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The Quantum Realm: Quantum Teleportation

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---***ABSTRACT***---
In this paper I have investigated what quantum teleportation is and its implications in the creation of the quantum internet. The paper begins with a broad description of quantum mechanics and the fascinating concepts of superposition of states and quantum entanglement, and how they are fundamental to quantum teleportation. Quantum teleportation is an intriguing consequence of quantum entanglement and superposition states of qubits. It is the technique of transmitting one qubit's state to another qubit, at a completely different location, without physically transporting the qubit. Taking the classic example of Alice and Bob the whole procedure of quantum teleportation is explained. The paper also focuses on the possibility of a quantum internet using the concepts of quantum teleportation and quantum repeaters.It states the advantages of the quantum internet and why it would be a huge leap for mankind. The paper also mentions the use of quantum teleportation to improve quantum cryptography for safer transactions. The conclusions of the paper focus mainly on the hurdles of the creation of the quantum internet such as the decoherence effect.

***Keywords*—** *Physics and Astronomy; Quantum Physics; Quantum Teleportation; Quantum Computation; Quantum Internet*

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I. INTRODUCTION

Quantum mechanics forms the base for nearly all of modern physics, explaining nearly everything, from the behaviour of an atom to the properties of magnetism. However, its equations cannot predict with certainty the outcome of any measurement, such as the momentum of an electron; it can only yield probabilities. Quantum particles such as electrons, hence, exist in clouds of uncertainty– mathematically defined by wave functions. It is impossible to simultaneously know the exact position and momentum of a quantum particle such as an electron. Thus, we cannot know for certain the state of a particle until observation. The act of observing makes this wave function "collapse" from a wave function to a single data point, according to the Copenhagen interpretation given by Niels Bohr and Werner Heisenberg [1]. Thus, until observation, we say that the quantum particle is in a state of superposition. In quantum mechanics, superposition is defined as the feature of a quantum system due to which it exists in several separate quantum states at the same time.

To make this concept clearer, we take the iconic example of Schrödinger's cat. The experiment is devised in such a way that a random subatomic event is linked to the fate of a hypothetical cat's survival. A cat is enclosed in a steel chamber, along with a Geiger counter– a device used for detecting and measuring ionisation radiation. The device is rigged so that if the Geiger counter fires then a hammer smashes a flask of poisonous acid, killing the cat. The Geiger counter is measuring the atomic decay of a small sample of radioactive substance, which by the very nature of quantum mechanics has equal probability of decaying or not decaying. If we leave this entire system undisturbed for an hour, we would conclude that the cat is still alive if no atom has decayed. On the other hand, we could also conclude that the cat would have died if there was atomic decay. The wave function of the entire system would involve a superposition of both states: alive and dead. Only upon observing the cat inside the chamber does this state of superposition collapse (changes to one of the two states) and we come to know whether the cat is alive or dead [2]. The phenomenon of superposition is a fundamental characteristic of qubits, which are the heart of quantum computing, the basic unit of quantum information and an integral part of the topics discussed in this paper [3].

So, what is a qubit? A qubit (quantum bit), unlike a classical bit which is either 0 or 1, is any unit vector (also called a "ket") in C^2. That means they are a quantum superposition of two states, $|0\rangle$ and $|1\rangle$. Qubits are much more complicated than classical bits as they are formed by these superpositions. Thus, as explained with the example of Schrödinger's cat, they have the ability to both "be" and "not be" in a state simultaneously. More precisely, a qubit takes the form

$$\alpha|0\rangle + \beta|1\rangle \quad (1)$$

Fig. 1: Representation of the form the qubit takes.

and has probability $|\alpha|^2$ of being in the state $|0\rangle$ and probability |□|^{2}of being in state $|1\rangle$.

Two classical bits can be in four possible states (00,01,10,11), but only one state at a time. On the other hand, two qubits can be in four possible states all at once (i.e. they take the form α|00〉 + □|01〉 + □|10〉 □|11〉), which means that instead of processing one input at time, we now have four inputs running side by side in some sense [4]. One way to understand this is as two regular computers running simultaneously while interfering with one another.

By adding more qubits, the power of a quantum computer grows exponentially. While qubits are theoretically ideal for quantum information, practically building a qubit out of a physical system is difficult due to a number of reasons. A few of these reasons are: it is difficult to isolate a quantum system, especially an engineered one, and since qubits are extremely sensitive to interactions with the environment, which collapses their wave functions; Quantum computation on qubits is accomplished by operating upon them with an array of transformations that are implemented in principle using small "gates", but practical schemes introduce inevitable errors in these transformations known as unitary errors. One example of a physical system which can function as a qubit, in which scientists can access and control quantum properties such as superposition and entanglement, is an atomic nucleus or ion. This is because the nucleus or ion can be in any superposition of spin-up and spin-down, analogous to a qubit. In many cases, scientists do this by manipulating the spin of individual electrons or protons. Controlling these spins has allowed scientists to access and manipulate quantum information to a great extent. This is done by using magnets and microwaves. The same concept that is used in magnetic resonance imaging (MRI) is applied here [5]. However, there are many advances being made in this field and scientists are now using mechanical oscillators, nanoscale spin multimeters to measure chemical potential, etc. Another example of a physical system which can be a qubit is a photon, which can have either left or right circular polarization or a superposition of the two. These photonic qubits can be transmitted and manipulated using optical fibers [6].

