Implementation of quantum controlled phase gate and preparation of multiparticle entanglement in cavity QED*

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Schemes are presented for realizing quantum controlled phase gate and preparing an N-qubit W-like state, which are based on the large-detuned interaction among three-state atoms, dual-mode cavity and a classical pulse. In particular, a class of W states that can be used for perfect teleportation and superdense coding is generated by only one step. Compared with the previous schemes, cavity decay is largely suppressed because the cavity is only virtually excited and always in the vacuum state and the atomic spontaneous emission is strongly restrained due to a large atom–field detuning.

Keywords: phase gate, W states, cavity QED

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1. Introduction

It is known that concatenation of a sequence of the quantum controlled phase gate and single-qubit gates is universal for quantum computation.[1] In general, it is easy to implement single-qubit gates. Thus the realization of two-qubit gates become the key to performing a quantum algorithm. In the past decades, a variety of systems were explored for the realization of practical quantum controlled gate, such as trapped ion,[2] nuclear magnetic resonance,[3,4] and so on. However, the decoherence, as a result of the coupling between the environment and the qubit system concerned, induces the gate infidelity far above the threshold value 1%.[5] The cavity QED system is a promising alternative for quantum information processing. In particular, the strong-detuned interaction between the cavity mode and atoms is widely concerned about since it can reduce the decoherence. For example, the scheme based on Ref. [6] has already been realized experimentally with a microwave cavity and long living Rydberg atoms.[7]

On the other hand, quantum entanglement lies at the heart of quantum information processing and universal quantum computation. It not only gives the possibility for test of quantum mechanics against local hidden theory,[8,9] but also plays a principal role in many quantum applications such as quantum teleportation,[10] quantum computation,[11] and quantum cryptography.[12] Also, very recently, Piani and Watrous proved that all the entangled states are useful for channel discrimination.[13] Most of the previous researches in quantum information processing focused on two-particle entanglement, while recent investigations show that multiparticle entangled states are valuable physical resources in distributed quantum computation[14] and multiparty quantum communication protocols.[15−18]

In this paper, we present schemes for implementing the two-qubit quantum controlled phase gate and generating an N-qubit W-like state based on the large-detuned interaction among three-state atoms, dual-mode cavity and a classical pulse. Our proposals have the following significant advantages. First, atomic spontaneous emission plays a neglected role because the excited state is not populated. Secondly, there is no transformation of quantum information between atoms and cavity fields due to the large detuning. Thirdly, cavity decay can be effectively suppressed

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since the cavity fields are always in the vacuum state.

2. The fundamental model

Assume that N identical 3-state atoms, with two low levels $|g\rangle$, $|f\rangle$ and a high level $|e\rangle$, simultaneously interact with a bimodal cavity field and a classical pulse, as shown in Fig. 1.

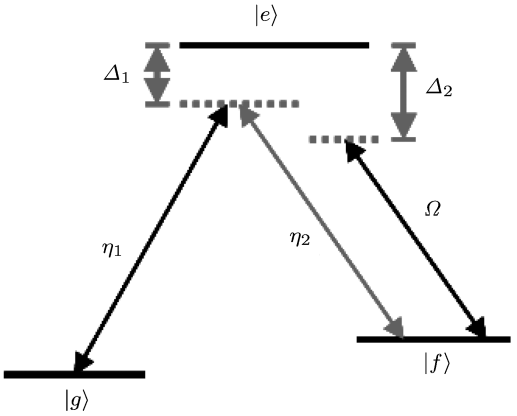


Fig. 1. Configuration of the atomic level structure and relevant transitions. The states $|g\rangle$ and $|f\rangle$ correspond to two low levels while $|e\rangle$ is a high level. The transition $|f\rangle \leftrightarrow |e\rangle$ of each atom is driven by the cavity field and the classical pulse with the detuning Δ_1 and Δ_2, while the transition of $|g\rangle \leftrightarrow |e\rangle$ is driven by the cavity field with the detuning Δ_1, η_1 and η_2 represent the coupling rate of the atom to cavity mode and Ω is the Rabi frequency of the classical pulse.

