Direct Counterfactual Communication with Single Photons

Article · March 2014
DOI: 10.1364/CLEO_QELS.2014.FM4A.6 · Source: arXiv

Yuan Cao
University of Science and Technology of China

Juan Yin
University of Science and Technology of China

Xiongfeng Ma
Tsinghua University

Direct Counterfactual Communication with Single Photons

Yuan Cao,[1, 2, *] Yu-Huai Li,[1, 2, *] Zhu Cao,[3] Juan Yin,[1, 2] Yu-Ao Chen,[1, 2] Xiongfeng Ma,[3] Cheng-Zhi Peng,[1, 2] and Jian-Wei Pan[1, 2]

[1]*Shanghai Branch, National Laboratory for Physical Sciences at Microscale and Department of Modern Physics, University of Science and Technology of China, Shanghai, China*
[2]*Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui, China.*
[3]*Center for Quantum Information, Institute for Interdisciplinary Information Sciences, Tsinghua University, Beijing, China.*

(Dated: March 21, 2014)

Intuition in our everyday life gives rise to a belief that information exchanged between remote parties has to be carried by physical particles. Surprisingly, by recent theoretical studies[1], quantum mechanics allows counterfactual communication even without actual transmission of physical particles. The mystery of counterfactual communication stems from a (non-intuitive) fundamental concept in quantum mechanics — wave-particle duality. All particles can be fully described by wave functions. To determine whether a light appears in a channel, one is referring to the amplitude of its wave function; whereas in counterfactual communication, the information is carried by the phase part of the wave function. Using a single photon source, we experimentally demonstrate counterfactual communication and successfully transfer a monochrome bitmap from one location to another by employing a nested version of the quantum Zeno effect. Besides of its fundamental interest, our experimental scheme is applicable to other quantum technologies, such as imaging and state preparation.

The counterfactual phenomena was first presented as interaction-free measurements using a Mach-Zehnder interferometer[2, 3], where the achievable efficiency is limited by 50%. Later, the efficiency is improved to 100%[4] with the help of the quantum Zeno effect[5–7], in which a physical state experiences a series of weak measurements. When the measurements are weak enough, the state is "freezed" to its initial state with a high probability. The scheme was later applied to quantum interrogation[8], quantum computation[9] and quantum cryptography[10]. Unfortunately, none of these schemes can be used for direct counterfactual communication, since particles would appear in the channel when information is transmitted. This challenge is solved by the recent breakthrough on direct counterfactual quantum communication by Salih, Li, Al-Amri, and Zubairy (SLAZ)[1]. The heart of the SLAZ scheme is the nested version of the quantum Zeno effect by utilizing a tandem interferometer nest. Such scheme requires an infinite number of tandem interferometers, which is impractical. Furthermore, the total visibility degrades exponentially with the number of interferometers. Here, we simplify the SLAZ scheme while preserving its counterfactual property with a nested polarization Michelson interferometer using a single photon source.

The schematic diagram of the simplified SLAZ scheme is shown in Fig. 1. Alice sends a single photon in the nested interferometer and detects it with three single-photon detectors, D_0, D_1 and D_f. If detector D_0 or D_1 clicks, Alice concludes logic 0 or 1, respectively. Otherwise if detector D_f clicks, Alice obtains an inconclusive result, which will be discarded in the data postprocessing. Denote the numbers of beam splitters (BS) in the outer and inner cycles as M and N, respectively. The reflectivity of each outer BS is $\cos^2(\pi/2M)$ and that of each inner BS is $\cos^2(\pi/2N)$[1].

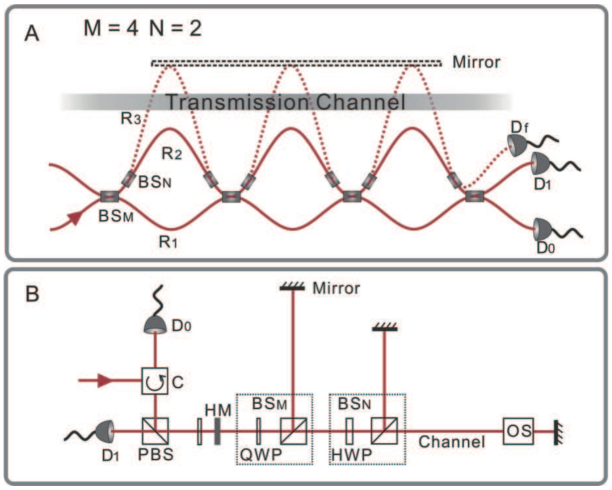

FIG. 1. Schematic diagrams of direct counterfactual quantum communication. (**A**), Theoretical proposal, using nested Zeno effect. (**B**), Experimental implementation, employing a nested polarization Michelson interferometer. Two types of BS are used: BS_M with transmittance of $\sin^2(\pi/2M)$ and BS_N with transmittance of $\sin^2(\pi/2N)$. In our experiment, we take $M = 4$ and $N = 2$. QWP: quarter-wave plate; HWP: half-wave plate; C: circulator; OS: optical switch.

