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Review-QUANTUM TELEPORTATION

Sub-title: A descriptive study of Quantum Teleportation and its relevant topics.

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Abstract:

Teleportation is the ability to travel by just reappearing at some other spot. Though teleportation has never been achieved, quantum teleportation is possible. Quantum teleportation is a process of transferring quantum state of a particle onto another particle, under the circumstance that one does not get to know any information about the state in the process of transformation. This paper presents a brief overview of quantum teleportation, discussing the topics like Entanglement, EPR Paradox, Bell's Theorem, Qubits, elements for a successful teleport, some examples of advanced teleportation systems (also covers few ongoing experiments), applications (that includes quantum cryptography), and the current hurdles for future scientists interested in this field. Finally, major advantages and limitations to the existing teleportation theory are discussed.

Keywords: Teleportation, Quantum Teleportation, Quantum Entanglement, Qubits, EPR Paradox, Bell States, Quantum Particles, Spooky action at a distance.

Introduction:

The old quantum theory was initiated by the work of Max Planck of black body radiation (emission and absorption of light in an ideal black body), with his discovery of Planck's law introducing quantum principles. Quantum theory is needed because many phenomena at the microscopic level cannot be explained using classical theory. [1]

Quantum theory is a branch of physics which demonstrates the behaviour of matter and energy at the atomic as well as subatomic levels. Quantum physics and quantum mechanics are the studies of the nature and behaviour of matter or energy in that energy level. [1]

In Quantum theory, Pauli's Exclusion principle states that "There are only certain allowed energy states for an electron and these states are said to be quantized. Further, it tells us that no two electrons, in the same system, can occupy the same energy state and that all the energy states are filled from the lowest levels to the highest levels". [1]

Until recently, the primary motivation for students who were not physicists or chemists to study quantum mechanics was to gain a better understanding of its impact on modern ideas. People who will be making business and technological decisions in the future will need to comprehend modern physics. Recent advances in electronics downsizing and nanotechnology have brought items into the business and engineering worlds that can only be understood using quantum mechanics ideas. [12]

The further quantum physicists study deeper into the nature of reality, the more evidence they are finding that everything is energy at the most fundamental levels. The new and fascinating topic in quantum physics is that reality is merely an illusion. [1]

Teleportation:

Imagine a situation where one can wake up in a remote corner of Mizoram, move to work in Mumbai, meet friends for lunch at Jaipur, and end the day by catching the scenic sunset in Rameswaram, interesting right!

This idea of relocating a person from one place to another used to be mentioned as a part of science fiction, but now scientists are starting to unveil the technologies that can make it into a reality.

The formal definition of teleportation goes as follows,

"Teleportation is the hypothetical transfer of matter or energy from one point to another without traversing the physical space between them."

Actual teleportation of living beings has never been achieved by modern science which is based on certain mechanistic methods and it is absolutely questionable if it can ever be realized because the transfer of any matter from one point to another without actually traversing the physical space between them violates the Newton's laws. However, teleportation in the quantum world is possible. [4]

Figure 1 'Anywhere Door' in the famous cartoon Doraemon is an example of teleportation [1]

Quantum Teleportation: One of the weirdest characteristics of quantum mechanics which was revealed back in the 1930s is that there is a particle over here and a particle over there and one can set these particles up in such a way that if an experiment is done on one particle it affects the other particle regards of how far the particles are. All the minute particles in this universe have the quality called spin, spin clockwise, or anticlockwise. Imagine two particles separated by a large distance. One particle spin clockwise and the other particle at that moment happens to spin anticlockwise even though there is no experiment on the second particle. Einstein

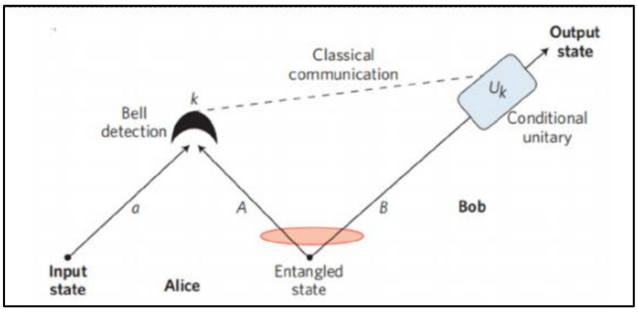

Figure 2 Theory of quantum teleportation [11]

called this phenomenon spooky action at a distance. These two particles even though they are at a distance communicate with each other. Now this concept is the foundation for teleportation.

