# Direct counterfactual transmission of a quantum state

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We show that an unknown quantum state can be transferred with neither quantum nor classical particle traveling in the transmission channel. Our protocol does not require prearranged entangled photon pairs and Bell measurements. By utilizing quantum Zeno effect and counterfactuality, we can entangle and disentangle a photon and an atom by nonlocal interaction. It is shown that quantum information is completely transferred from an atom to photon due to controllable disentanglement processes. There is no need to cross-check the result via classical channels.

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## I. INTRODUCTION

One fascinating result in quantum mechanics is that an unknown quantum state can be teleported from one place to another [1–5]. It has many applications including quantum networking [6], quantum repeater [7,8], secure communication [9] and black-hole investigation [10]. An essential resource to achieve quantum teleportation is quantum entanglement [1,5,11]. As the preparation of the conventional quantum teleportation, entangled photon (or physical particle) pairs are distributed to two communicators (Alice and Bob). In this stage, no information is transferred. Then, one communicator, Bob, makes a Bell measurement on his entangled photon and an object encoded in an unknown quantum state, which he wants to teleport to the other communicator, Alice. After measurement, the prearranged entangled photon pairs are disentangled; the state of Alice's photon is decided by Bob's measurement result. As the last step of the conversional quantum teleportation, a classical signal is transmitted to deliver the measurement result. This signal carries information. Recently, an unconventional scheme of transferring an unknown quantum state is proposed which does not need prearranged entangled photon pairs [12]. They generate entanglement counterfactually. Although the authors also claim that classical channel is not necessary in their protocol, they only have a 50% chance of getting the correct outcome even in the ideal case if the classical channel is not utilized. Therefore, a classical signal is still indispensable.

In this paper, we introduce a way to transfer an unknown quantum state by nonlocal interaction. There is no need to send any quantum or classical particle into the public transmission channel. In theory, the fidelity and the efficiency of communication are close to one. Our protocol could be utilized in such applications as nondestructive measurement, quantum gate, quantum sensing, secure communication, and single-photon router.

Before we describe the details of our protocol, we explain some concepts and introduce related works to help readers understand our work.

Our work is based on counterfactual communication [13,14], which utilizes concepts like interaction free measurement [15,16]. First of all, let us have a brief introduction about counterfactual communication.

In Fig. 1, the rectangle at Alice's end represents the setup of counterfactual communication protocol, which has one input and two outputs. The main function of the setup is to test whether the photon paths between Alice and Bob are blocked by Bob's object. Initially, a single photon is inserted by Alice. Then, the photon bounces in the setup for many cycles. In each cycle, Alice's photon has a tiny probability leaking into Bob's end. As for Bob, he has two options. His first option is to block the photon paths by some object. It means that if Alice's photon appears at Bob's end, it is absorbed. This blockage represents Bob sending a logic signal "1." Bob's second option is to return Alice's photon back without interruption, which represents logic "0." Bob takes the same actions for every photon cycle. Then, the evolution of Alice's photon is continually affected by Bob due to the quantum Zeno effect (QZE) [17–19], which says the continuous observation freezing the evolution of a quantum system. Finally, corresponding to Bob's different signals, Alice catches her photon from different outputs.

Next we explain why the communication is counterfactual. Apparently, if Bob's object absorbs Alice's photon, there is no output at Alice's end. However, if Bob unblocks the photon paths, the situation is a little bit complicated. In [13], we demonstrate that as long as Alice's photon passes through Bob's end, it must trigger one of Alice's detectors (these detectors are not for detecting outputs and they are not shown in Fig. 1) so that Alice gets no output. Taken together, once Alice obtains an output, her photon never appears at Bob's end. Consequently, Alice receives Bob's classical signal ("0" or "1") without any real physical particle traveling between them. This is counterfactual. The interaction between Alice and Bob is nonlocal.

In the above, Bob's object is classical. It could either block or unblock the photon paths. What happens if Bob utilizes a quantum object, which is in a superposition state of being blocked and unblocked? In [12], the authors answer the question. In their scheme, an atom prepared in a superposition state (excited/unexcited) is utilized as a quantum object to control the photon paths. If the atom is in its ground state, the photon paths are blocked. If the atom is in its excited state, the photon paths are unblocked. Consequently, after nonlocal interaction, Alice's photon is entangled with Bob's atom. If Alice's photon is found in output 1, Bob's atom must be in its excited state. If Alice's photon is found in output 2, Bob's

 

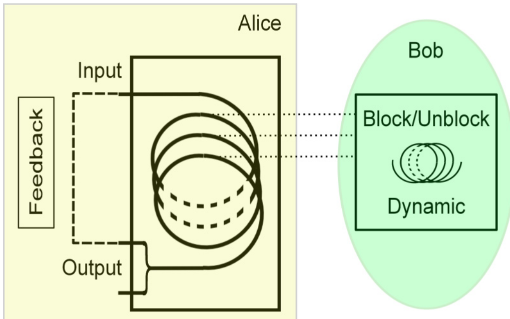


FIG. 1. (Color online) Schematic diagram of counterfactual communication and our proposed protocol of transferring an unknown quantum state counterfacutally. At Alice's end, it is a counterfactual communication setup. It detects whether the photon paths, which are represented by dotted lines, are blocked by Bob's object. Alice's photon bounces in her setup many times and its evolution is continually affected by Bob's actions. However, it can be demonstrated that Alice's output photon never leaks out of her setup. At Bob's end, the object which Bob utilizes to block the photon paths is classical in the counterfactual communication case. However, to transfer an unknown quantum state counterfactually, a quantum object is utilized. It is prepared in a superposition state of being blocked and unblocked initially. Then, Alice's photon can be entangled with Bob's quantum object. To disentangle them, a feedback is added in Alice's setup. In the meantime, Bob's object undergoes a dynamic evolution process, which is represented by the cylindrical spiral at Bob's end. The evolution of Bob's object is continually affected by Alice's photon due to the feedback until the object is disentangled with Alice's photon. Then, the initial state of Bob's atom is transferred to Alice.

atom must be in the ground state. In Sec. II, we show that this entanglement process is important to our protocol as well.

