Complete four-photon cluster-state analyzer based on cross-Kerr nonlinearity*

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We propose a method to construct an optical cluster-state analyzer based on cross-Kerr nonlinearity combined with linear optics elements. In the scheme, we employ two four-qubit parity gates and the controlled phase gate (CPG) from only the cross-Kerr nonlinearity and show that all the orthogonal four-qubit cluster states can be completely identified. The scheme is significant for the large-scale quantum communication and quantum information processing networks. In addition, the scheme is feasible and deterministic under current experimental conditions.

Keywords: cluster-state analyzer, quantum information, parity gate, cross-Kerr nonlinearity

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1. Introduction

Quantum entanglement, as one of the most important resources for quantum information science, can be widely used in quantum teleportation,[1,2] quantum key distribution,[3,4] quantum dense coding,[5] quantum secret sharing,[6,7] and so on. However, in recent years, many people have begun to pay attention to entanglement analysis, which is a significant process to obtain quantum state information and realize quantum information processing (QIP). The entanglement analysis of bipartite systems and tripartite systems, e.g., Bell-state analyzer and Greenberger–Horne–Zeilinger (GHZ) state analyzer, have been well studied.[8–13] As we know, as one of the possible candidates for engineering quantum entanglement, optical systems always attract much attention.[14–16] Photons are often considered as good flying qubits, which are most suitable for quantum network communication tasks owing to their high speed and robustness against decoherence. Therefore, people always choose polarization-entangled photon pairs to fulfil the tasks of quantum computation.[17] In 1998, the first photon GHZ-state analyzer was put forwarded based on linear-optics elements by Pan and Zeilinger.[12] However, because of the probabilistic nature of linear optical quantum gates, only two of the eight three-photon GHZ states can be distinguished. In attempt to overcome the probabilistic properties of linear optics QIP, Qian *et al.*[13] proposed an universal GHZ-state analyzer based on a parity detector which was composed of basic linear elements and weak cross-Kerr nonlinearity. By far, most QIP schemes are achieved based on weak cross-Kerr nonlinearity and an intense coherent pulse.[18] Nevertheless, several QIP schemes based on giant cross-Kerr nonlinearity were also proposed.[19–21] For instance, Vitali *et al.*[19] presented a scheme for Bell-state measurement via giant cross-Kerr nonlinearity and linear optical elements; the essential difficulty of their scheme is the implementation of the giant cross-Kerr nonlinearity. Fortunately, some significant schemes for achieving giant cross-Kerr nonlinearity have been proposed. Especially, references [20] and [22] have given specific ways to obtain π-cross phase shift. As we know, the cluster state is more immune to decoherence than the GHZ state and is a powerful tool for performing nonlocality tests in QIP.[23–25] Due to these advantages, the cluster has been widely studied theoretically and experimentally.[26–29] Therefore, a four-photon cluster-state analyzer is also worth studying, which is significant for large-scale one-way quantum computing.[30,31] Enlightened by these above works, we propose a four-photon cluster-state analyzer via cross-Kerr nonlinearity and photon resolving measurement.

The structure of this paper is organized as follows. In Section 2, we introduce the general method of the constructing a cluster-state analyzer. Then, we give the discussion in Section 3 and the conclusion in Section 4.

2. Implementation of cluster-state analyzer

Before describing our cluster state analyzer, we firstly review the control phase gate (CPG) using only the cross-Kerr nonlinearity mentioned in Ref. [32]. The cross-Kerr nonlinearity involving vertically polarization states has a Hamiltonian of the form

$$\hat{H}_{\mathrm{K}} = \hbar\chi\hat{n}_{1\mathrm{V}}\hat{n}_{2\mathrm{V}}, \tag{1}$$

