Conditional quantum phase gate using distant atoms and linear optics

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A scheme is proposed to implement a conditional quantum phase gate between atoms trapped in spatially separated cavities. Instead of direct interaction between atoms, quantum interference of polarized photons decayed from the optical cavities is used to realize the desired quantum operation between two distant atoms. The scheme requires a twofold coincidence detection, and is insensitive to the imperfection of the photon detectors.

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The manipulation and control of many distant atoms is an important challenge for implementation of quantum communication and computation [1]. Recently, several physical systems have been suggested as possible candidates for engineering quantum entanglement: cavity QED systems [2], trapped ion systems [3], quantum dot systems [4], and Josephson-junction device systems [5]. Among them, cavity QED systems are given more attention. This is due to the fact that cold and localized atoms are well suited for storing quantum information in long-lived internal states, and the photons are natural sources of fast and reliable transport of quantum information over a long distance. A number of schemes have been proposed for manipulating quantum entanglement between atoms and cavity fields [6,7]. In particular, entangled states of two or three particles have been demonstrated experimentally in high-Q cavities [8,9]. Schemes of this type are based on controlling direct or indirect interaction between the atoms, which are intended to be entangled. Since most of these schemes require a high-Q cavity field, decoherence caused by cavity decay can be neglected.

On the other hand, conditional measurements offer another possible way to engineer quantum entanglement and implement quantum information processing. In Ref. [10], Cabrillo *et al.* proposed a scheme to entangle quantum states of spatial, widely separated atoms by weak laser pulses and the detection of the subsequent spontaneous emission. Further, several schemes have also been proposed for generating the electron paramagnetic resonance (EPR) state between two distant atoms trapped in different optical cavities [11,12]. In Ref. [13], schemes were also proposed for generating quantum entanglement of many distant atoms. In Ref. [14], Protsenko *et al.* proposed a scheme for conditional implementation of a quantum controlled-NOT gate between two distant atoms by the detection of scattered photon. One disadvantage of this scheme requires a photon detector to distinguish zero photon, one photon, and more than one photon, so that the inefficiency of photon detector influences the fidelity of the quantum operations. Another disadvantage of the scheme is to require that the laser pulses have to be sufficiently weak to ensure that the probability of exciting both atoms is much smaller than the probability of exciting only one atom. For such a case, it will be a time-consuming task to detect scattered photons.

In this paper, we propose a scheme to implement a conditional quantum phase gate with two distant atoms trapped in different optical cavities by using two-photon coincidence detection. The protocol has the following favorable features: (1) The scheme is insensitive to the imperfection of the photon detectors, i.e., the scheme does not require distinguishing among zero, one, and two photons. (2) The scheme is insensitive to the phase accumulated by the photons on their way from the cavities to the place where they are detected. (3) The scheme does not need the weakly driven laser pulses as both atoms are excited simultaneously.

The schematic representation of the scheme for the conditional quantum phase gate is shown in Fig. 1, which consists of two identical atoms 1 and 2 confined separately in two optical cavities 1 and 2, respectively. The photons leaking out from cavities 1 and 2 are interfered with by a polarization beam splitter (PBS), with the outputs detected by four photon detectors after two half wave plates (HWPs) and two polarization beam splitters. For the photons decaying from