The cavity mode a (b) with coupling strength η_1 (η_2) couples to the transition $|g_j\rangle \leftrightarrow |e_j\rangle$ ($|f_j\rangle \leftrightarrow |e_j\rangle$) of the j-th atom, while the laser field with Rabi frequency Ω drives the transition $|f_j\rangle \leftrightarrow |e_j\rangle$. The Hamiltonian for the whole system is (setting $\hbar = 1$)

$$\begin{aligned} H =\ & \omega_1 a^\dagger a + \omega_2 b^\dagger b + \sum_{j=1}^{N} \{\omega_{\rm eg}|e_j\rangle\langle e_j| + \omega_{\rm fg}|f_j\rangle\langle f_j| \\ & + [\eta_1 |e_j\rangle\langle g_j| a + \eta_2 |e_j\rangle\langle f_j| b \\ & + \Omega |e_j\rangle\langle f_j| {\rm e}^{-{\rm i}\,\omega_{\rm L} t} + {\rm H.c.}]\}, \end{aligned} \tag{1}$$

where ω_{lg} ($l = e, f$) denotes the atomic transition frequency, ω_i ($i = 1, 2$) is the frequency of the cavity modes a and b, ω_L indicates the classical pulse frequency. For the sake of convenience, we assume η_i ($i = 1, 2$) and Ω to be real. The interaction Hamiltonian in the interaction picture can be written as

$$\begin{aligned} H_{\rm I} =\ & \sum_{j=1}^{N} (\eta_1 |e_j\rangle\langle g_j| a\, {\rm e}^{{\rm i}\,\Delta_1 t} + \eta_2 |e_j\rangle\langle f_j| b\, {\rm e}^{{\rm i}\,\Delta_1 t} \\ & + \Omega |e_j\rangle\langle f_j| {\rm e}^{-i\Delta_2 t}) + {\rm H.c.}, \end{aligned} \tag{2}$$

where $\Delta_1 = \omega_{\rm eg} - \omega_1 = \omega_{\rm ef} - \omega_2$, $\Delta_2 = \omega_{\rm ef} - \omega_{\rm L}$. In the case of $\Delta_1 \gg \eta_i$ ($i = 1, 2$) and $\Delta_2 \gg \Omega$, the high level $|e\rangle$ can be adiabatically eliminated and the Hamiltonian $H_{\rm I}$ is reduced to[19–22]

$$\begin{aligned} H_{\rm II} =\ & \sum_{j=1}^{N} \Big[-\frac{\eta_1^2}{\Delta_1} |g_j\rangle\langle g_j| a^\dagger a \\ & - \frac{\eta_2^2}{\Delta_1} |f_j\rangle\langle f_j| b^\dagger b - \frac{\Omega^2}{\Delta_2} |f_j\rangle\langle f_j| \\ & - \lambda_0 (|f_j\rangle\langle g_j| a b^\dagger + |g_j\rangle\langle f_j| a^\dagger b) \\ & - \lambda_1 (|f_j\rangle\langle g_j| a\, {\rm e}^{-{\rm i}\,\delta t} + |g_j\rangle\langle f_j| a^\dagger {\rm e}^{{\rm i}\,\delta t}) \\ & - \lambda_2 (|f_j\rangle\langle f_j| b\, {\rm e}^{-{\rm i}\,\delta t} + |f_j\rangle\langle f_j| b^\dagger\, {\rm e}^{{\rm i}\,\delta t}) \Big], \end{aligned} \tag{3}$$

where $\delta = \Delta_2 - \Delta_1$, $1/\Delta_{12} = (1/2)(1/\Delta_1 + 1/\Delta_2)$, $\lambda_0 = \eta_1\eta_2/\Delta_1$, $\lambda_1 = \eta_1\Omega/\Delta_{12}$, $\lambda_2 = \eta_2\Omega/\Delta_{12}$. In the case of $\delta \gg \eta_1^2/\Delta_1$, η_2^2/Δ_1, Ω^2/Δ_2, λ_0, λ_1, λ_2, the time averaging method can be used again.[19–23] The effective Hamiltonian is then given by

