Preparation of steady-state entanglement via a laser-excited resonant interaction*

Cheng Guang-Ling(程广玲), Chen Ai-Xi(陈爱喜)†, Geng Jun(耿 珺), Zhong Wen-Xue(钟文学), and Deng Li(邓 黎)

Department of Applied Physics, East China Jiaotong University, Nanchang 330013, *China*

(Received 3 January 2012; revised manuscript received 8 February 2012)

In this paper we propose a scheme in which two-mode entanglement in a steady state is produced by using two lasers to resonantly drive a single four-level atom embedded inside a two-mode optical cavity. In this scheme, atomic coherence induced by a classical laser plays an important role in the process of preparing the entangled state. With the coupling of a strong control field, direct two-photon transition is generated and the relatively weak pump field induces the parametric interaction between two photons, which makes them entangle with each other. By numerical calculation, we find that the degree of entanglement depends strongly on the Rabi frequencies of the classical laser fields and the cavity losses.

Keywords: two-mode entanglement, atomic coherence, resonant interaction

PACS: 42.50.Dv, 03.67.Mn, 42.50.Pq **DOI:** 10.1088/1674-1056/21/8/084206

1. Introduction

Continuously variable (CV) entanglement has recently attracted a great deal of attention, owing to its wide applications in quantum information,[1−8] such as quantum teleportation,[2] quantum key distribution,[3] quantum telecloning,[4] and so on. Moreover, a striking advantage of continuous variable entanglement is that it can be used to unconditionally implement many quantum information processes.[1] Therefore, the generation and measurement of a highly entangled state with continuous variables has been some of the top issues in quantum optics. Some typical systems have presented to prepare continuous variable entanglement.[9−16] For example, optical parametric down-conversion has been found to be an effective way for generating CV entanglement.[9−11] It has been shown that four-wave mixing can be used to achieve the narrow-band entangled photons.[12−16]

On the other hand, the correlated spontaneous emission laser has been another useful system for the generation of a macroscopic entangled state and has attracted much attention from researchers.[17−25] In the cascade three-level atom system, Xiong *et al.*[17] proposed to achieve entangled light with a large number of average photons in the cavity modes. Tan *et al.*[18] extended the theoretical research and discussed the entanglement properties in the Winger representation. Qamar *et al.*[20] proposed a scheme for generating bipartite entanglement in a V-type three-level atomic system. More recently, many schemes have been presented to generate entangled light with amplification. Especially, a single-atom laser system has been shown to be a much simpler system to achieve a macroscopic entangled laser.[22−25] It is noted that the above presented schemes concentrated on the generation of the entangled light with large average photons. That is to say, the entanglement is obviously time-dependent and exists only in a very limited time scale. As the photons increase, the entanglement will disappear.

In the field of quantum optics, the technology of atomic coherence has been extensively applied. Examples include electromagnetically induced transparency,[26−28] optical solitons,[29−31] four-wave mixtures,[32−35] and gain without inversion.[36] Here we, by using atomic coherence, present a scheme to

*Project supported by the National Natural Science Foundation of China (Grant Nos. 11047182, 11165008, and 11065007), the Natural Science Foundation of Jiangxi Province, China (Grant Nos. 20114BAB202001 and 2010GQW0011), and the Science Foundation of East China Jiaotong University, China (Grant Nos. 10JC03 and 10JC06).

†Corresponding author. E-mail: aixichen@ecjtu.jx.cn

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obtain the steady-state entangled light in a simple system where a single atom resonantly interacts with two classical fields and two cavity fields. In our scheme, the four fields are coupled with the dipole-allowed atomic transitions and then the scheme is feasible and simple to realize in experiment. The essential mechanism is atomic coherence, where a strong control field induces the direct two-photon transition processes, and the relatively weak pump field leads to the parametric interaction between such two photons, which is responsible for the entanglement generation. Our numerical results show that the degree of entanglement between the two cavity modes depends strongly on Rabi frequencies of the classical laser fields and the losses of the cavity modes.