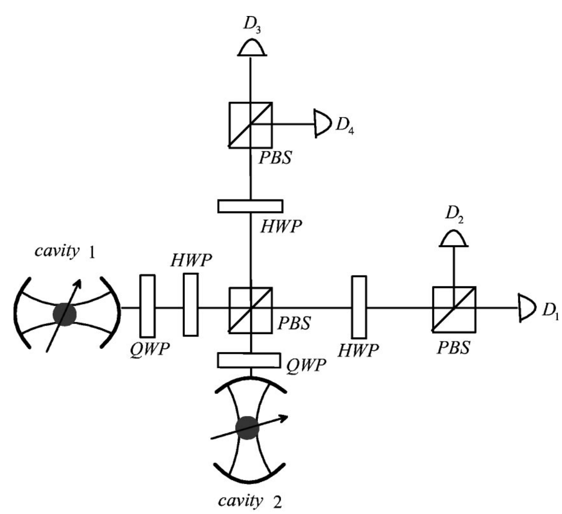

FIG. 1. Schematic setup for the conditional quantum phase gate of two distant atoms trapped in different optical cavities, which includes three polarization beam splitters (PBSs), which transmit the horizontal polarization and reflect vertical polarization, and two quarter wave plates (QWPs), which are used to map the left-circular photons (right-circular photons) out of the cavity on the horizontal polarization photons (vertical polarization photons), three half wave plates (HWPs), which implement transformation $|H\rangle \rightarrow (|H\rangle + |V\rangle)/\sqrt{2}$, $|V\rangle \rightarrow (|H\rangle - |V\rangle)/\sqrt{2}$, and four photon detectors.

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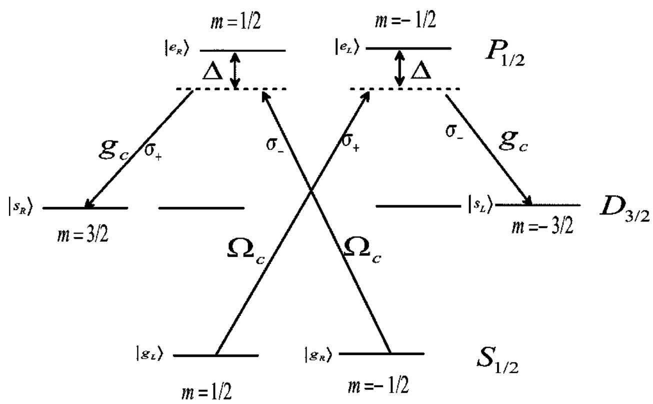

FIG. 2. The relevant level structure with ground state $|g_L\rangle$, $|s_L\rangle$, $|g_R\rangle$, $|s_R\rangle$ and excited states $|e_L\rangle$, $|e_R\rangle$. The transitions $|e_L\rangle \to |g_L\rangle$ and $|e_R\rangle \to |g_R\rangle$ are coupled by the classical lasers and the transitions $|e_L\rangle \to |s_L\rangle$ and $|e_R\rangle \to |s_R\rangle$ are coupled to two degenerate cavity modes with different polarization.

cavity 1, a quarter wave plate (QWP) and a half wave plate are inserted before the first polarization beam splitter. For the photons decaying from cavity 2, a quarter wave plate is inserted before the first polarization beam splitter. Two QWPs are used to map the left-circular photons (right-circular photons) out of the cavity on the horizontal polarization photons (vertical polarization photons). The level structure of the atom is shown in Fig. 2, which is a λλ configuration. Such an atomic level structure has been proposed to implement quantum computation in a single cavity [15], and generate entangled single-photon wave packets [16]. For concreteness, we consider a possible implementation using $^{40}Ca^+$, whose usefulness in the quantum information context has been demonstrated in recent experiments [17,18]. The ground states $|g_L\rangle$, $|g_R\rangle$ correspond to $|F=1/2, m=1/2\rangle$ and $|F=1/2, m=-1/2\rangle$ of $4^2S_{1/2}$, respectively. The excited states $|e_L\rangle$, $|e_R\rangle$ correspond to $|F=1/2, m=-1/2\rangle$ and $|F=1/2, m=1/2\rangle$ of $4^2P_{1/2}$, respectively. Further, one could use $|F=3/2, m=3/2\rangle$ and $|F=3/2, m=-3/2\rangle$ of $3^2D_{3/2}$ as the states $|s_R\rangle$ and $|s_L\rangle$, respectively. The lifetime of the atomic levels $|g_L\rangle$, $|g_R\rangle$, $|s_L\rangle$, $|s_R\rangle$ is comparatively long so that spontaneous decay of these states can be neglected. We encode the ground states $|g_L\rangle$ and $|g_R\rangle$ as logic zero and one states, i.e., $|g_L\rangle = |0\rangle$ and $|g_R\rangle = |1\rangle$. The transition $|s_L\rangle \Leftrightarrow |e_L\rangle$ ($|s_R\rangle \Leftrightarrow |e_R\rangle$) is coupled to cavity mode a_L (a_R) with the left-circular (right-circular) polarization. The transition $|e_L\rangle \Leftrightarrow |g_L\rangle$ ($|e_R\rangle \Leftrightarrow |g_R\rangle$) is driven by classical fields with left-circular (right-circular) polarization. We assume that the classical laser fields and the cavity fields are detuned from their respective transitions by the same amount Δ. In the case of large detuning, the excited states can be eliminated adiabatically to obtain the effective interaction Hamiltonian (in the interaction picture)

