# Quantum Entanglement Introduction

Ma Hongbao *, Margaret Young **, Yang Yan *

* Brookdale University Hospital and Medical Center, Brooklyn, New York 11212, USA, ma8080@gmail.com;
** Cambridge, MA 02138, USA

**Abstract:** Quantum entanglement describes when pairs or groups of particles are generated or interact in ways such that the quantum state of each particle cannot be described independently and the quantum state is a whole system. In the entangled system, the measurements of physical properties such as position, momentum, spin and polarization are on appropriately correlated. If a pair of particles are generated in such an entangled way that their total spin is zero. One particle of an entangled pair knows what measurement has been performed on the other, which at the time of measurement may be separated by arbitrarily big distances.

[Ma H, Young M, Yang Y. **Quantum Entanglement Introduction.** *Academ Arena* 2016;8(7):93-97]. ISSN 1553-992X (print); ISSN 2158-771X (online). http://www.sciencepub.net/academia. 13. doi:10.7537/marsaaj080716.13.

**Key words:** quantum entanglement; particle; system; physical property; position; momentum; spin; polarization

Quantum entanglement describes when pairs or groups of particles are generated or interact in ways such that the quantum state of each particle cannot be described independently and the quantum state is a whole system. In the entangled system, the measurements of physical properties such as position, momentum, spin and polarization are on appropriately correlated. If a pair of particles are generated in such an entangled way that their total spin is zero. One particle of an entangled pair knows what measurement has been performed on the other, which at the time of measurement may be separated by arbitrarily big distances.

Quantum entanglement was described in 1935 by Albert Einstein, Boris Podolsky and Nathan Rosen (abbreviated as EPR), and then by Erwin Schrödinger shortly thereafter. However, Einstein et al considered such quantum entanglement is impossible and thought that the formulation of quantum mechanics should be incomplete. Up to now, I think that Einstein was wrong in this point. The entangled particles are connected without speed limitation.

For the quantum entanglement, it is supposed the EPR paradox (Einstein, Podolsky, Rosen paradox), which thinks that the quantum mechanical theory is incomplete. After the EPR paper, Erwin Schrödinger wrote a letter to Einstein to describe the correlations between two particles that interact and then separate, as in the EPR experiment. Like Einstein, Schrödinger was dissatisfied with the concept of entanglement, because it seemed to violate the speed limit on the transmission of information implicit in the theory of relativity. Quantum entanglement effects could be used in communication and computation.

Bell's theorem is a no-go theorem that draws an important distinction between quantum mechanics and the world as described by classical mechanics. There is a way to escape the inference of superluminal speeds and spooky action at a distance. But it involves absolute determinism in the universe, the complete absence of free will. Free will is the ability to choose between different possible courses of action. Determinism suggests that only one course of events is possible, which is inconsistent with the existence of such free will.

Bell's inequality is important in this field. Bell's theorem states that no physical theory of local hidden variables can ever reproduce all of the predictions of quantum mechanics. Bell showed a possibility of using these super-strong correlations as a resource for communication. It led to the 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.

Bell's theorem states that any physical theory that incorporates local realism cannot reproduce all the predictions of quantum mechanical theory. Because numerous experiments agree with the predictions of quantum mechanical theory, and show differences between correlations that could not be explained by local hidden variables, the experimental results have been taken by many as refuting the concept of local realism as an explanation of the physical phenomena under test. For a hidden variable theory, if Bell's conditions are correct, the results that agree with quantum mechanical theory appear to indicate superluminal effects, in contradiction to the principle of locality.

The hidden variable theory refers to all types of the theory that attempt to account for the probabilistic features of quantum mechanics by the mechanism of underlying inaccessible variables. A local hidden variable theory has the added requirement of being consistent with local realism, requiring that distant events be independent, ruling out *instantaneous* interactions between separate events. The mathematical implications of a local hidden variable theory in regard to the phenomenon of quantum entanglement were explored by physicist John S Bell. Bell's 1964 paper showed that local hidden variables cannot reproduce the quantum measurement correlations that quantum mechanics predicts.

