Optimal multipartite entanglement concentration of electron-spin states based on charge detection and projection measurements

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We propose an optimal entanglement concentration protocol (ECP) for nonlocal N-electron systems in a partially entangled pure state, resorting to charge detection and the projection measurement on an additional electron. For each nonlocal N-electron system, one party in quantum communication, say Alice first entangles it with an additional electron, and then she projects the additional electron into an orthogonal basis for dividing the N-electron systems into two groups. In the first group, the N particles obtain a subset of N-electron systems in a maximally entangled state directly. In the second group, they obtain some less-entangled N-electron systems which are the resource for the entanglement concentration in the next round. By iterating the entanglement concentration process several times, the present ECP has the maximal success probability, the theoretical limit of an ECP as it just equals to the entanglement of the partially entangled state, far higher than others, without resorting to a collective unitary evolution.

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I. INTRODUCTION

The principles in quantum mechanics provide some novel ways for secure communication. Since Bennett et al. ¹ published the original quantum key distribution (QKD) protocol in 1984, quantum communication has attracted a lot of attention. For example, Ekert ² proposed a QKD protocol based on two-photon entanglement in 1991. Subsequently, Bennett, Brassard, and Mermin ³ simplified its process for eavesdropping check. In 1992, Bennett and Wiesner proposed a quantum dense coding protocol between two parties ⁴ and it was generalized to N parties with arbitrary d-dimensional quantum systems by Liu et al. ⁵ in 2002. In 1993, Bennett and Wiesner proposed a quantum teleportation protocol ⁶ for transmitting an unknown single-qubit state, without moving the qubit itself by setting up a quantum channel with a photon pair in a maximally entangled state. In 1999, Hillery, Bužek, and Berthiaume ⁷ presented an interesting quantum secret sharing protocol based on multipartite photon systems in a maximally entangled state. Subsequently, it is generalized to the case with two-photon entangled channels ⁸, arbitrary number of agents ⁹, and that to sharing an unknown quantum state ¹⁰,¹¹ with a quantum channel in a multipartite maximally entangled state. In 2002, Long and Liu ¹² proposed the first quantum secure direct communication (QSDC) protocol with a block of two-photon systems in Bell states. It was detailed in the two-step QSDC protocol ¹³ and was generalized to the case with sing photons ¹⁶ and high-dimensional entangled quantum systems ¹⁷,¹⁸.

Although there are some interesting quantum communication protocols, including those based on single photons ¹ or weak pulses ¹⁹,²⁰, quantum repeaters are required in long-distance quantum communication ²¹ because quantum signals can only be transmitted over an optical fiber or a free space not more than several hundreds kilometers with current technology. In a quantum repeater, entanglement is used to connect the two neighboring nodes. That is, the distribution of entanglement between two nodes is necessary for a quantum repeater. Moreover, the parties should store the quantum state for linking the other nodes in quantum communication network. In a practical transmission of a photon system, it will inevitably interact with its environment. That is, it will suffer from the channel noise. In the storage of the entangled quantum state, the decoherence will also decrease the entanglement of the system. The decoherence of the entangled quantum system will decrease the security of QKD protocol and even make a quantum teleportation and a quantum dense coding protocol fail.

