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# Scheme for Realizing Deterministic Entanglement Concentration with Atoms Via Cavity QED

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**Abstract** A scheme for concentrating entanglement in two partially entangled Einstein-Podolsky-Rosen (EPR) pairs using repetitious resonant interactions of the atoms with a single-mode cavity field is proposed. A maximally entangled EPR pair can be deterministically extracted with the success probability of 1.0. In the scheme, the two logical states of a qubit are represented by the two lowest levels of an atom while a higher-energy intermediate level is used to facilitate the realization of the unitary operations, and all the operations required to realize deterministic entanglement concentration can be implemented in a reasonable amount of time before decoherence sets in. The scheme might be experimentally realizable with presently available cavity QED techniques and gives a realistic means to realize entanglement concentration deterministically.

**Keywords** Deterministic entanglement concentration · Cavity QED · Resonant interaction

Quantum information theory has opened up the possibility of novel form of information processing tasks which are not possible classically. Quantum entanglement, which is a novel feature distinguishing the quantum mechanics from the classical physics, has been widely used in quantum-information processing, such as quantum teleportation [1, 2], quantum computing [3], quantum key distribution [4], quantum secret sharing [5–8], quantum dense coding [9, 10], quantum secure direct communication [11–17], and so on. All the above applications can be achieved ideally with the success probability of 1.0 and the fidelity of 1.0 when the quantum channels are composed of maximally entangled states. In practice, however, the two parties can not share maximally entangled state faithfully but some

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forms of non-maximally entangled pure state due to the influence of decoherence and the imperfection at the source. In this case, the success probability of the implementation will be less than 1.0. Usually, they are very low. Fortunately, many theoretical and experimental schemes [18–30], called entanglement concentration or entanglement purification, have been proposed to extract maximally entangled states from some partial entangled states by applying local operations and classical communication (LOCC). The basic idea of entanglement concentration is for Alice and Bob to convert some large number of copies of a known pure state $\varphi$ into as many copies of the Bell state $\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$ as possible using LOCC, requiring not that they succeed exactly, but only with high fidelity. In 1996 Bennett et al. [18] first proposed an entanglement purification scheme to purify Bell states by use of local operations on copies of noisy Bell pairs and classical communication between the two parties. After that, Yamamoto et al. [23] proposed an experimentally feasible concentration and purification scheme, in which a maximally entangled photon pair is obtained from two photon pairs in identical partially entangled states with a certain probability. Zhao et al. [24] also proposed a probabilistic scheme for entanglement concentration based on the principle of quantum erasure and the Schmidt projection method. In this scheme, one can concentrate entanglement from arbitrary identical non-maximally entangled pairs at distant locations. Yang and Cao also proposed schemes [25, 26] for entanglement concentration of unknown atomic entangled states via entanglement swapping and cavity decay in cavity QED, with lower success probability.

However, all these schemes mentioned above are probabilistic. Can we concentrate entanglement deterministically from a finite number of partially entangled pairs with the success probability of 1.0? Nielsen first answered the question in 1999. Nielsen [31] proved and gave the necessary and sufficient conditions for deterministic transformations between bipartite pure entangled states based on the linear-algebraic theory of majorization. Based on the theory of Nielsen, subsequently, Morikoshi and Koashi [32] proposed a scheme for deterministic extraction of Bell pairs from a finite number of partially entangled pairs, and proved that the optimal deterministic concentration needs only a two-pair collective manipulation in each step, and that a collective manipulation of all entangled pairs is not necessary. Jensen and Schack [33] proposed a simple algorithm for local conversion of pure states only using LOCC, and gave a detailed description to construct the algorithm. Following the ideas of Jensen and Schack [33], Gu et al. [34] explicitly construct a generalized positive operator-valued measure (POVM) and quantum circuits to concentrate entanglement deterministically from a finite (even small) number of entangled pairs without gambling. However, these schemes are only theory schemes. Up to now, none of these schemes has been experimentally realized.

In this paper, we propose a realistic scheme to extract a maximally entangled EPR pair deterministically from two partially entangled EPR pairs via cavity QED. As far as we know, this is the first scheme for realizing entanglement concentration with the success probability of 1.0. The essential idea of the paper is based on the deterministic entanglement concentration scheme proposed by Gu et al. [34]. In the scheme the atoms interact resonantly with the cavity mode time after time. The resonant transitions between two ground states and one excited state of an atom are changed alternately by adjusting the cavity frequency appropriately. Before the advent of decays of the atoms and the cavity field, all the unitary evolutions necessary for the deterministic entanglement concentration can be implemented directly in a reasonable amount of time. The scheme might be experimentally realizable with current cavity QED technique. In the mean time, we also give a realistic means to realize entanglement concentration deterministically.

