A simple scheme to generate χ-type four-charge entangled states in circuit QED*

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We propose a simple scheme to generate χ-type four-charge entangled states by using SQUID-based charge qubits capacitively coupled to a transmission line resonator (TLR). The coupling between the superconducting qubit and the TLR can be effectively controlled by properly adjusting the control parameters of the charge qubit. The experimental feasibility of our scheme is also shown.

Keywords: χ-type entangled state, superconducting quantum interference device, transmission line resonator, superconducting charge qubit

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1. Introduction

Quantum entanglement, one of the fundamental features of a quantum system, plays a very important role in quantum information processing. So, much attention has been paid to the investigation of entangled states in recent years.[1−5] Up to now, various schemes for preparing entangled states,[6,7] such as GHZ states,[1] cluster states,[2] W states,[3] χ-type states, etc. in different physical systems, such as cavity QED,[8] trapped ions,[9,10] Boson–Einstein condensation (BEC),[10−12] etc.) have been proposed.

The χ-type states[13−22] were first introduced by Yeo and Chua[13] and one of them takes the form

$$\begin{aligned}&|\chi^{00}\rangle_{3214}\\ &= \frac{1}{2\sqrt{2}}(|0000\rangle - |0011\rangle - |0101\rangle + |0110\rangle\\ &\quad + |1001\rangle + |1010\rangle + |1100\rangle + |1111\rangle)_{3214}.\end{aligned}$$

These states have proved to be maximally entangled four-qubit states,[23] and they have many interesting entanglement properties. They are widely used in quantum information processing. Using these states, Yeo and Chua[13] constructed a protocol to realize the teleportation of a two-particle arbitrary state. With dense coding, Lin *et al.*[16] and Xiu *et al.*[20] proposed a two-party quantum secure direct communication protocol. Using entanglement swapping, Xiu *et al.*,[19] Gao,[22] and Xiu *et al.*[18] proposed two-party deterministic quantum communication protocols. Further, Wang *et al.*[17] and Zhan *et al.*[21] applied them to implement quantum-information splitting. Therefore, it is significant to generate χ-type entanglement states. In fact, the schemes to prepare them in different systems were widely explored in recent years. For example, a scheme to prepare them in ion trap system was proposed by Wang and Yang,[24] schemes with a cavity QED system are introduced by the authors in Refs. [14], [15], [25], and [26], and schemes with linear optics elements were given by Wang and Zhang,[27] and Shen *et al.*[28]

The superconducting qubit is regarded as a promising candidate in quantum information processing because of its excellent scalability, thanks to well-established microfabrication techniques.[29,30] By combining superconducting qubits with a superconducting transmission line resonator (TLR), Blais *et al.*[31] proposed a special architecture which is called circuit QED. This architecture is considered as a promising candidate for scalable superconducting quantum computation because it strongly inhibits spontaneous emission,[32] allows high-fidelity quan-

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tum nondemolition (QND) measurements of multiple qubit states,[33] and can couple qubits separated by centimeter-scale distances.[34−36]

In this paper, enlightened by the proposals mentioned above, we propose an effective method to prepare χ-type entangled states in a combined system of charge qubits, which is based on superconducting quantum interference device (SQUID), and a TLR. The rest of the present paper is arranged as follows. In Section 2, we give the model and the Hamiltonian of the system. In Section 3, we show how to prepare the χ-type four-charge entangled states. Finally, we discuss the experimental feasibility of the scheme in Section 4.

2. Model and its Hamiltonian

We consider the model sketched in Fig. 1, in which superconducting charge qubits are coupled to a TLR. In the charge regime $k_{\rm B}T \ll E_{\rm J0} \ll E_{\rm C} \ll \Delta$ (where $k_{\rm B}$, T, $E_{\rm J0}$, $E_{\rm C}$, and Δ are the Boltzmann constant,[30,37] temperature, Josephson coupling energy, charging energy, and superconducting energy gap, respectively), there are only two charge states, $n = 0$ and $n = 1$, which are important for the dynamics of the system, then the device behaves as a two-level system.[37] Assume that all the superconducting quantum interference devices (SQUIDs) have the same charge energy $E_{\rm C}$ and superconducting gap energy $E_{\rm J0}$, then the Hamiltonian of the system can be described, in the basis $\sigma_{zi}\{|g\rangle, |e\rangle\}_i$, as

