $\delta=\pm g$, respectively. In the case that $g\gg\kappa$, we have $b_h^{\rm out}(t)\approx b_h^{\rm in}(t)$. In practice, it has been proved that the result is truth even if $g\sim\kappa$ [18]. From the above description, we conclude that the state of the whole system of atom cavity and free space acquires the phase π or 0 for $b_h^{\rm out}(t)\approx-b_h^{\rm in}(t)$ or $b_h^{\rm out}(t)\approx b_h^{\rm in}(t)$ after the photon pulse reflected by the cavity. The input-output process can be characterized by

$$(\alpha|0\rangle+\beta|1\rangle)|h\rangle\to(-\alpha|0\rangle+\beta|1\rangle)|h\rangle, \quad (8)$$

where we have discarded the state of cavity since it is always in the vacuum state, $|h\rangle$ denotes the state of free-space photon.

III. GENERATION OF *n*-ATOM GHZ STATE

Next we describe in detail how to generate an n-atom GHZ state. The basic idea is the use of unidirectional coupling among three cascaded optical cavities and a photonic interference effect, as shown in Fig. 3. Each cavity traps an alkali atom with initial state $|+\rangle=(|0\rangle+|1\rangle)/\sqrt{2}$, the unidirectional coupling between single-sided cavities is achieved by circulator (C), the polarization beam splitter (PBS) transmits only h polarization component and reflects the vertical (v) polarization component, the half-wave plate (HWP) changes the state $|h\rangle$ into $(|h\rangle+|v\rangle)/\sqrt{2}$ or the state $|v|$ into $(|h\rangle-|v\rangle)/\sqrt{2}$. Based on the results above, after reflection from the cavity, the h polarized component of the input pulse acquires a phase of $e^{i\pi}(e^{i0})$ if the atom system is initially in the state $|0\rangle$ ($|1\rangle$) while the v polarized component of the input pulse is reflected without shape and phase changes by the mirror M. First the single photon pulse initially prepared in an equal coherent superposition of two orthogonal polarization components which is expressed as $(|h\rangle+|v\rangle)/\sqrt{2}$, through a PBS enters cavity A with only atom 1 inside (see Fig. 3). If the photon pulse is sufficient long, reflection of the pulse from a resonant cavity will leave the pulse shape almost unchanged but flip its global phase. Hence, we perform this operation in the limit with $T\gg 1/\kappa$ (here T is the pulse

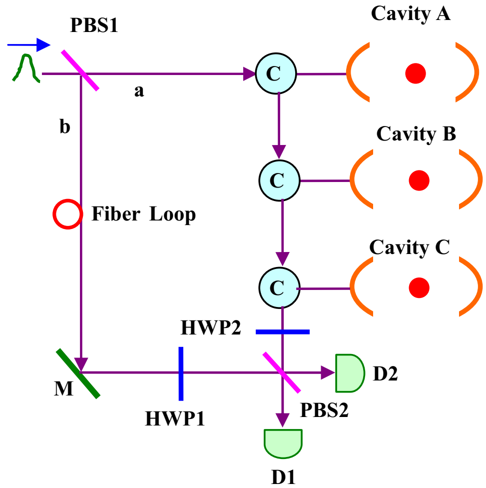

FIG. 3. (Color online) Schematic setup to prepare a three-atom GHZ state. The optical paths from PBS1→M→PBS2 and from PBS1→ cavities A, B, C→PBS2 are assumed to be equal.

duration). If the coupling rate satisfies $g \gg (1/T, \kappa, \gamma)$, then the frequency shift will have a magnitude comparable with g, so that the incident single-photon pulse will be reflected by an off-resonant cavity. Hence, both the shape and global phase will remain unchanged for the reflected pulse. After the interaction between the atom and cavity mode, a gate operation $U^{(1,p)} = \exp(i\pi|0\rangle_1\langle 0| \otimes |h\rangle_p\langle h|)$ is applied on the atom and the photon pulse. Then the pulse is reflected successively to enter cavity B with atom 2 again, so that the same operation is applied on atom 2 and the pulse. We repeat the step for n times. Finally, through a HWP and PBS, we obtain the atom state $(|+\rangle^{\otimes n} + |-\rangle^{\otimes n})/\sqrt{2}$ $((|+\rangle^{\otimes n} - |-\rangle^{\otimes n})/\sqrt{2})$ if $D1$ ($D2$) clicks. After applying a filter operation $\Pi_{i=1,2,3,\ldots,n}|1\rangle_i\langle +|+|0\rangle_i\langle -|$ on each atom, which can be implemented by radio-frequency (RF) pulses or the Raman transition applied on the atom, we obtain an n-qubit GHZ state as