Now we know that Bob's object could be quantum. The next problem is whether Alice can extract quantum information encoded in Bob's quantum object. To transfer a superposition state from Bob's object to Alice's photon, just to entangle the photon and the object is not enough. Alice and Bob need a disentanglement process as well. In [12], the disentanglement process is achieved by Bob measuring his atom. Only with the measurement result, Alice is able to complete the information transfer. Therefore, classical channel is necessary. A similar situation occurs in conventional quantum teleportation, in which disentanglement is achieved by Bell measurement. We emphasize that those disentanglement processes are irreversible. However, in this paper, we propose a different solution: a reversible disentanglement process. In other words, the entanglement between Alice's photon and Bob's quantum object is recoverable. Alice and Bob need to do two things to achieve that. First, at Bob's end, his quantum object must have a dynamic evolution. For example, if Bob's object is a two-level atom, it can undergo a Rabi oscillation process. Second, at Alice's end, she adds a feedback in the counterfactual communication setup as shown in Fig. 1. The feedback guarantees that Alice's photon can continually and nonlocally affect the evolution of Bob's quantum object by QZE. In Sec. II and Appendix B, we give all the details. As a result, an unknown quantum state can be transferred from Bob to Alice

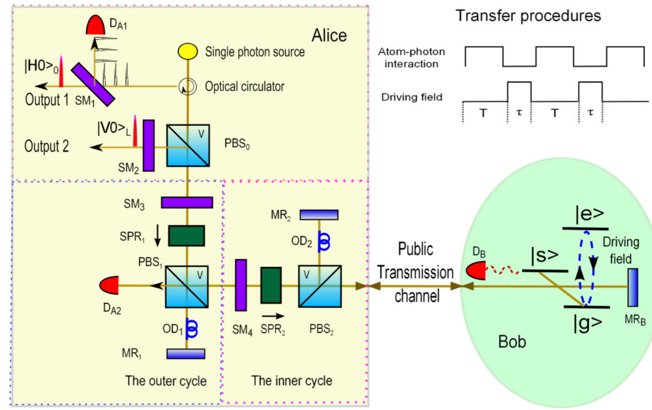


FIG. 2. (Color online) The proposed scheme for transferring an unknown quantum state counterfactually. In the oval shape, Bob's device includes a detector, a mirror, and a V-type three-level atom system for simplicity. More details are in the text.

certainly and counterfactually. There is no need for classical channel.

Generally speaking, our protocol has two steps. Both steps are counterfactual. The first step is to generate entanglement between Bob's quantum object and Alice's photon, while the second step is to disentangle them in a controllable manner. The second step is the key feature of this protocol. In Sec. II, we elaborate our theory with a specific scheme. In Sec. III, we show the numerical simulation results and error analyses such as the effect of photon loss. In Sec. IV, we have a discussion about experiment. In Sec. V, a short conclusion is given.

## II. THEORY AND DEMONSTRATION

Our proposed setup is sketched in Fig. 2, where we have two stations, one at Alice's side and another at Bob's side. Here, we start with Alice's setup where $D$ stands for detector, PBS stands for polarizing beam splitter which lets horizontally polarized ($H$) photons pass through but reflects vertically polarized ($V$) photons, SM stands for switchable mirror which can be transparent once it is turned off, MR stands for normal mirror, OD stands for optical delay, and $\text{SPR}_{1(2)}$ stands for switchable polarization rotator with rotation angle $\beta_{1(2)}$. The $\text{SPR}_{1(2)}$ operates in such way that $|H\rangle \rightarrow \cos\beta_{1(2)}|H\rangle + \sin\beta_{1(2)}|V\rangle$ and $|V\rangle \rightarrow \cos\beta_{1(2)}|V\rangle - \sin\beta_{1(2)}|H\rangle$. We assume $\text{SPR}_{1(2)}$ gets rotated only when the photon comes from the $\text{SM}_{3(4)}$ side. Similar to [13], here Alice's device includes two tandem Michelson interferometers. The two optical paths $\text{SM}_3 \rightarrow \text{MR}_1$ and $\text{SM}_3 \rightarrow \text{MR}_B$ belong to the first Michelson interferometer. Inside this outer cycle there is the inner cycle represented by paths $\text{SM}_4 \rightarrow \text{MR}_2$ and $\text{SM}_4 \rightarrow \text{MR}_B$ which belong to the second Michelson interferometer. In the following, we use $|0P\rangle$ and $|P0\rangle$ $(P = H,V)$ to represent photons inside and outside the second interferometer.

At Bob's side, there is a V-type three-level atom. It has two excited levels $|e\rangle$ and $|s\rangle$ that are coupled to ground level $|g\rangle$. However, their electric dipoles are orthogonal to each other. The transition between $|e\rangle$ and $|g\rangle$ is drove by an incoming driving field with Rabi frequency $\Omega$. We emphasize that the driving field is not continuous, as shown in Fig. 2. It continues for time $\tau$ and then vanishes, and the time period between two pulses is $T$. The transition between $|s\rangle$ and $|g\rangle$ is coupled by only Alice's photon.

The ultimate goal of our scheme is to counterfactually transfer an unknown quantum state $C_e|e\rangle + C_g|g\rangle$, where $C_e$ and $C_g$ are arbitrary complex amplitudes, from Bob's atom to Alice's photon polarization state $C_e|H\rangle + C_g|V\rangle$. Here the $H$ photon always goes via output 1, while the $V$ photon goes via output 2. Our protocol can avoid any need of classical channel.

Next we explain how to entangle and disentangle Alice's photon and Bob's atom. More details can be found in Appendices A and B.

*Step 1*. To entangle Alice's photon and Bob's atom.

Let us start with the entanglement process. All SMs are off allowing an $H$ polarized single photon to go through $PBS_0$ and $SM_3$ from Alice's single-photon source. After the photon passes through $SM_3$, we turn $SM_3$ on and keep the photon reflecting back and forth $M-1$ times for the outer cycles. In each of these cycles, the photon polarization is rotated by $SPR_1$ with $\beta_1 = \pi/2M$. Then, due to $PBS_1$, the photon is separated into two different paths: $H$ photon component ($|H0\rangle$) goes towards $MR_1$ while the $V$ photon component passes through $SM_4$ when it is off and goes into the inner cycle. Once the photon component is in the inner cycle, $SM_4$ is on until the $V$ photon component is reflected $N-1$ times. In each inner cycle, the photon polarization is rotated by $SPR_2$ with $\beta_2 = \pi/2N$. The $H$ photon component ($|0H\rangle$) leaks into the transmission channel.

Assuming perfect interaction between the atom and the photon, the leaked photon component ($|0H\rangle$) is absorbed by Bob's atom as long as it is in the ground state, i.e., $|0H\rangle|g\rangle \rightarrow |00\rangle|s\rangle$. After the photon bounces between $SM_4$ and $MR_B$ for $N$ times, we have

$$\begin{aligned} &C_e(\cos\beta_1|H0\rangle - \sin\beta_1|0H\rangle)|e\rangle \\ &\quad + C_g(\cos\beta_1|H0\rangle + \sin\beta_1\cos^N\beta_2|0V\rangle)|g\rangle \\ &\quad - C_g\sin\beta_1\sum_{j=1}^{N}\cos^{j-1}\beta_2\sin\beta_2|00\rangle_j|s\rangle. \end{aligned} \tag{1}$$

In Eq. (1), the last term indicates local interaction at Bob's end, which means Alice's photon appears in the public channel all the way to Bob. Therefore, we have to eliminate this term. One way to do so is to measure states $|00\rangle_j|s\rangle$ ($j \in [1,N]$) indirectly. This can be achieved by measuring whether the atom is in level $|s\rangle$ or not by using detector $D_B$. Detector clicking means failure of counterfactual transfer, while no clicking means Alice's photon has no contact with Bob's atom. We note that when $N$ goes to infinity, the probability of $D_B$ clicking tends to zero. Therefore we discard the last term in Eq. (1) under the approximation that $N$ is extremely large. This approximation also leads to $\cos^N\beta_2 \approx 1$.