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where $\hat{n}_{1V}$ and $\hat{n}_{2V}$ are the vertically polarized photon number operators of spatial modes 1 and 2, respectively, and χ is the strength of the nonlinearity. We consider a combined system of the two modes in an arbitrary two-photon polarization initially prepared in state

$$|\phi\rangle_{12} = \alpha|HH\rangle + \beta|HV\rangle + \gamma|VH\rangle + \delta|VV\rangle, \tag{2}$$

where $|H\rangle$ and $|V\rangle$ denote the horizontal and vertical polarizations, respectively. Let two photons respectively go through the probe mode and the signal mode of the cross-Kerr medium, the cross-Kerr nonlinearity causes the state changing of the combined system

$$\begin{aligned} &\exp(-\mathrm{i}\chi t\hat{n}_{1V}\hat{n}_{2V})|\phi\rangle_{12} \\ &= \alpha|HH\rangle + \beta|HV\rangle + \gamma|VH\rangle + \delta\exp(-\mathrm{i}\hat{n}_{1V}\hat{n}_{2V}\theta)|VV\rangle, \end{aligned} \tag{3}$$

where $\theta = \chi t$ denotes the phase shift induced by cross-Kerr nonlinearity and t is the interaction time for two optical fields in the cross-Kerr medium. When $\theta = \pi$, the action of cross-Kerr medium produces a π phase shift on the $|VV\rangle$ term, equation (3) can be written as

$$|\phi\rangle_{12} = \alpha|HH\rangle + \beta|HV\rangle + \gamma|VH\rangle - \delta|VV\rangle. \tag{4}$$

It is easy to see that a photonic two-qubit CPG is naturally implemented. Next, we introduce how to achieve a cluster-state analyzer.

Firstly, we give all sixteen complete orthogonal cluster states as

$$\begin{aligned} |\psi_{\mathrm{a}}^{\mu\nu}\rangle &= \frac{1}{2}(|H\mu H\nu\rangle + |H\mu V\overline{\nu}\rangle + |V\overline{\mu}H\nu\rangle - |V\overline{\mu}V\overline{\nu}\rangle), \\ |\psi_{\mathrm{b}}^{\mu\nu}\rangle &= \frac{1}{2}(|H\mu H\nu\rangle + |H\mu V\overline{\nu}\rangle - |V\overline{\mu}H\nu\rangle + |V\overline{\mu}V\overline{\nu}\rangle), \\ |\psi_{\mathrm{c}}^{\mu\nu}\rangle &= \frac{1}{2}(|H\mu H\nu\rangle - |H\mu V\overline{\nu}\rangle + |V\overline{\mu}H\nu\rangle + |V\overline{\mu}V\overline{\nu}\rangle), \\ |\psi_{\mathrm{d}}^{\mu\nu}\rangle &= \frac{1}{2}(|H\mu H\nu\rangle - |H\mu V\overline{\nu}\rangle - |V\overline{\mu}H\nu\rangle - |V\overline{\mu}V\overline{\nu}\rangle), \end{aligned} \tag{5}$$

where $\mu,\nu \in \{H,V\}$, $\overline{\mu}(\overline{\nu})$ is orthogonal polarization states of $\mu(\nu)$.

In order to distinguish the above sixteen states, we introduce a parity gate. It consists of the two two-qubit parity gates composed in Ref. [33], as shown in Fig. 1.

For the left-hand side parity gate, suppose that the state of photon 1 and photon 2 are one of the following four possible polarization states ($|H\rangle_1|H\rangle_2$, $|V\rangle_1|V\rangle_2$, $|H\rangle_1|V\rangle_2$, $|V\rangle_1|H\rangle_2$). The action of the PBS_1, cross-Kerr nonlinearities, and the phase shifter on the intense coherent probe beam evolves the initially combined system to

$$\begin{aligned} &|H\rangle_1|H\rangle_2 \longrightarrow |H\rangle_1|H\rangle_2|\alpha\rangle; \\ &|V\rangle_1|V\rangle_2 \longrightarrow |V\rangle_1|V\rangle_2|\alpha\rangle; \\ &|H\rangle_1|V\rangle_2 \longrightarrow |H\rangle_1|V\rangle_2|\alpha\mathrm{e}^{\mathrm{i}\theta}\rangle; \\ &|V\rangle_1|H\rangle_2 \longrightarrow |V\rangle_1|H\rangle_2|\alpha\mathrm{e}^{-\mathrm{i}\theta}\rangle. \end{aligned} \tag{6}$$

