Generation of a 4-qubit cluster of entangled coherent states in bimodal QED cavities

E M Becerra-Castro, W B Cardoso, A T Avelar and B Baseia

Instituto de Física, Universidade Federal de Goiás, 74.001-970, Goiânia (GO), Brazil
E-mail: wesleybcardoso@gmail.com and avelar@if.ufg.br

Received 31 October 2007, in final form 4 February 2008
Published 7 April 2008
Online at stacks.iop.org/JPhysB/41/085505

Abstract

We propose a scheme to generate a 4-qubit cluster of entangled coherent states in bimodal QED cavities. The scheme employs a single two-level atom that interacts dispersively with cavity modes initially prepared in coherent states. The fidelity and success probability of the state preparation are obtained considering the influence of atomic velocity spread and atomic efficiency detection. The scheme is also generalized for higher order cluster states.

1. Introduction

Entanglement is the most fantastic phenomenon of quantum mechanics and plays a fundamental role as resource for many advanced applications in quantum information processes such as quantum cryptography [1], quantum dense coding [2], quantum teleportation [3] and one-way quantum computation [4, 5]. There are various kinds of entangled states depending on the number of involved parties and of the entanglement ‘structure’, e.g., for bipartite entanglements there is only one example, the EPR state [6]; for 3-partite there are two kinds of entangled states, the GHZ [7] and W [8] states; for 4-partite, more interesting is the 4-qubit cluster state whose correlations cannot be described in terms of the local realism as experimentally demonstrated in [9]. In fact, this state is not biseparable and has a genuine 4-qubit entanglement.

According to applications of cluster states in universal quantum computation, schemes for their generation in a QED cavity have been presented [14–18]. In [14], Zou and Mathis proposed a scheme to generate cluster states of four distant atoms that are trapped separately in leaky cavities. They have also studied two additional schemes to generate the cluster states in the context of QED cavity using resonant atom–field interaction [15]. In [16], Blythe and Varcoe proposed a scalable one-way quantum computer using elements of microwave cavity QED. In this scheme, quantized light fields in miniaturized superconducting re-entrant microwave cavities on a millimetre scale are used to mediate atom–atom interactions, turning the atomic beam into a continuous entanglement resource to create atomic cluster states. As argued by the authors, the main advantages of this proposal are the low experimental overhead and the high degree of integration that can be achieved. In addition, all of the required components of such a system have been previously demonstrated.

Recently, some experimental realizations of 4-qubits cluster states have been achieved in optical systems: Walther et al [11] have prepared 4-qubit cluster states encoded into the polarization state of four photons and have implemented Glover’s search algorithm, which constituted an experimental proof of one-way quantum computing; Kielsen et al [12] have prepared a 4-qubit entangled cluster state in the polarization degree of freedom of photons to investigate its persistency; and Tame et al [13] reported the first experimental demonstration of an all-optical one-way implementation of Deutsch’s quantum algorithm on a 4-qubit cluster state.

Based on applications of cluster states in universal quantum computation, schemes for their generation in a QED cavity have been presented [14–18]. In [14], Zou and Mathis proposed a scheme to generate cluster states of four distant atoms that are trapped separately in leaky cavities. They have also studied two additional schemes to generate the cluster states in the context of QED cavity using resonant atom–field interaction [15]. In [16], Blythe and Varcoe proposed a scalable one-way quantum computer using elements of microwave cavity QED. In this scheme, quantized light fields in miniaturized superconducting re-entrant microwave cavities on a millimetre scale are used to mediate atom–atom interactions, turning the atomic beam into a continuous entanglement resource to create atomic cluster states. As argued by the authors, the main advantages of this proposal are the low experimental overhead and the high degree of integration that can be achieved. In addition, all of the required components of such a system have been previously demonstrated.
Although the cluster states have been conceived in finite discrete systems, recently Munhoz et al. [17] have proposed a generalization of 4-qubit cluster states for infinite-dimensional continuous variable systems by using coherent state encoding. They define the linear 4-qubit cluster-type entangled coherent states as

$$|\text{CLUSTER}_4^\alpha\rangle = \frac{1}{\sqrt{2}}(|\alpha, \alpha, \alpha, \alpha\rangle + |\alpha, \alpha, -\alpha, -\alpha\rangle) + \frac{1}{\sqrt{2}}(|-\alpha, -\alpha, \alpha, -\alpha\rangle - |-\alpha, -\alpha, -\alpha, \alpha\rangle).$$

