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Research Paper

Entanglement in Quantum Mechanics : Interpretation of Historical Aspect and its Implification

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Abstract: Quantum entanglement occurs when a pair or group of particles is generated, interact, or share spatial proximity in a way such that the quantum state of each particle of the pair or group cannot be described independently of the state of the others, including when the particles are separated by a large distance. This leads to correlations between observable physical properties of the systems. The topic of quantum entanglement is at the heart of the disparity between classical and quantum physics. Entanglement is a primary feature of quantum mechanics lacking in classical mechanics. Measurements of physical properties such as position, momentum, spin, and polarization performed on entangled particles can, in some cases, be found to be perfectly correlated. If a pair of entangled particles is generated such that their total spin is zero, and one particle is found to have clockwise spin on a first axis, then the spin of the other particle, measured on the same axis, will be found to be counter clockwise. This behavior gives rise to paradoxical effects. Any measurement of a property of a particle results in an irreversible wave function collapse of that particle and will change the original quantum state and such a measurement will affect the entangled system as a whole.

Key Words: Quantum entanglement, spatial proximity, historical .

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1. Introduction

In quantum physicsentangled particles remain connected so that actions performed on one affect the other, even when separated by great distances. The phenomenon so riled Albert Einstein he called it "spooky action at a distance." The rules of quantum physics state that an unobserved photon exists in all possible states simultaneously but, when observed or measured, exhibits only one state. Spin is depicted here as an axis of rotation, but actual particles do not rotate. Entanglement occurs when a pair of particles, such as photons, interact physically. A laser beam fired through a certain type of crystal can cause individual photons to be split into pairs of entangled photons. The photons can be separated by a large distance, hundreds of miles or even more. It is interpreted that the entanglement produces correlation between the measurements and that the mutual information between the entangled particles can be exploited, but that any transmission of information at faster-than-light speeds is impossible.

Quantum entanglement has been demonstrated experimentally with photons, neutrinos, electrons, molecules as large as buckyballs, and even small diamonds. The utilization of entanglement in communication, computation and quantum radar is a very active area of research and development.

2. Historical Background

The counterintuitive predictions of quantum mechanics about strongly correlated systems were first discussed by Albert Einstein in 1935, in a joint paper with Boris Podolsky and Nathan Rosen. In this study, the three formulated the Einstein–Podolsky–Rosen paradox (EPR paradox), a thought experiment that attempted to show that quantum mechanical theory was incomplete. They wrote: "We are thus forced to conclude that the quantum-mechanical description of physical reality given by wave functions is not complete." .Following the EPR paper ,Erwin Schrodinger wrote a letter to Einsteinin Germanin which he used the word Verschränkung (translated by himself as entanglement) to describe the correlations between two particles that interact and then separate, as in the EPR experiment. Schrodinger shortly there after published a seminal paper defining and discussing the notion of"entanglement."Inthepaper, he recognized the importance of the concept, and stated"I would not call [entanglement] one but rather the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought."Schrodinger was also dissatisfied with the concept of entanglement, because it seemed to violate the speed limit on the transmission of in formation implicitin the theory of relativity. The EPR paper generated significant interest among physicists ,which in spired much discussion about the foundations of quantum mechanics , perhaps most famously Bohm's interpretation of quantum mechanics. Despite the interest ,the weak point in EPR'sargument was not discovered until 1964, when John Stewart Bell proved that one of their key as sumptions, the principle of locality , as applied to the kind of hidden variables interpretation hoped for by EPR ,was mathematically inconsistent with the predictions of quantum theory. However, later the counter intuitive predictions of quantum mechanics were verified experimentally intestsin which polarization or spin of entangled particles were measured at separate locations, statistically violating Bell's inequality. Inearliertests, it couldn't be absolutely ruled out that the test result a one point could have been subtly transmitted to the remote point , affecting the out come at these cond location . However ,so-called"loophole-free"Bell tests have been performed in which the locations were separated such that communications at the speed of light would have taken longer--in one case 10,000times longer—than the interval between the measurements. Specifically, Bell demonstrated an upper limit, seen in Bell's inequality, regarding the strength of correlations that can be produced in any theory obeying local realism, and showed that quantum theory predicts violations of this limit for certain entangled systems. His inequality is experimentally testable, and there have been numerous relevant experiments, starting with the pioneering work of Stuart Freedman and John Clauser in 1972 and Alain Aspect's experiments in 1982. An early experimental breakthrough was due to Carl Kocher, who already in 1967 presented an apparatus in which two photons successively emitted from a calcium atom were shown to be entangled – the first case of entangled visible light. The two photons passed diametrically positioned parallel polarizers with higher probability than classically predicted but with correlations in quantitative agreement with quantum mechanical calculations. He also showed that the correlation varied only upon (as cosine square of) the angle between the polarizer settings and decreased exponentially with time lag between emitted photons. Kocher’s apparatus, equipped with better polarizers, was used by Freedman and Clauser who could confirm the cosine square dependence and use it to demonstrate a violation of Bell’s inequality for a set of fixed angles. All these experiments have shown agreement with quantum mechanics rather than the principle of local realism. For decades, each had left open at least one loophole by which it was possible to question the validity of the results. However, in 2015 an experiment was performed that simultaneously closed both the detection and locality loopholes, and was heralded as "loophole-free"; this experiment ruled out a large class of local realism theories with certainty. Alain Aspect notes that the "setting-independence loophole" – which he refers to as "far-fetched", yet, a "residual loophole" that "cannot be ignored" – has yet to be closed, and the free-will super determinism loophole is unclosable; saying "no experiment, as ideal as it is, can be said to be totally loophole-free."A minority opinion holds that although quantum mechanics is correct, there is no superluminal instantaneous action-at-a-distance between entangled particles once the particles are separated.