2. Physical model and equation

We consider a single double-Λ four-level atom embedded in a two-mode cavity. As shown in Fig. 1(a), the atomic transitions $|3\rangle \leftrightarrow |2\rangle$ and $|4\rangle \leftrightarrow |1\rangle$ are independently driven by one strong control field with frequency ω_0 and one relative pump weak field with frequency ω. Two cavity modes with the frequencies ν_1 and ν_2 couple with the atomic transitions $|3\rangle \leftrightarrow |1\rangle$ and $|4\rangle \leftrightarrow |2\rangle$, respectively. It is obvious that the four fields are applied to the dipole-allowed transitions and this makes our scheme feasible in the actual operation. In the dipole approximation and the interaction picture, the master equation for the density operator of the atom-field system is written as

$$\dot{\rho} = -\mathrm{i}\left[H_{\mathrm{I}}, \rho\right] + L_a\rho + L_c\rho, \tag{1}$$

with

$$H_{\mathrm{I}} = -\frac{\Omega}{2}\sigma_{41} - \frac{\Omega_0}{2}\sigma_{32} + g_1 a_1 \sigma_{31} + g_2 a_2 \sigma_{42} + \mathrm{H.c.}, \tag{2}$$

where $\sigma_{jk} = |j\rangle\langle k|$ $(j,k = 1\text{–}4)$ denote the atomic population operators for $j = k$ and the atomic flip operators for $j \neq k$. a_l and $a_l^\dagger$ $(l = 1, 2)$ are the creation and annihilation operator of the cavity mode, Ω and Ω_0 are Rabi frequencies associated with the driving fields, and g_l $(l = 1, 2)$ are the coupling strengths between the atom and the cavity modes, $L_a\rho$ and $L_c\rho$ describe the atomic decay and the losses of the cavity field, respectively, and they are expressed as $L_a = \sum_{j=1,2;k=3,4} \gamma_{jk} \left(2\sigma_{jk}\rho\sigma_{kj} - \sigma_{kj}\sigma_{jk}\rho - \rho\sigma_{kj}\sigma_{jk}\right)/2$ with decay rates γ_{jk} and $L_c = \sum_{l=1,2} \kappa_l (2a_l\rho a_l^\dagger - a_l^\dagger a_l\rho - \rho a_l^\dagger a_l)/2$ with the cavity losses κ_l. By tracing out the atomic variables, one can obtain the dynamics of the cavity field as

$$\dot{\rho}_c = -\mathrm{i}\mathrm{Tr}_a\left[H_{\mathrm{I}}, \rho\right] + L_c\rho_c. \tag{3}$$

For the present physical system, we will clarify the physical mechanism in the representation of the dressed states which are the eigenstates of the Hamiltonian $H_{a0} = -\Omega_0\left(\sigma_{32} + \sigma_{23}\right)/2$. Assume that the control field is much stronger than the relative weak pump field and the cavity modes, i.e., $\Omega_0 \gg \Omega$, $g_l\langle a_l\rangle$ $(l = 1, 2)$, then we will obtain a pair of the eigenstates as $|\pm\rangle = (|3\rangle \pm |2\rangle)/\sqrt{2}$. The dressed states $|\pm\rangle$ have the corresponding eigenvalues $\lambda_\pm = \Omega_0/2$. The bare states $|1\rangle$ and $|4\rangle$ remain unchanged. In the dressed-state picture, master Eq. (3) reduces to

$$\begin{aligned}\dot{\rho}_c = \{&-\mathrm{i}\left[H_{4+}, \rho_{+4}\right] - \mathrm{i}\left[H_{4-}, \rho_{-4}\right] - \mathrm{i}\left[H_{1+}, \rho_{+1}\right] \\ &- \mathrm{i}\left[H_{1-}, \rho_{-1}\right] + \mathrm{H.c}\} + L_c\rho_c,\end{aligned} \tag{4}$$

where $H_{4+} = -H_{4-} = g_2 a_2/\sqrt{2}$, and $H_{1+} = H_{1-} = g_1 a_1^\dagger/\sqrt{2}$. We note that the condition $|\lambda_+ - \lambda_-| \gg \gamma_{jk}$ can be satisfied when the driving field is very strong. Therefore, the secular approximation can be adopted. Following the standard procedure of laser theory,[37] the master equation for the reduced density operator of the cavity modes is obtained by tracing out the atomic variable

