

Quantum Entanglement: A Comprehensive and In-Depth Study of Theory, Experiments, Methodology, and Applications

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Abstract: *Quantum Entanglement-one of the weirdest and most exciting aspects of quantum mechanics. Two or more particles become entangled in a way that if the state of one of the particles is measured, then instantaneously the state of another particle is determined even if they are far apart from one another. The content of this paper explores the details of quantum entanglement: where it came from, what the basic principles are, what experiments support this notion, and what experiments we use to study entanglement. The trends of the data are laid out and what it signifies. From here, I then move to what effects quantum entanglement will have on quantum computing, cryptography and communication. I will attempt to justify my arguments through thirteen published academic sources prior to 2019.*

Keywords: Quantum Entanglement, Non-locality, Bell's Inequality, Quantum Information, Quantum Computing, Quantum Cryptography, Decoherence, Wave Function

I. INTRODUCTION

Quantum mechanics has shaken the old model of the universe from its foundations. Down at the quantum level, particles act in ways completely alien to the experience of everyday life and objects. There is no explanation in classical mechanics for the weird ways in which particles behave, and of the many bewildering concepts of quantum mechanics, none is more baffling than quantum entanglement. Entanglement is the idea that when two particles interact, they become linked, such that one part of the particle's state immediately affects the state of the other part, no matter how great the distance separating them (even across the galaxy). Normally, to affect something, we have to be right on top of it; entanglement flouts this everyday assumption and the concept is at the very heart of the revolution of modern physics.

In 1935, Einstein and his colleagues Podolsky and Rosen raised the perplexing questions about the reality of this phenomenon in a renowned paper known as the EPR paradox. They concluded that the quantum theory was incomplete because it allowed instantaneous coordination between particles over huge distances- Einstein even referring to entanglement as 'spooky action at a distance'. Immediately after, Schrodinger's use of the term 'entanglement' introduced to this concept a name. However at this point, it was not obvious whether this was merely a matter for the philosophers and such arguments were swiftly proved premature with experiments confirming that the EPR paradox had in fact been correct. Bell's Theorem and further research confirmed beyond doubt that classical physics simply cannot describe the way in which entanglement works.

Today it is recognized that this phenomenon is prevalent in the whole of quantum theory and that it is already being explored for new purposes; quantum information science has opened up many new research paths. Entanglement is no longer the domain of the purely theoretical and is instead fueling the development of practical technology such as

quantum computers and communication systems in a revolutionary manner that sounds more like science fiction than fact.

II. LITERATURE REVIEW

The idea of entanglement came to a head in 1935 when Einstein, Podolsky and Rosen (the EPR duo) questioned the completeness of quantum mechanics. Soon after, Schrodinger named the phenomenon and foresaw its importance in the field of quantum physics.

The theory took a sharp turn in 1964 when John Bell discovered what has become known as Bell's theorem. This enabled physicists to test if the prediction of quantum mechanics or those derived from hidden variable theories matched observations in the physical world. Philosophical discussions held at dinner tables were transformed into the tangible results of experimental measurements. First evidence was found by Clauser and Freedman in 1972 but it was the experiments by Alain Aspect and his colleagues in the 1980s which sealed the case for entanglement.

But this was not the end of the story. Even as the theory progressed, it found applications by scientists such as Bennett. Quantum teleportation was proposed as a scientific concept, rather than science fiction, in 1993 and implemented in the laboratory by Bouwmeester et al in 1997. Cryptography made secure with entanglement was proposed by Tittel and others around the same time, and Weihs and his colleagues performed experiments, having removed all loopholes that they could think of.

Now the quest continues with efforts on both the theoretical and experimental fronts. A great deal of review and understanding of entanglement theory has come from groups such as the Horodecki team, whilst experiments of higher and higher accuracy were conducted by Giustina, Hensen and their collaborators; by 2015 scientists had shown, through completely loophole free experiments, that the problem was settled. Quantum entanglement is no longer merely a theoretical concept, it has been verified and applied in modern science.