Aside from their property of superposition, a second fascinating feature of qubits is the property of entanglement. Entanglement is the phenomenon of correlation of qubits in certain special states, which prevents them from acting independently in a way never seen in classical physics. Albert Einstein once stated that quantum mechanics should allow two objects to influence each other's behaviour even when they are separated by a vast distance, which he called "spooky action at a distance." This is one of the main disparities between quantum physics and classical physics. An entangled system is defined as a system in which there are no independent particles but an inseparable whole: the quantum states cannot be factored into its local constituents. These entangled systems form the basis for quantum teleportation, a fascinating phenomenon which we turn to next [1].

THEORY

Quantum teleportation is one of the most intriguing applications of quantum mechanics. It is the technique of transmitting one qubit's state to another qubit at a different location, without physically transporting the qubit. It essentially involves destroying the state of the particle at the sender's end and creating a replica of the same state of the particle at the receiver's end. Contrary to the sci-fi definition of teleportation, there is no actual movement of the qubits that is involved; it is only the transmission of states between a pair of entangled qubits, using a third qubit, two classical bits and classical communication channel. Due to these reasons, quantum teleportation is not faster than the speed of light. However, for all intents and purposes, quantum teleportation is exactly equivalent to instantaneously transporting the qubit without any errors in the description of the superposition (i.e. the coefficients α and □)[7].

Quantum teleportation was first demonstrated between two independent photonic qubits and optically coherent states, and later on with Bell-state measurements. The field of quantum teleportation is still emerging and recent demonstrations include entanglement swapping, open destination teleportation and teleportation of ionic qubits. However, there are certain limitations to quantum teleportation. The recent demonstrations have certain drawbacks especially over long distances. In teleportation of ionic qubits, the shared entangled pairs are created locally, which limits the teleportation distance to a few micrometers and is difficult to extend to vast distances. In continuous-variable teleportation between light and matter, the experimental fidelity is extremely sensitive to the transmission loss—even in the ideal case, 10^{-1} is the maximum attenuation that is tolerable. The complicated protocol required for retrieving the teleported state in the matter is beyond the reach of technology that exists currently [8].

Any experiment regarding quantum teleportation is demonstrated by using Alice as the sender and Bob as the receiver, schematically shown in Fig. 1. Alice has a qubit which she will send to Bob. Alice and Bob also share a pair of entangled qubits, or a Bell state. Alice will perform a Bell measurement (defined below) on her pair of qubits, send Bob two bits of classical information, and then Bob will perform a transformation on his qubit so that it becomes an exact copy of Alice's first qubit.

The equations of quantum teleportation are based on the fact that Alice and Bob share a Bell state, Alice sends her qubit to Bob along with two classical bits of information, and Bob reproduces her qubit by using his own half of the Bell pair. Let us first define a Bell measurement. The Bell measurement is defined as a joint quantum-mechanical measurement that determines in which of the four Bell states the two qubits are in. Let the 4 Bell states be denoted as follows:

$$|b_{00}\rangle = (|00\rangle + |11\rangle)/\sqrt{2} \qquad (2a)$$
$$|b_{01}\rangle = (|00\rangle - |11\rangle)/\sqrt{2} \qquad (2b)$$
$$|b_{10}\rangle = (|01\rangle + |10\rangle)/\sqrt{2} \qquad (2c)$$
$$|b_{11}\rangle = (|01\rangle - |10\rangle)/\sqrt{2}. \qquad (2d)$$

Fig 2: Denotation of the 4 bell states.

