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RESEARCH ARTICLE

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Entanglement reciprocation between two charge qubits and two-cavity field

Abstract We propose a simple scheme to generate two-mode entangled coherent state in two separated cavities and realize the entanglement reciprocation between the superconducting charge qubits and continuous-variable system. By measuring the state of charge qubits, we find that the entanglement of two charge qubits, which are initially prepared in the maximally entangled state, can be transferred to the two-cavity field, and at this time the two-cavity field is in the entangled coherent state. We also find that the entanglement can be retrieved back to the two charge qubits after measuring the state of the two-cavity field.

Keywords entanglement transfer, entangled coherent state, superconducting quantum interference devices

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1 Introduction

Quantum entanglement and entangled states are useful in quantum information processing such as quantum cryptography [1, 2], superdense coding [3], and telecoloning [4]. Especially, entangled states of the electromagnetic field are of particular interest. Such states can be used, e.g., for quantum key distribution [2] and teleportation [5]. There are different types of entanglement for light fields. For instance, in the teleportation experiments of the Innsbruck group [6], it is the polarization directions of single photon that are entangled. In the Caltech teleportation experiment [7], two electromagnetic field modes are entangled with respect to photon numbers and the state used for teleportation is two-mode squeezed state.

Besides, there is another type of entangled states of two modes of the electromagnetic field. They are called entangled coherent states (ECS) [8, 9], and using these states people have proposed some schemes to teleport quantum states [10−12]. The ECS can be expressed as

$$|u^{\pm}\rangle = N_{\pm}(|\alpha, -\alpha\rangle \pm |-\alpha, \alpha\rangle) \tag{1}$$

where the normalization constants $N_{\pm} = (2 \pm 2\mathrm{e}^{-4|\alpha|^2})^{-1/2}$, $|\alpha\rangle$ is the coherent state and α is a complex parameter. It has been pointed out that the concurrence C of the ECS $|u^+\rangle$ increases with the increasing of α, and as $|\alpha| \to \infty$, $C \to 1$. While the amount of entanglement of the state $|u^-\rangle$ is independent of the parameter involved, and the concurrence of this state is always equal to 1 [8−10]. Recently, there has been increasing interest in the generation of entangled coherent states [8, 13−19]. Kuang and Zhou have proposed a scheme to generate atom-photon ECS in atomic Bose-Einstein condensation via electromagnetically induced transparency [13]. The generation of high-dimensional photon ECS in a double electromagnetically induced transparency system was proposed by Guo and Kuang [14]. Gerry [17, 18] was the first to propose an elegant scheme to realize GHZ-type ECS using three separated cavities. In Ref. [19], Solano *et al.* proposed a scheme to generate two-mode ECS in a cavity.

In recent years, entanglement transfer from the continuous-variable (CV) system to the qubits has been

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widely studied [20−23], and the inverse problem of entanglement transfer from the qubits to the CV system has also been discussed [24, 25]. Lee *et al.* [24] have investigated the entanglement reciprocation between the qubits and the CV system. They considered that two atoms, which are initially prepared in a maximally entangled state, enter into two spatially separated cavities, which are respectively prepared in a coherent state. It was shown that when the two atoms leave the cavities, their entanglement is transferred to the post-selected cavity fields. The generated field entanglement can be then transferred back to qubits, i.e., to another couple of atoms flying through the cavities. Zhou *et al.* [25] have also studied the entanglement transfer between atomic qubits and the CV system. They considered the model of that two identical atoms interacting with two spatially separated cavities, while the two atoms are driven by two classical fields respectively. It has been found that entanglement can be reciprocated between atomic qubits and entangled coherent state via postselection measurement.