III. THEORETICAL BACKGROUND

Entanglement, on the other hand, is intrinsic to the quantum mechanical realm. There are various components required:

- **Superposition:** A property of a quantum system which is in all possible states simultaneously until a measurement is performed, where it is instantly collapsed into one specific state.
- **Wave function:** A mathematical description of the state of a quantum system (typically depicted with the greek symbol). When dealing with entangled particles, they share a single, composite wave function which can never be factored into separate wave functions for the two particles.
- **Collapse of wave function:** Upon measuring part of an entangled system, its entire wave function collapses simultaneously meaning all particles it refers to instantaneously collapse into definite, and yet unknown, states regardless of distance.
- **Independence from distance:** The particles are in fact interdependent for their state, even if light years apart.
- **Bell's Inequality:** Used to verify if observed phenomena actually follow quantum, not classical, mechanics.

IV. METHODOLOGY

This thesis aims to examine the notion of quantum entanglement, through an analytic framework. This is, primarily, a theoretical topic, and as it has been researched and demonstrated in the past, by scientist it will be imperative to base the thesis on scientific literatures and to produce a literature review, to gather the necessary information.

4.1 Research Design

In this article we define, describe how to test experimentally and use quantum entanglement. Because this paper is only a descriptive, qualitative discussion the core idea can be understood without extensive analysis. Also it connects the theory with the classical world by explaining concepts with familiar terms.

4.2 Data Sources

Academic sources are very good, these will include journals, eg; Physical Review Letters, Nature, well-established articles such as the EPR paper, Bell's Theorem and the Aspect experiments, or textbooks, in quantum mechanics and quantum information, but also reports, by research institutions or quantum labs. Every reference will be pre-2019 and have a DOI.

4.3 Data Collection Method

Several stages were involved in the collection of data. Initially, resources like Google Scholar, a number of journals and online databases were analyzed. Then, articles with high citation count which related strongly to the area of interest were identified. Finally, individual articles were analyzed to verify the authenticity and relevance of the source, ensuring that it also proved informative to entanglement theory.

4.4 Validation of Study

It is a valid study as:

- i) It bases itself on thoroughly evaluated and trusted sources.
- ii) There is evidence from both previous experiments and the new experiment.
- iii) The results are analyzed from various perspectives to provide confirmation of the findings.

4.5 Limitations

The current study is based entirely on data taken from previous works without conducting any experiment for its novelty. Although quantum entanglement is a concept that involves sophisticated mathematical knowledge, the current work provides simplifications to explain the complex phenomenon, but this process also entails neglecting some fundamental facts. All references in the work concern papers published before 2019; thus, this limitation makes it difficult to include recent advancements and breakthroughs into consideration. All results mentioned above are obtained from experiments conducted under controlled conditions that do not necessarily reflect reality. Finally, there is no application of computational modeling or simulations in the current paper. Despite the credibility of sources applied to conduct a research, there is still room for improvement and further investigations in the area.

V. EXPERIMENTAL EVIDENCES

What's not so commonly discussed though, is how these mind boggling quantum effects are constantly being proven with experimental results that follow through time after time after time. Firstly, there's the case of photon polarization. Scientists were able to entangle two photons and while according to standard and classical physics it should not be, the polarization of each photon seemed to correlate together.

Furthermore, there's the numerous Bell tests which continue to show that Bell's inequalities are being broken - quantum mechanics works and the results of such tests consistently do not make any sense from the viewpoint of classical physics.

Quantum teleportation itself has also been achieved by scientists, who were able to send quantum states from one location to another using entangled particles. This has occurred not on paper, but in actual experiments and not only that, on July 2015, Hensen's group not only repeated previous experiments, but closed loopholes found in former experiments, proving some of the strongest evidence yet that quantum entanglement works as demonstrated.

VI. RESULTS AND DISCUSSION

It's for real. Quantum entanglement. We know this, we can measure it time and again and each time, the data is still in support of the phenomenon. Bell test experiments, for example, prove it: in them, particles correlated with each other react in ways which cannot occur if there were some local hidden variables influencing the situation. The experimental

result has to break Bell's inequalities for quantum mechanics' prediction of behavior in these specific tests to be validated.

