Bell's Theorem and Its Experiments

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Abstract

Quantum mechanics makes surprising predictions that defy our classical understanding of the world. Experiments done on entangled particles—particles with linked properties—prove that actions on one particle can affect the other one no matter the distance. In response, physicists came up with local hidden variable theories in an attempt to understand this quantum phenomena through a classical lens. John Bell formulated a way to test whether nature is dictated by local hidden variable theories or quantum mechanics, and since then it has been the goal of numerous physicists to experimentally test the theorem and improve upon the results. This paper describes the history of these experiments, their pros and cons, their advancements, and the potential applications that they will enable.

Background

Things that are far apart cannot interact with each other, right? Back in the 1900s, scientists discovered this fact to not be completely true. The field of quantum mechanics was created after results from experiments on particles at an atomic scale revealed that the observations of atoms did not line up exactly with classical mechanics. The creation of this branch of physics sparked a wave of discoveries that would go on and transform into various theories attempting to accurately describe quantum physics over the course of twenty-eight years.[1]

One significant theory, referred to as the EPR Paradox, was formulated in 1935 by physicists Einstein, Podolsky, and Rosen. It claimed that quantum mechanics was incomplete, suggesting that another variable was necessary to aptly explain quantum behavior. Numerous types of these "hidden-variable" theories, founded on classical mechanics, were suggested over the years in an attempt to complement what was understood about quantum mechanics at the time. In 1964, however, physicist John Stewart Bell—through what is now known as Bell's theorem—proved that any variant of the theory opposed the predictions of quantum mechanics.[2] To confirm this, Bell devised an experiment where quick, random measurements of two connected particles along different axes could determine the correlation of the results of one particle to the other. By doing so, the experiment would prove that the results of one particle would not influence the other, as the switch in measurement would be faster than light can travel. His theorem, crafted to satisfy any hidden-variable theory, distinguishes between local hidden-variable theories and quantum mechanics, and reveals that there are stronger correlations between particles in quantum mechanics. Experiments focused on his theorem have repeatedly shown this to be true, disproving the notion of hidden-variable theories.[3]

Over the years, modern Bell tests, experiments designed to test Bell's theorem, have continued to use finer and more advanced technology. This allows for more accurate and precise results. Each one has consistently proven the non-local nature of the world and subverted the common assumption that many have about reality. Repeating these experimental trials have allowed scientists to close key loopholes and better understand the field since its inception. Consequently, Bell experiments have effectively served as the evidence needed to debunk hidden-variable theories as a whole.

Bell's Theorem

Bell experiments test the idea that an event is only influenced by its immediate surroundings, a concept scientists call locality. The lack of locality is a cornerstone of quantum physics, as it highlights the fundamental differences it has compared to classical mechanics. While locality holds in classical mechanics, quantum mechanics defies this notion and provides a framework that explains the non-local phenomena in the world. In an attempt to understand this phenomenon, the EPR paradox was produced as a thought experiment to test the boundaries of quantum mechanics.

The paradox is based on the experiment focusing on two particles that are entangled, meaning their properties are linked no matter how far apart they are (Fig. 1). When each particle is placed far away from others and an observable parameter of one particle is measured, an observable parameter of the second particle is perfectly correlated to the first. The paradox claims that the particles' could not have instantaneous correlation and must have predetermined spins before measurement under the premise that nothing can travel faster than the speed of light. Therefore, it can be inferred from its conclusion that locality remained valid, contrary to the prediction of quantum mechanics. However, despite the argument, this is not truly the case.[2]