$$\begin{aligned}\dot{\rho}_c = &A_{11}[a_1^\dagger, \rho_c a_1] - (B_{11} + \kappa_1/2)[a_1^\dagger, a_1\rho_c] \\ &+ A_{12}[a_1^\dagger, \rho_c a_2^\dagger] - B_{12}[a_1^\dagger, a_2^\dagger\rho_c] \\ &+ A_{22}[a_2^\dagger, \rho_c a_2] - (B_{22} + \kappa_2/2)[a_2^\dagger, a_2\rho_c] \\ &+ A_{21}[a_2^\dagger, \rho_c a_1^\dagger] - B_{21}[a_2^\dagger, a_1^\dagger\rho_c] + \mathrm{H.c},\end{aligned} \tag{5}$$

where the coefficients are given in the appendix. Equation (5) describes the parametric interactions between the two cavity fields. The A_{ll} terms are the gains for the mode a_l while the B_{ll} terms are the absorptions, $l = 1, 2$. And the A_{lm} and B_{lm} terms $(l, m = 1, 2;\ l \neq m)$ describe the cross couplings between two cavity fields. When the condition $\Omega_0 \gg \Omega, g, \gamma$ is satisfied, the coefficients are given by $A_{ll} = B_{ll} = 0$, $A_{12} = B_{21} = 0$, and $A_{21} = -B_{12} = 2g_1 g_2 \Omega/D_0\Omega_0$. In terms of Eq. (5), the parametric oscillator is obtained in such an approximation.

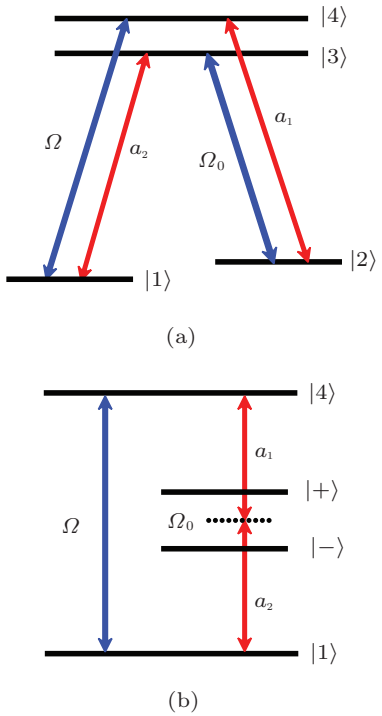


Fig. 1. (colour online) (a) A bare four-level Λ atomic system. Two classical fields are applied to the dipole-allowed transitions $|3\rangle \leftrightarrow |2\rangle$ and $|4\rangle \leftrightarrow |1\rangle$ with the Rabi frequencies Ω_0 and Ω, respectively. Two cavity modes interact with the transitions $|3\rangle \leftrightarrow |1\rangle$ and $|4\rangle \leftrightarrow |2\rangle$, respectively. (b) The level scheme of the dressed states associated with the strong pump field.

3. Analysis of steady-state entanglement

Now we analyse the entanglement properties in the present system. A quantum system is entangled if it is inseparable, i.e., $\rho_c \neq \sum_j p_j \rho_j^{(1)} \otimes \rho_j^{(2)}$ with $\sum_j p_j = 1$, which means that the density operator ρ_c for the system cannot be expressed as a combination of the product state. According to the criteria introduced by Duan *et al.*,[38] two cavity fields are entangled when the variance sum of two operators $\hat{u}$ and $\hat{v}$ satisfies the inequality

$$V = \langle (\Delta\hat{u})^2 + (\Delta\hat{v})^2 \rangle - a^2 + \frac{1}{a^2}, \tag{6}$$

