Traveling without moving: Quantum communication scheme transfers quantum states without transmitting physical particles

March 10 2015, by Stuart Mason Dambrot

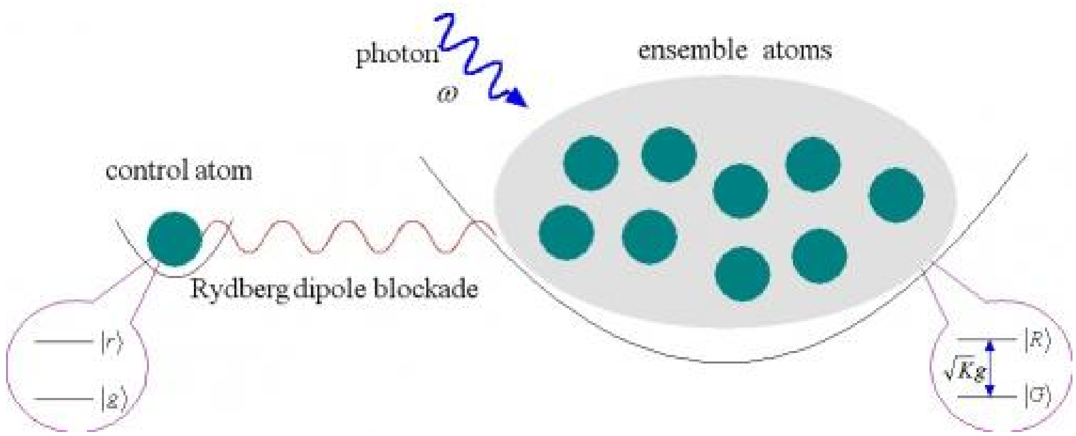

Figure 1 | Quantum control device for the passing or blocking of the incident single photon with the frequency ω. A control atom and a mesoscopic Rydberg atomic ensemble are stored in two separate trapping potentials, and the ensemble forms a superatom with the collective ground state |G> and the Rydberg state |R>. The single atom controls the transmission properties of the ensemble by Rydberg dipole interaction. The photon will be absorbed by the ensemble for the control atomic state | g>, and will pass through the ensemble for the control atomic state | r >. Credit: Guo, Q., Cheng, L.-Y., Chen, L., Wang, H.-F. & Zhang, S. Counterfactual quantum-information transfer without transmitting any physical particles. *Sci. Rep.* 5, 8416; DOI:10.1038/srep08416 (2015). Copyright © 2015, Rights Managed by Nature Publishing Group. Licensed under CC BY 4.0.

(Phys.org)—While Einstein considered quantum entanglement as "spooky action at a distance," and those who fully accept entanglement acknowledge it to be counterintuitive, current entanglement-based quantum communication schemes for transferring an unknown quantum state from one place to another require classical transportation of particles between sender and receiver. Now consider this: Recently, scientists in China at Harbin Institute of Technology, Yanbian University and Changchun University demonstrated what is known as a *counterfactual* approach in which quantum information can be transferred between two distant participants *without sending any physical particles between them*. The researchers accomplished this by entangling two nonlocal qubits with each other without interaction – meaning that the present scheme can transport an unknown qubit in a nondeterministic manner without prior entanglement sharing or classical communication between the participants. Moreover, the scientists state that their approach provides a new method for creating entanglement that allows two qubits to be entangled without interaction between them.

Prof. Shou Zhang discussed the paper that he and his colleagues published in *Scientific Reports*. "There's a long-held assumption in the classical information field that information transfer requires physical particles to travel between sender and receiver – an assumption first challenged in 2013 by Hatim Salih and his colleagues[1]," Zhang tells *Phys.org*. By using the so-called *chained quantum Zeno effect*, the 2013 paper showed how information can in fact be transferred between two locations without any physical particles traveling between them. (In the quantum Zeno effect, time evolution caused by quantum decoherence in quantum systems is suppressed by, for example, continuous observation or measurement, interaction with the environment, or stochastic fields. In a *chained* quantum Zeno effect, a series of secondary splitter/detector loops ensure that there is *never* a significant probability of decoherence.) "This mind-boggling and highly counterintuitive communication protocol inspired us to think whether quantum information can be transferred counterfactually," Zhang adds, "so in fact, our present scheme can be considered as an incremental extension of Salih's work from classical bit to quantum bit."

