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Cluster states prepared by using hot trapped ions*

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We propose a scheme for the preparation of one-dimensional and two-dimensional cluster states by using hot trapped ions. The scheme is based on the interaction between two ions and bichromatic radiation. The vibrational mode in our protocol is only virtually excited so that the system is insensitive to the thermal field. In addition, we only use two levels of ions as qubits and the successful probability may achieve 100%.

Keywords: cluster states, hot trapped ions, bichromatic radiation, two-level ions
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1. Introduction

In recent years, there has been aroused much interest in multi-particle entangled states which play an important role in testing quantum nonlocality[1−4] and implementing quantum information processing.[5−7] It has been shown that for systems shared by three or more parties, there exist several inequivalent classes of entangled states such as GHZ states, W states and cluster states.[8] Cluster states, first proposed by Briegel and Raussendorf,[9] have a higher persistence of entanglement than GHZ states, so they are more immune to decoherence. In addition, cluster states constitute a universal resource for one-way computation proceeding only by local measurements and feedforward of their outcomes.[10] In Ref.[9], the authors demonstrated that cluster states could be generated through an Ising-type interaction at a very low temperature. But it is very difficult to manipulate in experiment. Since then, much public attention has been paid to the study of cluster states.[3,4,11−17]

So far, there have been many theoretical protocols of preparing cluster states with cavity QED, optical systems, superconductor, atomic ensembles, trapped ions, and so on.[11−15] However, in experiment, one can only realize a four-photon cluster state in optical systems.[18] An ion-trap system, first suggested by Cirac and Zoller,[19] is considered to be an ideal candidate for quantum information processing and quantum computation.[20−24] Recently, an experimental scheme for preparing a six-qubit GHZ state and an eight-qubit W state has been reported in such a system, which motivates intensive research into the generation of cluster states. In Ref.[11], Zheng demonstrated two schemes for preparing a four-ion cluster state. One is based on resonant sideband excitation and the other requires an ancillary level instead of a vibrational mode as the memory. In this paper, we propose an alternate scheme to prepare 1D (one-dimensional) and 2D (two-dimensional) cluster states. The scheme is based on the interaction between two ions and bichromatic radiation in order to eliminate the vibrational mode as the memory. Moreover, we need only two-level ions without the requirement for an ancillary level, and the successful probability may reach 1.

The paper is organized as follows. In Section 2 we describe the interaction between two ions and bichromatic radiation; Section 3 is devoted to the preparation of a 1D cluster state of n ions; Section 4 treats preparing 2D cluster states; a discussion and conclusion are given in Section 5.

2. Interaction between two ions and bichromatic radiation

In this section, we consider two two-level ions interacting with bichromatic radiation. The two ions,

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trapped in a single-mode harmonic potential, are excited by two laser beams simultaneously. The frequencies of the two laser pulses, ω_1 and ω_2 satisfy $\omega_1 = \omega_0 + \nu - \delta$ and $\omega_2 = \omega_0 - \nu + \delta$, where ω_0 and ν are ionic transition frequency and the frequency of the vibration, respectively; δ is the detuning and satisfies $\delta \ll \nu$ so that we can neglect the contribution from all other vibrational modes. The Hamiltonian, in the rotating-wave approximation, reads ($\hbar = 1$)[22,25]

$$H = \frac{\omega_0}{2}\sum_{j=1}^{2}\sigma_z^j + \nu a^+ a + \sum_{j=1}^{2}\frac{\Omega_j}{2}\left\{\sigma_+^j \mathrm{e}^{\mathrm{i}\left[\eta\left(a^+ + a\right) - (\omega_0+\nu-\delta)t\right]} + \sigma_+^j \mathrm{e}^{\mathrm{i}\left[\eta\left(a^+ + a\right) - (\omega_0-\nu+\delta)t\right]} + \mathrm{H.c.}\right\}, \tag{1}$$

where $\sigma_z^j = |e\rangle_j \langle e| - |g\rangle_j \langle g|$, $\sigma_+^j = |e\rangle_j \langle g|$ with $|e\rangle$ and $|g\rangle$ being the excite and ground states of the jth ion; a^+ and a are the creation and annihilation operators for the centre-of-mass mode, Ω_j is the Rabi frequency of the jth ion interacting with vibrational mode. η is the Lamb–Dicke parameter and H.c. denotes conjugate terms.