where $\hat{u} = |a|\hat{x}_1 + \hat{x}_2/a$, $\hat{v} = |a|\hat{p}_1 - \hat{p}_2/a$ with $x_j = (a_j + a_j^\dagger)/\sqrt{2}$, $p_j = (a_j - a_j^\dagger)/\sqrt{2}\mathrm{i}$ $(j = 1, 2)$ and $|a| = \sqrt{\langle a_2^\dagger a_2\rangle / \langle a_1^\dagger a_1\rangle}$. Actually, equation (6) describes the correlation degree between two cavity modes. The smaller the values of the variance V, the larger correlation degree will be obtained. For the present two-mode Gaussian state, its quantum statistical properties are completely determined by its correlation matrix $C = \begin{pmatrix} C_1 & C_{12} \\ C_{12}^{\mathrm{T}} & C_2 \end{pmatrix}$, where the 2×2 matrixes are given by $C_1 = \begin{pmatrix} n_1 & 0 \\ 0 & n_2 \end{pmatrix}$, $C_2 = \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix}$, and $C_{12} = \begin{pmatrix} c_1 & 0 \\ 0 & c_2 \end{pmatrix}$. For the cavity field governed by Eq. (5), the parameters in correlation matrix C are determined by the cavity parameters: $n_1 = n_2 = n = \langle a_1^\dagger a_1\rangle + 1/2$, $m_1 = m_2 = m = \langle a_2^\dagger a_2\rangle + 1/2$, and $c_2 = -c_1 = c = |\langle a_1 a_2\rangle|$. Therefore, logarithmic negativity $N(\xi)$ can be defined as

$$N(\xi) = \begin{cases} -\ln 2\xi, & \text{if} \quad \xi < 1/2, \\ 0, & \text{otherwise}, \end{cases} \tag{7}$$

with $\xi = 2^{-1/2}\sqrt{\Sigma(C) - \sqrt{\Sigma^2(C) - 4\det C}}$ and $\Sigma(C) = \det C_1 + \det C_2 - \det C_{12}$, which can be used to determine the entanglement degree between two modes.[39] From Eq. (7), we can see that two cavity modes are entangled if and only if the parameter ξ satisfies $\xi < 1/2$. The larger the value of the function $N(\xi)$, the larger the entanglement degree and the stronger the entanglement between two cavity modes is.

In our numerical calculation, we scale Rabi frequencies, coupling constants, and cavity losses in units of γ. For simplicity we take $g_1 = g_2 = g$, $\kappa_1 = \kappa_2 = \kappa$, and the same atomic decay rates $\gamma_{jk} = \gamma$. In Fig. 2(a), we plot the sum variance V versus the Rabi frequency of the relative weak pump field. The parameters are chosen to be $\Omega_0 = 50$, $g = 1$, $\kappa = 0.02$ (solid), $\kappa = 0.05$ (dashed), and $\kappa = 0.1$ (dotted). It is clearly seen from Fig. 2(a) that the sum variance V is less than 0, which means that the entanglement occurs between two cavity modes. Furthermore, for the given cavity losses, the sum variance first decreases rapidly and then increases gradually with the increase of Rabi frequency Ω of the relative weak pump field. As the cavity loss rate decreases, the sum variance V becomes small, and the quantum correlation between two modes becomes stronger. Figure 2(b) shows the logarithmic negativity $N(\xi)$ versus Ω in the steady state. It is clear that the $N(\xi)$ is always greater than zero in a given region. This means that the steady-state entanglement is obtained. Moreover, the entanglement degree is strongly dependent on the Rabi frequency and the cavity loss. From Fig. 2, we find a fact that the logarithmic neg-

ativity reaches a maximal value when the sum variance is a minimal value. That is to say, for the light field being in the Gaussian states, the stronger the correlation between two cavity modes, the larger the entanglement degree is.

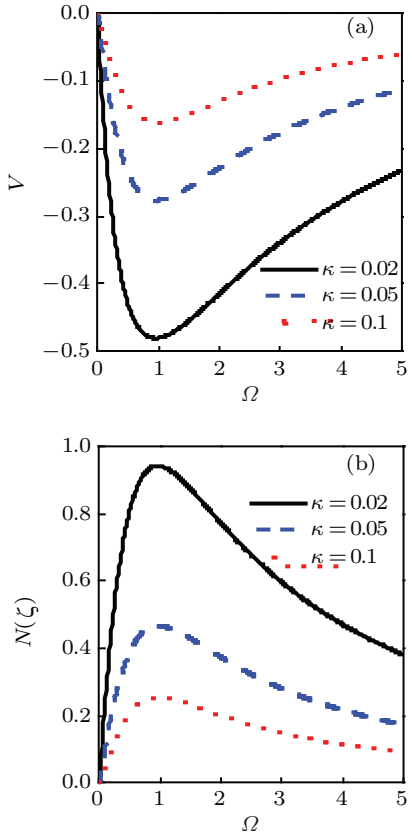


Fig. 2. (colour online) Sum variance V (a) and logarithmic negativity N (b) versus the Rabi frequency Ω of the relative weak pump field. The parameters are chosen to be $\Omega_0 = 50$, $g = 1$, $\kappa = 0.02$ (solid), $\kappa = 0.05$ (dashed), and $\kappa = 0.1$ (dotted).