Entanglement purification is used to extract a subset of high-fidelity entangled systems from a set of less-entangled systems in a mixed state. Since Bennett et al. ²⁴ proposed the first entanglement purification protocol (EPP) in 1996, many works were focused on it and many important EPPs have been proposed, resorting to different physical systems ²⁴–³⁷. Compared with an EPP, an entanglement concentration protocol (ECP) is usually more efficient for the two parties in quantum communication, say Alice and Bob, to distill some maximally entangled systems from an ensemble in a less-entangled pure state. Up to now, there are some interesting ECPs ³⁸–⁴⁵. For example, Bennett et al. ³⁸ proposed the first ECP for two-photon systems in 1996, called it the Schmidt projection method. In 1999, Bose et al. ³⁹ proposed another interesting ECP based on entanglement swapping of two photon pairs in a partially entangled pure state. Subsequently, Shi et al. ⁴⁰ presented a different ECP based on entanglement swapping and a collective unitary evolution. Both these ECPs ³⁹,⁴⁰ require that Alice and Bob know the information about the less-entangled pure state \(a|H\rangle_A|H\rangle_B + \beta|V\rangle_A|V\rangle_B\). Here \(|H\rangle\) and \(|V\rangle\) represent the horizontal and the vertical polarizations of photons. In 2001, Ya-
mamoto et al. [41] and Zhao et al. [42] proposed an ECP for photon pairs based on linear optical elements independently. In 2008, Sheng, Deng, and Zhou [43] proposed an ECP for photon systems based on cross-Kerr nonlinearities. By iteration of the entanglement concentration process, it has a far higher efficiency and yield than those in Refs. [41, 42]. Both these ECPs [41, 43] do not require that Alice and Bob know the parameters \(a\) and \(B\). Certainly, they have a lower efficiency than those in Refs. [39, 40]. In 2010, the first single-photon ECP [44] was discussed with cross-Kerr nonlinearity. In 2012, Sheng et al. [45] proposed an interesting ECP for for partially entangled photon pairs assisted by single photons.

An electron-spin system is an interesting qubit in quantum computation and quantum communication. For example, Beenakker et al. [46] exploited the charge detection [47] to construct a CNOT gate based on both the charge and the spin degrees of freedom of electrons in 2004. In 2007, Ionicioiu [48] used charge detection to complete the generation of the entangled spins. In 2006, Zhang, Feng, and Gao [49] presented a scheme for the multipartite entanglement analyzer. In 2005, Feng, Kwek, and Oh [50] proposed an EPP for two-electron systems based on charge detection. In 2011, an EPP for multi-electron systems [51] was proposed. Moreover, the entanglement concentration for multi-electron systems was discussed by Sheng et al. [52] based on charge detection and an ECP for two-electron systems was proposed by Wang et al. [53] based on quantum dots in micro-wave cavities.

In this paper, we proposed an optimal ECP for nonlocal \(N\)-electron systems in a partially entangled pure state, resorting to the projection measurement on an additional electron. In the present ECP, Alice first entangles each nonlocal \(N\)-electron system with an additional electron by performing a parity-check measurement on her electron and an additional electron \(a\), and then she projects the electron \(a\) into an orthogonal basis \(\{|\varphi\rangle, |\varphi^+\rangle\}\) for dividing the \(N\)-electron systems into two groups. In the first group, the \(N\) parties in quantum communication obtain the \(N\)-electron systems in a maximally entangled state directly. In the second group, they obtain some \(N\)-electron systems in another partially entangled state with less entanglement, which are the resource for entanglement concentration in the next round. By iterating the process several times, the present ECP has an optimal success probability, the theoretical limit as it is just the entanglement of the partially entangled state \(E\), twice of those based entanglement swapping and a collective unitary evolution [35, 40], far higher than other typical ECPs [41, 43, 52, 53]. Moreover, it does not require a collective unitary evolution, which decreases the difficulty of its implementation.

II. OPTIMAL MULTIPARTITE ENTANGLEMENT CONCENTRATION OF THREE-ELECTRON SPIN STATES

Before we describe the principle of our ECP for nonlocal \(N\)-electron systems, we first introduce the principle of the parity-check gate (PCG) for two electrons based on their charge detection, similar to that in Ref. [46], shown in Fig. 1. The charge detector (C) can distinguish the occupation number one from the occupation numbers 0 and 2, but it cannot distinguish the electron numbers between 0 and 2. That is, it can distinguish the occupation number even or odd, which means that this device can distinguish the even parity states \(|↑⟩_A|↑⟩_B\rangle\) and \(|↓⟩_A|↓⟩_B\rangle\) from the odd parity states \(|↑⟩_A|↓⟩_B\rangle\) and \(|↓⟩_A|↑⟩_B\rangle\). In detail, as the spin polarizing beam splitter (PBS: 50:50) can transmit an electron in the spin-up state \(|↑⟩\) and reflect an electron in the spin-down state \(|↓⟩\), one can see that the states \(|↑↑⟩\) and \(|↓↓⟩\) will lead the charge detection to have the charge occupation number \(C = 1\) as each electron passes through a different path after the first PBS. The states \(|↑↓⟩\) and \(|↓↑⟩\) will lead the charge detection to \(C = 0\) and \(C = 2\), respectively. The charge detection cannot distinguish 0 and 2, and it will show the same result, i.e., \(C = 0\) for simplicity. The states \(|↑↑⟩\) and \(|↓↓⟩\) can be distinguished from \(|↑↓⟩\) and \(|↓↑⟩\) by the different outcomes of the charge detection. So this device can be used to accomplish a parity check on a two-electron system, without destroying it. After the second PBS (PBS\(_2\)), the states and the positions of the two electrons are recovered when the electrons emit from the outputs \(A_3\) and \(A_4\), respectively. That is, the charge detection \(C\) is a nondestructive quantum nondemolition detection on the electron spins [46].

