Efficient electronic entanglement concentration assisted by single mobile electrons*

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We present an efficient entanglement concentration protocol (ECP) for mobile electrons with charge detection. This protocol is quite different from other ECPs for one can obtain a maximally entangled pair from a pair of less-entangled state and a single mobile electron with a certain probability. With the help of charge detection, it can be repeated to reach a higher success probability. It also does not need to know the coefficient of the original less-entangled states. All these advantages may make this protocol useful in current distributed quantum information processing.

Keywords: quantum communication, entanglement, entanglement concentration

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1. Introduction

Entanglement plays an important role in the current quantum communication,[1] such as the teleportation,[2–4] quantum key distribution (QKD) protocols,[5–7] quantum secret sharing,[8–10] quantum secure direct communication,[11–20] and other quantum information processing.[20–30]

For most of the practical quantum communication and computation protocols, people need to share a maximally entangled state with each other. However, the entanglement resource is fragile, for the maximally entangled state may be degraded into a mixed state or become a less-entangled state when it interacts with the noisy environment. People usually resort to the entanglement purification[31] to increase the fidelity of the mixed state and the entanglement concentration,[32–53] which will be detailed here, to recover the less-entangled state to a maximally entangled state. Currently, most of the protocols for concentration are focused on optical systems.[34–36,38–40,48] During the transmission, the photons have weak interaction with the environment.

On the other hand, there is another candidate for the flying qubit, that is, the mobile electron. The strong interaction between different electrons makes the interaction between the flying electron spins and other solid electron spins possible, since the Coulomb interaction between electrons is strongly screened. In recent years, the investigation on the flying electron qubits has become an active study area.[54–62] In 2004, Beenakker *et al.* broke through the obstacle of the no-go theorem with the help of charge detection and constructed a controlled-NOT(CNOT) gate using beam splitters and spin rotations almost deterministically.[54] With the help of a charge detector, people can construct the charge qubit,[59] perform entanglement purification,[31] construct entangled spins,[63] and prepare a multipartite entanglement analyzer, and cluster states.[64] In particular, the flying qubit can also be used in the one-dimensional system and create entanglement between two distant matter qubits. Ziberberg *et al.* discussed a meaurement-based implementation of a CNOT gate for free electron qubits.[65] Recently, Matsuzaki and Jefferson proposed a protocol for distributed quantum information processing with mobile electrons.[66] In their protocol, they used mobile electron spins as the mediators of the interaction between the static qubits at each node and finally created a high quality entanglement between each node. Unfortunately, the distributed quantum entanglement may also be degraded into the less-entangled state when it is coupled with the noisy environment. On the other hand, with current technology, it is difficult to operate each flying qubit perfectly, which can also lead the ideal maximally entangled state to be degraded.[66]

Entanglement concentration is a powerful tool to recover a less-entangled state into a maximally entangled one with only local operation and classical communication. The first entanglement concentration protocol (ECP) was proposed by Bennett *et al.* in 1996.[32] This method is called Schmidt projection method, in which one needs the collective measurement and needs to know the exact coefficient of the initial entangled state. In 2001, Zhao *et al.* and Yamamoto *et al.* proposed two similar simplified ECPs with linear optical elements based on the Schmidt projection method, respectively.

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In 2009, we proposed an ECP based on electrons.[37] Almost all the current ECPs need two pairs of less-entangled states, but after performing each ECP, at most one pair of maximally entangled state can be obtained with a certain success probability.

Actually, using two copies of less-entangled pairs to obtain one maximally entangled pair is not the optimal way. In this paper, we show that we can perform the ECP with the same success probability by using only one pair of less-entangled state and a single electron. Compared with the previous ECPs, less-entangled resources are not required as much by this protocol. Moreover, similar to Ref. [37], we adopt the charge detectors and polarization beam splitter (PBS) to reconstruct our protocol, which makes it have a higher success probability than those protocols with linear optics. This protocol can also be used to concentrate the multipartite entangled system. All these advantages may make this protocol more useful in current quantum communication and distributed quantum information processing.