Imagine a situation, Alice has managed to create a qubit in her lab and she wants to analyze that qubit. She doesn't know what the qubit looks like so she just imagines the qubit as,

$$|\psi\rangle = \alpha\,|0\rangle+\beta|1\rangle$$

but she doesn't know what α and β are. She wants to transport this qubit to Bob's lab, which is far away. They don't have a quantum channel between them for transferring quantum information. If Alice tries to figure out α and β by measuring the qubit, she might destroy the qubit which includes the phenomenon of superposition and she will learn very little information about α and β. so the major issue here is how can she transfer this qubit to Bob's lab. Here the answer is teleportation, to be precise, Quantum Teleportation.

"Quantum teleportation involves two distant, entangled particles in which the state of a third particle instantly teleports its state to the two entangled particles."

Another characteristic of quantum states is that they can be correlated with other quantum states, meaning that the physical conditions of one state can affect the other. In the year 1935, a paper authored by Albert Einstein, Nathan Rosen and Boris Podolsky tested how effectively entangled quantum states would interact with each other. They found that when two particles are strongly correlated, their individual quantum states are lost and share a unified state. This unified state is said to be in quantum entanglement. "Schrodinger" was the first to realize the strange character of entanglement, he described entanglement as the necessary aspect of quantum mechanics. [7]

If there is something to teleport, that can be brought next to the particle, allowing them to comingle, through the comingling which is sort of an experiment, properties of the particle which needs to be teleported gets imprinted on this particle and then with the little extra framework, that's where the maths of quantum mechanics comes into the picture, manipulating the particle to behave exactly like the particle to be teleported. Because the particle comingled with the original particle it gets affected or changed. So, the only version of the original article is this newly comingled particle. Hence the particle is said to be teleported. [4]

EPR Paradox:

Once the knowledge of one of the quantum states is known, automatically the quantum state of any entangled particles will also be known. In principle, one can place any two entangled particles on opposite ends of the globe and still have this instantaneous data, which goes against the concept of the limit of the speed of light. This result is called the EPR paradox (Einstein, Podolsky, and Rosen).

Despite the fact that Einstein used this paradox to prove that quantum theory was incomplete, experiments have often shown the influence of that entangled particle one another regardless of the distance between them and quantum mechanics remains valid to date. In general, the paradox does not have a resolution. Although entangled systems lack locality (one part can have an immediate influence on another part), they are causal systems, meaning that results always have been caused. As a consequence, a faraway observer will not get to know if the local observer has made changes to the entangled system or vice versa. They need to communicate at as fast a speed as light to confirm one another's observations.

As a result, with entangled systems, it seems difficult to communicate information faster than the speed of light. Although they might know a particle's status, but cannot communicate it faster than light can travel.

Qubits:

The information in the quantum world is encoded in qubits. The basic unit of quanta information is called the qubit. "A qubit is a two-level quantum system where the two basic quantum states are usually written as |0⟩ and |1⟩. A qubit can be in represented as |0⟩, |1⟩, or it is a linear combination of both the states."[9]

In simple words, Qubit is the quants m version of the classic binary bit physically realized with thee two-state (|0⟩, |1⟩) device.

