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Review paper

Does quantum Entanglement more Fundamental than Space-time?

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Abstract

One of the biggest unanswered questions is where from the space-time originate? Or we can ask is there anything more fundamental than space-time? To find causes responsible for the birth of space-time, general theory of relativity which describes gravity as a curvature of space-time and quantum mechanics which is used to describe entropy of the space must be taken into account. In this paper we are discussing different theories to explain the origin of space-time. The conclusion of our study is that quantum entanglement between particles on the boundary of the space whichis holding together the three dimensional universe within it, is more fundamental than space-time in some sense and as quantum entanglement, vanishes the three dimensional universe starts splitting itself.

Keywords: Entanglement, Space-time, Thermodynamics, Gravity.

Introduction

In physics every event is described by two variables one is space and other is time. These are considered as fundamental variables and other quantities are derived from these. Is there anything which is more fundamental than space-time? Finding the answer of this question is a difficult task. It is the belief of many researchers that only physics has its answer otherwise physics will not be complete. Physics may explain not only the origin of space-time but also the behaviour of space-time. To explain the fabric of space-time, we must unify atomic level quantum theory and planet level general relativity. Finding that one huge theory is a daunting challenge.A successful theory of quantum gravity is one of the biggest goals of modern physics. The entangled states are those states which cannot be written as a convex combination of product states, i.e.

$$\hat{\rho} \neq \sum_i p_i \hat{\rho}_i^1 \otimes \hat{\rho}_i^2 \otimes \cdots \otimes \hat{\rho}_i^n$$

Pure entangled states are those having maximum entanglement and examples are singlet state and Bell states. For bipartite system having subsystem 1 and 2, it has the following forms[1]:

$$|\phi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle),$$

$$|\psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle),$$

A class of noisy entangled states termed as Werner state has the form

$$\hat{\rho} = p|\psi\rangle\langle\psi| + (1-p)\frac{I}{4},$$

here $|\psi\rangle$ is pure entangled state while $(1-p)\frac{I}{4}$ is the noise and p is a parameter predicting the pure entanglement present in it and varies in between 0 and 1[2]. When p=0, the state is separable and p=1 corresponds to maximally entangled state.

Entanglement and space-time

The first idea to explain origin of space-time is to consider gravity as thermodynamics. It became clear that quantum mechanics and gravity were intimately interwined with thermodynamics by the discoveries made in early 1970's[3,4]. In 1974, Stephen Hawkings of University of Cambridge, UK, showed that black holes will spew out radiations as if it was hot due to the quantum effects in the space around it. These radiations are called as Hawking's radiations. Jacob Bekenstein at Hebrew University of Jerusalem showed that black holes possess entropy. In this context entropy has different meaning[5]. In general, entropy is governed by temperature but here it is proportional to the surface area of event horizon of black hole. Event horizon is defined as the boundary of black hole out of which light can not escape. It may be interpreted as encoding of information of black hole on the surface of event horizon just like a two dimensional hologram which encodes a three dimensional image. In the year 1995, a physicist at the University of Maryland in College Park, Ted Jacobson postulated that every point in space lies on a tiny black hole horizon which satisfies entropy area relationship[2]. Using this postulate, he succeeded in deriving Einstein's equation of general relativity with the help of laws of thermodynamics. But in the development of mathematics, the idea of bending space-time was not considered. The conclusion of his result is that gravity is also statistical. It is a macroscopic approximation to the unseen constituents of space-time just like the laws of thermodynamics.

Even though it is correct but it does not say anything about the fundamental constituents of space-time.

Another theory was given by Ashtekar and others in 1980's. This theory says that the space-time is evolved just like an evolving spider's web. The information about the area of the region is contained in the web of strand when they pass through it[6,7]. This information describes the shape of space-time in the vicinity of the strand. It is not possible to insert an extra strand of less area because strands carry information about area and volume. Therefore it will simply be disconnected from the rest of the web and will drop out of space time.