2. Results and discussion

Before we start to explain our ECP, we first introduce the charge detector (C) which is a key element shown in Fig. 1. The charge detector can distinguish the occupation number 1 from the occupation number 0 and 2. However, it cannot distinguish between the occupation number 0 and 2.[54] In both cases, we define that the charge detector will show 0 for simple. In Fig. 1, we suppose the source S_1 emits a pair of less-entangled state in the form of

$$|\Phi\rangle_{a1b1} = \alpha|\uparrow\rangle_{a1}|\uparrow\rangle_{b1} + \beta|\downarrow\rangle_{a1}|\downarrow\rangle_{b1}. \quad (1)$$

Here, $|\alpha|^2 + |\beta|^2 = 1$. $|\uparrow\rangle$ and $|\downarrow\rangle$ are spin up and spin down, respectively. Meanwhile, the source S_2 emits a single electron to Bob in the form of

$$|\Phi\rangle_{b2} = \alpha|\uparrow\rangle_{b2} + \beta|\downarrow\rangle_{b2}. \quad (2)$$

Bob receives two electrons from the spatial modes b1 and b2 and Alice only receives one electron from a1. Bob first performs a bit-flip operation and makes $|\Phi\rangle_{b2}$ become

$$|\Phi\rangle_{b2} \to |\Phi\rangle_{b3} = \alpha|\downarrow\rangle_{b3} + \beta|\uparrow\rangle_{b3}. \quad (3)$$

Therefore, the original entangled state of the three-electron state can be written as

$$\begin{aligned}|\Psi\rangle &= |\Phi\rangle_{a1b1} \otimes |\Phi\rangle_{b3} \\ &= (\alpha|\uparrow\rangle_{a1}|\uparrow\rangle_{b1} + \beta|\downarrow\rangle_{a1}|\downarrow\rangle_{b1}) \\ &\quad \otimes(\alpha|\downarrow\rangle_{b3} + \beta|\uparrow\rangle_{b3}) \\ &= \alpha^2|\uparrow\rangle_{a1}|\uparrow\rangle_{b1}|\downarrow\rangle_{b3} + \beta^2|\downarrow\rangle_{a1}|\downarrow\rangle_{b1}|\uparrow\rangle_{b3} \\ &\quad + \alpha\beta(|\uparrow\rangle_{a1}|\uparrow\rangle_{b1}|\uparrow\rangle_{b3} + |\downarrow\rangle_{a1}|\downarrow\rangle_{b1}|\downarrow\rangle_{b3}). \quad (4)\end{aligned}$$

Then, Bob lets his two electrons pass through the PBS, which fully transmits $|\uparrow\rangle$ and reflects $|\downarrow\rangle$. The $|\Psi\rangle$ becomes

$$\begin{aligned}|\Psi\rangle \to |\Psi\rangle' &= \alpha^2|\uparrow\rangle_{a1}|\uparrow\rangle_{c2}|\downarrow\rangle_{c2} + \beta^2|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\uparrow\rangle_{c1} \\ &\quad + \alpha\beta(|\uparrow\rangle_{a1}|\uparrow\rangle_{c1}|\uparrow\rangle_{c2} + |\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\downarrow\rangle_{c2}). \quad (5)\end{aligned}$$

From the above equation, one can find that the item $|\uparrow\rangle_{a1}|\uparrow\rangle_{c2}|\downarrow\rangle_{c2}$ means that the two electrons in Bob's location are both in the spatial mode c2 while the item $|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\uparrow\rangle_{c1}$ means that the two electrons are both in the mode c1. However, both the items $|\uparrow\rangle_{a1}|\uparrow\rangle_{c1}|\uparrow\rangle_{c2}$ and $|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\downarrow\rangle_{c2}$ mean that the two electrons are in the modes c1 and c2, respectively. Therefore, the charge detector will show 0 if the original state collapses to $|\uparrow\rangle_{a1}|\uparrow\rangle_{c2}|\downarrow\rangle_{c2}$ or $|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\uparrow\rangle_{c1}$. It will show 1 if the original state collapses to

$$|\Psi\rangle'' = \frac{1}{\sqrt{2}}(|\uparrow\rangle_{a1}|\uparrow\rangle_{c1}|\uparrow\rangle_{c2} + |\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\downarrow\rangle_{c2}). \quad (6)$$