By performing the displacement $D(-\alpha) = \exp(\alpha^* a - \alpha a^\dagger)$ on the probe beam, the combined state of the qubits and probe beam is

$$\begin{aligned} &|H\rangle_1|H\rangle_2 \longrightarrow |H\rangle_1|H\rangle_2|0\rangle; \\ &|V\rangle_1|V\rangle_2 \longrightarrow |V\rangle_1|V\rangle_2|0\rangle; \\ &|H\rangle_1|V\rangle_2 \longrightarrow \mathrm{e}^{-\mathrm{i}\alpha^2\sin\theta}|H\rangle_1|V\rangle_2|\alpha(\mathrm{e}^{\mathrm{i}\theta}-1)\rangle; \\ &|V\rangle_1|H\rangle_2 \longrightarrow \mathrm{e}^{\mathrm{i}\alpha^2\sin\theta}|V\rangle_1|H\rangle_2|\alpha(\mathrm{e}^{-\mathrm{i}\theta}-1)\rangle. \end{aligned} \tag{7}$$

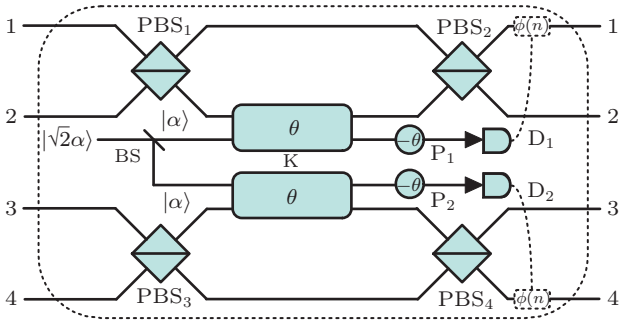


Fig. 1. (color online) Schematic setup of two photonic two-qubit parity gates. PBS oriented in the ($|H\rangle$, $|V\rangle$) basis will always transmit H-polarized photons and reflect V-polarized photons, K is a cross-Kerr medium, P_1 and P_2 are static phase shifters that impose a phase shift $-\theta$ on the coherent state, BS is a balanced 50/50 beam splitter, $\phi(n)$ is phase shift dependents on the result of the photon number measurement on the probe beam, D_1 and D_2 are two photon number detectors.

Another parity gate has the same evolutionary process. Thus, utilizing photon-number detectors D_1 and D_2, we can get the following measurement results. If both detectors 1 and 2 can not detect the photon, we obtain state $|\psi_i^{00}\rangle, (i = \mathrm{a,b,c,d})$; if the detector 1 registers photons and the detector 2 can not detect the photon, we obtain state $|\psi_j^{10}\rangle, (j = \mathrm{a,b,c,d})$; if the detector 2 registers photons and the detector 1 can not detect the photon, we obtain state $|\psi_k^{01}\rangle, (k = \mathrm{a,b,c,d})$; if both detectors 1 and 2 register the photons, we obtain state $|\psi_z^{11}\rangle, (z = \mathrm{a,b,c,d})$. Note that after the photon number measurement, if $n > 0$, a photon number measurement will project $\mathrm{e}^{-\mathrm{i}\alpha^2\sin\theta}|H\rangle_1|V\rangle_2|\alpha(\mathrm{e}^{\mathrm{i}\theta}-1)\rangle$ and $\mathrm{e}^{\mathrm{i}\alpha^2\sin\theta}|H\rangle_1|V\rangle_2|\alpha(\mathrm{e}^{-\mathrm{i}\theta}-1)\rangle$ into the states $\mathrm{e}^{\mathrm{i}\phi(n)}|H\rangle_1|V\rangle_2$ and $\mathrm{e}^{-\mathrm{i}\phi(n)}|H\rangle_1|V\rangle_2$, respectively, where $\phi(n) = n\tan^{-1}[\cot(\theta/2)]$. The phase shift ($\phi(n)$) can be simply removed by phase shifters. Up to now, all sixteen states are divided into four groups.