$$\begin{aligned} H_{\rm eff} =\ & \sum_{j=1}^{N} \Big[-\Big(\frac{\eta_1^2}{\Delta_1} + \frac{\lambda_1^2}{\delta}\Big) |g_j\rangle\langle g_j| a^\dagger a \\ & - \Big(\frac{\eta_2^2}{\Delta_1} b^\dagger b + \frac{\Omega^2}{\Delta_2} - \frac{\lambda_1^2}{\delta} a a^\dagger - \frac{\lambda_2^2}{\delta}\Big) |f_j\rangle\langle f_j| \\ & - \Big(\lambda_0 + \frac{\lambda_3}{\delta}\Big) (|f_j\rangle\langle g_j| a b^\dagger + |g_j\rangle\langle f_j| a^\dagger b) \Big] \\ & + \sum_{j,k=1, j\neq k}^{N} \frac{\lambda_1^2}{\delta} S_j^- S_k^+ \\ & + \sum_{\substack{j,k=1, j\neq k \\ j<k}}^{N} \frac{2\lambda_2^2}{\delta} |f_j\rangle\langle f_j| |f_k\rangle\langle f_k|, \end{aligned} \tag{4}$$

where $\lambda_3 = \eta_1\eta_2(\Omega/\Delta_{12})^2$, $S_j^+ = |f_j\rangle\langle g_j|$, $S_j^- = |g_j\rangle\langle f_j|$. The first and second terms in Eq. (4) are the Stark shifts for the level $|g\rangle$ and $|f\rangle$, respectively, which are evoked by the cavity mode and the classical pulse. The third term describes the interaction between both cavity modes assisted by the atoms. The last two terms mean the coupling between atoms j and k mediated by the cavity mode and the classical pulse. If both cavity modes are initially in the vacuum state, the effective Hamiltonian becomes

$$\begin{aligned} H_{\rm eff} =\ & \sum_{j=1}^{N} \Big(-\frac{\Omega^2}{\Delta_2} + \lambda_1' + \lambda_2' \Big) |f_j\rangle\langle f_j| \\ & + \sum_{j,k=1, j\neq k}^{N} \lambda_1' S_j^- S_k^+ \\ & + \sum_{\substack{j,k=1, j\neq k \\ j<k}}^{N} 2\lambda_2' |f_j\rangle\langle f_j| |f_k\rangle\langle f_k|, \end{aligned} \tag{5}$$

where $\lambda_1' = \lambda_1^2/\delta$, $\lambda_2' = \lambda_2^2/\delta$.

3. Implementation of the quantum controlled phase gate

Now we show in detail how to implement a quantum controlled phase gate based on Eq. (5) for $N = 2$. In this case there are only two atoms in the cavity. Given that the two low levels $|f\rangle$ and $|g\rangle$ of each atom represent two logical states of a qubit, the time evolutions of the four logical states for two-qubit, under the Hamiltonian (5), are as follows:

$$|g_j\rangle|g_k\rangle \rightarrow |g_j\rangle|g_k\rangle, \tag{6}$$

$$|f_j\rangle|g_k\rangle \rightarrow \mathrm{e}^{-\mathrm{i}(-\Omega^2/\Delta_2+\lambda_1'+\lambda_2')t}[\cos(\lambda_1' t)|f_j\rangle|g_k\rangle - \mathrm{i}\sin(\lambda_1' t)|g_j\rangle|f_k\rangle], \tag{7}$$

$$|g_j\rangle|f_k\rangle \rightarrow \mathrm{e}^{-\mathrm{i}(-\Omega^2/\Delta_2+\lambda_1'+\lambda_2')t}[\cos(\lambda_1' t)|g_j\rangle|f_k\rangle - \mathrm{i}\sin(\lambda_1' t)|f_j\rangle|g_k\rangle], \tag{8}$$

$$|f_j\rangle|f_k\rangle \rightarrow \mathrm{e}^{-\mathrm{i}(-2\Omega^2/\Delta_2+2\lambda_1'+4\lambda_2')t}|f_j\rangle|f_k\rangle. \tag{9}$$