A series of experiments, called Bell test experiments, have provided partial experimental confirmation of the entanglement phenomenon, but local hidden variable theory can still explain the probabilistic nature of quantum measurement due to loopholes in experimental Bell tests. The theory of quantum entanglement predicts that separated particles can briefly share common properties and respond to certain types of measurement as if they were a single particle. In particular, a measurement on one particle in one place can alter the probability distribution for the outcomes of a measurement on the other particle at a different location. If a measurement setting in one location instantaneously modifies the probability distribution that applies at a distant location, then local hidden variables are ruled out. For an expanded description, see Bell's theorem.

These three key concepts – locality, realism, freedom – are highly technical and much debated. In particular, the concept of *realism* is now somewhat different from what it was in discussions in the 1930s. It is more precisely called *counterfactual definiteness*; it means that we may think of outcomes of measurements that were not actually performed as being just as much part of reality as those that were made. *Locality* is short for *local relativistic causality*. (Currently accepted quantum field theories *are* local in the terminology of the Lagrangian formalism and axiomatic approach.) *Freedom* refers to the physical possibility of determining settings on measurement devices independently of the internal state of the physical system being measured.

Illustration of Bell test for spin-half particles such as electrons. A source produces a singlet pair, one particle is sent to one location, and the other is sent to another location. A measurement of the entangled property is performed at various angles at each location. The scheme for measurements on photon looks very similar: the quantum state is different but has very similar properties.

The theorem is usually proved by consideration of a quantum system of two entangled qubits. The most common examples concern systems of particles that are entangled in spin or polarization. Quantum mechanics allows predictions of correlations that would be observed if these two particles have their spin or polarization measured in different directions. Bell showed that if a local hidden variable theory holds, then these correlations would have to satisfy certain constraints, called Bell inequalities. However, for the quantum correlations arising in the specific example considered, those constraints are not satisfied, hence the phenomenon being studied cannot be explained by a local hidden variables theory.

An entangled system is defined to be one whose quantum state cannot be factored as a product of states of its local constituents and they are not individual particles but are as a whole. If entangled, one constituent cannot be fully described without considering the other. In a quantum entanglement system the state of a composite system is always expressible as a sum, or superposition, of products of states of local constituents, and 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.

As an example of entanglement: a subatomic particle decays 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 particle, so that the total momenta, angular momenta, energy, and so forth remains roughly the same before and after this process. For instance, a spin-zero particle could decay into a pair of spin -½ particles. Since the total spin before and after this decay must be zero according to the conservation of angular momentum, 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.

The paradox is that a measurement made on either of the particles apparently collapses the state of the entire entangled system. In the quantum formalism, 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 along the axis of measurement. A message connecting the events can 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 unambiguously say which of the measurements came first.

In the universe, all the particles take specific information, as position, momentum, spin and polarization, etc. The information can be transferred to other particles, can influence others and can be changed. The fundamental issue about measuring spin along different axes is that these measurements cannot have definite values at the same time as these measurements' maximum simultaneous precision is constrained by the uncertainty principle. The classically-communicated separable quantum states can be used to carry entangled states. As a side effect of quantum entanglement, the time is an entanglement phenomenon, which places all equal clock readings into the same history. The entanglement can be used to measure time.

The time is an emergent phenomenon for internal observers but absent for external observers of the universe. The quantum uncertainty gives rise to entanglement, the putative source of the arrow of time. The entanglement of a two-party state is necessary but not sufficient for the state to be non-local. A state of a quantum system is given by a unit vector in a Hilbert space. If one has a large number of copies of the same system, the state of this ensemble is described by a density matrix. Entanglement measures quantify the amount of entanglement in a (often viewed as a bipartite) quantum state, and entanglement entropy is the standard measure of entanglement for pure states. It is possible to create entanglement between quantum systems that never directly interacted, through the use of entanglement swapping.