Next, let the photons 2 and 3 pass through the two half wave plates. Here, the effect of half wave plates HWP_1 and HWP_2, with its major axis angle $\theta = \pi/4$ to horizontal direction, is $|H\rangle \leftrightarrow |V\rangle$, e.g., the σ_x operation is implemented, as shown in Fig. 2. If we obtain state $|\psi_i^{00}\rangle$, $(i = \mathrm{a,b,c,d})$, we perform a identity operator on photons 2 and 4, respectively; if we obtain state $|\psi_j^{10}\rangle$, $(j = \mathrm{a,b,c,d})$, we only perform a σ_x operation on photon 2; if we obtain state $|\psi_k^{01}\rangle$, $(k = \mathrm{a,b,c,d})$, we only perform a σ_x operation on photon 4; if we obtain

state $|\psi_z^{11}\rangle$, $(z = \mathrm{a,b,c,d})$, σ_x operations are performed on photons 2 and 4, respectively. Therefore, via classical information feed-forward process, we can transform all the sixteen complete orthogonal cluster states into $|\psi_i^{00}\rangle$, $(i = \mathrm{a,b,c,d})$.

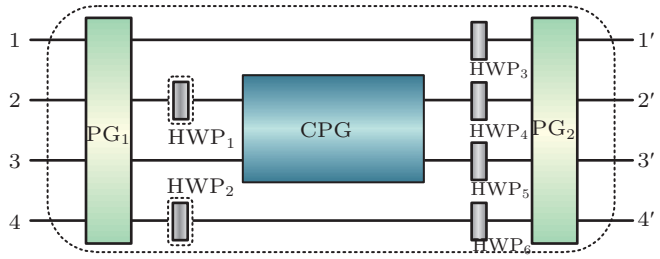


Fig. 2. (color online) Schematic diagram of the cluster-state analyzer. CPG: control phase gate. $\mathrm{PG_1}$ and $\mathrm{PG_2}$: two parity gates of the same principle. $\mathrm{PG_1}$ has two detectors named, $\mathrm{D_1}$ and $\mathrm{D_2}$, respectively, $\mathrm{PG_2}$ has two detectors named, $\mathrm{D_3}$ and $\mathrm{D_4}$, respectively. HWP: half wave plate.

Then, a CPG operation is applied on photons 2 and 3. Here, the cross-Kerr medium is used as a CPG as discussed above. Therefore, for the state $|\psi_i^{00}\rangle$, we can get the following four states

$$\begin{aligned}
|\phi_{\mathrm{a}}^{00}\rangle &= \frac{1}{2}[(|HHHH\rangle + |HHVV\rangle) \\
&\quad + (|VVHH\rangle + |VVVV\rangle)]_{1234}, \\
|\phi_{\mathrm{b}}^{00}\rangle &= \frac{1}{2}[(|HHHH\rangle + |HHVV\rangle) \\
&\quad - (|VVHH\rangle - |VVVV\rangle)]_{1234}, \\
|\phi_{\mathrm{c}}^{00}\rangle &= \frac{1}{2}[(|HHHH\rangle - |HHVV\rangle) \\
&\quad + (|VVHH\rangle - |VVVV\rangle)]_{1234}, \\
|\phi_{\mathrm{d}}^{00}\rangle &= \frac{1}{2}[(|HHHH\rangle - |HHVV\rangle) \\
&\quad - (|VVHH\rangle + |VVVV\rangle)]_{1234}. \qquad (8)
\end{aligned}$$

Later, let four photons pass four HWPs, as shown in Fig. 2. Here, all HWPs with their major axis angle $\theta = \pi/8$ to the horizontal direction, have the action given by the transformation

$$\begin{aligned}
|H\rangle &\longrightarrow \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle), \\
|V\rangle &\longrightarrow \frac{1}{\sqrt{2}}(|H\rangle - |V\rangle). \qquad (9)
\end{aligned}$$

After four photon pulses pass the $\mathrm{HWP}_i (i = 3,4,5,6)$ simultaneously, the resulting states of photon system are given by

$$\begin{aligned}
|\varphi_{\mathrm{a}}^{00}\rangle &= \frac{1}{2}[(|HHHH\rangle + |VVHH\rangle) \\
&\quad + (|HHVV\rangle + |VVVV\rangle)]_{1234}, \\
|\varphi_{\mathrm{b}}^{00}\rangle &= \frac{1}{2}[(|HVHH\rangle + |VHHH\rangle) \\
&\quad + (|HVVV\rangle + |VHVV\rangle)]_{1234}, \\
|\varphi_{\mathrm{c}}^{00}\rangle &= \frac{1}{2}[(|HHVH\rangle + |VVVH\rangle) \\
&\quad + (|HHHV\rangle + |VVHV\rangle)]_{1234}, \\
|\varphi_{\mathrm{d}}^{00}\rangle &= \frac{1}{2}[(|HVVH\rangle + |VHVH\rangle) \\
&\quad + (|HVHV\rangle + |VHHV\rangle)]_{1234}. \qquad (10)
\end{aligned}$$

Table 1. Results of photon polarization measurement corresponding to the initial cluster states. (N: the detector can not detect the photon; Y: the detector registers the photon).