Recently, condensed matter architectures based on Josephson junction qubits have appeared to be promising candidates for quantum information processing. Superconducting qubit has been successfully incorporated into a superconducting resonant cavity in order to perform analogous experiments in the strong coupling regime, forming a new field known as circuit QED [26]. In Ref. [27], Liu *et al.* have investigated the interaction between a single-mode microwave cavity field and a superconducting quantum interference device (SQUID). After some calculation they found that by measuring the charge state $|e\rangle$ or $|g\rangle$, the superpositions of macroscopic states of the cavity field can be produced. Following Ref. [27], we consider that two identical SQUID-type qubits 1 and 2 are in two spatially separated but identical cavities A and B respectively. First, the two charge qubits are initially prepared in the singlet state $\frac{1}{\sqrt{2}}(|eg\rangle - |ge\rangle)$, and we investigate the entanglement transfer from the two charge qubits to the two-cavity field. After some calculation we find that the two-cavity field, which is initially in vacuum state $|00\rangle$, can be prepared into ECS by entanglement transfer. Then we can fully retrieve the entanglement back to the two charge qubits from the ECS of the two-cavity field.

2 Model

Following Ref. [27], we consider that two identical SQUID-type qubits 1 and 2 are in two spatially separated but identical cavities A and B respectively [see Fig. 1(a)], and this setup has been used to investigate the entanglement transfer from the nonclassical state of the cavity field to a pair of superconducting charge qubits [21]. A SQUID-type qubit superconducting box [see Fig. 1(b)] with n excess Cooper-pair charges connects to a superconducting loop via two identical Josephson junctions with capacitors C_{J} and coupling energies E_{J}. A controllable gate voltage V_{g} is coupled to the box via the gate capacitor C_{g} with dimensionless gate charge $n_{\mathrm{g}} = C_{\mathrm{g}}V_{\mathrm{g}}/(2e)$. When $n_{\mathrm{g}} = 1/2$, only two charge states ($n = 0$ and $n = 1$) play a leading role, so the superconducting box can be considered as a two-level system or qubit. This superconducting two-level system can be represented by a spin-1/2 notation such that the charge states $n = 0$ and $n = 1$ correspond to eigenstates $|\uparrow\rangle$ and $|\downarrow\rangle$ of the spin operator σ_z, respectively. The ground and excited states for the qubit are respectively denoted by $|g\rangle = |\uparrow\rangle = (|+\rangle + |-\rangle)/2$ and $|e\rangle = |\downarrow\rangle = (|+\rangle - |-\rangle)/2$ where $|+\rangle(|-\rangle)$ is eigenstate of the Pauli operator σ_x with the eigenvalue $1(-1)$. In this model, the Hamiltonian of the whole system can be written as

$$H = H_{1,A} + H_{2,B} \tag{2}$$

where $H_{1,A}$ and $H_{2,B}$ are the effective Hamiltonians for the interaction between each qubit and its cavity. The effective Hamiltonian for the interaction between qubit 1 and cavity A has the form [27]

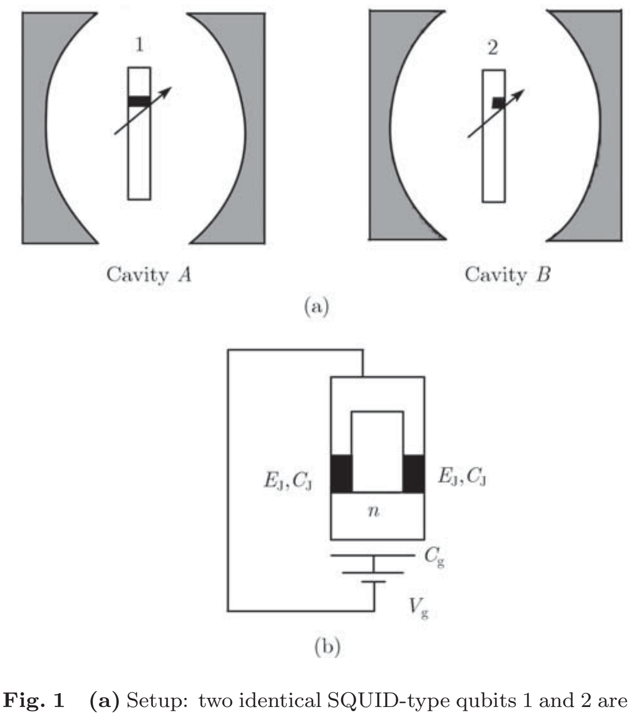

Fig. 1 **(a)** Setup: two identical SQUID-type qubits 1 and 2 are in two spatially separated but identical cavities A and B respectively; **(b)** A superconducting quantum interference device(SQUID).