It is interesting to note that the states (2) and (3) have the same properties since the overlap $|\langle \alpha | -\alpha \rangle|$ can be neglected for $\alpha \geq 2$. The authors also proposed its generation using five QED cavities, two Ramsey zones, a pair of two-level Rydberg atoms, an external classical field plus atomic ionization detectors. Additionally, Zhou, Yang and Dai [18] have proposed a scheme to produce coherent cluster states similar to the scheme of [15] employing dispersive interaction instead of resonant interaction. In view of the interesting idea in [17] and its potential applications, in this paper we will present an alternative and simplified scheme in the same QED cavity context for the generation of linear 4-qubit cluster-type entangled coherent states. Our scheme employs a pair of QED bimodal cavities, a single two-level (Rydberg) atom and only dispersive atom–field interaction. This paper concerns the creation of clusters of field modes inside cavities, instead of cluster of atomic energy levels, as considered in [16]. The simplicity of our scheme makes it attractive experimentally due to its feasibility in the present status of QED technology [19, 20].

### 2. Experimental setup

This proposal requires the experimental setup shown in figure 1. The source $S$ ejects rubidium atoms which are velocity selected and prepared in the circular Rydberg state, one at a time, by appropriated laser beams in the box $B$. The relevant atomic levels $|g\rangle$ and $|e\rangle$, with the principal quantum numbers 50 and 51, produce the atomic transition of 51.1 GHz. $R_1$, $R_2$ and $R_3$ stand for Ramsey zones which can perform a resonant π/2 pulse on the $e \rightarrow g$ transition. The two bimodal high-$Q$ superconducting cavities $C_1$ and $C_2$ are Fabry–Perot resonators made of two spherical niobium mirrors with two orthogonally polarized TEM00 modes separated by 1.2 MHz having the same Gaussian geometry (waist $w = 6$ mm), and photon damping times of 130 ms [20]. $D_1$ and $D_2$ are atomic detectors. These cavities are prepared at low temperature ($T \approx 0.6$ K) to reduce the average number of thermal photons; before starting the experiment the thermal field is erased [21].

To generate the cluster states in the four modes of the two bimodal cavities we need to make two operations: (i) the first one occurs when the atom crosses the Ramsey zones $R_1$, $R_2$ and $R_3$ and interacts with the classical fields resonant to the atomic transition between the states $|e\rangle$ and $|g\rangle$, with intensities adjusted to produce a π/2 rotation in the atomic state, i.e.,

$$|e\rangle \rightarrow (|g\rangle + |e\rangle)/\sqrt{2};$$

$$|g\rangle \rightarrow (|g\rangle - |e\rangle)/\sqrt{2};$$

(ii) the second operation occurs in $C_1$ and $C_2$ and involves dispersive atom–field interactions with their (selected) cavity modes, one at a time, in such a way that the atom crossing the cavity in the excited (ground) state $|e\rangle$ ($|g\rangle$) produces a negative (positive) phase shift in the desired mode state. The dispersive interaction is described by the effective atom–field Hamiltonian [19],

$$H_{ef} = g_\beta^2 \frac{\delta_\beta}{\delta_\beta^2} \left( \hat{a}_\beta^\dagger \hat{a}_\beta + 1 \right) |e\rangle\langle e| - \hat{a}_\beta^\dagger \hat{a}_\beta |g\rangle\langle g|,$$