$$\hat{H} = \hbar w_{\rm C} a^{\dagger} a + \sum_{i=1}^{N} \left[2E_{\rm C}(2n_{\rm gi} - 1)\sigma_{\rm zi} + \frac{E_{\rm J}(\Phi_{xi})}{2}\sigma_{xi} \right], \tag{1}$$

where $w_{\rm C}$ is the frequency of the TLR,

$$E_{\rm C} = \frac{e^2}{2C_{\Sigma}}, \quad C_{\Sigma} = 2c_{\rm J} + c_{\rm g},$$
$$E_{\rm J}(\Phi_{xi}) = 2E_{\rm J0}\cos\left(\pi\frac{\Phi_{xi}}{\Phi_0} + \pi\right),$$
$$\sigma_{zi} = |g\rangle_i\langle g| - |e\rangle_i\langle e|, \quad \sigma_{xi} = |g\rangle_i\langle e| + |e\rangle_i\langle g|,$$
$$n_{\rm gi} = n_{\rm gi}^{\rm dc} + n_{\rm gi}^{\rm ac} + n_{\rm g}^{\rm qu}, \tag{2a}$$
$$n_{\rm gi}^{\rm dc} = \frac{1}{2}, \quad n_{\rm g}^{\rm ac} = c_{\rm g} v_{0i}\cos(wt)/2e,$$
$$n_{\rm g}^{\rm qu} = c_{\rm g} v_0^{\rm qu}(a^{\dagger} + a)/2e. \tag{2b}$$

Assuming that $\Omega_i = 2E_{\rm C}c_{\rm g}v_{0i}/(\hbar e)$, $g = 2E_{\rm C}c_{\rm g}v_0^{\rm qu}/(\hbar e)$, and $w_i = E_{\rm J}(\Phi_{xi})/\hbar$ (we will always choose the w_0 non-negative, this condition can be easily satisfied by tuning the external flux Φ_{xi}), then substituting Eq. (2) into Eq. (1), the Hamiltonian becomes

$$H = \hbar w_{\rm C} a^{\dagger} a + \sum_{i=1}^{N} \Big[\frac{1}{2}\hbar w_i \sigma_{xi} + \hbar\Omega_i \cos(wt)\sigma_{zi} + \hbar g(a^{\dagger} + a)\sigma_{zi} \Big]. \tag{3}$$

Define a new basis as $S_{zi}\{|1\rangle, |0\rangle\}_i$, where $|1\rangle_i = (|g\rangle + |e\rangle)_i/2$, $|0\rangle = (|g\rangle - |e\rangle)_i/2$, then perform a basis transformation from σ_{zi} to S_{zi}, then equation (3) will become

$$H = H_0 + H_{\rm I}, \tag{4}$$

where

$$H_0 = \hbar w_{\rm C} a^{\dagger} a + \sum_{i=1}^{N} \frac{1}{2}\hbar w_i S_{zi},$$
$$H_{\rm I} = \sum_{i=1}^{N} [\hbar\Omega_i \cos(wt) S_{xi} + \hbar g(a^{\dagger} + a) S_{xi}].$$

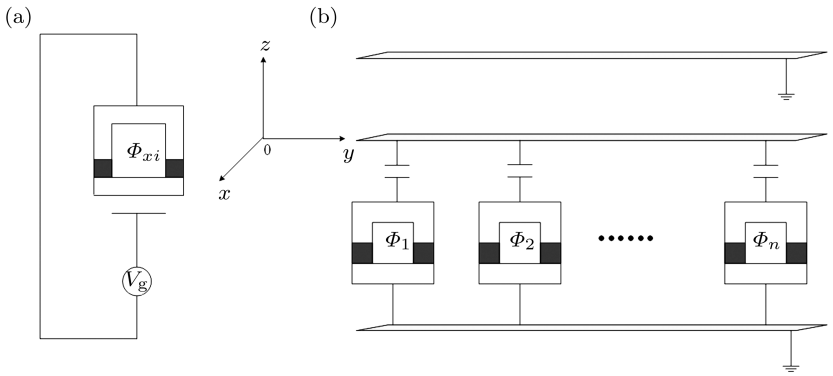


Fig. 1. (a) The basic circuit of the charge qubit (each dark part denotes one Josephson junction). $C_{\rm g}$ is gate capacitance, $V_{\rm g}$ is gate voltage, and Φ_{xi} is external magnetic flux applied to the SQUID. The circuit can be tuned by adjusting voltage $V_{\rm g}$ and external flux Φ_{xi}. (b) N charge qubits are placed in a quasi-one-dimensional TLR (the gray parts). Each qubit is placed at an antinode of the electric field, yielding a strong coupling between the qubit and the resonator mode. The qubits are capacitively coulped to the TLR.