Shown in Fig. 3 is the effect of the Rabi frequencies Ω and Ω_0 of two classical fields for $g = 1$, $\kappa = 0.02$ (solid), $\kappa = 0.05$ (dashed), and $\kappa = 0.1$ (dotted). It is seen that when the Rabi frequencies Ω and Ω_0 are not too far from each other, the sum variance is minimal. And the sum variance becomes large with the increase of ratio Ω_0/Ω. The influence of atomic coherence on the entanglement properties can be explained as follows. Here we focus on the case of $\Omega_0 \gg \Omega, g, \gamma$. At this moment, the strong control field Ω_0 induces the level splitting, and then the dispersive interaction of the cavity fields with the dressed levels is existent as shown in Fig. 1(b), which leads to the direct two-photon transition. According to the method introduced in Ref. [40], the effective interaction Hamiltonian in a dressed-state basis can be expressed as

$$H_{\rm I} = \Omega\left(\sigma_{41} + \sigma_{14}\right) - \frac{g_1 g_2}{\Omega_0}\left(a_1 a_2 \sigma_{41} + a_1^{\dagger} a_2^{\dagger} \sigma_{14}\right). \quad (8)$$

Equation (8) shows that the effective two-photon transition can occur as one-step process. With the help of the relative weak pump field, the parametric interaction between the two cavity fields is established, which can induce the generation of entanglement. Furthermore, we can see from Eq. (8) that the effective coupling of two modes with the atom is given by $g_e = g_1 g_2/\Omega_0$. When the Rabi frequency of strong control field is very strong, the effective interaction between the cavity field and the atom becomes weak. This makes the entanglement between two cavity modes weak. Actually, the effect of the Rabi frequency on the entanglement can be found via master Eq. (5). When the condition $\Omega_0 \gg \Omega, g, \gamma$ is satisfied, the coefficients are $A_{ll} = B_{ll} = 0$, $A_{12} = B_{21} = 0$, and $A_{21} = -B_{12} = 2g_1 g_2 \Omega/D_0\Omega_0$ with $D_0 = 2\left(\gamma + \Omega^2/\gamma\right)$. This describes the parametric interaction between two cavity modes, which induces the two cavity modes to be an entangled state. As the Rabi frequency Ω_0 increases, the parameters A_{21} and B_{12} become small and the parametric interaction becomes weak. Therefore, the entanglement becomes weak. On the other hand, we note that for the given Rabi frequency Ω_0, the parameters A_{21} and B_{12} have the minimal values when $\Omega = \gamma$. As a result, the correlation degree V has a minimal value in a region of $\Omega \approx \gamma$, as shown in Fig. 2.

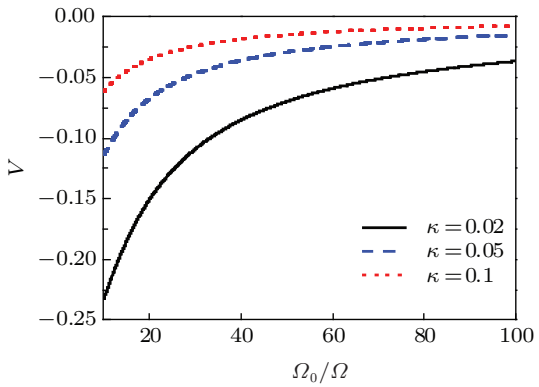


Fig. 3. (colour online) Sum variance V versus ratio Ω_0/Ω. The parameters are chosen to be $g = 1$, $\kappa = 0.02$ (solid), $\kappa = 0.05$ (dashed), and $\kappa = 0.1$ (dotted).