With the choices of $\lambda_1' t = \pi$, $\lambda_2' t = \pi/2$, $\Omega^2/\Delta_2 = \pi/2$, one has

$$\begin{aligned} &|g_j\rangle|g_k\rangle \rightarrow |g_j\rangle|g_k\rangle,\\ &|f_j\rangle|g_k\rangle \rightarrow |f_j\rangle|g_k\rangle,\\ &|g_j\rangle|f_k\rangle \rightarrow |g_j\rangle|f_k\rangle,\\ &|f_j\rangle|f_k\rangle \rightarrow -|f_j\rangle|f_k\rangle. \end{aligned} \tag{10}$$

Apparently, only if both atoms are initially in $|f\rangle$, the state of two-atom system acquires the phase π; otherwise, the state of two-atom system acquires the phase 0. Thus we have realized the desired quantum controlled phase gate, which is a well-known two-qubit universal logic gate.

4. Generation of multiparticle entanglement

In the following, we present an efficient scheme for preparation of two, three, or four particles entanglement, then extend it to n particles case.

Assume there are two atoms in the cavity and they are initially in the state $|f_j\rangle|g_k\rangle$. With the choice of $\lambda_1' t = \pi/4$ for Eq. (7), a maximally entangled two-atom state

$$|f_j\rangle|g_k\rangle \rightarrow \frac{1}{\sqrt{2}}(|f_j\rangle|g_k\rangle - \mathrm{i}\,|g_j\rangle|f_k\rangle) \tag{11}$$

will be obtained, where a common phase factor $\mathrm{e}^{-\mathrm{i}(-\Omega^2/\Delta_2+\lambda_1'+\lambda_2')t}$ has been discarded.

Assume that there are three atoms in the cavity and there are initially in the state $|f_j\rangle|g_k\rangle|g_j\rangle$, the state evolution of the three-atom system based on Eq. (5) for $N = 3$ is given by

$$\begin{aligned} |f_i\rangle|g_k\rangle|g_j\rangle \rightarrow \mathrm{e}^{-\mathrm{i}(-\Omega^2/\Delta_2+\lambda_2'+3\lambda_1'/2)t}\Big\{&\Big(\frac{2}{3}\mathrm{e}^{\mathrm{i}\,3\lambda_1' t/2} + \frac{1}{3}\mathrm{e}^{-\mathrm{i}\,3\lambda_1' t/2}\Big)|f_i\rangle|g_k\rangle|g_j\rangle\\ &+\Big(-\frac{1}{3}\mathrm{e}^{\mathrm{i}\,3\lambda_1' t/2} + \frac{1}{3}\mathrm{e}^{-\mathrm{i}\,3\lambda_1' t/2}\Big)(|g_i\rangle|f_k\rangle|g_j\rangle + |g_i\rangle|g_k\rangle|f_j\rangle)\Big\}. \end{aligned} \tag{12}$$

With the choice of $3\lambda_1' t/2 = \pi/3$, a maximally entangled three-particle W state is prepared, i.e.,

$$|f_i\rangle|g_k\rangle|g_j\rangle \rightarrow \frac{1}{\sqrt{3}}[\mathrm{e}^{\mathrm{i}\,\pi/6}|f_i\rangle|g_k\rangle|g_j\rangle - \mathrm{i}\,|g_i\rangle|f_k\rangle|g_j\rangle - \mathrm{i}\,|g_i\rangle|g_k\rangle|f_j\rangle], \tag{13}$$

where we have discarded the common phase factor $\exp[-\mathrm{i}(-\Omega^2/\Delta_2 + \lambda_2' + 3\lambda_1'/2)t]$.

