International Journal of Management, Sciences, Innovation, and Technology IJMSIT

Review Paper

Vol.2, Issue.6, pp.09-15, Nov (2021) **ISSN:** 0000-0000

Quantum Teleportation: Future Prospects

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Available online at: https://ijmsit.com/volume-2-issue-6/

Received: 19 Oct 2021 Revised: 10 Nov, 2021 Accepted: 17 Nov, 2021

Abstract— In science fiction, teleportation usually allows for instantaneous travel, which violates the speed limit set by Einstein in the theory of relativity that said that nothing can travel faster than the speed of light [see "Faster than light?", Science Magazine, No. 2 (1995), p. 58]. Teleportation is less troublesome than any ordinary means of space travel. G. Rodenberg, the creator of Star Trek, is said to have seen the "beam-conveyor" as a way to economize on simulated landings and takeoffs on alien planets.

Keywords— Science Fiction– Teleportation – Time Travel – Technology

I. Introduction

The procedures for teleportation in science fiction differ from one story to another, but they generally work as follows: A device scans the original object in order to extract all the information needed to characterize it. Then a transmitter broadcasts the information to the receiving station where it is used to obtain an exact copy of the original. In some cases the substance of which the original is made is also sent to the receiving station, perhaps in the form of "energy" of some kind, and in other cases the copy is made from the atoms and molecules originally present in the receiving station.

Quantum mechanics appears to prevent, in principle, the realization of teleportation. This is because Heisenberg's uncertainty principle requires that the exact position and momentum of an object cannot be known at the same time, and therefore a complete scan of the object to be teleported cannot be conducted, since the location or velocity of each atom and electron will be subject to error. Since the Heisenberg uncertainty principle also applies to other pairs of magnitudes, it is impossible to accurately measure the total quantum state of anything with certainty, given that such measurements are necessary to obtain the information needed to accurately describe the origin. (In "Migration to the Stars," the Heisenberg Compensator somehow overcomes this difficulty.)

And in 1993 a team of physicists upset this conventional wisdom when they discovered a way to use quantum mechanics itself in teleportation. The team of H.C. Bennett [of IBM], G. Brassard, C. Crepeau, and

 Gwoza [of the University of Montreal] and A. Peres [of the Technion Institute of Technology] and K.W. Waters of Williams College argues that a strange but fundamental property of quantum mechanics, entanglement, can be used to circumvent the constraints of Heisenberg's uncertainty principle without violating it.

II. COLLIDER

We're in the year 2100, and a friend, who loves to play with physics and fun tricks, has brought you a set of pairs of dice. And he asked you to throw it once, each pair alone. Carefully hold on to the first pair as you remember the fiasco for the Micro Black Hole at Christmas (1999). Finally, you roll the two dice and get a double 3. Then you toss the second pair and you find a double 6. Then next: 1 double. The two stones are always the same.

The dice in this tale behave like entangled quantum particles. Each stone alone is random and flawless, but its partner, intertwined with it, always gives, in some way, the same number as the first stone. Such behavior has been demonstrated and extensively studied for true entangled particles. In typical experiments, pairs of atoms, ions, or photons replace the dice, and properties such as polarization replace the different faces of the dice.

Let's consider the case of two photons whose polarization is entangled. They are random but identical. Beams of light, even single photons, consist of vibrations of electromagnetic fields, and polarization refers to the alignment of the vibrations of the electric field [see top illustration on page 40]. Suppose that Miss Summer has one of the two entangled photons and that Mr. Ahmed has another partner. When Samer measures her photon to see if it is vertically or horizontally polarized, each measurement result has a 50 percent probability. Ahmed's photon has the same possibilities, but entanglement ensures that he gets exactly the same results as Samar. Once Samar gets the "horizontal" result, you know that Ahmed's photon will be horizontally polarized. Before Samar took the measurement, neither of the photons had a particular polarization; The entangled state only specifies that a measurement will find that the two polarizations are equal.

The astonishing feature of this process is that it does not matter that Samar and Ahmed are far from each other, the process proceeds as long as their photons are entangled. Even if Samar is on the star Alpha Centauri and Ahmed is on the planet Earth, their results will agree when they compare between them. Every time things happen as if Ahmed's photon is magically affected by the measurement that Samar makes from a distance, and vice versa.

And you might wonder if we can explain entanglement by imagining that each particle carries within it some recorded instruction. Perhaps when we intertwine the two particles, we synchronize a hidden mechanism within them that determines the results that they will give when the measurement is made against them. This would be sufficient to explain the mysterious effect of Samar's measurement on

Ahmed's body. In the 1960s, however, Irish physicist John J. Bell argued that such an explanation based on "hidden variables" should, in certain cases, lead to results different from those predicted by (mainstream) quantum mechanics. Experiments have confirmed the predictions of quantum mechanics with very high accuracy.