Bell's work raised the possibility of using these super-strong correlations as a resource for communication. It led to the 1984 discovery of quantum key distribution protocols, most famously BB84 by Charles H. Bennett and Gilles Brassard and E91 by Artur Ekert. Although BB84 does not use entanglement, Ekert's protocol uses the violation of a Bell's inequality as a proof of security.

3. Fundamental Concepts

An entangled system is defined to be one whose quantum state cannot be factored as a product of states of its local constituent , they are not individual particles but are an inseparable whole. In entanglement, one constituent cannot be fully described without considering the others. The state of a composite system is always expressible as a sum, or superposition, of products of states of local constituents; it is entangled if this sum necessarily has more than one term. Quantum systems can become entangled through various types of interactions. For some ways in which entanglement may be achieved for experimental purposes. Entanglement is broken when the entangled particles decohere through interaction with the environment. Asubatomic particledecays into an entangled pair of other particles. The decay events obey the various conservation laws, and as a result, the measurement outcomes of one daughter particle must be highly correlated with the measurement outcomes of the other daughter particleso that the total momenta, angular momenta, energy, and so forth remains roughly the same before and after this process. Aspin-zero particle could decay into a pair of spin-½ particles. Since the total spin before and after this decay must be zero since conservation of angular momentum and whenever the first particle is measured to be spin up on some axis, the other, when measured on the same axis, is always found to be spin down, spin anti-correlated case. If the prior probabilities for measuring each spin are equal, the pair is said to be in the singlet state.

A classical system would display the same property, and a hidden variable theory would certainly be required to do so, based on conservation of angular momentum in classical and quantum mechanics alike. The difference is that a classical system has definite values for all the observables all along, while the quantum system does not. In a sense to be discussed below, the quantum system considered here seems to acquire a probability distribution for the outcome of a measurement of the spin along any axis of the other particle upon measurement of the first particle. This probability distribution is in general different from what it would be without measurement of the first particle. This may certainly be perceived as surprising in the case of spatially separated entangled particles. When observed , Photon A takes on an up-spin state. Entangled Photon B, though now faraway, takes up a state relative to that of Photon A (inthiscase , a down spinstate) .The transfer of state between Photon A and Photon B takes place a a speed of at least 10,000 times the speed of light possibly even instantaneously, regard less of distance . A proposed experiment would sendone photon of the entangled pair to the orbiting International Space Station, a distance of around 310miles (500kilometers). This would be the largestdistance that has been experimentally tested.