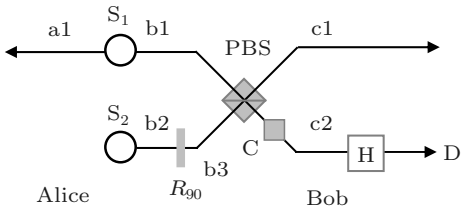


Fig. 1. Schematic drawing of the principle of our ECP based on charge detection. Only one pair of less-entangled state and a single electron are required here. PBS can fully transmit spin up $|\uparrow\rangle$ and reflect spin down $|\downarrow\rangle$. The charge detector (C) can distinguish the charge number 1 from 0 and 2, but cannot distinguish between numbers 0 and 2. D represents the detector.

The probability of obtaining the state given by Eq. (6) is $2|\alpha\beta|^2$. Obviously, it is the three-electron maximally entangled state. It is easy to obtain a two-electron maximally entangled state from Eq. (6). Bob needs to perform a Hadamard operation on his electron in the mode c2. It makes

$$\begin{aligned}|\uparrow\rangle_{c2} &\to \frac{1}{\sqrt{2}}(|\uparrow\rangle_{c2} + |\downarrow\rangle_{c2}), \\ |\downarrow\rangle_{c2} &\to \frac{1}{\sqrt{2}}(|\uparrow\rangle_{c2} - |\downarrow\rangle_{c2}). \quad (7)\end{aligned}$$

After Bob performs the Hadamard operation, equation (6) becomes

$$\begin{aligned}|\Psi\rangle'' &\to \frac{1}{2}[|\uparrow\rangle_{a1}|\uparrow\rangle_{c1}(|\uparrow\rangle_{c2} + |\downarrow\rangle_{c2}) \\ &\quad + |\downarrow\rangle_{a1}|\downarrow\rangle_{c1}(|\uparrow\rangle_{c2} - |\downarrow\rangle_{c2})] \\ &= \frac{1}{2}[(|\uparrow\rangle_{a1}|\uparrow\rangle_{c1} + |\downarrow\rangle_{a1}|\downarrow\rangle_{c1})|\uparrow\rangle_{c2} \\ &\quad + (|\uparrow\rangle_{a1}|\uparrow\rangle_{c1} - |\downarrow\rangle_{a1}|\downarrow\rangle_{c1})|\downarrow\rangle_{c2}]. \quad (8)\end{aligned}$$

Then, the last step for Bob is to measure the spin in the basis $Z = \{|\uparrow\rangle, |\downarrow\rangle\}$. From the above equation, if the measurement result is $|\uparrow\rangle_{c2}$, the electron pair in the modes a1c1 will become

$$|\phi^+\rangle_{a1c1} = \frac{1}{\sqrt{2}}(|\uparrow\rangle_{a1}|\uparrow\rangle_{c1} + |\downarrow\rangle_{a1}|\downarrow\rangle_{c1}). \quad (9)$$

If the measurement result is $|\downarrow\rangle_{c2}$, the electron pair in the modes a1c1 will become

$$|\phi^-\rangle_{a1c1} = \frac{1}{\sqrt{2}}(|\uparrow\rangle_{a1}|\uparrow\rangle_{c1} - |\downarrow\rangle_{a1}|\downarrow\rangle_{c1}). \quad (10)$$

Bob only needs to perform a phase-flip operation on his electrons to obtain $|\phi^+\rangle_{a1c1}$. If they share the pair $|\phi^\pm\rangle_{a1c1}$, Bob will tell Alice that the protocol is successful and asks Alice to retain her electron. In this way, they can share a maximally entangled state from a less-entangled state with the success probability of $2|\alpha\beta|^2$.

From the above description, Bob chooses the case that the charge detector's result is 1 and discards the case of 0. It is essentially the partial parity check gate which picks up the even parity states $|\uparrow\rangle|\uparrow\rangle$ and $|\downarrow\rangle|\downarrow\rangle$ but discards the odd parity states $|\uparrow\rangle|\downarrow\rangle$ and $\downarrow\rangle|\uparrow\rangle$. In this case, the function of PBS is similar to what it is in the optical systems.[34,35] In Refs. [34] and [35], they need to check that both the output modes of the optical PBS contain exactly and only one photon. It is so called the post-selection principle. Therefore, even if they successfully perform their ECPs, the maximally entangled state would be destroyed by the single photon detector. The maximally entangled photon pair cannot be maintained for further application. In this protocol, Bob can judge the successful case from the charge detection results. The charge qubit carries both the spin degree of freedom and the charge degree of freedom. As charge and spin are commutable and a measurement of charge leaves the spin qubit unaffected, the charge detection does not affect the entangled state of the electrons.