Assuming that the two ions are restricted to being in the Lamb–Dicke regime ($\eta\sqrt{\bar{n}+1} << 1$), the Hamiltonian, in the interaction picture, is

$$H_{\mathrm{I}} = \sum_{j=1}^{2}\frac{\Omega_j}{2}\left\{\sigma_+^j\left[\mathrm{e}^{\mathrm{i}(\nu-\delta)t} + \mathrm{e}^{-\mathrm{i}(\nu-\delta)t}\right] + \mathrm{i}\eta\sigma_+^j\left[a^+\left(\mathrm{e}^{\mathrm{i}\delta t} + \mathrm{e}^{\mathrm{i}(2\nu-\delta)t}\right) + a\left(\mathrm{e}^{-\mathrm{i}\delta t} + \mathrm{e}^{-\mathrm{i}(2\nu-\delta)t}\right)\right] + \mathrm{H.c.}\right\}. \tag{2}$$

In the case of the weak-field regime $\frac{\eta\Omega_{1,2}}{2} \ll \delta$, the fast oscillating terms $\sigma_+^j\left[\mathrm{e}^{\mathrm{i}(\nu-\delta)t} + \mathrm{e}^{-\mathrm{i}(\nu-\delta)t}\right] +$ H.c. and $\mathrm{i}\eta\frac{\Omega_j}{2}\sigma_+^j\left[a^+\mathrm{e}^{\mathrm{i}(2\nu-\delta)t} + a\mathrm{e}^{-\mathrm{i}(2\nu-\delta)t}\right]$+H.c. can be eliminated. Thus the Hamiltonian (2) reduces to

$$H_{\mathrm{I}} = \sum_{j=1}^{2}\frac{\Omega_j}{2}\left\{\mathrm{i}\eta\sigma_+^j\left(a^+\mathrm{e}^{\mathrm{i}\delta t} + a\mathrm{e}^{-\mathrm{i}\delta t}\right) + \mathrm{H.c.}\right\}. \tag{3}$$

Furthermore, in such a weak field, there exists no energy exchange between the ions and the vibrational mode, leading the effective Hamiltonian to be

$$H_{\mathrm{e}} = \lambda\left(|ee\rangle\langle gg| - |eg\rangle\langle ge| + \mathrm{H.c.}\right), \tag{4}$$

where $\lambda = \dfrac{\eta^2\Omega_1\Omega_2}{2\delta}$.

So the corresponding evolution operator of the two-ion system is $U(t) = \mathrm{e}^{-\mathrm{i}tH_{\mathrm{e}}}$. After the interaction time t, the different initial states of the two ions will evolve as

$$|ee\rangle \xrightarrow{U(t)} \cos\lambda t\,|ee\rangle - \mathrm{i}\sin\lambda t\,|gg\rangle, \tag{5a}$$

$$|gg\rangle \xrightarrow{U(t)} \cos\lambda t\,|gg\rangle - \mathrm{i}\sin\lambda t\,|ee\rangle, \tag{5b}$$

$$|eg\rangle \xrightarrow{U(t)} \cos\lambda t\,|eg\rangle + \mathrm{i}\sin\lambda t\,|ge\rangle, \tag{5c}$$

$$|ge\rangle \xrightarrow{U(t)} \cos\lambda t\,|ge\rangle + \mathrm{i}\sin\lambda t\,|eg\rangle. \tag{5d}$$

3. Generation of a 1D cluster state of n ions

In this section, we describe how to prepare a 1D cluster state of n ions. We suppose that all the n ions are initially prepared in the excited state $|e\rangle$. The detailed procedure is given as follows.

