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A scheme for generating a multi-photon NOON state based on cavity QED

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Abstract A scheme for generating the two-mode maximally path-entangled state of multi-photon, i.e., the so-called NOON state, through use of cavity QED techniques is proposed. In the present scheme, the entanglement between two spatial modes is established by guiding a laser pulse through a single atom cavity firstly, and then is transferred to the entanglement of the fields of the two cavities. The multi-photon state is generated in either one of the cavities via the strong atom-light interaction stimulated by the laser pulse adiabatically. Consequently, the desired optical NOON state is obtained.

Keywords Controlled SWAP gate · Stimulated Raman adiabatic passage · Multi-photon NOON state

It has been proved some kinds of the nonclassical light fields, such as the squeezed light field or entangled light field, have the ability to push the capability of precision measurements beyond the shot-noise limit which used to be regarded as the ultimate quantum limit. This great enhancement in metrology, imaging, and sensing motivates the development of the new research fields, such as quantum optical metrology,

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quantum imaging and quantum sensing. Among these kinds of nonclassical light fields, the light field in the so-called NOON state with the form $(|N0\rangle_{1,2} + e^{i\varphi}|0N\rangle_{1,2})/\sqrt{2}$ has attracted extensive attention due to its unique character that it can be applied to achieve the Heisenberg limit measurement [1–3]. The Heisenberg limit has a factor $\sqrt{N}$ of improvement relative to the shot-noise limit and has been proven to be the fundamental limit as imposed by the quantum mechanics. Recently, varies theoretical and experimental works for generating the optical NOON state have been reported in succession [4–14].

One of the approaches to produce the optical NOON state is to utilize the source of single-photon [such as the spontaneous parametric down-conversion (SPDC)] and the linear optical elements (for example, beamsplitter) [4–9]. By this means the NOON states with one, two, three, and four photons have been realized in experiment, respectively. However, with the increasing of the number of photons, the complexity of the experiment system will keep on growing and it will be more and more difficult to implement in practice. Meanwhile, the success probability will decrease greatly due to the postselection measurement involved in these schemes. For the purpose of producing NOON state with large number of photons, the theoretical schemes based on nonlinear optical process have been proposed [10,11]. Nevertheless, there is a crucial problem that the nonlinearity obtained in the present experimental condition can not meet the requirement needed in these schemes. Recently, the cavity QED system has aroused general interest, for it provides a platform to achieve the interaction between atoms and optical fields. On account of the advantage of the cavity QED, the generation of the quantum state of the nonclassical optical field has been explored both theoretically and experimentally, including the preparation of photonic NOON state [12–14].

In this paper, we propose a scheme for creating an optical NOON state with large photon numbers by adopting cavity QED techniques. The present scheme involves a two-side optical cavity A and two spatial separated one-side optical cavities B and C. In the cavity A, there is a ladder-type three-level atom F; while in each one of the cavities B and C there are N identical Λ-type three-level atoms. At the beginning, a path-entangled coherent light field is obtained by implanting the laser pules into the cavity A where the state of the atom F will determine whether the pulse is reflected or transmits through the cavity A. Then the entangled coherent light field is applied to stimulate the N atoms trapped in either one of the two cavities B and C located in different path. Through a stimulated Raman adiabatic passage (STIRAP), an N-photon Fock state will be produced from the N atoms. By this method, a maximally path-entangled photonic number state, i.e. the optical NOON state, is produced. Compared with the recent proposals based on atomic interferometer [13,14] where the atoms act as flying bits, the present scheme will greatly decrease the complexity of the operations on the atoms. Meanwhile, since the coupled STIRAP operation is adapted to generate the photonic Fock state in the present scheme, the requirement on the lifetime of the cavity is decreased relatively, and the number of the photons is increased as well.