$$H_j = \Omega(a_{jL}|g_L\rangle_{jj}\langle s_L| + a_{jL}^\dagger|s_L\rangle_{jj}\langle g_L| + a_{jR}|g_R\rangle_{jj}\langle s_R| + a_{jR}^\dagger|s_R\rangle_{jj}\langle g_R|), \qquad (1)$$

where a_{jL} and a_{jR} ($a_{jL}^\dagger$ and $a_{jR}^\dagger$) are the annihilation (creation) operators of the left-circular and right-circular polarization modes of the jth cavity. $\Omega = g_c\Omega_c/\Delta$ denotes the effective coupling constant. Here g_c (Ω_c) is the interaction strength of the atom coupled to their cavity fields (classical fields), which is assumed to be the same. In Ref. [16], Gheri *et al.* have considered the interaction Hamiltonian (1) for entanglement engineering of one-photon wave packets.

In order to investigate the quantum dynamics of the system, it is convenient to follow a quantum trajectory description [19]. The evolution of the system's wave function is governed by a non-Hermitian Hamiltonian

$$H_j' = H_j - i\kappa(a_{jL}^\dagger a_{jL} + a_{jR}^\dagger a_{jR}) \qquad (2)$$

as long as no photon decays from the cavity. Here we assume that two optical cavities have the same loss rate κ for all the modes. If a photon detector D_j ($j=1,2,3,4$) detects a photon, the coherent evolution according to H_j' is interrupted by a quantum jump. This corresponds to a quantum jump, which can be formulated with the operators b_j on the joint state vectors of two atom-cavity systems

$$b_1 = \frac{1}{2}(a_{1L} + a_{1R}) + \frac{1}{\sqrt{2}}a_{2R}, \quad b_2 = \frac{1}{2}(a_{1L} + a_{1R}) - \frac{1}{\sqrt{2}}a_{2R}$$
$$b_3 = \frac{1}{2}(a_{1L} - a_{1R}) + \frac{1}{\sqrt{2}}a_{2L}, \quad b_4 = -\frac{1}{2}(a_{1L} - a_{1R}) + \frac{1}{\sqrt{2}}a_{2L}. \qquad (3)$$

In the following equation, we analyze the scheme in detail. In order to demonstrate the conditional implementation of quantum phase gate, we assume that atoms, trapped in the jth ($j=1,2$) optical cavity, are initially prepared in the state

$$\alpha_j|g_L\rangle_j + \beta_j|g_R\rangle_j, \qquad (4)$$

and both polarization modes of the optical cavity are prepared in the vacuum states $|0,0\rangle_j$, where $|m,n\rangle_j$ denotes m photons in the left-circular polarization mode and n photons in the right-circular polarization mode. Now we switch on the Hamiltonian (1) in each atom-cavity system for a time τ. If no photon is emitted from the cavity, the jth atom-cavity system is governed by the interaction H_j'. In this case the atom-cavity state evolves to the entangled state

$$|\Psi\rangle_j = \alpha_j[a|g_L\rangle_j|0,0\rangle_j - ib|s_L\rangle_j|1,0\rangle_j] + \beta_j[a|g_R\rangle_j|0,0\rangle_j - ib|s_R\rangle_j|0,1\rangle_j], \qquad (5)$$

with

$$a = \frac{\cos(\Omega_\kappa\tau) - \dfrac{\sin(\Omega_\kappa\tau)\kappa}{2\Omega_\kappa}}{\sqrt{\left[\cos(\Omega_\kappa\tau) - \dfrac{\sin(\Omega_\kappa\tau)\kappa}{2\Omega_\kappa}\right]^2 + \dfrac{\sin^2(\Omega_\kappa\tau)\Omega^2}{\Omega_\kappa^2}}},$$