Initial cluster states	Measurement results
$\|\psi_{\mathrm{a}}^{00}\rangle = \frac{1}{2}(\|HHHH\rangle + \|HHVV\rangle + \|VVHH\rangle - \|VVVV\rangle)_{1234}$	$D_{1N}\ D_{2N}\ D_{3N}\ D_{4N}$
$\|\psi_{\mathrm{b}}^{00}\rangle = \frac{1}{2}(\|HHHH\rangle + \|HHVV\rangle - \|VVHH\rangle + \|VVVV\rangle)_{1234}$	$D_{1N}\ D_{2N}\ D_{3Y}\ D_{4N}$
$\|\psi_{\mathrm{c}}^{00}\rangle = \frac{1}{2}(\|HHHH\rangle - \|HHVV\rangle + \|VVHH\rangle + \|VVVV\rangle)_{1234}$	$D_{1N}\ D_{2N}\ D_{3N}\ D_{4Y}$
$\|\psi_{\mathrm{d}}^{00}\rangle = \frac{1}{2}(\|HHHH\rangle - \|HHVV\rangle - \|VVHH\rangle - \|VVVV\rangle)_{1234}$	$D_{1N}\ D_{2N}\ D_{3Y}\ D_{4Y}$
$\|\psi_{\mathrm{a}}^{01}\rangle = \frac{1}{2}(\|HHHV\rangle + \|HHVH\rangle + \|VVHV\rangle - \|VVVH\rangle)_{1234}$	$D_{1N}\ D_{2Y}\ D_{3N}\ D_{4N}$
$\|\psi_{\mathrm{b}}^{01}\rangle = \frac{1}{2}(\|HHHV\rangle + \|HHVH\rangle - \|VVHV\rangle + \|VVVH\rangle)_{1234}$	$D_{1N}\ D_{2Y}\ D_{3Y}\ D_{4N}$
$\|\psi_{\mathrm{c}}^{01}\rangle = \frac{1}{2}(\|HHHV\rangle - \|HHVH\rangle + \|VVHV\rangle + \|VVVH\rangle)_{1234}$	$D_{1N}\ D_{2Y}\ D_{3N}\ D_{4Y}$
$\|\psi_{\mathrm{d}}^{01}\rangle = \frac{1}{2}(\|HHHV\rangle - \|HHVH\rangle - \|VVHV\rangle - \|VVVH\rangle)_{1234}$	$D_{1N}\ D_{2Y}\ D_{3Y}\ D_{4Y}$
$\|\psi_{\mathrm{a}}^{10}\rangle = \frac{1}{2}(\|HVHH\rangle + \|HVVV\rangle + \|VHHH\rangle - \|VHVV\rangle)_{1234}$	$D_{1Y}\ D_{2N}\ D_{3N}\ D_{4N}$
$\|\psi_{\mathrm{b}}^{10}\rangle = \frac{1}{2}(\|HVHH\rangle + \|HVVV\rangle - \|VHHH\rangle + \|VHVV\rangle)_{1234}$	$D_{1Y}\ D_{2N}\ D_{3Y}\ D_{4N}$
$\|\psi_{\mathrm{c}}^{10}\rangle = \frac{1}{2}(\|HVHH\rangle - \|HVVV\rangle + \|VHHH\rangle + \|VHVV\rangle)_{1234}$	$D_{1Y}\ D_{2N}\ D_{3N}\ D_{4Y}$
$\|\psi_{\mathrm{d}}^{10}\rangle = \frac{1}{2}(\|HVHH\rangle - \|HVVV\rangle - \|VHHH\rangle - \|VHVV\rangle)_{1234}$	$D_{1Y}\ D_{2N}\ D_{3Y}\ D_{4Y}$
$\|\psi_{\mathrm{a}}^{11}\rangle = \frac{1}{2}(\|HVHV\rangle + \|HVVH\rangle + \|VHHV\rangle - \|VHVH\rangle)_{1234}$	$D_{1Y}\ D_{2Y}\ D_{3N}\ D_{4N}$
$\|\psi_{\mathrm{b}}^{11}\rangle = \frac{1}{2}(\|HVHV\rangle + \|HVVH\rangle - \|VHHV\rangle + \|VHVH\rangle)_{1234}$	$D_{1Y}\ D_{2Y}\ D_{3Y}\ D_{4N}$
$\|\psi_{\mathrm{c}}^{11}\rangle = \frac{1}{2}(\|HVHV\rangle - \|HVVH\rangle + \|VHHV\rangle + \|VHVH\rangle)_{1234}$	$D_{1Y}\ D_{2Y}\ D_{3N}\ D_{4Y}$
$\|\psi_{\mathrm{d}}^{11}\rangle = \frac{1}{2}(\|HVHV\rangle - \|HVVH\rangle - \|VHHV\rangle - \|VHVH\rangle)_{1234}$	$D_{1Y}\ D_{2Y}\ D_{3Y}\ D_{4Y}$