We consider a $\Lambda$-type three-level atom, which has one excited state $|r\rangle$ and two ground states $|g\rangle$ and $|e\rangle$. When the cavity mode is resonant with the transition $|g\rangle \longleftrightarrow |r\rangle$ while

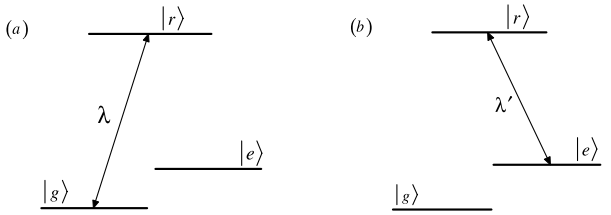


**Fig. 1** (**a**) Resonant interaction of the cavity mode with the $|g\rangle \longleftrightarrow |r\rangle$ transition while far off resonant with the $|e\rangle \longleftrightarrow |r\rangle$ transition and the $|g\rangle \longleftrightarrow |e\rangle$ transition of the atom, the atom-cavity coupling strength is λ. (**b**) Resonant interaction of the cavity mode with the $|e\rangle \longleftrightarrow |r\rangle$ transition while far off resonant with the $|g\rangle \longleftrightarrow |r\rangle$ transition and the $|g\rangle \longleftrightarrow |e\rangle$ transition of the atom, the atom-cavity coupling strength is $\lambda'$

far off resonant with the transition $|e\rangle \longleftrightarrow |r\rangle$ and the transition $|g\rangle \longleftrightarrow |e\rangle$ of the atom (Fig. 1(a)), in the rotating-wave approximation (RWA), the interaction Hamiltonian in the interaction picture is (assuming $\hbar = 1$)

$$H_I = \lambda(a^+|g\rangle\langle r| + a|r\rangle\langle g|), \tag{1}$$

where $a^+$ and $a$ are the creation and annihilation operators for the cavity mode, and λ is the coupling strength of the cavity mode with the $|g\rangle \longleftrightarrow |r\rangle$ transition of the atom.

Assume the cavity is initially in the photon number state $|n\rangle$. After an interaction time $t$, the time evolution of the states of the atom-cavity system, governed by Hamiltonian (1), is given by

$$\begin{aligned} |g\rangle|n\rangle &\longrightarrow \cos\sqrt{n}\lambda t|g\rangle|n\rangle - i\sin\sqrt{n}\lambda t|r\rangle|n-1\rangle, \\ |r\rangle|n\rangle &\longrightarrow -i\sin\sqrt{n+1}\lambda t|g\rangle|n+1\rangle + \cos\sqrt{n+1}\lambda t|r\rangle|n\rangle. \end{aligned} \tag{2}$$

Since the atoms may not be exactly placed at the same position in the cavity field, the coupling strength λ may not be identical for different atoms.

Adjust the cavity frequency appropriately, we can obtain the resonant interaction between the cavity mode and the $|e\rangle \longleftrightarrow |r\rangle$ transition of the atom (Fig. 1(b)). In this case, the interaction Hamiltonian in the interaction picture can be written as

$$H_I' = \lambda'(a^+|e\rangle\langle r| + a|r\rangle\langle e|), \tag{3}$$

where $\lambda'$ is the coupling strength of the cavity mode with the $|e\rangle \longleftrightarrow |r\rangle$ transition of the atom. The time evolution of the states of the atom-cavity system is similar to (2). We may substitute $|g\rangle$ for $|e\rangle$ in (2).

In this section, we show how to concentrate entanglement deterministically from two partially entangled pairs. The quantum circuit for concentrating entanglement proposed by Gu et al. [34] is shown in Fig. 2, where

$$\begin{aligned} U_{11} &= \begin{pmatrix} \sqrt{\frac{2\alpha-1}{2\alpha\beta}} & \sqrt{\frac{2\alpha\beta-2\alpha+1}{2\alpha\beta}} \\ -\sqrt{\frac{2\alpha\beta-2\alpha+1}{2\alpha\beta}} & \sqrt{\frac{2\alpha-1}{2\alpha\beta}} \end{pmatrix}, \qquad U_{22} = \begin{pmatrix} \sqrt{\frac{(2\alpha-1)(2\beta-1)}{2\alpha\beta-2\alpha+1}} & \sqrt{\frac{2(1-\alpha)\beta}{2\alpha\beta-2\alpha+1}} \\ -\sqrt{\frac{2(1-\alpha)\beta}{2\alpha\beta-2\alpha+1}} & \sqrt{\frac{(2\alpha-1)(2\beta-1)}{2\alpha\beta-2\alpha+1}} \end{pmatrix}, \\ U_{33} &= \begin{pmatrix} \sqrt{\frac{(1-2\alpha\beta)}{2\alpha(1-\beta)}} & \sqrt{\frac{2\alpha-1}{2\alpha(1-\beta)}} \\ -\sqrt{\frac{2\alpha-1}{2\alpha(1-\beta)}} & \sqrt{\frac{(1-2\alpha\beta)}{2\alpha(1-\beta)}} \end{pmatrix}, \qquad U_{44} = \begin{pmatrix} \sqrt{\frac{1-2\alpha\beta}{2(1-\alpha)(1-\beta)}} & \sqrt{\frac{(2\alpha-1)(2\beta-1)}{2(1-\alpha)(1-\beta)}} \\ -\sqrt{\frac{1-2\alpha\beta}{2(1-\alpha)(1-\beta)}} & \sqrt{\frac{(2\alpha-1)(2\beta-1)}{2(1-\alpha)(1-\beta)}} \end{pmatrix} \end{aligned} \tag{4}$$