A binary digit (0, 1), is a qubit to represent information in computers. As mentioned earlier in quantum world, information is represented using qubits. Qubit can be represented as a linear combination (or superposition) of its two orthonormal basis states (or basis vectors). The standard representation of these vectors is $|0\rangle = \begin{bmatrix}1\\0\end{bmatrix}$ and $|1\rangle = \begin{bmatrix}0\\1\end{bmatrix}$ and are expressed as "ket 0" and "ket 1" respectively. The set {|0⟩, |1⟩} is the computational basis because it is said to span the 2-D linear vector space of the qubit(Hilbert space). [9]

Figure 3 The two quantum particles or qubits [III]

Qubit basis states can be combined to form product basis states. A quantum register is said to be the set of qubits taken together.

For instance, two qubits could be represented in a 4-D linear vector space spanned by the mentioned product basis states,

$$|00\rangle = \begin{bmatrix}1\\0\\0\\ \end{bmatrix}, |01\rangle = \begin{bmatrix}0\\1\\0\\0\end{bmatrix}, |10\rangle = \begin{bmatrix}0\\0\\1\\0\end{bmatrix} \text{ and } |11\rangle = \begin{bmatrix}0\\0\\0\\1\end{bmatrix}.$$

Formally, a pure qubit is a coherent superposition of the basis states {|0⟩, |1⟩}.

$$|\psi\rangle = \alpha\,|0\rangle + \beta|1\rangle$$

where, α and β are the probability amplitudes and α, β € the set of complex numbers with $|\alpha|^2 + |\beta|^2 = 1$.[9]

Bell state:

The main differentiating characteristic between quantum bits and classical bits is that: multiple qubits (quantum bits) can exhibit the phenomenon of quantum entanglement, while the classical bits cannot.

Consider, two entangled qubits in the $|\Phi+\rangle$ bell state. The Bell states are the quantum states of two qubits that represent the simple examples of quantum entanglement conceptually. The Bell states are the form of entangled and normalized basis vectors. The physicist, "John Bell" was the first to prove that the Bell State measurement correlations are stronger than the correlations that could ever exist in classical systems. [2]

Quantum teleportation is considered as the application of Bell states. Consider the example of Alice and Bob again, where each of them took one of the qubits before they get separated. Now, Alice has to deliver her qubit of information to Bob, but she does not know the actual state of her qubit and can only send classical information about her qubit to Bob. [2]

This process involves some steps which are mentioned as follows. Alice sends the qubit through a CNOT gate, she then sends the qubit through the "Hadamard gate" (The Hadamard gate acts on a single qubit, which maps the basis states $|0\rangle \rightarrow \frac{|0\rangle+|1\rangle}{\sqrt{2}}$ and $|1\rangle \rightarrow \frac{|0\rangle-|1\rangle}{\sqrt{2}}$, it is represented by the matrix $H = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$). Alice measures the states of her qubits, obtaining one of four results, and sends the obtained information to Bob. Given Alice's measurements, Bob performs the necessary operations among four on his qubit and recovers the original quantum state. [2]

Experimental status of quantum teleportation:

In recent years, there has been a rise in interest in using quantum physics' unique properties for information processing. Quantum teleportation is a particularly appealing concept in this area. The experimental work of Bennett (1993) followed by the experimental work of others like Kwiat (1999), Zubairy (1998), Braunstein (1996), Braunstein and Kimble (1998), Kwiat (1995), Vaidman (1994), Stenholm and Bardroff (1998), Pan (1998), Yoran and Vaidman (1999); made the necessary breakthrough to demonstrate the principle of quantum teleportation. This brilliant technical step proved that the idea of quantum entanglement can be used to implement the teleportation process, transferring information between distant quantum systems. Bennett stated a simplified outline of the teleportation process in their work. It is a multi-step phenomenon by which a quantum state |ψ⟩ of a particle can be teleported from one location to another.