Recently, Agrawal and Pati have shown there is a class of W states that can be used for perfect teleportation and superdense coding.[24] Such a nonmaximally entangled three-qubit W state can be obtained by setting interaction time $3\lambda_1' t/2 = \arcsin(-3/4)$ in Eq. (12), i.e.,

$$|f_i\rangle|g_k\rangle|g_j\rangle \rightarrow \mathrm{i}\Big[\frac{\sqrt{2}}{2}\mathrm{e}^{\mathrm{i}\,\sigma}|f_i\rangle|g_k\rangle|g_j\rangle + \frac{1}{2}|g_i\rangle|f_k\rangle|g_j\rangle + \frac{1}{2}|g_i\rangle|g_k\rangle|f_j\rangle\Big], \tag{14}$$

where we have set a common phase factor $\mathrm{e}^{-\mathrm{i}(-\Omega^2/\Delta_2+\lambda_2'+3\lambda_1'/2)t} = \mathrm{i}$, $\sigma = \mathrm{arctg}\,(-1/\sqrt{7}) - \pi/2$.

Assume that there are four atoms in the cavity and they are initially in the state $|f_i\rangle|g_k\rangle|g_j\rangle|g_l\rangle$, the state evolution of the four-atom system based on Eq. (5) is

$$|f_i\rangle|g_k\rangle|g_j\rangle|g_l\rangle \rightarrow \mathrm{e}^{-\mathrm{i}(-\Omega^2/\Delta_2+2\lambda_1'+\lambda_2')t}\Big\{\Big(\frac{3}{4}\mathrm{e}^{2\mathrm{i}t\lambda_1'}+\frac{1}{4}\mathrm{e}^{-2\mathrm{i}t\lambda_1'}\Big)|f_i\rangle|g_k\rangle|g_j\rangle|g_l\rangle$$
$$+\Big(-\frac{1}{4}\mathrm{e}^{2\mathrm{i}t\lambda_1'}+\frac{1}{4}\mathrm{e}^{-2\mathrm{i}t\lambda_1'}\Big)(|g_i\rangle|f_k\rangle|g_j\rangle|g_l\rangle+|g_i\rangle|g_k\rangle|f_j\rangle|g_l\rangle+|g_i\rangle|g_k\rangle|g_j\rangle|f_l\rangle)\}. \quad (15)$$

With the choice of $2\lambda_1' t=\pi/2$, a maximally entangled four-particle W state is gained, i.e.,

$$|f_i\rangle|g_k\rangle|g_j\rangle|g_l\rangle \rightarrow \frac{1}{\sqrt{4}}\,\mathrm{i}\{|f_i\rangle|g_k\rangle|g_j\rangle|g_l\rangle-|g_i\rangle|f_k\rangle|g_j\rangle|g_l\rangle-|g_i\rangle|g_k\rangle|f_j\rangle|g_l\rangle-|g_i\rangle|g_k\rangle|g_j\rangle|f_l\rangle\}, \quad (16)$$

where a common phase factor $\mathrm{e}^{-\mathrm{i}(-\Omega^2/\Delta_2+2\lambda_1'+\lambda_2')t}$ has been discarded.

Generally, if N atoms in the cavity are initially in the state $|f_1\rangle|g_2\rangle\cdots|g_N\rangle$, the evolution of the state proceeds as follows:

$$|f_1\rangle|g_2\rangle\cdots|g_N\rangle \rightarrow \mathrm{e}^{-\mathrm{i}(-\Omega^2/\Delta_2+\lambda_2'+N\lambda_1'/2)t}\Big\{\Big(\frac{N-1}{N}\mathrm{e}^{\mathrm{i}N\lambda_1' t/2}+\frac{1}{N}\mathrm{e}^{-\mathrm{i}N\lambda_1' t/2}\Big)|f_1\rangle|g_2\rangle\cdots|g_N\rangle$$
$$+\Big(-\frac{1}{N}\mathrm{e}^{\mathrm{i}N\lambda_1' t/2}+\frac{1}{N}\mathrm{e}^{-\mathrm{i}N\lambda_1' t/2}\Big)(|g_1\rangle|f_2\rangle|g_3\rangle\cdots|g_N\rangle$$
$$+|g_1\rangle|g_2\rangle|f_3\rangle|g_4\rangle\cdots|g_N\rangle+\cdots+|g_1\rangle\cdots|g_{N-1}\rangle|f_N\rangle)\Big\}. \quad (17)$$

With the choice of an appropriate interaction time, one can obtain an N-particle W-like state.