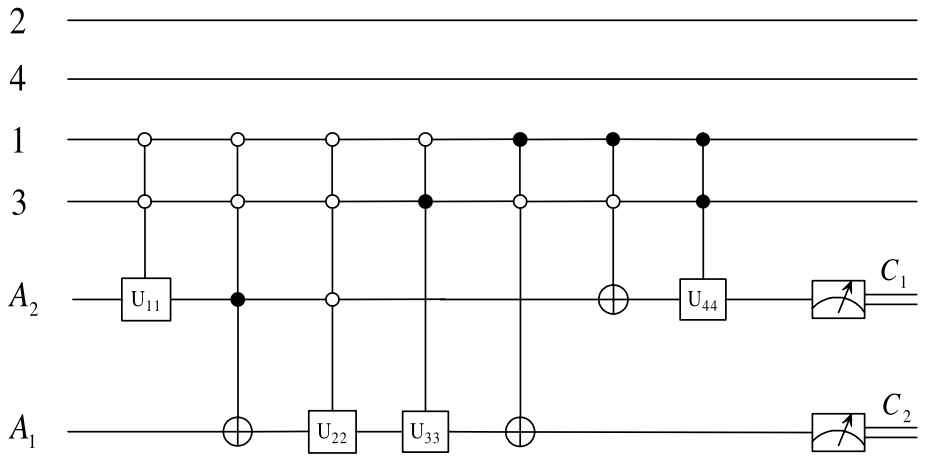


**Fig. 2** Schematic circuit for realizing entanglement concentration deterministically, where $U_{ii}$ is a single-qubit unitary operation performed on the target qubit under the different control condition

are single-qubit unitary operations. Initially, Alice and Bob share two partially entangled states of the atoms 12, and 34

$$|\psi\rangle = \sqrt{\alpha}|ge\rangle_{12} + \sqrt{1-\alpha}|eg\rangle_{12}, \tag{5}$$

$$|\varphi\rangle = \sqrt{\beta}|ge\rangle_{34} + \sqrt{1-\beta}|eg\rangle_{34}, \tag{6}$$

where the coefficients $\alpha$ and $\beta$ are positive real numbers and should be known in advance, $\frac{1}{\sqrt{2}} < \alpha \leq \beta < 1$, and $\alpha\beta \leq \frac{1}{2}$. Atoms 1 and 3 belong to Alice, and atoms 2 and 4 belong to Bob. Then Alice introduces two auxiliary atoms $A_1$ and $A_2$ with the states $|e\rangle_{A_1}$ and $|e\rangle_{A_2}$. The state of the whole system is

$$\begin{aligned}|\Psi\rangle_T &= |\psi\rangle \otimes |\varphi\rangle \otimes |e\rangle_{A_1}|e\rangle_{A_2} \\ &= (\sqrt{\alpha}|ge\rangle_{12} + \sqrt{1-\alpha}|eg\rangle_{12}) \otimes (\sqrt{\beta}|ge\rangle_{34} + \sqrt{1-\beta}|eg\rangle_{34}) \otimes |e\rangle_{A_1}|e\rangle_{A_2}. \end{aligned} \tag{7}$$

After that, Alice performs a series of unitary operations on atoms 1, 3, $A_1$, and $A_2$. From Fig. 2, One can see that the main operations for implementing deterministic entanglement concentration are the controlled-$U_{ii}$ ($CU_{ii}$) ($i = 1, 2, 3, 4$) gate operations and controlled-NOT (CNOT) gate operations under the different control conditions. For simplicity, we call these controlled operations in Fig. 2 as 00-$CU_{11}$, 001-CNOT, 000-$CU_{22}$, 01-$CU_{33}$, 10-CNOT, and 11-$CU_{44}$ gate operations, respectively, and time proceeds from the right to the left. In the following we give the explicit implementation of $CU_{ii}$ gate operations and CNOT gate operations.

