Study on the Relationship between Quantum Entanglement and Spacetime

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Abstract. Quantum entanglement and spacetime are strongly associated fields in modern physics. This paper investigated the connection between quantum entanglement and spacetime, particularly focusing on how they mutually form one another. The quantum mechanics and relativity theory cannot peacefully coexist in some cases, so it is difficult to combine them together. This article analyzes studies which suggest quantum entanglement can fabricate the continuous spacetime, and studies that imply spacetime geometry can explain quantum entanglement. These findings may bring us a better vision of the relation between quantum mechanics and relativity, as well as pave a path to the unification of quantum mechanics and relativity.

1. Introduction

Quantum entanglement is a phenomenon in quantum mechanics, that when two or more particles are entangled, their properties can no longer be described individually. Instead, they can be only described as an entity with wavefunction. Derived from this simultaneity, nonlocality is a principle which is used to explain the simultaneity of quantum entanglement across spacetime. It means that objects may affect simultaneous event that is not adjacent to them. Action at distance is hence possible. In this process, the information may still be unable to be transmitted faster than speed of light, as quantum entangled pair would disentangle once it is observed and the information observed would be random. Nonetheless, nonlocality might still “cannot be made to peacefully coexist with special relativity” [1]. For relativity theory, spacetime is a key concept. It is the four-dimensional entity that consists of three space dimensions and the dimension of time. Every particle’s position is presented by four parameters, three for space and one of time. The relativity theory and quantum mechanics are two fundamental theories that shape our current understanding of the physical world, yet they are not perfectly consistent. The author intends to find viable connections between spacetime and quantum entanglement, a field that has been studied in the last few decades, when some potential structures are found that can be used to describe the relation. Studies suggest that quantum entanglement is not the mere connection between different particles, but the connection of the degree of freedom of the spacetime where they are located [2]. What is more, the connection between spacetime and quantum entanglement can draw a larger picture: a universe which is fabricated by entangled spacetimes.

2. Quantum entanglement and nonlocality

2.1. Bell’s inequality and the violation of locality

The concept of quantum entanglement originates from the famous EPR paradox, come up by Einstein,
Podolsky, and Rosen. A quantum entangled particle pair can be only described with the same wave function, so their behaviors are interrelated. As one particle spins up, the other must be down. This process is immediate, so the information must be traveling with speed, greater than the speed of light if the behaviors of particles are at random. This odd property makes Einstein and the other two physicists draw the conclusion that there must be some hidden variables controlling their performance. Their conclusion is rooted in a simple idea: principle of locality. Principle of locality is that an object can only pass the influence of forces continuously through either field or space. This principle, nonetheless, had been disproved by the test of Bell’s inequality [1]. If that energy/matter and information cannot be transmitted faster than speed of light is still an axiom in physics, the principle of locality must not be true. Bell’s inequality is the formula based on the assumption of hidden variable. Hidden variable means that the collapse of wavefunction does not have an action at distance among the entangled particles. Every behavior of the paired particles is predicted by hidden variables, so uncertainty is not required in this theory. Therefore, the transmission of information is local since there is no action at distance among entangled pairs. Bell’s inequality is a property predicted by this theory. Bell’s inequality $|P_{x} - P_{y}| \leq 1 + P_{xy}$ predicts behavior of entangled particles different from that of quantum mechanics based on Copenhagen’s interpretation. According to the experimental examination of this inequality, this inequality is clearly violated. Therefore, nonlocality of quantum entanglement should be the only possible explanation that preserve the principle of constancy of light speed.

2.2. Nonlocality in relativistic frame of reference

Many works had been done in discovering the relation between the frame of reference and quantum entanglement. It has been verified with experiments that Bell’s inequality is still violated under Lorentz Boost [3]. This finding suggests that the correlations between entangled particles are preserve in all frames, even in those relativistic ones. Similar studies had been performed by other scholars, who mainly studied the cases of quantum entanglement between relativistic massive particles. This finding shows that degree of violation of Bell’s inequality is dependent on the relative velocity of the particle measured with respect to the laboratory [4], yet particle pairs do not disentangle as they reach a certain relative speed. Therefore, the finding further confirms conservation of nonlocality in all frame of reference.

3. The way that quantum entanglement and spacetime related with each other

3.1. Spacetime understood in terms of quantum entanglement

Whether quantum entanglement and spacetime are related is a profound question. A study made by Mark Van Raamsdonk finds that “emergence of classically connected spacetimes is intimately related to the quantum entanglement of degrees of freedom in a non-perturbative description of quantum gravity” [2]. The disentanglement of two separate spacetime is similar to that of two entangled particles. In fact, if two regions of spacetime is disentangled, they “pull apart” from each other. Built on the non-perturbative description of quantum gravity, this finding can be applied to spacetime of the physical world. Raamsdonk extended the discussion to some examples of gauge theory/gravity duality [5]. He found out that “in at least some cases, classically connected spacetimes may be understood as particular quantum superpositions of disconnected spacetimes” [6]. As distance between two regions of spacetime increases, the entanglement of degree of freedom degrades. Disentanglement of two separated regions of spacetime should be considered no longer connected.
These two studies rely on the non-perturbative description of quantum gravity and the gauge theory/gravity duality. Particularly, they rely on some particular cases of gauge theory/gravity duality. Therefore, if gauge theory’s prediction in this field is proved invalid, the results would also collapse. However, since the gauge theory well predict the behavior of quantum world, these examples might also be true. Yet they need further experimental verification.