where $\hat{a}_\beta$ ($\hat{a}_\beta^\dagger$) is the boson annihilation (creation) operator for mode $\beta$, with $\beta = A, B$ for the cavity $C_1$; the same is valid for the cavity $C_2$ with $\beta = C, D$; $|e\rangle$ and $|g\rangle$ are the atom-projectors, $g_\beta$ stands for the vacuum Rabi coupling with mode $\beta$ and $\delta_\beta$ is the detuning between atomic transition and the mode $\beta$. Although the cavity has two modes, the frequency splitting of 1.2 MHz between them ensures the atom being efficiently coupled only to a single mode [20]. Then, using the Stark effect we choose the detuning with the mode $\beta$ which will interact in dispersive regime, i.e., $g_\beta^2/\delta_\beta^2 \ll 1$, where $n$ stands for the average photon number in the cavity. The evolution operator associated with equation (6) reads

$$\hat{U}_{ef} = e^{-i\delta_\beta \phi_{\beta} \hat{a}_\beta^\dagger \hat{a}_\beta^\dagger} |e\rangle\langle e| + e^{i\delta_\beta \phi_{\beta} \hat{a}_\beta \hat{a}_\beta} |g\rangle\langle g|,$$

where $\phi_{\beta} = g_\beta^2 t_\beta / \delta_\beta$ and $t_\beta$ is the interaction time between the atom and the field in mode $\beta$.

### 3. Generating 4-qubit coherent states

Now we discuss our procedure to generate the cluster coherent state inside two bimodal cavities. Initially, all the modes $A$ and $B$ of $C_1$ and $C$ and $D$ of $C_2$ are prepared in a coherent state $|i\alpha\rangle$ whereas the atom is prepared in the ground or excited states. The initial and final atomic states determine the type of cluster state obtained. Before entering the first cavity the thermal field is erased [21].

The cavity context for the generation of linear 4-qubit cluster-type entangled coherent states. The initial and final atomic states determine the type of cluster state obtained. Before entering the first cavity the thermal field is erased [21].
dispersively ($\delta_B = \delta_\lambda$) with the mode $B$ for a time $t_B = t_\lambda$.
As a result the state of the whole system becomes
\[
|\psi(\delta_B)\rangle = \frac{1}{\sqrt{2}}(|g\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D
\]
\[
+ |e\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D).
\] (9)

When the atom emerges from the first cavity it crosses another Ramsey zone $R_2$, tuned to the transitions (4) and (5). In this way we obtain
\[
|\psi(R_2)\rangle = \frac{1}{\sqrt{2}}(|g\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D
\]
\[
- |e\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D \mp |g\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D
\]
\[
\pm |e\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D).
\] (10)

Next the atom enters the cavity $C_2$ and interacts dispersively with the modes $C$ and $D$, in the same way as found in $C_1$. So the whole state results
\[
|\psi(C_2)\rangle = \frac{1}{2\sqrt{2}}(|g\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D
\]
\[
+ |e\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D \mp |g\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D
\]
\[
\pm |e\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D).
\] (11)

Then the atom crosses another Ramsey zone $R_3$, leading the whole system to the state
\[
|\psi(R_3)\rangle = \frac{1}{2\sqrt{2}}(|g\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D
\]
\[
+ |e\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D \mp |g\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D
\]
\[
\pm |e\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D).
\] (12)

Finally, the atomic detection projects the state of the two cavities in one of the following 4-qubit coherent cluster states:
\[
|X_{1}^{(c,e)}\rangle = \frac{1}{2}(|\alpha\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D + |\alpha\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D - |\alpha\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D - |\alpha\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D),
\] (13)
\[
|X_{2}^{(c,e)}\rangle = \frac{1}{2}(-|\alpha\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D + |\alpha\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D + |\alpha\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D - |\alpha\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D),
\] (14)
\[
|X_{3}^{(c,e)}\rangle = \frac{1}{2}(|\alpha\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D + |\alpha\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D + |\alpha\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D - |\alpha\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D),
\] (15)
\[
|X_{4}^{(c,e)}\rangle = \frac{1}{2}(-|\alpha\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D - |\alpha\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D + |\alpha\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D + |\alpha\rangle|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D),
\] (16)

where we have omitted the subscripts of the modes; the superscripts in equations (13)–(16) indicate in which way the atomic state is prepared/detected. Note that the cluster states $|X_1^{(c,e)}\rangle$, $|X_2^{(c,e)}\rangle$, $|X_3^{(c,e)}\rangle$ and $|X_4^{(c,e)}\rangle$ correspond to [CLUSTER]$_A$, [CLUSTER]$_C$, $C'_B$ and $C'_{B}$, respectively, found in [17]. In the same way, other types of cluster states appearing in [17] can be obtained by convenient choices of initial states. For example, from the initial state $|\alpha\rangle_B|\alpha\rangle_C|\alpha\rangle_D$ we obtain the cluster state $|L_2^\alpha\rangle$ given in [17].