Note that |01〉, for example, is the quantum state associated with the first qubit being in state |0〉 and the second qubit in state |1〉 (known as a tensor state).
Let Alice and Bob share |b00〉 (it doesn't matter which of the four Bell states they initially share). Alice has her own qubit which has a wave function α |0〉 $_{A'}$ + □|1〉 $_{A'}$. Therefore, the total state is:

$$2^{-1/2}(\alpha\,|0\rangle_{A'} + \beta\,|1\rangle_{A'})(|00\rangle_{AB} + |11\rangle_{AB}) \qquad (3a)$$
$$= 2^{-1/2}(\alpha\,|000\rangle_{A'AB} + \alpha\,|011\rangle_{A'AB} + \beta\,|100\rangle_{A'AB} + \beta\,|111\rangle_{A'AB}) \qquad (3b)$$
$$= \frac{\alpha}{2}((|b_{00}\rangle_{A'A} + |b_{01}\rangle_{A'A})\,|0\rangle_B + (|b_{10}\rangle_{A'A} + |b_{11}\rangle_{A'A})\,|1\rangle_B)$$
$$+ \frac{\beta}{2}((|b_{10}\rangle_{A'A} - |b_{11}\rangle_{A'A})\,|0\rangle_B + (|b_{00}\rangle_{A'A} - |b_{01}\rangle_{A'A})\,|1\rangle_B) \qquad (3c)$$
$$= \frac{1}{2}\,[|b_{00}\rangle_{A'A}\,(\alpha\,|0\rangle_B + \beta\,|1\rangle_B) + |b_{01}\rangle_{A'A}\,(\alpha\,|0\rangle_B - \beta\,|1\rangle_B)$$
$$+ |b_{10}\rangle_{A'A}\,(\alpha\,|1\rangle_B + \beta\,|0\rangle_B) + |b_{11}\rangle_{A'A}\,(\alpha\,|1\rangle_B - \beta\,|0\rangle_B)]\,. \qquad (3d)$$

Fig 3: Representation of the total state of Alice's qubit.

In the first step we expand the equation and rewrite it. In the second step we take the common α and □ factors out and rewrite the equation. In the third step we rearrange the equation in terms of the four combinations we can get out of the two qubits states along with their probability terms.
Quantum teleportation proceeds with Alice measuring her pair of qubits in the Bell state basis and sending Bob a two-bit message, after which Bob will apply different quantum gates such as X, Y, or Z or a combination of these gates to his single qubit, where:

$$X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, Z = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Fig.4 Representation of the Pauli matrices of the quantum gates X, Y and Z.

Which gate he will apply depends on the two classical bits Alice sends. Alice sends the bits ab depending on which Bell state she measures. For example, if she measures |b01〉 she will send a message 01 classically. Bob will then run the operator X^aZ^b on his qubit. For example, if ab = 01 then Bob applies $X^0Z^1 = Z$, which is just a phase change. If Alice sends 10 then Bob applies X which is just a bit flip (i.e. |0〉 ⇔ |1〉). If Alice sends 11 he does both and if Alice sends 00 he does nothing. Then, miraculously, he has an exact copy of Alice's qubit! One can confirm that this works by inspecting Eq. (3). This is the fundamental concept behind quantum teleportation [9].

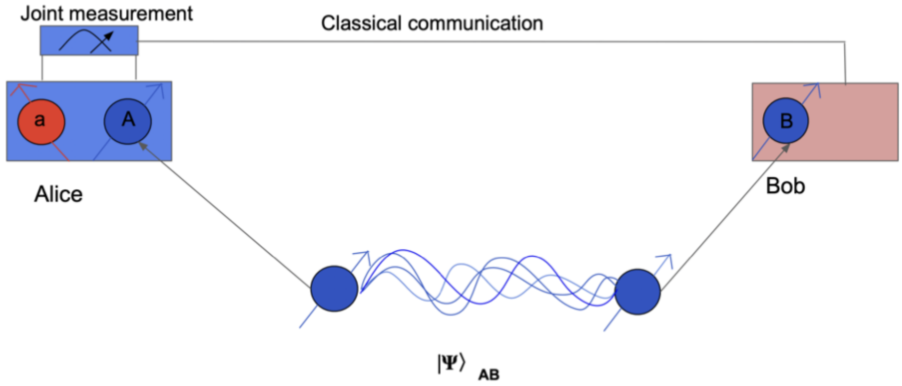

Fig. 5 A schematic of the quantum teleportation procedure. An entangled pair of qubits is shared while Alice has an initial qubit which is to be teleported. Alice measures her pair of qubits, sends classical information to Bob, and then Bob performs an action on his qubit 'B' resulting in an exact replica of Alice's initial qubit 'a', which is now destroyed. Thus, this procedure is equivalent to qubit 'a' teleporting.

THE QUANTUM INTERNET

The internet as we know it today has made our lives much more convenient and made things extremely accessible for us. This paper, for example, is in its entirety a product of the internet. Communication in general has become extremely easy with the advent of the internet. But what if there is an even faster, safer, and more efficient mode of communication?