$$|\Phi^+\rangle = (|0\rangle^{\otimes n} + |1\rangle^{\otimes n})/\sqrt{2} \tag{9}$$

$$|\Phi^-\rangle = (|0\rangle^{\otimes n} - |1\rangle^{\otimes n})/\sqrt{2}. \tag{10}$$

In the following, we quantify the quality of the three-atom GHZ state through a numerical simulation method. Assume that the input pulse is taken to be a Gaussian pulse $f(t) \propto \exp[-[t-(T/2)]^2/(T/5)^2]$ with duration $T=5$ μs, the parameters are referred to Ref. [21], i.e., $g=6\kappa$, $(\kappa,\gamma)/2\pi = (2.8, 6)$ MHz. Numerical calculation results show the fidelity of the three-atom GHZ state

$$F = |\langle \Psi_{\text{ideal}}|\Psi_{\text{real}}\rangle|^2 \approx 0.9919, \tag{11}$$

where $|\Psi_{\text{ideal}}\rangle$ refers to the state of the atomic system in the ideal case after a single-photon pulse reflected from the cavities; $|\Psi_{\text{real}}\rangle$ refers to one by numerical simulations. The fidelity change is about 10^{-6} for g varying from 2κ to 10κ. This means that the quality of the GHZ state is little affected even if the atoms are not localized in the Lamb-Dicke regime, which is very important on account of current experimental technology. Simultaneously, the scheme is intrinsically robust to some of the noises. The main noises in our scheme come from atomic spontaneous emission, output coupling inefficiency, and detector inefficiency, all of which contribute to loss of photons. Since single-photon detection will never occur if the photon is lost, these practical noises only decrease the success probability of the scheme but have no influence on the fidelity of the prepared GHZ state. Figure 4 shows the success probability P for preparing the GHZ state as a function of g/κ, which is well simulated by the empirical formula $P \approx 1/(1+\kappa\gamma/13g^2)$. Additionally, separately addressing within a tiny optical cavity is not required in our protocol, which greatly reduce experiment difficulties.

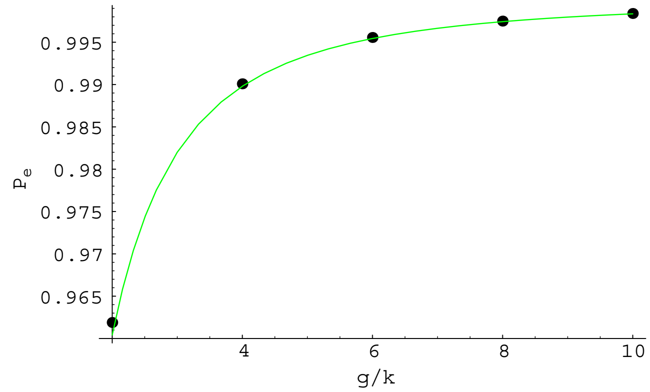

FIG. 4. (Color online) The success probability P of the scheme as a function of g/κ. The dots denote the results of numerical simulation, and the solid curve describes the empirical formula $P \approx 1/(1+\kappa\gamma/13g^2)$. Here, we have taken $(\kappa,\gamma)/2\pi = (2.8, 6)$ MHz, and $T=5$ μs.