\[|Φ⟩_{AB} = α|↑⟩_A|↑⟩_B + β|↓⟩_A|↓⟩_B.\]  
\[(1)\]

With the PCG shown in Fig 1, the principle of our ECP for nonlocal two-electron systems in a less-entangled pure state is shown in Fig 2. Suppose that the partially entangled pure state for two-electron systems after they suffer from the decoherence coming from the transmission or the storage in a noisy environment is

\[|Φ⟩_{AB} = α|↑⟩_A|↑⟩_B + β|↓⟩_A|↓⟩_B.\]  
\[(1)\]

where the subscripts \(A\) and \(B\) represent the two electrons shared by two remote parties in quantum communication, say Alice and Bob. \(α\) and \(β\) are two real numbers and satisfy the relation

\[|α|^2 + |β|^2 = 1.\]  
\[(2)\]
Alice and Bob know these two parameters before they distill a subset of maximally entangled electron pairs from a set of nonlocal electron pairs in the state $|\Phi_1\rangle_{AB}$, as the same as the ECPs with entanglement swapping and a collective unitary evolution \[34\text{-}40\]. In fact, it is not difficult to obtain this information about the partially entangled pure state by measuring some samples in a practical quantum communication.

For distilling a subset of maximally entangled electron pairs from a set of pairs in a partially entangled pure state $|\Phi_1\rangle_{AB}$, Alice prepares an additional electron $a$ in the spin state $|\Phi_a\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$ for each nonlocal two-electron system $AB$ and then performs a parity-check measurement on her electrons $A$ and $a$. If she obtains an even parity, the three-electron system $ABa$ is in the state

$$|\Psi_{e\rangle_{ABa}} = |\alpha\rangle|\uparrow\rangle_{A}|\uparrow\rangle_{B}|\uparrow\rangle_{a} + |\beta\rangle|\downarrow\rangle_{A}|\downarrow\rangle_{B}|\downarrow\rangle_{a}.\tag{3}$$

If she obtains an odd parity, the system is in the state

$$|\Psi_{o\rangle_{ABa}} = |\alpha\rangle|\uparrow\rangle_{A}|\downarrow\rangle_{B}|\uparrow\rangle_{a} + |\beta\rangle|\downarrow\rangle_{A}|\uparrow\rangle_{B}|\downarrow\rangle_{a},\tag{4}$$

and Alice can transform it into the state $|\Psi_{e\rangle_{AB}}$ by performing a bit-flip operation $\sigma_z = |\uparrow\rangle\langle\downarrow| + |\downarrow\rangle\langle\uparrow|$ on the electron $a$. That is, we need only describe the principle of the present ECP when Alice and Bob obtain their electron systems in the state $|\Psi_{e\rangle_{ABa}}$ below.