The procedure for generating the NOON state is depicted schematically in Fig. 1. N identical atoms, each one of which has two long-lived ground state $|f\rangle$ and $|g\rangle$ and an exited state $|e\rangle$, are loaded into the cavities B and C, respectively. Both the

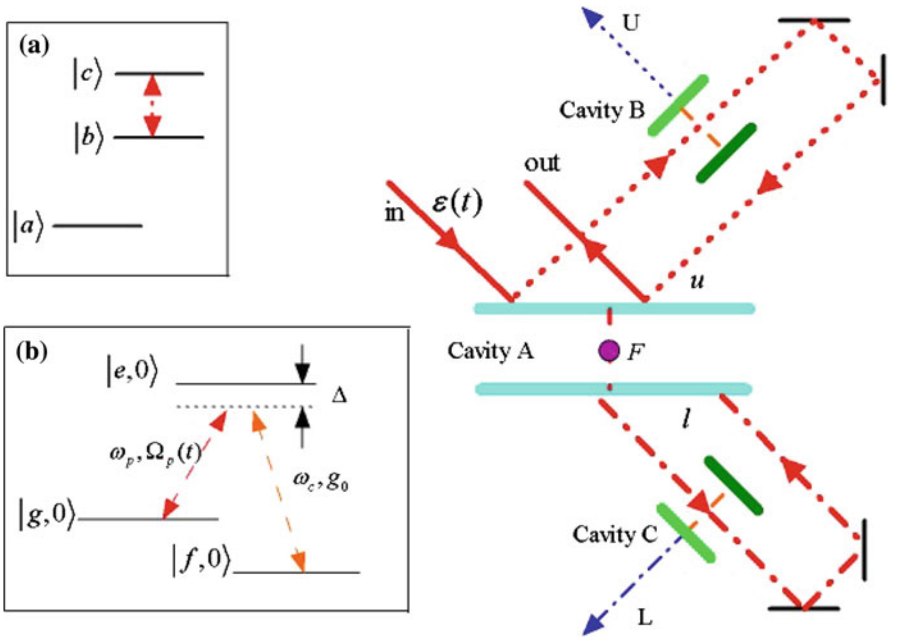

Fig. 1 Schematic diagram of the setup: the cavity A combined with the atom F acts as a quantum CSWAP gate. Due to the effect of the quantum CSWAP gate, the pump-laser pulse stimulates either the atomic ensemble trapped in the cavity B or the atomic ensemble trapped in the cavity C, where multi -photon Fock state can be generated via STIRAP process. And then the photons will emit from the cavity along either the direction U or the direction L. The *insets* show (**a**) the interaction between single atom F and the cavity A; (**b**) the STIRAP process of a single atom in either the cavity B or the cavity C

cavity B and the cavity C support a single eigenmode near resonant to the atomic transition between the level $|f\rangle$ and level $|e\rangle$ with coupling constant g_0 and the detuning $\Delta_c = \omega_c - \omega_f$, where ω_c is the cavity frequency and ω_f is the atomic transition frequency between $|f\rangle \leftrightarrow |e\rangle$. In number representation, the state of the cavity with N-atom can be expressed as a product state $|n_s, n\rangle_{B(C)}$, where $|n_s\rangle$ stands for the Fock state of the atomic mode with the subscript $s = g, e, f$ denoting the energy level of the atoms, and $|n\rangle$ represents the state of the cavity field. Both cavity B and cavity C are prepared in vacuum state initially, and the atoms are in the state $|g\rangle$. Thus, the initial state for each cavity with N atoms then is $\left|N_g, 0\right\rangle_{B(C)}$. Based on the idea elaborated in Refs. [15–17], when the N atoms in each cavity are exposed to a classical light field $\varepsilon(t)$, N-photon state will be generated deterministically from the strong coupled atom-cavity system through the adiabatically driven stimulated Raman transition between the two ground states of each atom. Herein, the pump laser is arranged to travel cross the cavity B (or cavity C) transverse to its axis. The frequency of the pump pulse ω_p is detuned with that of the atomic transition $|g\rangle \leftrightarrow |e\rangle$ denoted as ω_g by an amount $\Delta_p = \omega_p - \omega_g$. And its Rabi frequency $\Omega_p(t)$ is controlled to vary with the time t adiabatically. Under the condition $\Delta_p = \Delta_c = \Delta$, the interaction Hamiltonian for the system consisting of the atomic ensemble, the cavity B (or the cavity C) and the pump field can be described by [16]

$$H_{B(C)} = \sum_{i=1}^{N}[-\Delta\,|e\rangle\langle e| + \Omega_p(t)(|e\rangle\langle g| + |g\rangle\langle e|)$$
$$+g_0(a_{B(C)}\,|e\rangle\langle f| + a^{\dagger}_{B(C)}\,|f\rangle\langle e|)]_i, \tag{1}$$

