Complete deterministic multi-electron Greenberger-Horne-Zeilinger state analyzer for quantum communication

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We present a scheme for the multi-electron Greenberger-Horne-Zeilinger (GHZ) state analyzer, resorting to an interface between the polarization of a probe photon and the spin of an electron in a quantum dot embedded in a microcavity. All the multi-spin GHZ states can be completely discriminated by using single-photon detectors and linear optical elements. Our scheme has some features. First, it is a complete GHZ-state analyzer for multi-electron spin systems. Second, the initial entangled states remain after being identified and they can be used for a successive task. Third, the electron qubits are static and the photons play a role of a medium for information transfer, which has a good application in quantum repeater in which the electron qubits are used to store the information and the photon qubits are used to transfer the information between others.

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I. INTRODUCTION

Quantum entanglement is a vital resource in quantum information processing. It enables a powerful quantum computation\cite{1,2} and it is also widely used in quantum communication. A maximally entangled state of three or more particles, called a Greenberger-Horne-Zeilinger (GHZ) state\cite{3}, is one of the most important multiparticle entangled states, and has been fascinating quantum system to reveal the nonlocality of the quantum word. It is well known that a complete deterministic Bell-state analyzer (BSA) is an important prerequisite for many quantum communication protocols, such as teleportation\cite{4,5}, entanglement swapping\cite{6,7}, quantum superdense coding\cite{8,9}, and some quantum cryptography protocols\cite{10,11}. Its extension to a multipartite system, that is, the discrimination of GHZ states, is useful in quantum computation, quantum communication, and quantum network. Based on linear optical elements, a simple GHZ-state analysis scheme, in which one can distinguish two of eight maximally entangled three-qubit GHZ states, has been presented in Ref.\cite{12}. With weak cross-Kerr nonlinearity, Qian et al.\cite{13} proposed a destructive GHZ-state analyzer with a nearly unity probability in 2005. Based on dipole-induced transparency in a cavity-waveguide system, Qian et al.\cite{14} proposed a nondestructive GHZ-state analyzer scheme in 2007. A GHZ-state analyzer scheme based on the input-output relation of a cavity was presented in Ref.\cite{15} in 2009. Unfortunately, the photons are absorbed by the detectors and the initial entangled states are destroyed finally because of destructive measurements. Therefore, nondestructive analysis of entangled states is also an important and open problem, and more effective strategies are expected to overcome the difficulties.

Electron spin in a quantum dot (QD)\cite{27,32} hold great promising in quantum information processing. It has attracted much attention in recent years. In 2008, Hu et al.\cite{33,34} proposed an interesting device, which is the singly-electron spin confined in a charged QD inside a microcavity, and it provides some new methods for quantum information processing. Based on this spin-QD-cavity unit, teleportation\cite{35}, entanglement swapping\cite{36}, entanglements for photon-photon\cite{37}, photon-spin and spin-spin\cite{38}, controlled-not gate and phase-shift gates on a hybrid system\cite{39}, and BSA on photon systems\cite{40}, entanglement purification\cite{41}, were studied. Moreover, an interesting quantum repeater scheme\cite{42} based on spin-QD-cavity units was proposed by Wang, Song, and Long in 2012. In this quantum repeater scheme, the electron-spin qubits are static and act as the qubits for storing information. The photon qubits play a role of a medium for information transfer. When this quantum repeater scheme is extended to three-party quantum communication or a quantum network, GHZ state analysis on electron systems is required. Moreover, a GHZ state analyzer is essential for long-distance quantum communication and quantum network, especially in a multiparty quantum repeater.

In this paper, based on an interface between the polarization of a probe photon and the spin of an electron in a quantum dot embedded in a microcavity, we present a scheme for multi-electron GHZ-state analyzer. All the electron-spin GHZ states can be completely discriminated by using single-photon detectors and linear optical elements. Our scheme has some advantages. First, it can be used to distinguish all the GHZ states, not a part of the states. Second, the initial entangled electron-spin GHZ states are not changed after being identified and they can be used for a successive task. Third, this scheme has a good application in quantum repeater in which the electron qubits are static and are used to store

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the information, and the photon qubits play a role of information transfer. Moreover, it is essential for quantum communication and quantum network based on electron-spin qubits.