*Implementation of $CU_{ii}$ Gate Operation* The 00-$CU_{11}$ gate operation, which means that if and only if the atoms 1 and 3 is in the state $|00\rangle_{13}$, the $U_{11}$ operation is performed on the atom $A_2$, can be implemented with the following steps. Here the state $|g\rangle$ corresponds to the qubit $|0\rangle$ and $|e\rangle$ to be the qubit $|1\rangle$, respectively.

Step 1: Apply a classical microwave pulse to atom 1. The pulse is resonant with the $|g\rangle \longleftrightarrow |r\rangle$ transition of atom 1, leading to the $|g\rangle \longrightarrow |r\rangle$ transformation.

Step 2: Send atom 1 into the cavity. The cavity mode is initially in the vacuum state $|0\rangle_c$ and interacts resonantly with the $|g\rangle \longleftrightarrow |r\rangle$ transition of atom 1. After an interaction time $t_1 = \pi/2\lambda_1$, atom 1 leaves the cavity.

Step 3: Adjust the cavity frequency so that the cavity mode interacts resonantly with the $|e\rangle \longleftrightarrow |r\rangle$ transition of atom 3. Then send atom 3 into the cavity. After an interaction time $t_2 = \pi/2\lambda_3'$, atom 3 leaves the cavity.

Step 4: Send atom $A_2$ into the cavity. Bring the $|e\rangle \longleftrightarrow |r\rangle$ transition to atom $A_2$. After an interaction time $t_3 = 3\pi/2\lambda_{A_2}'$, atom $A_2$ leaves the cavity.

Step 5: Adjust the cavity frequency so that the cavity mode interacts resonantly with the $|g\rangle \longleftrightarrow |r\rangle$ transition of atom $A_2$. Then send atom $A_2$ into the cavity. After an interaction time $t_4 = \gamma/\lambda_{A_2}$, atom $A_2$ leaves the cavity.

Step 6: Adjust the cavity frequency so that the cavity mode interacts resonantly with the $|e\rangle \longleftrightarrow |r\rangle$ transition of atom $A_2$. Then send atom $A_2$ back into the cavity. After an interaction time $t_5 = 3\pi/2\lambda_{A_2}'$, atom $A_2$ leaves the cavity.

Step 7: Send atom 3 into the cavity. Bring the $|e\rangle \longleftrightarrow |r\rangle$ transition to atom 3. After an interaction time $t_6 = 3\pi/2\lambda_3'$, atom 3 leaves the cavity.

Step 8: Adjust the cavity frequency so that the cavity mode interacts resonantly with the $|g\rangle \longleftrightarrow |r\rangle$ transition of atom 1. Then send atom 1 into the cavity. After an interaction time $t_7 = 3\pi/2\lambda_1$, atom 1 leaves the cavity.

Step 9: Apply a classical microwave pulse to atom 1. The pulse is resonant with the $|g\rangle \longleftrightarrow |r\rangle$ transition of atom 1, leading to the transformation $|r\rangle \longrightarrow |g\rangle$.

After each step of the above operations, the states $|egg\rangle_{13A_2}$, $|ege\rangle_{13A_2}$, $|eeg\rangle_{13A_2}$, and $|eee\rangle_{13A_2}$ remain unchanged while the time evolution of the states $|ggg\rangle_{13A_2}$, $|gge\rangle_{13A_2}$, $|geg\rangle_{13A_2}$, and $|gee\rangle_{13A_2}$ are summarized below:

$$
\begin{array}{llllll}
|ggg\rangle_{13A_2}|0\rangle_c & & |rgg\rangle_{13A_2}|0\rangle_c & & -i|ggg\rangle_{13A_2}|1\rangle_c & -i|ggg\rangle_{13A_2}|1\rangle_c \\
|gge\rangle_{13A_2}|0\rangle_c & \xrightarrow{\text{Step 1}} & |rge\rangle_{13A_2}|0\rangle_c & \xrightarrow{\text{Step 2}} & -i|gge\rangle_{13A_2}|1\rangle_c & \xrightarrow{\text{Step 3}} \quad -i|gge\rangle_{13A_2}|1\rangle_c \\
|geg\rangle_{13A_2}|0\rangle_c & & |reg\rangle_{13A_2}|0\rangle_c & & -i|geg\rangle_{13A_2}|1\rangle_c & -|grg\rangle_{13A_2}|0\rangle_c \\
|gee\rangle_{13A_2}|0\rangle_c & & |ree\rangle_{13A_2}|0\rangle_c & & -i|gee\rangle_{13A_2}|1\rangle_c & -|gre\rangle_{13A_2}|0\rangle_c
\end{array}
$$