Step 1 The ions 1 and 2 are driven by two laser beams with the frequencies $\omega_1 = \omega_0 + \nu - \delta$ and $\omega_2 = \omega_0 - \nu + \delta$ simultaneously to implement the transformation (5a). With the choice of the interaction time $t_1 = \dfrac{\pi}{4\lambda}$, the whole system state evolves to

$$\begin{aligned}|\psi_1\rangle &= U_{12}\left(\frac{\pi}{4\lambda}\right)|ee\ldots e\rangle_{12\ldots n}\\ &= \frac{1}{\sqrt{2}}\left(|ee\rangle - \mathrm{i}\,|gg\rangle\right)_{12}|ee\ldots e\rangle_{34\ldots n}.\end{aligned} \tag{6}$$

Step 2 We also simultaneously drive the ions 2 and 3 by using the laser pulses with frequencies ω_1 and ω_2 mentioned above and choose the interaction time $t_2 = \dfrac{\pi}{4\lambda}$. The whole system state becomes

$$\begin{aligned}|\psi_2\rangle &= U_{23}\left(\frac{\pi}{4\lambda}\right)|\psi_1\rangle\\ &= \frac{1}{2}\left[|eee\rangle_{123} - \mathrm{i}\,|egg\rangle_{123} - i\,|gge\rangle_{123}\right.\\ &\quad\left. + |geg\rangle_{123}\right]|ee\ldots e\rangle_{45\ldots n}.\end{aligned} \tag{7}$$

Next, we perform the local unitary operator

$$P_2 = |e\rangle_2 \langle e| + \mathrm{i}\,|g\rangle_2 \langle g| \tag{8}$$

and Hadamard transformation (H_2)

$$\begin{aligned} H_2\,|e\rangle_2 &= |+\rangle_2 = \frac{1}{\sqrt{2}}\,(|e\rangle + |g\rangle)_2\,, \\ H_2\,|g\rangle_2 &= |-\rangle_2 = \frac{1}{\sqrt{2}}\,(|e\rangle - |g\rangle)_2 \end{aligned} \tag{9}$$

on the ion 2. The system state in Eq.(7) will be

$$|\psi_3\rangle = \frac{1}{2}\left[(|+\rangle_1\,|e\rangle_2 + |-\rangle_1\,|g\rangle_2)\;|e\rangle_3 + (|+\rangle_1\,|e\rangle_2 - |-\rangle_1\,|g\rangle_2)\;|g\rangle_3\right]|ee\ldots e\rangle_{45\ldots n}\,, \tag{10}$$

which can be rewritten as

$$|\varphi\rangle_3 = \frac{1}{2\sqrt{2}}\left(|e\rangle_1 + |g\rangle_1\,\sigma_z^2\right)\;\left(|e\rangle_2 + |g\rangle_2\,\sigma_z^3\right)\;(|e\rangle_3 + |g\rangle_3)\;|ee\ldots e\rangle_{45\ldots n}\,. \tag{11}$$

The above Eq.(11) shows that we have prepared a 1D cluster state of three ions.[9]

Step 3 We use the add-on strategy to prepare the 1D four-ion cluster state. The ions 3 and 4 are acted on by the unitary operators H_3, P_3^{-1}, $U_{34}\left(\dfrac{\pi}{4\lambda}\right)$, P_3, and H_3 in sequence, where P and H are expressed in Eq.(8) and Eq.(9), respectively; $P^{-1} = |e\rangle\langle e| - \mathrm{i}\,|g\rangle\langle g|$ and the subscript j denotes the jth ion. To show the process more clearly, we write out the evolutions of ions 3 and 4 in the different initial states respectively as follows:

$$\begin{aligned} |ee\rangle_{34} &\xrightarrow{H_3} |+\rangle_3\,|e\rangle_4 \xrightarrow{P_3^{-1}} \frac{1}{\sqrt{2}}\,(|e\rangle - \mathrm{i}\,|g\rangle)_3\,|e\rangle_4 \xrightarrow{U_{34}\left(\frac{\pi}{4\lambda}\right)} \frac{1}{2}\left[(|ee\rangle - \mathrm{i}\,|gg\rangle) - \mathrm{i}\,(|ge\rangle + \mathrm{i}\,|eg\rangle)\right] \\ &\xrightarrow{P_3} \frac{1}{2}\,(|ee\rangle + |eg\rangle + |ge\rangle + |gg\rangle) \xrightarrow{H_3} |e\rangle_3\,|+\rangle_4\,, \end{aligned} \tag{12a}$$