II. PHYSICAL MODEL

We consider a singly electron charged self-assembled GaAs/InAs as interface quantum dot insider an optical resonant double-side microcavity with both mirrors partially reflective (see Fig. 1(a)) [34, 38]. Singly electron charged QD, that is, an excess electron is injected into the QD, optical excitation creates an exciton $X^-$ that consists of two electrons bound to one hole. $X^-$ dominates the optical property of the device and the four relevant electronic levels are shown in Fig. 1(b). In the following, we consider that the dipole is resonant with the cavity mode and is probed with a resonant light. Due to Pauli’s exclusion principle, the spin selection rules for this device is described as follows: (i) If the excess electron in the spin state $|\uparrow\rangle \equiv |+\rangle_z$, the right-circular polarized photon $|R^+)\rangle$ with $s_z = +1$ (the superscript uparrow indicates its propagation direction along the normal direction of the cavity, that is, $z$ axis) or the left-circular polarized photon $|L^-)\rangle$ with $s_z = +1$ is couple to the dipole, the photon is reflected by the cavity, both the polarization and the propagation direction of the photon will be flipped. However, $|R^+)\rangle$ or $|L^-)\rangle$ ($s_z = -1$) is uncouple to the dipole, such photon transmits through the cavity and acquires a $\pi$ mod $2\pi$ phase shift relative to a reflected one; (ii) If the excess electron in the spin state $|\downarrow\rangle \equiv |-\rangle_z$, in the same way, $|R^-)\rangle$ or $|L^+)\rangle$ ($s_z = -1$) are are reflected by the cavity, or $|R^+)\rangle$ and $|L^-)\rangle$ ($s_z = +1$) are transmitted through the cavity. Therefore, the rule of the input states changed under the interaction between the photons with $s_z = \pm 1$ and the cavity is described as follows:

$$
|R^+)\rangle \rightarrow |L^-)\rangle, \quad |L^+)\rangle \rightarrow -|R^+)\rangle, \\
|R^-)\rangle \rightarrow -|R^-)\rangle, \quad |L^+)\rangle \rightarrow |R^-)\rangle, \\
|R^-)\rangle \rightarrow -|L^-)\rangle, \quad |L^+)\rangle \rightarrow -|L^-)\rangle.
$$

(1)

In Fig. 1 $|\uparrow\rangle$ and $|\downarrow\rangle$ represent the hole-spin states $|+\rangle_z$ and $|-\rangle_z$, respectively.

III. COMPLETE THREE-ELECTRON-SPIN GHZ-STATE ANALYZER

Before starting to discuss our GHZ-state analyzer, let us first extend the study of creating the two-qubit Bell states in Ref. [33] to the three-spin GHZ states via QD-spin-cavity units discussed above. The principle of our scheme for GHZ-state analysis is shown in Fig. 2(a) and Fig. 2(b). Consider three uncorrelated excess spins are in arbitrary states $|\psi_i^t\rangle = \alpha_i |\uparrow\rangle + \beta_i |\downarrow\rangle$ ($i = 1, 2, 3$) and the probe photon 1 and the probe photon 2 are in the polarization state $|R^+)\rangle$ and $|L^+)\rangle$, respectively. The two photons are sent through the input port and the polarizing beam splitter in the circular basis (C-PBS) one after another. The first C-PBS is rotated by $90^\circ$ after the first photon $|R^+)\rangle$ (label $m_1$) passes through it, so that the second photon $|L^+)\rangle$ (label $m_2$) deserts the first cavity and injects directly into the cavities 2 and 3 in sequence, and emits from the output port out2. The first photon $|R^+)\rangle$ (label $m_1$) passes through the cavities 1 and 2 in sequence, and emits from the port out1. Based on the rules in Eq. (1), the evolution of the system composed of two photons and three electron spins can be written as

$$
|\psi^f\rangle = (\alpha_1 \alpha_2 \alpha_3 |\uparrow\rangle |\uparrow\rangle |\uparrow\rangle + \beta_1 \beta_2 \beta_3 |\downarrow\rangle |\downarrow\rangle |\downarrow\rangle).
$$

(2)