Paradox

The paradox is that a measurement made on either of the particles apparently collapses the state of the entire entangled system—and does so instantaneously, before any information about the measurement result could have been communicated to the other particle (assuming that information cannot travel faster than light) and hence assured the properoutcome of the measurement of the other part of the entangled pair. In the Copenhagen interpretation, the result of a spin measurement on one of the particles is a collapse into a state in which each particle has a definite spin (either up or down) along the axis of measurement. The outcome is taken to be random, with each possibility having a probability of 50%. However, if both spins are measured along the same axis, they are found to be anti-correlated. This means that the random outcome of the measurement made on one particle seems to have been transmitted to the other, so that it can make the "right choice" when it too is measured. The distance and timing of the measurements can be chosen so as to make the interval between the two measurements spacelike, hence, any causal effect connecting the events would have to travel faster than light. According to the principles of special relativity, it is not possible for any information to travel between two such measuring events. It is not even possible to say which of the measurements came first.Therefore, the correlation between the two measurements cannot be explained as one measurement determining the other, different observers would disagree about the role of cause and effect.

Conception Regarding Hidden variables theory

A possible resolution to the paradox is to assume that quantum theory is incomplete, and the result of measurements depends on predetermined hidden variables. The state of the particles being measured contains some hidden variables, whose values effectively determine, right from the moment of separation, what the outcomes of the spin measurements are going to be. This would mean that each particle carries all the required information with itand nothing needs to be transmitted from one particle to the other at the time of measurement. Einstein and others originally believed this was the only way out of the paradox, and the accepted quantum mechanical description (with a random measurement outcome) must be incomplete. However local hidden variable theories fail,when measurements of the spin of entangled particles along different axes are considered. If a large number of pairs of such measurements are made (on a large number of pairs of entangled particles), then statistically, if the local realist or hidden variables view were correct, the results would always satisfy Bell's inequality. A number of experiments have shown in practice that Bell's inequality is not satisfied. However, prior to 2015, all of these had loophole problems that were considered the most important by the community of physicists. When measurements of the entangled particles are made in moving relativistic reference frames, in which each measurement (in its own relativistic time frame) occurs before the other, the measurement results remain correlated.The fundamental issue about measuring spin along different axes is that these measurements cannot have definite values at the same time—they are incompatible in the sense that these measurements' maximum simultaneous precision is constrained by the uncertainty principle. This is contrary to what is found in classical physics, where any number of properties can be measured simultaneously with arbitrary accuracy. It has been proven mathematically that compatible measurements cannot show Bell-inequality-violating correlations, and thus entanglement is a fundamentally non-classical phenomenon.

The experiment performedin2012and2013 predictedthat the polarization correlation was created between photons that never coexisted in time. The authors claimed that this result was achieved by entanglement swapping between two pairs of entangled photons after measuring the polarization of one photon of the early pair, and that it proves that quantum non-locality applies not only to space but also to time. In three independent experiments in 2013 it was shown that classically communicatedseparable quantum states can be used to carry entangled states. The first loophole-free Bell test was held in TU Delft in 2015 confirming the violation of Bell inequality.

Brazilian researcher Gabriela BarretoLemos and team inAugust2014,were able to take picturesof objects using photons that had not interacted with the objects, but were entangled with photons that did interact with such objects. Lemos, from the University of Vienna, is confident that this new quantum imaging technique could find application where low light imaging is imperative, in fields like biological or medical imaging. In 2015, Markus Greiner's group at Harvard performed a direct measurement of Renyi entanglement in a system of ultracoldbosonic atoms. From 2016 various companies like IBM, Microsoft etc. have successfully created quantum computers and allowed developers and tech enthusiasts to openly experiment with concepts of quantum mechanics including quantum entanglement.

4. Application

John Bell had found for the case of just two entangled particles that the perfect correlations can be explained from a local realistic viewpoint. For two spin one-half systems, these are for example spin measurements along the same direction. Only correlations at oblique measurement angles would contradict quantum mechanics. For three or more entangled particles, not even the perfect correlations can be explained in a local realistic way and a contradiction arises between quantum mechanics and local realism, Einstein's EPR view, already for individual quantum events and not just for statistical ensembles, as was the case of Bell's inequality . A generalization of two-particle interferometry explicitly proposed for a three-particle interferometry case would show exactly the kind of contradiction.

The first application of quantum entanglement in an information theoretic protocol was the experimental realization of hyper-dense coding. The basic concept had been proposed by Bennett and Wiesner in 1992 .Consider first a single photon's polarization. For example, one can encode into it one bit of classical information by choosing horizontal or vertical polarization at the basis. A vertically polarized photon may for example be considered to be equivalent to a particle with spin up and a horizontally polarized photon may be equivalent to one with spin down.