In the interaction picture, using rotating-wave approximation we obtain

$$\begin{aligned} H_{\rm int} &= H_1 + H_2, \\ H_1 &= \hbar \sum_{j=1}^{N} \Omega_j \left({\rm e}^{{\rm i}\Delta_j t} S_j^{\dagger} + {\rm e}^{-{\rm i}\Delta_j t} S_j^{-} \right), \\ H_2 &= g \sum_{j=1}^{N} \left({\rm e}^{-{\rm i}\delta_j t} a^{\dagger} S_j^{-} + {\rm e}^{{\rm i}\delta_j t} a S_j^{\dagger} \right), \end{aligned} \tag{5}$$

where $\Delta_j = w_j - w$, $\delta_j = w_j - w_{\rm C}$, $S_{zj} = |0\rangle_j \langle 0| - |1\rangle_j \langle 1|$, $S_j^{\dagger} = |1\rangle_j \langle 0|$, and $S_j^{-} = |0\rangle_j \langle 1|$.

3. Preparation of χ-type states

In this section, we will show how to generate χ-type four-charge entangled states in a combined system of SQUID-based charge qubits and the TLR, which is described by the above Hamiltonian. Our scheme is realized by the following two steps.

The first step: in Eq. (5) we choose $N = 4$, $w_1 = w_2 = w_3 = w$, $\Omega_1 = \Omega_2 = \Omega_3 = \Omega$, and $w_{04} \gg w_{\rm C}$, $\Omega_4 = 0$ (these conditions can be easily realized by adjusting flux Φ_{xi} and AC voltage v_{0i}). Then there are only three SQUIDs interacting with the TLR. The effective Hamiltonian is

$$H = \hbar\Omega \sum_{j=1}^{3} S_{xj} + g \sum_{j=1}^{3} \left({\rm e}^{-{\rm i}\delta t} a^{\dagger} S_j^{-} + {\rm e}^{{\rm i}\delta t} a^{-} S_j^{\dagger} \right). \tag{6}$$

In the strong driving regime where $2\Omega \gg \delta, g$ and $2\delta \gg g$, the evolution operator of the system is[38]

$$\begin{aligned} U(t) &= {\rm e}^{-{\rm i}H_0 t}\, {\rm e}^{-{\rm i}H_{\rm e} t}, \\ H_0 &= \hbar \sum_{j=1}^{3} \Omega (S_j^{\dagger} + S_j^{-}), \\ H_{\rm e} &= \hbar\lambda \Bigg[\sum_{j=1}^{3} \frac{1}{2} (|0\rangle\langle 0| + |1\rangle\langle 1|) \\ &\quad + \sum_{j=1, j\neq k}^{3} (S_j^{\dagger} S_k^{\dagger} + S_j^{\dagger} S_k^{-} + {\rm H.c.}) \Bigg], \end{aligned} \tag{7}$$

where $\lambda = g^2/2\delta$, and $H_{\rm e}$ is the effective interaction Hamiltonian of the system.

If we set the initial state to be $|\psi\rangle_{1234} = |mmmm\rangle_{1234}$, $m_j \in \{0,1\}_j$, $\bar{m}_j$ denotes the counterpart of the binary number m_j, after a period of time t, the state will evolve into

$$\begin{aligned} &|\psi(t)\rangle_{1234} \\ &= \frac{1}{16}\, {\rm e}^{-{\rm i}\lambda t/2} [(4\,{\rm e}^{-{\rm i}4\lambda t} \cos 3\Omega t \\ &\quad + 12\cos\Omega t)\, |mmmm\rangle_{1234} \\ &\quad - {\rm i}(4\,{\rm e}^{-{\rm i}4\lambda t} \sin 3\Omega t + 4\sin\Omega t) \\ &\quad \times (|mm\bar{m}m\rangle + |m\bar{m}mm\rangle + |\bar{m}mmm\rangle)_{1234} \\ &\quad + (4\,{\rm e}^{-{\rm i}4\lambda t} \cos 3\Omega t - 4\cos\Omega t) \\ &\quad \times (|m\bar{m}\bar{m}m\rangle + |\bar{m}\bar{m}mm\rangle + |\bar{m}m\bar{m}m\rangle)_{1234} \\ &\quad - {\rm i}(4\,{\rm e}^{-{\rm i}4\lambda t} \sin 3\Omega t - 12\sin\Omega t)\, |\bar{m}\bar{m}\bar{m}\bar{m}\rangle_{1234}. \end{aligned} \tag{8}$$