In quantum physics, entangled particles remain connected so that actions performed on one affect the other, even when separated by very large 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 (Tate, 2016).

In quantum physics, quantum state refers to the state of an isolated quantum system. A quantum state provides a probability distribution for the value of each observable, i.e. for the outcome of each possible measurement on the system. Knowledge of the quantum state together with the rules for the system's evolution in time exhausts all that can be predicted about the system's behavior. A mixed quantum state corresponds to a probabilistic mixture of pure states; however, different distributions of pure states can generate equivalent mixed states. Mixed states are described by so-called density matrices. A pure state can also be recast as a density matrix; in this way, pure states can be represented as a subset of the more general mixed states.

Quantum entanglement is a quantum mechanical phenomenon in which the quantum states of two or more objects have to be described with reference to each other, even though the individual objects may be spatially separated.

Quantum entanglement is thought to be one of the trickiest concepts in science, but the core issues are simple (Wilczek, 2016). It is possible that the quantum entanglement is involved in the life and human soul, and the spirit.

In 2012, physicists at the University of Calgary and at the Institute for Quantum Computing in Waterloo of Canada reported the new study in a new ingredient for a third entangled particle. The new form of three-particle entanglement demonstrated in this experiment, which is based on the position and momentum properties of photons, may prove to be a valuable part of future communications networks that operate on the rules of quantum mechanics, and could lead to new fundamental tests of quantum theory that deepen our understanding of the world around us. They directly generate three entangled photons using the nonlinear process of cascaded spontaneous parametric downconversion. In downconversion, a pump photon, with frequency $\omega_p$, inside a nonlinear material will occasionally fission into a pair of daughter photons with frequencies $\omega_0$ and $\omega_1$. The total energy in the process is conserved with $\hbar\omega_p = \hbar\omega_0 + \hbar\omega_1$. The daughter photons share strong energy and time correlations that are the hallmark of entanglement. The SPDC process is repeated with one of these daughter photons, at $\omega_0$, now serving as the pump, creating a pair of granddaughter photons simultaneously at $\omega_2$ and $\omega_3$. Again energy is conserved, and the total energy of the three photons created in C-SPDC must sum to the energy of the pump: $\hbar\omega_p = \hbar\omega_1 + \hbar\omega_2 + \hbar\omega_3$. The simplified representation of our three-photon state in frequency space, assuming a monochromatic pump. The three photons, consequently, share strong spectral correlations and exhibit genuine tripartite energy–time entanglement (Shalm, et al, 2012).

A pair of quantum systems in an entangled state can be used as a quantum information channel to perform computational and cryptographic tasks that are impossible for classical systems. The general study of the information-processing capabilities of quantum systems is the subject of quantum information theory. With the application of quantum entanglement, we could get the unbreakable codes, the most precise clocks ever made and superfast computers. A crucial difference between quantum and classical information is the possibility of selecting an exclusive disjunction, representing a global property of a function, among alternative possible disjunctions.

The theory of relativity usually encompasses two theories by Albert Einstein including special relativity and general relativity. Concepts introduced by the theories of relativity include spacetime as a unified entity of space and time, relativity of simultaneity, kinematic and gravitational time dilation, and length contraction.

The special relativity is based on two postulates: The laws of physics are invariant in all inertial systems and the speed of light in a vacuum is the same for all observers regardless of the motion of the light source. As of today, special relativity is the most accurate model of motion at any speed. Even so, the Newtonian mechanics model is still useful (due to its simplicity and high accuracy) as an approximation at small velocities relative to the speed of light. In the theory of relativity, time dilation is a difference of elapsed time between two events as measured by observers either moving relative to each other or differently situated from a gravitational mass or masses.

A clock at rest with respect to one observer may be measured to tick at a different rate when compared to a second observer's clock. This effect arises neither from technical aspects of the clocks nor from the propagation time of signals, but from the nature of spacetime.

General relativity generalizes special relativity and Newton's law of universal gravitation, providing a unified description of gravity as a geometric property of space and time, or spacetime. In particular, the curvature of spacetime is directly related to the energy and momentum of whatever matter and radiation are present. The relation is specified by the Einstein field equations, a system of partial differential equations.