The fact that quantum entanglement might form spacetime is an exciting finding. Quantum entanglement has long been considered irrelevant to relativistic theory. Typically, researchers did not treat entanglement, namely nonlocality, relevant to spacetime. These studies suggest a deep connection between two seemingly distinct physical entity, that classically continuous spacetime can be described as an extended object of quantum entanglement.

3.2. Quantum entanglement fabricated by the connection of spacetime

Instead of forming spacetime from quantum entanglement, there are other studies suggest that quantum entanglement can be described in terms of spacetime connection.

The first study derives from the coincidence of the maximum “probability of quantum entanglement of two particles” of 9.0169945% and “exactly the golden mean $\phi$ to the power of five $(\phi^5)$” [7]. This theory is somewhat surprising, yet it is supported with valid calculation. Its conclusion shows that quantum entanglement can be a result of complex spacetime geometry. The emergence of quantum entanglement might not solely be explained in term of quantum mechanics, which ignores the effect of spacetime geometry. In addition, it might also be intrinsically linked to the structure of spacetime.

Despite its exciting result, it is based on calculation of the coincidence of probability of quantum entanglement and golden mean to the fifth power. Whether it is a superficial coincidence or profound relation would greatly influence its validity. Besides, experimental verification is still needed. If the result is proven physical meaningless, it is also not a valid theory. Nonetheless, this study still provides some insights about how to describe quantum entanglement in terms of spacetime geometry.

The relation between quantum entanglement and spacetime has a more prominent meaning: quantum entangled pair can be seen as a non-traversable wormhole. Researchers “construct holographic dual of two colored quasiparticles in maximally supersymmetric Yang-Mills theory entangled in a color singlet Einstein-Podolsky-Rosen (EPR) pair” [8]. According to their research, entanglement is “encoded in a geometry of a non-traversable wormhole”. This finding is significant because it provides connection between the strangest predictions of quantum mechanics and that of relativistic theory. Wormhole is no less strange than quantum entanglement, yet they are the result of distinct mechanism. Wormhole is the result of severe torsion of spacetime, while quantum entanglement is relation between particle pairs. Combining these two phenomena is helpful to understand the properties of spacetime.
Combined together, these studies suggest a larger picture of physics study: a spacetime intrinsically linked by entanglement. From the point of view of quantum entanglement, it is the entanglement between different regions that fabricates the classic continuous spacetime. From the stance of spacetime, it is the intrinsic property of the entity itself that embodies the emergence of entanglement.

4. Gravity and Entanglement
A larger picture is implied by the entangled spacetime. According to the study made by Chunjun Cao, Sean M. Carroll, and Spyridon Michalakis, the spacetime itself seems to self-emerge from the entanglement. They “examined how space can emerge from an abstract quantum state in Hilbert space, and how something like Einstein’s equation is a natural consequence of this bulk emergent gravity program” [9]. What is more, the model allows classical wormhole to emerge as a result, which deepens the relation between quantum entanglement and spacetime, since this is an unexpected feature without putting the two entities together. “Lengths and other geometric quantities are determined by entanglement”, and “gravity appears to arise from quantum mechanics in a natural way”. Self-emergence of spacetime from quantum mechanics implies a new relation between gravity and quantum mechanics. The study combined and rebuilt the previous studies from a very solid basis, so that no semiclassical backgrounds like classical may have influenced the result. The rebuilt makes the result more convincing, in that it excluded assumptions of the previous studies that might be mistaken from this one. Starting from pure quantum state instead of “quantizing classical degree of freedom”, so the construction of spacetime from quantum entanglement would not be the result of those potentially mistaken assumptions.

The self-emergence of spacetime from quantum entanglement is helpful in constructing a quantum gravity theory. This is a crucial insight to our understanding of gravity, the last uncovered fundamental force in Yang-Mills theory. Described as the result of spacetime geometry in relativity theory, gravity cannot be described like other forces. For relativity theory, gravity is not a force at all, but an illusion produced by the movement of objects and the distorted geodesic of spacetime near a massive object. If the spacetime geometry can be successfully described in quantum scale, the gravity may be described in terms of quantum mechanics. With the interesting connection that is newly found, this long existing gap may be filled out.

5. Discussion
The spacetime can self-emerge from quantum entanglement, which can be explained by spacetime geometry. This shows that spacetime is closely linked by some rules of quantum mechanics. In addition, the fact that quantum entanglement might be understood as wormhole or the result of spacetime geometry also suggests quantum entanglement itself is closely related to the mechanics of
spacetime, a field which can be effectively explained by relativity theory. The studies of relations between quantum entanglement and spacetime are still restrained to hypotheses, nonetheless, meaning these results might still be invalidated by experimental verification. Despite these risks, studies in this field are still noteworthy because of the provision it brings. Besides, the failure of some predictions might show false understanding of some ideas in physics, so it can also lead to a new field of research even if these results are proven incompletely correct.

6. Conclusion
From the studies of quantum mechanics and relativity theory, the relation between quantum entanglement and the spacetime seems intrinsic. Derived from the known example of gauge theory/gravity duality [6], the continuous spacetime can be fabricated by quantum superpositions of disconnected spacetimes. This implies a potentially crucial role of quantum entanglement in spacetime. In addition, the study of space and Hilbert space shows that the quantum state naturally produces space. On the contrary, Cantorian spacetime geometry can explain quantum entanglement in context of spacetime geometry [7]. Moreover, the study of wormhole shows that quantum entanglement can be considered as non-traversable wormhole. In conclusion, all these studies imply that quantum entanglement and space can be mutually explained. These studies lack of direct evidence from experiment. Some further researches on the field might solve this problem, so the theory can make valid predictions.

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