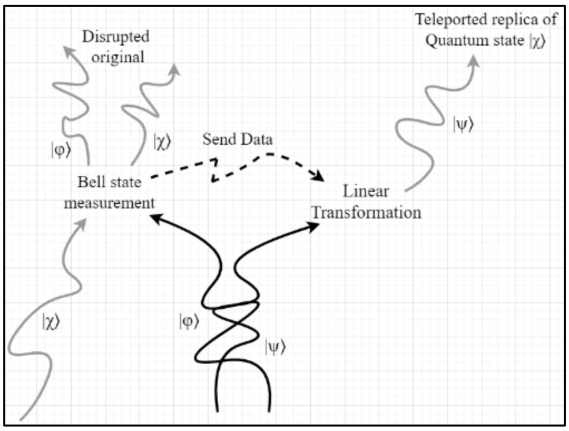

Figure 4 Schematic representation of the idea of quantum teleportation

Let the quantum state of a particle is to be teleported be $|\chi\rangle = \alpha\,|0\rangle + \beta|1\rangle$.

Initially, a pair of quantum systems |ϕ⟩ and |ψ⟩ are prepared in an EPR state so that both of them are linked together. For a two-qubit quantum system, four entangled states are possible. These are known as the Bell States and this was proved by John Bell:

$|\psi^{+}\rangle = (|00\rangle + |11\rangle)$

$|\psi^{-}\rangle = (|00\rangle - |11\rangle)$

$|\phi^{+}\rangle = (|01\rangle + |10\rangle)$

$|\phi^{-}\rangle = (|01\rangle - |10\rangle)$

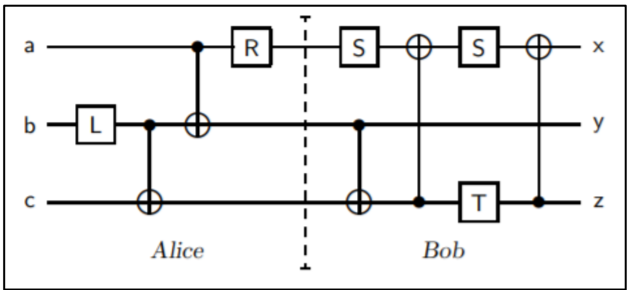

Figure 5 Teleportation circuit [IV]

The subsystems, |ϕ⟩ is sent to the location of sender "Alice" and |ψ⟩ is sent to the location of receiver "Bob". Alice and Bob can be many miles apart. It should be noted that the subsystems are non-casually correlated through entanglement, but they don't have any information about |χ⟩ at this stage. The subsystems indicate a ready-to-transmit information open quantum channel.

Alice will bring the state to be teleported |χ⟩ into contact with |ϕ⟩ (the entangled state) and performs measurements (Bell State) on the combined system {|ϕ⟩, |χ⟩}.

A classical communication medium is used, Alice sends Bob a detailed description of the result of the Bell states which will be performed on the combined system {|ϕ⟩, |χ⟩}.

|ψ⟩ is subjected to a set of linear transformations by Bob, that are dictated by the results of Alice's Bell State measurements. After the linear transformations, the Quantum subsystem that Bob originally received is no longer in the state |ψ⟩ as it is now in the same state as original state |χ⟩. As a result, Alice's |χ⟩ state has been teleported to Bob.

The teleportation mechanism destroys and recreates the quantum states of the particles, and not the particles themselves.

One should be aware that the quantum teleportation scenario described above is hypothetical. Because of the unrealistic assumption made that Alice and Bob shared a pair of the entangled systems, which was noise-free as well as decoherence-free. "Decoherence is the process through which information leaks to the environment or leaks from the environment (environmental noise) through stray interactions with the item, causing the system's quantum states to degrade." Alice and Bob have quantum systems or quantum pairs that interact directly or indirectly, like two ions in the ion trap interacting via the trap's phonon modes or Rydberg atoms in the laser cavity interacting through photons. [13]

1.Trapped atomic quantum bits: In this experiment, atomic Be^{+} are used to achieve teleportation. The qubits are coupled using the Raman transition from 2 lasers, which are used to implement the single-qubit rotations. The spin-echo pulses are then employed to avoid dephasing induced by magnetic field fluctuations, allowing the phase accumulation generated by the static magnetic field gradient to be offset. *[14]*