$$b = \frac{\sin(\Omega_\kappa\tau)\Omega}{\Omega_\kappa\sqrt{\left[\cos(\Omega_\kappa\tau) - \dfrac{\sin(\Omega_\kappa\tau)\kappa}{2\Omega_\kappa}\right]^2 + \dfrac{\sin^2(\Omega_\kappa\tau)\Omega^2}{\Omega_\kappa^2}}}$$

$$\Omega_\kappa = \sqrt{\Omega^2 - \kappa^2/4}. \tag{6}$$

The probability that no photon is emitted during this evolution becomes

$$P_{single} = e^{-\kappa\tau}\left\{\left[\cos(\Omega_\kappa\tau) - \frac{\sin(\Omega_\kappa\tau)\kappa}{2\Omega_\kappa}\right]^2 + \frac{\sin^2(\Omega_\kappa\tau)\Omega^2}{\Omega_\kappa^2}\right\}. \tag{7}$$

If the interaction time τ is chosen to satisfy $\tan(\Omega_\kappa\tau) = \kappa/2\Omega_\kappa$, Eq. (5) becomes

$$|\Psi\rangle_j = \alpha_j|s_L\rangle_j|1,0\rangle_j + \beta_j|s_R\rangle_j|0,1\rangle_j \tag{8}$$

and the corresponding success probability Eq. (7) becomes

$$P_{single} = e^{-\kappa\tau}\sin^2(\Omega_\kappa\tau)\Omega^2/\Omega_\kappa^2. \tag{9}$$

During this stage, we assume that the interaction Hamiltonian (1) is applied to each atom-cavity system simultaneously, so that the atom-cavity state $|\Psi\rangle_j$ ends at the same time. This implements the first step of the protocol. The probability that this stage is a success is the probability that no photon decays from either atom-cavity system during the preparation. This quantity is given by $P_{prep}=P_{single}^2$.

Next we consider the second step of the scheme, in which we make a photon number measurement with four photon detectors D_j $(j=1,2,3,4)$ on the output modes of the setup. In this step, the joint state of two atom-cavity systems becomes prepared in the form

$$|\Phi(0)\rangle = |\Psi\rangle_1 \otimes |\Psi\rangle_2, \tag{10}$$

where the state $|\Psi\rangle_j$ is given by Eq. (8). We assume that photons are detected at the time t. This assumption is posed to calculate the system's time evolution during this time interval in a consistent way with the "no-photon-emission-Hamiltonian" (2). The joint state of the total system evolves into

$$|\Phi(t)\rangle = |\Psi(t)\rangle_1 \otimes |\Psi(t)\rangle_2 \tag{11}$$

with

$$|\Psi(t)\rangle_j = \alpha_j e^{-\kappa t}|s_L\rangle_j|1,0\rangle_j + \beta_j e^{-\kappa t}|s_R\rangle_j|0,1\rangle_j. \tag{12}$$

The detection of one photon with the detector D_j corresponds to a quantum jump, which can be formulated with the operator b_j on the joint state $|\Phi(t)\rangle$. If D_1 and D_3 detect one photon at nearly the same time and D_2 and D_4 do not detect any photon, or vice versa, the state of the total system is projected into

$$\alpha_1\alpha_2|s_L\rangle_1|s_L\rangle_2 + \beta_1\alpha_2|s_R\rangle_1|s_L\rangle_2 + \alpha_1\beta_2|s_L\rangle_1|s_R\rangle_2 - \beta_1\beta_2|s_R\rangle_1|s_R\rangle_2. \tag{13}$$

If D_1 and D_4 detect one photon at nearly the same time and D_2 and D_3 do not detect any photons during that time interval, or vice versa, the state of the total system becomes projected into

$$\alpha_1\alpha_2|s_L\rangle_1|s_L\rangle_2 + \beta_1\alpha_2|s_R\rangle_1|s_L\rangle_2 - \alpha_1\beta_2|s_L\rangle_1|s_R\rangle_2 + \beta_1\beta_2|s_R\rangle_1|s_R\rangle_2. \tag{14}$$