"In quantum information science," Zhang continues, "the minimum information unit is quantum state-encoded qubit. However, to date, schemes for the transfer of an unknown quantum state required physical particles to travel – for example, quantum teleportation needs prior entanglement sharing and classical communication, and both entanglement sharing and classical communication cannot be done without transmitting physical particles. In our scheme, entanglement sharing and classical communication are not needed."

In short, existing quantum-information transfer schemes require a physical medium, and it was unclear if quantum information can be transferred without transmitting any physical particles – but this paper suggests that it can. To achieve this counterfactual scheme by entangling two nonlocal qubits with each other without interaction, Zhang says that their main challenge was determining how to place the obstructing object in Salih's scheme in an unknown quantum superposition state of presence and absence. "Entanglement is basic resource for many nonlocal quantum information tasks," Zhang notes. "However, it's well known that distant separable states cannot be entangled only by means of local operations and classical communication. Generally, people introduce nonlocal interaction by entanglement swapping or transmitting a mediating particle between distant quantum nodes. Interaction-free measurement provides a new way to create entanglement, and so, albeit inconceivably, two qubits can be entangled without interaction."

Zhang notes that there were also several challenges in the experiment in realizing the scheme by using a photon and a Rydberg atom assisted by a mesoscopic atomic ensemble, such as trapping atoms and the ensemble's coherent time. (A *Rydberg atom* is an excited atom with one or more electrons that have a very high principal quantum number, meaning that the electron has higher potential energy and is therefore less tightly bound to the nucleus.) "Given that this paper is a theoretical work, and these technical challenges have been well researched in the existing literature, we only consider the ideal case in the paper."

The key component in this work, Zhang tells *Phys.org*, is the quantum version of the obstructing object. "In fact, any atom with two energy levels resonant with the photon's frequency can be used to act as the quantum obstructing object to control the passing or absorption of the photon, but the coupling between a single atom and a photon is so weak that the scheme cannot be achieved with high probability. The present scheme uses a single Rydberg atom to control the atomic ensemble via Rydberg dipole blockade." A *Rydberg dipole blockade*, which results from the interactions shifting the energy levels of the atoms, can be used to inhibit transitions into all but singly excited collective states – and thereby to manipulate quantum information stored in collective states of mesoscopic ensembles.

