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Efficient scheme to produce multi-particle entanglement with superconducting charge qubits

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Abstract

We propose an efficient scheme to implement high-fidelity multi-particle entangled states in the system consisting of superconducting charge qubits coupled through a single cavity mode. The manipulation is simply to apply specific gate voltages and external magnetic fields threaded through SQUIDs for fixed time. The total number of qubits which can be entangled is limited only from the decoherence time achieved in experiments. The gate operations are based on unconventional geometric phases and thus have built-in fault-tolerant features. The produced multi-qubit entangled states may have many applications.
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Quantum entanglement plays a key role in quantum information processing and in demonstrating the extreme contradiction between quantum theory and local realism. In general, the more particles that can be entangled, the more clearly nonclassical effects are exhibited and the more useful the states are for quantum information processing [1]. So far, multi-particle entanglement was experimentally reported only in micro-particles, such as trapped ions [1] and photons [2]. The recent development in solid-state qubits opens up new possibilities to achieve quantum entanglement for macroscopic bodies [3–10]. The entanglement between two superconducting charge qubits has been reported before [4], and the next important but also challenge step for superconducting circuits is to produce the multiqubit entangled states needed for quantum information processing.

Recently, superconducting qubits coupled through cavity quantum electrodynamic (QED) has been shown to be a promising candidate of quantum information processing [6–10]. The strong coupling between cavity and superconducting nanocircuits was theoretically proposed [6] and then experimentally achieved [7]. These works open up a new possibility to study one of the fundamental processes occurring in nature—the interaction between matter and light. Comparing with trapped-ion quantum computing or cavity QED, a superconducting qubit plays the role of the atom, so it is not surprising that some nice techniques used in trapped-ion or cavity QED can be transplanted to superconducting qubit quantum computing. An elegant entanglement technique in trapped-ion system was proposed by Mølmer and Sørensen in Ref. [11] and it was used to experimental implementation of entanglement between four ions [1]. Moreover, the scheme is based on geometric phase and then is robust against certain kinds of unwanted noises [12–14]. As an application of this method in superconducting qubit quantum computing, a useful scheme has been proposed to implement a universal set of quantum gates, multiqubit entanglement and quantum error-correcting codes in quantum information processing [10].

In this Letter, we propose a simple approach to achieve multiqubit entanglement in the Greenberger–Horne–Zeilinger (GHZ) form with superconducting charge qubits coupled through a cavity mode. A significant feature in the proposal is that the entangled states for any number of qubits can be realized by just simply applying specific gate voltages and external magnetic fields threaded through all SQUIDs for fixed

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time. Comparing with the method used in trapped-ion system, we find that some particular features in the present system allow several additional advantages in the implementation of multiparticle entanglement. (i) GHZ state for more than four ions is not easy to be experimentally achieved in ion-trap system by Mølmer–Sørensen proposal, since the collective motion that each particle participates with equal amplitude is a critical requirement [11]. Thus, only two collective motions in trapped-ion system are most appropriate in Mølmer–Sørensen proposal. One is the center of mass mode, and in principle it can be used to achieve multi-qubit entanglement for any number of ions; however, this mode has a main drawback that the quantum coherence of this mode vanishes quickly due to the large heating rate. Before substantially reducing the heating rates, center of mass mode is not suitable to be applied to produce multi-qubit entanglement (very recently, creation of the GHZ states with 6 ions and the W states with 8 ions mediated by the center of mass mode was reported [15]). The other collective motion state that each particle participates with equal amplitude is a non-center-of-mass mode for qubit number $N = 2$ and $N = 4$ only [16]. The heating rate is indeed much lower for this non-center-of-mass mode, and quantum entanglement for four ions has been experimentally demonstrated [1]. However, the method could not be extended to any other number of ions. In principle, other modes of motion can also be used for entanglement, as long as the laser intensity on each ion is adjusted to compensate for the difference in mode amplitude of that ion; but this requirement makes experiments more difficult. This disadvantage does not exist in the present system, as the required collective state we proposed is a cavity mode, which has longer decoherence time, thus the limit for the number of entangled qubits is only from the experimentally achieved decoherence time of Josephson qubits itself. (ii) The coupling between qubits and collective mode is simpler and the qubits can be set at the degeneracy point by changing the controllable gate voltage. These features lead to distinguishing merits in the present system: the operation similar to bichromatic lights and rotating wave approximation, which are essential in the trapped-ion system, are not required in the present system. Therefore, the experimental operation is much simpler. On the other hand, since the approach in Ref. [10] is parallel to that in Ref. [11], the second advantage does not exist there. In addition, only one SQUID is required for one qubit and the time-independent magnetic flux is used here, hence the setup and the operations proposed here would be favor for the experimentalists.