$$
\begin{array}{lll}
 & -i|ggg\rangle_{13A_2}|1\rangle_c & -i|gg\rangle_{13}(\cos\gamma|g\rangle_{A_2}|1\rangle_c - i\sin\gamma|r\rangle_{A_2}|0\rangle_c) \\
\xrightarrow{\text{Step 4}} & -|ggr\rangle_{13A_2}|0\rangle_c & \xrightarrow{\text{Step 5}} \quad -|gg\rangle_{13}(-i\sin\gamma|g\rangle_{A_2}|1\rangle_c + \cos\gamma|r\rangle_{A_2}|0\rangle_c) \\
 & -|grg\rangle_{13A_2}|0\rangle_c & -|grg\rangle_{13A_2}|0\rangle_c \\
 & -|gre\rangle_{13A_2}|0\rangle_c & -|gre\rangle_{13A_2}|0\rangle_c
\end{array}
$$

$$
\begin{array}{ll}
 & -i|gg\rangle_{13}(\cos\gamma|g\rangle_{A_2} + \sin\gamma|e\rangle_{A_2})|1\rangle_c \\
\xrightarrow{\text{Step 6}} & -i|gg\rangle_{13}(-\sin\gamma|g\rangle_{A_2} + \cos\gamma|e\rangle_{A_2})|1\rangle_c \\
 & -|grg\rangle_{13A_2}|0\rangle_c \\
 & -|gre\rangle_{13A_2}|0\rangle_c
\end{array}
$$

$$
\begin{array}{ll}
 & -i|gg\rangle_{13}(\cos\gamma|g\rangle_{A_2} + \sin\gamma|e\rangle_{A_2})|1\rangle_c \\
\xrightarrow{\text{Step 7}} & -i|gg\rangle_{13}(-\sin\gamma|g\rangle_{A_2} + \cos\gamma|e\rangle_{A_2})|1\rangle_c \\
 & -i|geg\rangle_{13A_2}|1\rangle_c \\
 & -i|gee\rangle_{13A_2}|1\rangle_c
\end{array}
$$

$$
\begin{array}{ll}
 & |rg\rangle_{13}(\cos\gamma|g\rangle_{A_2} + \sin\gamma|e\rangle_{A_2})|0\rangle_c \\
\xrightarrow{\text{Step 8}} & |rg\rangle_{13}(-\sin\gamma|g\rangle_{A_2} + \cos\gamma|e\rangle_{A_2})|0\rangle_c \\
 & |reg\rangle_{13A_2}|0\rangle_c \\
 & |ree\rangle_{13A_2}|0\rangle_c
\end{array}
$$

$$\begin{array}{l} |gg\rangle_{13}(\cos\gamma|g\rangle_{A_2}+\sin\gamma|e\rangle_{A_2})|0\rangle_c \\ \xrightarrow{\text{Step 9}} |gg\rangle_{13}(-\sin\gamma|g\rangle_{A_2}+\cos\gamma|e\rangle_{A_2})|0\rangle_c \\ |geg\rangle_{13A_2}|0\rangle_c \\ |gee\rangle_{13A_2}|0\rangle_c \end{array}. \tag{8}$$

With the choice of $\cos\gamma=\sqrt{\frac{2\alpha-1}{2\alpha\beta}}$, $\sin\gamma=-\sqrt{\frac{2\alpha\beta-2\alpha+1}{2\alpha\beta}}$, the 00-$CU_{11}$ gate operation is implemented. Similarly, the 000-$CU_{22}$, 01-$CU_{33}$, and 11-$CU_{44}$ gate operations can also be implemented by using the same method with some modifications.

*Implementation of CNOT Gate Operation* For simplicity, we only show how to implement 001-CNOT gate operation, the 10-CNOT gate operation can also be implemented using the same method with some modification. The 001-CNOT gate operation, which means that if and only if the atoms 1, 3, and $A_2$ is in the state $|001\rangle_{13A_2}$, the NOT operation is performed on atom $A_1$, can be implemented with the following steps.

Step 1′: Perform the Hadamard transformation ($H$ transformation) on atom $A_1$. The $H$ transformation can be realized by applying a classical microwave pulse to atom $A_1$. Choose the amplitudes and phases of the pulse appropriately so that atom $A_1$ undergoes the transition

$$\begin{aligned} |g\rangle_{A_1} &\longrightarrow \frac{1}{\sqrt{2}}(|g\rangle_{A_1}+|e\rangle_{A_1}), \\ |e\rangle_{A_1} &\longrightarrow \frac{1}{\sqrt{2}}(|g\rangle_{A_1}-|e\rangle_{A_1}). \end{aligned} \tag{9}$$

Step 2′: Apply a classical microwave pulse to atom 1. The pulse is resonant with the $|g\rangle \longleftrightarrow |r\rangle$ transition of atom 1. After that, we can obtain the transformation $|g\rangle \longrightarrow |r\rangle$.