5. Discussion and conclusion

Now, we give a simple discussion for the generation of N-qubit W state. According to Eq. (17), a maximal entanglement W state can be prepared when the condition

$$\Big|\frac{N-1}{N}\mathrm{e}^{\mathrm{i}N\lambda_1' t/2}+\frac{1}{N}\mathrm{e}^{-\mathrm{i}N\lambda_1' t/2}\Big| = \Big|-\frac{1}{N}\mathrm{e}^{\mathrm{i}N\lambda_1' t/2}+\frac{1}{N}\mathrm{e}^{-\mathrm{i}N\lambda_1' t/2}\Big| \quad (18)$$

is satisfied, which leads to $\sin(N\lambda_1' t/2)=\pm\sqrt{N}/2$. Taking into account that the inequality $|\sin(N\lambda_1' t/2)|\leq 1$ must be met, a maximally entangled W state can be gained only for $N\leq 4$ by choosing the proper interaction time, whereas a nonmaximally entangled W-like state is always obtained for $N\geq 5$. Then, we briefly address the approximation condition of the fundamental model. The required atomic level configuration and transitions can be achieved in neutral atoms trapped in a solid-state system cavity. For instance, we can take the cesium atom as our choice.[25] The ground states $|g\rangle$ and $|f\rangle$ can be achieved by $|F=3,M=1\rangle$ and $|F=3,M=-1\rangle$ of $6^2\mathrm{S}_{1/2}$, the upper state corresponds to $|F=3,M=0\rangle$ of $6^2\mathrm{P}_{1/2}$. With the choices of $\eta_1=2\eta_2$, $\Delta_1=10\eta_2$, $\Delta_2=11\eta_2$ and $\Omega=1.05\eta_2$, the large-detuned conditions $\Delta_1\gg\eta_i$ $(i=1,2)$, $\Delta_2\gg\Omega$ and $\delta\gg\eta_1^2/\Delta_1$, η_2^2/Δ_1, Ω^2/Δ_2, λ_0, λ_1, λ_2 can be satisfied. For solid-state system, strong-coupling and Lamb–Dicke limits can be easier to achieve.[26] In the past few years, much attention has been paid to superconducting devices such as artificial defects into photonic crystal microcavities,[27,28] superconducting electrical circuits QED,[29] and Cooper pair box, since these solid-state artificial atoms are relatively easy to scale up and have been demonstrated to have relatively long decoherence time.[30] Recently, for the photonic crystals and nanocavities, cavity quality factors of up to 2 million have been realized while maintaining very small mode volumes and both spontaneous-emission modification (the Purcell effect) and strong-coupling phenomena have been demonstrated.[31–33] All of these technological progresses provide possibility for the experimental implementation of the schemes. Compared with Ref. [34], there are some advantages in our schemes: (i) the influence of cavity decay on the success probability is greatly suppressed since cavity fields are always in the vacuum state; (ii) the influence of the atomic spontaneous emission is strongly restrained because two logical states of a qubit is encoded by long-live two ground states, and the excited state is not involved due to the large-detuned condition during the evolution.

In summary, we have presented the protocols for realizing quantum controlled phase gate and generating multiparticle entanglement based on the large-detuned interaction among three-state atoms, dual-

cavity and a classical pulse. In particular, a class of W states that can be used for perfect teleportation and superdense coding is generated by only one step. On account of no transformation of quantum information between the atoms and the cavity, the schemes are inherently robust to some decoherence processes including cavity decay and atomic spontaneous emission, which allow that the quality of the cavity is greatly reduced and efficient decoherence time is greatly prolonged.