Now, we come to discuss briefly the feasibility of our scheme. Our scheme is based on a simple system, in which the classical fields and quantized fields are all

coupled with the dipole-allowed transitions of a single atom. Thus the proposed scheme for the entanglement generation is experimentally viable as compared with previous directly driven correlated-emission laser system. On the other hand, our double-Λ level structure can be easily obtained in a large number of atoms. For example, we can use sodium atom vapour, where the lower states are at two hyperfine levels $|F=1\rangle$ and $|F=2\rangle$ of $3^2S_{1/2}$, and the upper states are $|F=1\rangle$ and $|F=2\rangle$ of $3^2P_{1/2}$, respectively.

4. Conclusion

In this paper, the entanglement properties are investigated in a single four-level atom resonantly interacting with the cavity modes and two classical fields. Our numerical results show that the two cavity modes are entangled with each other in a steady state. We also utilize the method of logarithmic negativity to analyse the entanglement degree. It is shown that the degree of the entanglement is dependent on the losses of the cavity fields and Rabi frequencies of the classical fields.

Appendix

The expressions of coefficients A_{ij} and $B_{ij}(i,j=1,2)$ are given by

$$A_{11}=\frac{g_1^2}{2T}\left(\Gamma_1+\mathrm{i}\frac{\Omega_0}{2}\right)\rho_{++}^{(0)}+\text{c.c},$$

$$B_{11}=\frac{g_1^2}{2T}\left[\left(\Gamma_1+\mathrm{i}\frac{\Omega_0}{2}\right)\rho_{11}^{(0)}+\mathrm{i}\frac{\Omega}{2}\rho_{14}^{(0)}\right]+\text{c.c},$$

$$A_{12}=\frac{g_1g_2}{4T}\mathrm{i}\Omega\rho_{++}^{(0)}+\text{c.c},$$

$$B_{12}=\frac{g_1g_2}{2T}\left[\left(\Gamma_1+\mathrm{i}\frac{\Omega_0}{2}\right)\rho_{41}^{(0)}+\mathrm{i}\frac{\Omega}{2}\rho_{44}^{(0)}\right]+\text{c.c},$$

$$A_{22}=\frac{g_2^2}{2T}\left[\left(\Gamma_2+\mathrm{i}\frac{\Omega_0}{2}\right)\rho_{44}^{(0)}-\mathrm{i}\frac{\Omega}{2}\rho_{14}^{(0)}\right]+\text{c.c},$$

$$B_{22}=\frac{g_2^2}{2T}\left(\Gamma_2+\mathrm{i}\frac{\Omega_0}{2}\right)\rho_{++}^{(0)}+\text{c.c},$$

$$A_{21}=\frac{g_1g_2}{2T}\left[-\left(\Gamma_2-\mathrm{i}\frac{\Omega_0}{2}\right)\rho_{41}^{(0)}+\mathrm{i}\frac{\Omega}{2}\rho_{11}^{(0)}\right]+\text{c.c},$$

$$B_{21}=\frac{g_1g_2}{4T}\mathrm{i}\Omega\rho_{--}^{(0)}+\text{c.c},$$

where

$$\rho_{14}^{(0)}=\frac{\mathrm{i}\Omega}{D_0},\quad \rho_{41}^{(0)}=\frac{-\mathrm{i}\Omega}{D_0},\quad \rho_{44}^{(0)}=\frac{\Omega^2}{D_0(\gamma_{14}+\gamma_{24})},$$

$$\rho_{++}^{(0)}=\rho_{--}^{(0)}=\frac{\Omega^2\gamma_{24}}{D_0\gamma_{13}(\gamma_{14}+\gamma_{24})},$$

$$\rho_{11}^{(0)}=\frac{(\gamma_{14}+\gamma_{24})^2+\Omega^2}{D_0(\gamma_{14}+\gamma_{24})},$$

$$\Gamma_1=\frac{2(\gamma_{14}+\gamma_{24})+(\gamma_{13}+\gamma_{23})}{4},\quad \Gamma_2=\frac{\gamma_{13}+\gamma_{23}}{4},$$

$$D_0=\gamma_{14}+\gamma_{24}+\frac{2\Omega^2(\gamma_{13}+\gamma_{24})}{(\gamma_{14}+\gamma_{24})\gamma_{13}},$$

and

$$T=\left(\Gamma_1+\mathrm{i}\frac{\Omega_0}{2}\right)\left(\Gamma_2+\mathrm{i}\frac{\Omega_0}{2}\right)+\frac{\Omega^2}{4}.$$

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