The success probability of conditional generation of Eqs. (13) and (14) is $P_{meas}=(1-e^{-2\kappa t})^2/2$. Based on the result of the measurement, we can apply fast Raman transitions to individually manipulate atoms 1 and 2, and map the states of Eq. (13) or (14) to the state

$$\alpha_1\alpha_2|g_L\rangle_1|g_L\rangle_2 + \beta_1\alpha_2|g_R\rangle_1|g_L\rangle_2 + \alpha_1\beta_2|g_L\rangle_1|g_R\rangle_2 - \beta_1\beta_2|g_R\rangle_1|g_R\rangle_2, \tag{15}$$

which demonstrates the conditional implementation of the quantum controlled phase gate

$$|g_L\rangle|g_L\rangle \to |g_L\rangle|g_L\rangle, \quad |g_L\rangle|g_R\rangle \to |g_L\rangle|g_R\rangle,$$
$$|g_R\rangle|g_L\rangle \to |g_R\rangle|g_L\rangle, \quad |g_R\rangle|g_R\rangle \to -|g_R\rangle|g_R\rangle. \tag{16}$$

The total probability of success of the protocol is given by $P_{succ}=P_{prep}P_{meas}=(1-e^{-2\kappa t})^2 e^{-2\kappa\tau}\sin^4(\Omega_\kappa\tau)\Omega^4/2\Omega_\kappa^4$. In order to make the success probability as large as possible, the coupling parameters g_c, Ω_c and detuning Δ have to be adjusted to satisfy the condition $\Omega=g_c\Omega_c/\Delta \gg \kappa$, i.e., $\Omega_\kappa \gg \kappa$. This corresponds to the requirement of the strong coupling cavity QED and the high-quality cavity. In the cavity QED experiment using ^{40}Ca [18], the parameters $g_c=0.92$ MHz and $\kappa=1.2$ MHz have been reported, which cannot satisfy the condition of the scheme. Thus to satisfy the requirement of the scheme, experimental setup needs to be further improved. In the cavity QED, parameters g_c and κ are fixed by the hardware of the system, which can be modified through the length L and finesses F of the cavity [18]: $g_c \sim L^{-3/4}$ and $\kappa \sim (FL)^{-1}$. If we can increase the cavity finesse of Ref. [18] by 2 orders of magnitude and decrease the length of the cavity to about 2 mm, we have the parameters $g_c \approx 2.6$ MHz and $\kappa \approx 0.048$ MHz, which satisfy the requirement of the scheme. If we choose $\Omega_c=2.6$ MHz, $\Delta=6.76$ Hz, and $t=50\nu$s, we find the success probability of the scheme is about 0.48. This is a little lower than the ideal success probability of 0.5 because the preparation stage has an extremely small chance of failure.

We now give a brief discussion on the influence of practical noise on the scheme. First, it is evident that the scheme is inherently robust to photon loss, which includes the contribution from channel attenuation, and the inefficiency of the photon detectors. All of these kinds of noise can be considered by an overall photon loss probability η [11]. It is noticed that the present scheme is based on the two-photon coincidence detection. If one photon is lost, a click from each of the detectors is never recorded. In this case, the scheme fails to generate the expected quantum operation. Therefore the photon loss only decreases the success probability P_{succ} by a factor of $(1-\eta)^2$, but has no influence on the fidelity of the expected operation. We now consider the influence of the dark count of the photon detectors on the scheme. The dark count is another imperfection of photon detector, i.e., the photon detector fires, although no light is incident upon it. Let P_D denote the dark count probability of each detector, i.e., the probability of the detector's firing in the absence of the real signal. For simplicity we only consider the events: D_1 and D_3 to detect the photon at the same time. Considering the dark count of the photon detectors, Eq. (13) becomes

$$\rho_D = \frac{1}{1 + P_D^2 + 4P_D}|\Psi_0\rangle\langle\Psi_0|(1 + P_D^2) + 2P_D|\Psi_1\rangle\langle\Psi_1| + 2P_D|\Psi_3\rangle\langle\Psi_3| + 2P_D|\Psi_4\rangle\langle\Psi_4|, \qquad (17)$$