$$H_{1,A}=\hbar\omega a^\dagger a+E_z\sigma_z-E_{\rm J}\sigma_x\cos\frac{\pi\Phi_c}{\Phi_0}$$
$$+E_{\rm J}\sigma_x\sin\frac{\pi\Phi_c}{\Phi_0}(\xi a+\xi^* a^\dagger)\tag{3}$$

where ω is frequency of the cavity field and $E_z=-2E_{ch}(1-2n_{\rm g})$ with $E_{ch}=e^2/(C_{\rm g}+2C_{\rm J})$. Here Φ_0 is the flux quantum, Φ_c is the flux through the SQUID. ξ is defined by

$$\xi=\frac{\pi}{\Phi_0}\int_S u(r)\cdot{\rm d}S\tag{4}$$

where $u(r)$ is the mode function of the single-mode cavity field, with annihilation (creation) operators $a(a^\dagger)$, and S is the surface defined by the contour of the SQUID. In this paper, we denote the two cavities A and B when the context requires us to differ them, but otherwise they are supposed to be identical. So the Hamiltonian $H_{2,B}$ for the interaction between qubit 2 and cavity B has the same form as Eq. (3). Then the total unitary time-evolution operator, thus can be constructed by a direct product of two unitary time-evolution operators representing evolutions of two independent qubit-field interactions $U_T(t)=U_{1,A}(t)\otimes U_{2,B}(t)$.

3 Entanglement transfer from charge qubits to two-cavity field

Now, we will investigate entanglement transfer from the two qubits to the two-cavity field. We suppose that the two qubits be initially prepared in the singlet state $\frac{1}{\sqrt{2}}(|eg\rangle-|ge\rangle)$, and the two-cavity field be in the vacuum state $|0,0\rangle_{A,B}$ initially, then

$$|\Psi(0)\rangle=\frac{1}{\sqrt{2}}|0,0\rangle_{A,B}\otimes(|eg\rangle-|ge\rangle)$$
$$=\frac{1}{\sqrt{2}}(|0e\rangle\otimes|0g\rangle-|0g\rangle\otimes|0e\rangle)\tag{5}$$

After adjusting each gate voltage $V_{\rm g}$ and classical magnetic field such that $n_{\rm g}=1/2$ and $\Phi_c=\Phi_0/2$, the state of the whole system evolves into

$$|\Psi(t)\rangle=U_T(t)\,|\Psi(0)\rangle$$
$$=\frac{1}{\sqrt{2}}(U_{1,A}(t)\otimes U_{2,B}(t))(|0e\rangle\otimes|0g\rangle-|0g\rangle\otimes|0e\rangle)$$
$$=\frac{1}{\sqrt{2}}[(U_{1,A}(t)\,|0e\rangle)\otimes(U_{2,B}(t)\,|0g\rangle)$$
$$-(U_{1,A}(t)\,|0g\rangle)\otimes(U_{2,B}(t)\,|0e\rangle)].\tag{6}$$

As an example, we calculate $U_{1,A}(t)\,|0e\rangle$ as follows [27]:

$$U_{1,A}(t)\,|0e\rangle=\exp\{-{\rm i}[\omega a^\dagger a+\sigma_x(\Omega^* a+\Omega a^\dagger)]t\}\,|0e\rangle$$
$$=\frac{1}{2}[A(\Omega)\,|0\rangle\,|+\rangle-A(-\Omega)\,|0\rangle\,|-\rangle]$$
$$=\frac{1}{2}[(|\alpha\rangle+|-\alpha\rangle)\,|e\rangle+(|\alpha\rangle-|-\alpha\rangle)\,|g\rangle]\tag{7}$$

where the complex Rabi frequency $\Omega=\xi^* E_{\rm J}/\hbar$, $A(\pm\Omega)=\exp\{-{\rm i}[\omega a^\dagger a\pm(\Omega^* a+\Omega a^\dagger)]t\}$, and a global phase factor $\exp[-{\rm i}(\xi^* E_{\rm J}/\hbar\omega)^2\sin(\omega t)+{\rm i}\xi^{*2}E_{\rm J}^2 t/(\hbar^2\omega)]$ has been neglected. $|\pm\alpha\rangle$ denotes coherent state

$$|\pm\alpha\rangle\equiv{\rm e}^{-|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{(\pm\alpha)^n}{\sqrt{n!}}\,|n\rangle\tag{8}$$

with

$$\alpha=\frac{\xi^* E_{\rm J}}{\hbar\omega}({\rm e}^{-{\rm i}\omega t}-1)\tag{9}$$

