A Road to Entanglement

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At present time, most of the breakthrough technologies are based on the existence of a quantum state called entanglement. Even though this state is a direct prediction from quantum theory, but it turns out that, at the time this state was proposed, it’s very difficult to prove its existence in experiment. Nevertheless nowadays we figure out an efficient way to show this in experiment, which is much easier than what pioneers did in the past, and the theory used to describe this state is also well established than the past and yet there are still a lot more left to study about this state.

Back to the early twentieth century when Quantum Theory is still in developing age, E. Schrödinger succeeded in discovering the equation, which is named after him, to describe the phenomena in atomic scale in 1926 [1]. Although the first success is already done by W. Heisenberg [2] a year before which lacks of physical relation to physics background at that time, Schrödinger equation has a strong relation to Hamiltonian Mechanics, which is one the most successful theories in nineteenth century. But along with the successful predictions for many atomic scale behaviors, this equation also introduces us a peculiar result as pointed out by A. Einstein, B. Podolsky, and N. Rosen in 1935 [3]. In their famous paper, they pointed out that the equation also predicts the existence of a state which seems to behave non-locally. If this were true, one part of the system can communicate with the other parts of the system with speed faster than light which is impossible according to special theory of relativity. Hence the quantum theory has not yet a complete theory but needs some expansion. They also provided the possible theory to describe such a state which is now known as (local) hidden variable. This difficulty in theory of physics is referred to as EPR paradox. In response to this, N. Bohr, one of the pioneers in formulating quantum theory based on Schrödinger equation, commented that these kinds of state cannot be considered each part separately since the first place and the quantum theory is actually complete.

This argument lasts for almost thirty years without a practical method to prove, until J.S. Bell came up with a possible way to distinguish the system which behave according to hidden variable theory out of from the system behave quantum mechanically. He proposed a mathematical relation, known as Bell’s Inequalities, which put the limit for a quantity associated with all system for the system which behaves according to hidden variable theory [4]. The violation of this inequality implies that the system does not behave under an influence of hidden variable, speak roughly the hidden variable does not exist. Unfortunately, at that stage the inequality is proved in term of abstract mathematic method which is difficult for practical use in many manners. Nevertheless five years later, J. Clauser, M. Horne, A. Shimony, and R. Holt pushed the frontier of physics a bit forward by figured out the way to use Bell’s inequalities in practical experiment with photon. They re-derived the inequality and came up with a new form of the inequality, the CHSH inequality [5]. With this step we are now ready to justify the EPR-Bohr argument from theoretical point of view. But on the experimental side other problems still exist. First of all is how to produce such state. In the very first proposition by J. Clauser, M. Horne, A. Shimony, and R. Holt in the same publication, we could ideally use two photons from pair annihilation of electron-position pair in positronium decay which, according to quantum prediction and experimental verification, they are in entangled state [6]. Unfortunately, at that time we don’t have any suitable devices to perform the experiment by using this source. Since the photons from this process are high energy photons in gamma ray region far beyond any detectors can measure with reliable result. Furthermore most of the optical devices available at that time cannot handle this high energy. Nevertheless they also proposed another candidate, using two photons emission from calcium atom [7]. Two photons are obtained by exciting the calcium atom up to certain energy level and let the deexcitation occurs by emitting two photons successively. These two photons have the same signature as the photons from pair annihilation when analyzed with the same method. This method in producing photons pair is more practically possible because the source and the wavelength of the photons created this way can be handled relatively easier that the photons from pair annihilation. The violation is then searched for by many groups of physicists. A few groups obtained the violation as predicted but not distinctive
enough to confidently justify the statement [8], [9], [10]. Finally in 1981 the first concrete experimental result is published by A. Aspect [11] and this result could be regarded as strong evidence against (local) hidden variable. And again quantum theory successfully predicts the experimental result and the entanglement does exist. After this point many improvements have been done in many aspects, such as a better source of entangled photons [12], a better detecting system and a simplified experimental set up [13],[14], etc.

On the theory side of view, even though Bell’s inequality in the form of CHSH inequality could be used for verifying entanglement, this method is not flexible enough to apply to general cases. Since Bell’s inequality itself is too abstract and it does not state directly about entanglement, but puts the limit for the state which cannot be described without entanglement, roughly speaking, even we achieve the entangled system we could find that the inequality is not violated, therefore simplification and assumption are needed for practical using. Even in CHSH inequality form, it is not applicable to any system because it is derived for special case of two photons system and based on rotational invariant system. In the late twentieth century, entanglement is studied and formulated in a deeper level. Up till now, many other methods for verifying the existence of entanglement have been proposed. There are two methods which are strikingly interesting. The first method is Peres Separability Criteria [15] which is proposed in 1996 by A. Peres [15]. Unlike Bell’s inequality which focuses on outcome of the measurement, the method focuses on the state itself. This method is used for distinguishing an entanglement from other states by considering the properties of the density matrix representing the entangled state and typical state. In addition to the capability to identify an entangled state this method is also capable to consider the limit of classical noise that is mixing with the entangled state so that we can still observe the entanglement. This method is considered to be stronger justification method than Bell’s Inequality, since now the characteristic of entanglement can be extract out directly. Another remarkable theory is Entanglement of Formation by W. Wootters in 1997 [16]. With this theory, entanglement can be studied as a continuous variable ranged from not-entangled to maximally entangled which is very useful in characterizing the system and studying for its applications. This method also uses the properties of the state itself but with more complicated way than Peres Separability. At this time the entanglement is not limited on just photons or two particle system any more, for example, studying entanglement between to atom [17], entanglement between three particles [18]. Similar to other branches of science, the better the physicists understand the entanglement the more possible applications have been proposed, such as high resolution 3D imaging [19], [20], quantum teleportation [21], quantum cryptography [22],[23].

Needless to say, entanglement is another successful prediction from quantum theory which also yields us fruitful applications. Many science-fiction dreams about cutting edge technologies, at least in principle, could come true based on entanglement. Despite the fact that this state is counter intuitive in many ways similar to other predictions from quantum theory, long researches and studies provide us an unavoidable conclusion that this state really exists out there. And the story is not at the end yet many investigations and researching are required to push the frontier of knowledge of mankind outward to the mysterious world of entanglement.

References