Step 3′: Send atom 1 into the cavity. Bring the $|g\rangle \longleftrightarrow |r\rangle$ transition to atom 1. After an interaction time $t_1'=\pi/2\lambda_1$, atom 1 leaves the cavity.

Step 4′: Adjust the cavity frequency so that the cavity mode interacts resonantly with the $|e\rangle \longleftrightarrow |r\rangle$ transition of atom 3. Then send atom 3 into the cavity. After an interaction time $t_2'=\pi/2\lambda_3'$, atom 3 leaves the cavity.

Step 5′: Adjust the cavity frequency so that the cavity mode interacts resonantly with the $|g\rangle \longleftrightarrow |r\rangle$ transition of atom $A_2$. Then send atom $A_2$ into the cavity. After an interaction time $t_3'=\pi/2\lambda_{A_2}$, atom $A_2$ leaves the cavity.

Step 6′: Send atom $A_1$ into the cavity. Bring the $|g\rangle \longleftrightarrow |r\rangle$ transition to atom $A_1$. After an interaction time $t_4'=\pi/\lambda_{A_1}$, atom $A_1$ leaves the cavity.

Step 7′: Send atom $A_2$ into the cavity. Bring the $|g\rangle \longleftrightarrow |r\rangle$ transition to atom $A_2$. After an interaction time $t_5'=\pi/2\lambda_{A_2}$, atom $A_2$ leaves the cavity.

Step 8′: Adjust the cavity frequency so that the cavity mode interacts resonantly with the $|e\rangle \longleftrightarrow |r\rangle$ transition of atom 3. Then send atom 3 into the cavity. After an interaction time $t_6'=\pi/2\lambda_{\lambda_3}'$, atom 3 leaves the cavity.

Step 9′: Adjust the cavity frequency so that the cavity mode interacts resonantly with the $|g\rangle \longleftrightarrow |r\rangle$ transition of atom 1. Then send atom 1 into the cavity. After an interaction time $t_7'=\pi/2\lambda_{\lambda_1}$, atom 1 leaves the cavity.

Step 10′: Apply a classical microwave pulse to atom 1. The pulse is resonant with the $|g\rangle \longleftrightarrow |r\rangle$ transition of atom 1, leading to the $|r\rangle \longrightarrow |g\rangle$ transformation.

Step 11′: Perform the $H$ transformation on atom $A_1$ again.

After the above operations, the states $|eggg\rangle_{13A_2A_1}$, $|egge\rangle_{13A_2A_1}$, $|egeg\rangle_{13A_2A_1}$, $|egee\rangle_{13A_2A_1}$, $|eegg\rangle_{13A_2A_1}$, $|eege\rangle_{13A_2A_1}$, $|eeeg\rangle_{13A_2A_1}$, and $|eeee\rangle_{13A_2A_1}$ remain unchanged,

while the time evolution of the states $|gggg\rangle_{13A_2A_1}$, $|ggge\rangle_{13A_2A_1}$, $|ggeg\rangle_{13A_2A_1}$, $|ggee\rangle_{13A_2A_1}$, $|gegg\rangle_{13A_2A_1}$, $|gege\rangle_{13A_2A_1}$, $|geeg\rangle_{13A_2A_1}$, and $|geee\rangle_{13A_2A_1}$ are summarized below:

$$
\begin{array}{l}
|gggg\rangle_{13A_2A_1}|0\rangle_c \\
|ggge\rangle_{13A_2A_1}|0\rangle_c \\
|ggeg\rangle_{13A_2A_1}|0\rangle_c \\
|ggee\rangle_{13A_2A_1}|0\rangle_c \\
|gegg\rangle_{13A_2A_1}|0\rangle_c \\
|gege\rangle_{13A_2A_1}|0\rangle_c \\
|geeg\rangle_{13A_2A_1}|0\rangle_c \\
|geee\rangle_{13A_2A_1}|0\rangle_c
\end{array}
\xrightarrow{\text{Step } 1'}
\begin{array}{l}
|ggg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|ggg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
|gge\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|gge\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
|geg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|geg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
|gee\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|gee\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c
\end{array}
\xrightarrow{\text{Step } 2'}
\begin{array}{l}
|rgg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|rgg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
|rge\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|rge\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
|reg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|reg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
|ree\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|ree\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c
\end{array}
$$