The Austrian physicist <E. Schrödinger, one of the innovators of quantum mechanics, has described entanglement as a "key feature" of quantum physics. Entanglement is often called the "EPR effect" and the particles are called "EPR pairs" after Einstein, B. Podolsky and N. Rosen, who in 1935 analyzed the manifestations of effective entanglement over great distances. Einstein used to talk about it like a "ghostly act at a distance." If someone tried to interpret the results as signals that travel between the two photons, the signals would have to travel faster than the speed of light. Many have wondered, of course, whether it is possible to use this effect to transmit information faster than the speed of light.

Unfortunately, quantum rules do not allow this. Each local measurement made on a solitary photon produces a completely random result and therefore carries no information from the remote location. It only tells us what the probabilities of the dimensionality result might be based on what was measured there. However, we can take advantage of entanglement in an ingenious way to access quantum teleportation.

III. TAKE ADVANTAGE OF ENTANGLED PHOTONS

John and Mary plan to do a photon teleportation, and in preparation they share an auxiliary entangled pair of photons. Mary takes photon A, while John takes photon B. Instead of making a measurement on them, they each store their own photon without disturbing the delicate entanglement.

Mary has, in time, a third photon--let's call it an X photon--that she wants to teleport to John. She does not know what the state of the X photon is, however she wants John to have a photon with the same polarization as X. However, she cannot simply measure the photon's polarization and send the result to John, because, on the whole, the result of her measurement will not be identical to the photon's original state. This is a consequence of the Heisenberg Uncertainty Principle.

Instead, to teleport photon X, Marie makes a measurement of it and photon A together without specifying their respective polarizations. You might find, for example, that their polarizations are "orthogonal" (but remain ignorant of either absolute polarization anyway). Technically, the combined measurement of the A and X photons is called the Bell-state measurement. Marie's measurement has a subtle effect: it changes the John photon in such a way that it becomes proportional to a combination of the result of its measurement and the state in which the photon was X origin. In fact, Photon John now carries the state of Photon Marie X, either exactly or in a slightly modified form.

Quantum teleportation of a person (which is practically impossible but is a good example of aiding imagination) can begin by placing them inside the measurement chamber (left) and with an equal mass of the adjuvant (green) next to them, after the adjuvant has been quantum-latched to its counterpart in a station remote receiver (right)

To complete the teleportation, Mary must send John a message that is transmitted by the usual means, such as a telephone call or a note written on a piece of paper. John can, if necessary, after he receives this message, transform Photon B so that it eventually becomes an exact copy of the original Photon X. The conversion that John should make depends on the result of Mary's measurement.

There are four potentials corresponding to four quantum relationships between photons A and X. One of the typical transformations that John should perform on his photon is to change its polarization by 90 degrees, which can be done by passing the photon through a crystal with the appropriate optical properties.

The result that Mary gets from the four possibilities is completely random and independent of the original state of X. So John doesn't know how to process his photon unless he gets Mary's measurement result. It can be said that the John photon instantaneously contains all the information, from the original Mari photon, which was transmitted to it by means of quantum mechanics. To know how to read this information, John must wait for the arrival of classical information, which consists of two bits that cannot travel faster than the speed of light.

Skeptics can claim that the only thing that teleports is the photon's polarization state, or more generally, its quantum state, not the photon "itself". However, since the quantum state of a photon is what its distinguishing features are, teleportation of its state is exactly equivalent to teleportation of a particle.

Note that quantum teleportation does not produce two copies of the X photon. Classical information can be copied as many times as we want, but a complete (replica) copy of quantum information is impossible, and this is known as the no-cloning theorem, which was proved by Waters. and <H.W. Zurik of Los Alamos National Laboratory in 1982. (If we could clone a quantum state, we could use clones to violate Heisenberg's principle.)

IV. GETTING AROUND HEISENBERG

Isn't it an exaggeration to call this teleportation? What is teleported is, after all, only a quantum state and not a real object. This question raises the deeper philosophical question about what we mean by identity. How do we know that something - say the car we find in our garage in the morning - is the same thing we saw a while ago? As long as it has all the correct descriptions and properties. Quantum physics underscores this point: particles of the same type and in the same quantum state are undifferentiated even in principle. If one could trade iron atoms in the car for iron atoms from an ores and could exactly recreate the quantum states of the atoms, the end result would be identical, at the deepest levels, to the original car. Identity cannot mean more than the following: that something be the same in all its properties.

Isn't it like a "quantum fax"? Sending a fax generates a copy that is easily recognizable from the original, while the thing being teleported is indistinguishable even in principle. In addition, the origin must be destroyed in the case of quantum teleportation.

Can we really hope to teleport something complex? There are many difficult obstacles. The first thing must be in a pure quantum state, and such states are very fragile. Photons do not interact with air very much, so we can conduct our experiments outdoors, but experiments using atoms and large objects must be conducted in a vacuum to avoid collisions with gas molecules. In addition, the larger the object, the easier it is to perturb its quantum state. A very small mass of material can cause its disturbance even thermal radiation from the walls of the devices. This is why we don't usually see quantum effects in our everyday world. Quantum interference, an effect that is easier to generate than entanglement or teleportation, has been demonstrated experimentally using 60-carbon spheres. Such work will evolve into larger bodies, perhaps even small viruses, but do not hold your breath and think that it can be repeated using bodies the size of footballs!