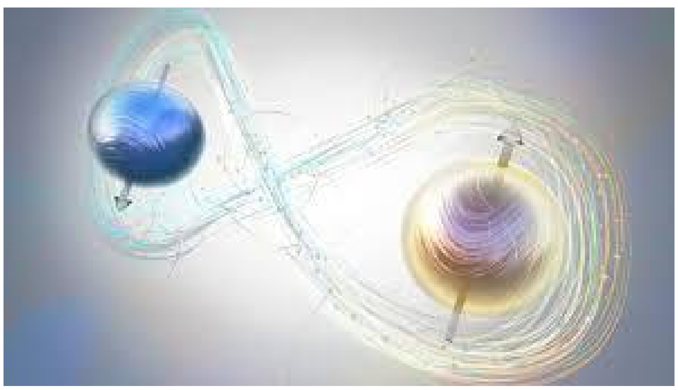

Fig. 1: Representation of entangled particles, an essential part of quantum mechanics tested by Bell's Theorem. The arrows show the spin of the particles, linked by their entanglement.[4]

Shortly after the paradox was publicized, theoretical physicist Niels Bohr refuted the claim it made about locality. Bohr strongly believed that the setup of the experiment, including the measurement on the first particle, affected the predictions made about the second particle. He suggested that changes in the setup would result in different predictions, preventing the predictions in each experiment from forming a solid conclusion about the particles when compared to one another. As a result, Bohr argued that each experiment must be viewed individually, and that quantum mechanics simply did not act in accordance with locality.[5]

In spite of the arguments against quantum mechanics, it has been widely accepted that classical mechanics is insufficient to fully describe our current world. Quantum mechanics postulates that, unlike in classical mechanics, particles can exist in different states all at once, causing them to have undeterminable characteristics and properties before they are measured and resulting in random outcomes during measurement. Moreover, particles exhibit stronger correlations in quantum mechanics as compared to classical mechanics.[3] The experiments scientists have conducted since the birth of quantum mechanics have shed light on the truth of reality.

Bell Tests #1: First Generation of Experiments

One of the first Bell tests proposed by scientists was in 1969 by John Clauser, a Columbia University graduate student at the time. Along with colleagues Michael Horne, Abner Shimony, and Richard Holt, Clauser would modify Bell's original theorem and convert it into an experimental prediction that could be tested. This was known as the Clauser–Horne–Shimony–Holt (CHSH) inequality. Clauser, collaborating with then Berkeley graduate student Stuart Freedman, enacted an experiment in 1972 to verify through experimentation that Bell's theorem applied to two separated particles in an entangled state.[6]

In the experiment, calcium atoms were excited and de-excited afterwards to obtain an abundance of entangled photons. Two photon detectors equipped with polarizers—devices that filter light based on their polarization and orientation—were also placed approximately ten feet apart on opposite sides of the calcium source. After their orientations were set up randomly, the experimentalists measured the rates at which the photons hit the photon detectors at the same time. This is known as the coincidence rate. At the end of the experiment, the polarizers tentatively demonstrated that quantum mechanical predictions differed significantly from local hidden-variable predictions at certain angles. The coincidence rates gathered from 200 hours of data violated the CHSH inequality, suggesting the existence of quantum entanglement. His findings, founded on Bell's Theorem, later played a pivotal role in proving that quantum entanglement does not fit with EPR's original idea of a local world. Further testing by Clauser would also continue to corroborate the results obtained by the first experiment.[7]

Although these experiments are generally regarded today as the first step to proving that the world is truly non-local, there were some "loopholes," or potential backdoors, in the experiments that were still used to argue for the presence of locality. The most important of these are the locality and detection loopholes, which were infamous for being difficult to close in experimentation. The locality loophole concerned the impact each polarizer could have on the experiment as a whole. Since the polarizer orientations were predetermined, some debated whether or not the way one polarizer was set up could secretly influence the other polarizer or the entangled photons in a manner that would imitate the predictions made by quantum mechanics. Another notable loophole in Clauser and Freedman's first experiment was one of detector efficiency, known as the detection loophole. Back then, highly efficient photon detectors were not readily available, meaning that some entangled photons would pass by undetected. As a result, critics argued that the missing photons could be correlated to certain outcomes of the measurements, inadvertently causing the violated inequality. This loophole, however, was eventually avoided and rectified in Clauser's second published experimental test of local hidden-variable theories.[8] Though findings were not unequivocal, the first generation of experiments pertaining to Bell's theorem helped enforce the idea that non-local quantum entanglement is an undeniable feature of quantum mechanics.