Finally, let four photons go through the parity gates (PG_2), as shown in Fig. 2. Here, there are two photon-number detectors named D_3 and D_4. if both detectors 3 and 4 can not detect the photon, we can get state $|\varphi_a^{00}\rangle$; if detector 3 registers the photon and detector 4 can not detect the photon, we can get state $|\varphi_b^{00}\rangle$; if detector 4 registers photon and detector 3 can not detect the photon, we can get state $|\varphi_c^{00}\rangle$; if both detector 3 and detector 4 register photons, we can get state $|\varphi_d^{00}\rangle$. Hence, we can unambiguously distinguish all the sixteen complete orthogonal cluster states according to the results of four photon detectors. All details are listed in Table 1.

3. Discussion

So far, we have designed a four-photon cluster-state analyzer based on PG and CPG. In our cluster-state analyzer scheme, we used four PGs, the error probability of every PG is $P_{err} \sim |\langle 0|\alpha(e^{\pm i\theta}-1)|^2 = \exp[-2\alpha^2(1-\cos\theta)]$. For $\theta \ll 1$, $P_{err} \sim \exp(-\alpha^2\theta^2)$ is less than 10^{-4} when $\alpha\theta > \pi$.[22] Obviously, the feasibility of the present schemes depends on the implementation of giant cross-Kerr nonlinearity, i.e., $\theta = \pi$. Some experiments gave hopeful phenomena to back up giant cross-Kerr nonlinearity. For instance, based on the light-storage technique in laser-cooled ^{87}Rb, Chen *et al.* demonstrated a low-light-level cross-phase modulation (XPM) scheme, which made possible conditional phase shifts on the order of π with single photons.[34] Next, Li *et al.* reported experimental observations on the simultaneous electromagnetically induced transparency (EIT) effects as well as the enhanced XPM between the probe and trigger fields in a four-level tripod EIT system of the D_1 line of the ^{87}Rb atoms. Their result shows that when $\Omega_c = 30$ MHz, a conditional phase shift based on the XPM between the two pulses with single photon will reach 1.2 rad, which may allow us to perform the quantum phase gate operation though it is smaller than π.[35] For real experimental parameters ($T < 10$ K, $S \simeq 1$ μm^2 the number of semiconducting carbon nanotube quantum dot trapping electron $N = 1$, the height of QD $L \simeq 40$ nm, $\gamma_{31}^{-1} = 40$ ps, $\Delta_1 = 0.1$ meV), the nonlinear phase shift π could be achieved with the fidelity $F \simeq 1$ with $B_\perp \simeq 18$ T.[18] As we have mentioned above, all of these significant facts make us more confident about the feasibility of the proposed schemes.

4. Conclusion

In summary, we propose a optical scheme for implementing a photon cluster-state analyzer based on cross-Kerr nonlinearity combined with linear optics elements. It is shown that under a certain condition, the scheme is feasible by using the current experimental technology. Furthermore, the scheme opens promising perspectives for large-scale quantum communication and QIP networks.

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