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QUANTUM TELEPORTATION: THE CURRENT STATE OF RESEARCH

Alamgir Khan*, Jamal Shah
Department of physics, Abdul Wali Khan University, Mardan, 23200 KPK, Pakistan.
Corresponding Author: Alamgir Khan, Email: alamgirkhan03414946231@gmail.com

Abstract: Through the process of quantum teleportation, a transfer of quantum information takes place from one particle to another while maintaining zero physical movement between the two. Quantum teleportation requires two entangled particles along with projective measurements followed by exchanging two bits of classical information. The process requires quantum mechanics principles which combine superposition with entanglement. Quantum entanglement occurs when two or more particles create an inseparable relationship that cuts off a separate description of an individual particle. Experimental realizations of quantum teleportation continue to operate on different physical platforms which include photons as well as atoms and superconducting circuits. Applications of Quantum teleportation includes quantum computing, secure communication, and cryptography. In future Scientists believe that a breakthrough in quantum computing technology could make teleportation a reality, including the ability to teleport a whole human. This paper provides the present research in quantum teleportation, including the theoretical framework, experimental implementations, and potential applications. We also discuss the challenges and limitations of quantum teleportation and propose future directions for research.

Keywords: Quantum teleportation; Quantum entanglement; Quantum decoherence; Quantum technology; Quantum computing

1 INTRODUCTION

Bennett et al. proposed quantum teleportation in 1993 as a method for transferring quantum information between particles without physical transport [1, 2]. Teleportation is dreamed of as the ability to travel by merely reappearing at a distant place. In classical physics, an object eligible for teleportation can be completely described by its properties, which can be ascertained through measurement [3, 4]. In quantum communication, the space restriction of openly transmitting quantum states can be overcome by quantum teleportation, as can the difficulty of achieving long distance exchanges between qubits in quantum computation [5, 6]. The main protocols in quantum information is quantum teleportation [7, 8]. Quantum teleportation, which leverages the physical resource of entanglement, acts as a fundamental component in numerous quantum information tasks and is a crucial element for quantum technologies. It plays an essential role in the advancement of quantum communication, quantum computing, and quantum networks [9, 10]. One of the essential elements of the nascent domains of quantum communication and quantum computation is the potential to transfer quantum information [11, 12]. There has been rapid advancement in the theoretical understanding of quantum information processing, but due to the challenges associated with managing quantum systems, progress in experimentally implementing new proposals has not kept pace [13, 14]. Since that time, there have been considerable advancements in both the theoretical and experimental aspects of quantum teleportation development [15, 16]. This article offers a summary of the existing research on quantum teleportation.

2 QUANTUM SUPERPOSITION

The key alteration among qubits and bits lies in the point that a qubit can exist in a linear arrangement (superposition) of the states $|0\rangle$ and $|1\rangle$ [17, 18]. consider $\propto$ and β represent the probability amplitudes of an electron in the ground state $|0\rangle$ and the excited state $|1\rangle$, respectively. The superposition of these states can be expressed [19, 20] of states are

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \tag{1}$$

Here, α and β are complex numbers, and due to the normalization condition, they satisfy,

$$|\alpha|^2 + |\beta|^2 = 1 \tag{2}$$

In this context, |α|^2 represents the probability of finding the state $|\psi\rangle$ in $|0\rangle$, while |β|^2 represents the probability of finding $|\psi\rangle$ in $|1\rangle$ [21, 22]. Consequently, when a qubit is measured, it collapses to either ‘0’ or ‘1’ probabilistically, based on these probabilities [23, 24]. Let’s examine an example of how a qubit is represented,

$$
\begin{gathered}
|\Psi\rangle = \left(\frac{1}{\sqrt{2}}\right)|0\rangle + \left(\frac{1}{\sqrt{2}}\right)|1\rangle \\
\therefore \propto = \frac{1}{\sqrt{2}} \; and \;\; \beta = \frac{1}{\sqrt{2}} \\
|\propto|^2 = |\beta|^2 = 1/2
\end{gathered}
\tag{3}
$$

This implies that there is a 50% probability of the qubit being measured in the $|0\rangle$ state and an equal 50% probability of it being measured in the $|1\rangle$ state. The superposed states are often referred to as *state vectors* or *state spaces*, while $|0\rangle$ and $|1\rangle$ are known as the *basis states*. [25, 26] (See Figure 1).