We can rewrite the state $|\Psi_{e\rangle_{ABa}}$ under the orthogonal basis $|\varphi\rangle_a = |\alpha\rangle|\uparrow\rangle - |\beta\rangle|\downarrow\rangle, |\varphi^\perp\rangle_a = |\alpha\rangle|\uparrow\rangle + |\beta\rangle|\downarrow\rangle$, i.e.,

$$|\Psi_{e\rangle_{ABa}} = \frac{(\alpha^2 |\uparrow\rangle_{A}|\uparrow\rangle_{B} - \beta^2 |\downarrow\rangle_{A}|\downarrow\rangle_{B})|\varphi\rangle_a 
+ \sqrt{2}\alpha\beta \cdot |\uparrow\rangle_{A}|\downarrow\rangle_{B} + |\downarrow\rangle_{A}|\uparrow\rangle_{B})|\varphi^\perp\rangle_a.\tag{5}$$

Alice can use a PBS$_\theta$, whose axial direction is placed at the angle $\theta$ along the incidence electron, and two detectors to complete the projection measurement on the additional electron $a$ with the basis $|\varphi\rangle_a, |\varphi^\perp\rangle_a$, shown in Fig. 2. Here $\cos\theta = \alpha$ and $\sin\theta = -\beta$. If Alice obtains the state $|\varphi^\perp\rangle_a$ when she measures the additional electron $a$, the electron pair $AB$ is in the maximally entangled state $|\phi^+\rangle_{AB} = \frac{1}{\sqrt{2}} (|\uparrow\rangle_{A}|\uparrow\rangle_{B} + |\downarrow\rangle_{A}|\downarrow\rangle_{B})$, which takes place with the probability of $2\alpha^2\beta^2$. If Alice obtains the state $|\varphi\rangle_a$, the electron pair $AB$ is in another partially entangled pure state

$$|\Phi_2\rangle_{AB} = \frac{1}{\sqrt{\alpha^4 + \beta^4}} (\alpha^2 |\uparrow\rangle_{A}|\uparrow\rangle_{B} - \beta^2 |\downarrow\rangle_{A}|\downarrow\rangle_{B}),\tag{6}$$

which takes place with the probability of $\alpha^4 + \beta^4 = 1 - 2\alpha^2\beta^2$.

It is obvious that the less-entangled pure state $|\Phi_2\rangle_{AB}$ has the same form as the state $|\Phi_1\rangle_{AB}$ shown in Eq. (1). We need only replace $\alpha$ and $\beta$ with $\alpha' = \frac{\alpha^2}{\sqrt{\alpha^4 + \beta^4}}$ and $\beta' = \frac{\beta^2}{\sqrt{\alpha^4 + \beta^4}}$, respectively. That is, Alice and Bob can distill the maximally entangled state $|\phi^+\rangle_{AB}$ from the state $|\Phi_2\rangle_{AB}$ with the probability of $2(\alpha^4 + \beta^4)\alpha^2\beta^2$ by adding another additional electron $a'$ and a parity-check measurement. Moreover, they can distill the electron pairs in the maximally entangled state $|\phi^+\rangle_{AB}$ from the less-entangled systems in the next round yet. That is, by iterating the entanglement concentration process $n$ times, the total success probability of this ECP is

$$P_n = 2[\alpha^2\beta^2 + \frac{\alpha^4\beta^4}{\alpha^4 + \beta^4} + \frac{\alpha^6\beta^6}{(\alpha^4 + \beta^4)(\alpha^8 + \beta^8)} + \frac{\alpha^8\beta^8}{(\alpha^4 + \beta^4)(\alpha^8 + \beta^8)(\alpha^{16} + \beta^{16})} + \cdots]$$

$$+ \frac{\alpha^{2n}\beta^{2n}}{(\alpha^4 + \beta^4)(\alpha^8 + \beta^8)\cdots(\alpha^{2n} + \beta^{2n})].\tag{7}$$

![FIG. 2: The schematic diagram of the present entanglement concentration protocol for electron-spin systems in a partially entangled pure state. One of the parties in quantum communication, say Alice performs some local operations on her electron $A$ in the system and an additional electron $a$ in the state $|\Phi_a\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$. PBS$_\theta$ represents a PBS whose axial direction is placed at the angle $\theta$ along the incidence electron.](image)

![FIG. 3: (Color online) The relation between the success probability of the present ECP $P$ and the entanglement of the partially entangled state $E$ under the iteration numbers of entanglement concentration process $n = 1, 2, 3, 4$ and 5, respectively.](image)
between the success probability $P$ that the two parties obtain a nonlocal two-electron system $AB$ in the maximally entangled state $|\phi^+\rangle_{AB}$ from a system in the partially entangled state $|\Phi_1\rangle_{AB}$ and the entanglement $E$ is shown in Fig 3. When $E < 0.4$, Alice and Bob need only perform the entanglement concentration process twice ($n=2$) for obtaining the success probability $P$ nearly equivalent to the entanglement $E$. When $0.4 < E < 0.72$ ($0.72 < E < 0.88$), they should perform the process 3 (4) times for obtaining an optimal success probability. From Fig 3, one can see that 5 times for the iteration of the entanglement concentration process is usually enough to obtain an optimal success probability.