Bell Tests #2: Second Generation of Experiments

Years after the earliest Bell tests, scientists were determined to establish more concrete proof for the validity of Bell's theorem. In an effort to close the locality loophole found in Clauser's experiments, French physicist Alain Aspect and his associates at the Institut d'Optique Graduate School conducted a more refined Bell test in 1982 that made important changes to previous trials. These changes aimed to enhance test performance and led Aspect and his team to carry out three separate experiments in the same year.[5]

In the first experiment, the researchers utilized two adaptable lasers that allowed the scientists to more efficiently excite the particles and procure a purer source of entangled photons needed for the experiment. This helped improve statistical accuracy by ensuring higher coincidence rates per second in a shorter amount of time—a process that took days in Clauser's experiment.[9] In Aspect's second experiment, polarizers that could detect both horizontal and vertical polarization simultaneously, known as two-channel polarizers, were used instead of single-channel polarizers. Single-channel polarizers made researchers unable to distinguish if detector inefficiency or the photons' movement was the reason for a detector not registering a measurement.This motivated the use of two-channel polarizers.[10] Lastly, the third experiment employed more advanced two-channel polarizers that could be altered as the experiment occurred. This new type of polarizer let the scientists quickly and randomly switch the orientations of the polarizers during the experiment, causing light to not have enough time to travel from one polarizer to another and influence them in some way as the photons moved toward the detectors. This last experiment (Fig. 2) was the closest to an ideal test out of the three, and would finally close the locality loophole for good.[9] All three experiments remained consistent with quantum mechanics and mirrored the same results achieved in Clauser's work.

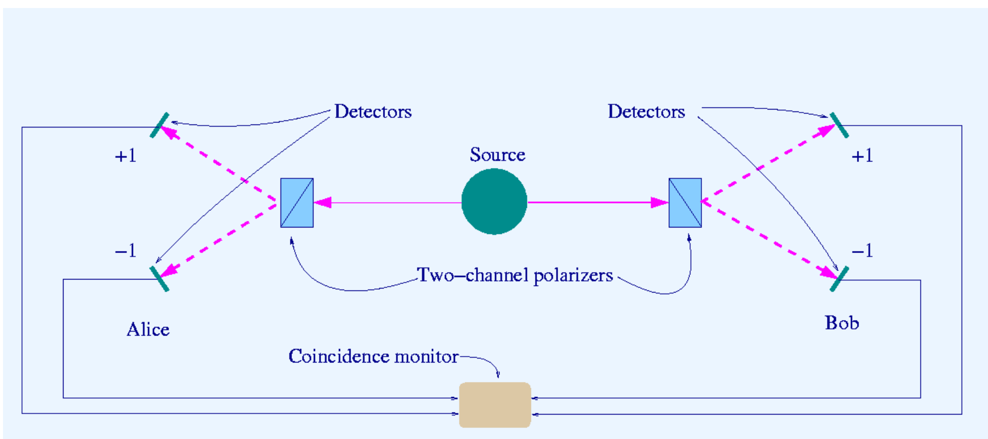

Fig. 2: Representation of Aspect's Bell Test. The detectors, named Alice and Bob, measure entanglement. The polarization of the particles, which are entangled, are sent toward the detectors and correspond to a value of +1 or -1. The number of instances in which they have the same polarization are recorded by the coincidence monitor.[11]

Aspect's final Bell test was the first of its kind to get rid of the locality loophole, and the outcome of all three experiments continued to prove local hidden-variable theories wrong. Due to this, there was much stronger proof that quantum mechanics holds true.[10] Despite its success, the third experiment contained the detection loophole—not all entangled photons were measured, preventing local hidden-variable theories from being completely ruled out. In addition, the polarizers were not entirely random.[12] While Aspect's experiments were not perfect, they served as stepping stones to not only convince scientists that local hidden-variable theories were untenable, but also paved the way for researchers to perform accurate and more reliable Bell tests in the future.