In the case of logic 0, Bob puts the mirrors in the corresponding positions so that the transmission channel is clear, as shown in Fig. 1. In the limit of infinite M and perfect interference, the single photon will go to D_0 with probability one. A finite M may cause erroneous event, where D_1 clicks for logic 0. And a finite M allows a photon to pass through the channel with a non-zero probability, in which case, due to the interference of Route 2 and Route 3, the photon can be only detected by D_f. In the case where information successfully transferred from Bob to Alice, no photon will pass through the transmission. That is, the counterfactual property is preserved in the case of logic 0 for finite M and N when single photons are used.

In the case of logic 1, Bob removes the mirrors and then the inner interferometer cycle is broken, as shown in Fig. 1. Then the transmission channel is broken and hence any detection on Alice's side is not caused by photons transmitted through channel. That is, the counterfactual property is preserved for the case of logic 1 in practical case. If N goes to infinite and the interferometer is perfect, the probability of the single photon goes to D_1 tends to 100%. An imperfect interferometer may cause erroneous event, where D_0 clicks for logic 1.

In summary, no photons pass through the transmission channel (Route 3) when Alice is able to learn the logic state (pass or block) of Bob's setting. Considering that errors of logic 0 is only relating to the number of M, we choose $M = 4$ for the outer loop and $N = 2$ for the inner loop. Note that the single photon source used in modified SLAZ scheme cannot be replaced by a coherent state light when the number of interferometers is finite and the interferometer is imperfect. Otherwise, the counterfactual property cannot be maintained.

The experimental setup of counterfactual communication is shown in Fig. 2a. A heralded single photon source from a spontaneous parametric down-conversion process is used on Alice's side. The generated photon pairs are coupled into two single-mode fibers. In the heralding arm, the photon enters detector D_t directly, whose timing is recorded by a high-speed and high-accuracy time-to-digital converter (TDC). In the signal arm, the photon goes into a concatenation of two polarization Michelson interferometers via a collimator as for counterfactual communication.

As shown in Fig. 2a, a continual wave ultraviolet laser (405 nm, 16 mW) is used to pump a type-II periodically poled potassium titanyl (PPKTP), creating a pair of photons in the state $|HV\rangle$. This type of SPDC source yields about 2×10^7 pair/s photons at 810 nm. The emitted photon pairs are split into two spatial modes by a polarizing beam splitter (PBS) which only reflects vertically polarized photons V, namely heralding arm and signal arm respectively. In the heralding arm, the efficiencies of fiber coupling and detection are about 30% and 60%, respectively with an overall heralding efficiency around 18%. So the brightness of our heralding single photon source is about 3.6×10^6/s.

In order to realize $M = 4$ for the outer loop, the signal photon needs to pass the nested Michelson interferometer three times, which can be realized as follows. Step 1, a mirror is placed in the entrance of the interferometer after photon incidence. Step 2, the photon oscillates through the interferometer for three times. Step 3, the mirror is taken away so that the photon can come out from the interferometer for detection in D_0 or D_1. Such scheme[1] requires to put and take away the mirror so frequently that it can match the photon pulse frequency. In our case, this speed needs to be in the order of microseconds, which is technically challenging. Thus, we replace the mirror with a half mirror, which does not require to move the mirror at all. The cost of this replacement is extra system loss. It can be shown that the optimal reflectivity of the half mirror is given by $(M - 2)/M$ and hence in our case is 50% for $M = 4$.

Another challenge in this experiment is how to ensure that the exit photons have been traveled through the interferometer for exactly three times ($M = 4$). We distinguish between the desired and undesired photons by the spacial and timing modes. First, we tilt the half mirror with a tiny angle to separate the photons experiencing different cycles of the interferometer by the angles of emergence. Only the desired photons with the right spacial mode can be coupled to the single-mode fibers in front of D_0 and D_1. Meanwhile, we take the usage of the time delay between the photon triggers from D_t and the detection clicks from D_0 and D_1 to select out the desired events.

Biased BSs are used in the nested Zeno effect setting, as shown in Fig. 1. We employ a wave plate and a polarizing beam splitter (PBS) to realize the function of a biased BS. According the SLAZ scheme[1], we align the optical axis of two quarter-wave plates, Q_1 and Q_2, to $\pi/16$ as for $M = 4$, and that of a half-wave plate H_1 to $\pi/8$ as for $N = 2$, as shown Fig. 2.