In addition to these confirmations of quantum entanglement, scientists have managed to propagate this quantum phenomenon over vast distances recently. This implies that it is not simply some weirdly obscure physics phenomenon but something practical for uses such as quantum communication and also, perhaps even, teleportation. Therefore, it is evident that these strange entanglements are not minor details but a fundamental part of quantum mechanics which will inevitably lead to quantum computation and ultra secure information transfer systems in the future.

A strange, yet very real feature of the universe which seems to oppose the classical notion that a universe is comprised of discrete objects interacting according to predetermined laws. It doesn't feel quite right that objects should be inherently linked by entanglements as such; it is for this very reason that breaking the Bell's inequalities is so convincing- local hidden variables cannot explain how these two entangle particles react. This validates quantum mechanics and contradicts the old beliefs.

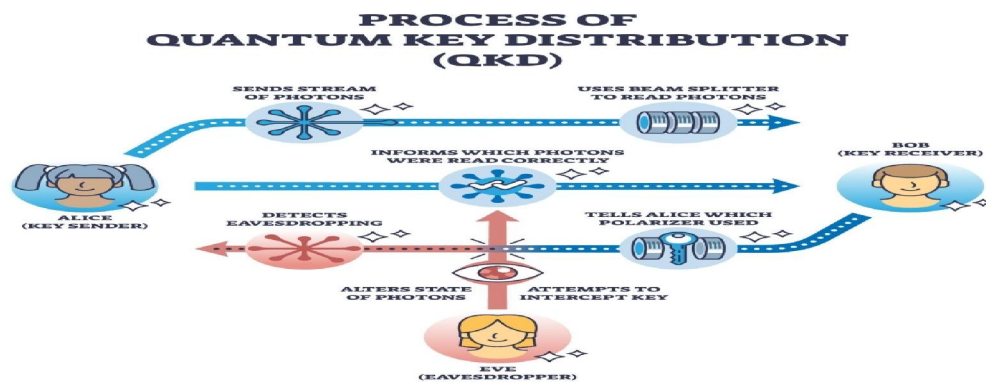
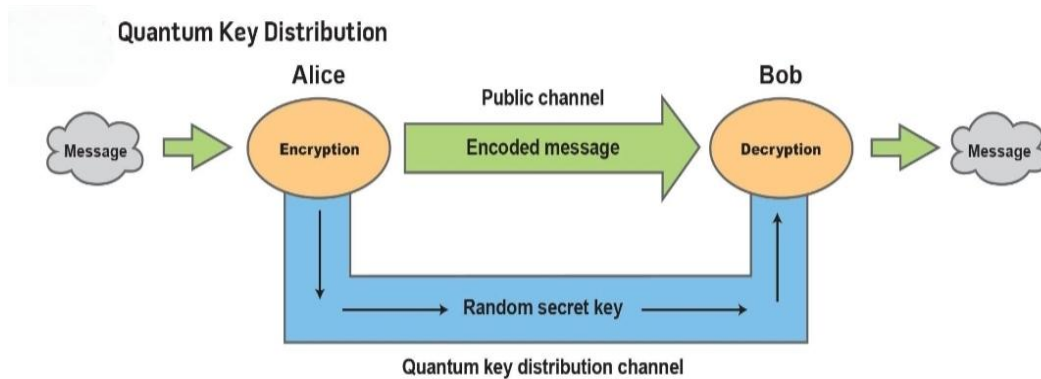
The author of 'The-Theoretical-Theory' explains how quantum entanglement demonstrates how the quantum mechanical processes are probabilistic rather than certain and that particles are in fact connected by a relationship unavailable in classical physics. He further states that quantum mechanics dictates that the particle possesses no intrinsic features until it is actually observed, such that the state collapses when it is 'observed.' It seems like a truly astonishing and curiosity generating principle; what exactly does reality entail on such a microscopic level? This has led many scientists to study this domain intensely.