where $a_{B(C)}$ ($a^{\dagger}_{B(C)}$) is the annihilation (creation) operator of the cavity mode. During the adiabatic process, there are two conserved quantities, one is the total number of the atoms T and the other is the difference value D between the number of the photons in the cavity and that of the atoms in the state $|f\rangle$. Corresponding to a given set of $T = N$ and $D = 0$, the dynamics of the system is governed by the dark state expressed as follows

$$|\psi(t)\rangle_{B(C)} = \frac{1}{Z}\sum_{j=0}^{N}\frac{[-\Omega_p(t)/g_0]^j}{\sqrt{(N-j)!j!j!}}\left|j_f, j\right\rangle_{B(C)}, \tag{2}$$

where Z is the normalization factor. That means there are j photons in the cavity, j atoms in level $|f\rangle$, all the other atoms are in level $|g\rangle$, and no atom is in the excited state $|e\rangle$. With the Rabi frequency of the pump field increasing to $\Omega_p(t) \gg g_0$ within the adiabaticity constraint, the state of the system can evolute from $\left|N_g, 0\right\rangle_{B(C)}$ to $\left|N_f, N\right\rangle_{B(C)}$, i.e., the N atoms are transferred from the state $|g\rangle$ to the state $|f\rangle$ and N photons are generated in the cavity B (or the cavity C).

In order to attain the optical NOON state, the pump pulse is fed into the two-sided cavity A before interacting with the atomic ensemble, as shown in Fig. 1. The cavity A is initially prepared in vacuum state and the frequency of the cavity mode is resonant to the pump-laser. The transition between the energy level $|b\rangle$ and $|c\rangle$ of atom F trapped in cavity A, is supported by the cavity A with the coupling constant g_A, while the state $|a\rangle$ of atom F is decoupled from the cavity mode a. In the interaction picture, the Hamiltonian of the interaction between the atom and the cavity field can be written as

$$H = g_A(\sigma^+ a + \sigma^- a^+), \tag{3}$$

where $\sigma^+ = |c\rangle\langle b|$ is the atomic raising operator. The cavity mode a is resonantly driven by the input laser pulse $\varepsilon(t)$ incident on the mirror of the cavity. As a two-sided cavity, there are two input ports and two output ports, and the equation of motion for the cavity field is then given by [18]

$$\frac{da(t)}{dt} = -\frac{\mathrm{i}}{\hbar}[a(t), H] - \frac{1}{2}(\kappa_u + \kappa_l)a(t) + \sqrt{\kappa_u}a_u^{in}(t) + \sqrt{\kappa_l}a_l^{in}(t)$$
$$= -\mathrm{i}g_A\sigma^-(t) - \frac{1}{2}(\kappa_u + \kappa_l)a(t) + \sqrt{\kappa_u}a_u^{in}(t) + \sqrt{\kappa_l}a_l^{in}(t), \tag{4}$$

where the subscripts u and l stand for the two spatial modes at the upper side and at the lower side of the cavity A, respectively, $a_u^{in}(t)$ and $a_l^{in}(t)$ denote the field operators for the input pulse from the upper side and the lower side, respectively, with $\left\langle a^{in}_{u(l)}(t)\right\rangle = \varepsilon(t)$ and $[a^{in}_{u(l)}(t), a^{in\dagger}_{u(l)}(t')] = \delta(t-t')$. κ_u and κ_l are the cavity decay rates of upper side and lower side cavity mirrors. The relationship between the input and output modes can be expressed as [18]

$$a_{u(l)}^{out}(t) = -a_{u(l)}^{in}(t) + \sqrt{\kappa_{u(l)}}a(t). \tag{5}$$

In addition, the equation of motion for the atomic operator is in the form

$$\frac{d\sigma^{-}(t)}{dt} = -\mathrm{i}[\sigma^{-}(t), H] - \frac{1}{2}\gamma\sigma^{-}(t) + \sqrt{\gamma}\sigma^{z}V, \tag{6}$$