where $|\Psi_0\rangle$ and $|\Psi_1\rangle$ are given by Eqs. (13) and (14), and $|\Psi_3\rangle=(\alpha_1|g\rangle_1+\beta_1|s\rangle_1)\beta_2|s\rangle_2$ and $|\Psi_4\rangle=(\alpha_1|g\rangle_1 - \beta_1|s\rangle_1)\alpha_2|g\rangle_2$. In order to quantify how close the state (17) comes to the state (13), we calculate the fidelity

$$F = \langle\Psi_0|\rho_D|\Psi_0\rangle = \frac{1 + P_D^2 + 2P_D(|\alpha_1| - |\beta_1|)^2 + 2P_D(|\alpha_2| - |\beta_2|)^2}{1 + p_D^2 + 4P_D}, \qquad (18)$$

which is dependent on the input states. If $P_D < 0.001$, the quantum operation can be implemented with the high fidelity ($F > 0.99$). Next we show that the scheme is insensitive to the phase accumulated by the photons on their way from the ions to the place where they are detected. The phases $\varphi_1 = kL_1$ and $\varphi_2 = kL_2$, where k is the wave number and L_j are the optical lengths whose photons travel from the jth ions toward the photon detectors, lead only to a multiplicative factor $e^{i(\varphi_1+\varphi_2)}$ in Eqs. (13) and (14). This result demonstrates that phases accumulated by the photons have no effect on the conditional implementation of the quantum operation. Third, the influence of atomic recoil on the implementation of the quantum phase gate could be suppressed. When an atom absorbs or emits photons, it is always accompanied by a recoil. In our scheme, both atoms absorb and emit photons with the same energy simultaneously. If one detects two photons at the same time, the influence of the atomic recoil on the scheme can thus be suppressed. Finally, it is noted that we should choose a sufficiently large detuning of optical frequencies from the atomic transition connecting the excited levels, so that excited states can be decoupled from the evolution and the scheme is immune to the effect of atomic spontaneous emission [11].

In summary, a scheme has been proposed to implement the conditional quantum phase gate for two distant atoms trapped in different optical cavities by combining cavity QED and linear optical elements. Instead of direct interaction between atoms, quantum interference of polarized photons decaying from the optical cavities is used to create the desired quantum operation between two distant atoms. The scheme requires a twofold coincidence detection, and is insensitive to the imperfection of the photon detectors which have no influence on the fidelity of the conditional quantum operation, but decrease the success probability P_{succ} by a factor of $(1-\eta)^2$.

One possible application of the present scheme is to create quantum entanglement between many distant atoms trapped in different optical cavities. Recently, researchers have focused their interest on characterizing and generating multipartite entanglement, and used it for more general and useful applications [20]. For example, by employing the quantum logic networks proposed in Ref. [21], we can apply the present scheme to conditionally generate any quantum state of many distant atoms [22].

Finally we should mention an experimental problem of the simultaneous detection of photons out of the cavities. This requirement is also met in Refs. [11–13]. These schemes require quantum interference from independent photon resources. In the experiment, one has to impose a finite time interval to define two counts as coincident detection. In Ref. [23], theoretical works have been done on quantum interference and correlation from independent photon resources. If we assume that $\Delta\omega$ is the bandwidth of the photon wave packets decayed from cavities, to obtain the two-photon coincidence detection, the time interval Δt between two clicks on two detectors should satisfy the condition $\Delta t < 1/\Delta\omega$. Otherwise, we fail to implement the scheme, and should repeat the process again until we find two-photon coincidence detection. The influence of the experimental parameters on the photon wave packet decayed from the cavity needs to be studied further.

[1] P. Shor, *Proceeding of the 35th Annual Symposium on the Foundation of Computer Science* (IEEE Computer Society Press, Los Alomitos, CA, 1994), pp. 124–134; Lov K. Grover, Phys. Rev. Lett. **80**, 4329 (1998); A. Einstein, B. Podolsky, and N. Rosen, Phys. Rev. **47**, 777 (1935); J. S. Bell, Physics (Long Island City, N.Y.) **1**, 195 (1965); A. K. Ekert, Phys. Rev. Lett. **67**, 661 (1991); C. H. Bennett and S. J. Wiesner, *ibid.* **69**, 2881 (1992); C. H. Bennett, G. Brassard, C. Crepeau, R. Jozsa, A. Peres, and W. K. Wootters, *ibid.* **70**, 1895 (1993).