After the operation time t_1 under the condition $\Omega t_1 = 2n\pi$, $\lambda t_1 = \pi/4$, we obtain

$$\begin{aligned} |\Psi\rangle_{1234} = \frac{1}{2} \big(&|mmmm\rangle - |m\bar{m}\bar{m}m\rangle - |\bar{m}m\bar{m}m\rangle \\ &- |\bar{m}\bar{m}mm\rangle \big)_{1234}. \end{aligned} \tag{9}$$

The second step: properly adjust the parameters of the fourth charge qubit and let $w_1 = w_2 = w_3 = w_4 = w$, and $\Omega_1 = \Omega_2 = \Omega_3 = \Omega_4 = \Omega'$. In the same theory as that in the first step, we can obtain the evolution operator of the system

$$\begin{aligned} &U(t) \\ &= {\rm e}^{-{\rm i}H_0' t/\hbar}\, {\rm e}^{-{\rm i}H_{\rm e}' t/\hbar} \\ &= {\rm e}^{-{\rm i}2\lambda' t} \left[\prod_{j=1}^{4} (\cos\Omega' t - {\rm i} S_j^x \sin\Omega' t) \right] \\ &\quad \times \left\{ \prod_{j=1}^{3} \left[\prod_{k=j+1}^{4} (\cos\lambda' t - {\rm i} S_j^x S_k^x \sin\lambda' t) \right] \right\}. \end{aligned} \tag{10}$$

When the operation time t_2 satisfies $\Omega' t_2 = n\pi$ and $\lambda' t_2 = \pi/4$, the evolution operator reduces into

$$U(t_2) = \frac{1}{\sqrt{2}} \left[1 + {\rm i} \prod_{j=1}^{4} S_j^x \right]. \tag{11}$$

Thus, an arbitrary state $|mmmm\rangle_{1234}$ will be evolved as follows:

$$|mmmm\rangle_{1234} = |mmmm\rangle_{1234} + {\rm i}\, |\bar{m}\bar{m}\bar{m}\bar{m}\rangle_{1234}. \tag{12}$$

According to the above equation, state $|\psi\rangle_{1234}$ in Eq. (9) will become

$$\begin{aligned} &|\chi_{mmmm}\rangle'_{1234} \\ &= \frac{1}{2\sqrt{2}} [|mmmm\rangle + {\rm i}\, |\bar{m}\bar{m}\bar{m}\bar{m}\rangle - |m\bar{m}\bar{m}m\rangle \\ &\quad - {\rm i}\, |\bar{m}mm\bar{m}\rangle - |\bar{m}m\bar{m}m\rangle - {\rm i}\, |m\bar{m}m\bar{m}\rangle \\ &\quad - |\bar{m}\bar{m}mm\rangle - {\rm i}\, |mm\bar{m}\bar{m}\rangle]_{1234}. \end{aligned} \tag{13}$$

Obviously, it is one of the χ-type four-charge states. Let m_1, m_2, m_3, $m_4 = 0, 1$, then equation (13) will describe 16 χ-type four-charge entangled states.

For example, if the initial state is $|0000\rangle_{3214}$, we will obtain

$$\begin{aligned}|\chi^{00}\rangle'_{3214} = \frac{1}{2\sqrt{2}}[&|0000\rangle - \mathrm{i}\,|0011\rangle - \mathrm{i}\,|0101\rangle \\ &- |0110\rangle - \mathrm{i}\,|1001\rangle - |1010\rangle \\ &- |1100\rangle + \mathrm{i}\,|1111\rangle]_{3214}.\end{aligned}$$

It is obvious that $|\chi^{00}\rangle'_{3214} = \text{l.u.}\,|\chi^{00}\rangle_{3214}$, where "l.u." indicates that the equality holds up to a local unitary on one or more of the qubits.[39] Thus, we obtain the χ-type four-charge entangled states in the circuit QED.