In the derivation of Eq. (7), we use the formula $\exp[\theta(\beta_1 a+\beta_2 a^\dagger a+\beta_3 a^\dagger)]=\exp(f_1 a^\dagger)\exp(f_2 a^\dagger a)\exp(f_3 a)\exp(f_4)$ with the relations $f_1=\beta_3({\rm e}^{\beta_2\theta}-1)/\beta_2$, $f_2=\beta_2\theta$, $f_3=\beta_1({\rm e}^{\beta_2\theta}-1)/\beta_2$, and $f_4=\beta_1\beta_3[{\rm e}^{\beta_2\theta}-\beta_2\theta-1]/\beta_2^2$. Similarly, we can calculate $U_{2,B}(t)\,|0g\rangle$, $U_{1,A}(t)\,|0g\rangle$ and $U_{2,B}(t)\,|0e\rangle$ respectively. After inserting them into Eq. (6) we obtain the state of the whole system:

$$|\Psi(t)\rangle=\frac{1}{2\sqrt{2}}[(|\alpha,-\alpha\rangle+|-\alpha,\alpha\rangle)\,|eg\rangle$$
$$-(|\alpha,-\alpha\rangle-|-\alpha,\alpha\rangle)\,|ee\rangle$$
$$+(|\alpha,-\alpha\rangle-|-\alpha,\alpha\rangle)\,|gg\rangle$$
$$-(|\alpha,-\alpha\rangle+|-\alpha,\alpha\rangle)\,|ge\rangle]\tag{10}$$

At time t, we let $\Phi_c=0$ by adjusting each classical magnetic field, then the interaction between each charge qubit and its cavity field is switched off. When the condition ${\rm e}^{-{\rm i}\omega t}\neq 1$ is satisfied, by measuring the state of two qubits, we find that if the two qubits are found in the state $|eg\rangle$ or $|ge\rangle$, the two-cavity field is in the ECS $|u^+\rangle$, otherwise it will be in the ECS $|u^-\rangle$. So when $\omega t\neq 2\pi m$ (m is an integer), whatever state the two qubits are in, the two-cavity field will collapse into ECS, i.e., as time evolves, the entanglement has been transferred from the two qubits to the CV system. Especially, when the two qubits are measured in the state $|ee\rangle$ or $|gg\rangle$, the two-cavity field is in the ECS $|u^-\rangle$ and now the entanglement of the two qubits is completely transferred to the two-cavity field, because the amount of entanglement for the state $|u^-\rangle$ is exactly one ebit [8–10].

4 Entanglement transfer from two-cavity field to charge qubits

In this part we will retrieve the entanglement from the two-cavity field, i.e., entanglement transfer from the ECS of the two-cavity field to the two qubits. We suppose that at time t the two-cavity field be in the ECS $|u^-\rangle$, which has been obtained by measuring the state of two qubits, for example, when the two qubits are measured in their ground state $|gg\rangle$. After normalization, the initial state of the whole system now is

$$|\psi(t)\rangle = N_-(|\alpha, -\alpha\rangle - |-\alpha, \alpha\rangle)\,|gg\rangle \tag{11}$$

where α has been defined in Eq. (9). Then we will adjust each gate voltage V_{g} and classical magnetic field such that $n_{\mathrm{g}} = 1/2$ and $\Phi_c = \Phi_0/2$, so that the two qubits will interact with their cavity fields respectively again. By using the same method as in the derivation of Eq. (10), we can also obtain the state of whole system at time τ:

$$\begin{aligned}|\psi(\tau)\rangle = \frac{N_-}{4}[&(|\alpha_-, -\alpha_+\rangle - |-\alpha_+, \alpha_-\rangle)\,|{+}{+}\rangle \\ &+(\mathrm{e}^{-2\mathrm{i}\varphi}\,|\alpha_-, -\alpha_-\rangle - \mathrm{e}^{2\mathrm{i}\varphi}\,|-\alpha_+, \alpha_+\rangle)\,|{+}{-}\rangle \\ &+(\mathrm{e}^{2\mathrm{i}\varphi}\,|\alpha_+, -\alpha_+\rangle - \mathrm{e}^{-2\mathrm{i}\varphi}\,|-\alpha_-, \alpha_-\rangle)\,|{-}{+}\rangle \\ &+(|\alpha_+, -\alpha_-\rangle - |-\alpha_-, \alpha_+\rangle)\,|{-}{-}\rangle]\end{aligned} \tag{12}$$

where

$$\varphi = \mathrm{Im}\left[\frac{\xi E_{\mathrm{J}}}{\hbar\omega}\alpha(1 - \mathrm{e}^{-\mathrm{i}\omega\tau})\right] \tag{13}$$

and

$$\alpha_{\pm} = \alpha\mathrm{e}^{-\mathrm{i}\omega\tau} \pm k(1 - \mathrm{e}^{-\mathrm{i}\omega\tau}) \tag{14}$$

with

$$k = \frac{\xi^* E_{\mathrm{J}}}{\hbar\omega} \tag{15}$$

At time τ, we can switch off the interactions between the charge qubits and the cavity fields by setting $\Phi_c = 0$ and $n_{\mathrm{g}} = 1/2$. In order to improve the entanglement transfer, postselection measurement on the two-cavity field is needed. In this part, we want to retrieve the entanglement back to the two qubits, so we will project the two-cavity field with $P = |00\rangle\langle 00|$, i.e., at this time the two-cavity field is supposed to be detected in the state $|00\rangle$. After the measurement from Eq. (12), we obtain the state of the qubit system in the qubit basis as

$$|\psi(\tau)\rangle_q = \frac{1}{\sqrt{A_{eg}^2 + A_{ge}^2}}(A_{eg}\,|eg\rangle + A_{ge}\,|ge\rangle) \tag{16}$$

where

$$A_{eg} = -A_{ge} = \frac{N_-}{2}(\mathrm{e}^{-2\mathrm{i}\varphi}\mathrm{e}^{-|\alpha_-|^2} - \mathrm{e}^{2\mathrm{i}\varphi}\mathrm{e}^{-|\alpha_+|^2}) \tag{17}$$

After inserting the Eq. (17) into Eq. (16) we obtain the state of two qubits as

$$|\psi(\tau)\rangle_q = \frac{1}{\sqrt{2}}(|eg\rangle - |ge\rangle) \tag{18}$$

We note that the entanglement of the two-cavity field has been completely transferred back to the qubit system, i.e., the first process has been reversed. We also find that if the two qubits are detected in their excited state $|ee\rangle$, we can completely retrieve the entanglement back from the ECS $|u^-\rangle$ too.

At time t, if the two qubits are detected in the state $|eg\rangle$, the two-cavity field will be in the ECS $|u^+\rangle$. After normalization, the initial state of the whole system now is

$$|\phi(t)\rangle = N_+(|\alpha, -\alpha\rangle + |-\alpha, \alpha\rangle)\,|eg\rangle \tag{19}$$

By using the same method as in the derivation of Eq. (16), we can also obtain the state of two qubits at time τ:

$$\begin{aligned}|\psi(\tau)\rangle_q = &\frac{1}{\sqrt{A_{ee}'^2 + A_{eg}'^2 + A_{ge}'^2 + A_{gg}'^2}}(A'_{ee}\,|ee\rangle \\ &+A'_{eg}\,|eg\rangle + A'_{ge}\,|ge\rangle + A'_{gg}\,|gg\rangle)\end{aligned} \tag{20}$$

where

$$\begin{aligned}A'_{ee} &= P_{++} + P_{--} - P_{+-} - P_{-+} \\ A'_{eg} &= P_{++} - P_{--} + P_{+-} - P_{-+} \\ A'_{ge} &= P_{++} - P_{--} - P_{+-} + P_{-+} \\ A'_{gg} &= P_{++} + P_{--} + P_{+-} + P_{-+}\end{aligned} \tag{21}$$

with

$$\begin{aligned}P_{++} &= -P_{--} = \frac{N_+}{2}\mathrm{e}^{-\frac{|\alpha_+|^2 + |\alpha_-|^2}{2}} \\ P_{+-} &= -P_{-+} = \frac{N_+}{4}(\mathrm{e}^{-2\mathrm{i}\varphi}\mathrm{e}^{-|\alpha_-|^2} + \mathrm{e}^{2\mathrm{i}\varphi}\mathrm{e}^{-|\alpha_+|^2})\end{aligned} \tag{22}$$