Another problem is the Bell case measurement. What could a Bell-state measurement on a 107-atom virus mean? How can we extract the 108 bits of information generated by such a measurement? As for an object not exceeding several grams, the number becomes impossible: 1024 bits of data.

Will teleportation of a human require quantum precision? Being in the same quantum state does not seem to be necessary for someone to be the same person. We change states all the time and we're the same people - at least as far as we know! Conversely, identical twins, or biological relatives, are not "the same person" because they have different memories. Does Heisenberg's skepticism prevent us from copying a person so accurately that he thinks he is exactly the same as the original? nobody knows. Interestingly, however, the quantum non-reproduction theorem prevents us from making full-resolution copies of someone.

There is no doubt that we can use current technology to teleport elementary states, such as the photon states in our experiment, over distances of several kilometres, and may deliver them to satellites. The technology that allows the transfer of states of single atoms is now available: the group led by S. Arush at the Ecole Normale Supérieure in Paris demonstrated the entanglement of atoms. It is reasonable to expect the entanglement and teleportation of molecules during the first decade of the twenty-first century. What happens after that is left to the imagination of whoever wants it?

One of the most important applications of teleportation may be the field of quantum computing, where the ordinary concept of bits (zeros and ones) is generalized to qubits, which can exist in the form of superpositions and entanglements of zeros and ones. Perhaps teleportation could be used to exchange quantum information between quantum processors. Quantum dimensional vectors can also serve as essential components for building a quantum computer.

Quantum mechanics is perhaps one of the most profound theories ever discovered. The questions he poses to our everyday intuitions led Einstein to harshly criticize quantum mechanics. He insisted that the task of physics is to attempt to understand and perceive existing reality independent of our observation of it. Yet he knew very well that we would get into deep trouble when we tried to give a physical truth to each individual in the entangled pair. His feat, the Danish physicist <N. Bohr insisted that the whole system should be taken into account—that is, the arrangement of all the particles together in the case of an entangled pair. And what Einstein wished for every particle to have an independent real state but something devoid of any meaning.

V. QUANTUM COMPUTERS

Perhaps the most realistic application of quantum teleportation, other than purely physical research, is in the field of quantum computing. A normal digital computer deals with qubits that take one of two values 0 or 1, but a quantum computer uses quantum qubits [see: “Quantum computing with particles” Journal of Science, Nos. 8/9 (1999), p. 36]. Quantum bits can be in superpositions of 0 and 1 just as a photon can be in superpositions of horizontal and vertical polarizations. In fact, when a single photon is transmitted, the fundamental quantum teleporter emits one quantum bit of information.

Superpositions of numbers may seem strange, but as <R. Landauer of IBM: "When we were young children we were learning how to count on our classic sticky fingers, and we knew nothing about quantum mechanics and about superpositions. We realize that there can be an overlap of both."

A quantum computer can affect the superposition of many different inputs at once. For example, it can run an algorithm on a million inputs simultaneously, using as many qubits as a normal computer would need to run the algorithm once in a single input. Theorists have demonstrated that algorithms running on quantum computers can solve some problems faster (that is, in fewer computational steps) than any known algorithm running on a classical computer can. These issues include finding vocabulary in the database and analyzing large numbers into factors, which is of great importance in decoding secret codes.

So far, only the most primitive elements of quantum computers have been built: logic gates that can process one or two qubits. A small quantum computer is still a long way off. One of the fundamental problems is the reliable transfer of quantum data between different logic gates or processors, whether within a single quantum computer or over quantum networks. Quantum teleportation is one solution.

In addition to the above, D. Gottesman [of Microsoft] demonstrated.

L. I. Chuang of IBM recently reported that a general-purpose quantum computer could be built from three basic components: entangled particles, quantum dimensional vectors and gates that operate on one qubit at a time. This result provides a systematic method for constructing gates operating on two quantum bits. The basis for constructing a two-qubit gate from a dimensional vector is the teleportation of two qubits from the gate's input to its output using carefully modified entangled pairs. The entangled pairs are modified in such a way that the output of the gate receives the appropriate processing of the processed qubit. Thus, performing quantum logic on two unknown quantum bits is reduced to the task of preparing certain previously defined entangled states, followed by teleportation. Undoubtedly, a full Bell-state measurement, which is necessary for 100 percent successful teleportation, is the same as a kind of two-qubit manipulation.

VI. CONCLUSION

Contrary to its exciting name, quantum teleportation does not involve physical objects disappearing and then suddenly appearing elsewhere. It is, instead, a nice and clever technique for transferring an unknown "quantum state" of one system (usually a single particle) to another specially prepared system. This sounds more attractive and more interesting than the reality. Before we even get to quantum teleportation, I'll describe how "classical teleportation" works, and you can judge whether the word "teleport" is ever appropriate. This is great for parties (or, more likely, for the Dr. Hoo marathons at your mom's house).

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