Now $SM_4$ is turned off and all the photon components are out of the inner cycle. The photon component $|0H\rangle$ passes through $PBS_1$ and is detected by $D_{A2}$ as shown in Fig. 2. Nevertheless, if $D_{A2}$ clicks, it implies that the photon has appeared at Bob's end [13] and counterfactual transfer fails. If $D_{A2}$ does not click, then the photon is reflected by $SM_3$ allowing the $V$ photon component to go into the second interferometer for another $N$ cycles. The process runs many times until $SM_3$ is turned off. Once that is completed, and if there are no detector clicks, then the whole system can be represented as [12]

$$C_e|H0\rangle|e\rangle + C_g|V0\rangle|g\rangle. \tag{2}$$

Here we have used the approximation $\sin\beta_1 \approx 0$, which indicates that the probability of $D_{A2}$ clicking is negligible with extremely large $M$. In Sec. III, we will discuss what if $D_B$ and $D_{A2}$ click with certain probabilities. Coming back to Eq. (2), clearly, it shows that Bob's atom and Alice's photon are entangled. The entanglement is generated by nonlocal interaction.

*Step 2*. To disentangle Alice's photon and Bob's atom.

So far Alice has achieved the first round of atom-photon interaction with Bob ($M \times N$ cycles) which needs time $T$ to be completed. Next we show how to disentangle the atom and the photon so that information can be transferred without classical channel. Equation (2) indicates that there are two atomic subsystems. They have initial states $|H0\rangle|e\rangle$ and $|V0\rangle|g\rangle$, respectively. By utilizing the quantum Zeno effect [17–19], the evolution of two atomic subsystems can be controlled and they evolve at different rates.

After one round of atom-photon interaction, Bob turns on the driving field for time $\tau$. During this time, there is no atom-photon interaction. The atomic evolution in the presence of driving field can be written as $|e\rangle \rightarrow \cos(\Omega\tau/2)|e\rangle + \sin(\Omega\tau/2)|g\rangle$ and $|g\rangle \rightarrow \cos(\Omega\tau/2)|g\rangle - \sin(\Omega t/2)|e\rangle$ [20], where $\Omega$ is Rabi frequency.

The atom driving field interaction is irrelevant to Alice. When it is finished, Alice gives a feedback by routing her output photon from output 2 to the input of her device. More specifically, the photon component towards output 1 ($|H0\rangle$) is stored, while the photon component towards output 2 ($|V0\rangle$) is reflected back into the system for extra rounds of atom-photon interactions. This reflection is achieved by $SM_2$, which is in front of output 2 as shown in Fig. 2. Its job is to keep reflecting photon component $|V0\rangle$ back for $L$ times. In addition, since Alice's device requires the input photon being $H$ polarized, she lets $SPR_1$ give an additional $-\pi/2$ degree of rotation to the $|V0\rangle$ photon so that $|V0\rangle_0 \rightarrow |H0\rangle_1$. Here the subscript is used to count how many times the photon is reflected by $SM_2$. Then, the second round of atom-photon interaction takes place. According to Eq. (2), the result is

$$\begin{aligned} &C_e[\cos(\Omega\tau/2)|e\rangle + \sin(\Omega\tau/2)|g\rangle]|H0\rangle_0 \\ &\quad - C_g\sin(\Omega\tau/2)|e\rangle|H0\rangle_1 + C_g\cos(\Omega\tau/2)|g\rangle|V0\rangle_1. \end{aligned} \tag{3}$$

The first term of Eq. (3) represents the time evolution of the first subsystem, while the second and third terms represent the evolution of the second subsystem. The second term indicates that a photon component ($|H0\rangle_1$) is flying into output 1. If Alice makes a measurement on this state and does not get a click, then the second subsystem projects back into its initial state $|g\rangle$. The evolution of the second subsystem is frozen. In practice, this can be done by putting $SM_1$ in front of output 1 as shown in Fig. 2. Alice allows the first photon component ($|H0\rangle_0$) to pass through $SM_1$ so that the evolution of the first subsystem is not interrupted. The following photon component ($|H0\rangle_1$), which belongs to the second subsystem, is reflected towards detector $D_{A1}$ and measured by Alice. The clicking of

$D_{A1}$ indicates failure of counterfactual transfer. To guarantee the probability of $D_{A1}$ clicking is nearly zero, we assume $\tau$ is very small so that $\sin \Omega\tau/2 \approx 0$.

After the second round of atom-photon interaction, the atom evolves for another period of time $\tau$ due to the driving field. This is a sequential process that continues until there are $L + 1$ rounds of atom-photon interaction and $L\tau$ period of atom driving field interaction where $L = \pi/\Omega\tau$. Since the photon component $|H0\rangle$ is not reflected back to Alice's device, the first subsystem with initial state $|H0\rangle|e\rangle$ evolves naturally. It is easy to see that the final state of the first subsystem turns out to be $|H0\rangle|g\rangle$. In contrast to the first subsystem, the evolution of the second subsystem, with the initial state $|V0\rangle|g\rangle$, is always interrupted by Alice. In the $l$th ($l \in L$) round, there is a probability of $|C_g|^2 \cos^{2(l-2)}(\Omega\tau/2)\sin^2(\Omega\tau/2)$ that $D_{A1}$ detects a photon ($|H0\rangle_{l-1}$). Those photon components ($|H0\rangle_{l-1}$) come from the second subsystem. By making continual measurements on them, the evolution of the second atomic subsystem is frozen at the ground state. Finally, with the approximations that $M$, $N$, and $L$ are extremely large, which implies probabilities of $D_{A1}$, $D_{A2}$, and $D_B$ clicking are negligible, the atom-photon system evolves to

$$(C_e|H0\rangle_0 + C_g|V0\rangle_L)|g\rangle. \tag{4}$$

Thus far, Alice's photon state is independent of Bob's atom. They are disentangled by nonlocal interaction. Consequently, the counterfactual transfer of an unknown quantum state is achieved. The state $|H0\rangle_0$ goes through output 1 while the state $|V0\rangle_L$ goes through output 2. Here we also emphasize that if the process keeps going, the first subsystem can evolve back to $|H0\rangle|e\rangle$. Then, Eq. (2) is recovered.