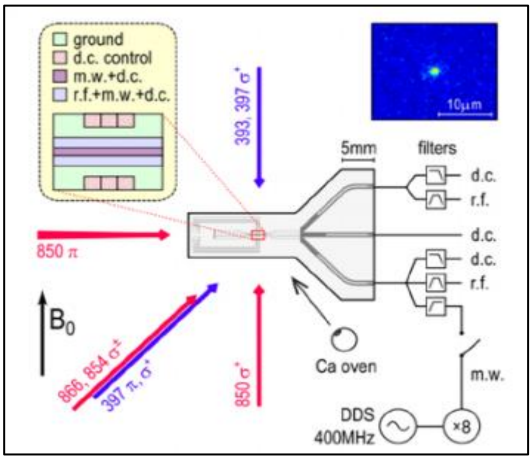

Figure 6 Structure of ion trap [V]

2. Atomic State Teleportation via Cavity Decay: By precisely monitoring photon decays from the cavities, it has been demonstrated that the behavior of an atom trapped in a cavity can be transported to a another atom trapped in a remote cavity. *[11]*

3. Teleportation within matter and light*:* A quantum network precisely the scalable one, necessitates a large number of nodes, some of which may be located far apart, necessitating the use of long-range teleportation. The EPR entangled beams which are sent to Alice and Bob are created using squeezed light. The input beam is the coherent state with an unknown complex amplitude. This state is then teleported to Bob with high fidelity which is possible only by making use of the quantum entanglement. Entangled EPR light beams are produced by combining the two squeezed light beams at a fifty/fifty (50/50) beam splitter. The first EPR beam travel to Alice's sending station, where it is entangled with an unknown input state, here, a coherent state of an unknown complex amplitude, at a fifty/fifty (50/50) beam splitter. Alice performs the Bell-state measurement on the combined state amplitudes using two sets of balanced homodyne detectors. *[5]*

4. Biological Quantum Teleportation: There exist several challenges in teleporting large complex objects, especially biological entities. The primary impediment is decoherence. Because of the macroscopic nature of most biological entities, the fact that such systems reside at near room temperature, and the fact that biological entities are always in contact with the environment, detectable quantum effects in the biological matter are assumed to be substantially suppressed (the source of decoherence). These conditions cause the relevant quantum wavefunctions to collapse very quickly to one among the biological entities allowed classical states. *[11]*

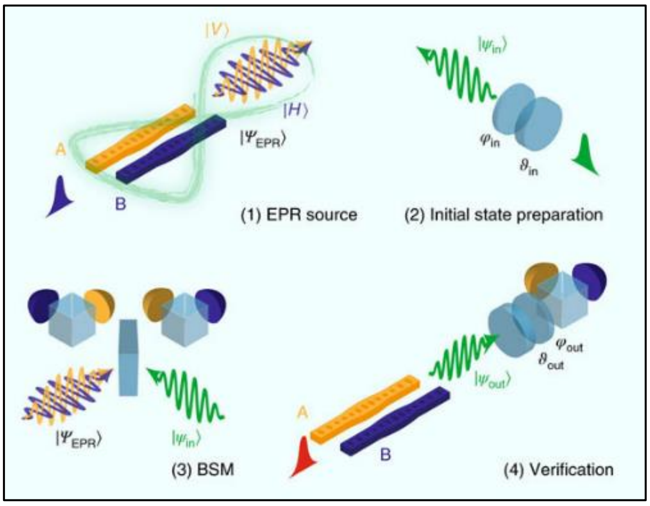

Figure 7 Schematic representation of the key steps of teleportation protocol and its verification [VI]