Now we show how to deterministically distinguish from among the above 16 basis states $\{|\chi_{mmmm}\rangle'_{1234}$, m_1, m_2, m_3, $m_4 = 0, 1\}$. Firstly, we operate the system, which is initially in the state $|\chi_{mmmm}\rangle'_{1234}$, with the same scheme described in the above second step. After a period of evolution time $t'_1 = \pi/4\lambda'$, we then let the system evolve in the same process as that described in the first step above. Then, after another period of evolution time $t'_2 = \pi/4\lambda$, the total evolution of the system can be described as

$$|\chi_{mmmm}\rangle'_{1234} \to i\,|\bar{m}\bar{m}\bar{m}\bar{m}\rangle_{1234}\,,$$

which means that each of the 16 basis states $\{|\chi_{mmmm}\rangle'_{1234}$, m_1, m_2, m_3, $m_4 = 0, 1\}$ can be transformed into a corresponding product state of particles 1, 2, 3, 4. So the experimental identification of these states can be achieved by the individual detection of the related qubits, which can be easily implemented by using a single electron transistor (SET).

4. Discussion and conclusion

We now give a brief discussion about the experiment. In the experiment, charging energy E_{C}, Josephson coupling energy E_{J}, and Rabi frequency Ω can reach the values $E_{\mathrm{C}}/h \sim 2\pi \times 32$ GHz, $E_{\mathrm{J}}/h \sim 2\pi \times 5$ GHz, and $\Omega \sim 2\pi \times 300$ MHz,[40,41] respectively. The coupling constant $g = 2\pi \times 22$ MHz is also attainable.[42] So we can set $\Omega = 2\pi \times 176$ MHz, $g = 2\pi \times 22$ MHz, $\sigma = 4g$, and operation time $t_1 = \pi/4\lambda \approx 50$ ns, then set $\Omega' = 2\pi \times 275$ MHz, $\sigma' = 2g$, and operation time $t_2 = \pi/4\lambda' \approx 25$ ns. As is known, energy relaxation time, dephasing time, and κ^{-1} for resonator with $Q = 10^5$ are 7.3 μs, 500 ns, and 794 ns,[43,44] respectively. Therefore, it is obvious that the total operation time $t_{\mathrm{total}} = t_1 + t_2 = 75$ ns $\ll 500$ ns.

We can also calculate the possibility of the fourth charge qubit excited by the TLR during the first step. Let $w_4 = E_{\mathrm{J}4}/\hbar = 2\pi \times 10$ GHz, $w = 2\pi \times 4.9$ GHz, $g = 2\pi \times 22$ MHz, and $w_c = 2\pi \times 5$ GHz, then the possibility will be[45]

$$P \approx \frac{2}{4 + (\Delta_4/g)^2} \approx 3.9 \times 10^{-5},$$

which is obviously very small (where $\Delta_4 = w_4 - w_c$). So, during the first step, only three charge qubits evolve and the fourth charge qubit is always in its initial state, and our scheme is feasible.

In conclusion, we proposed an effective method to prepare χ-type four-charge entangled states in a combined system of SQUIDs and a TLR. In the scheme, the interaction between a SQUID and a TLR is mediated by exchanging virtual rather than real photons because of the large detuning between them. So, our proposal is insensitive to the initial state of the TLR, and then no preparation for the initial state of the TLR is needed. We also showed that the scheme is feasible in experiment.

References

[1] Greenberger D M, Horne M A, Shimony A and Zeilinger A 1990 *Am. J. Phys.* **58** 1131
[2] Briegel H J and Raussendorf R 2001 *Phys. Rev. Lett.* **86** 910
[3] Dür W, Vidal G and Cirac J I 2000 *Phys. Rev.* A **62** 062314
[4] Jiang N Q and Zheng Y Z 2006 *Phys. Rev.* A **74** 012306
[5] Jiang N Q, Wang Y J, Zheng Y and Cai G C 2008 *Chin. Phys. Lett.* **25** 1943
[6] Lin Q 2010 *Acta Phys. Sin.* **59** 2976 (in Chinese)
[7] Wang S J and Ma S J 2011 *Acta Phys. Sin.* **60** 030302 (in Chinese)
[8] Zheng S B 2001 *Phys. Rev. Lett.* **87** 230404
[9] Li G X 2006 *Phys. Rev.* A **74** 055801
[10] Xue L, Huang S S, Wu L, Ji Y Y and Jiang N Q 2011 *Chin. Phys.* B **20** 050313
[11] Gerry C C and Campos R A 2003 *Phys. Rev.* A **68** 025602
[12] Xu Y, Fan W, Chen B and Li Z X 2011 *Acta Phys. Sin.* **60** 060305 (in Chinese)
[13] Yeo Y and Chua W K 2006 *Phys. Rev. Lett.* **96** 060502
[14] Xiu L 2010 *Chin. Phys. Lett.* **27** 044207
[15] He Y and Jiang N Q 2010 *Opt. Commun.* **283** 1558
[16] Lin S, Wen Q Y, Gao F and Zhu F C 2008 *Phys. Rev.* A **78** 064304
[17] Wang X W, Xia L X, Wang Z Y and Zhang D Y 2010 *Opt. Commun.* **283** 1196
[18] Xiu X M, Dong L and Gao Y J 2011 *Opt. Commun.* **284** 2065
[19] Xiu X M, Dong H K, Dong L, Gao Y J and Chi F 2009 *Opt. Commun.* **282** 2457
[20] Xiu X M, Dong L, Gao Y J and Chi F 2009 *Commun. Theor. Phys.* **52** 60