IV. GENERATION OF *n*-ATOM GRAPH STATE

We can prepare a multiple-atom graph state by making a small modification on the scheme above. In the following we briefly review the definition and properties of graph states [3,4]. An n-qubit graph state is defined as the co-eigenstate of n independent stabilizer operators $K_G^{(a)} = \sigma_x^{(a)} \Pi_{b \in N_a} \sigma_z^{(b)}$, where a denotes qubit a (each qubit is associated with a vertex of the graph), b runs over all the neighbors of qubit a, and σ_x, σ_z are Pauli operators. The graph state $|G\rangle$ can be obtained by applying a sequence of commuting unitary two-qubit operations $U^{(a,b)}$ to the state $|+\rangle^{\otimes n}$ corresponding to the empty graph: $|G\rangle = \Pi_{(a,b)\in E} U^{(a,b)}|+\rangle^{\otimes n}$, where E denotes the set of edges in the graph G, and $|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$. The unitary two-qubit operation on the vertices a, b, which adds or removes the edge $\{a,b\}$, is given by

$$U^{(a,b)} = P_{z,+}^{(a)} \otimes I^{(b)} + P_{z,-}^{(a)} \otimes \sigma_z^{(b)} = U^{(a,b)\dagger}, \tag{12}$$

which is simply a controlled-Z (CZ) gate operation on qubits a and b, i.e.,

$$U^{(a,b)} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}. \tag{13}$$

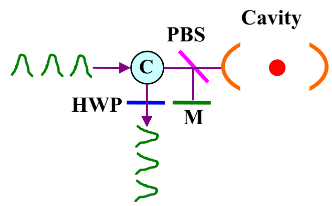

FIG. 5. (Color online) Schematic setup to prepare a three-photon GHZ state. Here suppose that the optical paths from PBS →M and from PBS→Cavity are equal.

Here, $P_{z,+}^{(a)}=(1\pm\sigma_z^{(a)})/2$ denotes the projector onto the eigenvector $|z,\pm\rangle$ of the $\sigma_z^{(a)}$ with eigenvalue ±1.

For example, an n-qubit GHZ state can be obtained by a so-called star graph state shown as this form:

$$|\psi_t\rangle = \exp(-iHt)|\psi_0\rangle = (|0\rangle|+\rangle^{\otimes n-1} + |1\rangle|-\rangle^{\otimes n-1})/\sqrt{2}, \tag{14}$$

where $|\psi_0\rangle=|+\rangle^{\otimes n}$. The unitary evolution operator $U(t)=e^{-iHt}$ in Eq. (14) can equivalently be described by a product $U(t)=\Pi_{l=2,3,\ldots,n}U^{(1,l)}$ of commuting controlled-Z gates shown in Eq. (13) which acts on pairs of qubits $(1,l)$, where $l=2,3,\ldots,n$. After applying a filter operation $\Pi_{i=2,3,\ldots,n}|1\rangle_i\langle+|+|0\rangle_i\langle-|$ on $|\psi_t\rangle$ shown in Eq. (14), we obtain the n-qubit GHZ state shown in Eq. (9).

In a recent paper [12], Cho and Lee showed a proposal to prepare another important example of graph states—cluster states of an arbitrary configuration. We show here using the controlled-Z operation the proposal can be expanded to generate an arbitrary graph state.

For physical implementation of graph state engineer in our scheme, we now introduce one of the important basic tools—controlled-Z gate operation [18] which can be obtained by making a little change to the realistic setting. The steps to realize the CZ gate between atoms 1 and 2 are as follows, and the overall processes. (i) The input single-photon pulse is first reflected by cavity A with atom 1. (ii) A Hadamard operation is made on the polarization direction of the single-photon pulse via a HWP. (iii) The single-photon pulse is subsequently reflected by cavity B with atom 2. (iv) Another Hadamard operation is made on the single photon state. (v) The single-photon pulse is reflected again by cavity A with atom 1, and then leaves the setup.

The net effect of these two subprocesses is that the reflection of a single-photon pulse from the cavity actually performs a controlled-Z operation $U^{(1,2)}=\exp(i\pi|00\rangle_{1,2}\langle 00|)$ on the two atoms. With the CZ gate operations on any two of atoms and single qubit rotations, we can generate an arbitrary graph state.