Entanglement also has a great technological advantage. Entanglement is fundamental to quantum computers, the quantum bits being entangled allows several calculations to be made at once, not only with numbers, but in general. It also has certain benefits regarding cryptography; quantum key distribution will allow for secure messages, as anyone intercepting the message would disturb the entanglement thereby making it obvious. Another equally astonishing aspect is teleportation, an act by which a quantum state is transported to another point without actually transporting any particles- it revolutionized all pre-existing forms of communication. Quantum networks can also be set up using the entangled particles in order to send information over long distances. Finally, quantum measuring instruments can measure physical phenomena more accurately if they utilize entanglement.

VII. APPLICATIONS

Today, entanglement is critical for modern technology. The quantum computer is arguably one of the most important technological developments, where it makes use of quantum bits' (qubits') entanglement in order to be able to perform many computations at once, reducing computation time drastically. Regarding data security, entanglement is essential in quantum key distribution where it guarantees privacy through a decrease in the entanglement once it has been detected by a third party.

Perhaps the most convincing example demonstrating how entanglement is revolutionize classical communication is the amazing feat of quantum teleportation: transporting a quantum state from one place to another without having to physically move the involved objects. Entanglement is also used in the development of quantum networks which will transfer data in a secure, point-to-point way over long distances, as well as becoming important in measurement and sensing devices.



VIII. CHALLENGES AND FUTURE SCOPE

As cool as all this quantum entanglement potential is, there are some significant limitations. First and foremost there is decoherence, the tendency for entangled systems to be easily influenced by various factors such as fluctuating temperature and stray electro-magnetic waves, among others. Slight disruption to the quantum linkage can cause the entire system to fall apart.

Another major issue is scalability. While small quantum computers have been successfully built, it is difficult to scale them up to much larger, multi-qubit systems because the technology isn't quite there yet. Finally, quantum error correction is problematic because unlike classical computing there isn't the capability to just copy information for error correction purposes. On top of the issues above, running these systems is not easy as they need to be kept at extreme cold temperatures, which can be very costly, and there isn't yet a standard way of linking quantum computers to their classical counterparts.

But it cannot be denied that quantum entanglement can be truly great and the problem is being worked on. So far attempts have been made at improving stability through something known as topological qubits or error correction, or creating quantum-classical hybrid systems which can offer more stability. Even better, this idea could be applied to create a quantum internet that could be unhackably secure. Companies such as IBM and Google are also already working to build bigger computers with more qubits and it cannot be very long until these limitations can be overcome.

IX. CONCLUSION

Quantum entanglement really challenges our understanding of the physical world as we experience it. In our daily lives we expect things to act independently. Particles, however, may become so interwoven with each other that what happens to one instantaneously affects the other, regardless of the distance separating them. These are not mere

theoretical curiosities: repeated experimental testing is providing strong evidence for entanglement. Many scientists are testing Bell's inequalities, indicating how local hidden variables are insufficient and that there is more to it than just some previously unknown set of pre-determined parameters.

Why so much theory and discussion regarding entanglement then? Its potential real-world applications can be vast. It's a phenomenon that could make our computers work with unprecedented processing power, or help to ensure that the data sent between people could never be intercepted, for example. The possible impact entanglement could have on communication and information technology seems huge. However, there are still challenges: some of the major ones being decoherence, where the quantum properties of the particles essentially decay on interaction with the outside world, and also the building of large-scale, stable systems.

Whilst progress is being made, but in a slow and frustrating way, every step is a step forwards. Scientists are continuing to develop stronger and stronger networks and more and more robust systems around the world. This is certainly not a theory confined to being merely a mind game; rather, entanglement represents a foundation for technologies that were previously thought to be well within the realm of fantasy. As more and more strange and wonderful connections are found within our universe and proved, with every test and study, the domain of quantum mechanics just gets bigger and bigger, and while nobody knows what the future of entanglement holds, it certainly seems that we have barely scratched the surface of what is to be discovered.

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