The idea of hyper-dense coding is based on an interesting feature of entanglement. When one looks at the maximally entangled states of two photons, the four orthogonal Bell states result. These four orthogonal states represent two independent bits of classical information.The basic point of hyper-dense coding is that in order to switch around among all four two-photon Bell states, one needs to have access to just one photon . It suffices to manipulate the polarization and the phase of one photonand only. operating on a single non-entangled beam, only one bit of information could be encoded. But because the photon is entangled with another, proper identification of the entangled states results in four possibilities, i.e. two bits of information which can be encoded and decoded.

In 1992, Bennett, Brassard, Crépeau, Jozsa, Peres and Wootters proposed the concept of quantum teleportation.Quantum teleportation allows one to teleport the quantum state of an unknown system over an arbitrary distance without sender having to send the state itself to the receiver.A crucial step used in teleportation became important in many future protocols anda simple beam splitter can be used to entangle independent photons. In entanglement swapping, two photons which have never interacted with each other become entangled.One takes two entangled pairs and projects one photon from each pair onto an entangled state, with the result that one knows that the other two photons, one from each pair, which can be at distant locations, have now become entangled. In consequence, one has an entangled state for these two distant photons at hand. This evidently holds for any kind of entangled particles.It is interestingto use entanglement swapping in a Bell test has recently been implemented in two experiments closing many loopholes at once. In that case, it was the creation of entanglement between two spins or between two atoms . They became entangled with each other by entangling one photon each emitted from each spin or atom.

Quantum cryptography is the application which has become most mature today. In a broad sense, there are two types of quantum cryptography, one based on individual quantum systems and the other one on quantum entanglement. A forerunner is the proposal of unforgeable quantum money by Wiesner. Apparently, it is well known in the community that Wiesner had these ideas already in the early 1970s, communicating them verbally at least to Charles Bennett, but being unable to get a paper published. That early proposal already contains some important features of quantum information, such as the randomness of the individual measurement events encoding in conjugate bases and, implicitly, the no-cloning-theorem which was later formalized most elegantly by Wooters and Zurek. These concepts also play a central role in the first proposal of quantum cryptography by Bennett and Brassard. Interestingly, entanglement was the main fundamental quantum concept that was not yet contained in the Wiesner idea.In the entanglement-based version of quantum cryptography, one uses the perfect correlations in entangled systems to establish a secure key at two locations at the same time . Due to entanglement, the key comes into existence at both separations because of the correlation between the measurement results on the two entangled photons or more precisely, the two measurements can be so far removed from each other that no communication between them can establish the key.

Quantum computation has to utilize the interaction between two quantum bits or simply qubits. Thus, it has to employ some nonlinear element. This is in practice not possible for individual photons, because the nonlinear effects introduced by a single photon in any medium are too small to significantly modify the quantum state of another photon.

5. Conclusion

The experience of many scientists world wide with a multitude of quantum phenomena for individual systems has led to a much better understanding of fundamental issues of quantum mechanics.There was a significant disagreement about whether quantum mechanics describes individual systems or only statistical ensembles, what the role of the environment is, or what quantum nonlocality really implies.It is now commonly accepted and understood that nature cannot be described in a local way, that entanglement is a fundamental part of our description of the world, that objective randomness exists, and many more. The viewpoint that quantum physics describes the behavior of individual quantum systems if seen in the right way has become broadly accepted.There is a much better understanding of the role of the environment and of decoherence, and many new phenomena were discovered on a fundamental level. The emerging viewpoint now is that information plays a very fundamental role in the understanding of quantum mechanics. The development of the Copenhagen Interpretation of quantum mechanics is as expressed for example by Werner Heisenberg, who said that the quantum state is a representation of our knowledge, and Erwin Schrödinger, who in his famous 1935 paper on the present situation in quantum mechanics talked about the quantum state representing expectation catalogues.There is a very good chance that somedayquantum information technologies will replace traditional information technologies, if not completely, then in significant ways.A typical most interesting recent example is the emergence of quantum experiments at space scale.The first quantum satellite was launched by the Chinese Academy of Sciences in 2016. A specific vision for the future is a world-wide quantum internet, where ground stations are directly connected to quantum communication links using glass fibers, and over long distances and intercontinentally via quantum satellite networks.With the rise of quantum information science in the 1990s, it was understood in a theoretical sense as the key to remarkable quantum technologies. Physicists’ fantasies of a future quantum internet are a bit closer to reality. Recent examples of such technologies include the Chinese teleportation experiment from ground to satelliteas well as Google's quantum-computational supremacy achievement last year.

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