V. GENERATION OF n-PHOTON GHZ STATE

In this section, we focus on preparing a multiple-photon GHZ state via the cavity input-output process. N single-photon pulses with initial state $|\phi\rangle_p=(|h\rangle+|v\rangle)_p/\sqrt{2}$ are successively reflected from the mirror M or the single-sided cavity (see Fig. 5 for details), which contains a trapped alkali atom with an equal superposition of the two ground states, i.e., $|+\rangle$. After the HWP, the state of the whole system, whose initial state is

$$|\Theta\rangle \propto (|0\rangle+|1\rangle)(|h\rangle+|v\rangle)_p^{\otimes n}, \tag{15}$$

evolves into

$$|\Theta'\rangle \propto (|0\rangle+|1\rangle)(|h\rangle^{\otimes n}-|v\rangle^{\otimes n})_p-(|0\rangle-|1\rangle)(|h\rangle^{\otimes n}+|v\rangle^{\otimes n})_p. \tag{16}$$

Here we have assumed the optical paths from PBS to mirror and from PBS to cavity are equal. Then the state of the atom is measured in the bases $\{|+\rangle,|-\rangle\}$. If measurement outcome is $|+\rangle$, the state of n-photon is projected into

$$|\Phi^-\rangle_p = (|h\rangle^{\otimes n}-|v\rangle^{\otimes n})_p/\sqrt{2}, \tag{17}$$

whereas measurement outcome is $|-\rangle$, into the state

$$|\Phi^+\rangle_p = (|h\rangle^{\otimes n}+|v\rangle^{\otimes n})_p/\sqrt{2}. \tag{18}$$

Thus, an n-photon GHZ state is generated.

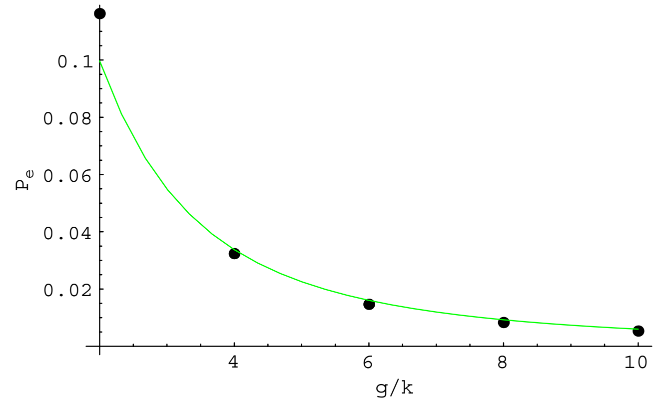

FIG. 6. (Color online) The probability P_e of the leakage error as a function of g/κ while the system is initially in the state $|\Theta\rangle$. The parameters are the same as those in Fig. 4. The dots denote the results of numerical simulation, and the solid curve describes the empirical formula $P_e\approx 2/7(1+g^2/\kappa\gamma)$.

The fidelity analysis of the n-photon GHZ state is the same as that of the n-atom GHZ state above. Atomic spontaneous emission is also the dominant noise. The reason is that spontaneous emission only leads to a vacuum-state output when the input is a single-photon pulse, and thus introduces the leakage error. If the system is initially in $|\Theta\rangle$, the probability P_e of the leakage error as a function of g/κ is shown in Fig. 6, which is almost identical with the empirical formula $P_e\approx 2/7(1+g^2/\kappa\gamma)$. In the case that each photon pulse is registered through a quantum nondemolition measurement, the leakage error only affects the probability to register a photon from each pulse but has no influence on the fidelity of the n-photon GHZ state.

VI. CONCLUSION

In summary, based on the input-output relation of the cavity, we propose schemes for preparing multiple-atom entangled states and a multiple-photon GHZ state, respectively.

The numerical simulations show that the produced multiple-particle entangled states have high fidelity even if the atoms are not localized in the Lamb-Dicke regime. Some practical quantum noises, such as atomic spontaneous emission and output coupling inefficiency, only decrease the success probability but exert no influence on the fidelity of multiple-particle entangled states. The successful probabilities of our protocols approach unity in the ideal case. Meanwhile, no need for individually addressing keeps the schemes easy to implement from the experimental point of view. In addition, in a review recent experiment in cavity QED, great advances have been made. The trapping and cooling of individual atoms in a regime of strong coupling have been achieved [22,23]. In particular, trapping lifetimes in excess of 1 s have been obtained [24]. The ability to localize the atom to within $\lambda/10$ at a cavity antinode has been demonstrated [25]. The transmission spectrum for an atom trapped and strongly coupled to the field of a high finesse optical resonator has been observed [26]. A single-photon source and the interference of two single photons emitted from a coupled atom-cavity system have also been realized [27,28]. All of these progresses make our proposals possible to implement experimentally in the near future.

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