$$\begin{aligned} |eg\rangle_{34} &\xrightarrow{H_3} |+\rangle_3\,|g\rangle_4 \xrightarrow{P_3^{-1}} \frac{1}{\sqrt{2}}\,(|e\rangle - \mathrm{i}\,|g\rangle)_3\,|g\rangle_4 \xrightarrow{U_{34}\left(\frac{\pi}{4\lambda}\right)} \frac{1}{2}\left[(|eg\rangle + \mathrm{i}\,|ge\rangle) - \mathrm{i}\,(|gg\rangle - \mathrm{i}\,|ee\rangle)\right] \\ &\xrightarrow{P_3} \frac{1}{2}\,(-|ee\rangle + |eg\rangle - |ge\rangle + |gg\rangle) \xrightarrow{H_3} -|e\rangle_3\,|-\rangle_4\,, \end{aligned} \tag{12b}$$

$$\begin{aligned} |ge\rangle_{34} &\xrightarrow{H_3} |-\rangle_3\,|e\rangle_4 \xrightarrow{P_3^{-1}} \frac{1}{\sqrt{2}}\,(|e\rangle + \mathrm{i}\,|g\rangle)_3\,|e\rangle_4 \xrightarrow{U_{34}\left(\frac{\pi}{4\lambda}\right)} \frac{1}{2}\left[(|ee\rangle - \mathrm{i}\,|gg\rangle) + \mathrm{i}\,(|ge\rangle + \mathrm{i}\,|eg\rangle)\right] \\ &\xrightarrow{P_3} \frac{1}{2}\,(|ee\rangle - |eg\rangle - |ge\rangle + |gg\rangle) \xrightarrow{H_3} |g\rangle_3\,|-\rangle_4\,, \end{aligned} \tag{12c}$$

$$\begin{aligned} |gg\rangle_{34} &\xrightarrow{H_3} |-\rangle_3\,|g\rangle_4 \xrightarrow{P_3^{-1}} \frac{1}{\sqrt{2}}\,(|e\rangle + \mathrm{i}\,|g\rangle)_3\,|g\rangle_4 \xrightarrow{U_{34}\left(\frac{\pi}{4\lambda}\right)} \frac{1}{2}\left[(|eg\rangle + \mathrm{i}\,|ge\rangle) + \mathrm{i}\,(|gg\rangle - \mathrm{i}\,|ee\rangle)\right] \\ &\xrightarrow{P_3} \frac{1}{2}\,(|ee\rangle + |eg\rangle - |ge\rangle - |gg\rangle) \xrightarrow{H_3} |g\rangle_3\,|+\rangle_4\,. \end{aligned} \tag{12d}$$

The above procedure transforms the system state (10) into

$$|\psi_6\rangle = \frac{1}{2}\left[(|+\rangle_1\,|e\rangle_2 + |-\rangle_1\,|g\rangle_2)\;|e\rangle_3\,|+\rangle_4 + (|+\rangle_1\,|e\rangle_2 - |-\rangle_1\,|g\rangle_2)\;|g\rangle_3\,|-\rangle_4\right]\;|ee\ldots e\rangle_{56\ldots n}\,, \tag{13}$$

which can be rewritten as

$$|\varphi\rangle_4 = \frac{1}{4}\;\left(|e\rangle_1 + |g\rangle_1\,\sigma_z^2\right)\;\left(|e\rangle_2 + |g\rangle_2\,\sigma_z^3\right)\;\left(|e\rangle_3 + |g\rangle_3\,\sigma_z^4\right)\;(|e\rangle_4 + |g\rangle_4)\;\;|ee\ldots e\rangle_{56\ldots n}\,. \tag{14}$$

The state in Eq.(14) indicates the success in preparing a 1D four-ion cluster state via an add-on strategy.

In the same way, we can generate a 1D cluster state of n ions. What we have to do is repeat the manipulation described in Step 3 $(n-4)$ times. Namely, we can prepare a 1D n-ion cluster state in the form of [9]

$$|\varphi\rangle_n = \frac{1}{2^{n/2}}\;\left(|e\rangle_1 + |g\rangle_1\,\sigma_z^2\right)\;\left(|e\rangle_2 + |g\rangle_2\,\sigma_z^3\right)\;\ldots\left(|e\rangle_{n-1} + |g\rangle_{n-1}\,\sigma_z^n\right)\;(|e\rangle_n + |g\rangle_n)\,. \tag{15}$$