The single superconducting charge qubit we considered is shown in Fig. 1(a) [3]. It consists of a small superconducting box with n excess Cooper-pair charges, formed by a SQUID with capacitances C_0 and Josephson coupling energies E_0, pieced by a magnetic flux ϕ. A control gate voltage V_g is connected to the system via a gate capacitor C_g. The Hamiltonian of the system becomes

$$H = E_c(n - \bar{n})^2 - E_0(\cos\Gamma_1 + \cos\Gamma_2), \tag{1}$$

where n is the number operator of excess Cooper-pair charges on the box, $E_c = 2e^2/(C_g + 2C_0)$ is the charging energy, $\bar{n} = C_g V_g/2$ is the induced charge and can be controlled by

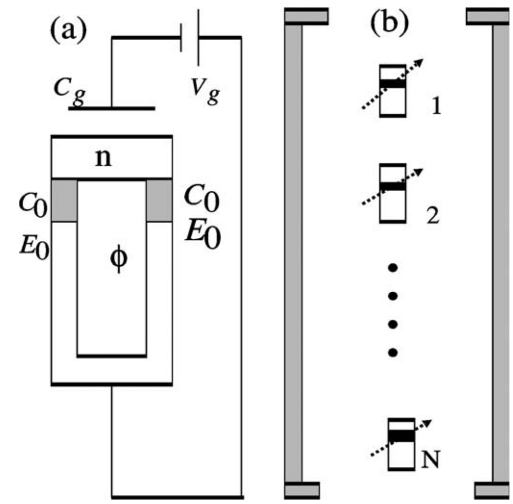

Fig. 1. Schematic Josephson charge qubits. (a) A single Josephson charge qubit. (b) N Josephson charge qubits coupled through a cavity. The substrate and electrical leads attached to each qubit in (b) have been neglected.

changing V_g. Γ_m (with $m = 1, 2$) is the gauge-invariant phase difference between points on opposite sides of the mth junction. Assume that this superconducting qubit locates within a single-mode cavity with frequency $\omega_c/2\pi$ (Fig. 1(b)), we have $\Gamma_1 + \Gamma_2 = 2\Theta$, and $\Gamma_1 - \Gamma_2 = 2\pi\phi/\phi_0 + 2g(a + a^\dagger)$, where $\phi_0 = \pi\hbar/e$ is the flux quantum, Θ conjugates to the Cooper-pair number n, g is the coupling constant between the junctions and the cavity, and a and $a^\dagger$ are the creation and annihilation operator for the single mode [8,10]. The Hamiltonian for single-qubit may be rewritten as

$$H = \sum_n \left\{ E_c(n - \bar{n})^2 |n\rangle\langle n| - E_0 \cos\left[\tilde{\phi} + g\left(a^\dagger + a\right)\right] S_n^{n+1} \right\}, \tag{2}$$

where $\tilde{\phi} = \pi\phi/\phi_0$ and $S_n^{n+1} = |n+1\rangle\langle n| + |n\rangle\langle n+1|$. In the charging regime and at temperature much lower than the charging energy, the relevant physics is captured by considering only the two charge eigenstates $n = 0, 1$. Assume we have N such qubits within one cavity, the total system can be considered as N two-state particles coupled to a quantum harmonic oscillator. Expanding the Hamiltonian of the system to the first order of g in the Lamb–Dicke limit (i.e., $g\sqrt{\langle a^\dagger a\rangle + 1} \ll 1$), we may find

$$H_0 = \hbar\omega_c\left(a^\dagger a + 1/2\right) + \sum_{j=1}^{N} E_{\bar{n}_j}\sigma_j^z/2, \tag{3}$$

$$H_1 = -E_0 \sum_{j=1}^{N} \left[\cos\tilde{\phi}_j - g\sin\tilde{\phi}_j\left(a^\dagger + a\right)\right]\sigma_j^x, \tag{4}$$

where $E_{\bar{n}_j} = 2E_c(\bar{n}_j - 1/2)$, σ_j^x and σ_j^z are Pauli matrix for qubit j. In the derivation, we have assume that the effective flux $g\langle a^\dagger + a\rangle$ induced by cavity mode is much less than $\tilde{\phi}$, which is reasonable since g is a number during $10^{-2} \sim 10^{-5}$ [8].

We now show that the Hamiltonian described in Eqs. (3) and (4) can be used easily to produce the GHZ state. We consider the case where all qubits are set at the degeneracy point (i.e., $E_{\bar{n}_j} = 0$) and with the same magnetic flux $\tilde{\phi}_j = \tilde{\phi}$. In the

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