Actually, the charge detector and PBS are more powerful than it has been described above, for the discarded items are essentially the lesser-entangled state which can be reconcentrated in the second step. That is to say, we cannot only pick up the even parity states, but also pick up the odd parity states. In Fig. 2, we add another PBS, i.e., PBS_2, to reconstruct our ECP. We denote the whole setup P gate shown in Fig. 2. If the charge detector's result is 0, the original state will collapse to

$$|\Psi\rangle''' = \alpha^2|\uparrow\rangle_{a1}|\uparrow\rangle_{c2'}|\downarrow\rangle_{c2'} + \beta^2|\downarrow\rangle_{a1}|\downarrow\rangle_{c1'}|\uparrow\rangle_{c1'}. \quad (11)$$

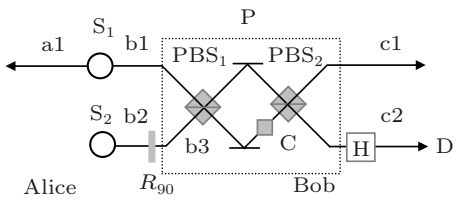


Fig. 2. Schematic drawing of the principle of reconstructing our ECP. If the measurement result of charge detector is 0, the remaining lesser-entangled pair can also be reused to perform the entanglement concentration. PBS_2 is used to couple the state into the same spatial mode. P plays an essential role of the parity check gate.

It means that after passing through the PBS_1, both the electrons are in the same spatial mode, while with the help of PBS_2, they are coupled into

$$|\Psi\rangle''' = \alpha^2|\uparrow\rangle_{a1}|\uparrow\rangle_{c1}|\downarrow\rangle_{c2} + \beta^2|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\uparrow\rangle_{c2}. \quad (12)$$

It means that the two electrons in Bob's location are in different spatial modes, say c1 and c2, respectively. Then after performing the Hadamard operation and measuring the spin of the electron on the mode c2, they can obtain

$$|\Phi\rangle_1 = \alpha^2|\uparrow\rangle_{a1}|\uparrow\rangle_{c1} + \beta^2|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}. \quad (13)$$

If the measurement result is $|\uparrow\rangle$, they can obtain

$$|\Phi\rangle_2 = \alpha^2|\uparrow\rangle_{a1}|\uparrow\rangle_{c1} - \beta^2|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}, \quad (14)$$

if the measurement result is $|\downarrow\rangle$. Both equations (13) and (14) are lesser-entangled states. They can be reconcentrated in the next step. Briefly speaking, if they obtain $|\Phi\rangle_1$, Bob needs to choose another single electron in the form of

$$|\Phi\rangle'_{b2} = \alpha^2|\uparrow\rangle_{b2} + \beta^2|\downarrow\rangle_{b2}. \quad (15)$$

After performing a bit flip operation with R_{90} shown in Fig. 2, it becomes

$$|\Phi\rangle'_{b3} = \alpha^2|\downarrow\rangle_{b3} + \beta^2|\uparrow\rangle_{b3}. \quad (16)$$

Then, the three-electron system evolves as

$$\begin{aligned}|\Phi\rangle_2 \otimes |\Phi\rangle'_{b3} &= (\alpha^2|\uparrow\rangle_{a1}|\uparrow\rangle_{c1} + \beta^2|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}) \\ &\quad \otimes (\alpha^2|\downarrow\rangle_{b3} + \beta^2|\uparrow\rangle_{b3}) \\ &= \alpha^4|\uparrow\rangle_{a1}|\uparrow\rangle_{c1}|\downarrow\rangle_{b3} + \beta^4|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\uparrow\rangle_{b3} \\ &\quad + \alpha^2\beta^2(|\uparrow\rangle_{a1}|\uparrow\rangle_{c1}|\uparrow\rangle_{b3} + |\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\downarrow\rangle_{b3}).\end{aligned} \quad (17)$$

Obviously, if the measurement result of the charge detection is 1, they can obtain the same three-electron state as described in Eq. (6) with a probability of $2|\alpha\beta|^4$. Otherwise, if the charge detection's result is 0, the remaining state is a lesser-entangled state and can be reconcentrated in a third round. In this way, they can repeat this protocol to achieve a higher success probability than other protocols.