Next we calculate the total time $\tau$ spent for the generation of the 4-qubit cluster coherent states. First, note that $\alpha$ must be chosen in a way that the cluster coherent states (13)–(16) be orthogonal and this choice determines the value of detuning $\delta_B$ satisfying the dispersive condition $\delta_B \gg g_B \sqrt{\eta}$.

Figure 2. Fidelity of the prepared cluster state for the ideal case ($\Delta\theta = 0$) and real case including the influence of speed spread ($\Delta\theta \neq 0$).

Setting $\alpha = 2$ leads to $|\alpha - |\alpha\rangle|^2 = e^{-4\alpha^2} \approx 10^{-7} \approx 0$ and $\delta_B = 40 g_B$. Now, using recent experimental data [20] for the central Rabi frequency $g_B \approx 2 \pi \times 51$ kHz (with $\beta = A, B$) one obtains the interaction time $t_B = \pi g_B / 2g_B^2 = 196 \mu$s to produce a phase shift $\pi/2$ in the state of mode $\beta$. This requires the atomic velocity $v = \sqrt{\eta} w / (t_B + t_F) = 27$ m s$^{-1}$ to get an effective atom–field interaction time when taking into account the variation of the Rabi frequency due to the atomic motion across the Gaussian cavity mode. The selected atomic velocity belongs to the typical interval $200$–$500$ m s$^{-1}$ available in laboratories. The total time required for the interaction of the atom with the four modes in the two cavities is $\tau = 0.784$ ms. The scheme presented here can be mathematically generalized for a higher order of particles in the cluster coherent state simply by including more cavities in the experiment. However, in view of the decoherence effects affecting the preparation of field states, one should take into account the total time spent to accomplish the experiment.

Till now we have considered all calculations in an ideal experiment. In a realistic case the effect of velocity spread, detection efficiency and dissipation should be taken into account. First, we know that the atomic velocity determines the pulse $\theta$ in the Ramsey zones and the phase shift $\phi$ in the cavity mode; so any atomic velocity spread produces uncertainties in the values of $\theta$ and $\phi$. Hence calculating the fidelity between the ideal and real cluster states, including the influence of the velocity spread, one obtains
\[
F(\Delta\theta) = \frac{(1 + 2 \sin^2(\pi/4 + \Delta\theta))^2}{4\cos^2(\pi/4 + \Delta\theta) + 3 \sin^4(\pi/4 + \Delta\theta)}.
\]

For the experimental velocity spread $\Delta v = \pm 2$ m s$^{-1}$ [19] the fidelity spread is \(\approx 3\%\), as shown in the figure 2. Second, there is no problem with respect to detector efficiency since the scheme works with a single atom. Third, the total time $\tau$ of experiment ($\tau = 0.784$ ms, neglecting the spatial separation between cavities) is much less than photon damping times ($T_d = 130$ ms) and atomic radiative times ($T_a \simeq 30$ ms, for
Rydberg atoms, so we will neglect dissipation and the scheme may be experimentally feasible in the microwave realm.