## III. NUMERICAL SIMULATION AND ERROR ANALYSES

In the above, we described the ideal situation. However, in practice, some important issues must be considered. For example, with finite $M$, $N$, and $L$, the probabilities of the three detectors $D_{A1}, D_{A2}$, and $D_B$ clicking are nonzero, which reduce the communication efficiency and fidelity. The quality of the public transmission channel needs to be considered as well. Although Alice's photon does not really pass through the transmission channel, the probability that the channel is unexpectedly blocked by some other object, i.e., the probability of the photon loss in the transmission channel [12], has a significant impact on communication fidelity. One other issue is that the channel may be unexpectedly unblocked. This situation happens when Alice's photon misses Bob's atom. In the following, we discuss the three cases one by one. Those discussions are valid when Bob's quantum object is modified (see Sec. IV).

First, let us start by discussing the influence of detectors, where the transfer procedure is intact. However, we need numerical simulation to investigate the detectors clicking influence. We define the probability of any of the three detectors clicking as $P_D$ and the transfer efficiency as $E_{ff} = 1 - P_D$. Moreover, the clicking of detectors leads to errors in the transfer results, i.e., finding the atom in its excited state $|e\rangle$ even after the disentanglement process. Therefore, the real output with errors can be written as $[(C_1'|H0\rangle_0 + C_2'|V0\rangle_L)|g\rangle + (C_3'|H0\rangle_0 + C_4'|V0\rangle_L)|e\rangle]/\sqrt{E_{ff}}$ where the

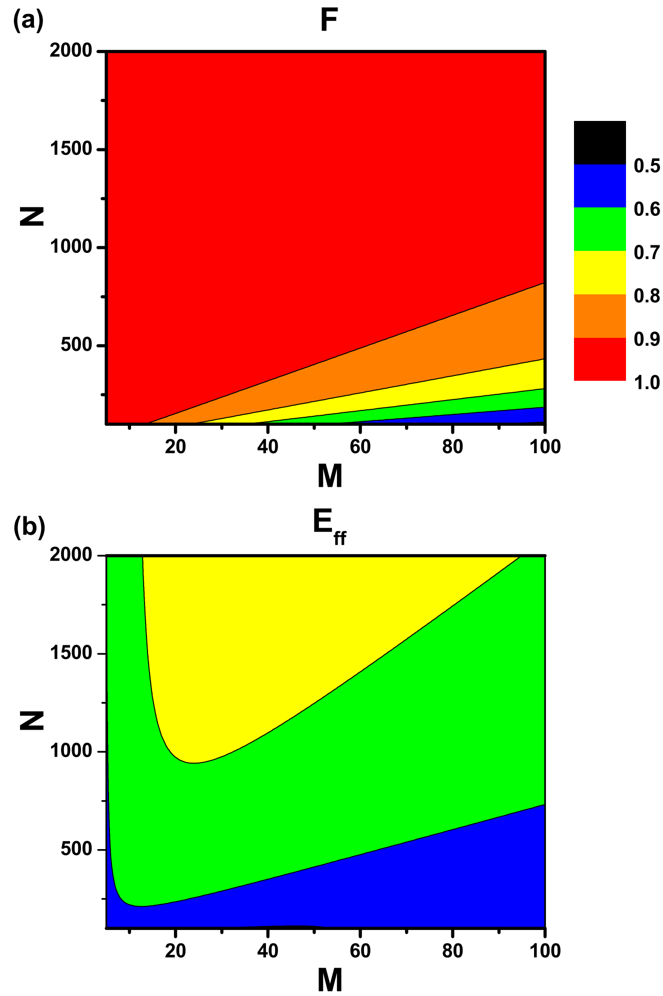


FIG. 3. (Color online) Transfer efficiency ($E_{ff}$) and effective fidelity ($F$) for finite $M$ and $N$.

denominator comes from normalization since we exclude the cases of any detector clicking. Then, the effective fidelity ($F$) under the condition that there is no detector clicking can be defined as $F = |C_e^* C_1' + C_g^* C_2'|^2/E_{ff}$.

We note that $E_{ff}$ and $F$ depend on $N$, $M$, and $L$. Before we show our numerical simulation results, let us have a brief discussion about how to select $N$, $M$, and $L$. Consider the situation in which the atom is in its ground state. In the $m$th outer cycle, the probability that Alice's photon does not leak into the transmission channel is $|A_1|^2 + |A_2|^2 \cos^{2N}\beta_2 \geqslant \cos^{2N}\beta_2$ where $|A_1|^2$ is the probability of the photon in the state $|H0\rangle$ and $|A_2|^2$ of the photon inside the inner cycle. Therefore, the probability of Alice's photon staying inside her device is $\cos^{2NM}\beta_2$, after $M \times N$ cycles. Considering $L + 1$ round of interactions, the chance of the photon found in output 2 is $\cos^{2MN(L+1)}\beta_2 \cos^{2L}(\Omega\tau/2)$. If we want this value to be close to one, then the condition $N \gg ML$ should be satisfied.

In Fig. 3, we plot the transfer efficiency and effective fidelity with different $M$ and $N$ without any approximation. We can see that the fidelity is very good while the efficiency is under 80%, where we have set $C_e = C_g = 1/\sqrt{2}$ and $L = 5$. It is obvious that the influence of detectors clicking is mainly on the transfer efficiency. Nevertheless, the efficiency can be increased by

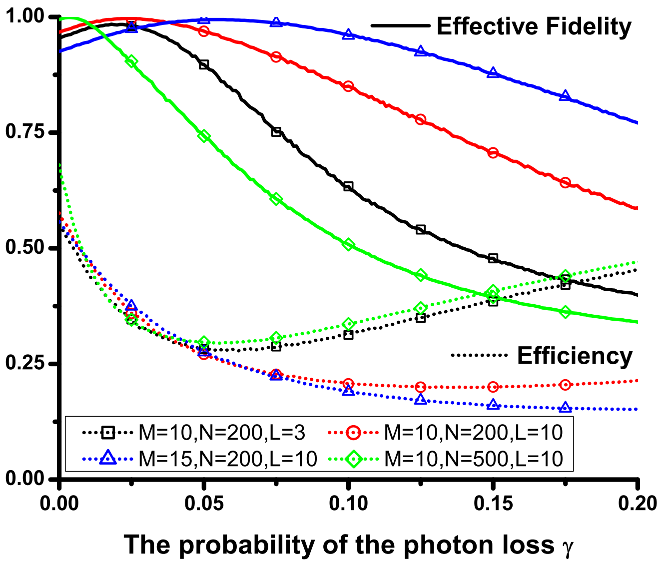


FIG. 4. (Color online) Transfer efficiency and effective fidelity versus the probability of the photon loss in the transmission channel $\gamma$ for different values of $M$, $N$, and $L$.

increasing $N$, $M$, and $L$. For example, if $L = M = 60$ and $N = 2.5 \times 10^5$, the efficiency is 95%. However, the time needed to complete the atom-photon interaction ($T$) is going to be very long.