References

[1] DiVincenzo D P 1995 *Phys. Rev.* A **51** 1015

[2] Kaler F S, Häffner H, Riebe M, Gulde S, Lancaster G P T, Deuschle T, Becher C, Roos C F, Eschner J and Blatt R 2003 *Nature* **422** 408

[3] Jones J A, Mosca M and Hansen R H 1998 *Nature* **393** 344

[4] Gershenfeld N A and Chuang I L 1997 *Seience* **275** 350

[5] Sleator T and Weinfurter H 1995 *Phys. Rev. Lett.* **74** 4087

[6] Zheng S B and Guo G C 2000 *Phys. Rev. Lett.* **85** 2392

[7] Osnaghi S, Bertet P, Auffeves A, Maioli P, Brune M, Raimond J M and Haroche S 2001 *Phys. Rev. Lett.* **87** 037902

[8] Kafatos M 1989 *Bell's Theorem, Quantum Theory and Conceptions of the Universe* (London: Kluwer Academic Publishers)

[9] Greenberger D M, Horne M A, Shimony A and Zeilinger A 1990 *Am. J. Phys.* **58** 1131

[10] Bennett C H, Brassard G, Crepeau C, Jozsa R, Peres A and Wootters W 1993 *Phys. Rev. Lett.* **70** 1895

[11] Deutsch D and Jozsa R 1992 *Proc. R. Soc. London* Ser. A **439** 553

[12] Ekert A K 1991 *Phys. Rev. Lett.* **67** 661

[13] Piani M and Watrous J 2009 *Phys. Rev. Lett.* **102** 250501

[14] Cirac J I, Ekert A E, Huelga S F and Macchiavello C 1999 *Phys. Rev.* A **59** 4249

[15] Bose S, Vedral V and Knight P L 1998 *Phys. Rev.* A **57** 822

[16] Hillery M, Bužek V and Berthiaume A 1999 *Phys. Rev.* A **59** 1829

[17] Chen Y A, Zhang A N, Zhao Z, Zhou X Q, Lu C Y, Peng C Z, Yang T and Pan J W 2005 *Phys. Rev. Lett.* **95** 200502

[18] Yu X M, Gu Y J, Ma L Z and Zhou B A 2008 *Chin. Phys.* B **17** 462

[19] James D F and Jerke J 2007 *Can. J. Phys.* **85** 625

[20] James D F V 2000 *Fortschr. Phys.* **48** 823

[21] Zou X B, Xiao Y F, Li S B, Yang Yong and Guo G C 2007 *Phys. Rev.* A **75** 064301

[22] Xiao Y F, Zou X B and Guo G C 2007 *Phys. Rev.* A **75** 012310

[23] Lin G W, Zou X B, Ye M Y, Lin X M and Guo G C 2008 *Phys. Rev.* A **77** 032308

[24] Agrawal P and Pati A 2006 *Phys. Rev.* A **74** 062320

[25] Steck D A http://steck.us/alkalidata/

[26] Wallraff A, Schuster D I, Blais A, Frunzio L, Huang R S, Majer J, Kumar S, Girvin S M and Schoelkopf R J 2004 *Nature* **431** 162

[27] Painter O, Lee R K, Scherer A, Yariv A, O'Brien J D, Dapkus P D and Kim I 1999 *Science* **284** 1819

[28] Noda S, Chutinan A and Imada M 2000 *Nature* **407** 608

[29] Blais A, Huang R H, Wallraff A, Girvin S M and Schoelkopf R J 2004 *Phys. Rev.* A **69** 062320

[30] Vion D, Aassime A, Cottet A, Joyez P, Pothier H, Urbina C, Esteve D and Devoret M H 2002 *Science* **296** 886

[31] Noda S, Fujita M and Asano T 2007 *Nat. Photon.* **1** 449

[32] Yoshie T, Scherer A, Hendrickson J, Khitrova G, Gibbs H M, Rupper G, Ell C, Shchekin O B and Deppe D G 2004 *Nature* **432** 200

[33] Gibbs G, Kira H M, Koch M and Scherer S W 2006 *Nat. Phys.* **2** 81

[34] Deng Z J, Feng M and Gao K L 2006 *Phys. Rev.* A **73** 014302