5. Teleporting a laser beam that is embedded with a radio signal: A laser beam can be transported from one point in a laboratory to another, according to research. The researchers used a laser beam to embed a radio signal, which they then dissolved and reconstructed a metre away practically quickly. The laser beam was destroyed during the teleportation process, but the radio signal was not. An optical communications system's laser light was disassembled and recreated elsewhere in the lab. The laser beam did not survive teleportation, but the message it contained did. This technology might be used to transfer secure data, allowing a perfect cryptography system to be built. When two parties desire to communicate with one another, the communication's confidentiality can be maintained. *[11]*

Applications of Quantum teleportation:

Due to its ability to transmit data securely, In the field of information science, quantum teleportation is extremely essential. Quantum teleportation is the foundation for many technologies, including quantum gate teleportation, computation, quantum networks and port-based teleportation. Quantum teleportation has been demonstrated in several laboratories using a variety of techniques.

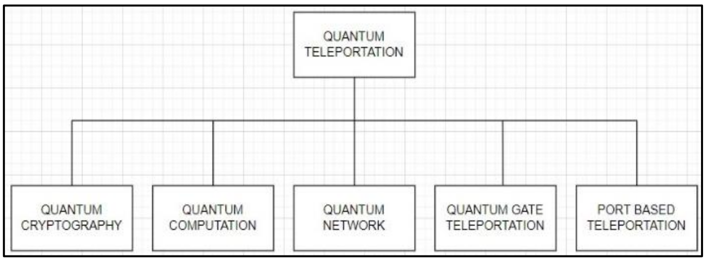

Figure 8 Applications of Quantum Teleportation

Quantum computation:

In 2019, IBM released the "IBM Q" Quantum Computing System, which is the world's first industrial quantum computing system for business and science applications. [5]

Quantum Network:

In 2016, a Chinese team used an existing fibre network to achieve quantum teleportation over relatively long distances. [5]

Quantum Cryptography:

Quantum Cryptography allows for the confidential transmission of data. One of the basic principles of quantum technology is that it is impossible to measure the state without Alice and Bob being aware of it, at which point they can try to share more entanglement. This ensures that the data shared between Alice and Bob has no duplicate anywhere in the world, thus maintaining the secrecy of the information shared between them. Quantum cryptography is beyond Anonymous' control. Quantum cryptography, with proper development, is incredibly strong in today's globalized world. [14]

Challenges faced in quantum teleportation:

Many conditions should be satisfied for optimal quantum teleportation. They are listed as follows. There is no limitation for the input information. Anyone can supply and verify the input information and output except the receiver and sender. The conditional unified transmission should be carried out before the third-party verification. Teleportation should have a higher degree of fidelity than the classical protocol. [5]

Most of the Bell state measurement subsets are not achievable, and the feed-forward is either unachieved or artificially replicated in postprocessing, therefore the conditions complete Bell measurement and conditional unified transmission are not satisfied. [5]

However, in the case of real-world teleportation, the problem may be a bit different. When scaling up from two-dimension to N dimension, for instance, one thing that needs to be considered carefully is whether all N dimensions maintain a coherent superposition to achieve the teleportation. If teleportation in N dimension is to be achieved, some hypotheses that are specific to N dimensions may need to be combined with basic assumptions that apply to all dimensions. Other challenges to address in quantum teleportation are light propagation losses and an atomic coherence lifetime, which were raised by classical protocol. [5]

Moreover, currently, there are only a few techniques to prepare entangled states. Teleportation has evolved into a powerful technique that is utilized regularly in labs all over the world, as well as certain demonstrations in real-world fiber networks. The challenge today is to adapt this to the new technologies being developed for quantum repeaters to increase the distances across which entanglement and quantum resources can be distributed. [5]

Future scope:

Quantum teleportation's ultimate use as part of a scalable quantum system is predicated on quantum memory compatibility. In respect of storage duration, conversion efficiency, read-write fidelity, and bandwidth, quantum memories require exceptional radiation-matter interactions (high rate and storage capacity). Quantum repeaters could, for instance, be used to enhance quantum communication beyond direct transmission utilising quantum error-correcting codes. Not only would the development of good quantum memory enable the distribution of entangled over a network and quantum transmission, but would also enable the coherent processing of the quantum data stored. As a result, the network might become a globally dispersed quantum computer or the future quantum internet's backbone. [6]