Here we emphasize two issues: First, the main function of detectors $D_B$ and $D_{A2}$ is to eliminate all photon components which may have local interaction with the atom. Therefore, Alice's output is generated by only nonlocal interaction. Second, Bob does not need to inform Alice that $D_B$ clicks since there is no output at Alice's end. Without destroying the photon information, Alice can indirectly know what happens to her photon as follows. Alice prepares two entangled photons, and makes a complete Bell measurement on one of the entangled photons and the photon at Alice's output. The outcome can be distinguished by measuring the polarization of the entangled photon and the photon at Alice's output independently [21]. If $D_B$ does not click, the unknown state is transferred from the photon at Alice's output to the other entangled photon. However, the detectors measuring the polarization of the photon at Alice's output does not click when no photon is there.

Next we discuss the effect of the photon loss in the transmission channel. In Fig. 4, we plot effective fidelity (solid lines) and efficiency (dotted lines) versus the probability of the photon loss in the transmission channel, $\gamma$, with $C_e = C_g = 1/\sqrt{2}$. These curves are sensitive to $\gamma$. It is because, in an ideal case, the $V$ photon component needs to be continuously rotated to $H$. When an unexpected blockade takes place, the rotation process is interrupted. In the cases $M = 10$, $N = 200$, $L = 10$ and $M = 15$, $N = 200$, $L = 10$, the fidelities are around 70%, but the chances of Alice getting output are only around 20% when the probability of the photon loss is close to 15%. We notice that the fidelity increases when the value of $\gamma$ is very low. This is because the effect of the photon loss is canceled by the effect caused by finite cycle numbers $M$, $N$, and $L$. At first, we consider the situation in which the probability of the photon loss is zero. The probability of the photon being found in output 1 correctly (i.e., the photon is $H$ polarized when the atom is in the excited state before the atom driving field interaction) is $|C_1'|^2 = |C_e|^2 \cos^{2M}(\pi/2M)$. This is the result of unblocking processes and the output ($|H0\rangle|e\rangle$) is stored by Alice after only one round of atom-photon interaction. Therefore, $|C_1'|^2$ is irrelevant with $N$ and $L$. Here we should also mention that when the transmission channel is not blocked, the chance of Alice obtaining a wrong output ($|V0\rangle|e\rangle$) is zero. As for $|C_2'|^2$, which represents the probability of the photon being found in output 2 correctly (i.e., $|V0\rangle_L|g\rangle$), it is jointly decided by $M$, $N$, and $L$. This does not have a simple analytical expression. However, according to Appendices A and B, its value is less than $|C_g|^2 \cos^{2L}(\pi/2L)$. Since, in Fig. 4, we have set $C_e = C_g = 1/\sqrt{2}$ and $L \leqslant M$, we obtain that $|C_1'|^2 > |C_2'|^2$. Now we consider the situation in which there is a small photon loss in the transmission channel. After one round of atom-photon interaction, the photon component $|V0\rangle_0|e\rangle$ appears since the unblocking precesses are interrupted. Although its probability is small due to small $\gamma$, the chance of the photon being found in output 1 is reduced, i.e., $|C_1'|^2 < |C_e|^2 \cos^{2M}(\pi/2M)$. Then, the photon component $|V0\rangle_0|e\rangle$ is sent back to Alice's device ($|V0\rangle_0|e\rangle \rightarrow |H0\rangle_1|e\rangle$) for the next round of atom-photon interaction. We note that before the atom-photon interaction, Bob's atom undergoes an atom driving field interaction. Accordingly, we have $|H0\rangle_1|e\rangle \rightarrow \cos(\pi/2L)|H0\rangle_1|e\rangle + \sin(\pi/2L)|H0\rangle_1|g\rangle$. Then, the second round of atom-photon interaction takes place. Since $\gamma$ is small, the photon component $|H0\rangle_1|e\rangle$ has a large chance of being absorbed by $D_{A1}$, while it has a small chance to become $|V0\rangle_1|e\rangle$. This implies that after $L+1$ round of atom-photon interaction, the chance of the photon being found in output 2 incorrectly (i.e., $|V0\rangle_L|e\rangle$) is nearly zero, i.e., $|C_4'|^2 \approx 0$. As for the photon component $|H0\rangle_1|g\rangle$, it evolves to $|V0\rangle_1|g\rangle$ after the second round of atom-photon interaction. It compensates for the decrease of $|C_2'|^2$ due to finite $N$, $M$, and $L$. However, this is a small effect since the value of $\sin^2(\pi/2L)$ is small and the probability of $|V0\rangle_0|e\rangle$ appearing is also small. In addition, we notice that the photon loss has no effect on blocking processes. This indicates two things. First, $|C_2'|^2$ is nearly unchanged compared to that in the zero photon loss case. Second, the chance of the photon being found in output 1 incorrectly (i.e., $|H0\rangle_0|g\rangle$ before the atom driving field interaction) is not changed. According to the parameters given in Fig. 4, it is nearly zero. As a result, the transfer efficiency decreases, while the probabilities that Alice gets wrong outputs remain nearly unchanged. In the meantime, we can see that the difference between $|C_1'|^2$ and $|C_2'|^2$ decreases. This means that the quality of Alice's output state becomes better. Taken together, according to the definition $F = |C_e^* C_1' + C_g^* C_2'|^2/(|C_1'|^2 + |C_2'|^2 + |C_3'|^2 + |C_4'|^2)$, the effective fidelity increases. However, when the probability of the photon loss keeps increasing, it becomes the dominant effect.