where γ is the spontaneous emission rate of the atomic level $|c\rangle$, $\sigma^{z} = |c\rangle\langle c| - |b\rangle\langle b|$, and V is the corresponding vacuum noise operator. In the adiabatic limit, the population in the excited state $|c\rangle$ can be negligible. Thus, the above equation can be rewritten as

$$\frac{d\sigma^{-}(t)}{dt} = -\mathrm{i}g_{A}Pa(t) - \frac{1}{2}\gamma\sigma^{-}(t) + \sqrt{\gamma}PV, \tag{7}$$

with $P = |b\rangle\langle b|$. By taking the Fourier transforms, the solution of the output field of the cavity A is obtained

$$a_{u(l)}^{out}(\omega) = R(\omega)a_{u(l)}^{in}(\omega) + T(\omega)a_{l(u)}^{in}(\omega) + M(\omega)V(\omega) \tag{8}$$

where $a_{u(l)}^{in}(\omega)$ and $V(\omega)$ are the Fourier transforms of $a_{u(l)}^{in}(t)$ and V, and

$$\begin{aligned}
R(\omega) &= \frac{i\omega + g_{A}^{2}P/(i\omega - \gamma/2)}{\kappa_{A} - i\omega - g_{A}^{2}P/(i\omega - \gamma/2)}\\
T(\omega) &= \frac{\kappa_{A}}{\kappa_{A} - i\omega - g_{A}^{2}P/(i\omega - \gamma/2)}\\
M(\omega) &= \frac{i\sqrt{\kappa_{A}\gamma}g_{A}P/(i\omega - \gamma/2)}{\kappa_{A} - i\omega - g_{A}^{2}P/(i\omega - \gamma/2)}
\end{aligned}$$

This result is similar to what was demonstrated in Ref. [19]. In the conditions $\gamma \ll g_{A}^{2}/\kappa_{A}$ and that the pulse bandwidth $\delta\omega$ is much smaller than the rates κ_{A} and g_{A}^{2}/κ_{A}, the output field is controlled by the state of the atom F. When the atom F is in the state $|b\rangle$, then $R(\omega) \sim -1$ and $a_{u(l)}^{out}(\omega) \sim a_{u(l)}^{in}(\omega)$; whereas, if the atom F is in the state $|a\rangle$, there will be $T(\omega) \sim 1$ and $a_{u(l)}^{out}(\omega) \sim a_{l(u)}^{in}(\omega)$. Thus, when the atom F is prepared in state $|b\rangle$, the transmission spectrum of the cavity will be modified by the strong atom-cavity coupling, and then the pump-laser pulse will be reflected by the cavity mirror. On the other hand, if the atom F is in the state $|a\rangle$, the pump-laser pulse will transmit through the cavity and loose out from the other side mirror directly.

In the present scheme, the atom F is prepared in the superposition of the states $|a\rangle$ and $|b\rangle$, i.e. $(|a\rangle + |b\rangle)/\sqrt{2}$. Suppose the pumping pulse is injected into the cavity A from the upper side mirror. At this stage, the state of the light field on the upper side of the cavity can be described as a coherent state $|\alpha\rangle$, and that on the lower side can be regarded as a vacuum state $|0\rangle$. The system consisting of the auxiliary atom F and the light field on both sides of the cavity A will undergo the following evolution

$$\frac{1}{\sqrt{2}}(|a\rangle + |b\rangle)_F\, |\alpha\rangle_u\, |0\rangle_l \to \frac{1}{\sqrt{2}}(|a\rangle_F\, |0\rangle_u\, |\alpha\rangle_l + |b\rangle_F\, |\alpha\rangle_u\, |0\rangle_l). \tag{9}$$

It can be made out from the above equation that an entangled light field between the two spatial modes is established. In fact, the cavity A with the trapped atom F can be regard as a quantum controlled SWAP (CSWAP) gate, which makes two target qubits, spatial modes u and l, exchange their quantum states conditioned on the state of the control qubit atom F. As shown in Fig. 1, the quantum CSWAP gate makes the pump-laser pulse either travel through the cavity A and lighten the atoms in cavity C; or be reflected by the mirror of the cavity A and interact with the atoms in cavity B.