The future of quantum teleportation mainly aims at teleporting humans or any other living beings from one location to another. The discussion which was made till now restricts the teleportation to only a few numbers of particles, to be precise quantum particles. A teleportation device would work similarly to a fax machine, but on three-dimensional items. It would make a perfect replica rather than a close imitation and destroy the source during the scanning process.

Extending this quantum entanglement process to a huge number of particles is not easy. Consider a situation where a person is to be teleported from Australia to Los Angeles. Now, millions of these quantum particles of that person in Australia have to be enabled to comingle with a collection of particles that are entangled with ones in Los Angeles. This entanglement process or the teleportation process involves the measurement of every single particle in the human being, how it comingles with the particles here and somehow transfer every qubit of that human to its entangled particles in Los Angeles or it can be said that this huge number of particles should be able to manipulate every particle in Los Angeles. It's this huge number that is creating a problem in teleporting humans however teleporting very few numbers of particles can be achieved. [6]

Conclusion:

In this brief discussion about quantum teleportation, conclusion drawn from the fundamental principles of quantum physics is that quantum states can be transferred from one particle to another over endless distances. Quantum teleportation is not limited to photon polarisation states. Entangling photons with atoms or photons with ions are a possibility. This opens the door to quantum memory, in which incoming photon information might be stored on trapped ions that are properly insulated from the outside world. Branches of Quantum teleportation like quantum gate teleportation, port-based teleportation, Quantum computing, optical modes, nuclear magnetic resonance, photonic qubits, atomic ensembles are achievable theoretically as well as experimentally. These technologies have both successes and failures. Certain technologies are only appropriate for a specific type of practical situation. Those technologies are flawed in some ways, which raises a slew of technical concerns, the majority of which are expected to be answered when additional trials are designed.

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Conflict of Interest:

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[I] Figure adapted from: https://otakuusamagazine.com/tourists-flock-to-park-with-anywhere-door-from-doraemon/

[II] Figure adapted from: *Pirandola, Stefano & Eisert, Jens & Weedbrook, Christian & Furusawa, Akira & Braunstein, Samuel. (2015). Advances in Quantum Teleportation. Nature Photonics. 9. 10.1038/nphoton.2015.154.*

[III] Figure adapted from: https://www.youtube.com/watch?v=mumfEob6se8

[IV] Figure adapted from: *M. A. Bashar, M. A. Chowdhury, R. Islam, M. S. Rahman and S. K. Das, "A Review and Prospects of Quantum Teleportation," 2009 International Conference on Computer and Automation Engineering, 2009, pp. 213-217, doi: 10.1109/ICCAE.2009.77.*

[V] Figure adapted from: *Liu, Tao. (2020). The Applications and Challenges of Quantum Teleportation. Journal of Physics: Conference Series. 1634. 012089. 10.1088/1742-6596/1634/1/012089*

[VI] Figure adapted from: *N. Fiaschi et al. Optomechanical quantum teleportation. Nat. Photon, published online October 7, 2021; doi: 10.1038/s41566-021-00866-z*

[VII] Figure adapted from: *Zhou, T.; Shen, J.; Li, X.; Wang, C.; Shen, J. Quantum Cryptography for the Future Internet and the Security Analysis. Secur. Commun. Netw. 2018, 2018, 8214619.*

[VIII] Figure adapted from: *V. Padamvathi, B. V. Vardhan and A. V. N. Krishna, "Quantum Cryptography and Quantum Key Distribution Protocols: A Survey," 2016 IEEE 6th International Conference on Advanced Computing (IACC), 2016, pp. 556-562, doi: 10.1109/IACC.2016.109.*