The advantage of this theory is the concept of minimum area which restricts the infinite amount of curvature to an infinitesimal point. It is a good sign that it can not produce the kind of singularities because Einstein's equations of general relativity does not hold good for singularities and break down at the centres of black holes.

It is not a complete unified theory because it does not include any other forces as well as the emergence of space-time from such a web of information is yet to be shown.

Meanwhile, Van Raamsdonk proposed a very different idea about the origin of space-time. It is based on the holographic principle which was given by Juan Maldacena. He is a string theorist at the Institute of Advanced Study in Princeton, New Jersey. He proposed an influential model of a universe in 1998. According to his model universe has a three dimensional space containing strings and black holes governed by gravity and is bounded by a two dimensional boundary of elementary particles and fields that obeys ordinary quantum laws without gravity. The boundary is infinitely far away from the hypothetical residents of universe. He developed an explicit mathematical form for entropy of black holes. These equations describe dynamics of an event in three dimensional universe. The event can also be described by the equations of the two dimensional boundary. He also suggested that the entropy of black holes lies on its surface.

In 2010, Van Raamsdonk studied quantum entanglement of particles. Quantum entanglement is a very strange phenomenon of quantum mechanics which says that measurement on one particle affect the other i.e. particles are connected with each other without any physical media. He then using the concept of quantum entanglement explained that if the two dimensional boundary of three dimensional universe is divided into 2 parts and as the quantum entanglement between these two parts disappears then the space would start dividing itself like a splitting cell. This process of splitting of universe will stop till the last connection between two halves snaps. Van Raamsdonk concluded that the three dimensional universe is being held together by quantum entanglement on the boundary. As Van Raamsdonk said, "in some sense, quantum entanglement and space-time are the same thing".

Another way of understanding the relation between entanglement and space-time as suggested by Raamsdonk is to consider a specific quantum system associated with gravity such that each state of the system corresponds to some space-time[8]. Now consider a larger system having N quantum states with no entanglement present between them then there will be no connection between the space-time of individual state but if we consider quantum superposition of these states with enough entanglement then the resulting complicated state can be interpreted as a single connected space-time via a wormhole. Since all the individual states had interpretations as disconnected space-times, therefore we can say that a quantum superposition of disconnected space-time has produced a connected space-time. Alternately, one can say that by entangling the two parts of the original system, we have managed to connect up two parts of the corresponding space-time.

According to Becker[9] entanglement and wormholes are connected with each other and this connection was first proposed in 2009.According to this proposal, the neighbouring fields of black holes are more entangled than with region farther away in space or in time. It means that black holes are entangled with each other. This inspires Van Raamsdonk to think that the geometry of space-time may be related with entanglement. Very soon he showed that space-time is flexible i.e. the shape of space-time can be altered by altering the entanglement between fields. In this way Raamsdonk managed to connect the bendy space-time of general relativity, with quantum mechanics."If you change the pattern of entanglement, you also change the geometry of space-time," says Juan Maldacena in support to Van Raamsdonk. Van Raamsdonk, gave a theoretical model to show that entanglement and wormholes are connected. This model is based on Hawking's radiation emitted by a black hole which contains half of its mass and when these radiations collapse a second black hole is created. "Now you have two black holes, maximally entangled," says Van Raamsdonk. "Do the exact solution and you find you have two black holes connected by a wormhole" That ups the likelihood that space-time's bendy structure comes from entanglement – and that wormholes do too.

Another reasoning in favour of wormhole entanglement is as follows: black hole emits Hawking's radiations i.e. particles which must be entangled with black holes as well as with each other. As the entanglement between black hole and its radiation vanishes, an intense high energy blast will take place immediately inside the event horizon, which is against the laws of general relativity. According to general relativity, black holes interior should be smooth. Susskind and Maldacena, adds that things will be changed if we assume that entanglement gives rise to wormholes. This will not violate laws of quantum monogamy which removes the need to break entanglement[10]. As Maldacenasays: "This suggests that quantum is the most fundamental, and space-time emerges from it."

Conclusion

We can say that quantum entanglement is more fundamental than space-time.

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