In the cases $M = 10$, $N = 200$, $L = 3$ and $M = 10$, $N = 500$, $L = 10$, we find that the transfer efficiencies decrease at first and then increase. This means that the probabilities of Alice getting output increase when $\gamma$ is large. This is because Alice's photon is led to output 2 incorrectly when Bob's atom is in the excited state. Finding a photon in output 2 is supposed to represent that Bob's atom is in its ground state. Therefore,

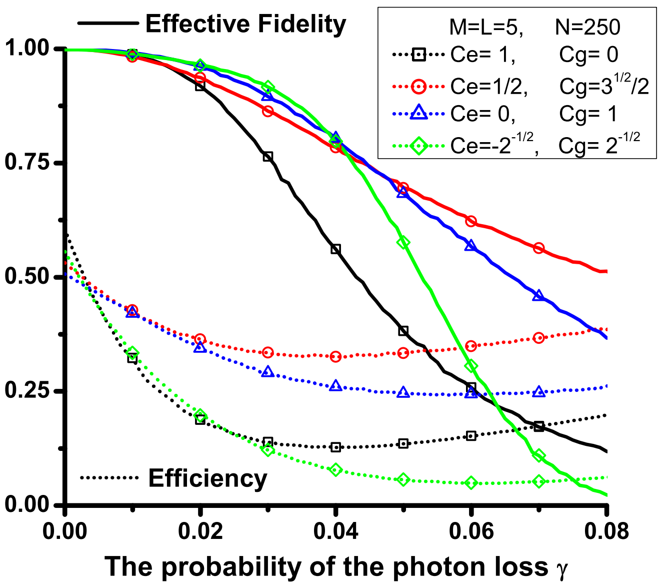


FIG. 5. (Color online) Transfer efficiency and effective fidelity versus the probability of photon loss in the transmission channel $\gamma$ for different transmitted states.

the increase of the efficiency has no contribution to transfer fidelity. As shown in the figure, fidelities still decay fast.

As a complement to Fig. 4, we plot Fig. 5 for the effect of the photon loss according to different transmitted states. We have set that $M = L = 5$ and $N = 250$. The curve for the transmitted state with $C_e = C_g = 1/\sqrt{2}$ is not shown in the figure since its behavior is similar to the red curve which is plotted for $C_e = 1/2$ and $C_g = \sqrt{3}/2$. As shown in the figure, we can see that the fidelity of the transmitted state with $C_e = -1/\sqrt{2}$ and $C_g = 1/\sqrt{2}$ decays faster than others. This is because the decrease of $|C_2'|^2$ is accelerated by the presence of the photon component $-|V0\rangle|e\rangle$.

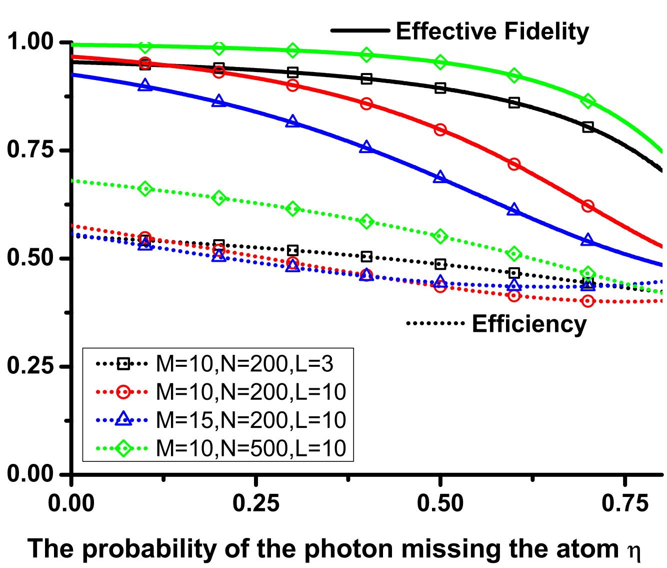


FIG. 6. (Color online) Transfer efficiency and effective fidelity versus the probability $\eta$ of Alice's photon missing Bob's atom for different values of $M$, $N$, and $L$.

We have shown that our protocol is sensitive to the photon loss in the transmission channel. On the contrary, our protocol is not sensitive to errors due to unexpected unblocking. In Fig. 6, effective fidelity (solid lines) and efficiency (dotted lines) versus the probability $\eta$ of Alice's photon missing Bob's atom are plotted. We have set $C_e = C_g = 1/\sqrt{2}$. We can see that the fidelities are above 80% and the efficiencies are around 50% when $\eta$ reaches to 30%.

## IV. DISCUSSION ABOUT EXPERIMENT

In experiment, single-photon absorbtion by one atom is hard to realize and observe [22] due to the tiny coupling strength between a single atom and a single photon. Although the V-type three-level atom model is a very good example to explain our theory, it is not good enough for experiment. Notably, one essential thing in our protocol is that the photon path at Bob's end must be blocked when the atom is in the ground state. It does not matter whether the photon is absorbed or scattered. We can utilize other quantum phenomena such as Rydberg blockade [23,24], photon blockade [25], and nondemolition measurement of an optical photon [26,27] rather than single-photon absorbtion. In the following, we show how to utilize an existing scheme [27,28] to control the photon path.

In Fig. 7, we schematically modify Bob's device for experiment, where $CM_1$ and $CM_2$ compose a single-side cavity [27]. The ground state $|g\rangle$ is selected as $|5^2S_{1/2}, f = 1, m_f = 1\rangle$ of a $^{87}$Rb atom. There are lower excited state $|e\rangle$ and upper excited state $|u\rangle$ where $|e\rangle$ is $|5^2S_{1/2}, f = 2, m_f = 2\rangle$ and $|u\rangle$ is $|5^2P_{3/2}, f = 3, m_f = 3\rangle$. The transition between $|u\rangle$ and $|e\rangle$ is strongly coupled by the cavity. The Rabi oscillation between $|g\rangle$ and $|e\rangle$ is achieved by using a pair of Raman lasers [27,29,30]. As shown in [27,31], if the atom is in the ground state, a photon which is resonant with the empty cavity goes into the cavity, and then it is reflected by a $\pi$ phase shift. However, if the atom is in the excited state, according to vacuum Rabi splitting [32], the photon is reflected directly by $CM_1$ without $\pi$ phase shift. To show the mechanism of blocking and not blocking, we add outside the cavity a beam splitter (BS) with equal transmissivity and reflectivity in order to build a Michelson interferometer at Bob's end. The cavity is just in one arm of the interferometer. It is easy to see, without $\pi$ phase shift, the incoming photon returns back to Alice's device (unblocking case). Otherwise, the photon is detected by $D_B$ (blocking case).

In [27], the authors indicate the probability of getting a reflected photon directly is 62% (atom is in the excited state). Considering Bob's interferometer, the corresponding probability that the photon path is blocked unexpectedly is about 20%. In other words, the probability of the photon loss here is $\gamma = 20\%$. As shown in Fig. 4, the fidelity

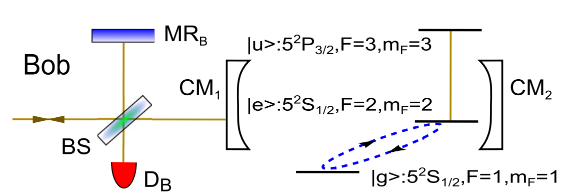


FIG. 7. (Color online) Modified Bob's device for experiment.

can be acceptable but the corresponding efficiency is very low. However, we must emphasize that $\gamma$ tends to zero with increasing coupling strength between the atom and the cavity [27], which can be achieved by utilizing a whispering-gallery-mode microresonator [33,34].