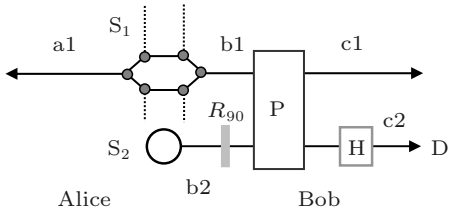


Fig. 3. Schematic diagram of the multipartite entanglement concentration protocol. N particles in the multipartite GHZ state from the source S_1 are sent to N parties: Alice, Bob, Charlie, etc. The source S_2 also emits a single electron to Bob. The parity check gate denoted as P is shown in Fig. 2. It comprises the PBS_1, charge detector C, and PBS_2. Only Bob needs to perform this concentration.

It is straightforward to extend this protocol to multipartite pure entangled state systems. An N-electron less-entangled system can be described as

$$|\Phi\rangle_N = \alpha|\uparrow\rangle_1|\uparrow\rangle_2\cdots|\uparrow\rangle_N + \beta|\downarrow\rangle_1|\downarrow\rangle_2\cdots|\downarrow\rangle_N. \quad (18)$$

The N electrons are emitted from S_1 and sent to N parties: Alice, Bob, Charlie, etc, as shown in Fig. 3. Alice receives the electron of number 1 in the spatial mode a1. Bob receives number 2 in the spatial mode b1, Charlie receives number 3, and so on. The source of S_2 also emits a single electron to

Bob with the same form of Eq. (2). After rotating it by 90°, the composite system can be described as

$$\begin{aligned}|\Psi\rangle_{N+1} &= |\Phi\rangle_N \otimes |\Phi\rangle_{b3} \\ &= (\alpha|\uparrow\rangle_1|\uparrow\rangle_2\cdots|\uparrow\rangle_N + \beta|\downarrow\rangle_1|\downarrow\rangle_2\cdots|\downarrow\rangle_N) \\ &\quad \otimes(\alpha|\downarrow\rangle_{b3} + \beta|\uparrow\rangle_{b3}) \\ &= \alpha^2|\uparrow\rangle_1|\uparrow\rangle_2|\downarrow\rangle_{b3}\cdots|\uparrow\rangle_N \\ &\quad + \beta^2|\downarrow\rangle_1|\downarrow\rangle_2|\uparrow\rangle_{b3}\cdots|\downarrow\rangle_N) \\ &\quad + \alpha\beta(|\uparrow\rangle_1|\uparrow\rangle_2|\uparrow\rangle_{b3}\cdots|\uparrow\rangle_N \\ &\quad + |\downarrow\rangle_1|\downarrow\rangle_2|\downarrow\rangle_{b3}\cdots|\downarrow\rangle_N). \end{aligned} \tag{19}$$

Subsequently, the electrons in the spatial modes b1 and b3 in Bob's location pass through the P gate. If the charge detector's result is 1, equation (19) will collapse into

$$\begin{aligned}|\Psi'\rangle_{N+1} &= \frac{1}{\sqrt{2}}(|\uparrow\rangle_1|\uparrow\rangle_2|\uparrow\rangle_{c2}\cdots|\uparrow\rangle_N \\ &\quad + |\downarrow\rangle_1|\downarrow\rangle_2|\downarrow\rangle_{c2}\cdots|\downarrow\rangle_N), \end{aligned} \tag{20}$$

with a probability of $2|\alpha\beta|^2$. Finally, Bob performs a Hadamard operation, and measures the electron in the mode c2 in the basis $Z = \{|\uparrow\rangle, |\downarrow\rangle\}$. If the measurement result is $|\uparrow\rangle$, they will have

$$|\Psi'\rangle_N = \frac{1}{\sqrt{2}}(|\uparrow\rangle_1|\uparrow\rangle_2\cdots|\uparrow\rangle_N + |\downarrow\rangle_1|\downarrow\rangle_2\cdots|\downarrow\rangle_N), \tag{21}$$

and if the measurement result is $|\downarrow\rangle$, they will have

$$|\Psi''\rangle_N = \frac{1}{\sqrt{2}}(|\uparrow\rangle_1|\uparrow\rangle_2\cdots|\uparrow\rangle_N - |\downarrow\rangle_1|\downarrow\rangle_2\cdots|\downarrow\rangle_N). \tag{22}$$