4. Preparing 2D cluster states

Although 1D cluster states can act as a resource for some simple quantum information processing and quantum computation,[14,18] they cannot be used to implement complex ones.[10] Thus, the generation of 2D cluster states[10,26] is of great importance. In what follows, we show how to prepare a 2D cluster state via fusing two 1D ones. According to Refs.[26, 27], we can rewrite the two 1D cluster states as

$$|C_i\rangle = \frac{1}{\sqrt{2}}\left(|e\rangle_i\,|\eta_{i1}\rangle + |g\rangle_i\,|\eta_{i2}\rangle\right), \quad i \in \{m,\ n\}, \tag{16}$$

where the ith ionic state is entangled with the subsystems, and $|\eta_{i1}\rangle$ ($|\eta_{i2}\rangle$) is an arbitrary normalized cluster state of the subsystems and $\langle\eta_{i1} \mid \eta_{i2}\rangle = 0$. Due to Eqs.(12), if we perform the series of unitary operators H_m, P_m^{-1}, $U_{mn}\left(\frac{\pi}{4\lambda}\right)$, P_m, and H_m on the ions m and n, the initial system state

$$\frac{1}{2}\left(|e\rangle_m\,|\eta_{m1}\rangle + |g\rangle_m\,|\eta_{m2}\rangle\right)\left(|e\rangle_n\,|\eta_{n1}\rangle + |g\rangle_n\,|\eta_{n2}\rangle\right) \tag{17}$$

will evolve to

$$\begin{aligned}&\frac{1}{2}[|e\rangle_m\,|+\rangle_n\,|\eta_{m1}\rangle\,|\eta_{n1}\rangle - |e\rangle_m\,|-\rangle_n\,|\eta_{m1}\rangle\,|\eta_{n2}\rangle\\ &+ |g\rangle_m\,|-\rangle_n\,|\eta_{m2}\rangle\,|\eta_{n1}\rangle + |g\rangle_m\,|+\rangle_n\,|\eta_{m2}\rangle\,|\eta_{n2}\rangle].\end{aligned} \tag{18}$$

Then we measure the state of the ion n in the basis $\{|+\rangle_n, |-\rangle_n\}$, and if the measurement result is $|+\rangle_n$, the system state (18) reduces to

$$\frac{1}{2}\left(|e\rangle_m\,|\eta_{m1}\rangle\,|\eta_{n1}\rangle + |g\rangle_m\,|\eta_{m2}\rangle\,|\eta_{n2}\rangle\right), \tag{19a}$$

which is just a 2D cluster state.[26] But if the detecting result is $|-\rangle_n$, we can also obtain a 2D cluster state in the other form

$$\frac{1}{2}\left(-|e\rangle_m\,|\eta_{m1}\rangle\,|\eta_{n2}\rangle + |g\rangle_m\,|\eta_{m2}\rangle\,|\eta_{n1}\rangle\right). \tag{19b}$$

In this way, we obtain a 2D cluster state.

5. Discussion and conclusion

Now we give a brief discussion on the feasibility for the proposed scheme. From Refs.[21, 22], we choose $\delta = 0.1\nu$, $\eta = 0.1$, $\Omega_1 = \Omega_2 = 0.05\nu$ and $\frac{\nu}{2\pi} = 200\,\mathrm{kHz}$, then the condition $\delta \ll \nu$ and $\delta \gg \frac{\eta\Omega_{1,2}}{2}$ can be easily satisfied. For the Rydberg ions with principal numbers 50 and 51, the radiative time is about $\Gamma_a = 3 \times 10^{-2}\,\mathrm{s}$. The required interaction time for entangling two ions is $\tau = \frac{\pi}{4\lambda} = \frac{\pi\delta}{2\eta\Omega_1\Omega_2} \approx 10^{-3}\,\mathrm{s}$, which is much shorter than the ionic life time. The single-qubit rotations can be manipulated much faster than the two-qubit gates,[28] leading the time required for preparing cluster states to be determined mainly by the two-qubit ones. In the case of the weak field and the Lamb–Dicke approximation, the heating effect of the vibrational motion, due to the interaction with the environment, is small even though the change in average vibrational number is larger than unity.[29,30] Hence our scheme may be realized under current technology.