## V. CONCLUSION

In summary, we present a protocol to transfer an unknown quantum state counterfactually. By utilizing the quantum Zeno effect and counterfactual communication, a photon and an atom are entangled and then disentangled without any real particle traveling between them. After a controllable disentanglement process, information is transferred completely and certainly from the atom to the photon. With unlimited resources, the efficiency and fidelity is close to one. The error analyses for the practical situation are also discussed.

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## APPENDIX A: ATOM-PHOTON ENTANGLEMENT BY NONLOCAL INTERACTION

In this appendix, we give the detailed calculation of Eq. (2). The initial condition of the atom-photon system is

$$(C_e|e\rangle + C_g|g\rangle)|H0\rangle. \tag{A1}$$

In the first inner cycle of the first outer cycle, i.e., after Alice's photon passing through $SPR_1$ and $SPR_2$, the state of the atom-photon system is

$$\begin{aligned}&(C_e|e\rangle + C_g|g\rangle)(\cos\beta_1|H0\rangle\\&\quad + \sin\beta_1\cos\beta_2|0V\rangle - \sin\beta_1\sin\beta_2|0H\rangle).\end{aligned} \tag{A2}$$

Here polarization rotation of $SPR_{1(2)}$ can be represented as

$$\begin{aligned}|V\rangle &\rightarrow \cos\beta_{1(2)}|V\rangle - \sin\beta_{1(2)}|H\rangle,\\|H\rangle &\rightarrow \cos\beta_{1(2)}|H\rangle + \sin\beta_{1(2)}|V\rangle.\end{aligned} \tag{A3}$$

We indicate that the state $|0H\rangle$ represents the photon component leaking into Bob's end. It has local interaction with Bob's atom. In the text, we have assumed that the interaction is perfect absorption, i.e.,

$$|0H\rangle|g\rangle \rightarrow |00\rangle|s\rangle. \tag{A4}$$

After absorption, the state of the atom-photon system is

$$\begin{aligned}&C_e|e\rangle[\cos\beta_1|H0\rangle + \sin\beta_1(\cos\beta_2|0V\rangle - \sin\beta_2|0H\rangle)]\\&\quad + C_g|g\rangle(\cos\beta_1|H0\rangle + \sin\beta_1\cos\beta_2|0V\rangle)\\&\quad - C_g\sin\beta_1\sin\beta_2|s\rangle|00\rangle,\end{aligned} \tag{A5}$$

where $|s\rangle$ is measured by $D_B$.

Then, photon components $|0V\rangle$ and $|0H\rangle$ are reflected back by $MR_2$ and $MR_B$, respectively. After that, they pass through $PBS_2$ and $SPR_2$. Since $SPR_2$ gets rotated only when the photon comes from the $SM_4$ side, these photon components are reflected by $SM_4$ without any change of their polarizations. After being reflected by $SM_4$, Alice's photon passes through $SPR_2$ again. This moment is the beginning of the second inner cycle of the first outer cycle. During the second inner cycle, the probability that Bob's atom is excited by Alice's photon is $|C_g\sin\beta_1\cos\beta_2\sin\beta_2|^2$. The atom-photon system can be represented as

$$\begin{aligned}&C_e|e\rangle[\cos\beta_1|H0\rangle + \sin\beta_1(\cos 2\beta_2|0V\rangle - \sin 2\beta_2|0H\rangle)]\\&\quad + C_g|g\rangle(\cos\beta_1|H0\rangle + \sin\beta_1\cos^2\beta_2|0V\rangle)\\&\quad - C_g\sin\beta_1\cos\beta_2\sin\beta_2|s\rangle|00\rangle_2\\&\quad - C_g\sin\beta_1\sin\beta_2|s\rangle|00\rangle_1.\end{aligned} \tag{A6}$$

Here $|s\rangle|00\rangle_j$ represents that Bob's atom is in the $|s\rangle$ level in the $j$th inner cycle. Detector $D_B$ continuously measures $|s\rangle$ in every inner cycle. We keep those terms for the convenience of calculating the total probability of $D_B$ clicking.

It is easy to obtain that, in the $n$th inner cycle of the first outer cycle, the state of the atom-photon system is

$$\begin{aligned}&C_e|e\rangle[\cos\beta_1|H0\rangle + \sin\beta_1(\cos n\beta_2|0V\rangle - \sin n\beta_2|0H\rangle)]\\&\quad + C_g|g\rangle(\cos\beta_1|H0\rangle + \sin\beta_1\cos^n\beta_2|0V\rangle)\\&\quad - C_g\sin\beta_1\sum_{j=1}^{n}\cos^{j-1}\beta_2\sin\beta_2|s\rangle|00\rangle_j,\end{aligned} \tag{A7}$$

while the probability of $D_B$ clicking is

$$\sum_{j=1}^{n}|C_g\sin\beta_1\cos^{j-1}\beta_2\sin\beta_2|^2 \leqslant n\sin^2\beta_2. \tag{A8}$$

For the case $n = N$ and $\beta_2 = \pi/2N$, we have the limitation

$$\lim_{N\rightarrow\infty} N\sin^2\frac{\pi}{2N} = 0. \tag{A9}$$

In the following, we assume that the total inner cycle number $N$ is very large so that the probability of $D_B$ clicking is negligible. Accordingly, Eq. (A7) can be rewritten as

$$\begin{aligned}&C_e|e\rangle(\cos\beta_1|H0\rangle - \sin\beta_1|0H\rangle)\\&\quad + C_g|g\rangle(\cos\beta_1|H0\rangle + \sin\beta_1|0V\rangle).\end{aligned} \tag{A10}$$

For simplicity, the evolution of the atom-photon system after $N$ inner cycles can be represented as

$$\begin{aligned}|e\rangle|0V\rangle &\rightarrow -|e\rangle|0H\rangle,\\|g\rangle|0V\rangle &\rightarrow |g\rangle|0V\rangle.\end{aligned} \tag{A11}$$

Next we consider the evolution of the atom-photon system in outer cycles. Once $N$ inner cycles are finished, $SM_4$ is switched off and all Alice's photon components fly towards $PBS_1$. The component in state $|0V\rangle$ is reflected back towards $SM_3$ (i.e., $|0V\rangle \rightarrow |V0\rangle$), while the component in state $|0H\rangle$ is measured by $D_{A2}$. In the following, we utilize the relation

$$|e\rangle|0H\rangle \rightarrow |e\rangle|00\rangle_j \tag{A12}$$

to represent the process that Alice's photon is detected by $D_{A2}$ in the $j$th outer cycle. We keep these terms in deduction for the convenience of calculating the total probability of $D_{A2}$ clicking.