On Bob's side, a liquid crystal phase modulator (LCPM) and a PBS are used to realize the active choice between the two states, Pass (logic 0) and Block (logic 1). If Bob chooses logic 1, in order to block the transmission channel, the LCPM applies a π-phase delay on the arrived photon, converting the polarization from horizontal (H) to vertical (V). Then the photon will be reflected by P_1 and discarded, so that the transmission channel is broken. Otherwise, the LCPM does not affect the arrived photon. On Alice's side, she records bit 0 on the coincident detection of D_0 and D_t, and bit 1 on the coincident detection of D_1 and D_t.

The nested interferometer requires stability in the sub-wavelength order to maintain a high visibility for counterfactual communication. To suppress mechanical vibration and temperature drift, we employ a technique of active phase locking in the experiment. An additional phase-locking laser with the same wavelength as the single photon source is coupled into the inner and outer interferometer. Mirrors M_1 and M_B are placed on two piezoceramics translation stage that can precisely adjust the interferometers according to the feedback signal. A

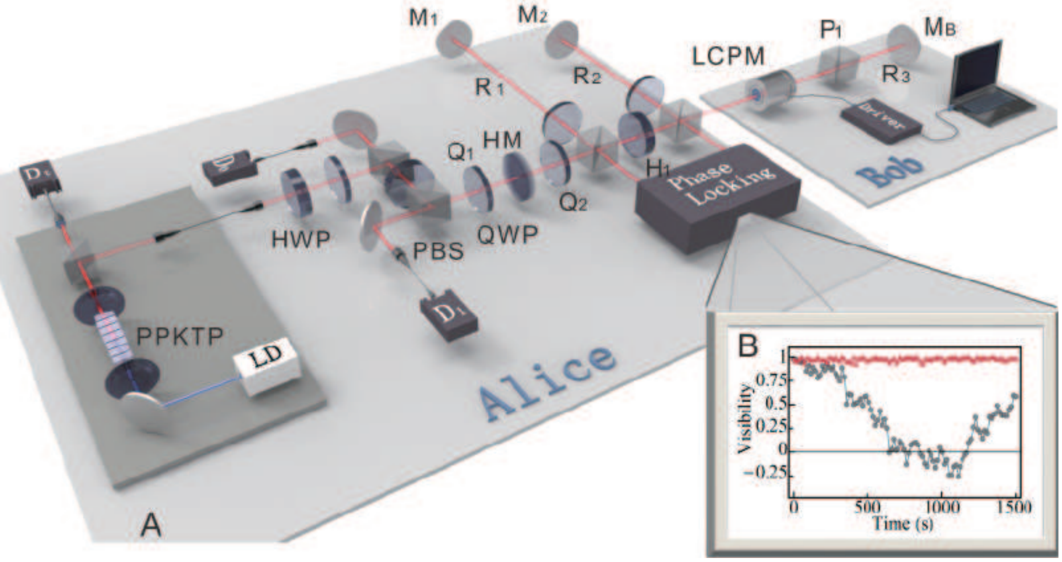

FIG. 2. (**A**), Experimental setup. An SPDC source is employed as a heralded single-photon source. D_0, D_1 and D_t: single-photon detectors; QWP: quarter-wave plate; HWP: half-wave plate; PBS: polarizing beam splitter, reflecting vertically polarized photons; LCPM: liquid crystal phase modulator. The two optical paths R_1 and R_2 correspond to the outer cycle of the nested Zeno effect in the Michelson interferometer setup, while the paths R_2 and R_3 (the transmission channel) correspond to the inner cycle interferometer. (**B**), Experimental test for the active phase locking in a 25-min continuous sampling test. The triangle curve shows the visibility in terms of time when active phase locking is turned on. The circle curve shows the case without active phase locking. Here, the visibility is defined as the ratio between the difference of two output intensities from an interferometer and their sum.

visibility comparison of interferometers with and without the active phase-locking technique is shown in Fig. 2B. With the technique, the visibility can maintain 98% for hours.

In our experiment, we demonstrate direct counterfactual communication by transmitting a 100 × 100 pixel monochrome bitmap (Chinese knot), as shown in Fig. 3. Bit by bit, Bob controls his LCPM according to 10 Kbits bitmap information. After Alice obtained a successful detection event, either D_0 and D_t click or D_1 and D_t click, she sends Bob a feedback and then Bob continues on the next bit until the 10 Kbits information is all transmitted.