[2] Q. A. Turchette, C. J. Hood, W. Lange, H. Mabuchi, and H. J. Kimble, Phys. Rev. Lett. **75**, 4710 (1995).

[3] C. Monroe, D. M. Meekhof, B. E. King, W. M. Itano, and D. J. Wineland, Phys. Rev. Lett. **75**, 4714 (1995); J. I. Cirac and P. Zoller, *ibid.* **74**, 4091 (1995).

[4] D. Loss and D. P. DiVincenzo, Phys. Rev. A **57**, 120 (1998).

[5] Y. Makhlin and G. Schon, Nature (London) **398**, 305 (1999).

[6] J. M. Raimond *et al.*, Rev. Mod. Phys. **73**, 565 (2001).

[7] J. I. Cirac and P. Zoller, Phys. Rev. A **50**, R2799 (1994); C. C. Gerry, *ibid.* **53**, 2857 (1996); W. Lange and H. J. Kimble, *ibid.* **61**, 063817 (2000).

[8] E. Hagley, X. Maître, G. Nogues, C. Wunderlich, M. Brune, J. M. Raimond, and S. Haroche, Phys. Rev. Lett. **79**, 1 (1997).

[9] A. Rauschenbeutel *et al.*, Science **288**, 2024 (2000).

[10] C. Cabrillo, J. I. Cirac, P. Garcia-Fernandez, and P. Zoller, Phys. Rev. A **59**, 1025 (1999).

[11] S. Bose, P. L. Knight, M. B. Plenio, and V. Vedral, Phys. Rev. Lett. **83**, 5158 (1999).

[12] X. L. Feng *et al.*, Phys. Rev. Lett. **90**, 217902 (2003); L. M. Duan and H. J. Kimble, *ibid.* **90**, 253601 (2003); D. E. Browne, M. B. Plenio, and S. F. Huelga, *ibid.* **91**, 067901 (2003); C. Simon and W. T. M. Irvine, *ibid.* **91**, 110405 (2003).

[13] X. B. Zou, K. Pahlke, and W. Mathis, Phys. Rev. A **68**, 024302 (2003); C. D. Fidio and W. Vogel, J. Opt. Soc. Am. B

5, 105 (2003).

[14] I. E. Protsenko, G. Reymond, N. Schlosser, and P. Grangier, Phys. Rev. A **66**, 062306 (2002).

[15] T. Pellizzari, S. A. Gardiner, J. I. Cirac, and P. Zoller, Phys. Rev. Lett. **75**, 3788 (1995).

[16] K. M. Gheri, C. Saavedra, P. Törmä, J. I. Cirac, and P. Zoller, Phys. Rev. A **58**, R2627 (1998) C. Saavedra, K. M. Gheri, P. Törmä, J. I. Cirac, and P. Zoller, *ibid.* **61**, 062311 (2000).

[17] F. Schmidt-Kaler *et al.*, Nature (London) **422**, 408 (2003); Ch. Roos *et al.*, Phys. Rev. Lett. **83**, 4713 (1999); F. Schmidt-Kaler *et al.*, J. Phys. B **36**, 623 (2003); B. Mundt *et al.*, Phys. Rev. Lett. **89**, 103001 (2002).

[18] M. Keller *et al.*, Nature (London) **431**, 1075 (2004); New J. Phys. **6**, 95 (2004).

[19] M. B. Plenio and P. L. Knight, Rev. Mod. Phys. **70**, 101 (1998).

[20] D. M. Greenberger, M. Horne, A. Shimony, and A. Zeilinger, Am. J. Phys. **58**, 1131 (1990); W. Dur, G. Vidal, and J. I. Cirac, Phys. Rev. A **62**, 062314 (2000).

[21] M. Sasura and V. Buzek, Phys. Rev. A **64**, 012305 (2001).

[22] H. J. Briegel and R. Raussendorf, Phys. Rev. Lett. **86**, 910 (2001).

[23] M. Zukowski *et al.*, Phys. Rev. Lett. **71**, 4287 (1993); S. L. Braunstein and A. Mann, Phys. Rev. A **51**, R1727 (1995).