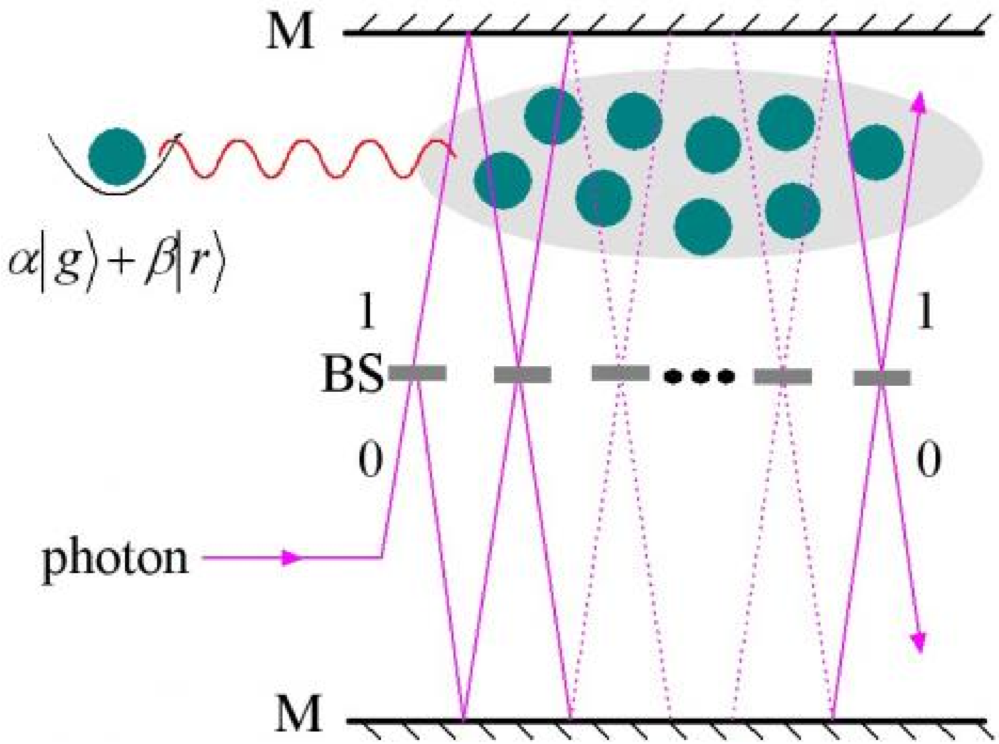

Figure 2 | Schematic of interaction-free nonlocal entangled state generation. N unbalanced beam splitters BS form a tandem Mach-Zehnder-type interferometer with the two optical paths 0 and 1. The ensemble is inserted in the path 1, and the single photon enters the interferometer from the path 0. M is normal mirror. Credit: Guo, Q., Cheng, L.-Y., Chen, L., Wang, H.-F. & Zhang, S. Counterfactual quantum-information transfer without transmitting any physical particles. *Sci. Rep.* 5, 8416; DOI:10.1038/srep08416 (2015). Copyright © 2015, Rights Managed by Nature Publishing Group. Licensed under CC BY 4.0.

"The Rydberg dipole blockade can block transitions of more than one Rydberg excitation in mesoscopic atomic ensembles," Zhang explains. "The combined system of the single atom and the atomic ensemble forms a quantum control device to control the passing or absorption of the photon. The ensemble is initially in the collective ground state; if the single atom is in the Rydberg state, the photon can pass through the ensemble, while if the single atom is in the ground state, the photon will be absorbed by the ensemble. Therefore, the combined system acts as a quantum obstructing object, and the passing or absorption of the photon depends on the quantum state of the single atom. By inserting the quantum obstructing object in a nested Mach-Zehnder interferometer as shown in Figure 3 in our paper, and then connecting many such interferometers in series, the quantum state of the single atom will appear on the path qubit of the photon after the photon passes through the interferometer series and the sender measures his atom." (A Mach–Zehnder, or MZ, interferometer is a device used to determine the relative phase shift variations between two collimated beams derived by splitting light from a single source.)

What's key is that during the entire process, *the photon did not enter the channel between sender and receiver*: As long as the photon passes through the channel, it will be absorbed by the ensemble if the control atom is in the ground state – but if the atom is in the Rydberg state, the photon will be absorbed by the detector. In this way, an unknown quantum state can be transferred between two distant participants without any physical particles traveling between them.

"The advantages of using the combined system," Zhang explains, are twofold: the coupling strength of the photon with the quantum obstructing object is greatly enhanced; and the individual addressing of an atom is not required. In principle, as long as the quantum obstructing object can be implemented, this scheme is universal for other physical systems of quantum information processing, such as trapped ion systems, superconducting quantum systems and quantum dot systems."

Unlike typical teleportation, the present scheme can transport an unknown qubit between two distant participants in a nondeterministic manner. "Typical teleportation can teleport an unknown quantum state perfectly by using subsequent local operations. However," Zhang points out, "in the last step of the present scheme, the sender will obtain two measurement results of the single atom state, and the recipient can obtain the teleported state perfectly *only* if the sender's measurement result is a Rydberg state. If the sender's measurement result is ground state, the quantum state the recipient receives has a phase flip error compared with the teleported state. Hence, the success probability is 50%. On the other hand, if the recipient wants to obtain the quantum information deterministically, the sender only needs to send one bit of information – that is, single-qubit detection results – to the recipient for the transfer of one qubit. However, in the one-qubit teleportation procedure, two bits of classical communication – that is, Bell-state measurement results – are required."

Regarding the implications and limits of their approach, Zhang says that the present scheme requires the single photon go through a large number of cycles in the nested interferometer, so the main limits of the scheme are the distance of the two parties and the coherent time of the Rydberg atom. "In principle, however, quantum information can be transferred without entanglement sharing or classical communication between the two parties regardless of the physical distance separating them." However, he emphasizes that since the coherent time of the atom is finite in practice, the counterfactual quantum-information transfer can be only implemented over a limited distance.