Some predictions of general relativity differ significantly from those of classical physics, especially concerning the passage of time, the geometry of space, the motion of bodies in free fall, and the propagation of light. Examples of such differences include gravitational time dilation, gravitational lensing, the gravitational redshift of light, and the gravitational time delay. The predictions of general relativity have been confirmed in all observations and experiments to date. Although general relativity is not the only relativistic theory of gravity, it is the simplest theory that is consistent with experimental data. However, unanswered questions remain, the most fundamental being how general relativity can be reconciled with the laws of quantum physics to produce a complete and self-consistent theory of quantum gravity.

Einstein's theory has important astrophysical implications. For example, it implies the existence of black holes—regions of space in which space and time are distorted in such a way that nothing, not even light, can escape—as an end-state for massive stars. There is ample evidence that the intense radiation emitted by certain kinds of astronomical objects is due to black holes; for example, microquasars and active galactic nuclei result from the presence of stellar black holes and black holes of a much more massive type, respectively. The bending of light by gravity can lead to the phenomenon of gravitational lensing, in which multiple images of the same distant astronomical object are visible in the sky. General relativity also predicts the existence of gravitational waves, which have since been observed directly by physics collaboration LIGO. In addition, general relativity is the basis of current cosmological models of a consistently expanding universe.

Length contraction is the phenomenon of a decrease in length of an object as measured by an observer who is traveling at any non-zero velocity relative to the object. This contraction is usually only noticeable at a substantial fraction of the speed of light. Length contraction is only in the direction parallel to the direction in which the observed body is travelling. This effect is negligible at everyday speeds, and can be ignored for all regular purposes. Only at greater speeds does it become relevant.

The above contents are the collected information from Internet and public resources to offer to the people for the convenient reading and information disseminating and sharing.

**References**

1. Baidu. http://www.baidu.com. 2016.
2. Frank Wilczek. Entanglement Made Simple. https://www.quantamagazine.org/20160428-entanglement-made-simple. 2016.
3. Google. http://www.google.com. 2016.
4. Karl Tate. **How Quantum Entanglement Works (Infographic).** http://www.livescience.com/28550-how-quantum-entanglement-works-infographic.html. 2016.
5. L. K. Shalm, D. R. Hamel, Z. Yan, C. Simon, K. J. Resch, T. Jennewein. **Three-photon energy–time entanglement**. *Nature Physics*, 2012; DOI: 10.1038/nphys2492. http://www.nature.com/nphys/journal/v9/n1/full/nphys2492.html.

**6.** Ma H, *Chen G*. Stem cell. The Journal of American Science 2005;1(2):90-92.

7. Ma H, Cherng S. *Eternal Life and Stem Cell.* Nature and Science. 2007;5(1):81-96.
8. Ma H, Cherng S. Nature of Life. Life Science Journal 2005;2(1):7-15.
9. Ma H, Yang Y. Turritopsis nutricula. Nature and Science 2010;8(2):15-20. http://www.sciencepub.net/nature/ns0802/03_1279_hongbao_turritopsis_ns0802_15_20.pdf.
10. Ma H. The Nature of Time and Space. Nature and science 2003;1(1):1-11. Nature and science 2007;5(1):81-96.
11. National Center for Biotechnology Information, **U.S. National Library of Medicine.** http://www.ncbi.nlm.nih.gov/pubmed. 2016.
12. ScienceDaily. https://www.sciencedaily.com/releases/2012/12/121214191522.htm. 2016.
13. ScienceDaily. https://www.sciencedaily.com/terms/quantum_entanglement.htm. 2016.
14. Wikipedia. The free encyclopedia. http://en.wikipedia.org. 2016.
15. WITZE A. 75 years of entanglement. Science, Vol. 178 #11, November 20, 2010, p. 25. https://www.sciencenews.org/article/75-years-entanglement. 2010.

7/20/2016