Taking the STIRAP process discussed aforementioned into the consideration, we find that when the auxiliary atom F is prepared in the state $|a\rangle$, then the pump laser will transmit to the lower side of the cavity A and the N-photon Fock state will be generated in the cavity C ; in contrast, if the state of the atom F is $|b\rangle$, then the pump laser will be reflected back to the upper side of the cavity A and the N-photon Fock state will be produced in the cavity B. The whole system experiences the following evolution

$$\begin{aligned}&\frac{1}{\sqrt{2}}(|a\rangle_F\, |0\rangle_u\, |\alpha\rangle_l + |b\rangle_F\, |\alpha\rangle_u\, |0\rangle_l) \otimes \left|N_g, 0\right\rangle_B \left|N_g, 0\right\rangle_C \\ &\quad\to \frac{1}{\sqrt{2}}(|a\rangle_F\, |0\rangle_u\, |\alpha\rangle_l \left|N_g, 0\right\rangle_B \left|N_f, N\right\rangle_C + |b\rangle_F\, |\alpha\rangle_u\, |0\rangle_l \left|N_f, N\right\rangle_B \left|N_g, 0\right\rangle_C).\end{aligned} \tag{10}$$

Due to the cavity decay, these photons emit out of the cavity through the mirror severed as an output coupler. If the photons are generated in the cavity B, then they will travel along the direction U; otherwise, the photons will propagate along the direction L, as displayed in Fig. 1. Therefore, the state of the whole system including the spatial modes U and L can be written as

$$\begin{aligned}&\frac{1}{\sqrt{2}}(|a\rangle_F\, |0\rangle_u\, |\alpha\rangle_l \left|N_g, 0\right\rangle_B \left|N_f, 0\right\rangle_C |0\rangle_U\, |N\rangle_L \\ &\quad + |b\rangle_F\, |\alpha\rangle_u\, |0\rangle_l \left|N_f, 0\right\rangle_B \left|N_g, 0\right\rangle_C |N\rangle_U\, |0\rangle_L).\end{aligned} \tag{11}$$

After this process, all the sub-systems are entangled, and it is necessary to disentangle the unwanted sub-system from the entangled system.

For this purpose, two re-pumping lasers, which are resonant with the $|f\rangle \leftrightarrow |e\rangle$ transition of the atoms, are fitted on both the cavity B and the cavity C, respectively. When the re-pumping lasers are turned on, the atoms in the state $|f\rangle$ are pumped to the state $|e\rangle$ by the re-pumping laser pulses, and then decays to the initial state $|g\rangle$ spontaneously. Thus, the states of the cavity including the trapped atomic ensembles will be transformed back to the initial state $\left|N_g, 0\right\rangle$

from the state $\left|N_f, 0\right\rangle$, and the whole system will be converted into the following state

$$\frac{1}{\sqrt{2}}(|g_1\rangle_{F_1}|0\rangle_u|\alpha\rangle_l|0\rangle_U|N\rangle_L+|e_1\rangle_{F_1}|\alpha\rangle_u|0\rangle_l|N\rangle_U|0\rangle_L)\otimes\left|N_g,0\right\rangle_B\left|N_g,0\right\rangle_C. \tag{12}$$

That means the cavities B and C with the atomic ensembles are disentangled from the system.

At the same time, the pump pulse is injected back to the cavity A. Since the cavity A and the atom F form a quantum CSWAP gate, the entangled system undergoes the following evolution

$$\begin{aligned}&\frac{1}{\sqrt{2}}(|a\rangle_F|0\rangle_u|\alpha\rangle_l|0\rangle_U|N\rangle_L+|b\rangle_F|\alpha\rangle_u|0\rangle_l|N\rangle_U|0\rangle_L)\\&\to\frac{1}{\sqrt{2}}(|a\rangle_F|0\rangle_U|N\rangle_L+|b\rangle_F|N\rangle_U|0\rangle_L)\otimes|\alpha\rangle_u|0\rangle_l\end{aligned} \tag{13}$$

Clearly, the information of the spatial modes u and l is erased from the pump laser. The last step is to let the control atom F pass through a Ramsey field which can realize the rotation $|a\rangle\to\frac{1}{\sqrt{2}}(|a\rangle+|b\rangle)$ and $|b\rangle\to\frac{1}{\sqrt{2}}(|a\rangle-|b\rangle)$, and then detect it in the basis $\{|a\rangle,|b\rangle\}$, so that the atom F is separable from entangled system. No matter what the result of the detection of the atom F is, the remainder entangled system will reduce to

$$\frac{1}{\sqrt{2}}(|0\rangle_U|N\rangle_L\pm|N\rangle_U|0\rangle_L), \tag{14}$$

which is just the desired state, i.e. a two-mode path-entangled photon-number state.