III. OPTIMAL MULTIPARTITE ENTANGLEMENT CONCENTRATION OF N-ELECTRON SPIN STATES

It is straightforward to generalize our ECP for reconstructing maximally entangled $N$-electron GHZ-class states from partially entangled GHZ-class states. Suppose the partially entangled $N$-electron GHZ-class states are described as follows:

$$|\Phi_N\rangle = |\alpha\rangle |\uparrow\downarrow\cdots\uparrow\rangle_{AB-Z} + |\beta\rangle |\downarrow\cdots\downarrow\rangle_{AB-Z}, \quad (8)$$

where $|\alpha|^2 + |\beta|^2 = 1$. The subscript $A$, $B$, ..., and $Z$ represent the electrons held by Alice, Bob, ..., and Zach, respectively. For obtaining a subset of nonlocal $N$-electron systems in a maximally entangled state, Alice prepares an additional electron $a''$ in the state $|\downarrow\rangle_{a''}$ and she performs a parity-check measurement on her electron $A$ and the additional electron $a''$. If she obtains an even parity, the $(N+1)$-electron system is in the state

$$|\Phi_{N+1}\rangle_e = |\alpha\rangle |\uparrow\rangle_{A} |\uparrow\rangle_{a''} |\uparrow\cdots\uparrow\rangle_{B-Z} + |\beta\rangle |\downarrow\rangle_{A} |\downarrow\rangle_{a''} |\downarrow\cdots\downarrow\rangle_{B-Z}. \quad (9)$$

If Alice obtains an odd parity, the system is in the state

$$|\Phi_{N+1}\rangle_o = |\alpha\rangle |\uparrow\rangle_{A} |\downarrow\rangle_{a''} |\uparrow\cdots\uparrow\rangle_{B-Z} + |\beta\rangle |\downarrow\rangle_{A} |\uparrow\rangle_{a''} |\downarrow\cdots\downarrow\rangle_{B-Z}. \quad (10)$$

Obviously, the state $|\Phi_{N+1}\rangle_e$ can be transformed into the state $|\Phi_{N+1}\rangle_e$ with a bit-flip operation $\sigma_x$ on the additional electron $a''$. By projecting the state of the additional electron $a''$ into the orthogonal basis $|\psi_{a''}\rangle = |\alpha\rangle |\uparrow\downarrow\cdots\uparrow\rangle_{B-Z}$, the parties obtain the maximally entangled state $|\phi^+\rangle = (|\uparrow\downarrow\cdots\uparrow\rangle_{B-Z} + |\downarrow\cdots\downarrow\rangle_{B-Z})/\sqrt{2}$, which takes place with the probability of $2\alpha^2\beta^2$. If Alice obtains the state $|\psi_{a''}\rangle$, the parties obtain a partially less-entangled pure state

$$|\Phi_{N}\rangle = \frac{1}{\sqrt{\alpha^4 + \beta^4}} (|\alpha^4\rangle |\uparrow\downarrow\cdots\uparrow\rangle_{AB-Z} + |\beta^4\rangle |\downarrow\cdots\downarrow\rangle_{AB-Z}). \quad (11)$$

The parties can also distill some maximally entangled state from this partially less-entangled state, similar to the case with nonlocal two-electron systems in a partially entangled pure state. That is, this ECP works for $N$-electron systems in a partially entangled pure state yet.