$$
\begin{array}{l}
-i|ggg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
-i|ggg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c \\
-i|gge\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
-i|gge\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c \\
-i|geg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
-i|geg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c \\
-i|gee\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
-i|gee\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c
\end{array}
\xrightarrow{\text{Step } 3'}
\begin{array}{l}
-i|ggg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
-i|ggg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c \\
-i|gge\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
-i|gge\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c \\
-|grg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
-|grg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
-|gre\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
-|gre\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c
\end{array}
\xrightarrow{\text{Step } 4'}
\begin{array}{l}
-i|ggg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
-i|ggg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c \\
-i|gge\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
-i|gge\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c \\
-|grg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
-|grg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
-|gre\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
-|gre\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c
\end{array}
$$

$$
\begin{array}{l}
-|ggr\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
-|ggr\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
-i|gge\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
-i|gge\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c \\
-|grg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
-|grg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
-|gre\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
-|gre\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c
\end{array}
\xrightarrow{\text{Step } 5'}
\begin{array}{l}
-|ggr\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
-|ggr\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
-i|gge\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
-i|gge\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c \\
-|grg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
-|grg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
-|gre\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
-|gre\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c
\end{array}
\xrightarrow{\text{Step } 6'}
\begin{array}{l}
-|ggr\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
-|ggr\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
i|gge\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c \\
i|gge\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
-|grg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
-|grg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
-|gre\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
-|gre\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c
\end{array}
$$

$$
\begin{array}{l}
i|ggg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
i|ggg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c \\
i|gge\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c \\
i|gge\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
-|grg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
-|grg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
-|gre\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
-|gre\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c
\end{array}
\xrightarrow{\text{Step } 7'}
\begin{array}{l}
i|ggg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
i|ggg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c \\
i|gge\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c \\
i|gge\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
-|grg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
-|grg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
-|gre\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
-|gre\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c
\end{array}
\xrightarrow{\text{Step } 8'}
\begin{array}{l}
i|ggg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
i|ggg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c \\
i|gge\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c \\
i|gge\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
i|geg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
i|geg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c \\
i|gee\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|1\rangle_c \\
i|gee\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|1\rangle_c
\end{array}
$$

$$
\begin{array}{l}
|rgg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|rgg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
|rge\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
|rge\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|reg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|reg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
|ree\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|ree\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c
\end{array}
\xrightarrow{\text{Step } 9'}
\begin{array}{l}
|rgg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|rgg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
|rge\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
|rge\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|reg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|reg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
|ree\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|ree\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c
\end{array}
\xrightarrow{\text{Step } 10'}
\begin{array}{l}
|ggg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|ggg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
|gge\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
|gge\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|geg\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|geg\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c \\
|gee\rangle_{13A_2}(|g\rangle_{A_1}+|e\rangle_{A_1})|0\rangle_c \\
|gee\rangle_{13A_2}(|g\rangle_{A_1}-|e\rangle_{A_1})|0\rangle_c
\end{array}
$$

$$\begin{array}{l} |gggg\rangle_{13A_2A_1}|0\rangle_c \\ |ggge\rangle_{13A_2A_1}|0\rangle_c \\ |ggee\rangle_{13A_2A_1}|0\rangle_c \\ \xrightarrow{\text{Step } 11'} |ggeg\rangle_{13A_2A_1}|0\rangle_c \\ |gegg\rangle_{13A_2A_1}|0\rangle_c \\ |gege\rangle_{13A_2A_1}|0\rangle_c \\ |geeg\rangle_{13A_2A_1}|0\rangle_c \\ |geee\rangle_{13A_2A_1}|0\rangle_c \end{array}. \tag{10}$$

In this way, the 001-CNOT gate operation is implemented. The essential feature of the method for implementing the controlled operations is to produce a single photon through sending one of the control atoms into the cavity and then exchanging the single photon between the control atoms and the cavity mode before and after the $U_{ii}$ gate operation (or one NOT gate operation) is performed on the target atom. Therefore, all the controlled operations required to realize the deterministic entanglement concentration can be implemented directly using resonant interaction between the atoms and the single-mode cavity field. After these operations displayed in Fig. 2, the state of the system in (6) becomes

$$\begin{aligned} |\Psi\rangle_T^g =& \sqrt{(1-\alpha)\beta}(|ge\rangle + |eg\rangle)_{12} \otimes |ge\rangle_{34} \otimes |gg\rangle_{A_1A_2} \\ &+ \sqrt{\frac{2\alpha-1}{2}}(|ge\rangle + |eg\rangle)_{34} \otimes |ge\rangle_{12} \otimes |ge\rangle_{A_1A_2} \\ &+ \sqrt{\frac{(2\alpha-1)(2\beta-1)}{2}}(|gege\rangle + |egeg\rangle)_{1234} \otimes |eg\rangle_{A_1A_2} \\ &+ \sqrt{\frac{1-2\alpha\beta}{2}}(|ge\rangle + |eg\rangle)_{12} \otimes |eg\rangle_{34} \otimes |ee\rangle_{A_1A_2}, \end{aligned} \tag{11}$$

where we have normalized the coefficients.