[21] Zhan Y B, Zhang Q Y and Wang Y W 2010 *Commun. Theor. Phys.* **53** 847
[22] Gao G 2010 *Phys. Scr.* **81** 065005
[23] Xue L, Wu L, Cai G C and Jiang N Q 2011 *Int. J. Quantum Infor.* **9** 875
[24] Wang X W and Yang G J 2008 *Phys. Rev.* A **78** 024301
[25] Wang X W 2009 *Opt. Commun.* **282** 1052
[26] Liu G Y and Kuang L M 2009 *J. Phys.* B: *At. Mol. Opt. Phys.* **42** 165505
[27] Wang H F and Zhang S 2009 *Phys. Rev.* A **79** 042336
[28] Shen H W, Wang H F, Ji X and Zhang S 2009 *Chin. Phys.* B **18** 3706
[29] You J and Nori F 2005 *Phys. Today* **58** 11
[30] Makhlin Y, Sch G and Shnirman A 2001 *Rev. Mod. Phys.* **73** 357
[31] Blais A, Huang R S, Wallraff A, Girvin S M and Schoelkopf R J 2004 *Phys. Rev.* A **69** 062320
[32] Houck A A, Schreier J A, Johnson B R, Chow J M, Koch J, Gambetta J M, Schuster D I, Frunzio L, Devoret M H, Girvin S M and Schoelkopf R J 2008 *Phys. Rev. Lett.* **101** 080502
[33] Gambetta J, Blais A, Schuster D I, Wallraff A, Frunzio L, Majer J, Devoret M H, Girvin S M and Schoelkopf R J 2006 *Phys. Rev.* A **74** 042318
[34] Majer J, Chow J, Gambetta J, Koch J, Johnson B, Schreier J, Frunzio L, Schuster D, Houck A and Wallraff A 2007 *Nature* **449** 443
[35] Leek P J, Filipp S, Maurer P, Baur M, Bianchetti R, Fink J M, Göpple M, Steffen L and Wallraff A 2009 *Phys. Rev.* B **79** 180511
[36] DiCarlo L, Chow J, Gambetta J, Bishop L S, Johnson B, Schuster D, Majer J, Blais A, Frunzio L and Girvin S 2009 *Nature* **460** 240
[37] Clarke J and Wilhelm F K 2008 *Nature* **453** 1031
[38] Zheng S B 2003 *Phys. Rev.* A **68** 035801
[39] Linden N, Massar S and Popescu S 1998 *Phys. Rev. Lett.* **81** 3279
[40] Astafiev O, Pashkin Y A, Nakamura Y, Yamamoto T and Tsai J S 2004 *Phys. Rev. Lett.* **93** 267007
[41] Baur M, Filipp S, Bianchetti R, Fink J M, Göpple M, Steffen L, Leek P J, Blais A and Wallraff A 2009 *Phys. Rev. Lett.* **102** 243602
[42] Schuster D, Houck A, Schreier J, Wallraff A, Gambetta J, Blais A, Frunzio L, Johnson B, Devoret M and Girvin S 2006 *arXiv*: cond-mat/0608693
[43] Wallraff A, Schuster D I, Blais A, Frunzio L, Majer J, Devoret M H, Girvin S M and Schoelkopf R J 2005 *Phys. Rev. Lett.* **95** 060501
[44] Yang C P, Liu Y X and Nori F 2010 *Phys. Rev.* A **81** 062323
[45] Yang C P 2010 *Phys. Rev.* A **82** 054303