Both equations (21) and (22) are the N-electron maximally entangled states. Otherwise, if the charge detector's result is 0, then equation (19) becomes

$$\begin{aligned}|\Psi''\rangle_{N+1} &= \alpha^2|\uparrow\rangle_1|\uparrow\rangle_2|\downarrow\rangle_{b3}\cdots|\uparrow\rangle_N \\ &\quad + \beta^2|\downarrow\rangle_1|\downarrow\rangle_2|\uparrow\rangle_{b3}\cdots|\downarrow\rangle_N. \end{aligned} \tag{23}$$

After performing the Hadamard operation and measuring the electron in c2 mode in the Z basis, the above state becomes

$$|\Psi^{\pm}\rangle_N = \alpha^2|\uparrow\rangle_1|\uparrow\rangle_2\cdots|\uparrow\rangle_N \pm \beta^2|\downarrow\rangle_1|\downarrow\rangle_2\cdots|\downarrow\rangle_N. \tag{24}$$

Compared with Eq. (18), it is also a multipartite less-entangled state which can be reconcentrated into a maximally entangled state. '+' or '−' is decided by the measurement results of $|\uparrow\rangle$ or $|\downarrow\rangle$, respectively.

So far, we have fully described our ECP. It is interesting to compare this protocol with Ref. [37]. In Ref. [37], we use two copies of less-entangled pairs to perform the concentration. We can obtain one pair of maximally entangled states with a success probability of $2|\alpha\beta|^2$. In this protocol, we use only one pair of less-entangled state and a single electron which can reach the same success probability with Ref. [37]. Moreover, during the whole protocol, only one-way classical communication is required. That is, Alice only needs to receive the information from Bob's measurement and to judge whether the protocol is successful or not. If the protocol is a failure, Alice needs to do nothing. If the protocol is successful, Bob will tell Alice the remaining state is $|\phi^+\rangle$ or $|\phi^-\rangle$ according to his measurement. In previous protocols,[34,35,37] all of the parties have to participate in the whole procedure, to measure their electrons and check their results with each other. According to the results, they can judge whether the protocol is successful. Thus, this protocol is much simpler, especially when it is used to concentrate a multi-partite system, for only one of the parties needs to perform the protocol and then reports his results to others. Finally, let us briefly discuss the key ingredient of this protocol here, that is, the charge detector.[67–69] It has been realized in a two-dimensional electron gas. It was reported that currently achievable time resolution for charge detection is microsecond.[68] In a semiconductor, it was reported that the resolution required for ballistic electrons is less than 5 ps.[69] Compared with flying qubits, it may be more practical to use isolated electrons in an array of quantum dots, as suggested by Ref. [54]. Another key element in this ECP is the PBS. The function of PBS for electrons is equivalent to the optical PBS. In 2003, Ionicioiu and D'Amico discussed such devices to polarize spin currents.[70] By adding the magnetic flux threading the interferometer, it can generate an Aharonov–Bohm phase, and it induces a phase difference in the electronic wave functions between the two different arms. Therefore, with the help of two beam splitters and a Rashba phase generated by an electric field on one of the arms, such a device essentially is the spin-polarizing beam splitter.

3. Conclusion

In conclusion, we have proposed a mobile electron ECP based on charge detection. Compared with other protocols, it has several advantages: (i) it does not require the post-selection principle, and can be repeated to reach a higher efficiency than those based on linear optical elements, (ii) only one pair of less-entangled state and one-way classical communication are required, which make this protocol more economic and simpler than others. All these advantages make this ECP more useful in current quantum communication and distributed quantum information processing.

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