4. Generating $N$-qubit coherent states

To generalize this scheme we need to add new single-mode cavities and Ramsey zones between the bimodal cavities. Before pursuing this goal, we write the general form for linear cluster-type entangled coherent states

$$| \phi^N \rangle = \frac{1}{2^{N/2}} \prod_{a=1}^{N} \left( | \alpha \rangle_a + | -\alpha \rangle_a \sigma^{(a+1)} \right),$$  \hspace{0.5cm} (17)

where $\sigma^{(a+1)} = | \alpha \rangle_{a+1} \langle -\alpha | - | -\alpha \rangle_{a+1} \langle \alpha |$. The state in equation (17) can be rewritten up to local unitary transformations as

$$| \phi^N \rangle = \frac{1}{2^{N/2}} \left( | \alpha \rangle_{1,2} + | -\alpha \rangle_{1,2} \sigma^{(3)} \right) \prod_{a=3}^{N-2} \left( | \alpha \rangle_a + | -\alpha \rangle_a \sigma^{(a+1)} \right) \left( | \alpha \rangle_{N-1,N} + | -\alpha \rangle_{N-1,N} \right),$$  \hspace{0.5cm} (18)

which corresponds to a convenient form for generalization. In order to achieve the generalization, we will employ the same procedure of [15] and will consider a set of $N - 4$ block composed by a single-mode cavity followed by a Ramsey zone placed between the Ramsey zone $R_2$ and the bimodal cavity. Next assume $N$ cavity modes initially prepared in the coherent states $| \alpha \rangle_{1} | \alpha \rangle_{2} | \alpha \rangle_{3} | \alpha \rangle_{4} \cdots | \alpha \rangle_{N-2} | \alpha \rangle_{N-1} | \alpha \rangle_{N}$ and an atom in the atomic state $|g\rangle$. According to equation (10), the whole system state after the atom crosses $R_1, C_1$ and $R_2$ will be

$$\frac{1}{\sqrt{2}} (|e\rangle + |e\rangle \sigma^{(2)}) \left( |\alpha\rangle_{1,2} + | -\alpha \rangle_{1,2} \right) \prod_{a=3}^{N-2} \left( | \alpha \rangle_a + | -\alpha \rangle_a \sigma^{(a+1)} \right) \left( | \alpha \rangle_{N-1,N} + | -\alpha \rangle_{N-1,N} \right),$$  \hspace{0.5cm} (19)

Before the atom enters the next cavity, it crosses a new Ramsey zone adjusting it to produce $|g\rangle \rightarrow |f\rangle$. In the following, the atom enters the next cavity and interacts dispersively with the cavity mode during a specific time to produce a phase shift $\pi$; the state of the system reads

$$\frac{1}{\sqrt{2}} (|f\rangle | \alpha \rangle_{1,2} | \psi_1 \rangle + |e\rangle | -\alpha \rangle_{1,2} | \psi_2 \rangle),$$  \hspace{0.5cm} (20)

where

$$| \psi_1 \rangle = (| \alpha \rangle_{1} | \alpha \rangle_{2} + | -\alpha \rangle_{1} | -\alpha \rangle_{2} ) \prod_{a=3}^{N-2} | \alpha \rangle_{a} \cdots | \alpha \rangle_{N-2} | \alpha \rangle_{N-1} | \alpha \rangle_{N}/2,$$

$$| \psi_2 \rangle = \sigma^{(2)} (| \alpha \rangle_{1} | \alpha \rangle_{2} + | -\alpha \rangle_{1} | -\alpha \rangle_{2} ) \prod_{a=3}^{N-2} | -\alpha \rangle_{a} \cdots | -\alpha \rangle_{N-2} | -\alpha \rangle_{N-1} | -\alpha \rangle_{N}/2.$$

In sequence the atom crosses a Ramsey zone, which produces the transformations $|e\rangle \rightarrow |e\rangle$ and $|f\rangle \rightarrow |f\rangle - |e\rangle$, and the whole state evolves into

$$\frac{1}{\sqrt{2}} (|f\rangle - |e\rangle \sigma^{(N-2)}) \left( |\alpha\rangle_{1,2} + | -\alpha \rangle_{1,2} \right) \left( | \alpha \rangle_{1} | \alpha \rangle_{2} | \psi_1 \rangle + | -\alpha \rangle_{1} | -\alpha \rangle_{2} | \psi_2 \rangle \right).$$  \hspace{0.5cm} (21)

If we repeat the procedure $N - 5$ times, we will obtain

$$\frac{1}{2^{N/2}} \left( |f\rangle - |e\rangle \sigma^{(N-2)} \right) \prod_{a=N-2}^{3} \left( | \alpha \rangle_a + | -\alpha \rangle_a \sigma^{(a+1)} \right) \left( | \alpha \rangle_{1,2} + | -\alpha \rangle_{1,2} \right).$$  \hspace{0.5cm} (22)

Finally, the atom passes through a last Ramsey zone (adjusting $|f\rangle \rightarrow -|g\rangle$), the bimodal cavity $C_2$ and Ramsey zone $R_N$, and the detection completes the preparation of the cluster state (17).