When the two-photon system is in the states $|R^+)\rangle |L^+)\rangle$, $|R^+)\rangle |R^+)\rangle$, $|L^+)\rangle |R^+)\rangle$ and $|L^+)\rangle |L^+)\rangle$, the three-spin system is in the states $|\psi_0\rangle$, $|\psi_1\rangle$ and $|\psi_3\rangle$, respectively. Here

$$
|\psi_0\rangle = 2(\alpha_1 \alpha_2 \alpha_3 |\downarrow\rangle |\downarrow\rangle |\downarrow\rangle + \beta_1 \beta_2 \beta_3 |\uparrow\rangle |\uparrow\rangle |\uparrow\rangle), \quad |
\psi_1\rangle = 2(\alpha_1 \alpha_2 \alpha_3 |\uparrow\rangle |\downarrow\rangle |\downarrow\rangle + \beta_1 \beta_2 \beta_3 |\downarrow\rangle |\uparrow\rangle |\uparrow\rangle), \\
|\psi_2\rangle = 2(\alpha_1 \alpha_2 \alpha_3 |\downarrow\rangle |\downarrow\rangle |\downarrow\rangle + \beta_1 \beta_2 \beta_3 |\uparrow\rangle |\uparrow\rangle |\uparrow\rangle), \\
|\psi_3\rangle = 2(\alpha_1 \alpha_2 \alpha_3 |\downarrow\rangle |\downarrow\rangle |\downarrow\rangle + \beta_1 \beta_2 \beta_3 |\uparrow\rangle |\uparrow\rangle |\uparrow\rangle).
$$

(3)

By setting the coefficient $\alpha_i$ and $\beta_i$ to $\frac{1}{\sqrt{2}}$, or any one of $\alpha_i$ and $\beta_i$ to $-\frac{1}{\sqrt{2}}$ and the others to $\frac{1}{\sqrt{2}}$, one can obtain...
the eight maximally entangled three-spin GHZ states

\[
\begin{align*}
|\psi^+_0\rangle &= \frac{1}{\sqrt{2}}(|\uparrow\uparrow\downarrow\rangle \pm |\downarrow\downarrow\uparrow\rangle), \\
|\psi^+_1\rangle &= \frac{1}{\sqrt{2}}(|\uparrow\uparrow\downarrow\rangle \pm |\downarrow\downarrow\uparrow\rangle), \\
|\psi^+_2\rangle &= \frac{1}{\sqrt{2}}(|\uparrow\downarrow\uparrow\rangle \pm |\downarrow\uparrow\downarrow\rangle), \\
|\psi^+_3\rangle &= \frac{1}{\sqrt{2}}(|\uparrow\downarrow\uparrow\rangle \pm |\downarrow\uparrow\downarrow\rangle). 
\end{align*}
\] (4)

Now, we explain how to implement a complete deterministic three-spin GHZ-state analyzer. The setup of our scheme is depicted in Fig. 2. It consists of three parts: (i) the photon 1 in the polarization state \(|R_1^0\rangle\) (label \(in_1\)) is injected into the cavity 1 and the cavity 2 in succession and it is detected at the port \(out_1\); (ii) the photon 2 in the polarization state \(|L_2^0\rangle\) (label \(in_2\)) is injected into the cavity 2 and cavity 3 in sequence and a 90° rotation on the first C-PBS is performed before the second photon \(|L_2^0\rangle\) passes through it (so that the photon \(|L_2^0\rangle\) deserts the first cavity and injects directly into the cavity 2 and the cavity 3 in sequence), and it is detected at the port \(out_2\); (iii) a Hadamard transformation (e.g., using a \(\pi/2\) microwave pulse) \(|\uparrow\rangle \rightarrow \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle), \\
|\downarrow\rangle \rightarrow \frac{1}{\sqrt{2}}(|\uparrow\rangle - |\downarrow\rangle)\) on each spin is applied and then the probe photon 3 in the polarization state \(|R_3^0\rangle\) (label \(in_3\)) is injected into the cavity 1, the cavity 2 and the cavity 3 in sequence with a 90° rotation on the first C-PBS again before the photon 3 passes through it.

In the first step, one can distinguish \(|\psi^+_0\rangle\) and \(|\psi^+_1\rangle\) from \(|\psi^+_2\rangle\) and \(|\psi^+_3\rangle\) by simply discriminating the instance which detector is clicked by the photon. After the photon passes through cavity 1 and cavity 2 in succession, it will emit from the port \(out_1\) and is in the state

\[
|\psi^+_0\rangle \xrightarrow{\text{through cavity 1, 2}} |\psi^+_0\rangle, \\
|\psi^+_1\rangle \xrightarrow{\text{through cavity 1, 2}} |\psi^+_1\rangle, \\
|-\psi^+_1\rangle \xrightarrow{\text{through cavity 1, 2}} -|\psi^+_1\rangle, \\
|-\psi^+_2\rangle \xrightarrow{\text{through cavity 1, 2}} -|\psi^+_2\rangle. \] (5)

Hence, we can distinguish \(|\psi^+_0\rangle\) and \(|\psi^+_1\rangle\) (corresponds to the instance that the photon is detected by detector \(D_2\)) from \(|\psi^+_2\rangle\) and \(|\psi^+_3\rangle\) (corresponds to the instance that the photon is detected by detector \(D_1\)).