After inserting the Eqs. (21) and (22) into Eq. (20) we obtain the state of two qubits as

$$|\phi(\tau)\rangle_q = \frac{1}{\sqrt{A_{eg}'^2 + A_{ge}'^2}}(A'_{eg}\,|eg\rangle + A'_{ge}\,|ge\rangle) \tag{23}$$

where

$$A'_{eg} = \frac{N_+}{2}(\mathrm{e}^{-\mathrm{i}\varphi}\mathrm{e}^{-\frac{|\alpha_-|^2}{2}} + \mathrm{e}^{\mathrm{i}\varphi}\mathrm{e}^{-\frac{|\alpha_+|^2}{2}})^2$$

$$A'_{ge} = -\frac{N_+}{2}(\mathrm{e}^{-\mathrm{i}\varphi}\mathrm{e}^{-\frac{|\alpha_-|^2}{2}} - \mathrm{e}^{\mathrm{i}\varphi}\mathrm{e}^{-\frac{|\alpha_+|^2}{2}})^2 \tag{24}$$

From Eqs. (13), (14) and (24) we know that when $\omega\tau \neq 2\pi m$ (m is an integer) is satisfied, $A'_{ge} \neq 0$, at this time the state (23) is an entangled state but it is not the maximally entangled state, because $A'_{ge} \neq A'_{eg}$. Similarly, when the two qubits are detected in the state $|ge\rangle$, the entanglement also can not be completely retrieved back from the ECS $|u^+\rangle$. It is noted that the entanglement can be completely retrieved back to the two qubits from the ECS $|u^-\rangle$, while it can not be completely retrieved back from the ECS $|u^+\rangle$. This might be understood as that the degree of entanglement of the ECS $|u^+\rangle$ depends on the parameter α and is less than 1 with limited α, while the entanglement of the ECS $|u^-\rangle$ is exactly one ebit.

5 Discussion and conclusion

We have proposed a simple scheme to generate ECS in two separated cavity fields and realize the entanglement reciprocation between two SQUID-type qubits and the CV system. When the ECS are produced, the interaction between each cavity field and its qubit can be switched off by adjusting each classical magnetic field, so that there will not be information transfer between the cavity fields and the qubit system. When we want to retrieve the entanglement back to the two qubits, we will adjust the gate voltages and classical magnetic fields in order that the two qubits can respectively interact with their cavity fields again. In addition, the method in our scheme is only local measurement on the state of two qubits or the two-cavity field, whereas this technology is used extensively in quantum state engineering. In recent years, the entanglement transfer from the CV system to the qubits has been widely studied. The model in this paper has been used to investigate the entanglement transfer from the nonclassical state of the cavity field to a pair of superconducting charge qubits [21]. While we have investigated the inverse problem, which is entanglement transfer from the qubits to the CV system, and the two charge qubits are initially prepared in the singlet state $\frac{1}{\sqrt{2}}(|eg\rangle - |ge\rangle)$. In Ref. [28], the Bell state $|\psi^+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$ for two cavity fields has been realized by sending a qubit across both cavities, which have two different pulses. And Zou *et al.* [23] have investigated the entanglement transfer from different two-mode nonclassical state fields to a pair of separable and mixed qubits. They found that no matter what state the qubit system is initially prepared in, at the specific time $gt \approx 11.07$ the entanglement of the Bell state fields can be almost completely transferred to the qubit system, and at this time the two qubits can be prepared in the singlet state. However, the prepared ECS will be influenced by some sensitive physical quantities such as the Rabi frequency, the lifetime of qubits and cavity fields, and so on. Liu *et al.* [27] have analyzed these factors for the possibility of realization in experiments and shown that the measurement is possible with current technology.

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