Now Alice makes a orthogonal measurement on the auxiliary atoms $A_1$ and $A_2$, which leads the whole system collapses into the following states

$$\begin{aligned} {}_{A_1A_2}\langle gg|\Psi\rangle_T^g &\longrightarrow \frac{1}{\sqrt{2}}(|ge\rangle + |eg\rangle)_{12} \otimes |ge\rangle_{34}, \\ {}_{A_1A_2}\langle ge|\Psi\rangle_T^g &\longrightarrow \frac{1}{\sqrt{2}}(|ge\rangle + |eg\rangle)_{34} \otimes |ge\rangle_{12}, \\ {}_{A_1A_2}\langle eg|\Psi\rangle_T^g &\longrightarrow \frac{1}{\sqrt{2}}(|gege\rangle + |egeg\rangle)_{1234}, \\ {}_{A_1A_2}\langle ee|\Psi\rangle_T^g &\longrightarrow \frac{1}{\sqrt{2}}(|ge\rangle + |eg\rangle)_{12} \otimes |eg\rangle_{34}, \end{aligned} \tag{12}$$

with the probability of $(1-\alpha)\beta$, $(2\alpha-1)/2$, $(2\alpha-1)(2\beta-1)/2$, and $(1-2\alpha\beta)/2$, respectively. It should be pointed out that when Alice's measurement result is $|eg\rangle_{A_1A_2}$, a maximally entangled Greenberger-Horne-Zeilinger (GHZ) state is obtained. At this time, Alice and Bob perform a CNOT gate operation on atoms 13 and 24, respectively. In this way a maximally entangled EPR pair can be extracted successfully from two non-maximally entangled EPR pairs. The total success probability is 1.0.

So far we have proposed a detailed way to concentrate entanglement from two partial entangled EPR pairs. The resonant transitions between two ground states and one excited

state of an atom can be changed alternately by adjusting the cavity frequency appropriately, and the cavity field remains in the vacuum state during the whole process of operation. The scheme has the following merits: (i) the time required to achieve the scheme is very short due to the resonant interaction; (ii) all the controlled operations shown in Fig. 2 can be implemented directly using resonant interactions between the atoms and a single-mode cavity field; (iii) the interaction among the atoms can be canceled since the atoms 1, 3, $A_1$, and $A_2$ across the cavity one after another such that no more than one atom remains in the cavity simultaneously; (iv) the atom-cavity coupling strength may not be identical for atoms 1, 3, $A_1$, and $A_2$ and thus the atoms may not be sent through the cavity with precise tracks and velocities, which makes the experiment easier.

Now we briefly discuss the feasibility of the proposed scheme. For the Rydberg atoms with principal quantum numbers 50 and 51, the radiative time $T_r = 3.0 \times 10^{-2}$ s, and the coupling strength is $\lambda = 2\pi \times 25$ kHz [35–39]. Hence the interaction times of atoms 1, 3, $A_1$, and $A_2$ with the cavity field are $\pi/2\lambda = 1.0 \times 10^{-5}$ s, $\pi/\lambda = 2.0 \times 10^{-5}$ s, $3\pi/2\lambda = 3.0 \times 10^{-5}$ s, and $\gamma/\lambda \simeq 5.0 \times 10^{-6}$ s, respectively. For simplicity, we have set $\lambda_1 = \lambda_1' = \lambda_3 = \lambda_3' = \lambda_{A_1} = \lambda_{A_1}' = \lambda_{A_2} = \lambda_{A_2}' = \lambda$. Thus the total time required to complete the whole procedure is about $7.0 \times 10^{-4}$ s, much shorter than $T_r$. In recent experiments, the decay time of the cavity field was $T_c \simeq 1.0 \times 10^{-3}$ s [35–39], longer than the required time. In fact, we can also reduce the required operation time by (i) increasing the coupling strength of atom-cavity (ii) adjusting the frequency of the cavity field rapidly. Therefore, based on the current cavity QED techniques, the proposed scheme might be experimentally realizable.

In summary, we have proposed a scheme for realizing entanglement concentration deterministically by using repetitious resonant interactions between the atoms and a single-mode cavity field. The time required to complete the whole operation is reasonable before decoherence sets in. As far as we know, no one has yet demonstrated how to realize entanglement concentration deterministically with the success probability of 1.0 in experiment. We hope that the present scheme can provide an alternative effective way for concentrating entanglement from a finite number of partially entangled pairs in a deterministic fashion.

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