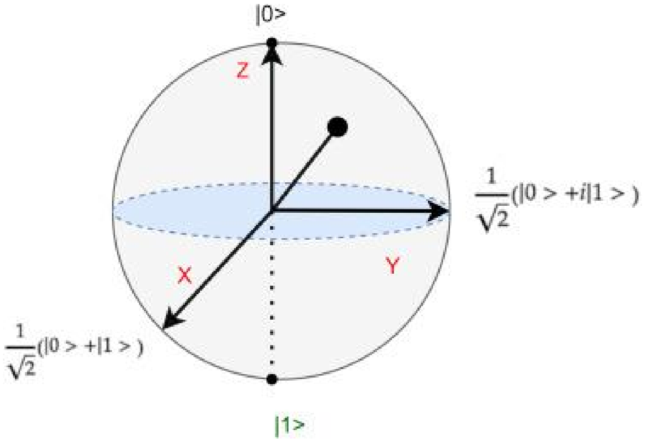

Figure 1 Graphical Representation of Qubit

3 QUANTUM ENTANGLEMENT

The mysterious phenomenon in the existing universe is Quantum entanglement where particles become intricately linked, forming a unified system that remains interconnected regardless of the distance separating them [27, 28]. When particles are entangled, their properties are so deeply correlated that measuring one rapidly effects the state of the other, even if they are light-years apart [29]. Quantum information science relies on this special state of interdependence because it makes possible revolutionary technologies including quantum communication and teleportation as well as quantum cryptography [29]. Maximum entangled states act as essential elements for establishing quantum communication channels between distant users. The protection of entangled states proves difficult when securing long-distance links because environmental noises degrade their quality and negatively impact information security [30]. The implementation of quantum repeaters enables the division of extended transmission lines into smaller segments by implementing entanglement purification and swapping to reduce noise and allow entanglement span longer distances [31, 32]. The process of entanglement purification obtains purified high-fidelity entangled states from mixed quantum systems and the process of entanglement swapping creates connections between entangled pairs which forms bridges for quantum nodes that are positioned far apart [33, 34]. Entangled photons follow the same principles as electron entangled particles by using quantum properties such as polarization and angular momentum. The spin states of electrons find their equivalent in circular polarization states of photons which make them suitable for creating entangled pairs [35]. The angular momentum of photons contains both polarization states and spatial dispersion characteristics that present a complicated visualization even though they fundamentally affect photon behavior [36]. Atom decay emissions based on their angular momentum cause photons to emit polarization states of either RHC or LHC according to atomic spin alignment [37, 38]. Similar to other quantum processes photon absorption and scattering heavily depend on angular momentum conservation principles as a demonstration of quantum state-physical manifestation linkage [39, 40]. Quantum mechanics receives deeper comprehension through these principles which simultaneously enables the development of secure communication technology and information processing systems [41, 42]. For two particles, A and B, with wave functions ψA and ψB, the entangled wave function can be written as:

$$\psi AB = \alpha\psi A\psi B + \beta\psi A\psi B \tag{4}$$

$$|\alpha|^2 + |\beta|^2 = 1 \tag{5}$$

Entanglement swapping is a process that enables the transfer of entanglement from one particle to another [43, 44] (See Figure 2). The mathematical equation for entanglement swapping can be written as:

$$|\psi\rangle_{AB} = \alpha|00\rangle + \beta|11\rangle \tag{6}$$

$$|\psi\rangle_{CD} = \gamma|00\rangle + \delta|11\rangle \tag{7}$$

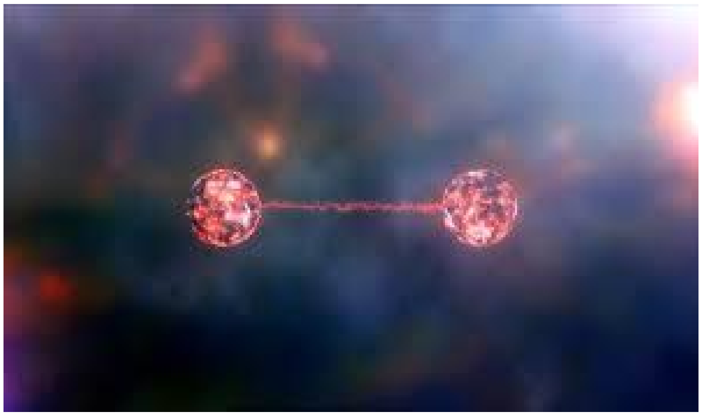

Figure 2 Representation of Two Entanglement States of Particles

4 QUANTUM TELEPORTATION

Alice and Bob share an entangled pair of qubits (**A** and **B**) in the Bell state:

$$|\Phi+\rangle AB = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)AB \tag{7}$$