5. Conclusion

In summary, inspired by (and taking advantage of) a previous work [17] and also motivated by its potential applications for one-way quantum computing [4], we have presented an alternative scheme to generate a 4-qubit cluster of coherent states. It employs two bimodal QED cavities and a single two-level Rydberg atom, constituting an economic version compared with [17]. Furthermore, this scheme is faster than that of [18], since one needs phase $\pi/2$, instead of $\pi$ used in [18]. Here we have also considered the variation of the Rabi frequency due to the atomic motion across the Gaussian cavity mode: it results in the total time of experiment $\tau = 0.784$ ms, smaller than that in [17]. In addition, the success probability to get a specific cluster state of the family in equations (13)–(16) is 50%, instead of the 25% found in [17]. We have also taken advantage of a recent result by the Haroche group [20], allowing us to neglect the decoherence of the state during the generation process. Finally, we have also extended the scheme to generate $N$-cluster coherent states.

Acknowledgments

We thank the CAPES, CNPq, FEBRASCI-O, Brazilian agencies and PRPPG/UFG, for the partial supports.

References

[1] Ekert A K 1991 Phys. Rev. Lett. 67 661
[2] Bennett C H and Wiesner S J 1992 Phys. Rev. Lett. 69 2881
[3] Bennett C H, Brassard G, Crepeau C, Jozsa R, Peres A and Wootters W K 1993 Phys. Rev. Lett. 70 1895
[4] Raussendorf R and Briegel H J 2001 Phys. Rev. Lett. 86 5188
[5] Nielsen M A 2006 Rep. Math. Phys. 57 147
[6] Lo H K and Popescu S 2001 Phys. Rev. A 63 022301
[7] Dur W, Vidal G and Cirac J I 2000 Phys. Rev. A 62 062314
[8] Acin A, Bruß D, Lewenstein M and Sanpera A 2001 Phys. Rev. Lett. 87 040401
[9] Walther P, Aspelmeyer M, Resch K J and Zeilinger A 2005 Phys. Rev. Lett. 95 020403
[10] Briegel H J and Raussendorf R 2001 Phys. Rev. Lett. 86 910
[11] Walther P, Resch K J, Rudolph T, Schenck S, Weinfurter H, Vedral V, Aspelmeyer M and Zeilinger A 2005 Nature 434 169
[12] Kiesel N, Schmid C, Weber U, Töbi G, Gühne O, Ursin R and Weinfurter H 2005 Phys. Rev. Lett. 95 210502
[13] Tame M S, Prevedel R, Paternostro M, Bowi P, Kim M S and Zeilinger A 2007 Phys. Rev. Lett. 98 140501
[14] Zou X B, Ohike K and Mathis W 2004 Phys. Rev. A 69 052314
[15] Zou X B and Mathis W 2005 Phys. Rev. A 72 013809
[16] Blythe P J and Varcoe B T H 2006 New J. Phys. 8 231
[17] Munhoz P P, Semiao F L, Vidiella-Barranco A and Roversi J A 2007 Preprint 0705.1549
[18] Zhou Y-L, Yang L-J and Dai H-Y 2007 Chin. Phys. Lett. 24 3304
[19] Raimond J M, Brune M and Haroche S 2001 Rev. Mod. Phys. 73 565
[20] Gleyzes G, Rauchmanbeutel A, Osnaghi S, Brune M, Raimond J M and Haroche S 2007 Nature 446 297
[21] Nogues G, Rauchmanbeutel A, Osnaghi S, Brune M, Raimond J M and Haroche S 1999 Nature 400 239