From the perspective of the feasibility in practice, we give a brief discussion on the present scheme. Firstly, to realize the quantum CSWAP gate composed of the cavity A and the single atom F, the condition of the bandwidth of the pump pulse $\delta\omega\ll\kappa_A, g_A^2/\kappa_A$ is required. This requirement can be satisfied with the present cavity QED technique in the light of the typical parameters for strong coupled atom-cavity system $(g_A,\kappa_A,\gamma_A)=2\pi\times(32,4.2,2.6)$ MHz and $\delta\omega=0.1\kappa_A$. At this moment, the fidelity of the quantum CSWAP gate, which characterizes the effect of this pulse shape distortion, will be 99.75 %, as studied in the Ref. [19]. Secondly, the STIRAP process, which is applied to generate the photonic Fock state in the present scheme, has been studied theoretically and experimentally in great detail in Refs. [15–17]. We notice that in the experiment for generating the determined single-photon source through the similar STIRAP process it takes only 2 μs to increase the Rabi frequency of the pump laser from zero to $\Omega_p>2g_0$ [17]. Combined with the numerical simulations in Ref. [16], the STIRAP process can be implemented in a strong coupling cavity with the parameters, for example, $(g_0,\gamma,\kappa)/2\pi=(120,2.5,35)$ MHz [20], and the time for this process is in microsecond scale. This implies that the requirement on the lifetime of the cavity is loosened compared with the previous works. Besides, during the STIRAP process there is no atom in the excited state, and the large cavity detuning also depresses the spontaneous emission, the effect of the spontaneous emission of the atoms can be ignored. However, it should be pointed out that the present scheme cannot be applied to generate the NOON state containing arbitrary number of the photons when the following two factors are taken into account. One factor is that the collective interaction between the atomic ensemble and the cavity requires all of the atoms in the cavity are exposed to the same coupling strength with the cavity as well as the pump field. And the other factor is that the integrate noises increase with the increasing of the number of the atoms, and would beyond one photon when the number of the atoms exceeds 200. Therefore, it is necessary to restrict the total number of atoms trapped in the cavity B (or C) to about 100; consequently, the number of photons in our scheme is not arbitrary but is up to 100. In spite of that, the number of photons has been improved relative to the previous works [13, 14]. In principle, we believe that the present scheme is feasible for manipulation in practice.

In summary, we have proposed a physical scheme for generating the maximally path-entangled state with multi-photon based on strong coupling interaction between atom and cavity. The whole process for generating the desired optical NOON state can be divided into two steps, one step for generating entanglement between two spatial modes firstly and then the other step for entanglement transferring. In the first step, an entangled coherent light field is produced by using a quantum CSWAP gate consisting of a two-side cavity A and a three-level atom F. Then, in the second step, the entanglement is transferred from the light field in coherent state to the field of the two spatially separated cavities B and C in Fock state through the STIRAP-type adiabatic transition of the atom ensemble trapped in either one of the two cavities. In comparison with the previous works [13, 14], our approach seems to be more feasible in the practical operation. On the one hand, the entanglement between two spatial modes is established firstly on the coherent light field instead of the flying atom utilized in Refs. [13, 14], and thus the control on the coherent light field takes place of the complex operation on atom. On the other hand, the N-photon Fock state is obtained from the collective interaction between the atom ensemble and the cavity so that the lifetime of the cavity is loosen and the number of photons can be increased greatly compared with the previous schemes in which the photonic Fock state is produced through the excitation and deexcitation of N atoms (one atom produces a photon at a time) [13] or through N-times excitation and deexcitation of a single atom [14]. We hope that the present scheme will benefit to the research on the generation of entangled state, and the approach described here can be applied to generate NOON state with about 100 photons deterministically in the near future with the rapid developments on the realization of the strong coupling optical cavity and the possibility of generating deterministic photon number state inside a high-Q cavity.

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