This means qubits **A** (with Alice) and **B** (with Bob) are maximally entangled. Alice has a third qubit (**C**) in an unknown state:

$$|\psi\rangle C = \alpha|0\rangle C + \beta|1\rangle C \tag{8}$$

Here, α and β are complex numbers which satisfy the normalization condition $|\alpha|^2 + |\beta|^2 = 1$.
The combined state of the three qubits (**A**, **B**, and **C**) is

$$|\psi\rangle C \otimes |\Phi+\rangle AB = (\alpha|0\rangle C + \beta|1\rangle C) \otimes \frac{1}{\sqrt{2}}(|00\rangle+|11\rangle)AB \tag{9}$$

Expanding this, we get:

$$|\psi\rangle CAB = \frac{1}{\sqrt{2}}(\alpha|0\rangle C + \beta|1\rangle C)(|00\rangle + |11\rangle)AB \tag{10}$$

Alice performs a Bell state measurement on qubits C and A. To do this, we rewrite the state $|\psi\rangle CAB$ in terms of the Bell basis for qubits C and A. The four Bell states are,

$$|\Phi+\rangle = \frac{1}{\sqrt{2}} (|00\rangle + |11\rangle) \tag{11}$$

$$|\Phi-\rangle = \frac{1}{\sqrt{2}} (|00\rangle - |11\rangle) \tag{12}$$

$$|\Psi+\rangle = \frac{1}{\sqrt{2}} (|01\rangle + |10\rangle) \tag{13}$$

$$|\Psi-\rangle = \frac{1}{\sqrt{2}} (|01\rangle - |10\rangle) \tag{14}$$

Rewriting $|\psi\rangle CAB$ in terms of these Bell states

$$|\psi\rangle CAB = \frac{1}{\sqrt{2}} [|\Phi+\rangle CA (\alpha|0\rangle B + \beta|1\rangle B) +$$

$$|\Phi - \rangle CA \quad (\alpha|0\rangle B \quad - \beta|1\rangle B \quad) + |\Psi + \rangle CA \quad (\alpha|1\rangle B \tag{15}$$

$$+\beta|0\rangle B \quad) + |\Psi - \rangle CA \quad (\alpha|1\rangle B \quad - \beta|0\rangle B \quad)]$$

When Alice measures qubits C and A, she collapses the system into one of the four possible Bell states. As a result, the state of Bob's qubit (B) is determined by the specific outcome of Alice's measurement, corresponding to one of the four entangled states.

1. If Alice measures $|\Phi+\rangle$ CA $|\Phi+\rangle$ CA

$$|\psi\rangle B \quad = \alpha|0\rangle B + \beta|1\rangle B \tag{16}$$

Bob's qubit is already in the correct state.

2. If Alice measures $|\Phi-\rangle$ CA $|\Phi-\rangle$ CA

$$|\psi\rangle B = \alpha|0\rangle B \quad - \beta|1\rangle B \tag{17}$$

Bob needs to apply a Pauli-Z gate (ZZ) to recover the original state.

3. If Alice measures $|\Psi+\rangle$ CA $|\Psi+\rangle$ CA ,

$$|\psi\rangle B = \alpha|1\rangle B + \beta|0\rangle B \tag{18}$$

Bob needs to apply a Pauli-X gate (XX) to recover the original state.

4. If Alice measures $|\Psi-\rangle$ CA $|\Psi-\rangle$ CA

$$|\psi\rangle B = \alpha|1\rangle B - \beta|0\rangle B \tag{19}$$

Bob needs to apply a Pauli-X gate followed by a Pauli-Z gate (XZ) to recover the original state. Alice sends the result of her Bell state measurement (2 classical bits) to Bob. Based on this information, Bob applies the appropriate quantum gate to his qubit (B) to reconstruct the original state $|\psi\rangle$. After applying the correct operation, Bob's qubit (B) is in the state,

$$|\psi\rangle B \quad = \alpha|0\rangle B \quad + \beta|1\rangle B \tag{20}$$

This is the original state of qubit C, successfully teleported from Alice to Bob (See Figure 3).