After detection, the atom-photon system can be represented as

$$C_e|e\rangle(\cos\beta_1|H0\rangle - \sin\beta_1|00\rangle_1) + C_g|g\rangle(\cos\beta_1|H0\rangle + \sin\beta_1|V0\rangle). \quad (A13)$$

Then, Alice's photon passes through $SPR_1$. After that, it is reflected by $SM_3$ and passes through $SPR_1$ again. At that moment, Alice's photon goes into the second outer cycle. Taking into account that $SPR_1$ gets rotated only when the photon comes from the $SM_3$ side, after $m$th outer cycles, the state of the atom-photon system is

$$C_e|e\rangle\left(\cos^m\beta_1|H0\rangle - \sum_{j=1}^{m}\cos^{j-1}\beta_1\sin\beta_1|00\rangle_j\right) + C_g|g\rangle(\cos m\beta_1|H0\rangle + \sin m\beta_1|V0\rangle). \quad (A14)$$

Here Eq. (A11) is utilized. The probability of $D_{A2}$ clicking is

$$\sum_{j=1}^{m}|C_e\cos^{j-1}\beta_1\sin\beta_1|^2. \quad (A15)$$

We set that $m = M$ and $\beta_1 = \pi/2M$. Under the approximation that $\sin\beta_1 \approx 0$, which means the probability of $D_{A2}$ clicking can be neglected, Eq. (A14) can be rewritten as

$$C_e|e\rangle|H0\rangle + C_g|g\rangle|V0\rangle. \quad (A16)$$

## APPENDIX B: ATOM-PHOTON DISENTANGLEMENT BY NONLOCAL INTERACTION

In this appendix, we give the detailed calculation of Eq. (4). We start with Eq. (2) [or Eq. (A16)], which indicates that Alice's photon and Bob's atom have been entangled.

Before Alice's further action, Bob's atom has an evolution which only depends on the driving field. The corresponding atomic evolution can be described as

$$\begin{aligned}|e\rangle &\to \cos(\Omega t/2)|e\rangle + \sin(\Omega t/2)|g\rangle,\\ |g\rangle &\to \cos(\Omega t/2)|g\rangle - \sin(\Omega t/2)|e\rangle.\end{aligned} \quad (B1)$$

The driving field continues for time period $\tau$. After the atomic evolution, the atom-photon system can be represented as

$$C_e[\cos(\Omega\tau/2)|e\rangle + \sin(\Omega\tau/2)|g\rangle]|H0\rangle + C_g[\cos(\Omega\tau/2)|g\rangle - \sin(\Omega\tau/2)|e\rangle]|V0\rangle. \quad (B2)$$

Then, the driving field is vanished. Alice sends the photon in state $|V0\rangle$ back to her device for the second round of atom-photon interaction. Before the interaction takes place, the polarization of Alice's photon is rotated from $V$ to $H$ by $SPR_1$. Accordingly, Eq. (B2) evolves to

$$C_e[\cos(\Omega\tau/2)|e\rangle + \sin(\Omega\tau/2)|g\rangle]|H0\rangle_0 + C_g[\cos(\Omega\tau/2)|g\rangle - \sin(\Omega\tau/2)|e\rangle]|H0\rangle_1. \quad (B3)$$

Here the subscript of $|H0\rangle$ represents how many times Alice's photon is reflected by $SM_2$.

The process of the second round of atom-photon interaction is the same as what we have described in Appendix A. After $M \times N$ cycles, the state of the atom-photon system is

$$C_e[\cos(\Omega\tau/2)|e\rangle + \sin(\Omega\tau/2)|g\rangle]|H0\rangle_0 + C_g\cos(\Omega\tau/2)|g\rangle|V0\rangle_1 - C_g\sin(\Omega\tau/2)|e\rangle|H0\rangle_1. \quad (B4)$$

Since the photon in state $|H0\rangle_0$ is stored by Alice, it does not interrupt Bob's atom.

At the end of the second round of atom-photon interaction, the photon component $|H0\rangle_1$ is measured by $D_{A1}$. The last term of Eq. (B4) indicates that the probability of $D_{A1}$ clicking is $|C_g\sin(\Omega\tau/2)|^2$. We keep this term in deduction for the convenience of calculating the total probability of $D_{A1}$ clicking. This term does not evolve in the following.

Now the driving field appears again while Alice does nothing. After a period of time $\tau$, the atom-photon system becomes

$$C_e[\cos(\Omega\tau)|e\rangle + \sin(\Omega\tau)|g\rangle]|H0\rangle_0 + C_g\cos(\Omega\tau/2)[\cos(\Omega\tau/2)|g\rangle - \sin(\Omega\tau/2)|e\rangle]|V0\rangle_1 - C_g\sin(\Omega\tau/2)|e\rangle|H0\rangle_1. \quad (B5)$$

Then, Alice sends the photon of state $|V0\rangle_1$ back to her device for the third round of atom-photon interaction. After that, the state of the atom-photon system becomes

$$\begin{aligned}&C_e[\cos(\Omega\tau)|e\rangle + \sin(\Omega\tau)|g\rangle]|H0\rangle_0\\ &+ C_g\cos^2(\Omega\tau/2)|g\rangle|V0\rangle_2\\ &- C_g\cos(\Omega\tau/2)\sin(\Omega\tau/2)|e\rangle|H0\rangle_2\\ &- C_g\sin(\Omega\tau/2)|e\rangle|H0\rangle_1.\end{aligned} \quad (B6)$$

At the end of the third round of atom-photon interaction, the photon component of state $|H0\rangle_2$ is measured by $D_{A1}$.

After the third round of atom-photon interaction, there is another $\tau$ period of atom driving field interaction and the fourth round of atom-photon interaction. The procedures are repeated many times. The result of the $l + 1$ round of atom-photon interaction is

$$\begin{aligned}&C_e[\cos(\Omega l\tau/2)|e\rangle + \sin(\Omega l\tau/2)|g\rangle]|H0\rangle_0\\ &+ C_g\cos^l(\Omega\tau/2)|g\rangle|V0\rangle_l\\ &- C_g\sum_{j=1}^{l}\cos^{l-1}(\Omega\tau/2)\sin(\Omega\tau/2)|e\rangle|H0\rangle_j.\end{aligned} \quad (B7)$$

The total probability of $D_{A1}$ clicking is

$$\sum_{j=1}^{l}|C_g\cos^{l-1}(\Omega\tau/2)\sin(\Omega\tau/2)|^2. \quad (B8)$$

If $\sin(\Omega\tau/2) \approx 0$, which means the probability of $D_{A1}$ clicking is negligible, the last term in (B7) can be discarded. Then, after $L + 1$ round of atom-photon interaction and $L\tau$ period of atom driving field interaction where $L = \pi/\Omega\tau$, Alice's photon and Bob's atom are disentangled as

$$(C_e|H0\rangle_0 + C_g|V0\rangle_L)|g\rangle. \quad (B9)$$

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