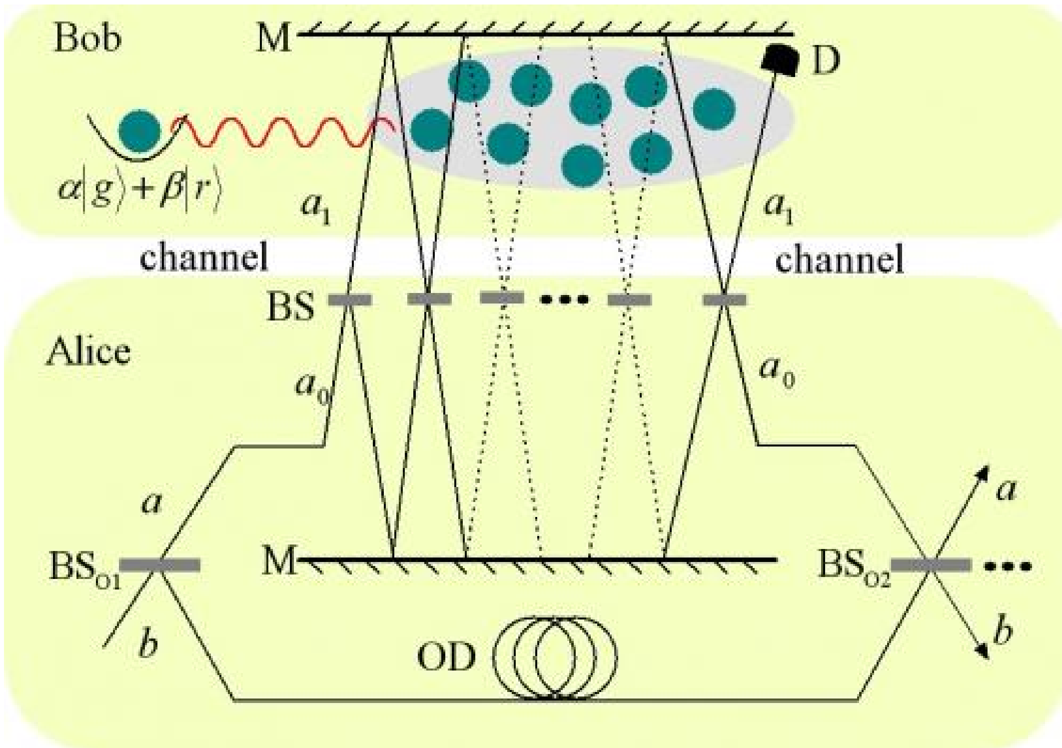

Figure 3 | The nested Mach-Zehnder-type interferometer shared by two distant participants, sender Bob and receiver Alice. The interferometer in Fig. 2 as an inner interferometer is nested in one arm of an outer Mach-Zehnder-type interferometer. Connecting M such outer interferometers in series, we can implement counterfactual nonlocal entangled state generation and quantum state transfer. The two optical paths of the outer interferometer are labeled as a and b, and the two optical paths of the inner interferometer are a0 and a1. OD: optical delay line used to match the optical path lengths of the different paths of the interferometer. D: conventional photon detector used to absorb the photon exits from the output port of a1. Credit: Guo, Q., Cheng, L.-Y., Chen, L., Wang, H.-F. & Zhang, S. Counterfactual quantum-information transfer without transmitting any physical particles. *Sci. Rep*. 5, 8416; DOI:10.1038/srep08416 (2015). Copyright © 2015, Rights Managed by Nature Publishing Group. Licensed under CC BY 4.0.

"Theoretically," Zhang acknowledges, "a galactic or intergalactic internet may be possible based on the present scheme, which would require a so-called long-arm intra- or intergalactic interferometer and a quantum obstructing object with very long coherent time. Obviously, however, it's currently unpractical to construct a long-arm interferometer, and there is no known quantum state with such a very long coherent time."

Despite the effect of the imperfections mentioned in the paper, Zhang tells *Phys.org* that the key component in the experimental system indicating that their scheme may be feasible using current technology is the combined system of a single atom and a mesoscopic atomic ensemble – specifically, the development of the cold Rydberg gas with alkali-metal vapor. "Moreover," he adds, "the remaining elements in the scheme are the most common optical elements found in the laboratory."

Moving forward, Zhang notes that the scientists are now researching the deeper mechanism behind the counterfactual quantum-information transfer, which he says may involve the foundation of quantum mechanics. "In addition, using the basic idea of the scheme, many nonlocal quantum information tasks could be achieved. We may develop other counterfactual quantum information protocols, such as quantum cloning or quantum algorithms."

In closing, Zhang says that the present scheme provides a new way for nonlocal quantum information processing, so it may lead to a quantum network that does not require physical particle transmission. "We also hope the present scheme can be realized in a physical experiment. On the other hand, the deeper mechanism behind the counterfactual scheme has not been revealed, which may well excite people's interest in the fundamental of quantum mechanics, such as quantum interference and wave-particle duality."

More information: Counterfactual quantum-information transfer without transmitting any physical particles, *Scientific Reports* (2015) **5:** 8416, doi:10.1038/srep08416

Related:

[1]Protocol for direct counterfactual quantum communication, *Physical Review Letters* (2013) **110**:170502, doi:10.1103/PhysRevLett.110.170502