In summary, we have proposed a scheme for preparing 1D and 2D cluster states by using hot trapped ions. The scheme has the following advantages compared with the previous protocols.[11,26,27] The first one is that the vibrational mode in our scheme is only virtually excited so that the system is insensitive to the heating of vibrational modes, while the protocols demonstrated in Refs.[11, 27], in which the centre-of-mass mode was used as memory, are sensitive to the thermal field. The second one is that we use only two levels of ions as qubits instead of three-level ions. The elimination of an auxiliary level can remove the possible existence of spectator internal atomic levels.[31] The third one is that the successful probability may achieve 100%, while the protocol[26] in linear optical system can never reach such a high successful probability. We should emphasize that the drawback of our scheme is that the entanglement speed is low since it requires the laser pulse to be very weak. In order to overcome such disadvantage, we can fuse several small-scale cluster states to prepare a large-scale one. Therefore, our scheme of generating cluster states may be feasible based on the current technology.

References

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

[2] Wu C F, Chen J L, Kwek L C and Oh. C H 2006 *Phys. Rev.* A **73** 012310

[3] Scarani V, Acin A, Schenck E and Aspelmeyer M 2005 *Phys. Rev.* A **71** 042325

[4] Walther P, Aspelmeyer M, Resch K J and Zeilinger A 2005 *Phys. Rev. Lett.* **95** 020403

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

[6] Huang Z P and Li H C 2005 *Chin. Phys.* **14** 974

[7] Tan J and Fang M F 2006 *Chin. Phys.* **15** 1695

[8] Dür W, Cirac J I and Tarrach R 1999 *Phys. Rev. Lett.* **83** 3562

[9] Briegel H J and Raussendorf R 2001 *Phys. Rev. Lett.* **86** 910

[10] Raussendorf R and Briegel H J 2001 *Phys. Rev. Lett.* **86** 5188

[11] Zheng S B 2006 *Phys. Rev.* A **73** 065802

[12] Zheng X H, Dong P, Xue Z Y and Cao Z L 2006 quant-ph/0605240

[13] Zhang X L, Gao K L and Feng M 2006 *Phys. Rev.* A **74** 024303

[14] Yang R C, Li H C, Chen M X and Lin X 2006 *Chin. Phys.* **15** 2315

[15] Zou X B and Mathis W 2005 *Phys. Rev.* A **72** 013809

[16] Duan L M and Raussendorf R 2005 *Phys. Rev. Lett.* **95** 080503

[17] Raussendorf R, Browne, D E and Briegel H J 2003 *Phys. Rev.* A **68** 022312

[18] Walther P, Resch K J, Rudolph T, Schenck E, Weinfurter H, Vedral V, Aspelmeyer M and Zeillinger A 2005 *Nature* (London) **434** 169

[19] Cirac J I and Zoller P 1995 *Phys. Rev. Lett.* **74** 4091

[20] Zheng X J, Fang M F, Cai J W and Liao X P 2006 *Chin. Phys.* **15** 0492

[21] Mølmer K and Sørensen A 1999*Phys. Rev. Lett.* **82** 1835

[22] Sørensen A and Mølmer K 1999*Phys. Rev. Lett.* **82** 1971

[23] Zheng S B 2005 *Chin. Phys.* **14** 2222

[24] Monroe C, Leibfried D, King B E, Meekhof D M, Itano W M and Wineland D J 1997 *Phys. Rev.* A **55** R2489

[25] Zheng S B 2003 *Phys. Rev.* A **68** 035801

[26] Browne D E and Rudolph T 2005 *Phys. Rev. Lett.* **95** 010501

[27] Yang W X, Zhan Z M and Li J H 2005 *Phys. Rev.* A **72** 062108

[28] Steane A, Roos C F, Stevens D, Mundt A, Leibfried D, Schmidt-Kaler F and Blatt R 2000 *Phys. Rev.* A **62** 042305

[29] Sørensen A and Mølmer K 2000 *Phys. Rev.* A **62** 022311

[30] Cai L H, Hai W H and Lu G B 2006 *Chin. Phys.* **15** 2275

[31] Monroe C, Leibfried D, King B E, Meekhof D M, Itano W M and Wineland D J 1997 *Phys. Rev.* A **57** R2489