As the same as that in the first step, after the photon 2 passes through the cavity 2 and the cavity 3 in succession, the evolution of the system can be written as

\[
|\psi^+_0\rangle \xrightarrow{\text{through cavity 2, 3}} |\psi^+_0\rangle, \\
|\psi^+_1\rangle \xrightarrow{\text{through cavity 2, 3}} -|\psi^+_1\rangle, \\
|-\psi^+_1\rangle \xrightarrow{\text{through cavity 2, 3}} -|\psi^+_1\rangle, \\
|-\psi^+_2\rangle \xrightarrow{\text{through cavity 2, 3}} -|\psi^+_2\rangle. \] (6)

As the same as that in the first step, after the photon 2 passes through the cavity 2 and the cavity 3 in succession, the evolution of the system can be written as

\[
|\psi^+_0\rangle \xrightarrow{\text{through cavity 2, 3}} |\psi^+_0\rangle, \\
|\psi^+_1\rangle \xrightarrow{\text{through cavity 2, 3}} -|\psi^+_1\rangle, \\
|-\psi^+_1\rangle \xrightarrow{\text{through cavity 2, 3}} -|\psi^+_1\rangle, \\
|-\psi^+_2\rangle \xrightarrow{\text{through cavity 2, 3}} -|\psi^+_2\rangle. \] (6)

That is, one can distinguish \(|\psi^+_0\rangle\) (corresponds to the photon is detected by detector \(D_2\)) from \(|\psi^+_1\rangle\) (corresponds to the detector \(D_1\)) and distinguish \(|\psi^+_2\rangle\) (corresponds to the detector \(D_4\)) from \(|\psi^+_3\rangle\) (corresponds to
the detector $D_3$).

With two steps of the quantum nondemolition detectors (QND) shown in Fig.2, the eight GHZ states are divided into four groups, that is, $|\psi_0^\pm\rangle$, $|\psi_1^\pm\rangle$, $|\psi_2^\pm\rangle$ and $|\psi_3^\pm\rangle$. The next task is only to distinguish the different relative phases in each group and it can be accomplished by applying Hadamard transformation on each spin as the eight GHZ states will be transformed into

\[
|\psi_0^+\rangle \xrightarrow{H} \frac{1}{\sqrt{2}}(|\uparrow\downarrow\uparrow\rangle + |\downarrow\uparrow\downarrow\rangle + |\downarrow\downarrow\uparrow\rangle + |\uparrow\uparrow\downarrow\rangle),
\]

\[
|\psi_0^-\rangle \xrightarrow{H} \frac{1}{\sqrt{2}}(|\uparrow\downarrow\uparrow\rangle + |\downarrow\uparrow\downarrow\rangle + |\downarrow\downarrow\uparrow\rangle + |\uparrow\uparrow\downarrow\rangle),
\]

\[
|\psi_1^+\rangle \xrightarrow{H} \frac{1}{\sqrt{2}}(|\uparrow\downarrow\uparrow\rangle + |\downarrow\uparrow\downarrow\rangle - |\downarrow\downarrow\uparrow\rangle - |\uparrow\uparrow\downarrow\rangle),
\]

\[
|\psi_1^-\rangle \xrightarrow{H} \frac{1}{\sqrt{2}}(|\uparrow\downarrow\uparrow\rangle + |\downarrow\uparrow\downarrow\rangle - |\downarrow\downarrow\uparrow\rangle - |\uparrow\uparrow\downarrow\rangle),
\]

\[
|\psi_2^+\rangle \xrightarrow{H} \frac{1}{\sqrt{2}}(|\uparrow\downarrow\uparrow\rangle - |\downarrow\uparrow\downarrow\rangle - |\downarrow\downarrow\uparrow\rangle + |\uparrow\uparrow\downarrow\rangle),
\]

\[
|\psi_2^-\rangle \xrightarrow{H} \frac{1}{\sqrt{2}}(|\uparrow\downarrow\uparrow\rangle - |\downarrow\uparrow\downarrow\rangle - |\down\down\up\rangle + |\up\up\down\rangle),
\]

\[
|\psi_3^+\rangle \xrightarrow{H} \frac{1}{\sqrt{2}}(|\up\down\up\rangle - |\down\up\down\rangle + |\down\down\up\rangle + |\up\up\down\rangle),
\]

\[
|\psi_3^-\rangle \xrightarrow{H} \frac{1}{\sqrt{2}}(|\up\down\up\rangle - |\down\up\down\rangle + |\down\down\up\rangle + |\up\up\down\rangle). \tag{7}
\]

Obviously, one can distinguish $|\psi_i^+\rangle$ (corresponds to the instance that the number of the state $|\up\rangle$ is odd, that is, corresponds to the detector $D_4$) from $|\psi_i^-\rangle$ (corresponds to an even number of the state $|\up\rangle$, that is, corresponds to the detector $D_3$).