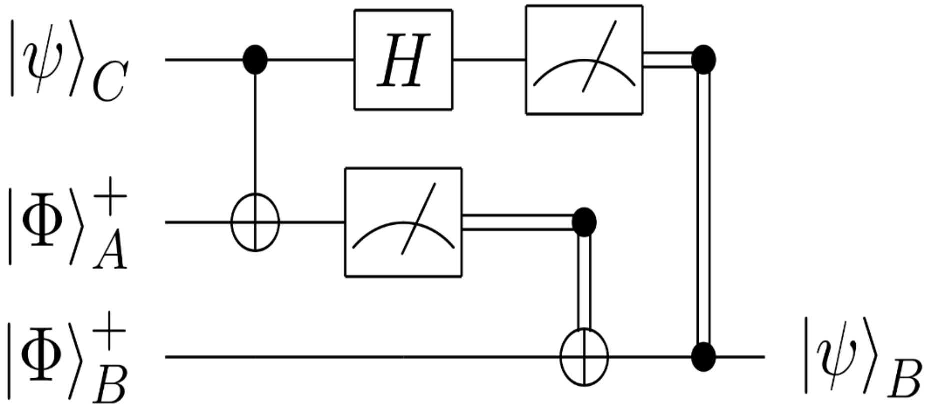

Figure 3 Circuit Diagram of Quantum Teleportation

The quantum circuit for teleporting a quantum state, as described, begins with a Bell state and the qubit to be teleported as inputs [45]. The circuit involves a series of operations: a CNOT gate, a Hadamard gate, and measurements on two qubits [46]. Following the measurements, two classically controlled gates are applied—a Pauli X gate and a Pauli Z gate—which are executed based on the measurement outcomes [47]. Specifically, if the measurement result corresponds to a particular value, the respective Pauli gate is activated. Once the circuit completes its execution, the quantum state originally held by the input qubit is successfully teleported to the target qubit [48]. After measurement results are obtained the target qubit ends in either its initial state or an altered quantum state. The circuit serves an essential role for quantum teleportation and also enables the swapping of entangled states [49]. Quantum circuits enable the transmission of entanglement from the input qubit that belongs to an entangled pair to another qubit according to the description [50].

5 CHALLENGES

Several obstacles stand in the way of practical application of quantum teleportation as an innovative concept [51, 52]. The teleportation procedure accumulates errors because of noise and decoherence effects occurring within quantum systems. Small-scale operations represent the current method used to achieve quantum teleportation [53, 54]. Control over quantum systems and low error rates present the main technical barrier to scale up their operation capabilities. The extended distribution of entanglement particles poses difficulties since it needs the preserved connection between entangled states [47, 55]. Quantum teleportation depends on maintaining high fidelity conditions for the state to stay stable. Achieving exact measurement of quantum systems and maintaining process control becomes a complex challenge during telecommunications [56, 57]. Quantum teleportation needs parties to exchange genuine classical data between each other. Error correction methods which need developmental work must be implemented because of teleportation errors which occur.

6 CONCLUSION

Research and physicists have remained fascinated by quantum teleportation ever since decades passed. This research evaluated every relevant study about quantum teleportation both theoretically and practically to investigate foundational concepts and experimental challenges and possible applications of this phenomenon. The study demonstrates that quantum teleportation serves as a complex operational technique that needs total control of quantum states built into particles. Science proves quantum teleportation functions both theoretically and experimentally yet the process remains unstable due to decoherence-caused sensitivity to errors. The investigation points to beneficial features of quantum teleportation despite the multiple challenges that exist. Quantum communication development requires permanent maintenance of mobile quantum particles which need to stay in different locations for information exchange. The research into quantum teleportation enabled scientists to learn better how essential quantum mechanics ideas of entanglement and superposition work. The research conducted for this study generated vital improvements that propel the development of quantum technology particularly for quantum computing as well as quantum cryptography and quantum communication systems. The review process calls for additional experimental work and theoretical validation research in order to understand quantum teleportation properly.

7 FUTURE RESEARCH

Scientists need to invest greater effort developing experimental methods that strengthen quantum teleportation fidelity and decrease its performance errors. The research of quantum teleportation through both fresh superconducting qubit and topological quantum systems offers new insights into theoretical and practical applications. Scientists need to conduct more research to build sophisticated theoretical models that accurately follow quantum system conduct during teleportation procedures.

CONFLICT OF INTEREST

The authors have no relevant financial or non-financial interests to disclose.

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