IV. DISCUSSION AND SUMMARY

Let us compare the efficiency of the present ECP for electron systems with those in others [38, 40, 52]. Of course, there are some differences between the present ECP and others. The present ECP requires that the parties know the information about the initial state of the nonlocal $N$-electron systems, as the same as those in Refs. [39, 40]. However, these in Refs. [38, 52] do not require the parties to know the information. In essence, all existing ECPs [38, 40, 52] for electron systems are based on the Schmidt projection method in which the parties exploit the combination of a pair of systems with the same parameter to obtain a system in a maximally entangled state with an average success probability of $\alpha^2\beta^2$. The ECP in Ref. [40] exploits an additional collective unitary evolution on one qubit in the system and an additional qubit to improve the success probability to be $\alpha^2$. The ECP for electron systems in Ref. [52] simplified the implementation by sacrificing the efficiency, compared with those in Refs. [38, 40]. However, the present ECP distills an $N$-electron system from a system in a partially entangled pure state and an additional electron, not a pair of $N$-electron systems, which is far different from all existing ECPs [38–40, 52]. Moreover, the success probability of the present ECP is $2\alpha^2\beta^2$, which is the same as those in Refs. [39, 40]. However, these in Refs. [38, 52] do not require the parties to know the information. In essence, all existing ECPs [38, 40, 52] for electron systems are based on the Schmidt projection method in which the parties exploit the combination of a pair of systems with the same parameter to obtain a system in a maximally entangled state with an average success probability of $\alpha^2\beta^2$. The ECP in Ref. [40] exploits an additional collective unitary evolution on one qubit in the system and an additional qubit to improve the success probability to be $\alpha^2$. The ECP for electron systems in Ref. [52] simplified the implementation by sacrificing the efficiency, compared with those in Refs. [38, 40]. However, the present ECP distills an $N$-electron system from a system in a partially entangled pure state and an additional electron, not a pair of $N$-electron systems, which is far different from all existing ECPs [38–40, 52]. Moreover, the success probability of the present ECP is $2\alpha^2\beta^2$, which is the same as those in Refs. [39, 40]. However, these in Refs. [38, 52] do not require the parties to know the information.
her electron $A$ and the additional electron $a$ in the state $|\uparrow\rangle_a$, which makes the state of the three-electron system $ABA$ become $|\Psi_{3}\rangle_{ABA} = \alpha |\uparrow\rangle_A |\uparrow\rangle_B |\uparrow\rangle_a + \beta (|\downarrow\rangle_A |\downarrow\rangle_B |\downarrow\rangle_a |\downarrow\rangle_a)$. The $PBS_{a1}$ will project the state of the additional electron $a$ into the orthogonal basis $|\phi^-\rangle_a = |\downarrow\rangle B \& |\downarrow\rangle A |\uparrow\rangle \rangle - |\uparrow\rangle B \& |\downarrow\rangle A |\downarrow\rangle \rangle)$. When the additional electron is filtered out from the output $D_1$, the two-electron system $AB$ is in the maximally entangled state $|\Psi^+\rangle_{AB} = \frac{1}{\sqrt{2}}(|\uparrow\rangle A |\uparrow\rangle B + |\downarrow\rangle A |\downarrow\rangle B)$. Otherwise, the additional electron will be recovered to be the initial state $|\uparrow\rangle_a$ and enter into the next round of entanglement concentration. When the additional electron is detected at the outputs $D_1$, $D_2$, $\cdots$, or $D_n$, the two-electron system $AB$ will be in the maximally entangled state.

In summary, we have proposed an optimal ECP for non-local $N$-electron systems in a partially entangled pure state, resorting to charge detection and the projection measurements on additional electrons. One of the $N$ parties, say Alice exploits the PCG based on charge detection to extend the partially entangled $N$-electron system to an $(N+1)$-electron system first and then she projects the additional electron into an orthogonal basis. By detecting the output of the additional electron from a PBS, the $N$-parties in quantum communication can divide their $N$-electron systems into two groups. One is in the maximally entangled state. The other is in another partially entangled state with less entanglement, which is just the resource for the entanglement concentration in the next round. By iterating the entanglement concentration process several times, the $N$ parties can obtain a subset of $N$-electron systems in the maximally entangled state with the maximal success probability which is just equivalent to the entanglement of the partially entangled state. Compared with other ECPs \cite{28,40,52}, the present ECP has the optimal success probability, the theoretical limit, without resorting to a collective unitary evolution.

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