Bell Tests #3: Third Generation of Experiments

Three decades after Aspect's initial experiments, scientific instruments—including the detectors and polarizers needed for Bell tests—had undergone significant improvements due to leaps in technological innovation. This permitted scientists to execute even better Bell tests that would be more precise than any experiments ever done before. In 2015, Austrian physicist Anton Zeilinger and his colleagues from the University of Vienna and the Austrian Academy of Sciences ran a Bell test with the goal of showing that a Bell test free of loopholes was indeed possible.[13]

To do this, they injected entangled photons into optical fibers that moved the photons 30 meters in opposite directions, where they would be measured by highly efficient polarizers. The polarizers, unlike in Aspect's experiment, relied on generators that quickly changed their orientations after the photons were emitted from the source. This made the switch truly independent of the state of the particles. In addition, the detectors were separated far away from each other such that light would not be able to go from one to the other before measurement, allowing the experiment to close the locality loophole. These modern polarizers were also able to detect a large number of entangled photons, enough to avert the detection loophole as well.

Even with these advances, however, physicists now recognize that previously unconsidered loopholes may still affect Bell test results. Some of these loopholes were able to be addressed in the experiment, such as the memory loophole. Others, like the freedom-of-choice loophole—which claims that results are affected by the ability of researchers to choose the measurement taken on the entangled particles—were left open to debate. To remedy this, another Bell test—performed by Zeilinger in 2016—measured the color of entangled photons through two telescopes spaced 144 kilometers from the source. Since the color would already be decided when the light is emitted, it meant that the hidden effect—if there was one—would have to be emitted over 600 years ago by a nearby star. As a result, the hidden influence needed to be made before the experiment, rendering it unlikely that it would be able to affect the correlation of the particles.[14] In the end, the experiments affirmed the validity of quantum non-locality, assuring scientists that local hidden-variable theories is inconsistent with the intrinsic features of the universe.

Zeilinger's experiments have completely turned local hidden-variable theory upside down and contributed to what scientists deem "the start of the second quantum revolution." As Bell tests get closer and closer to being ideal, their "loophole-free" results confirm to researchers that they have evolved from being only able to confirm fundamental physics phenomena to actively driving scientific advancements that can potentially shape people's lives in the future, whether it be through the creation of new academic fields or revolutionary technological innovations. The improvement of Bell tests over the years sets the bounds for how well experimental applications such as quantum communication and three-level quantum systems,which exhibit even larger violations,will operate in reality. This helps scientists to further push the limits of Bell tests and discover the secrets quantum mechanics has yet to reveal.[15]

Conclusion

Through precise measurements and cosmic-scale tests, Bell tests have permanently changed how people perceive reality as well as human knowledge about the world as it is known. They not only changed key classical concepts such as locality to be viewed in a quantum perspective, but also resulted in our best description of reality to date. The exploration into quantum mechanics in the modern day has allowed scientists to develop potential applications for it in daily human life. Quantum cryptography, along with quantum communication, would allow digital belongings to become increasingly secure since the quantum nature of particles makes it essentially impossible for thieves to suddenly alter their quantum states without being detected. Quantum clocks would let people determine the time incredibly precisely since each particle assists in the process of time measurement and could be linked together to create a global timekeeping network that remains accurate no matter the location.[16] Quantum supercomputers would be a major step-up compared to classical computers, as entangled particles can contain much more information in their quantum states. This would enable them to perform the same processes in a couple of hours that it takes for classical computers to perform in billions of years.[17] No matter how distant things may appear, quantum mechanics reveals a profound interconnectedness—not just between subatomic particles, but possibly in everyday human life as well.

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