In ideal case of the SLAZ scheme when $M = 4$ and $N = 2$, the probability for Alice to rightfully identify Bob's logic 0 is 85.4% and logic 1 is 100%. In our experiment, due to imperfect interference of the interferometer, these two numbers are reduced to 83.4% and 91.2% for logic 0 and 1, respectively. As shown in Fig. 3, the Chinese knot bitmap is successfully transmitted from Bob to Alice with high visibility.

In our current realization of counterfactual communication, the information transmitted is classical. When Bob's logical state is "quantum" so that it can be in the superposition of pass (logic 0) and block (logic 1), an interesting question to ask is that whether counterfactual communication can also transmit quantum information. Such quantum communication scheme can also be viewed as a quantum remote state preparation scheme.

The mysterious phenomenon of counterfactual communication can also be understood from the imaging point of view. Traditionally, a typical photography tool, such as camera, records the light intensity that contains the object information. In 1940s, a new technique — holography — is developed to record not only the intensity but also the phase of the light[11], which enables 3-D imaging. Now, one can ask a question: can the phase of the light itself be used for imaging? The answer is *yes* from our experiment demonstration. Therefore, our counterfactual communication setup can be viewed as a phase imaging tool, where the intensity information is irrelevant. Such technique might be useful in some practical situations, such as imaging ancient arts where lights are not allowed to shine on.

We acknowledge insightful discussions with T.-Y. Chen, H.-L. Yin, Q. Zhang, Z. Zhang, and B. Zhao. This work has been supported by the National Basic Research Program of China Grants No. 2011CB921300, No. 2013CB336800, No. 2011CBA00300 and No. 2011CBA00301, the National Natural Science Foundation of China Grants No. 61073174, No. 61033001, and No. 61061130540, and the Chinese Academy of Sciences.

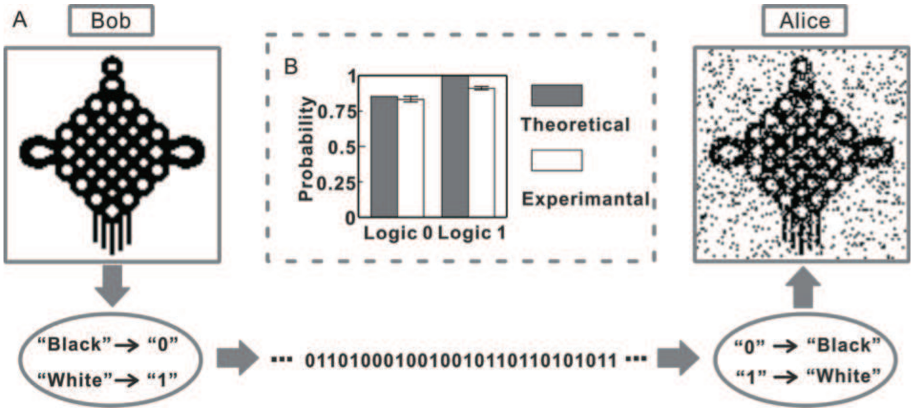

FIG. 3. Experiment direct counterfactual communication, transmitting a Chinese knot image. (**A**) The original and transferred images are compared. The black pixel is defined as logic 0, while the white one is defined as logic 1. (**B**) The probabilities of successfully transmitting logic 0 and logic 1. The experiment results are compared with theoretical limits.

---

* These authors contributed equally to this work

[1] H. Salih, Z.-H. Li, M. Al-Amri, and M. S. Zubairy, Phys. Rev. Lett. **110**, 170502 (2013).
[2] R. Dicke, Am. J. Phys **49**, 925 (1981).
[3] A. Elitzur and L. Vaidman, Foundations of Physics **23**, 987 (1993).
[4] P. Kwiat, H. Weinfurter, T. Herzog, A. Zeilinger, and M. A. Kasevich, Phys. Rev. Lett. **74**, 4763 (1995).
[5] B. Misra and E. C. G. Sudarshan, Journal of Mathematical Physics **18**, 756 (1977).
[6] A. Peres, American Journal of Physics **48**, 931 (1980).
[7] G. S. Agarwal and S. P. Tewari, Physics Letters A **185**, 139 (1994).
[8] P. G. Kwiat, A. G. White, J. R. Mitchell, O. Nairz, G. Weihs, H. Weinfurter, and A. Zeilinger, Phys. Rev. Lett. **83**, 4725 (1999).
[9] O. Hosten, M. T. Rakher, J. T. Barreiro, N. A. Peter, and P. G. Kwiat, Nature **439**, 949 (2006).
[10] T.-G. Noh, Phys. Rev. Lett. **103**, 230501 (2009).
[11] D. Gabor, Nature **161**, 777 (1948).