From the analysis above, one can see that the role of the photon is only the medium for distinguishing the eight GHZ electron-spin states and the spins are not destroyed. With the first step, one can distinguish $|\psi_0^+\rangle$, $|\psi_0^-\rangle$ from $|\psi_1^+\rangle$, $|\psi_1^-\rangle$. The second QND can distinguish $|\psi_2^+\rangle$, $|\psi_2^-\rangle$, $|\psi_3^+\rangle$, $|\psi_3^-\rangle$ from $|\psi_0^+\rangle$, and then all of the GHZ states are divided into four groups $|\psi_i^\pm\rangle$. With the third step, the two states with different relative phases are distinguished. The possible measurement results for each three-spin GHZ state in each step is given in Table I.

### IV. COMPLETE MULTI-ELECTRON-SPIN GHZ-STATE ANALYZER

Combing Eq. 1 and Fig.2, we find that the polarization of the probe photon will remain after the probe photon $|R_3^1\rangle$ or $|L_3^1\rangle$ interacts with the two cavities, if the two excess electron spins in the cavities are parallel ($|\up\down\rangle$ or $|\down\up\rangle$); otherwise, the polarization of the probe photon will be flipped. That is, the present scheme for three-electron-GHZ-state analyzer (see Fig.2) can be generalized to multi-electron-spin qubits. The N-qubit GHZ states can be written as

\[
|\Psi_2\rangle = \frac{|B_N(i)|}{\sqrt{2}} |\up\up\cdots\cdots\cdots\down\rangle, \tag{8}
\]

\[
= |\up\down\cdots\cdots\cdots\up\rangle, \quad (\forall k = 2, 3, \ldots, N) \text{ and } \bar{t}_k \text{ is the result of flipping each bit of } t_k, \text{ and } B_N(i) = b_1, b_2, \cdots, t_N \text{ is the binary notation and } i = 1, 2, \ldots, 2^N-1 - 1.
\]

The complete deterministic multi-electron GHZ-state analysis can also be accomplished with three steps: (i) the first probe photon in state $|R_3^1\rangle$ is injected only into the cavity 1 and the cavity 2 in succession and it is detected; (ii) the $j$th probe photon in the state $|L_j^1\rangle$ deserts the cavity 1, ..., the cavity $j-1$ and is injected directly into the cavity $j$ and the cavity $j+1$ and it is detected ($j = 2, \ldots, N-1$); (iii) a Hadamard transformation on each spin is applied, and $N_{th}$ probe photon in state $|R_N^1\rangle$ is injected into all the cavities in succession and it is detected. The possible measurement results corresponds to its probe photon is given in Fig.3.

### V. DISCUSSION AND SUMMARY

We have proposed a scheme for three-electron-spin GHZ-state analyzer and extend it to multi-electron-spin case. The three-spin (multi-spin) GHZ state is prepared in QD spins in optical resonant microcavities. A QD spins can be used to store and process quantum information due to the long electron-spin coherence time $\sim \mu s$ which is limited by the spin-relaxation time $\sim ms$. Spin manipulation is well developed using pulsed magnetic-resonance techniques, and single spin detection can be implemented by distinguishing whether the polarization of the probe photon is flipped or not after it passes through the cavity. Assume that the probe photon is in the state $|R_3^1\rangle$, the flip of the polarization indicates the fact that the electron is in the state $|\down\rangle$; otherwise, the electron is in the state $|\up\rangle$.
Our scheme can distinguish all GHZ states with single-photon detectors and linear-optical elements. In our scheme, the initial entangled states remain after being identified and they can be used for a successive task. Moreover, the electron-spin qubits are static, and the photons are only a medium for information transfer. The multi-particle GHZ-state analyzer is essential for multi-particle generalizations of quantum teleportation, quantum dense coding, entanglement swapping, and quantum networks. The present GHZ analysis scheme may be useful in quantum computing, quantum communication and quantum network.

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