If we apply the concept of quantum teleportation as discussed above on a large scale, we then have ourselves the concept of the quantum internet. Analogous to the classical internet, which connects classical computers, which function on classical bits, the quantum internet will connect quantum computers which function on qubits. The possibility of communication via quantum channels is possible because of the aforementioned properties of quantum systems such as superposition and entanglement. Using the principles of quantum teleportation and quantum computing we can potentially create a quantum network. However, as with any new technology, it is hard to predict the uses of such a network. In the late 1980s and early 1990s the same problems were faced with the internet as we know it today. Huge firms, universities, and even people started connecting on the internet but accomplishing anything on the internet was a real task before the invention of the world wide web. Searching for information on the net was very difficult and almost impossibly dense. However, with the creation of the world wide web, a decentralised repository of information, shareable with anyone who could connect to it, by Tim Berners-Lee, the internet started being of much use to people, and slowly evolved into the vast network as we know it today [10]. This could be the case with the quantum internet as well. It is still in its rudimentary form and only with time will it truly evolve into something very useful for not only mathematicians to perform complex calculations, but also for chemists, biologists, physicists to model simulations of subatomic particles, atoms, molecules, etc. and even transport simple quantum systems across the world. It could be immensely powerful and useful even for the general public, as it will open the gates to faster communication and safer transactions [11].

Understanding the basics of how the quantum internet can be formed is very important in order to understand its applications. The quantum internet effectively is a network enabling quantum communication among remote quantum nodes. The main purpose and the heart of quantum communication is enabling a qubit on a person's device to entangle with a qubit on someone else's. This incorporates the concept of quantum teleportation as discussed above. The challenge with teleportation is that it is extremely difficult to achieve a quantum system of two qubits at long distances. This means that in order for qubits to become useful in actual communication, we must avoid their random coupling with the external environment– a phenomenon known as the decoherence effect [12]. Another difficulty for photonic qubits is that when they are transmitted in an optical fiber, the intensity of a photon is exponentially attenuated with the transmission distance [8]. This problem, however, can be solved using quantum repeaters.

In classical communication, a repeater amplifies the compensation signal and can supplement the energy lost during the transmission of information. How- ever, the classical repeater cannot be applied to quantum communication due to the no-cloning theorem of the quantum state. The no-cloning theorem states that it is fundamentally impossible to clone a quantum state using only the original state (note that quantum teleportation is not cloning in this sense). Furthermore, the noise– such as unwanted electromagnetic radiation– generated by the classical repeaters is too large, inevitably leading to communication failure. Quantum repeaters primarily have the ability to manipulate qubits. They are a quantum analog of classical repeaters and perform operations such as storing and measuring qubits. Therefore, they guarantee high fidelity (i.e. high quality) transmission of qubits, an essential step in building the network of the quantum internet [13].

The two most important technologies of quantum repeaters are the quantum entanglement switching and quantum entanglement purification. Quantum memories constitute the nodes of the quantum communication network and connections between these nodes (relay stations) need to use quantum entanglement switching technology to extend the communication distance.

The current applications of a successful quantum internet are secure communication, clock synchronization, extending the baseline of telescopes, secure identification, achieving efficient agreement on distributed data, and exponential savings in communication to name a few. Owing to quantum cryptography, the quantum internet can be potentially useful for government agencies, research institutions, and banks. The main feature of entangled systems is that the entangled state is only shared between two qubits. Thus, if a third person tries to eavesdrop– if a third qubit interferes– it will be easily detectable, thus keeping systems secure and private. The reason why quantum internet protocols can outperform classical communication with relatively few resources is because their advantages rely solely on properties such as quantum entanglement, which can be used with very few qubits.

II. SUMMARY AND OUTLOOK

The biggest hurdle for quantum computing and the quantum internet is the decoherence effect. Decoherence in simple terms means the loss of information from the qubit to the environment as time passes. A qubit is fragile in nature and easily interacts with the environment, thus the environment is in some sense "measuring" the qubit and causing its state to collapse. Given this major challenge, shouldn't isolating qubits solve the problem? The problem is that isolating qubits as of now is really difficult to achieve in practice with the state-of-the-art quantum technologies. Furthermore, perfectly isolating qubits would prevent them from interacting with other qubits, thus defeating the purpose of the quantum internet in the first place. The decoherence effect is quantified using decoherence times, where the greater the decoherence time, the longer the information in the qubit lasts. Currently, the decoherence time for superconducting qubits is 10-100 microseconds, and it is expected to gradually increase with better quantum technologies. Moreover, long-distance entanglement distribution, though deeply investigated by the physics community in the last twenty years, still constitutes a key issue due to the decay of the entanglement distribution rate as a function of the distance between the two qubits. Given the very fragile nature of qubits and Bell states, the challenges posed by sharing of quantum resources will demand a large amount of conceptual work in the development of both new networking protocols and quantum and classical algorithms [14]. However, realising the quantum internet will be a huge breakthrough in the field of computation and communication and the benefits of such an internet far outweigh its drawbacks and limitations.

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